Status of the SoLid experiment and recent analysis developments

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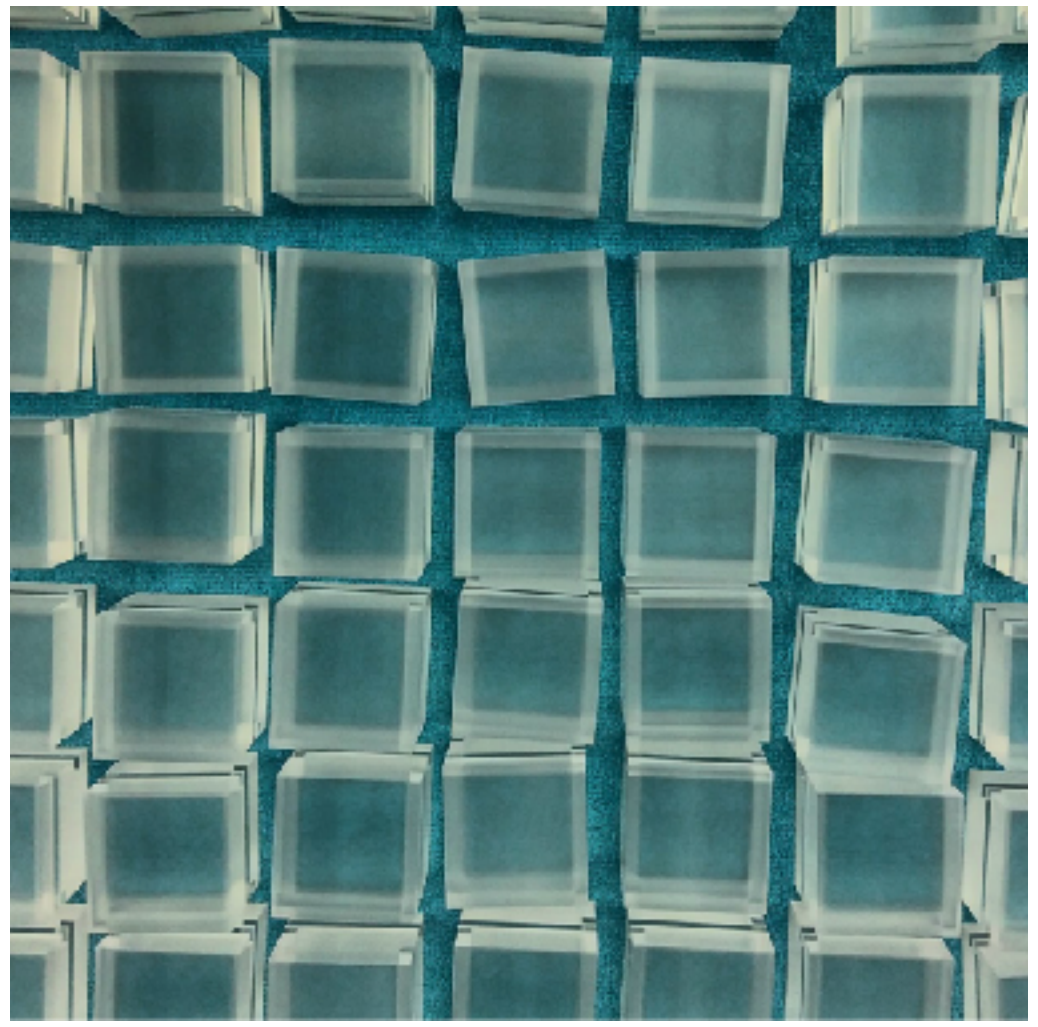
for the SoLid Collaboration

Solid-experiment.org

Technical meeting on Nuclear Data needs for Antineutrino Spectra Applications

16th January 2022



SoLid

Outline

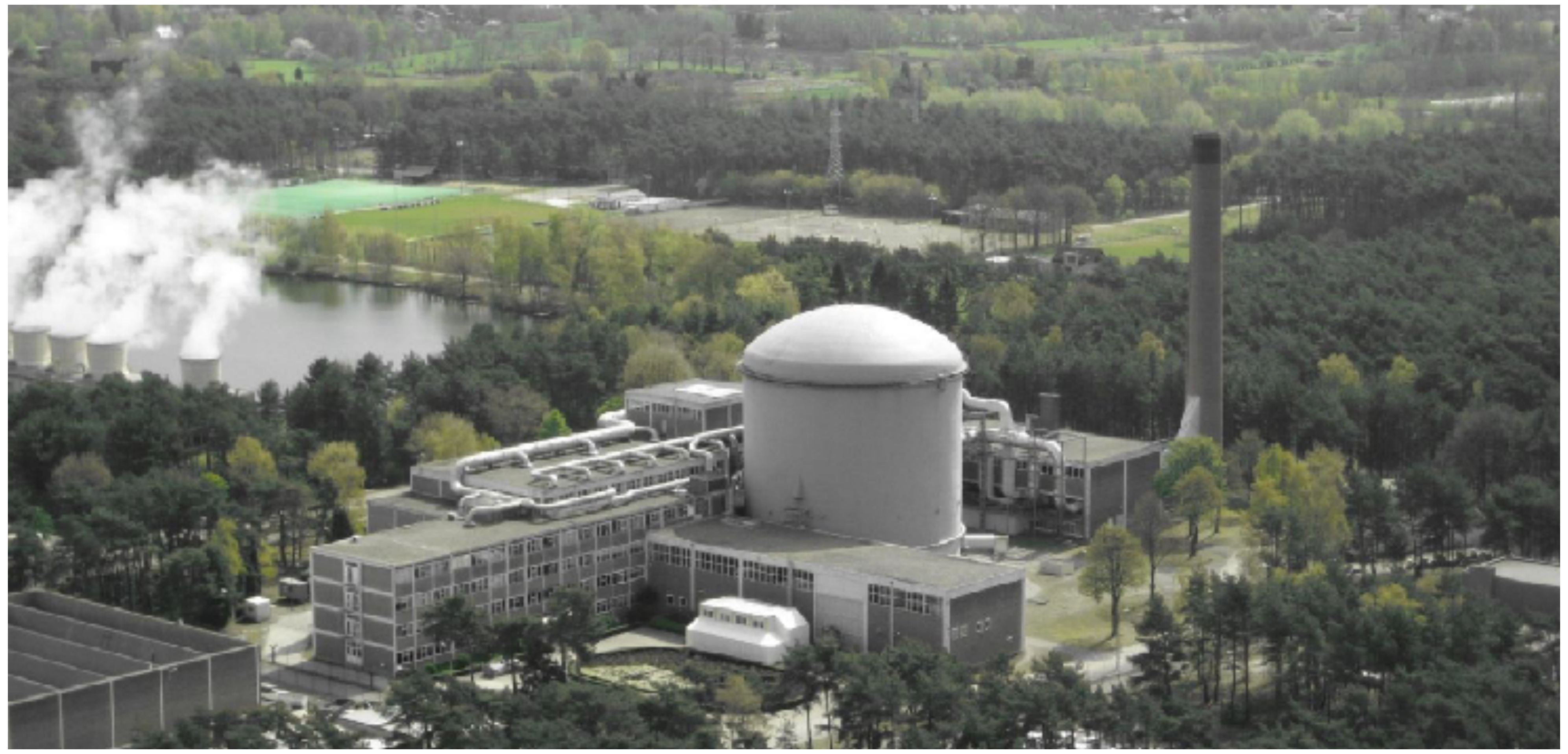
Overview of the SoLid experiment

Reconstruction & calibration

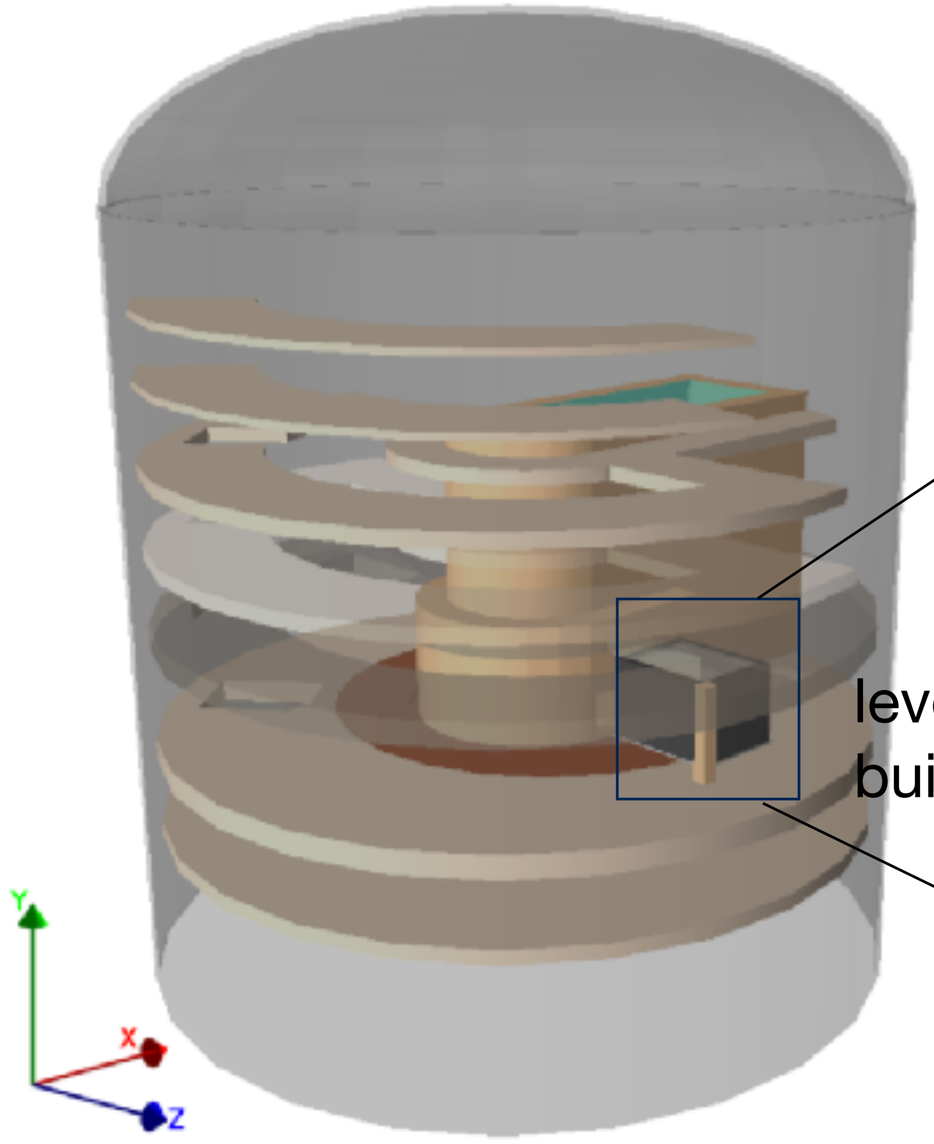
Status of the antineutrino analysis

Summary and outlook

The SoLid experiment at the SCK-CEN BR2 reactor

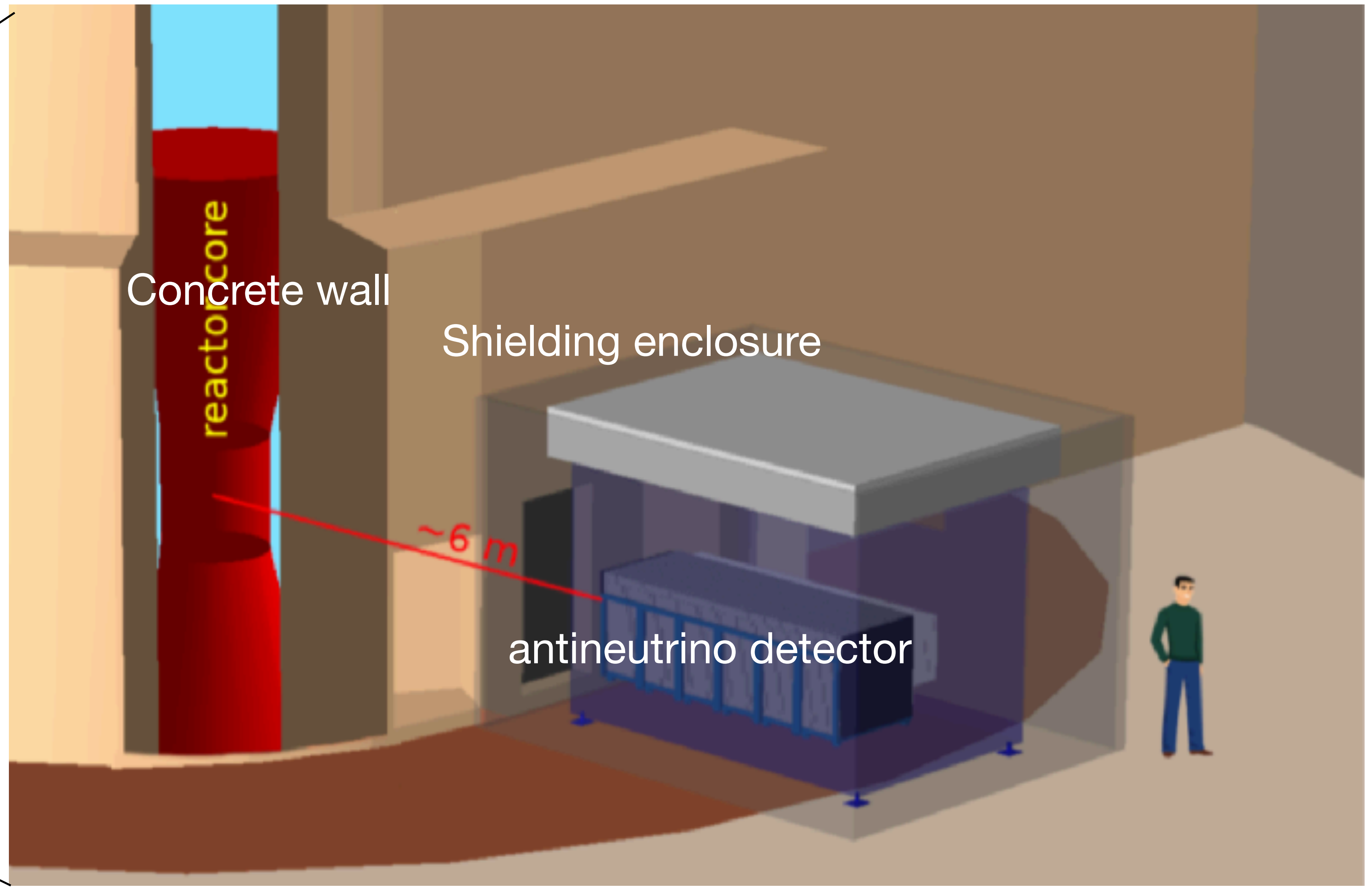


- Detector baseline : **6-9 m** from the BR2 reactor
  - **5x** movable modules on rail system, **1.6 tonnes** fiducial mass
  - **ISO-freight container** to control external noise and SiPM dark count rate
  - **Low Z external** shielding based on H_20 bricks and PE slabs and **Cadmium** sheets around container
  - High Z gamma-ray shielding in front of reactor
  - High security area with **restricted access**



Detector located on level 10 of the BR2 building

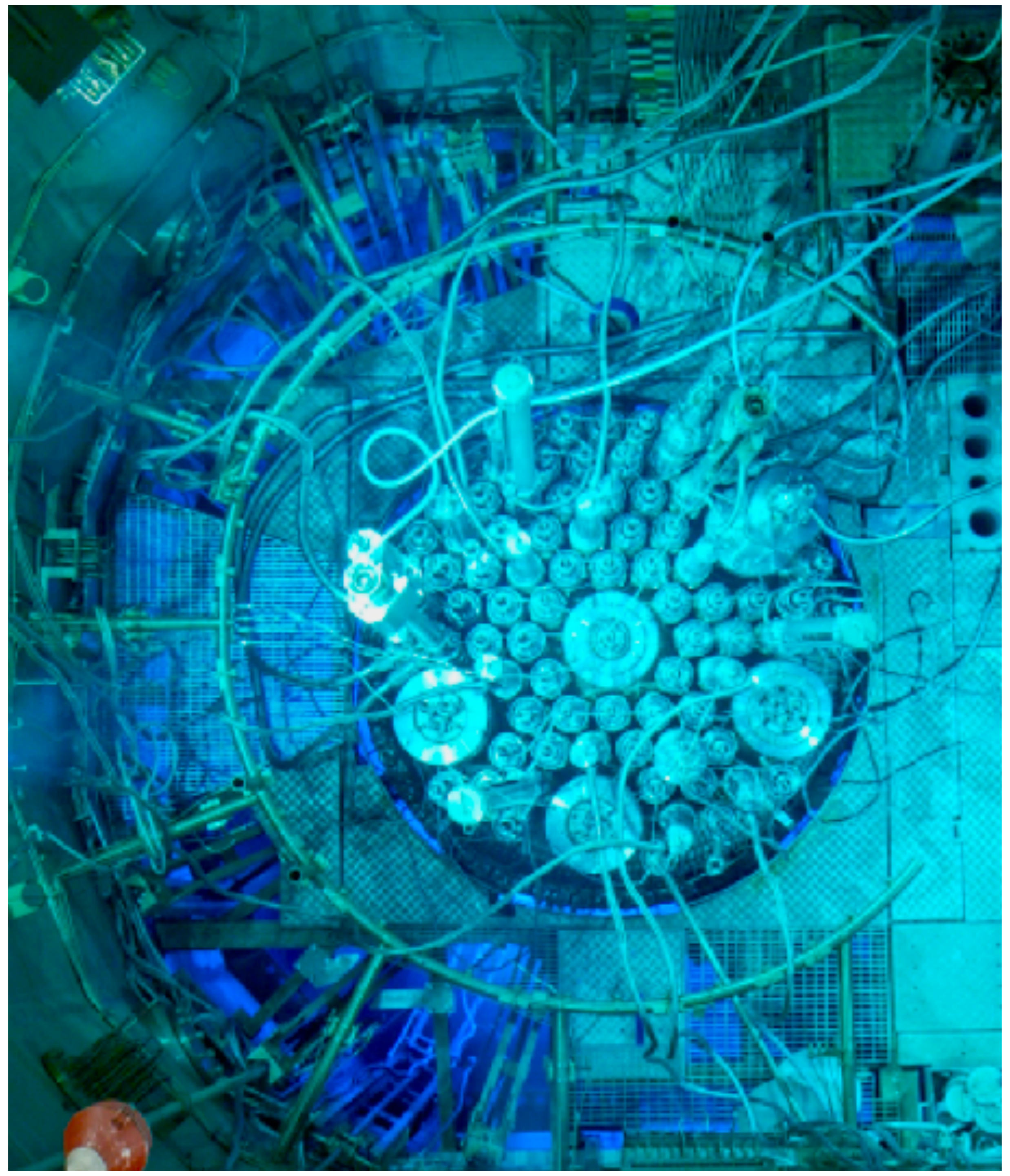
BR2 building

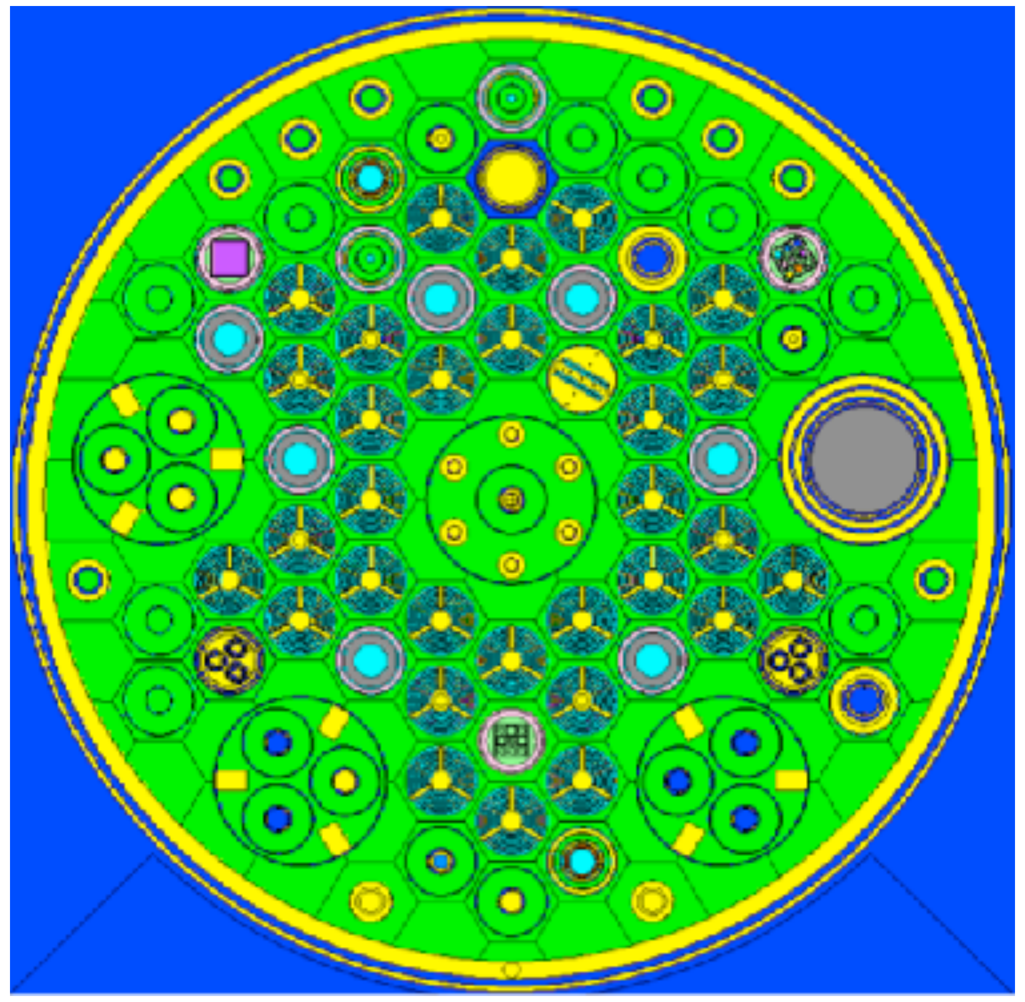


https://iopscience.iop.org/article/10.1088/1748-0221/16/02/P02025

The BR2 reactor

- Tank in Pool MTR research reactor
- Licensed to operate at power up to 100 MW
  - Variable operating power (45-80 MW)
  - 6 cycles per year on average (140 days)
  - Beam ports shut / no other experiments
    - Low level of reactor background
  - Core evolution modelled in MCNP-CINDER
    - used to predict antineutrino spectrum





SoLid

SoLid : a different approach ?

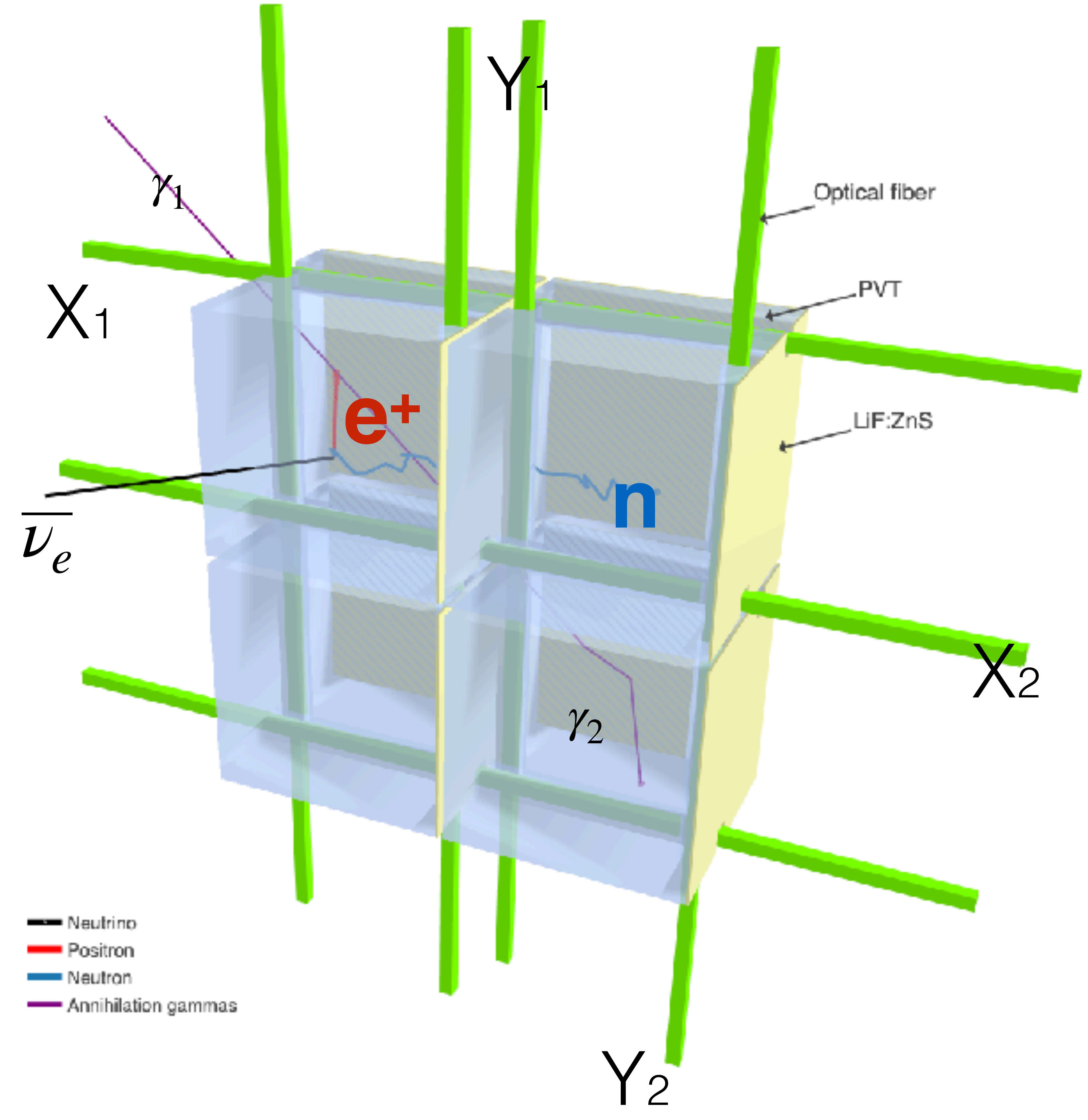
- Plastic scintillator detector provides alternative technology for antineutrino measurement
  - **Excellent linearity of response**
- Highly segmented technology:
  - **Isolate positron energy**
  - Uses IBD topologies to classify signal and backgrounds
- **SoLid provide a unique dataset for sterile neutrino and U-235 spectrum analyses**

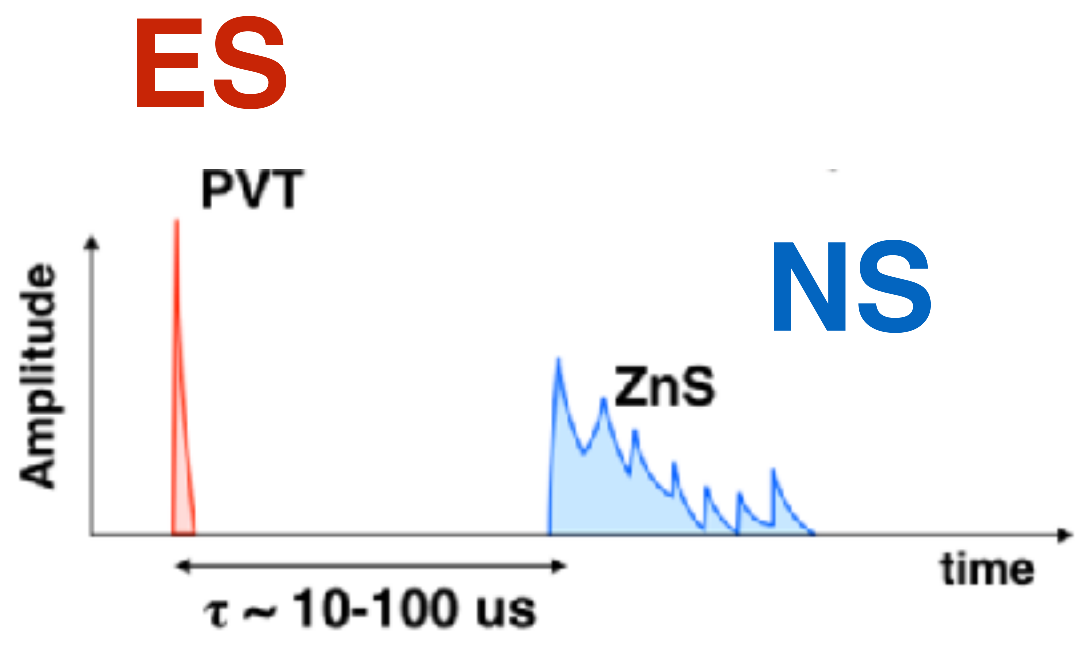
- Challenges of SoLid technology:
  - Heterogenous detector
  - High segmentation
  - Large number of read out channels
  - No gamma-neutron PSD
  - Different backgrounds

SoLid

Scintillator cube detector technology

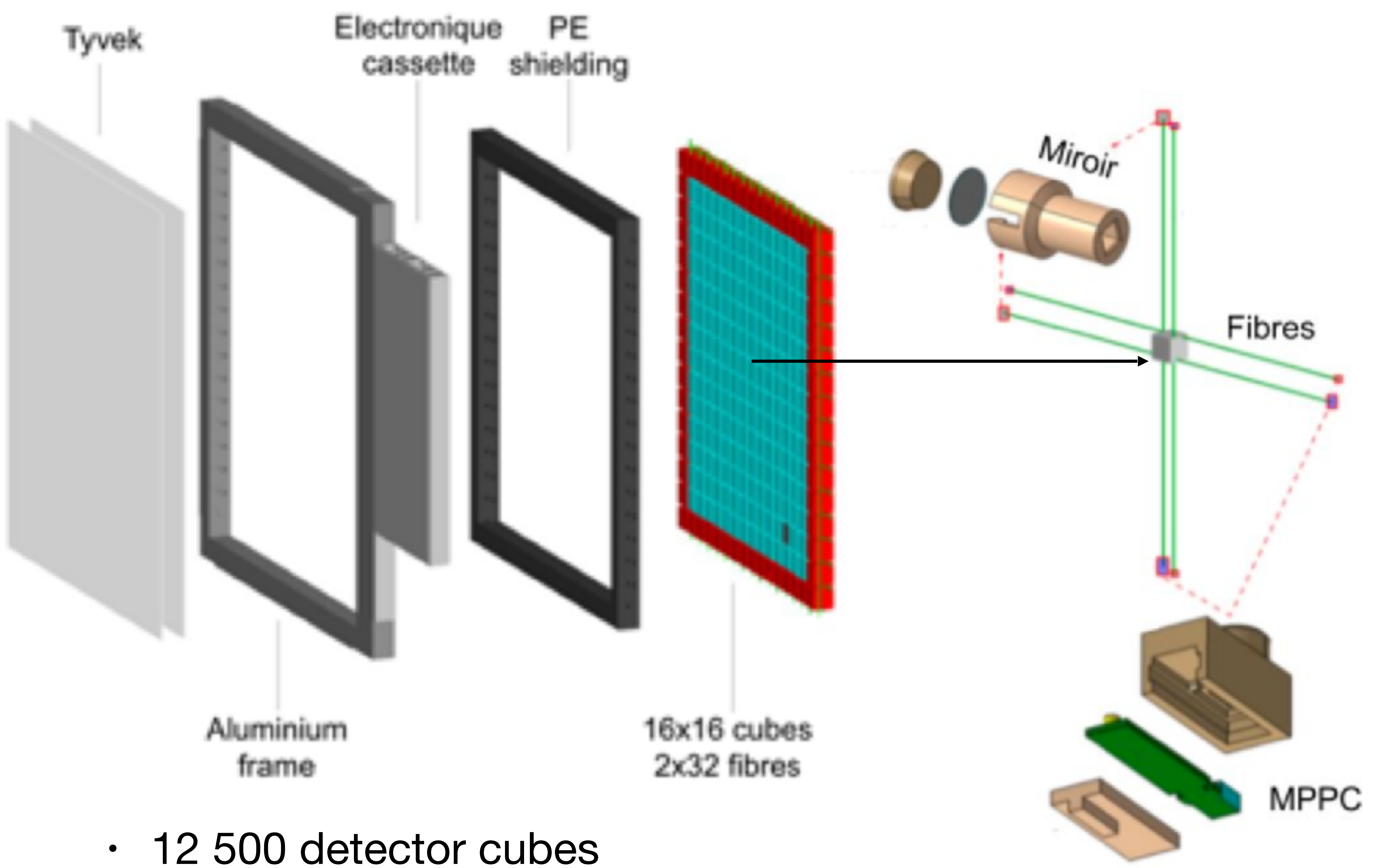
- Stack of 5 x 5 x 5 cm cubes
- Covered with two LiF:ZnS(Ag) sheets
- Wrapped in reflective material (Tyvek)
- Four Wavelength shifting fibres crosses each cube ($X_{1,2}$ and $Y_{1,2}$)
- Electron Signals (**ES**) are fast signals in PVT/ZnS
- Nuclear Signals (**NS**) defines ZnS slow scintillation
- Time and spatial signature of event



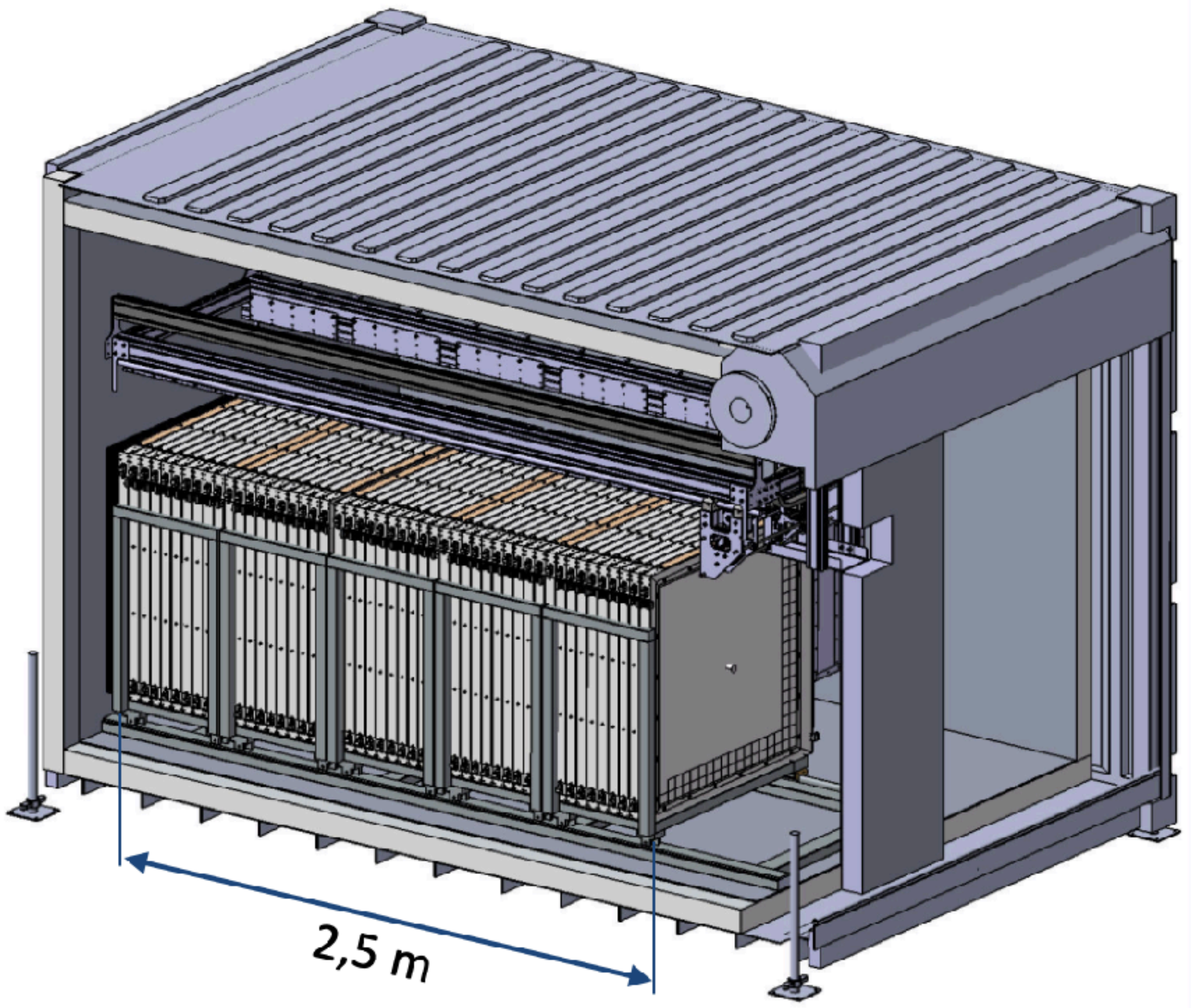


SoLid

SoLid Phase 1 detector



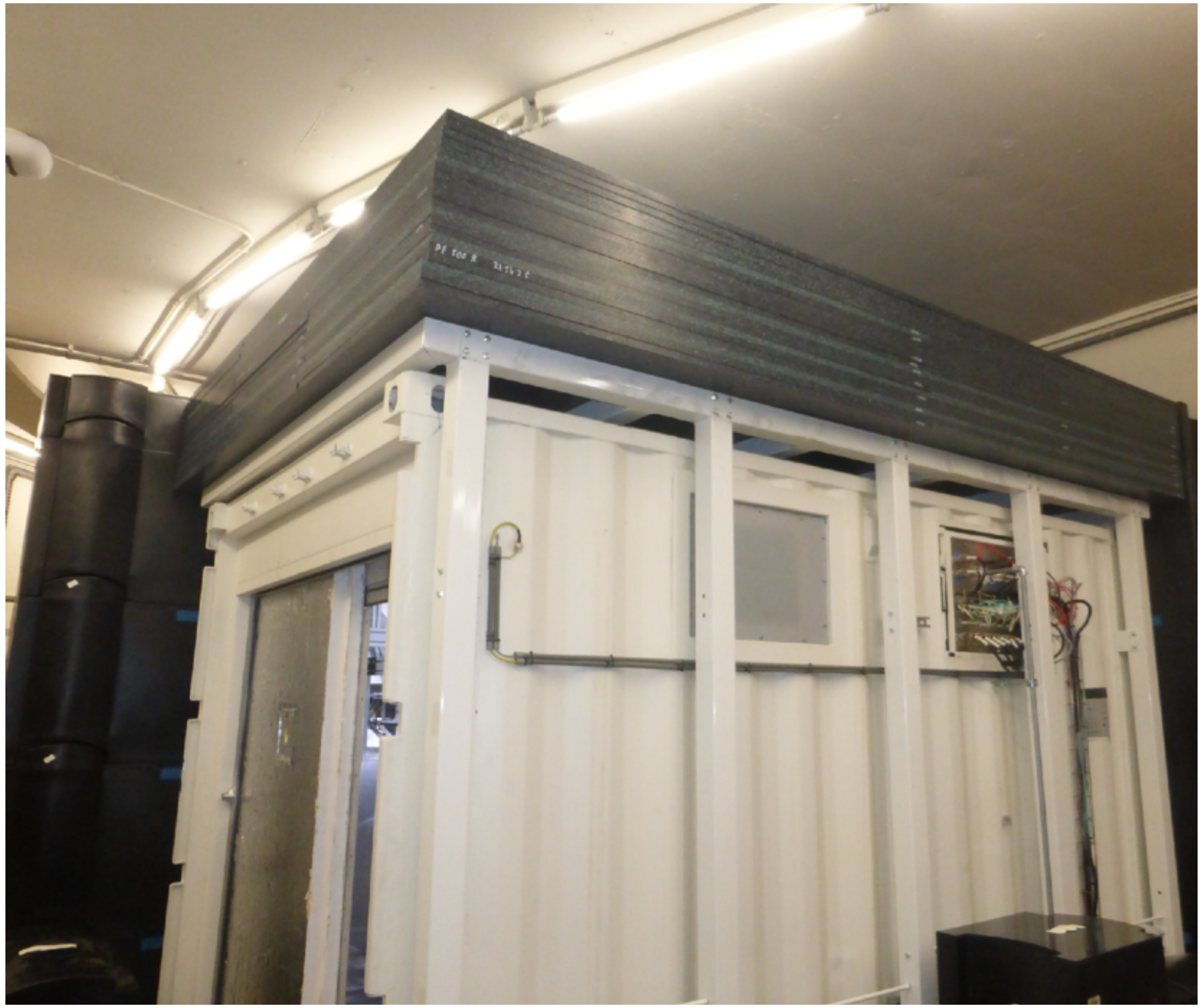
- 12 500 detector cubes
  - 256 cubes / plane
- 3200 read out channels
  - 64 BCF-91A fibres + S12 series MPPCs / plane
- 5 modules
- 10 planes / module

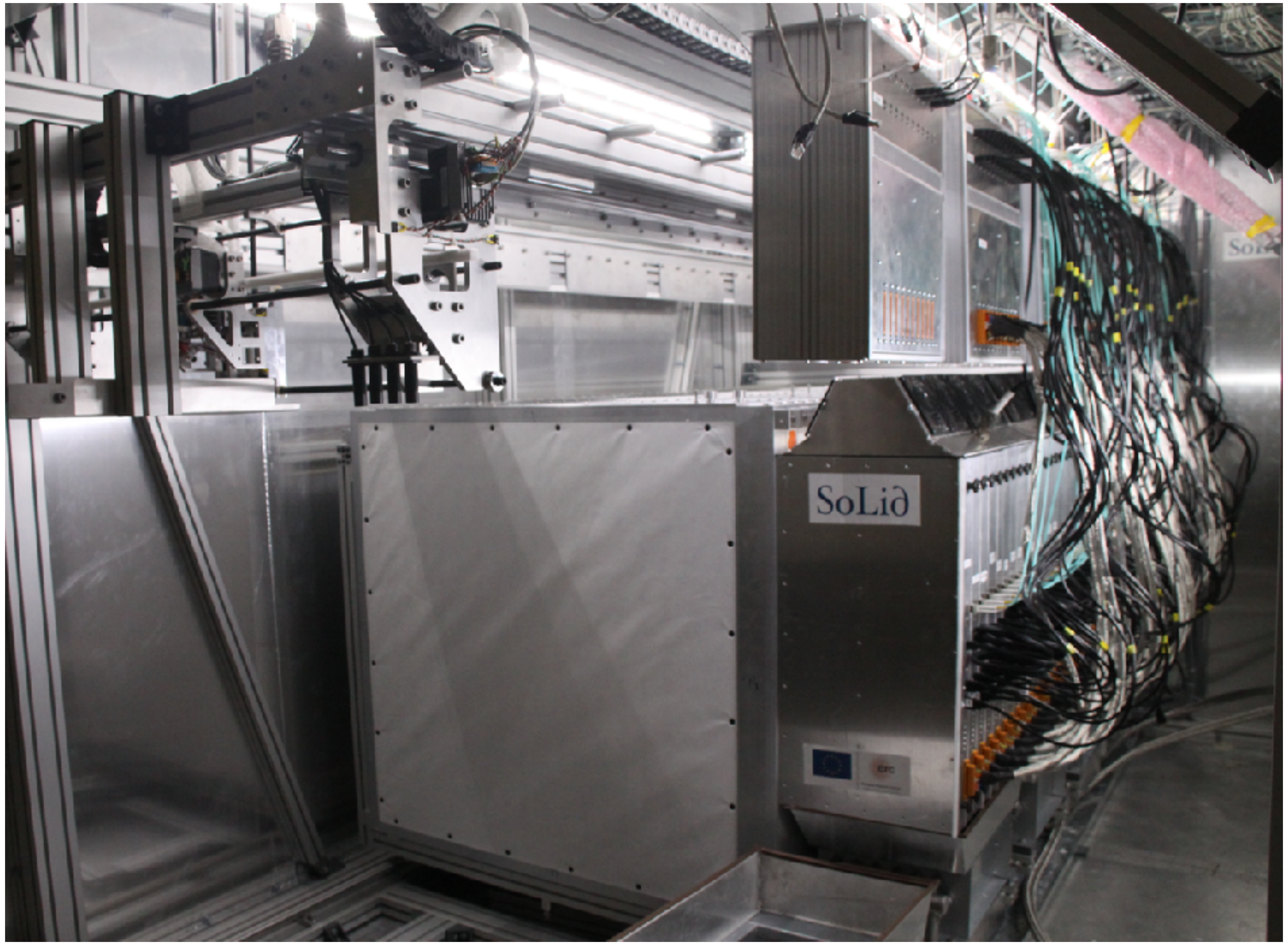


Rail system to stack modules

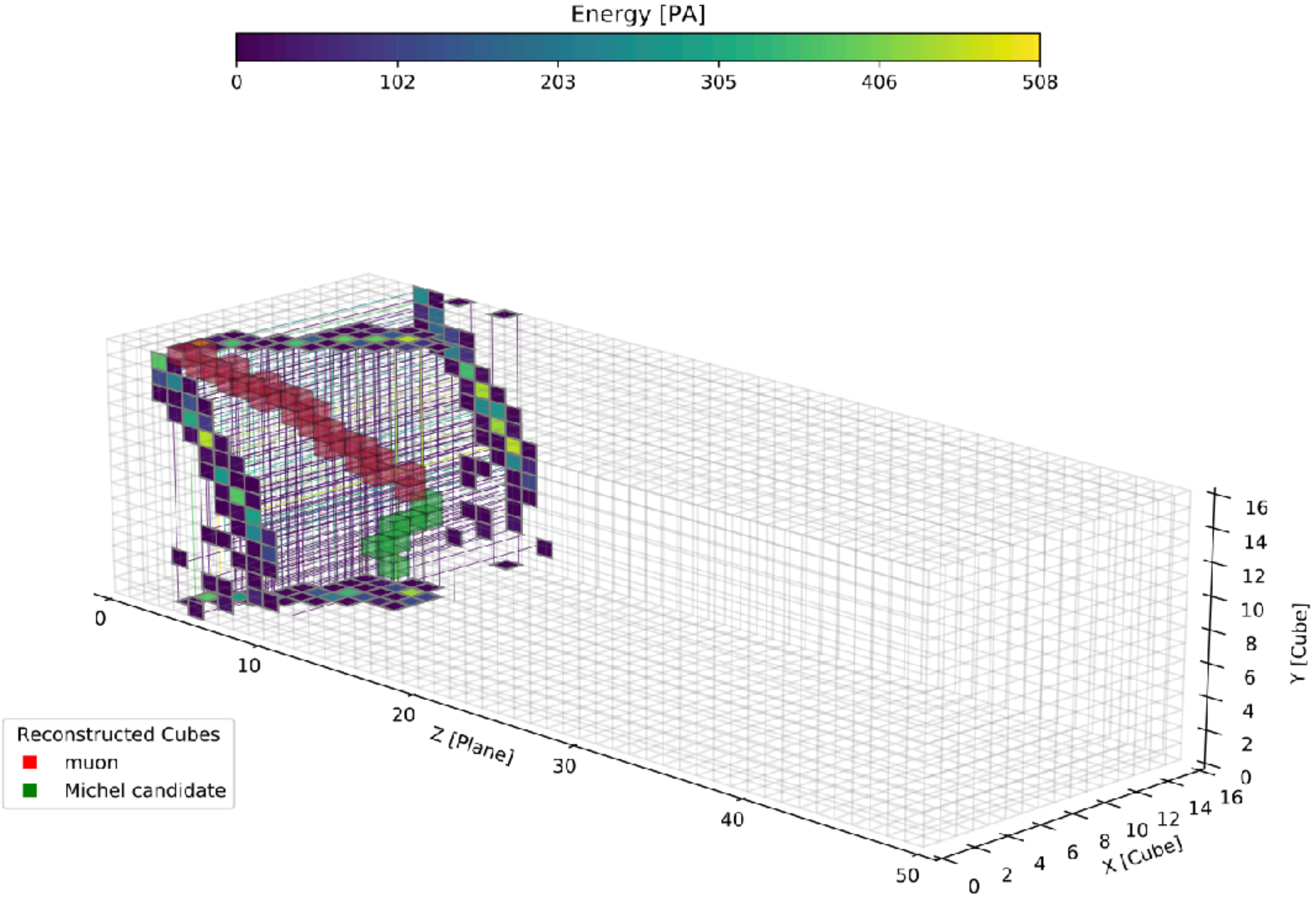
SoLiд

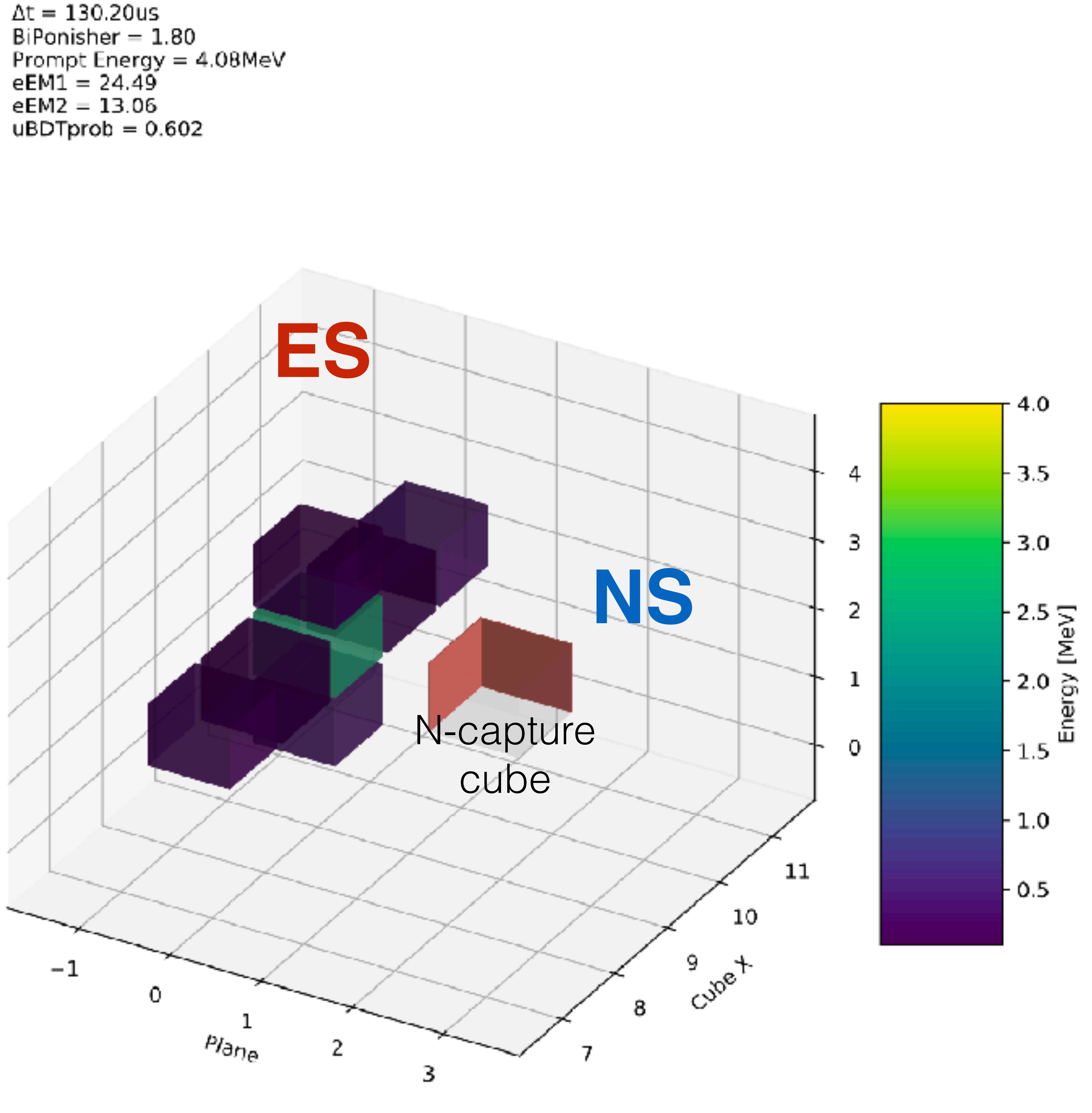
Deployment at BR2





Event displays





Stopping muon event with michel electron

IBD candidate

SoLid

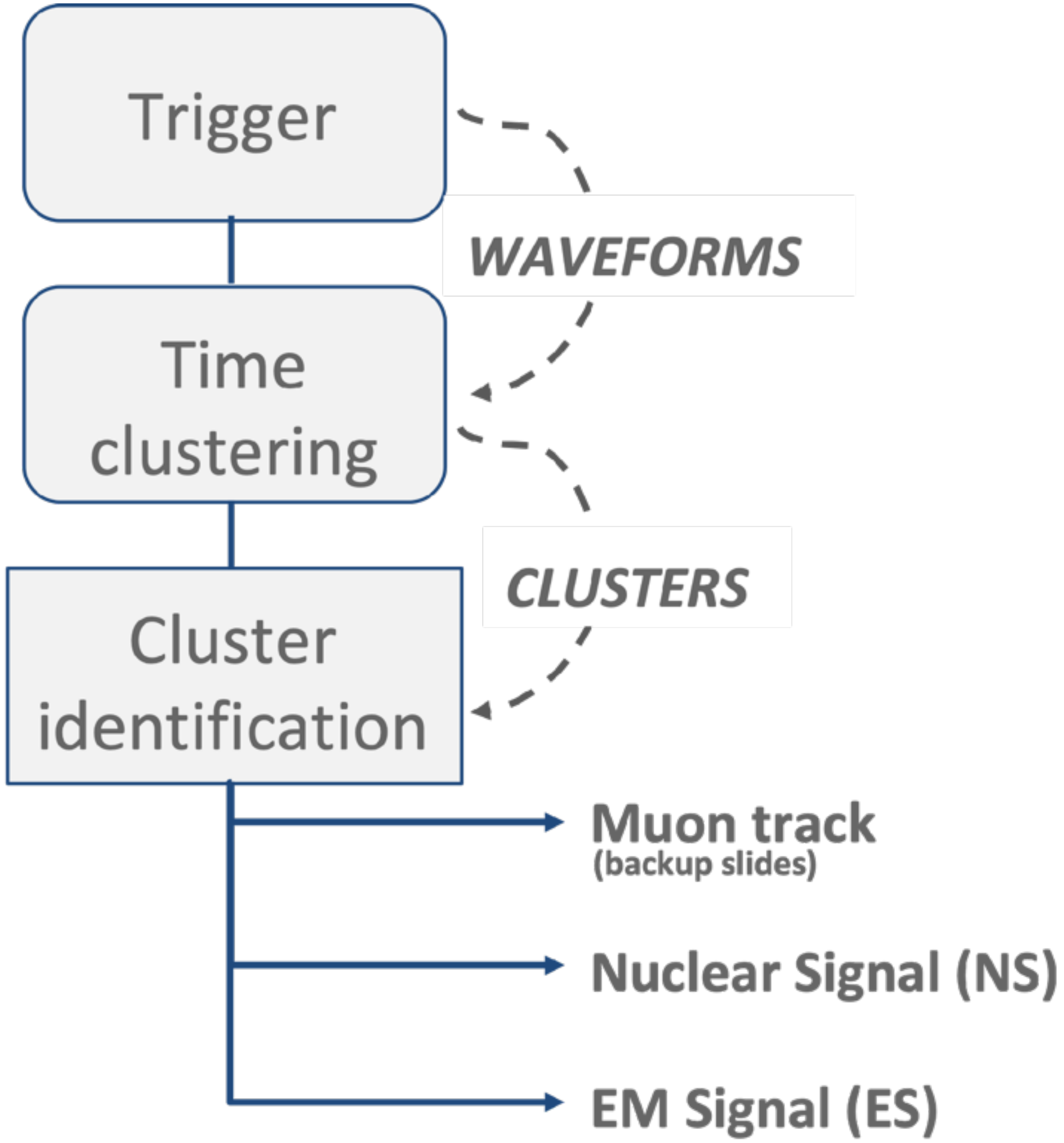
Operational experience

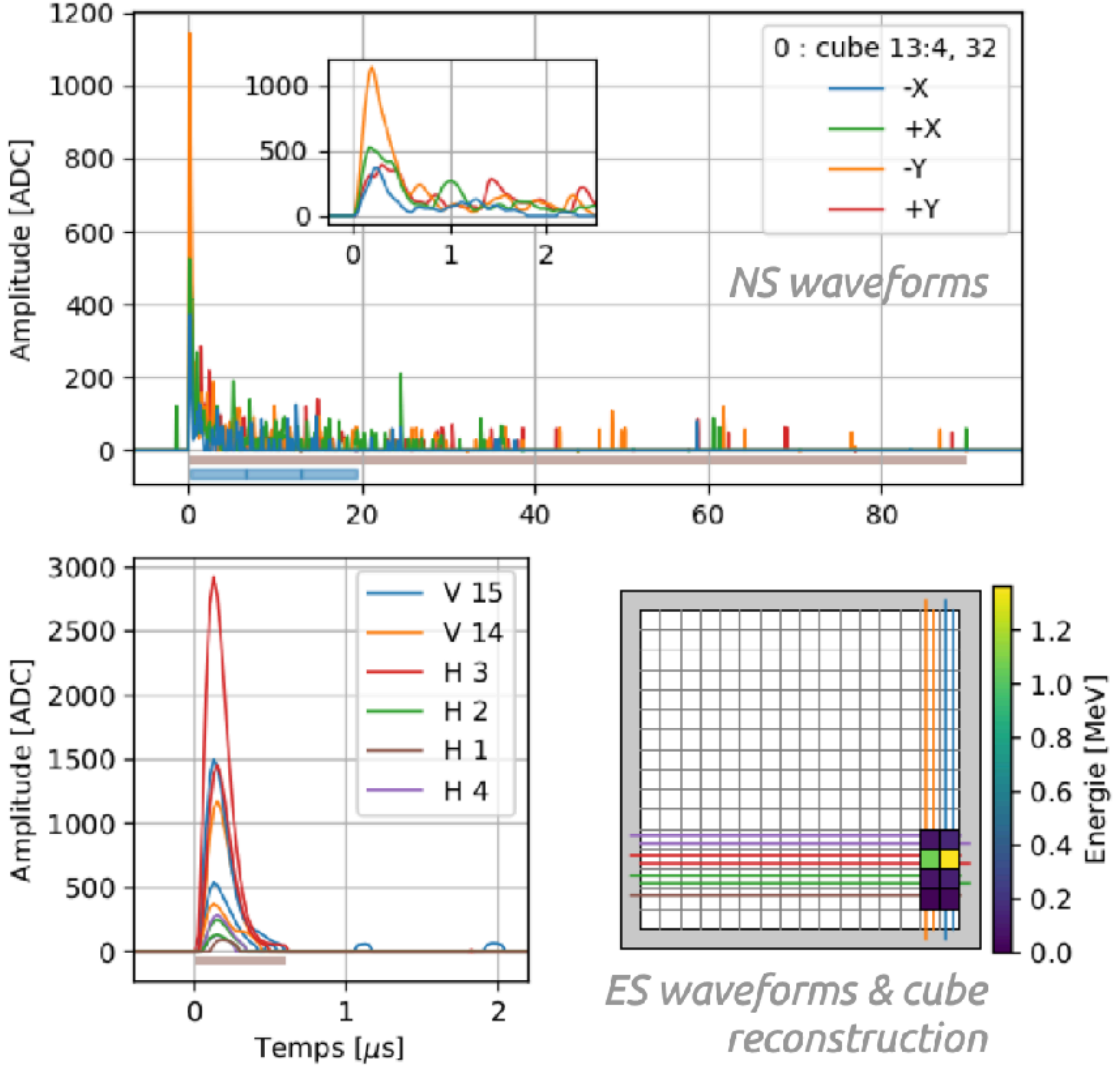
- **Long term operation of SoLid detector in ISO container well demonstrated**
  - SoLid detector operational has been running stability for the nominal 4 years (2018-2022)
  - Number of dead channel is < 1% and has stayed stable over that period
  - One major emergency shut down due to chiller stopping without warning was recorded in May 2019
- **System was operated remotely**
  - Most issues with DAQ and electronics power cycling can be addressed remotely
  - Limited local intervention necessary for moving source in situ or to switch power supplies
  - System can be shut down at short notice before routine evacuations, security and building pressure tests

Reconstruction & calibration

SoLid

Event reconstruction



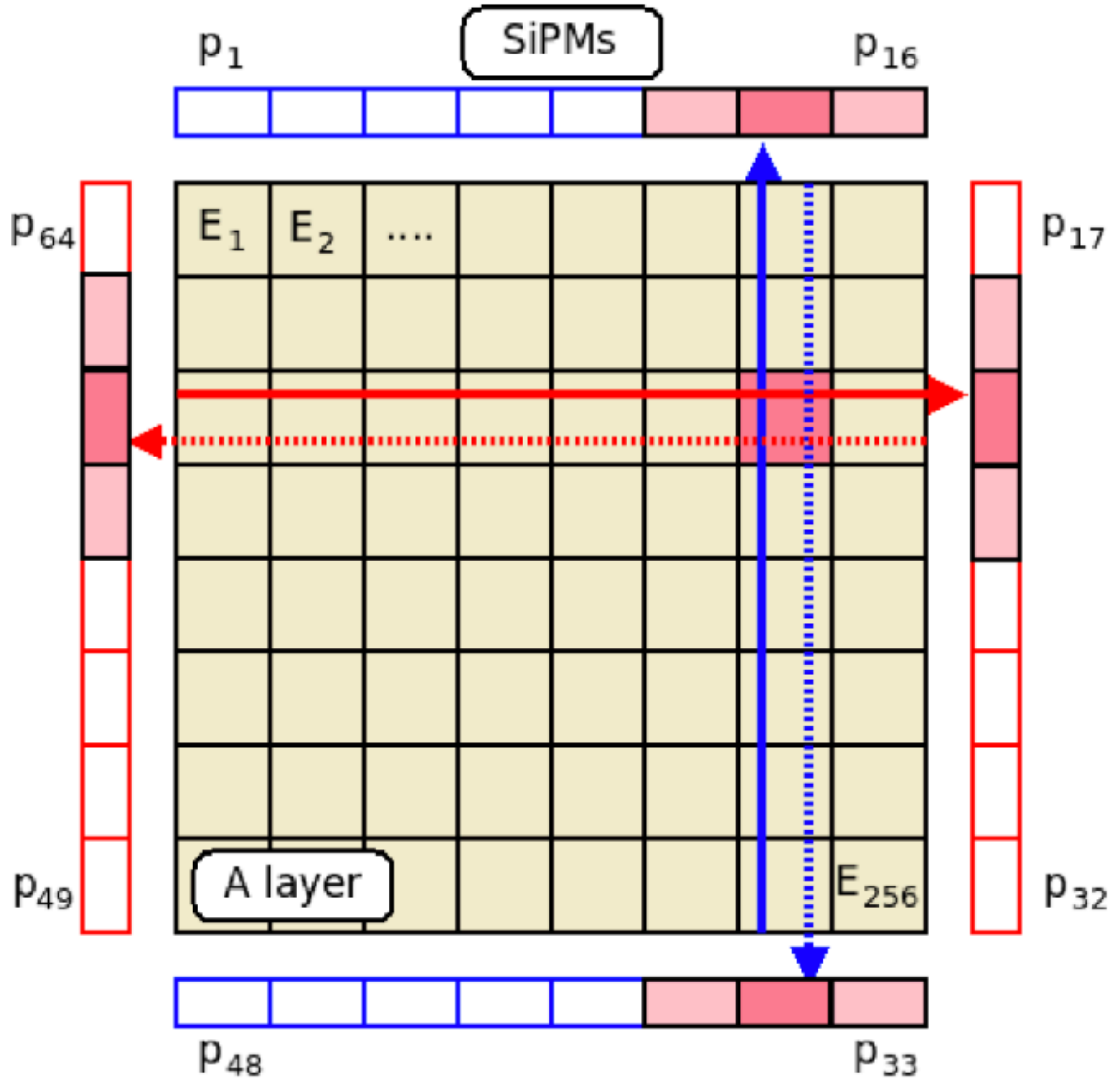


SoLi∂ Reconstruction and allocation of energy deposits

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

$$S_{SiPM} = AE_{dep}$$

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



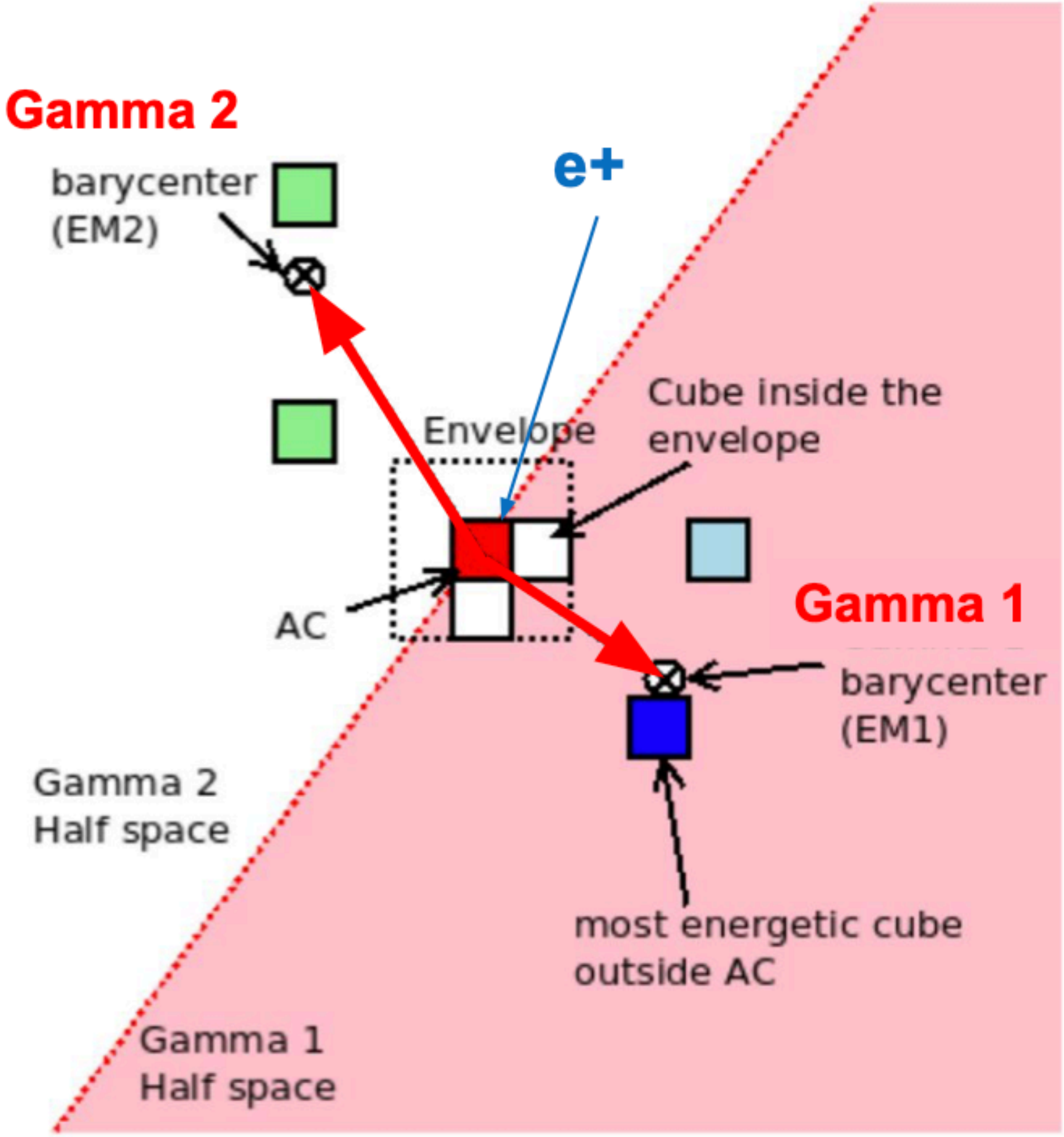
Method	FISTA	FISTA+ML-EM	sOMP+ML-EM
👻 (%)	15.8	11.4	6.9
ε (%)	75.3	76.3	77.7
E_{res} Std. dev.	0.13	0.13	0.13

NEW

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

SoLiđ

Event topology classification

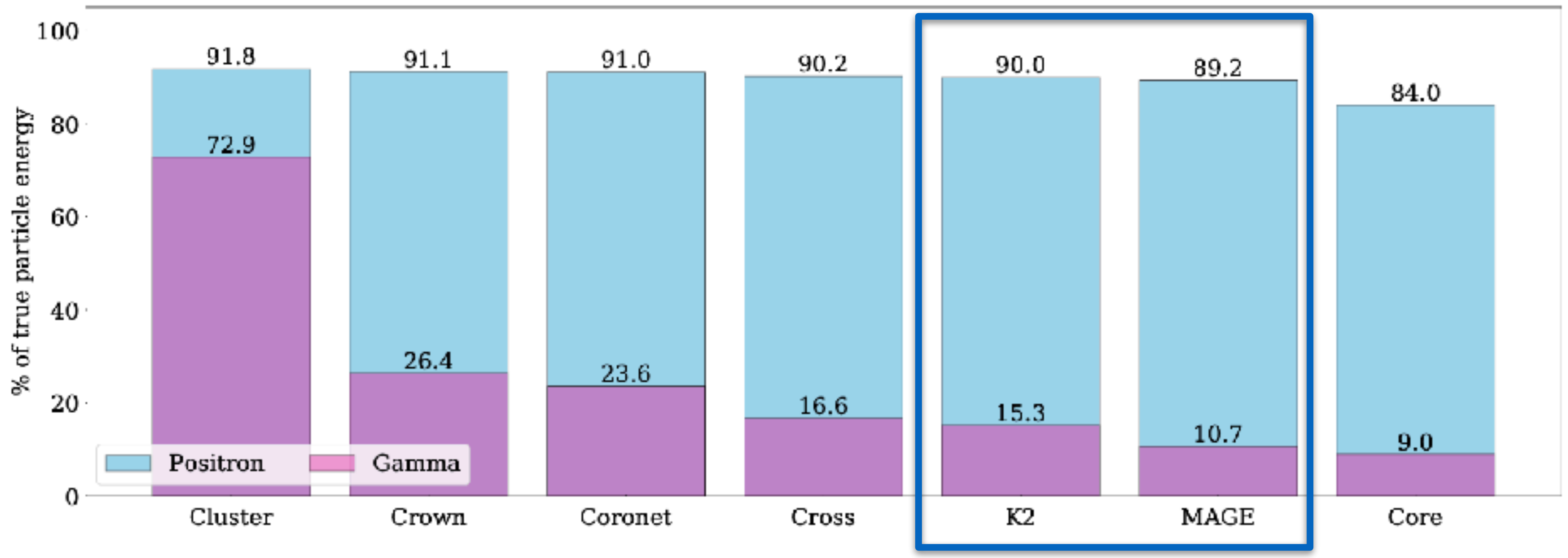


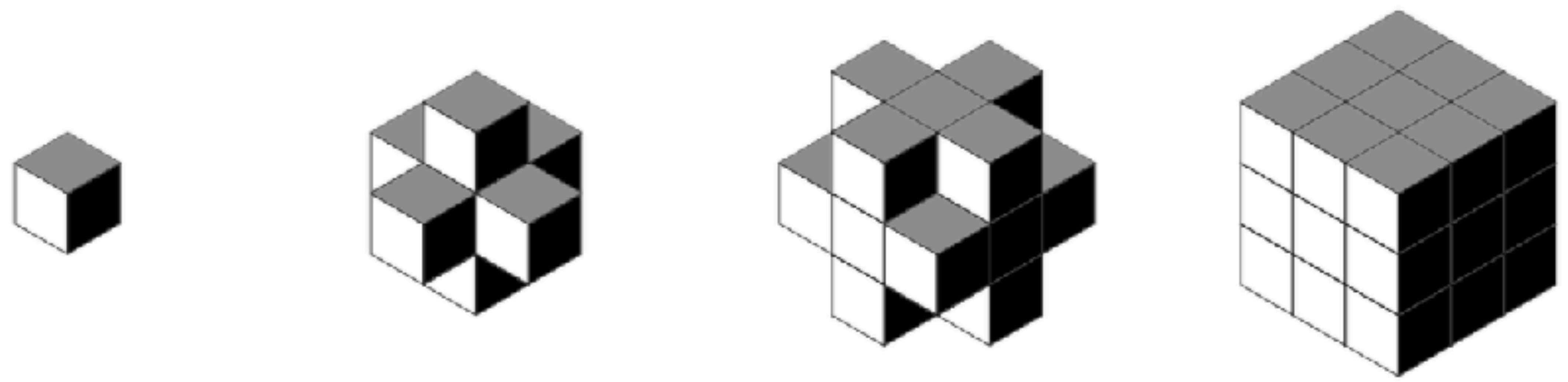
- Segmentation of the detector volume enables a more detailed categorisation of event topologies
- High level quantities are constructed based on prior physics knowledge of the IBD kinematics
    - Main positron dEdx cube (AC)
    - Extension of cube activity from annihilation gamma deposits
    - Inputs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

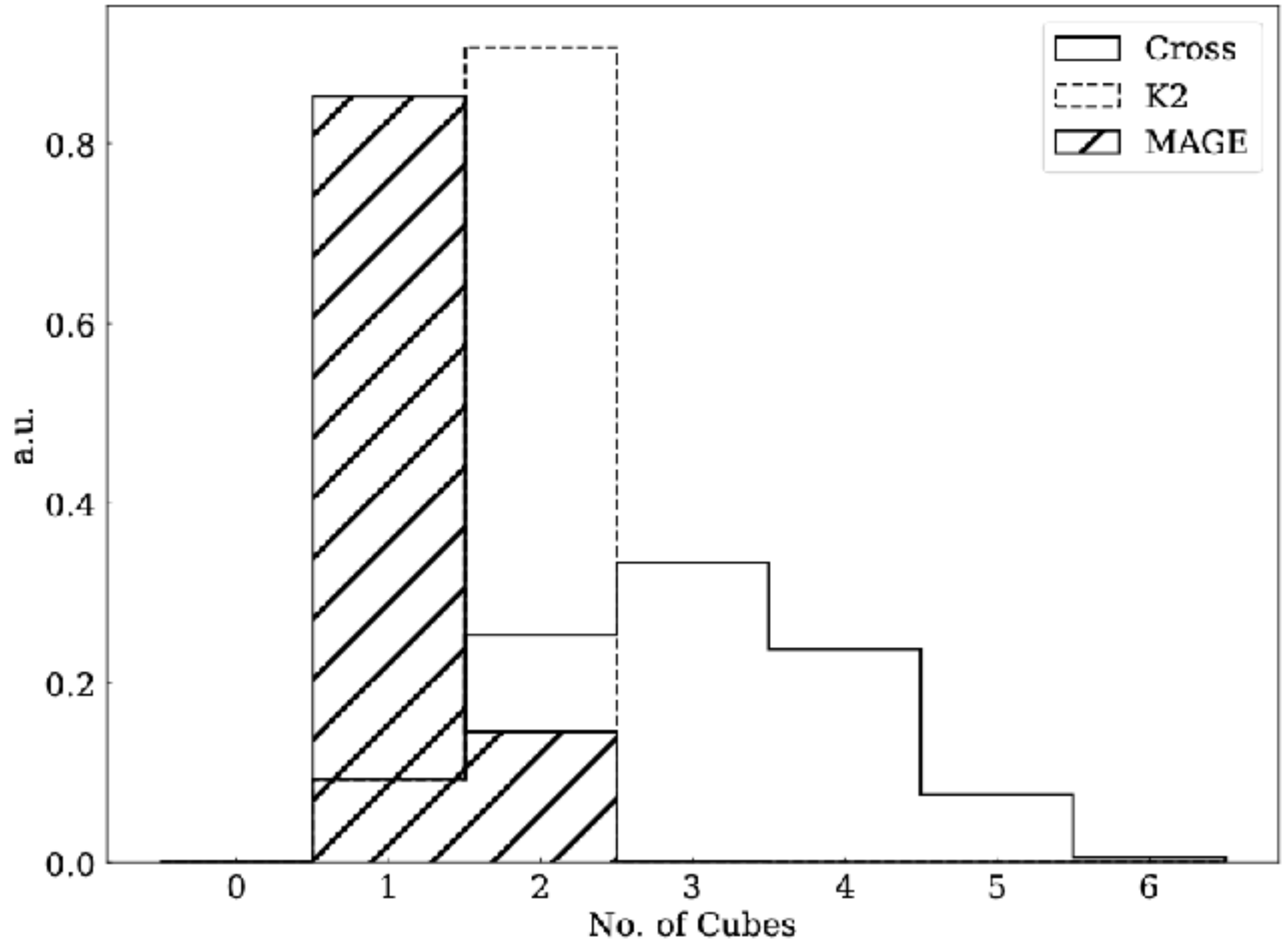
SoLid

ES energy estimation NEW

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



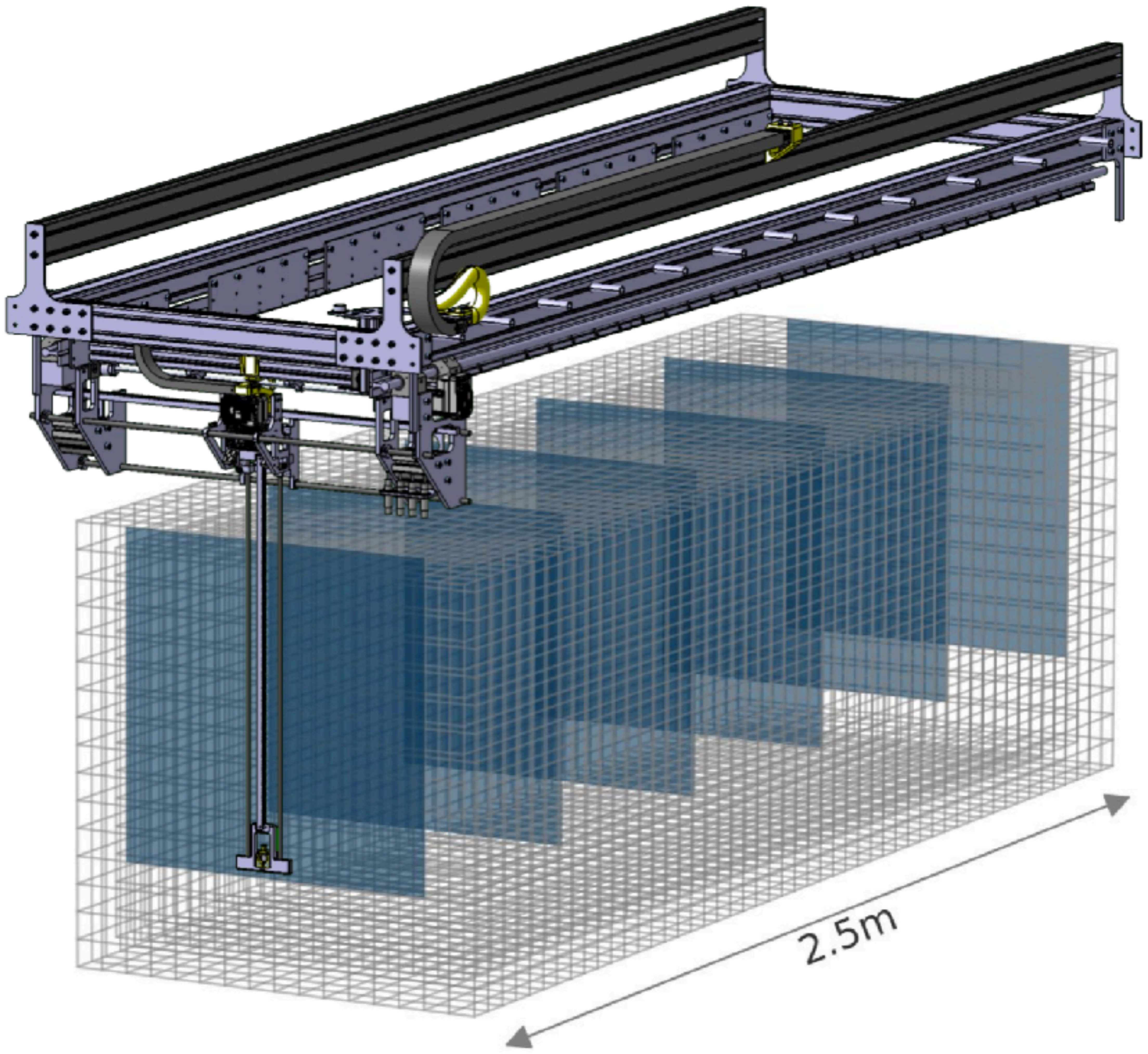




Estimator	Definition (sum of cube energies $E_{cube} > 0$ satisfying)
Core	$E_{cube} = E^1_{max}$
Cross	$\Delta X \leq 1, \Delta Y \leq 1, \Delta Z \leq 1$ and $\Delta R \leq \sqrt{1}$
Coronet	$\Delta X \leq 1, \Delta Y \leq 1, \Delta Z \leq 1$ and $\Delta R \leq \sqrt{2}$
Crown	$\Delta X \leq 1, \Delta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

NEW

CROSS calibration robot

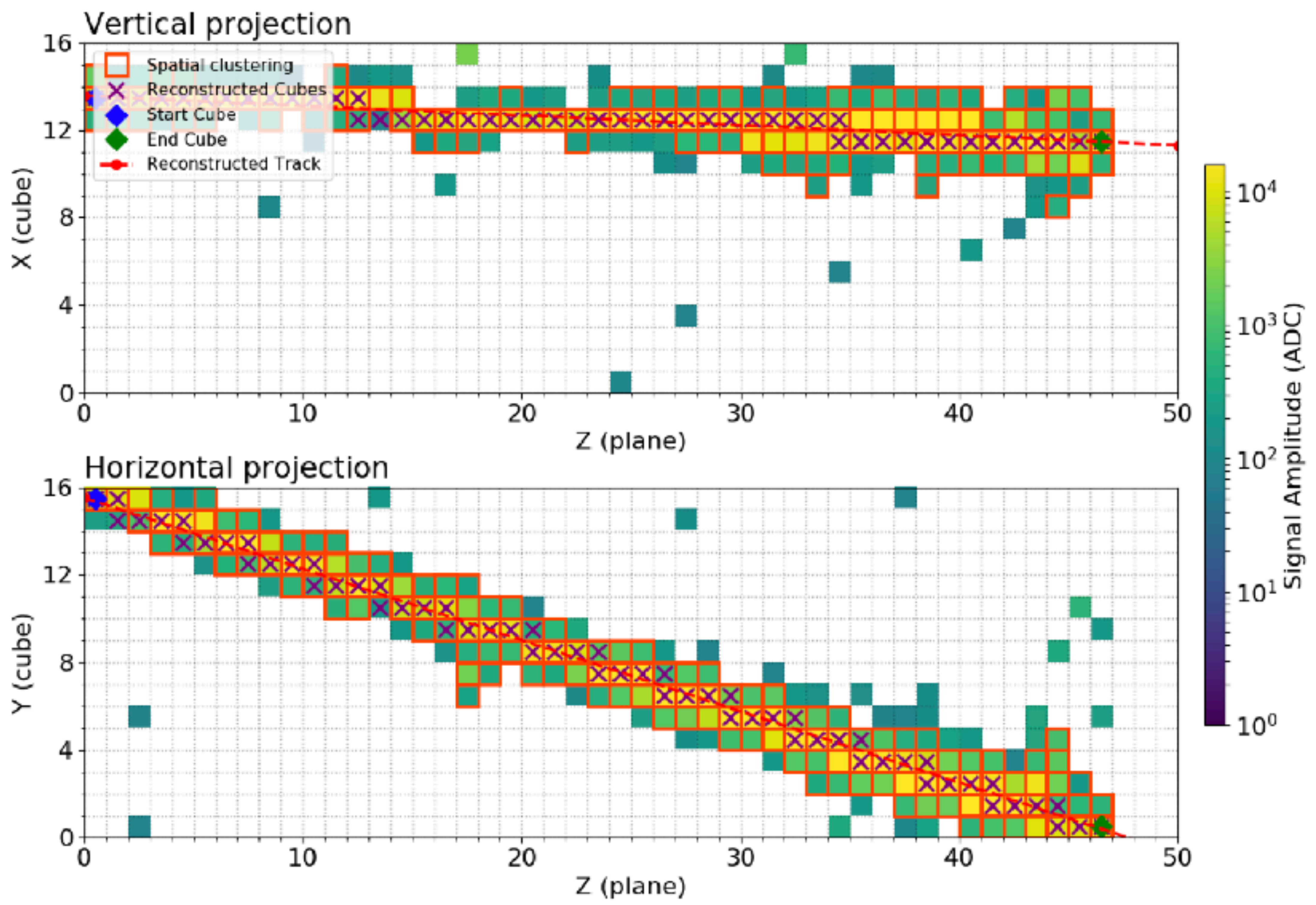


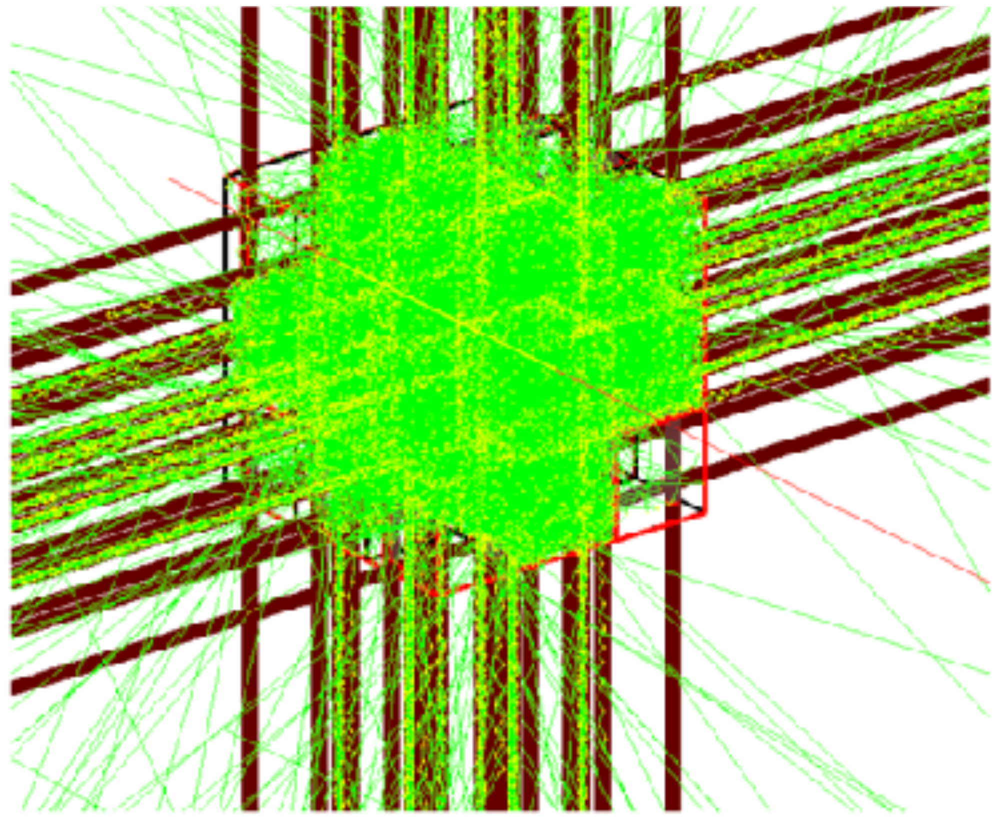
- Automated X-Y source scan of 6 gaps within detector
- Measure absolute efficiency and energy scale calibration at % level
  - Gamma-ray: ^{207}Bi, ^{60}Co, ^{22}Na
  - Neutrons: AmBe, ^{252}Cf

SoLid

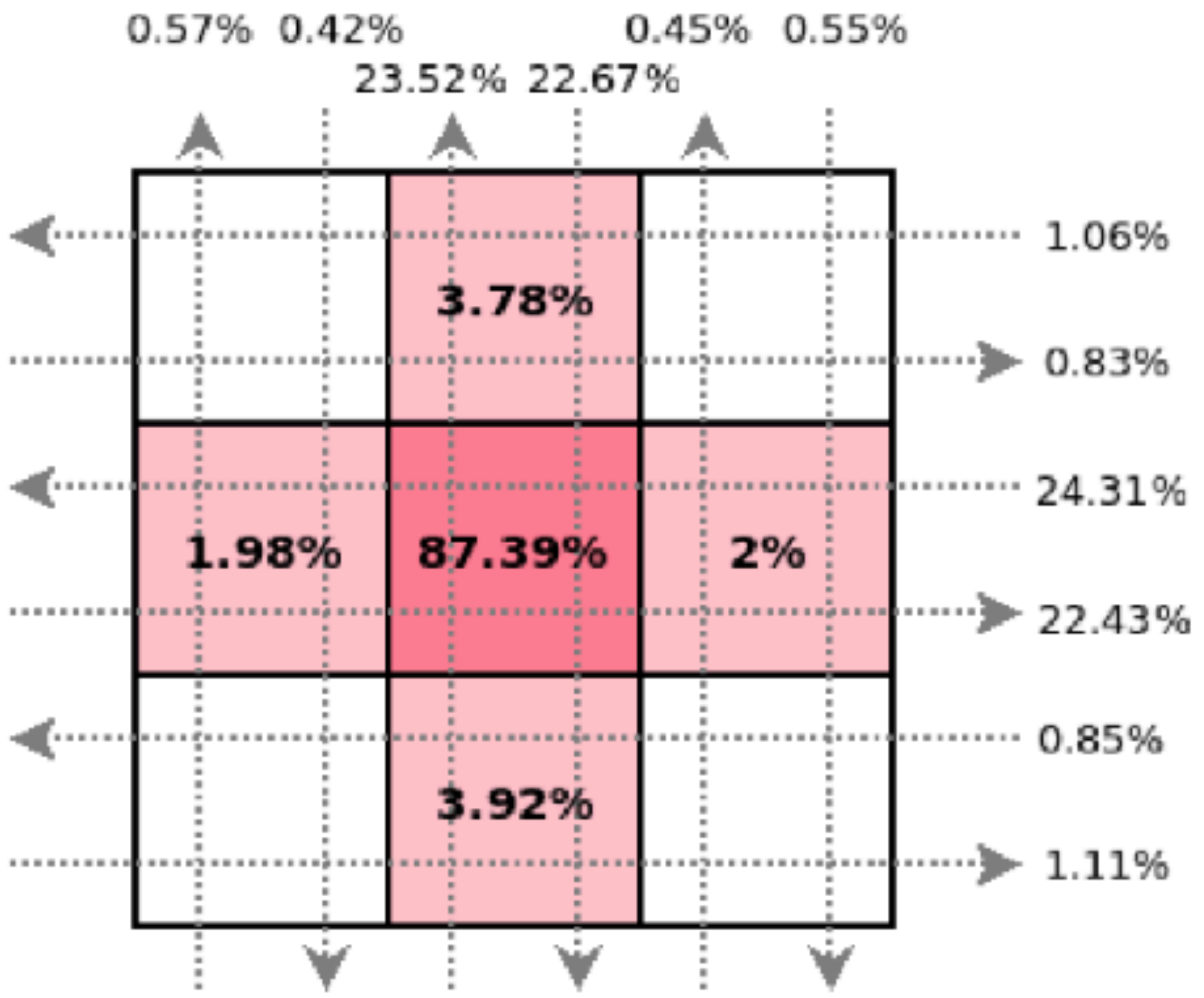
Horizontal muon calibration

NEW

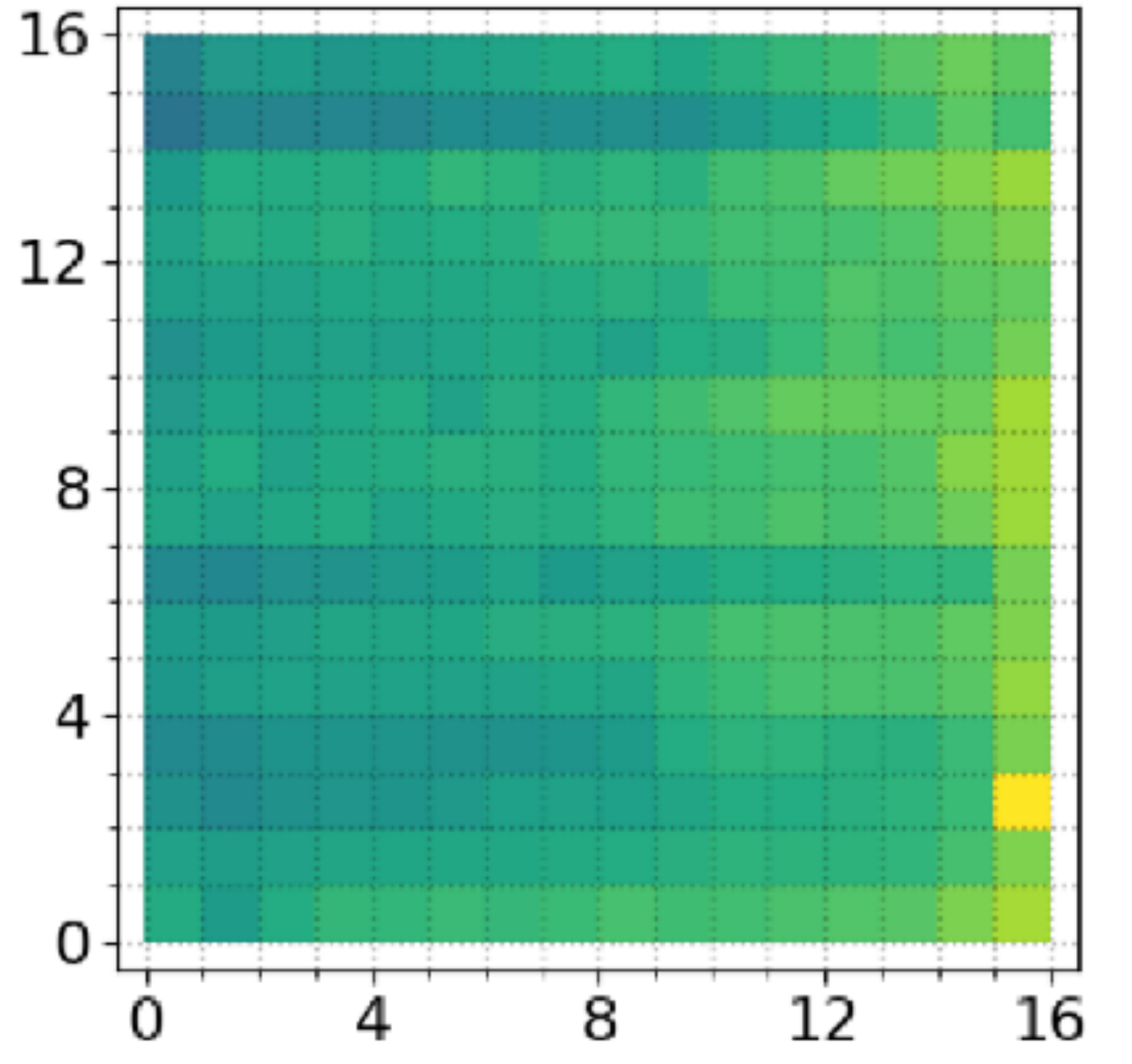




- Horizontal muons allows the calibration of channel and cubes :
- Separate channel effects for a more precise energy calibration
- Light leakages to neighbouring cubes characterised
  - Informed the detector response in MC



Fibre X2 after deconvolution



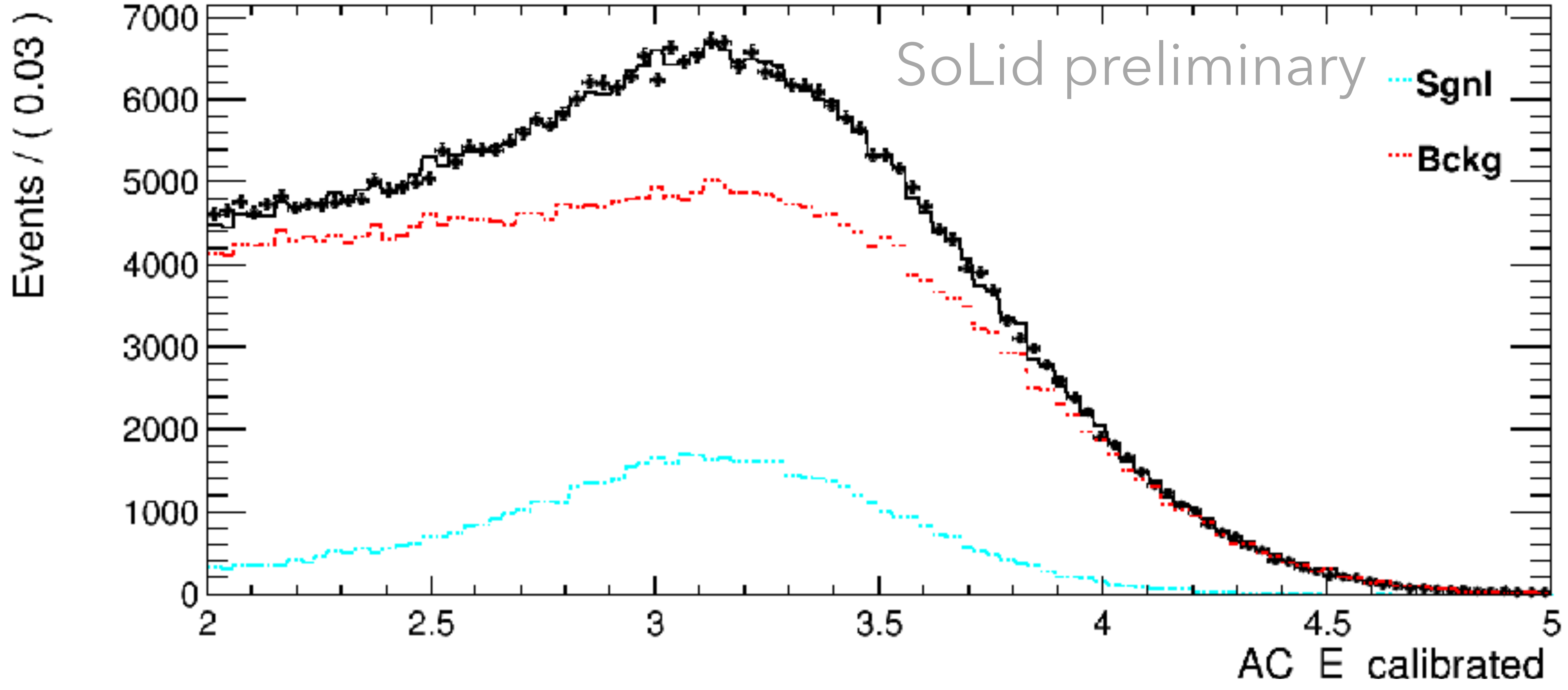
H. Chanal et al., Using horizontal muons for the calibration of the reconstruction of the SoLid experiment, IEEE NSS 2022

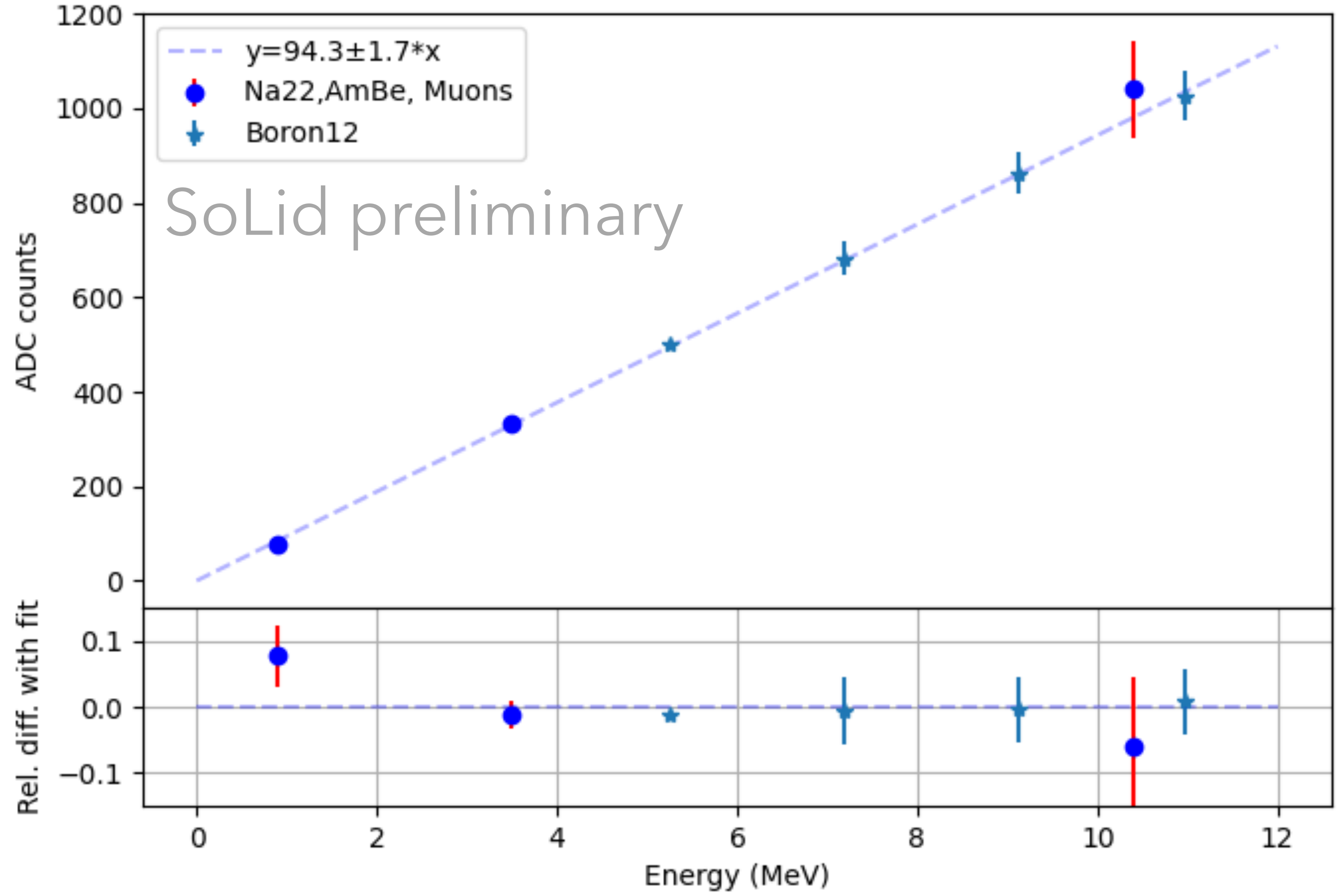
SoLid

Energy scale calibration

NEW

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





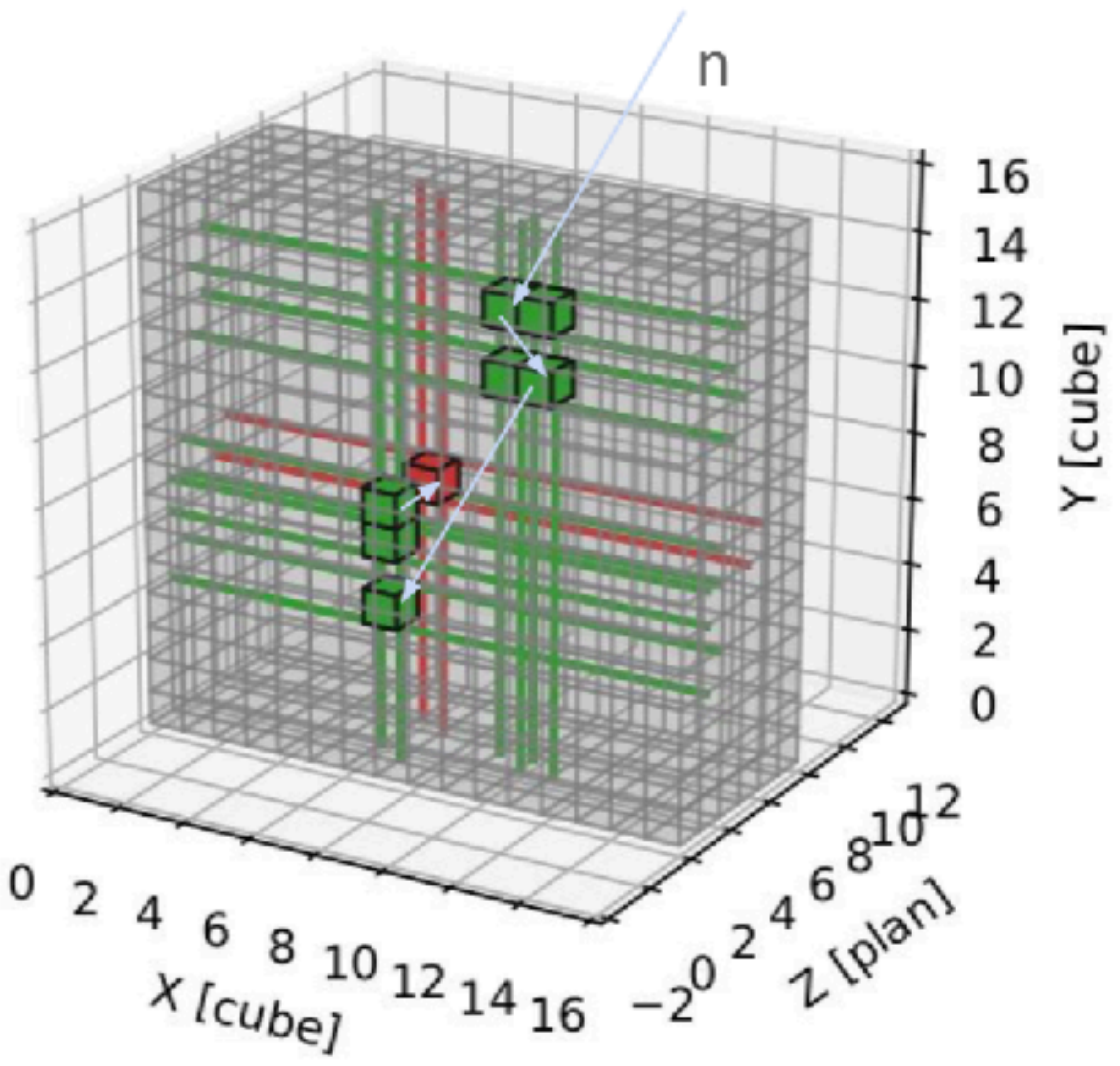
Antineutrino analyses

Phase-I dataset

- 14 reactor cycles available in the phase 1 dataset
- Reactor off periods for physics are scarce : counts for 1/3 of downtime periods (calibration, maintenance, pressure tests…)

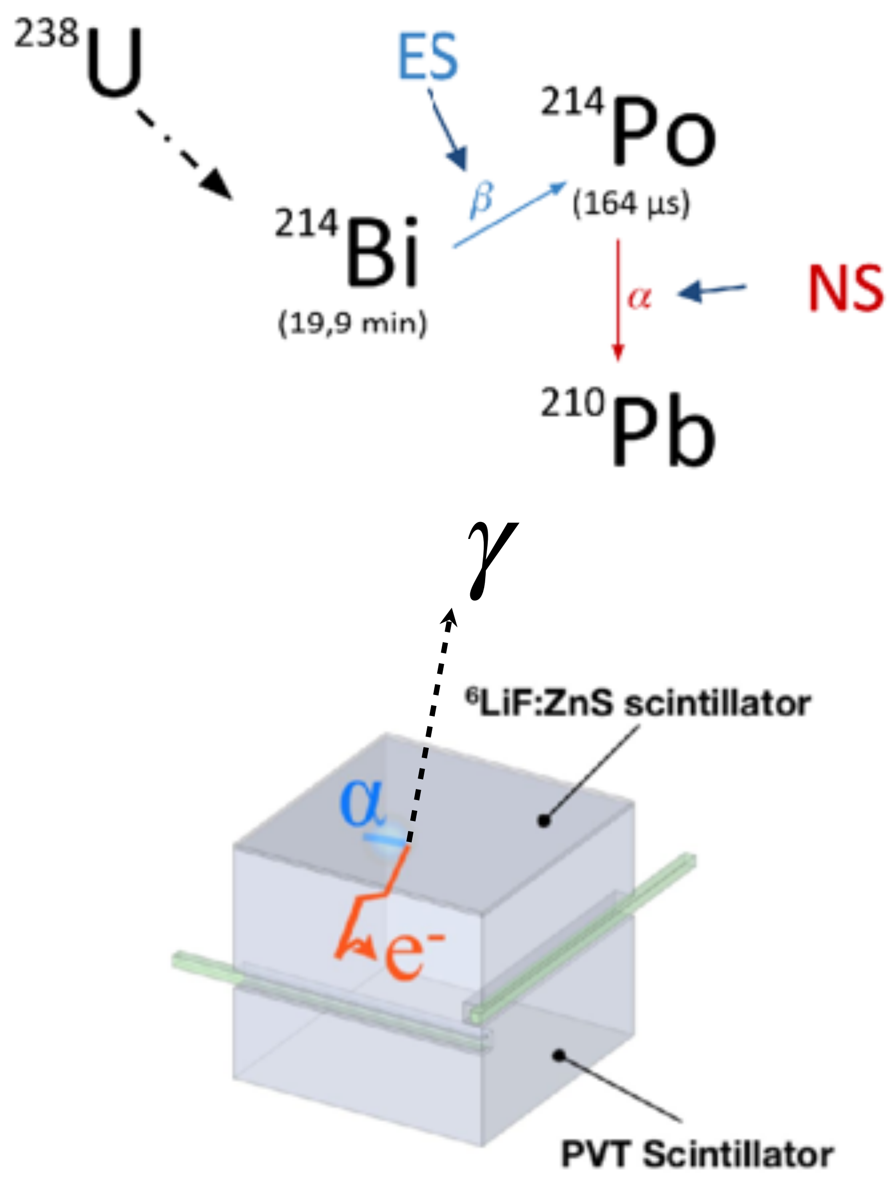
SoLid antineutrino backgrounds

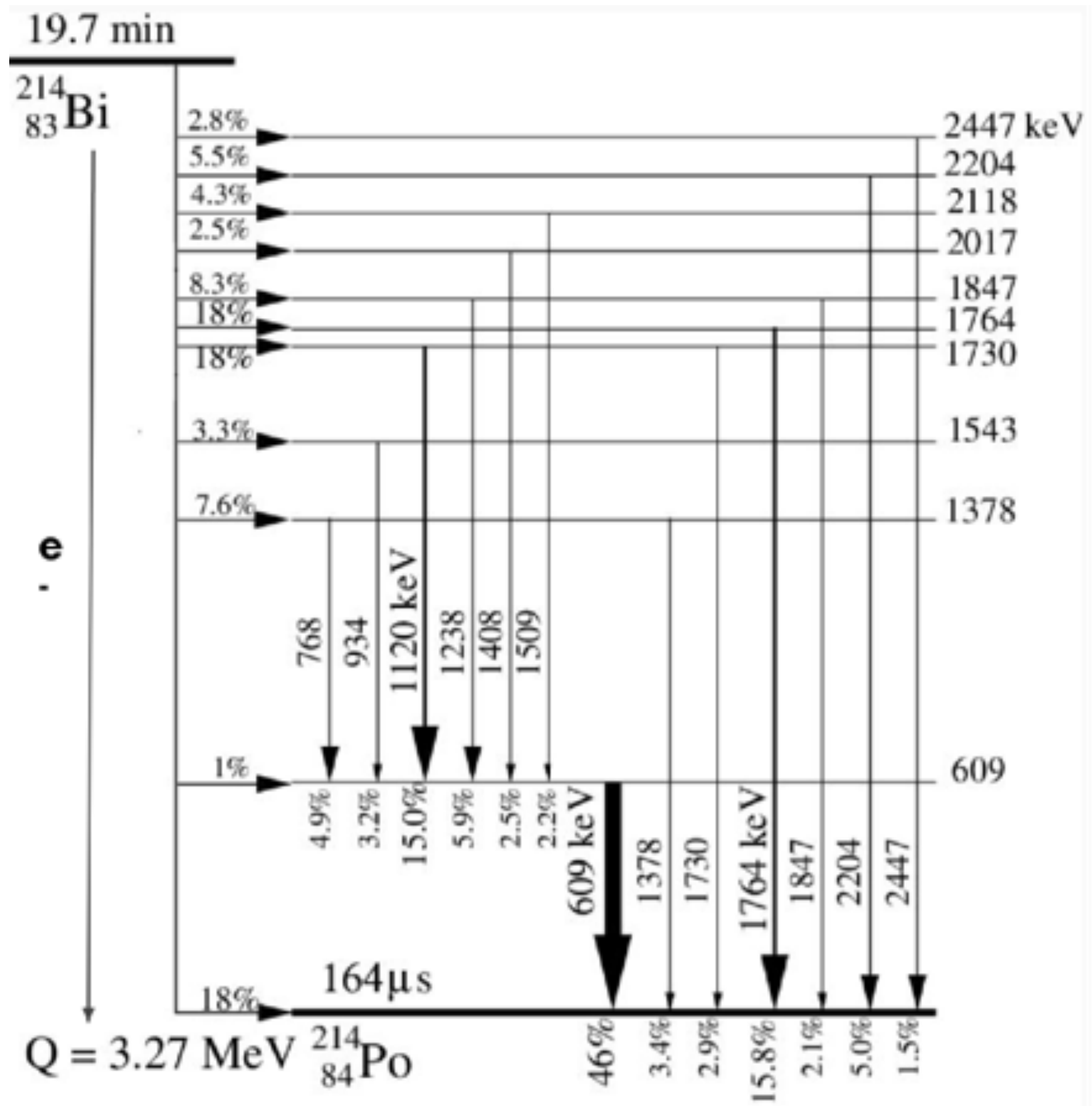
External



- Fast neutrons: atmospheric shower and spallation neutrons
- Gamma-rays (Ar-41) : reactor accidentals < 1.5 MeV
- Radon emanation from the building

Internal

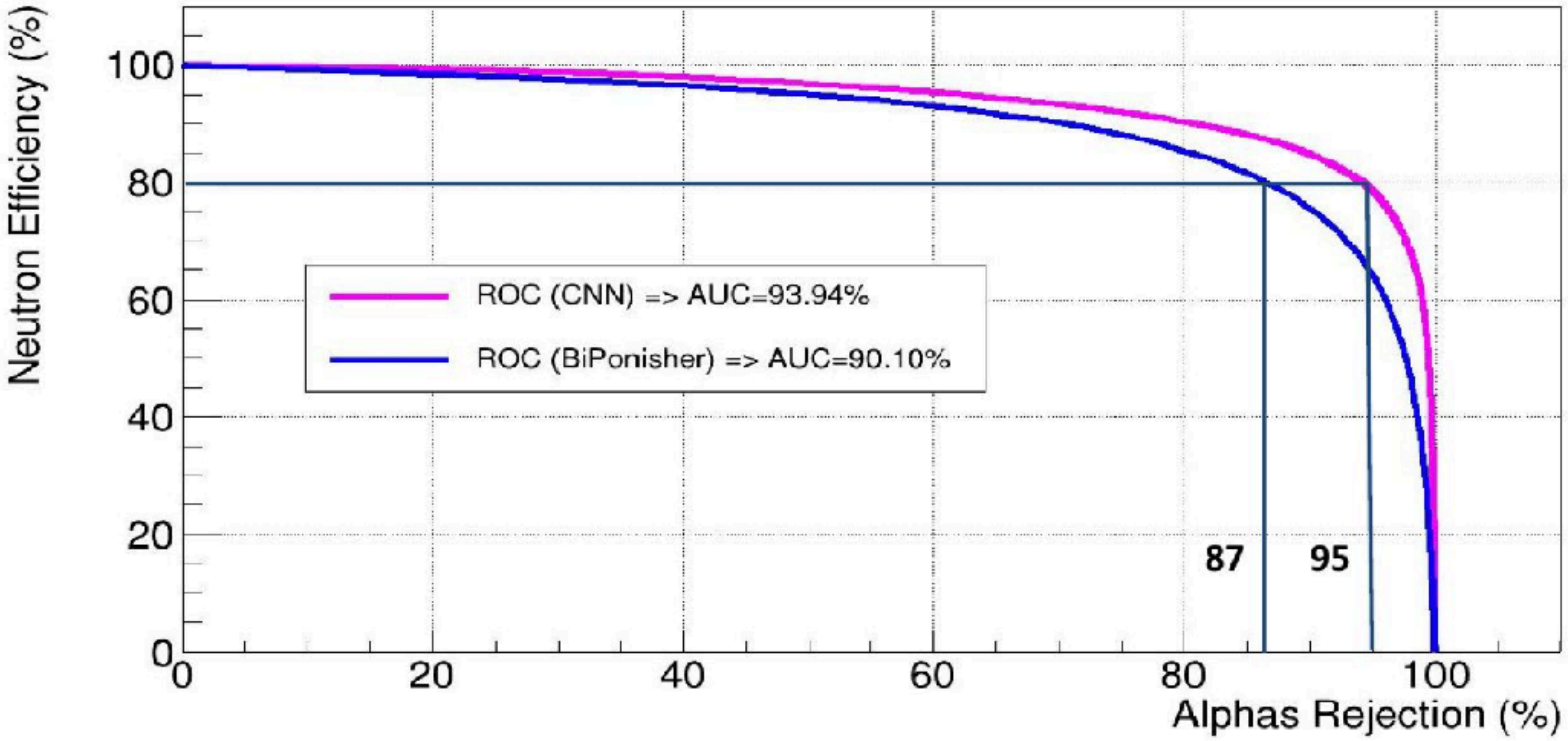


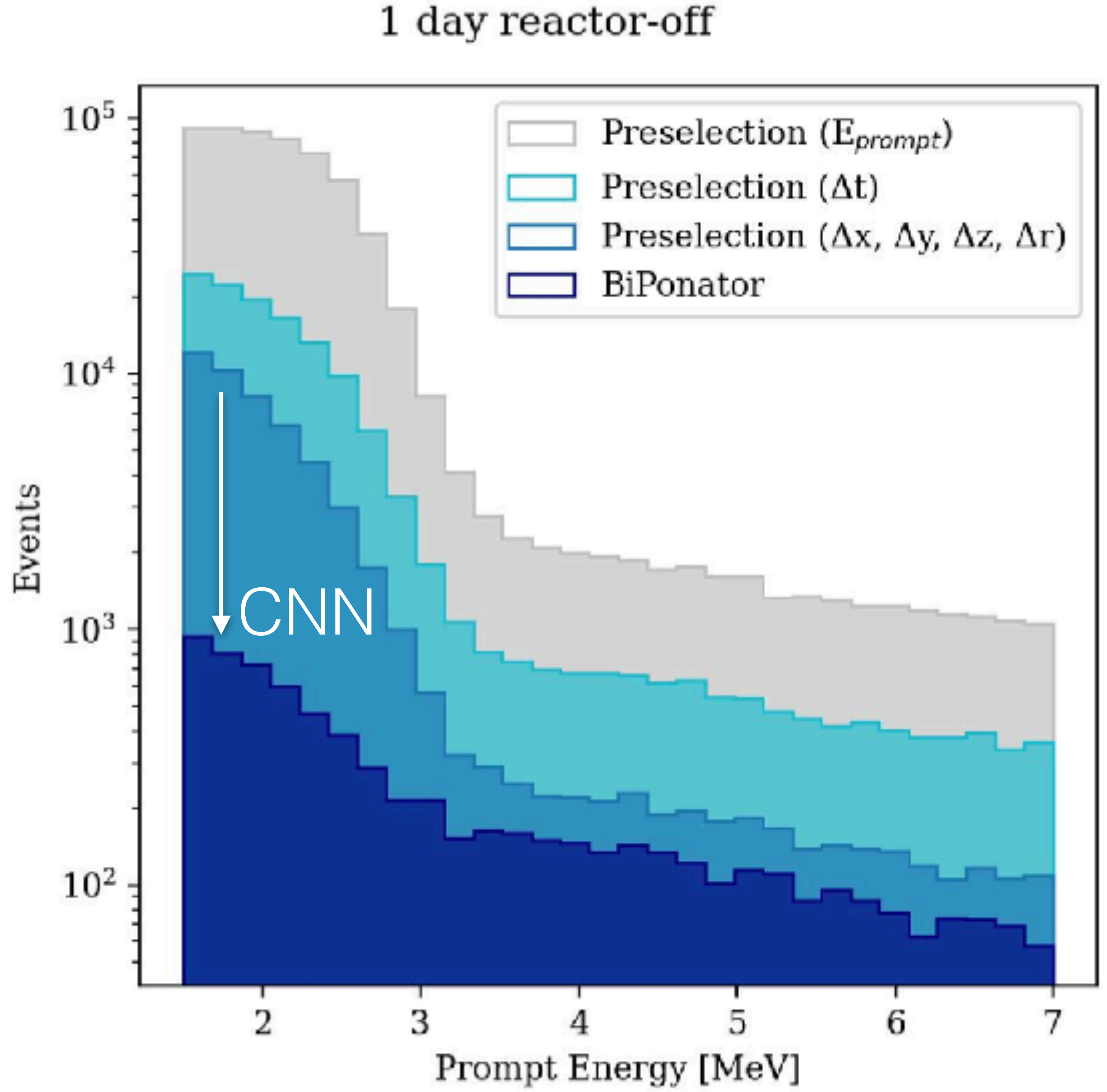


- Bi-Po 214 from U-238 / Th progenies mainly in LiF:ZnS(Ag)
- Radiative decays with additional gammas
- Alpha generates similar NS signal as Lithium capture

SoLid Alpha-neutron background discrimination

- LiF:ZnS(Ag) has PSD capabilities (ZnS is an inorganic scintillator)
  - Shape of alpha waveforms are different from Lithium-6 neutron capture !
- **Convolutional Neural Net** classifier on raw waveforms
  - Most powerful cut to reduce BiPo background (95% reduction) : big improvement over previous method based on charge integration





SoLid

Antineutrino selection 2022

rBDT NEW

- IBD rate selection
- Optimised for high efficiency selection
- Rate vs power analysis
- Directionality

nuBDT : 1&2γ selection NEW

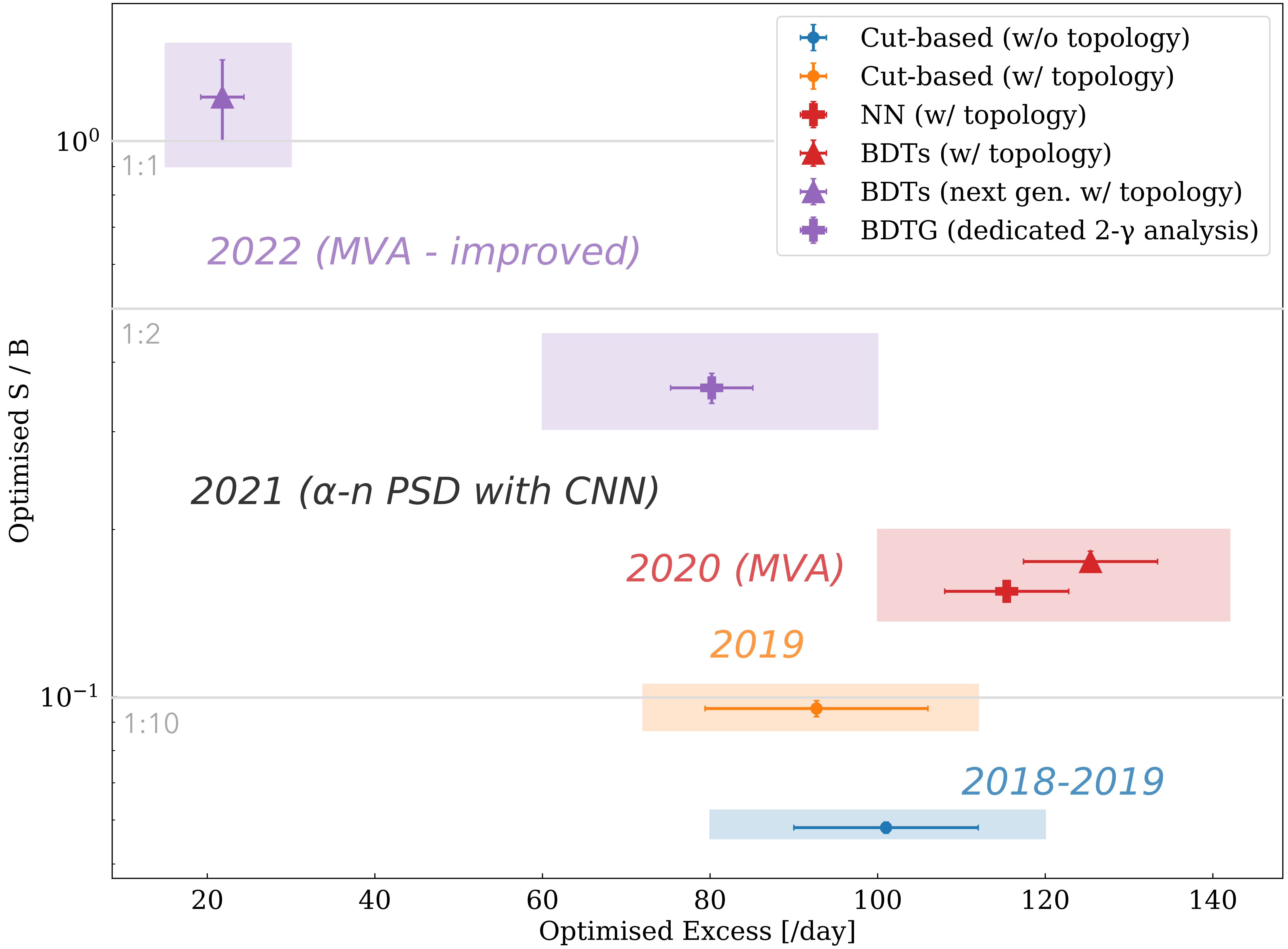
- Select positron energy (MAGE)
- Maximal use of topology to distinguish signal and background quantities
- Subtraction method
- Optimised for the oscillation analysis
  - Uniform BDT ensures **flat efficiency** selection

BDTG : 2γ selection

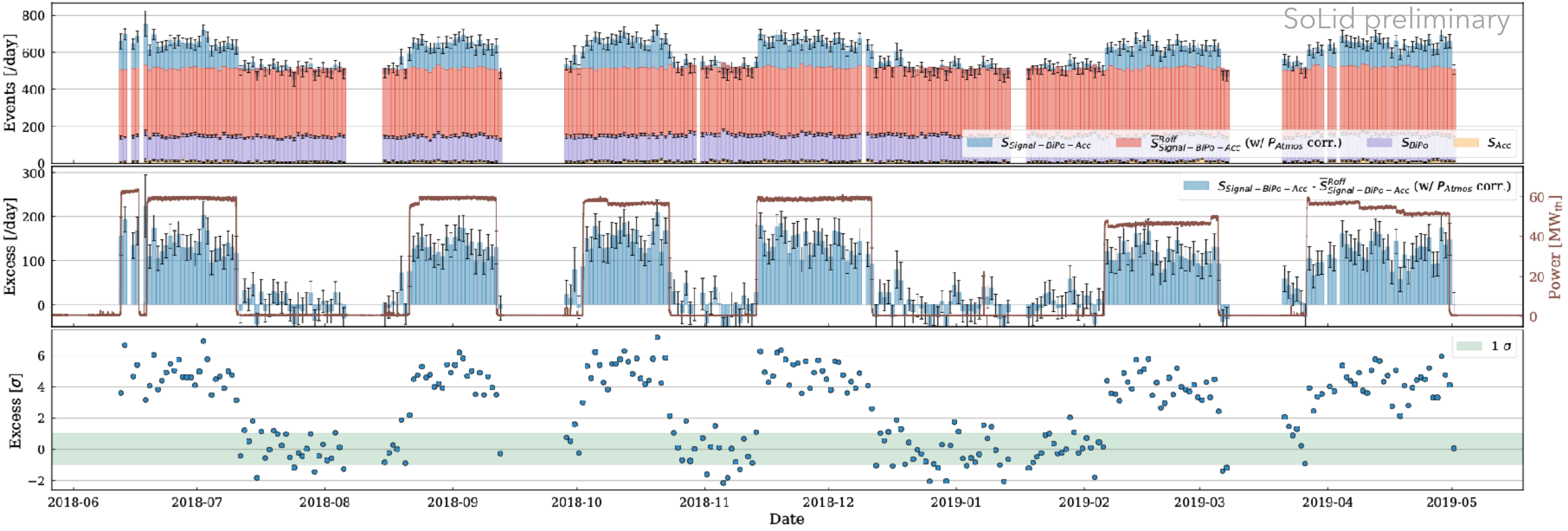
- 2γ energy deposit
- Maximal use of topology to distinguish signal and background quantities
- multi-Dim simultaneous fit to determine background components
- Optimised for oscillation analysis

SoLid Antineutrino Analysis improvements timeline

- SoLid IBD/oscillation analysis requires a sensitive selection :
  - A good understanding of the detector response and calibration
  - Development of novel background discrimination techniques
  - Categorisation of signal and background based on spatial information
  - Multi-variate analysis

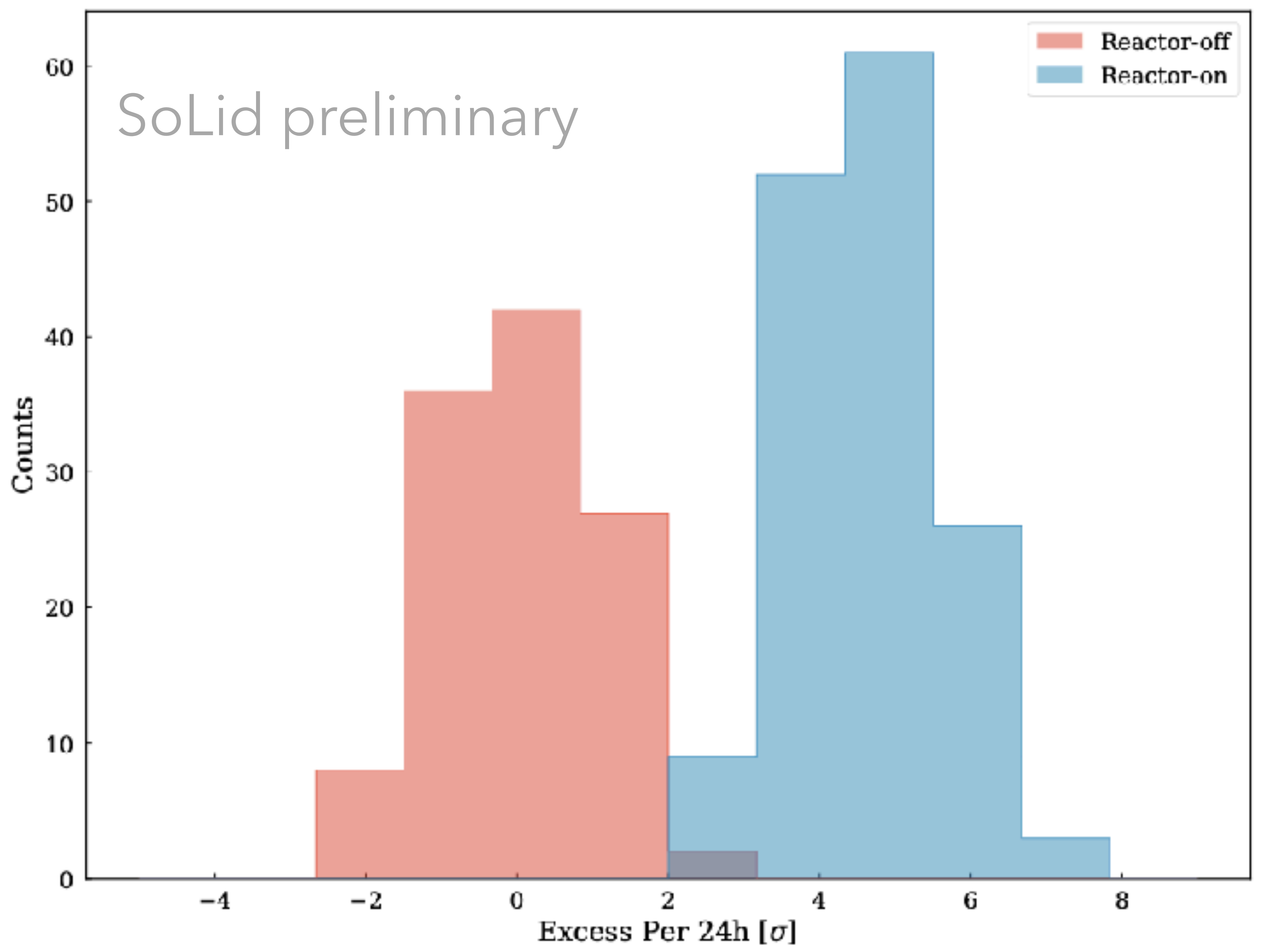


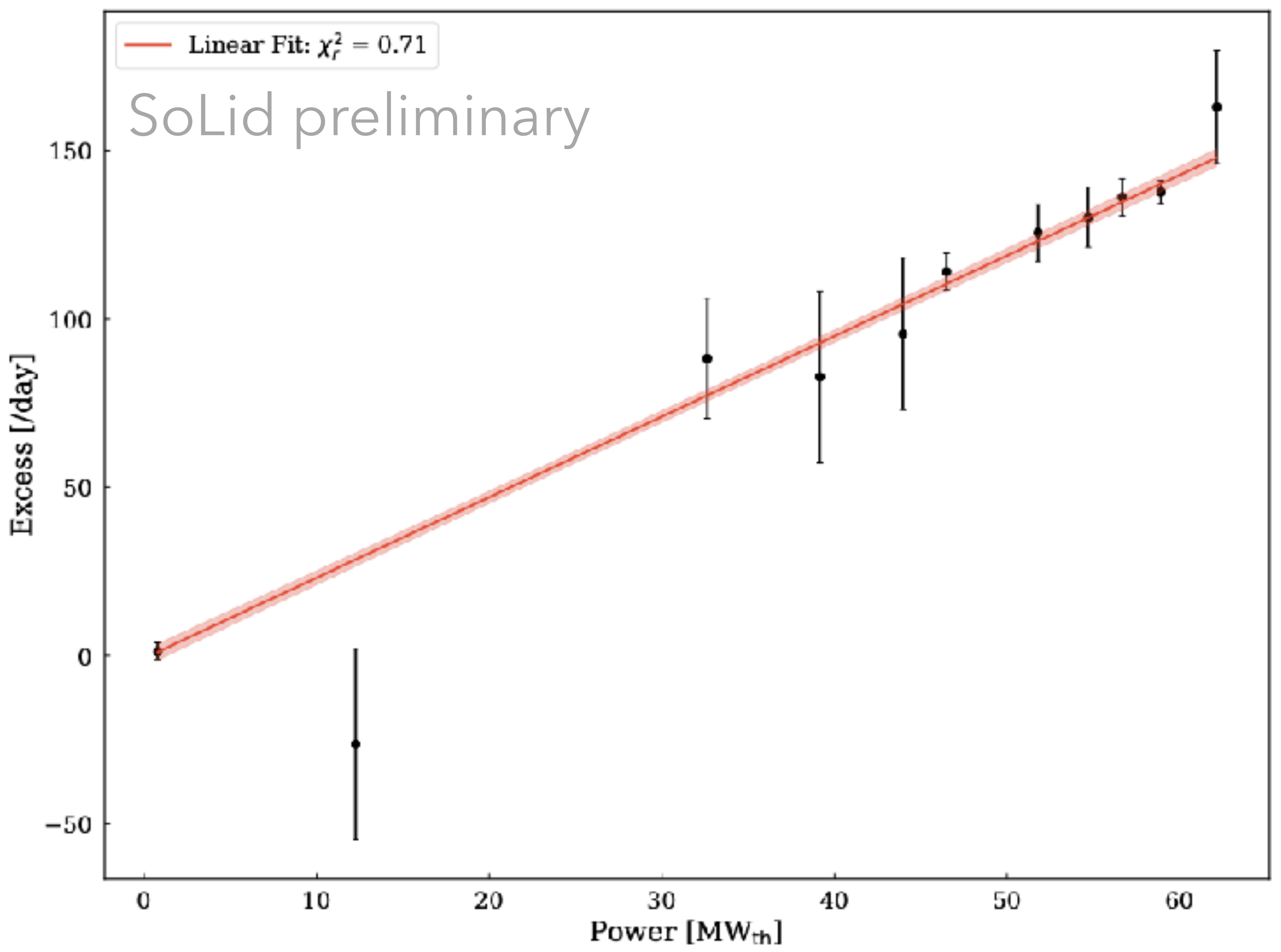
rBDT - Rate analysis I



- Rate analysis on first half of the phase-I data shows stable signal extraction
- Atmospheric background is dominant with BiPo background now 1/3 of total after CNN discrimination

rBDT - Rate analysis II

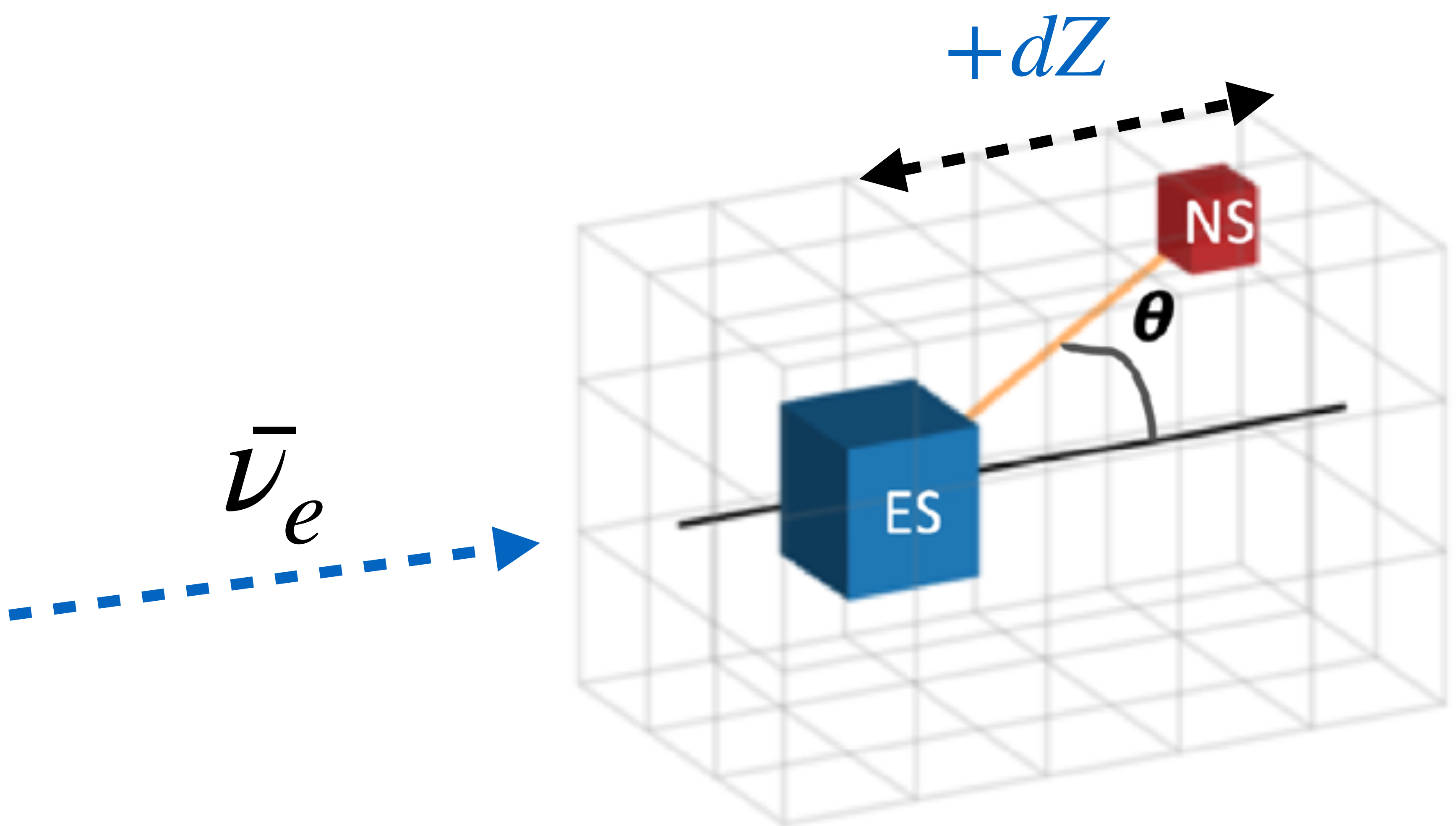


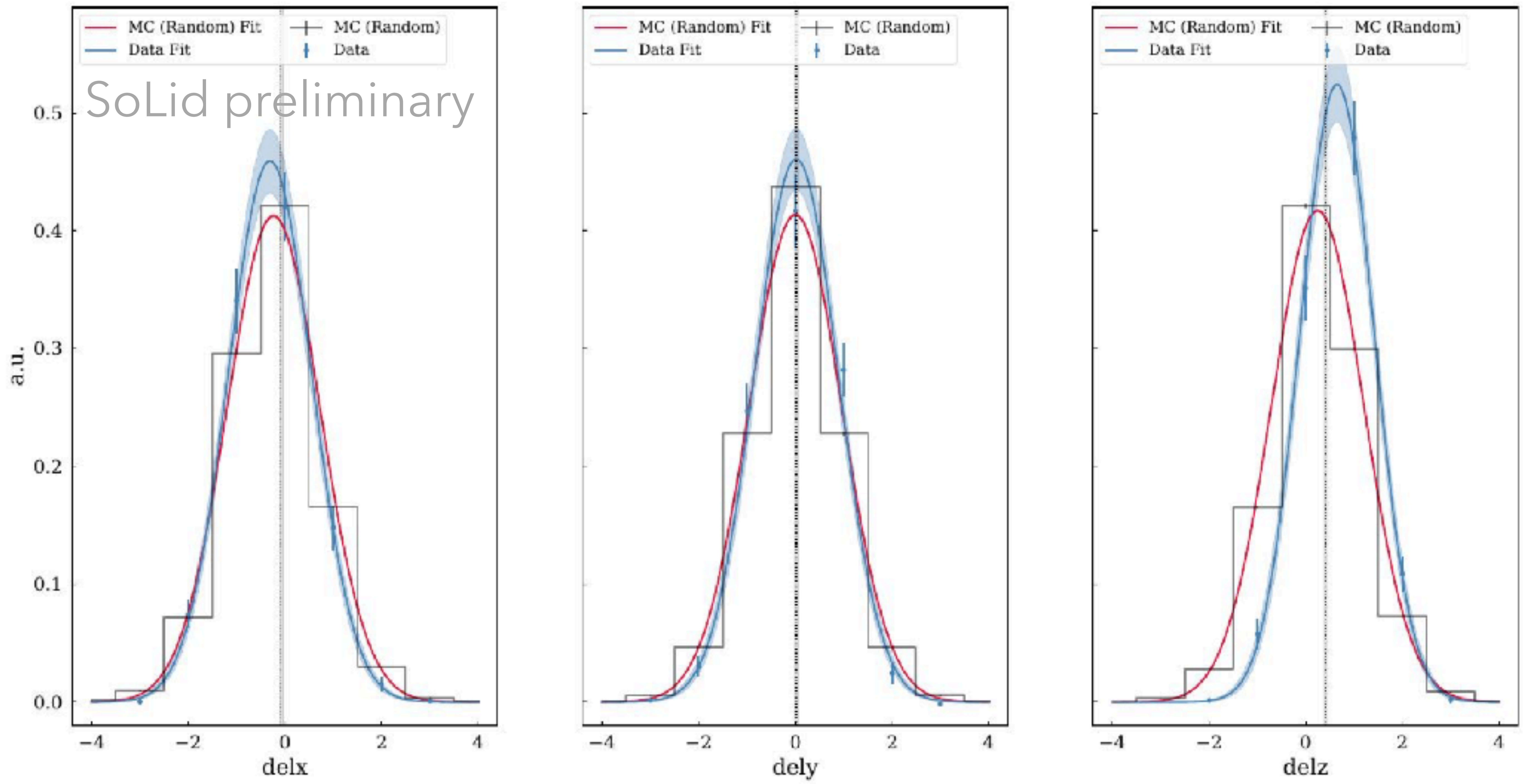


- 5σ significance per 24 hours
- Antineutrino signal proportional to reactor power well demonstrated
  - Data point at zero is reactor OFF data consistent with zero

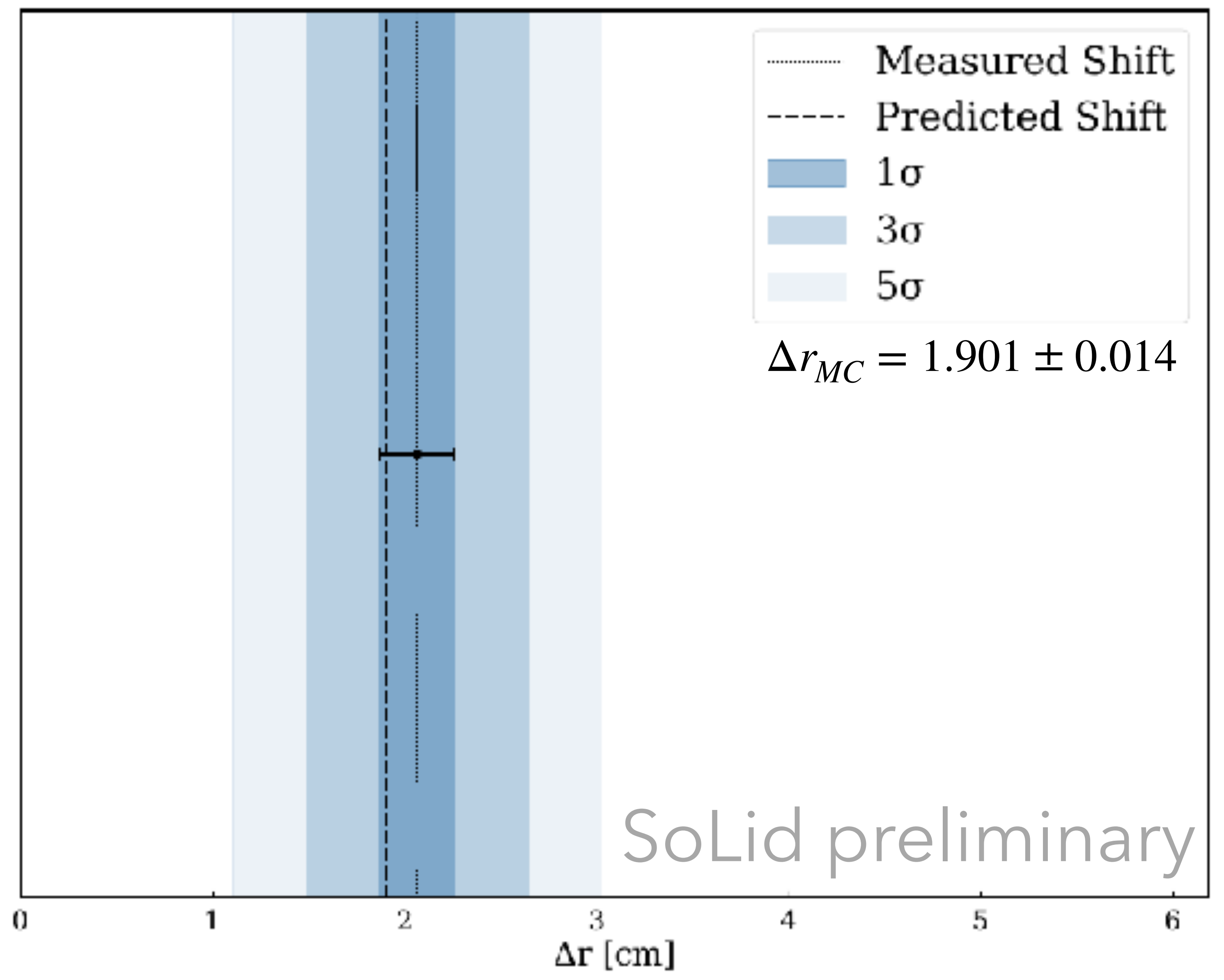
SoLid Antineutrino direction measurement

- SoLid detector sensitive to antineutrino directionality measurement
- Segmentation provides possibly to measure the ES-NS "displacement" dZ from IBD kinematics.
- Test deviation from zero hypothesis using MC with random sample (uncorrelated positron and neutron events)
  - Expect 3σ measurement with ~ 100 IBD events so a couple of days of operation or less





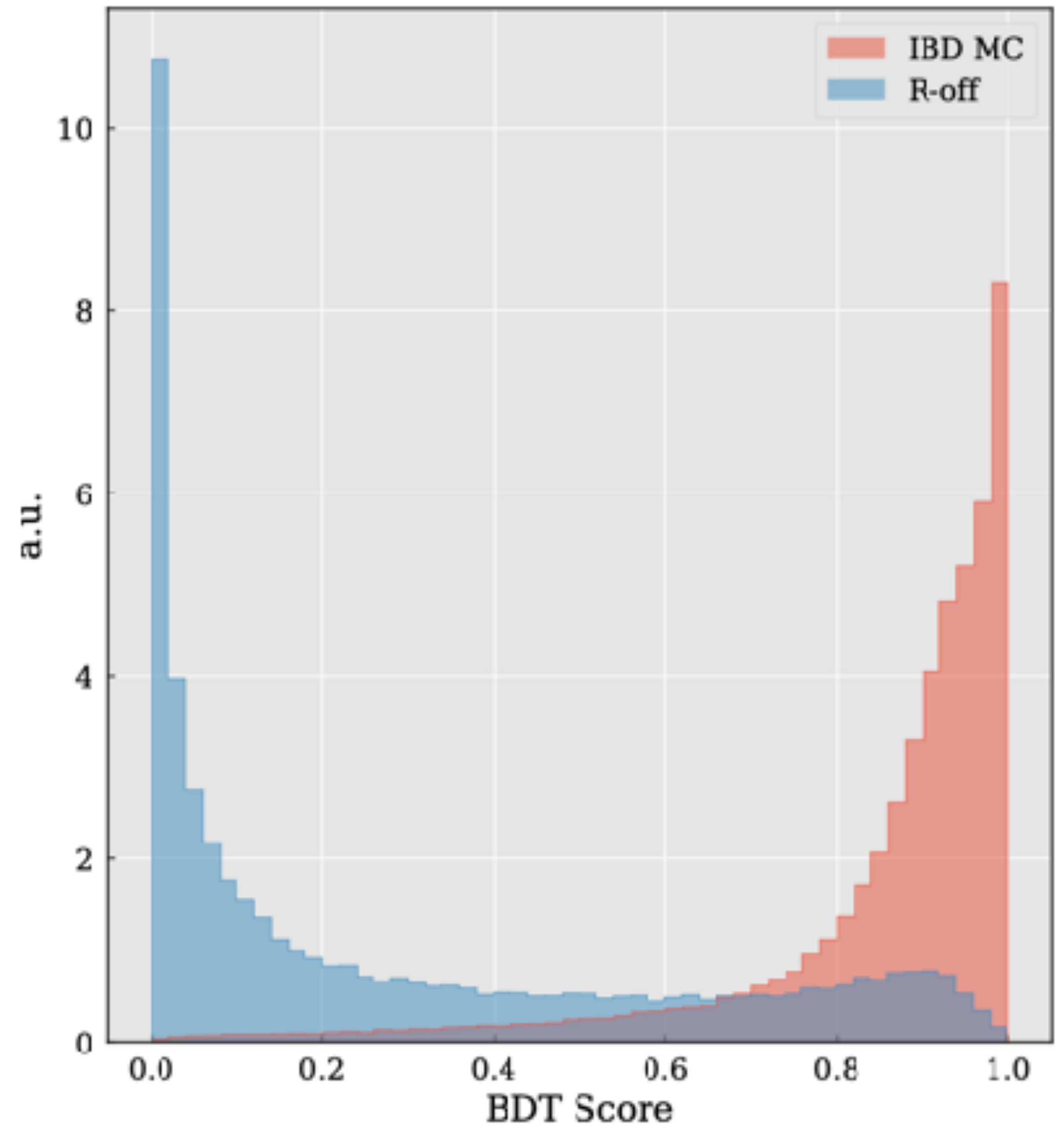
$$< \Delta r > = \sqrt{< dX^2 > + < dY^2 > + < dZ^2 >}$$

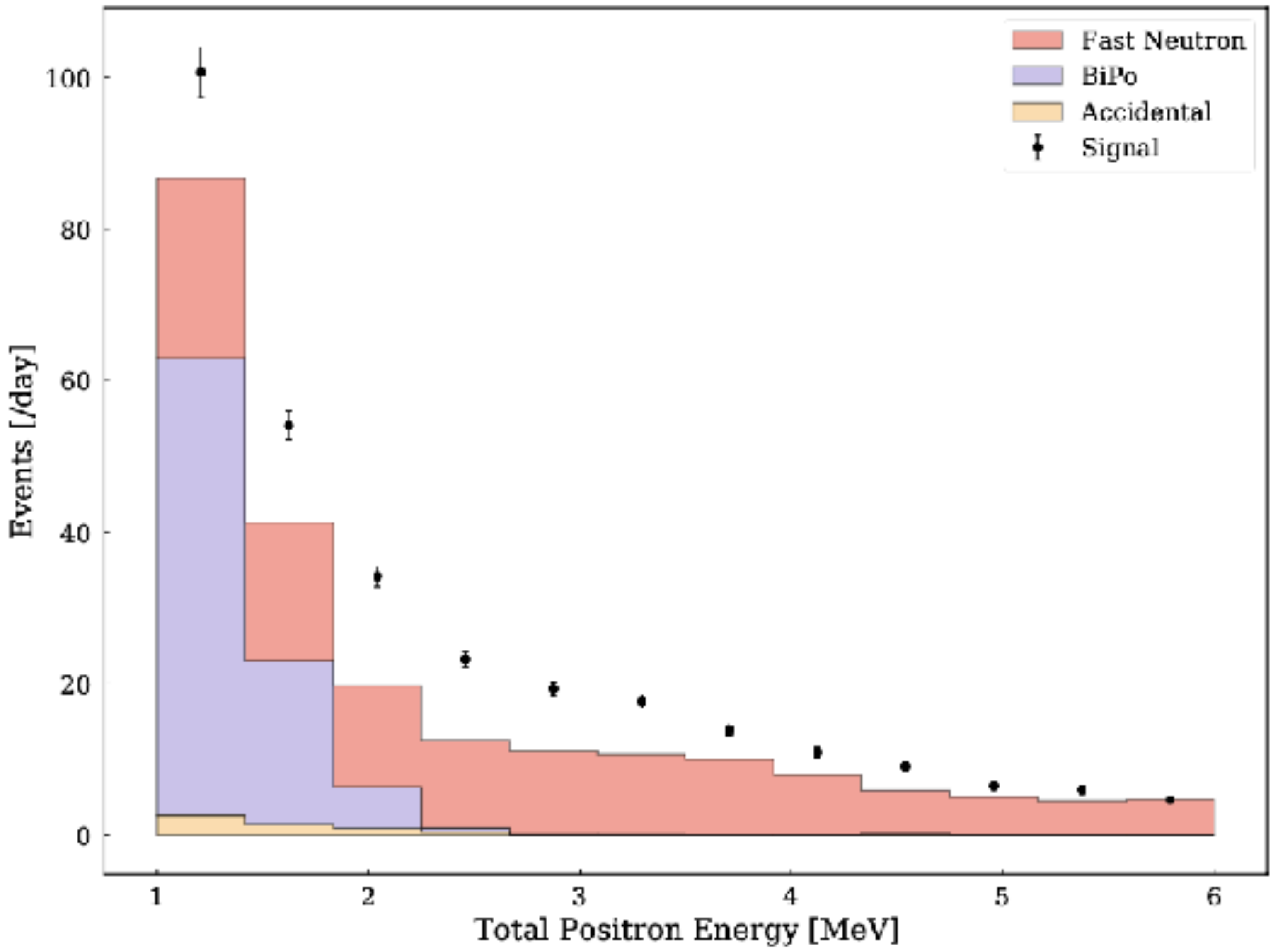


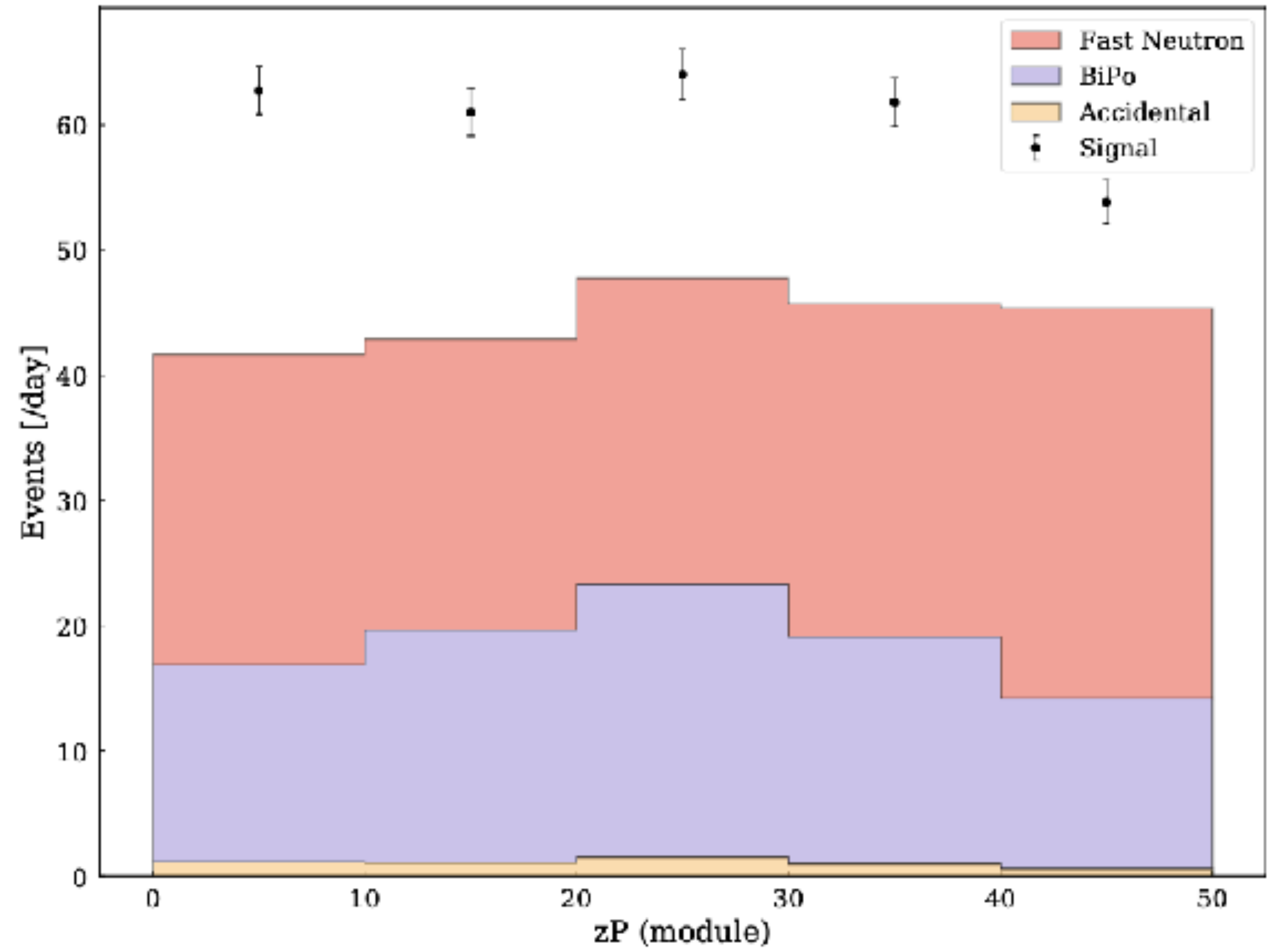
SoLid

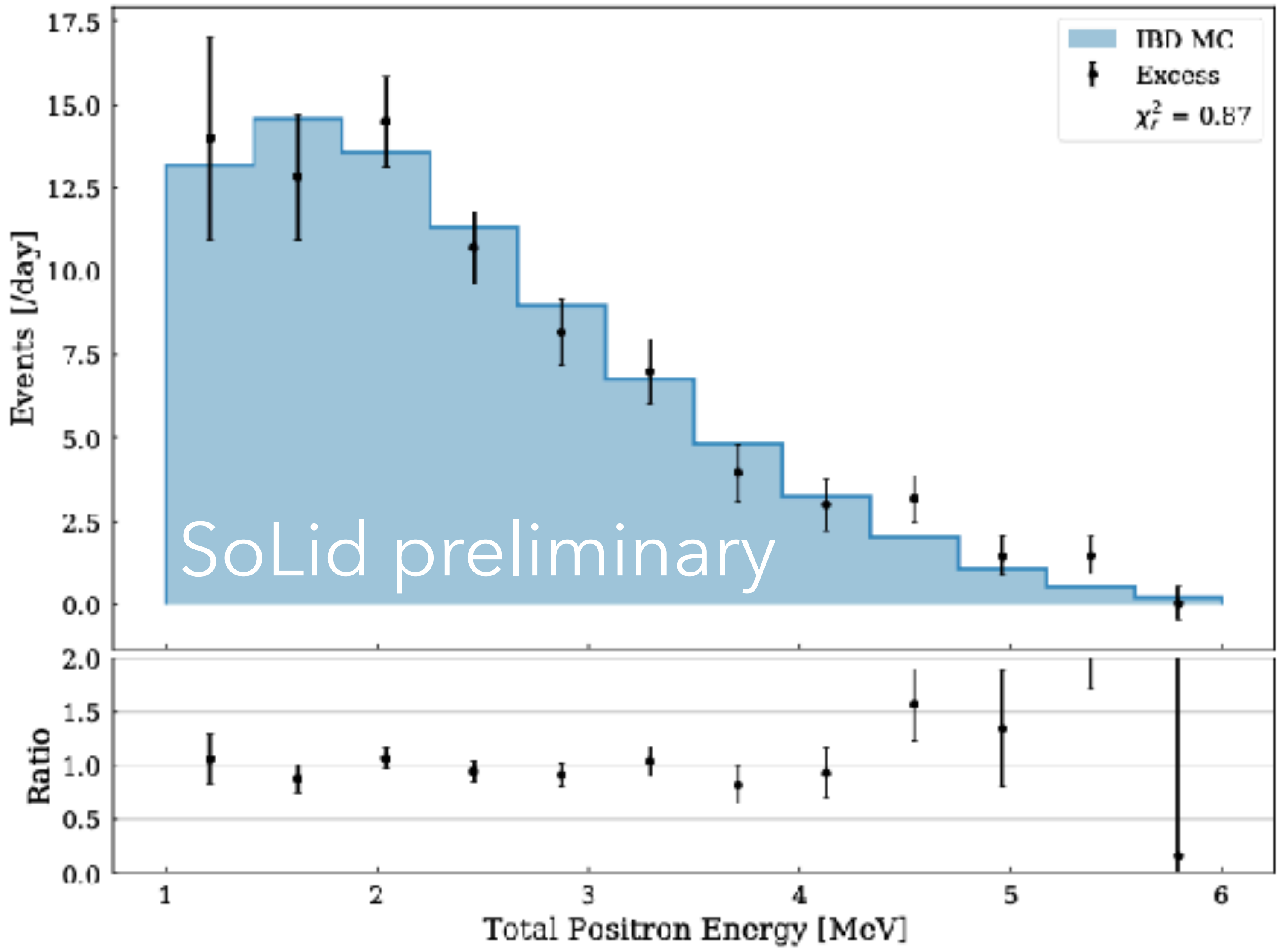
nuBDT selection

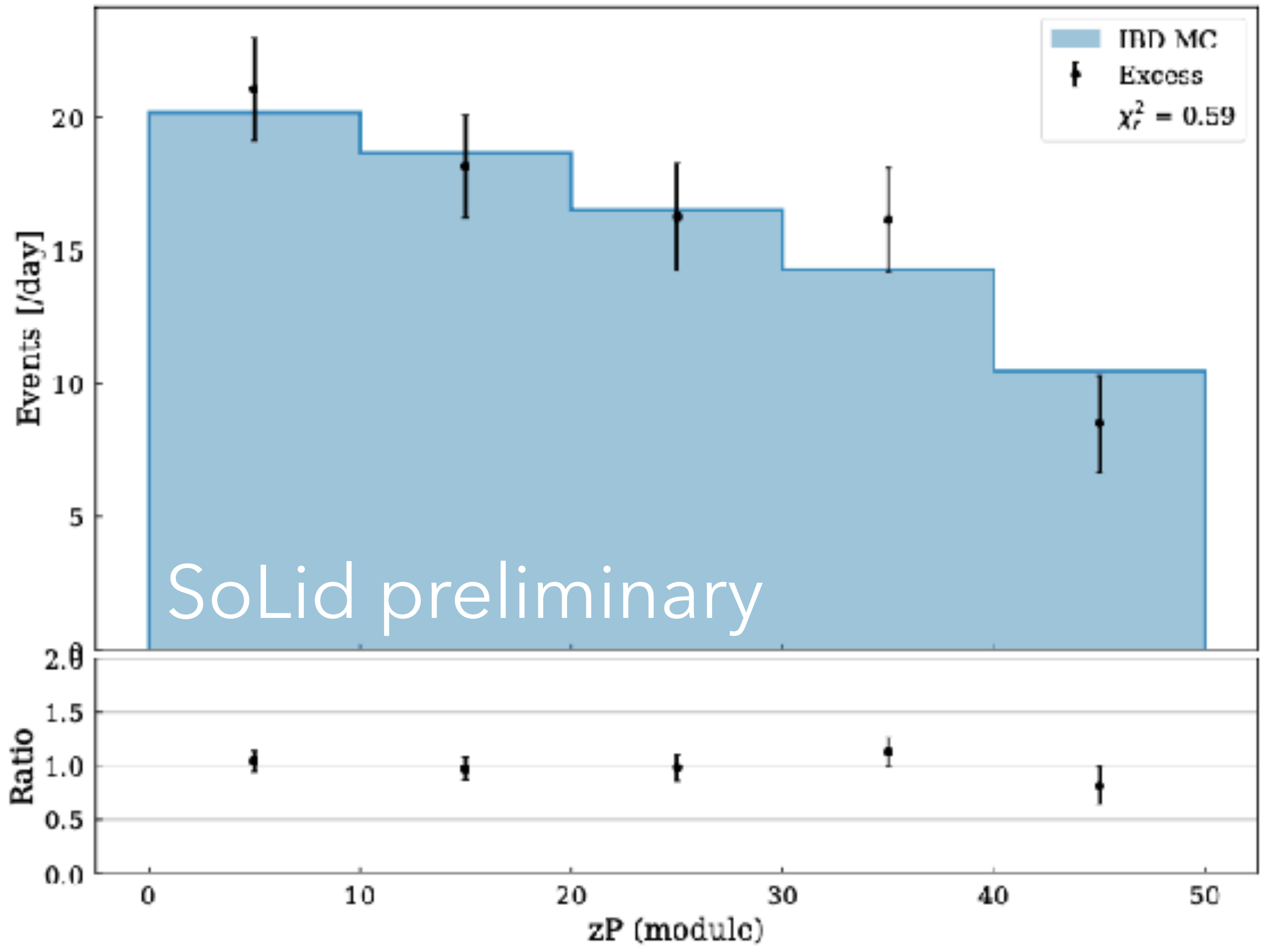
- nuBDT selection tuned on opened dataset
- Good stability of signal on low statistical sample in energy and Z







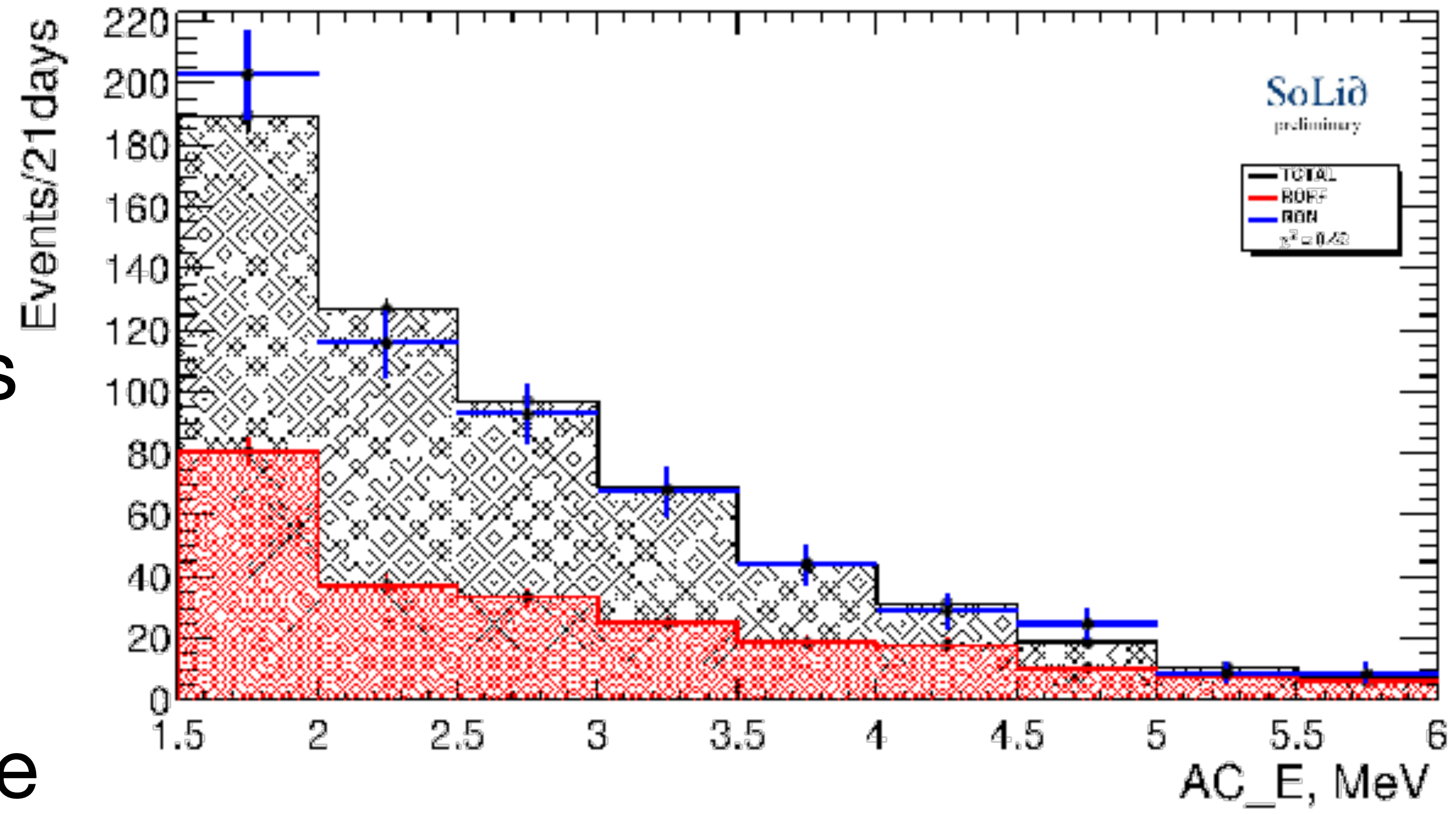


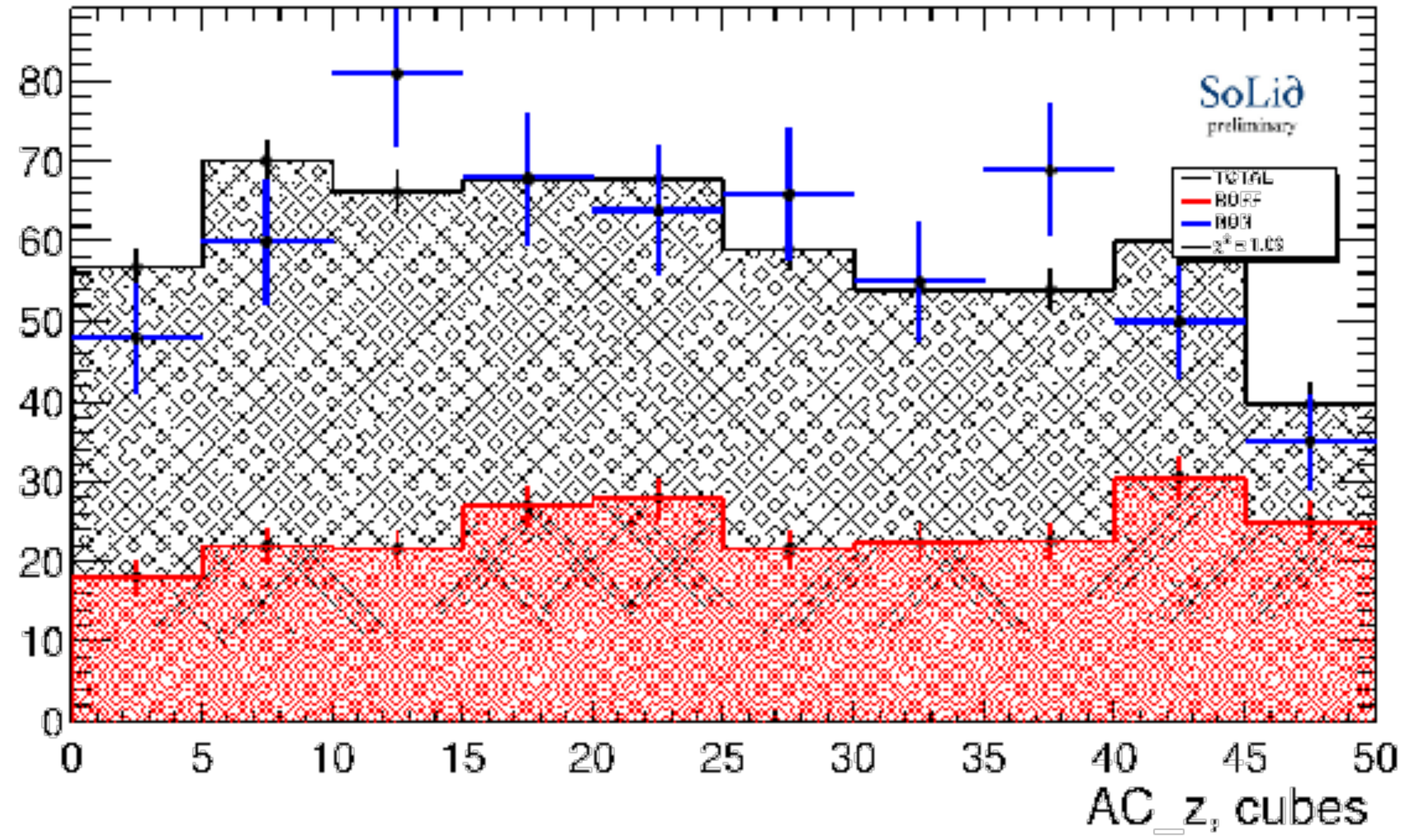


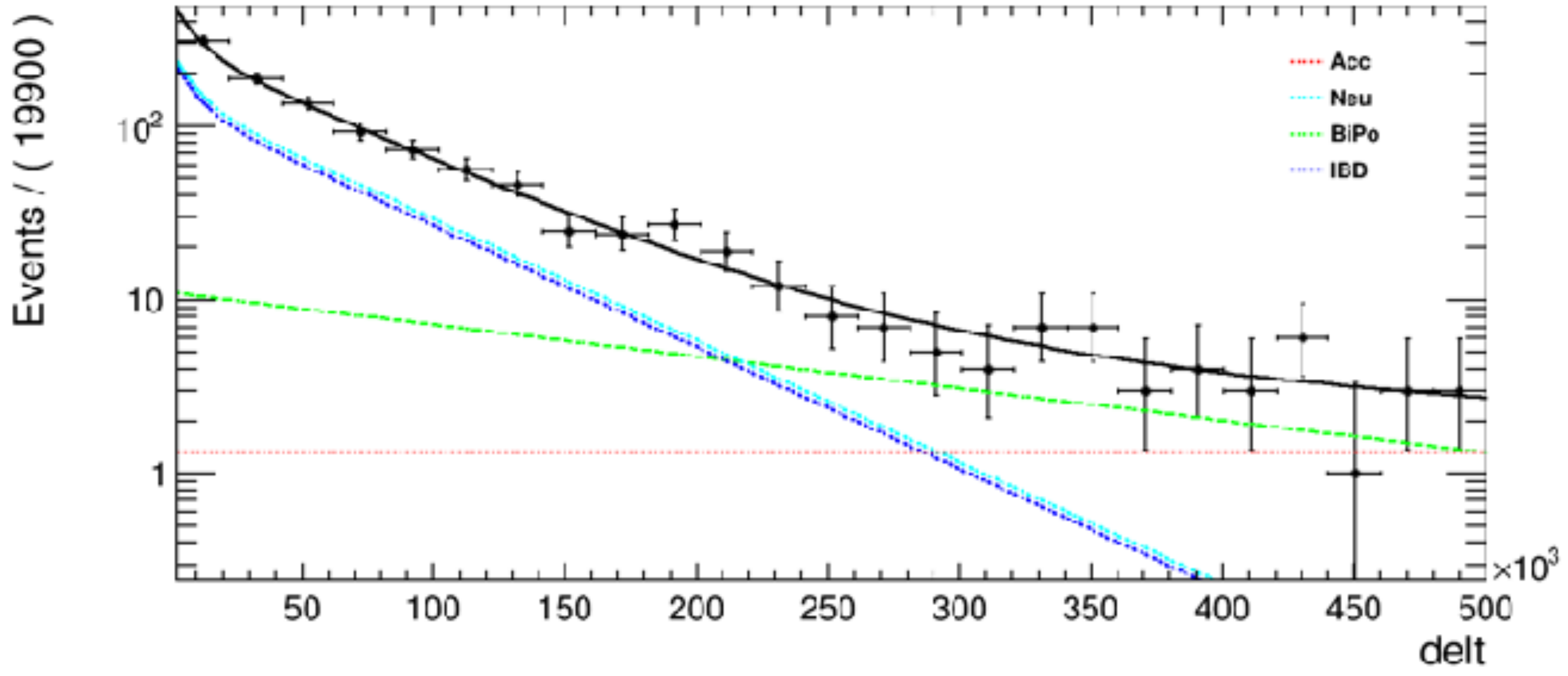
SoLi∂

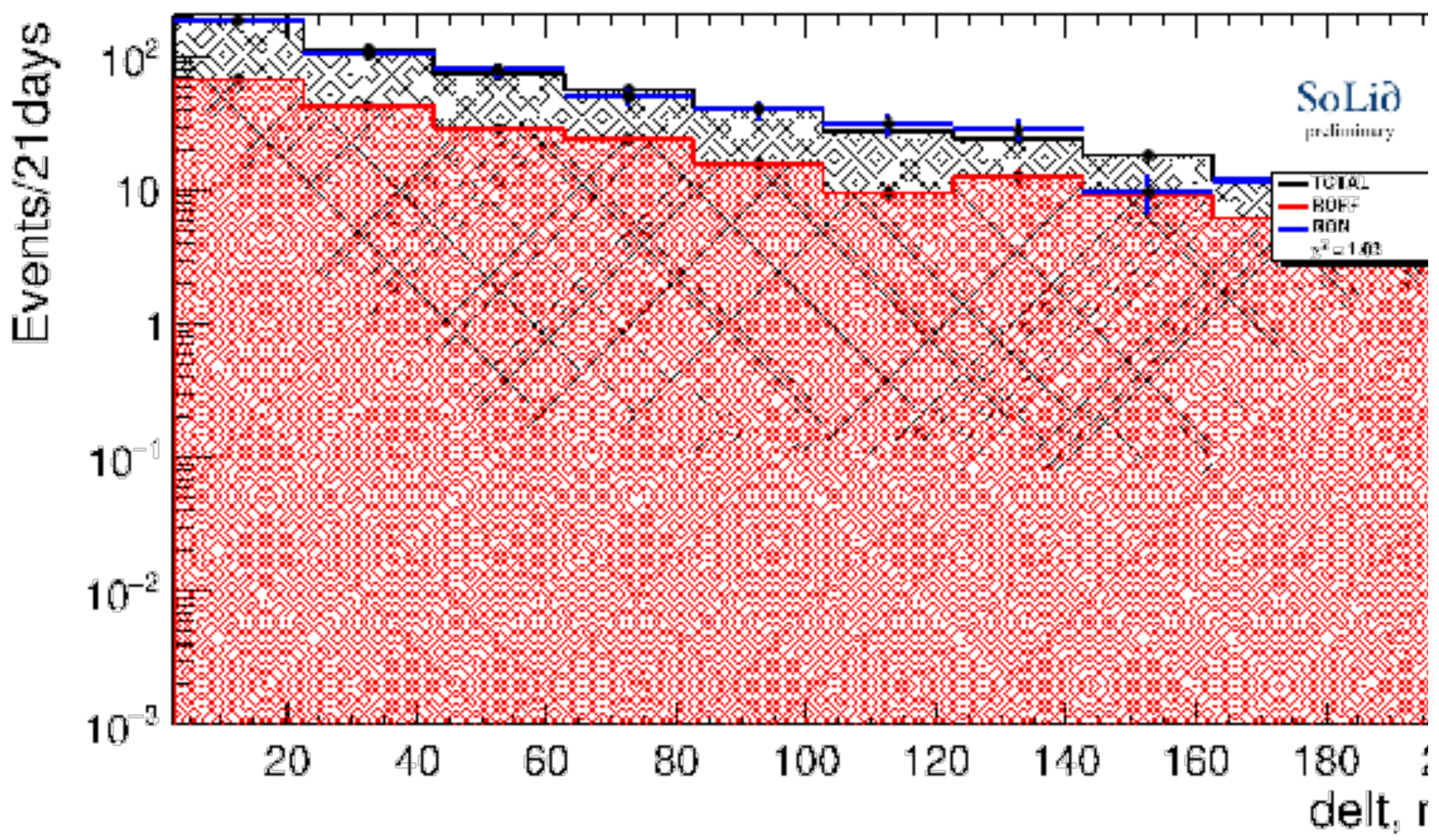
2γ topology selection

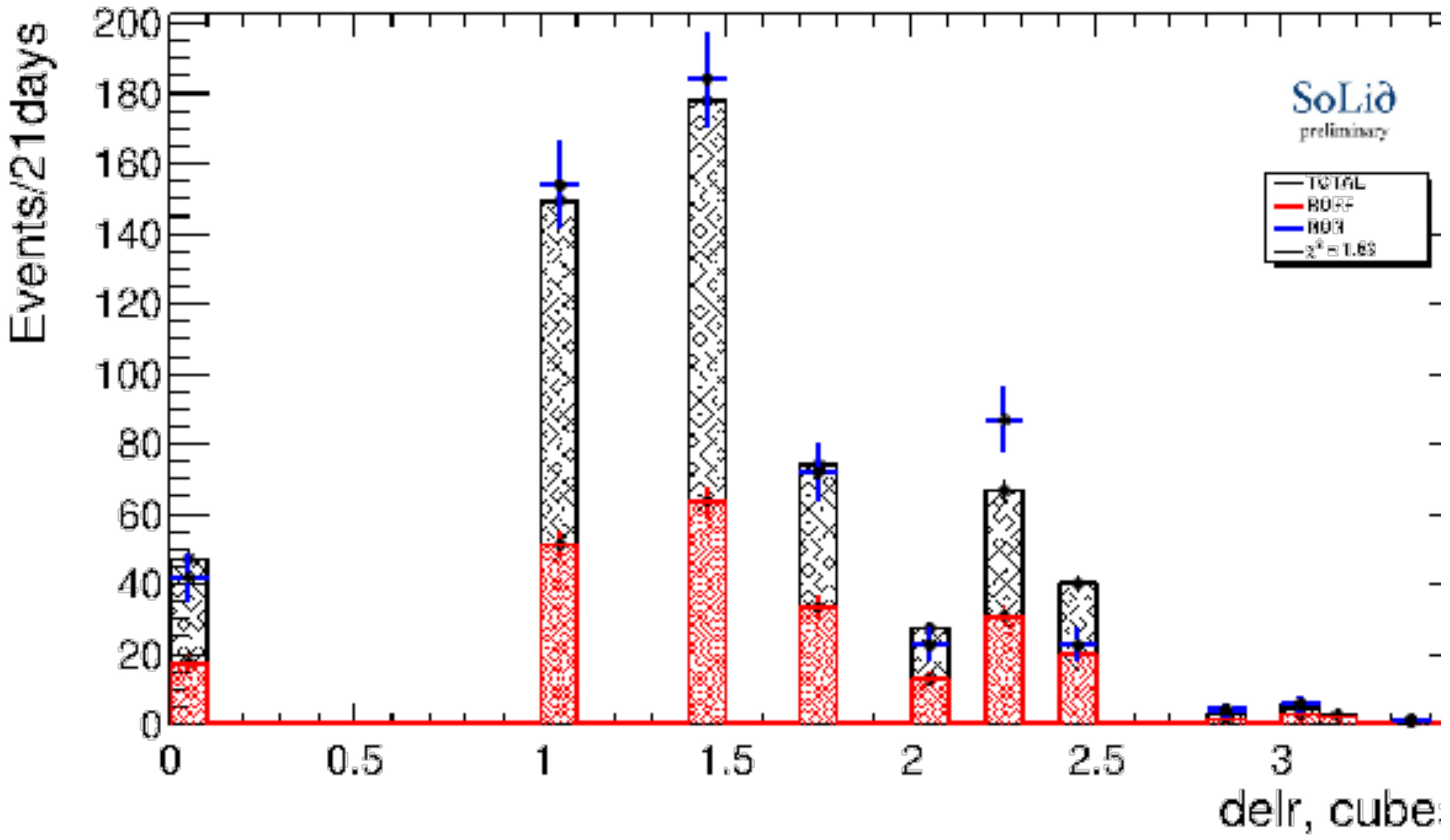
- Very good agreement also with the BDTG analysis
- Good prediction of background levels reactor OFF and ON based on multi-dim fit
- Approach may be extended to include 1γ topologies to raise efficiency











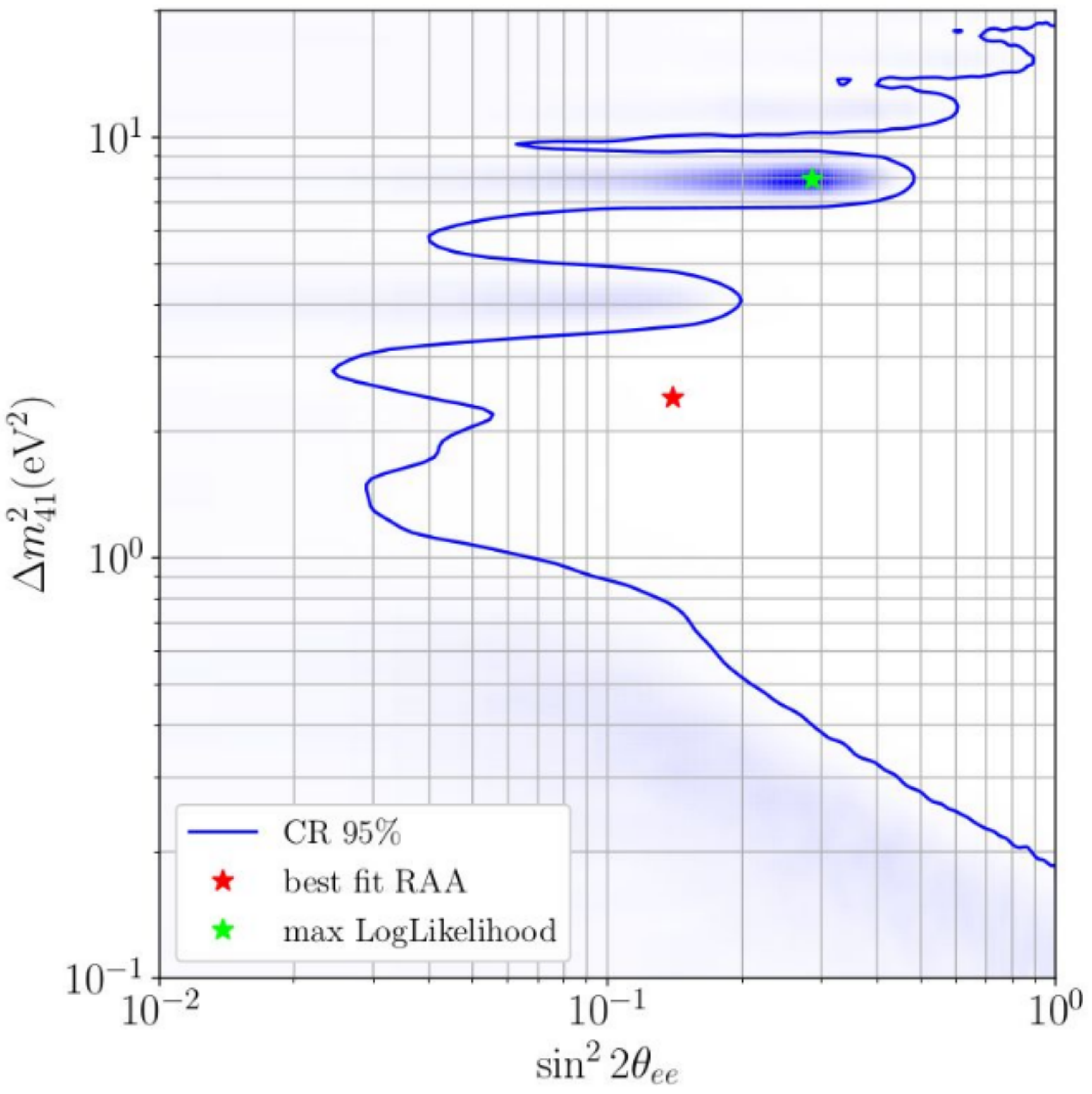
SoLid

Oscillation fit

- Oscillation fit tools are ready
- Detector response modelled with migration matrix
  - Standard frequentist approach based on Feldman-Cousins
  - Bayesian MCMC fit developed last year
    - Tested with B-12 spectrum
- Systematics well understood
- Ready to perform oscillation fit on data

MCMC fit using B-12 Energy spectrum instead of IBD

NEW



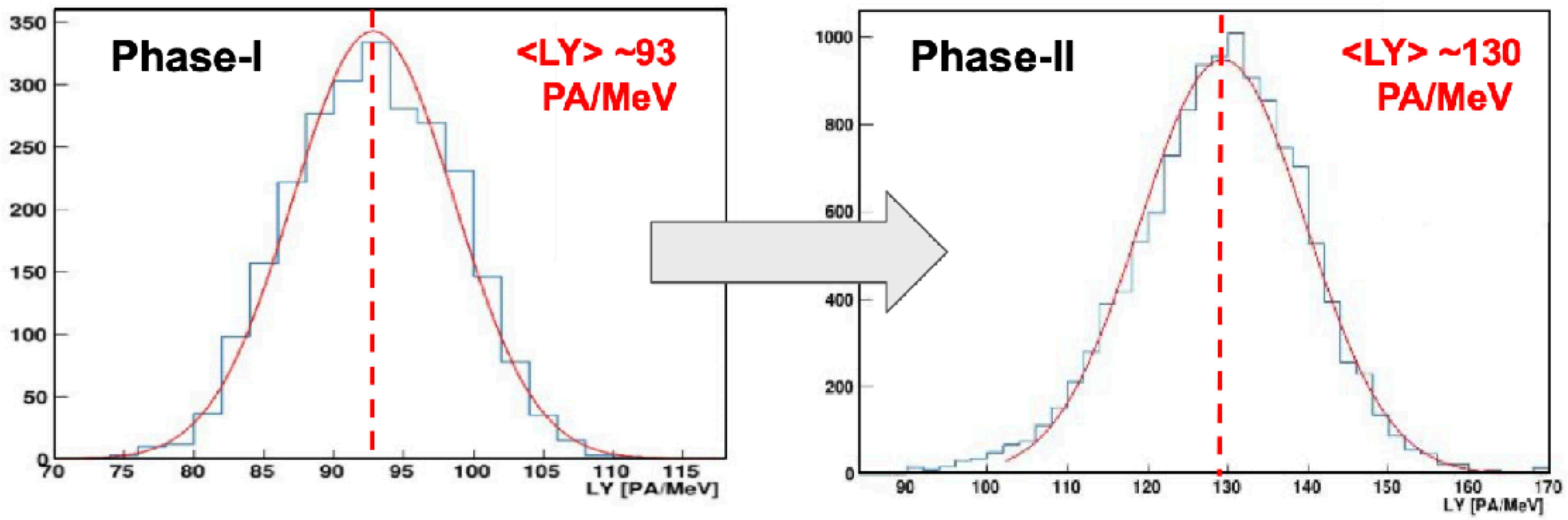
SoLid

SoLid Phase-II (2020-22)

Upgrading the detector with new MPPCs (S14 series)

- Better photon detection efficiency compared to S12 series ⇒ translates to a 40% increase in light yield
- **Cross-talk** reduced by a factor of two
- Improved **energy resolution**
- Expected improvement of **annihilation gamma** reconstruction

Taking data with Phase-II detector since late 2020



SoLid

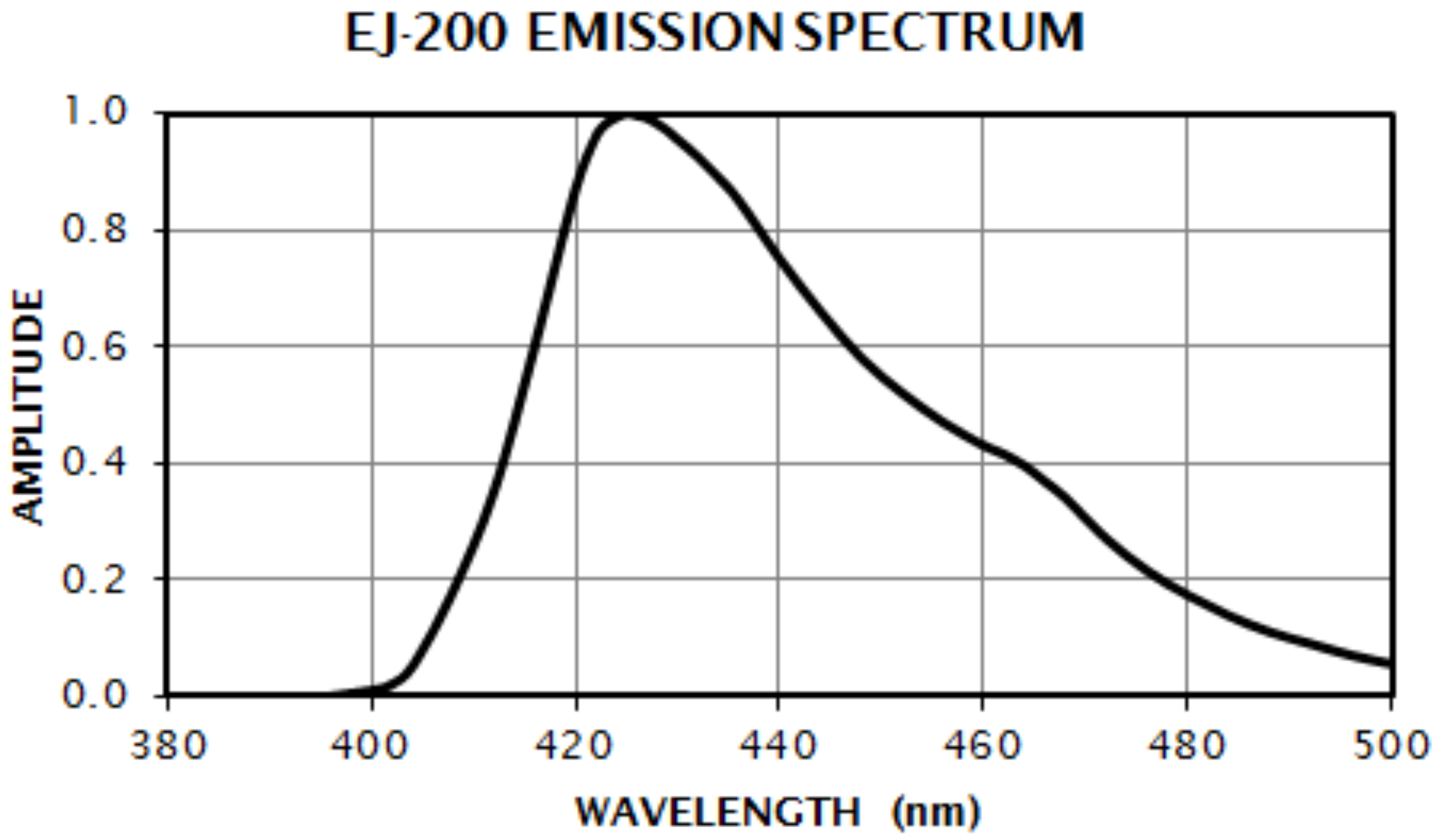
Summary

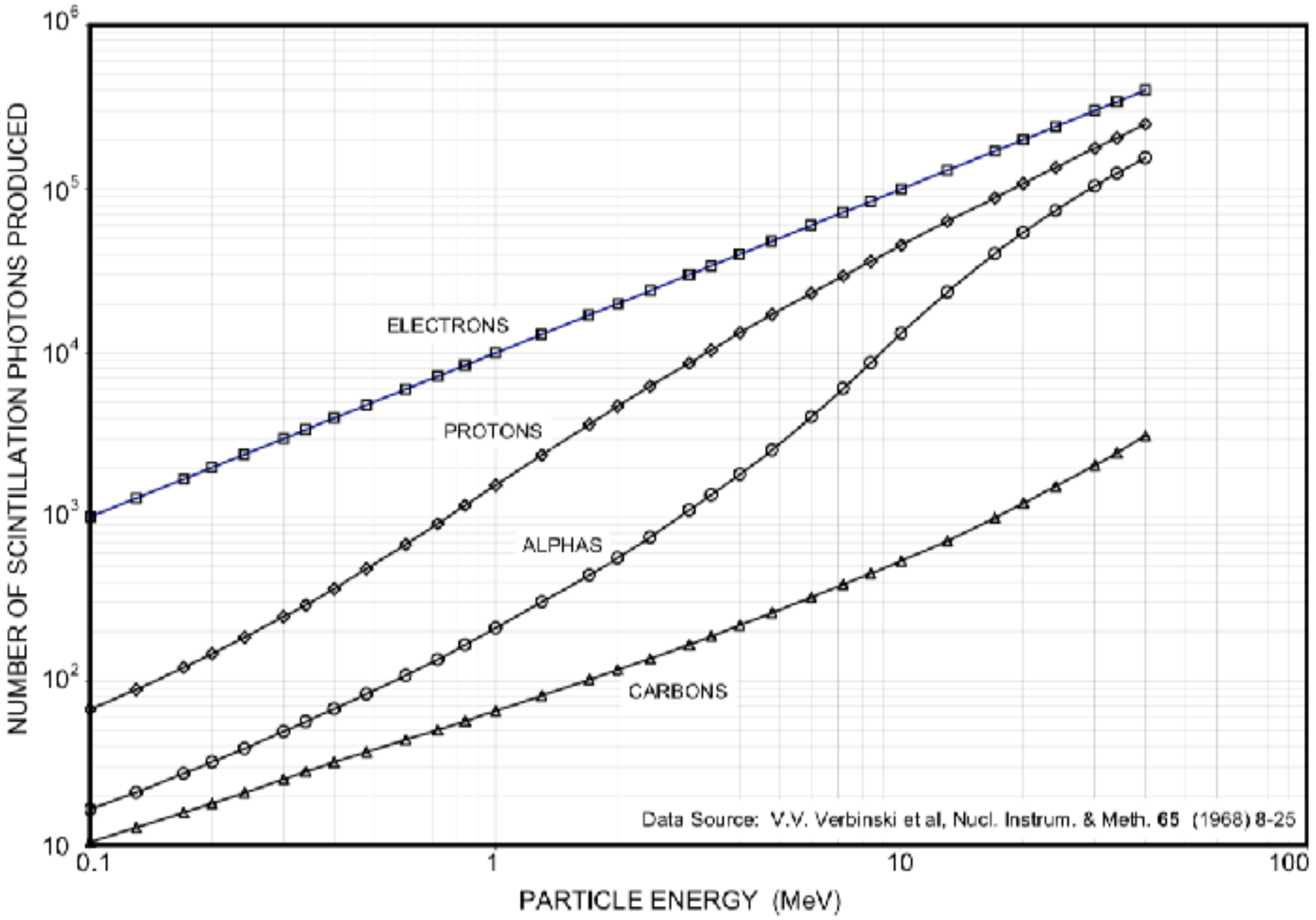
- SoLid has operated successfully at the BR2 research reactor between spring 2018 and spring 2022
- SoLid has ~ four years of data on tape : Phase-I and a Phase-II dataset using new SiPMs with 40% more light
- Antineutrino analysis based on this novel detector technology requires careful use of IBD signal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

Thank you !

SoLid

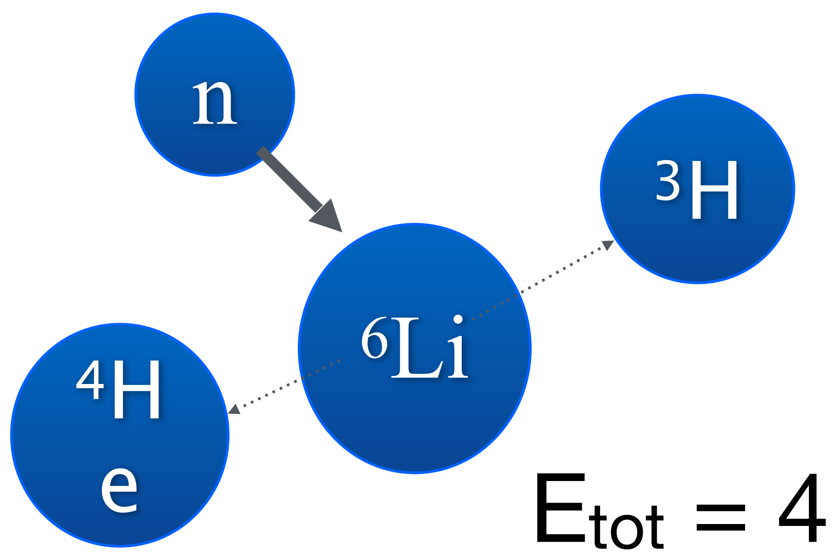
PVT scintillator cubes





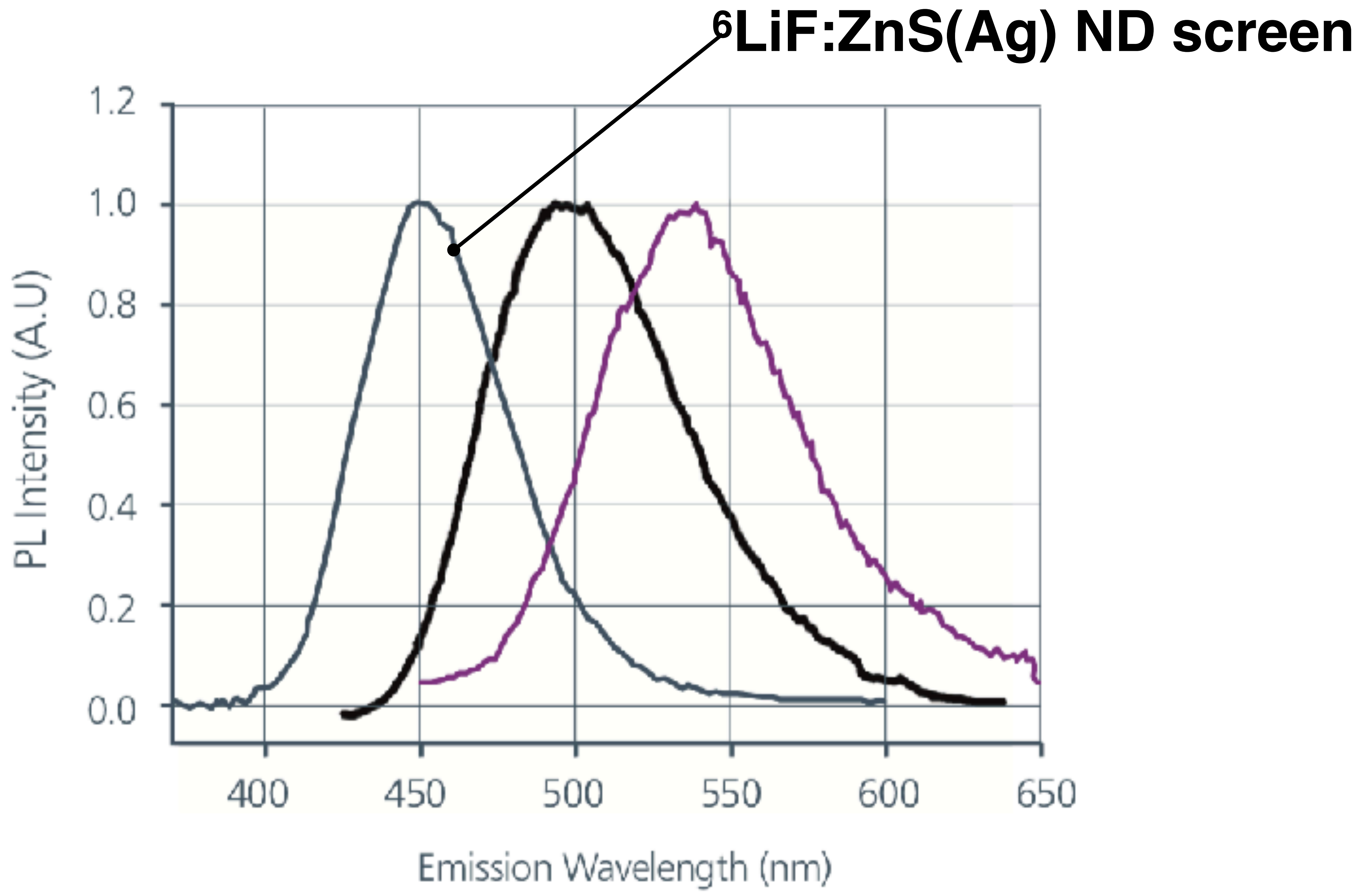
- Organic scintillator Polyvinyl toluene ELJEN EJ-200
  - best cost-performance ratio (at the time)
  - 10 000 photons/MeV
  - Linear in electron energy down to 60 keV
  - Scintillation quenching well known

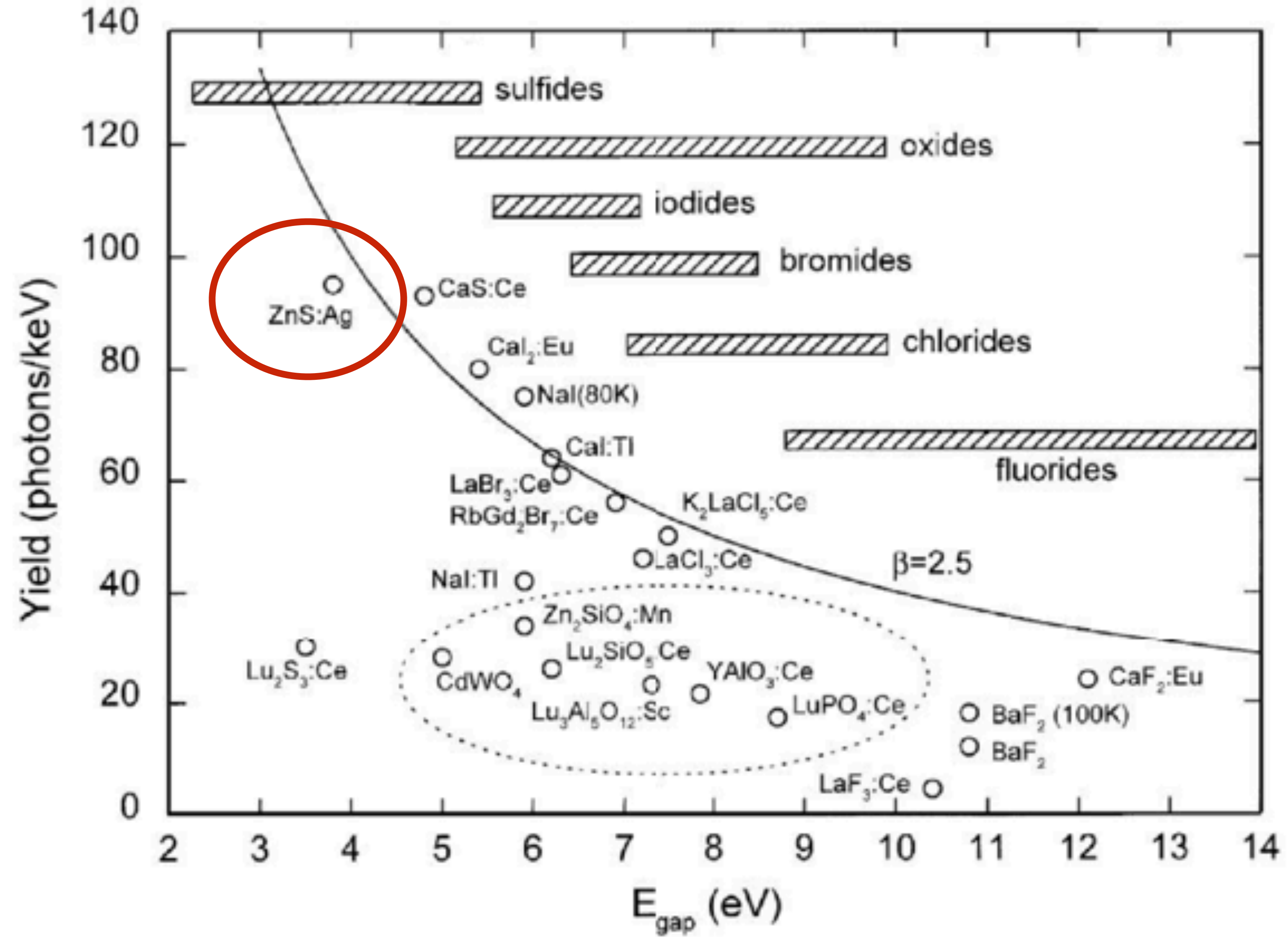
LiF:ZnS(Ag) scintillator



E_{tot} = 4.78 MeV

- ZnS(Ag) phosphor screen with LiF (Lithium-6 at 95%) from Scintacor (ND screens)
  - 1:2 (LiF:ZnS) ratio, 250 um with reflective backing thickness to maximise neutron detection
  - 24% neutron capture efficiency
- ZnS(Ag) is one of oldest and brightest inorganic scintillator
  - Emits around 450 nm
  - 170 000 photons/n capture





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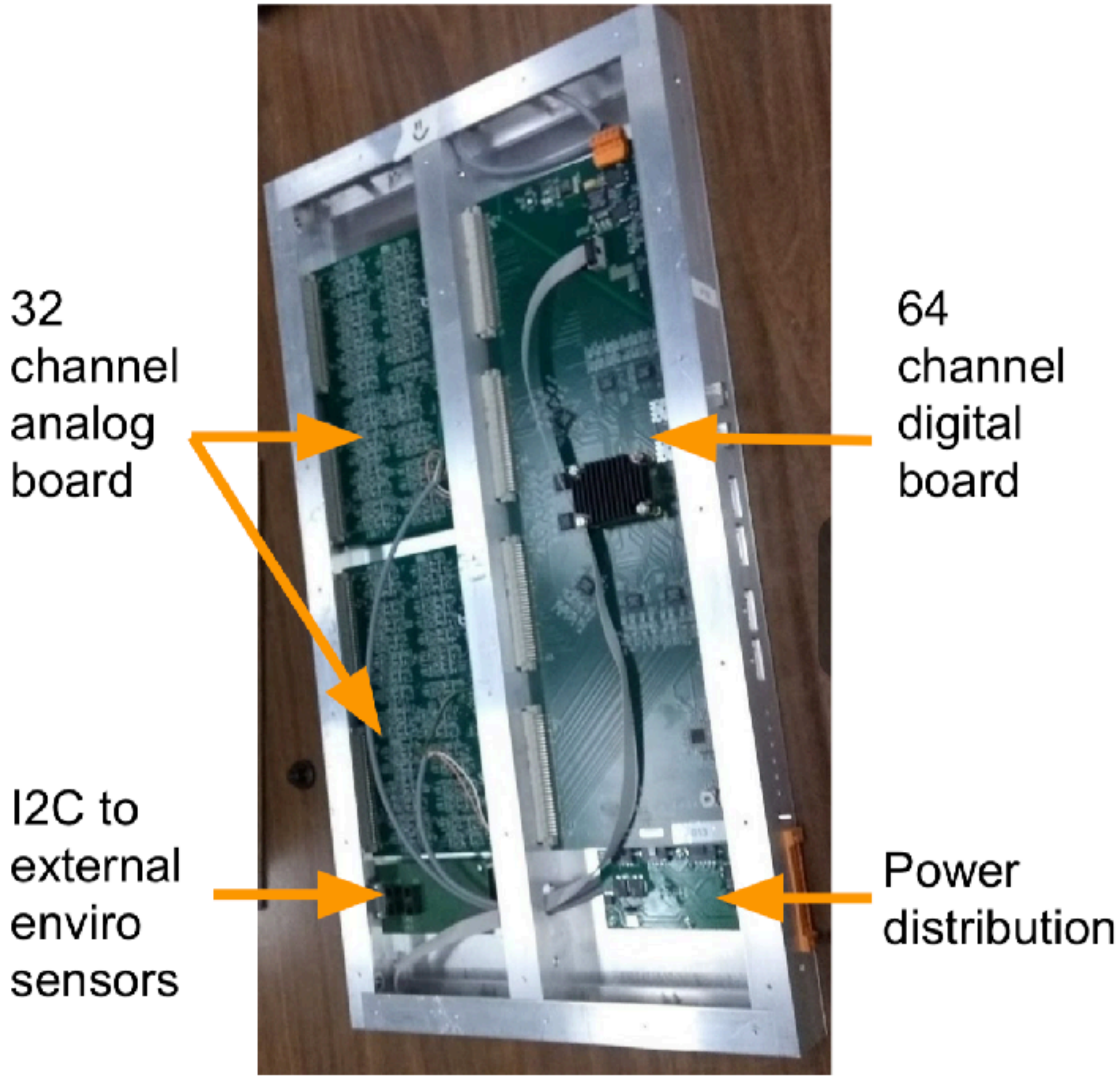
Detector read out

- Low cost, custom-made digitiser electronics streaming data from 3200 read out channels at 40 MHz
  - Very large data size 2 Tb/s (similar to ATLAS tracker) reduced to 1.5 TB/day
  - Flexible event building and transmission of data storage
  - Modular design to ease assembly and maintenance
- Data recorded to server and transfered to SoLid data centers at Tier 2 sites in Brussels and Imperial College



https://iopscience.iop.org/article/10.1088/1748-0221/14/11/P11003

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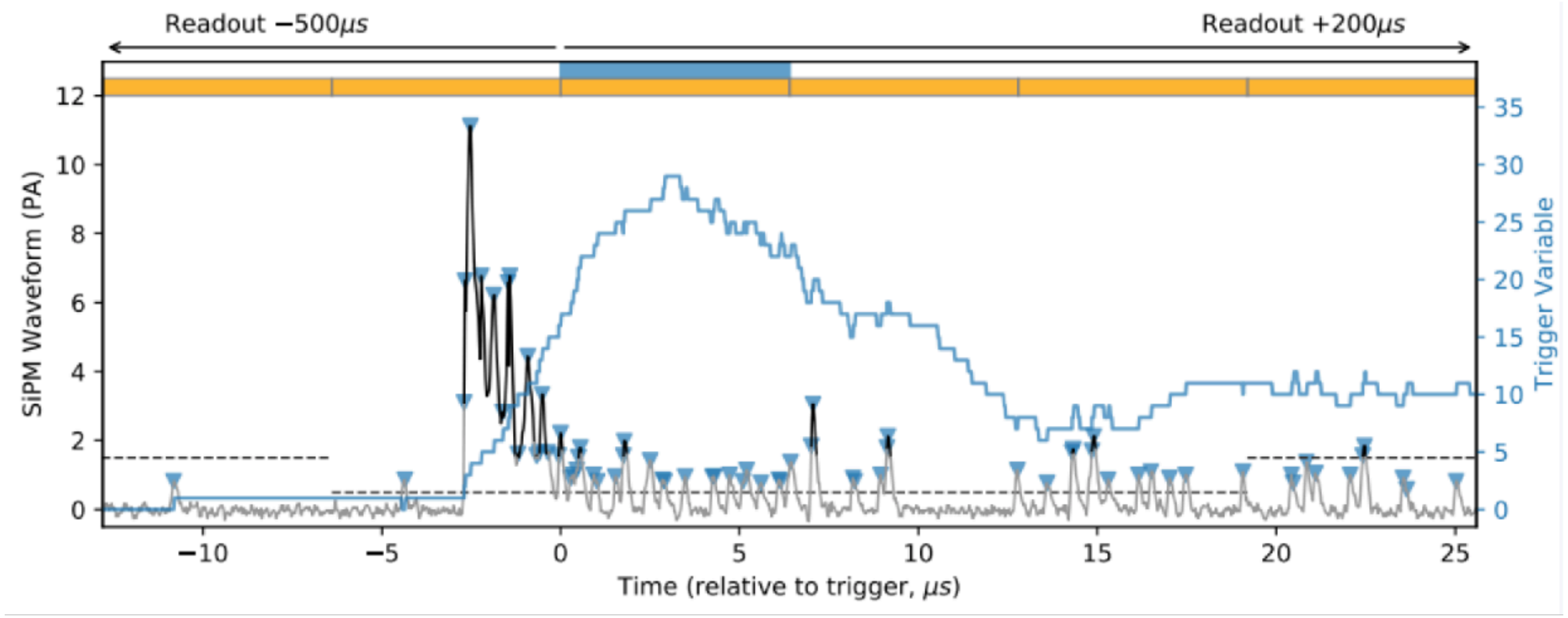
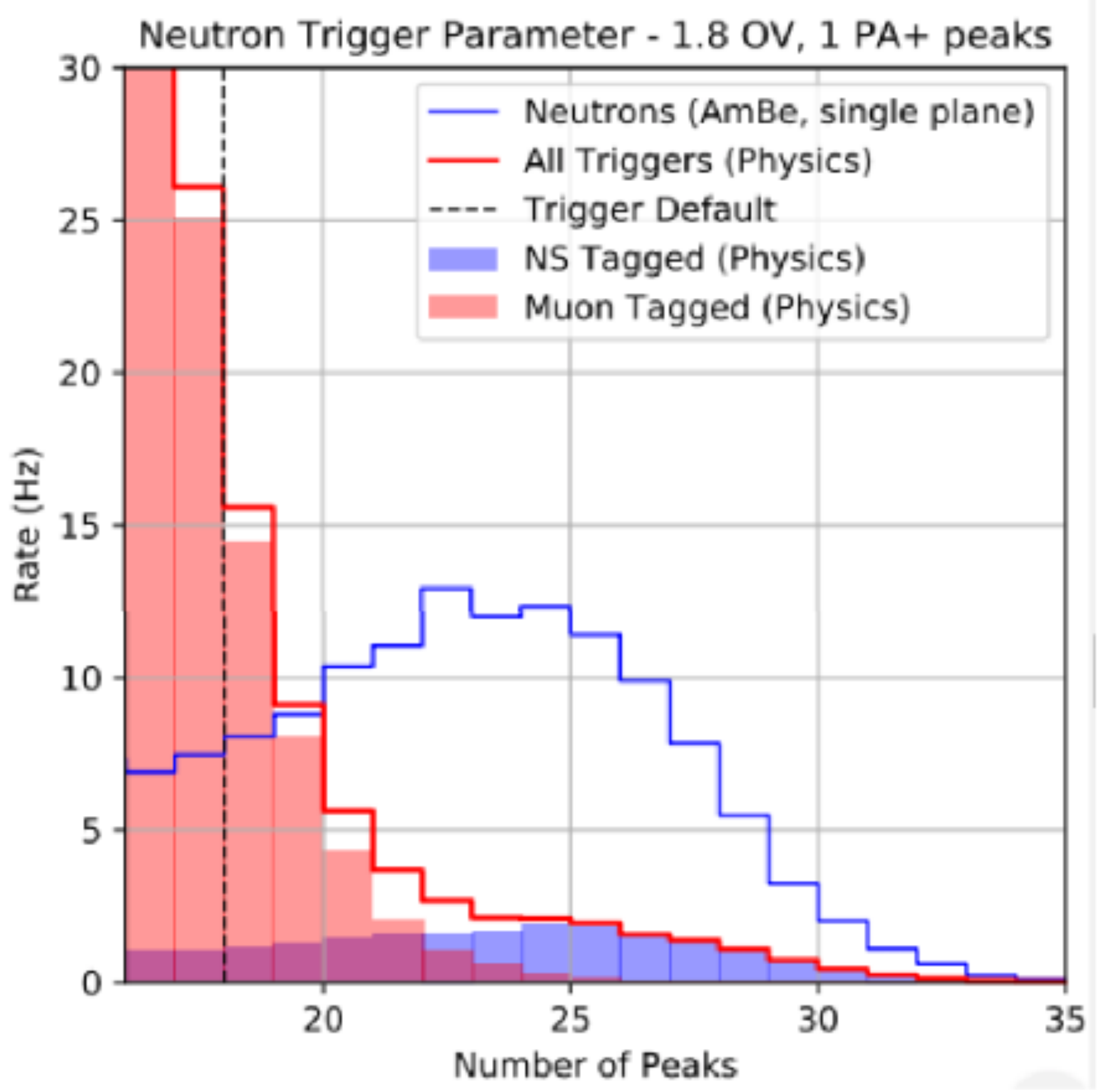
Front-end triggers





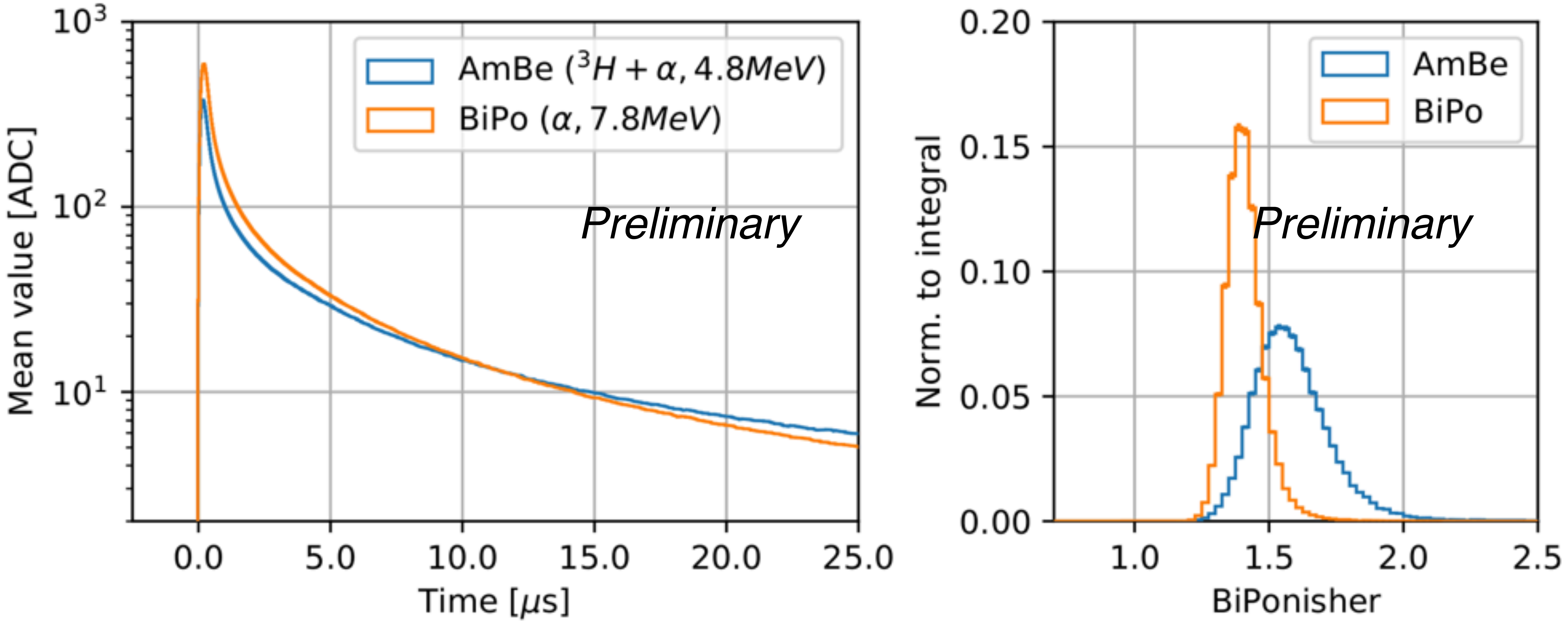
- Three triggers during physics run:
- NS trigger (neutrino trigger)
  - Buffer large window around the NS trigger (-500 us : + 200 us)
  - ± 3 planes around trigger plane read out at the same time
- Threshold trigger at 1.5 MeV to record activity in between NS triggers
- Random trigger

SoLi∂

Alpha - Neutron CI discrimination

- LiF:ZnS(Ag) has PSD capabilities (ZnS is an inorganic scintillator)
  - Shape of alpha waveforms are different from Lithium-6 neutron capture !
- Most powerful cut to reduce BiPo background (75% reduction)

α-n discrimination using Pulse Shape Discrimination in ZnS : BiPonisher (Q_{long}/Q_{short})



BiPonisher > 1,45 :

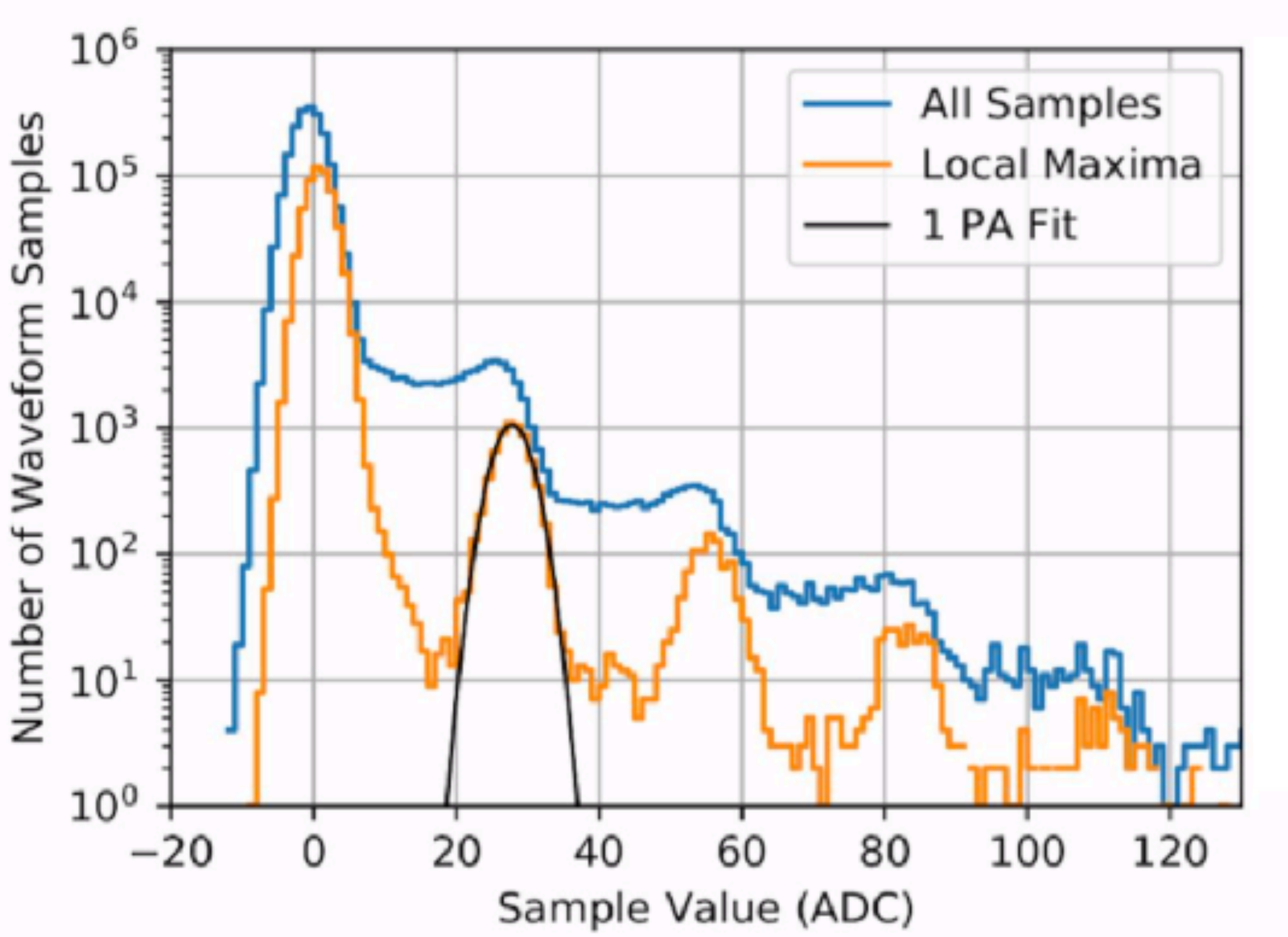
- Reject 75% of α
- Keep 85% of **n**

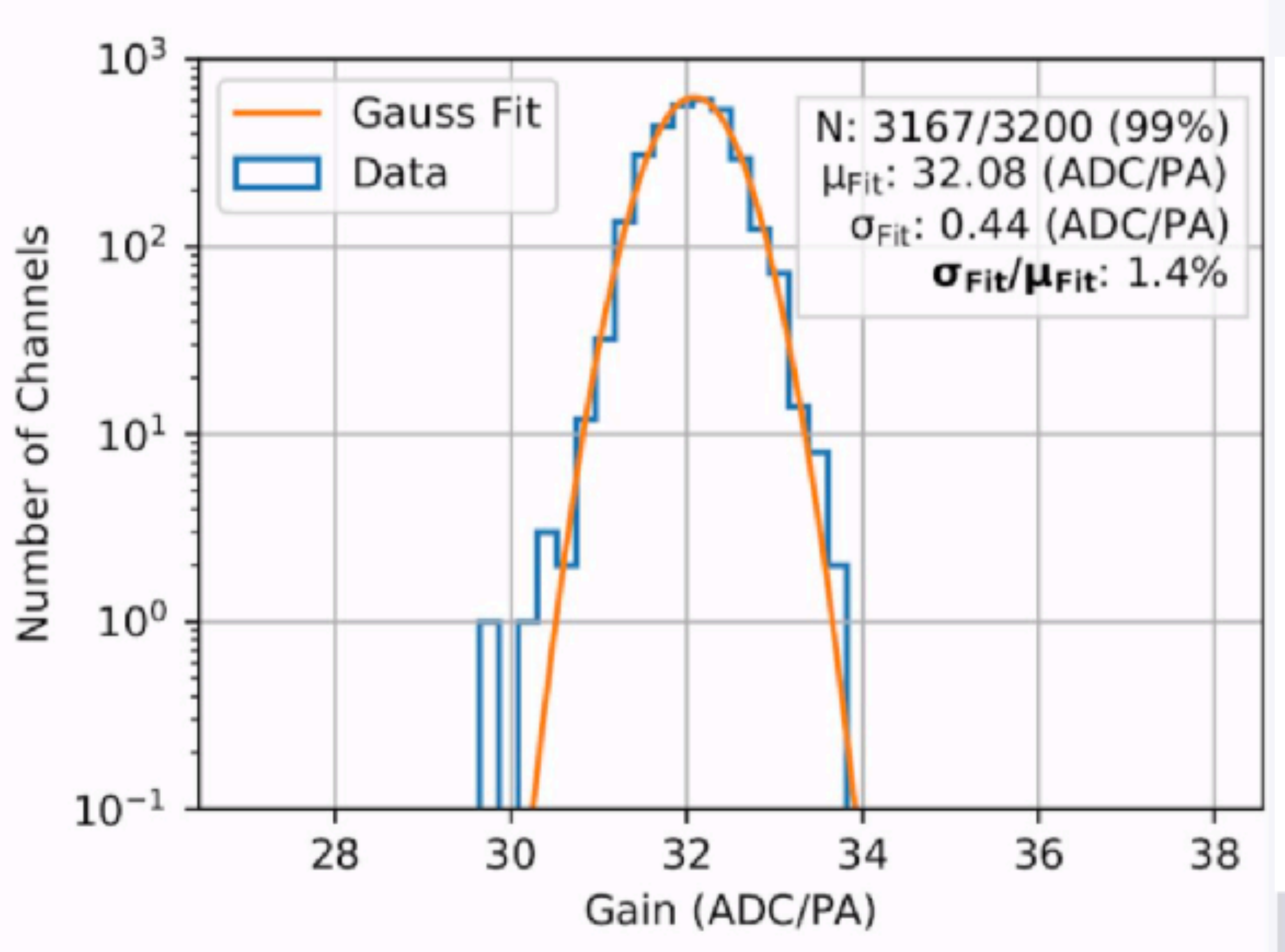
SoLid

Detector channel equalisation

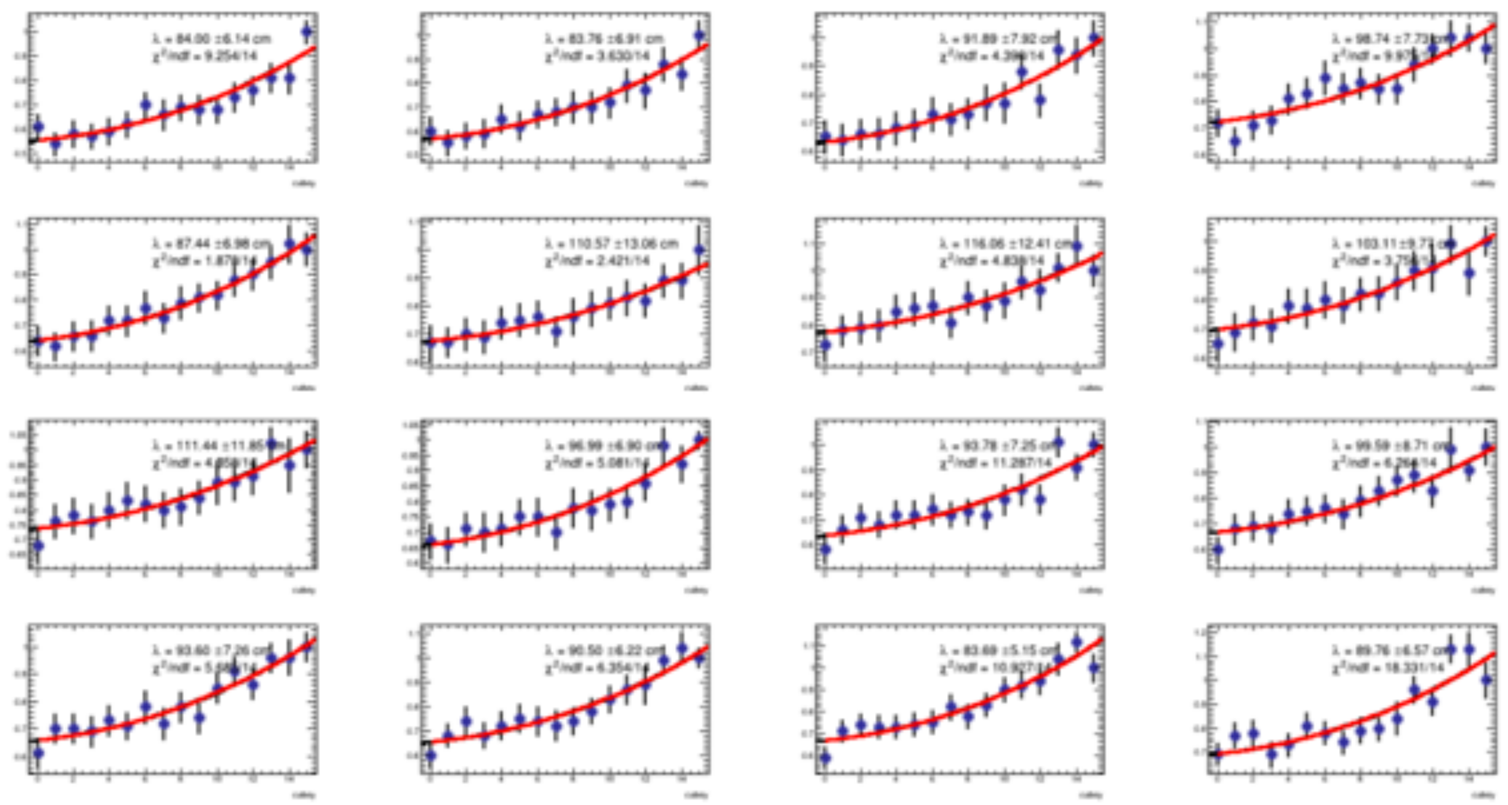
- SiPM have individual voltage trims
  - Gain equalised at few percent level (1.4%)
- Additional channel equalisation:
  - Fibre-SiPM coupling
  - Attenuation correction
- Currently at the level of ~3% across all cubes
  - Validation ongoing

SiPMs

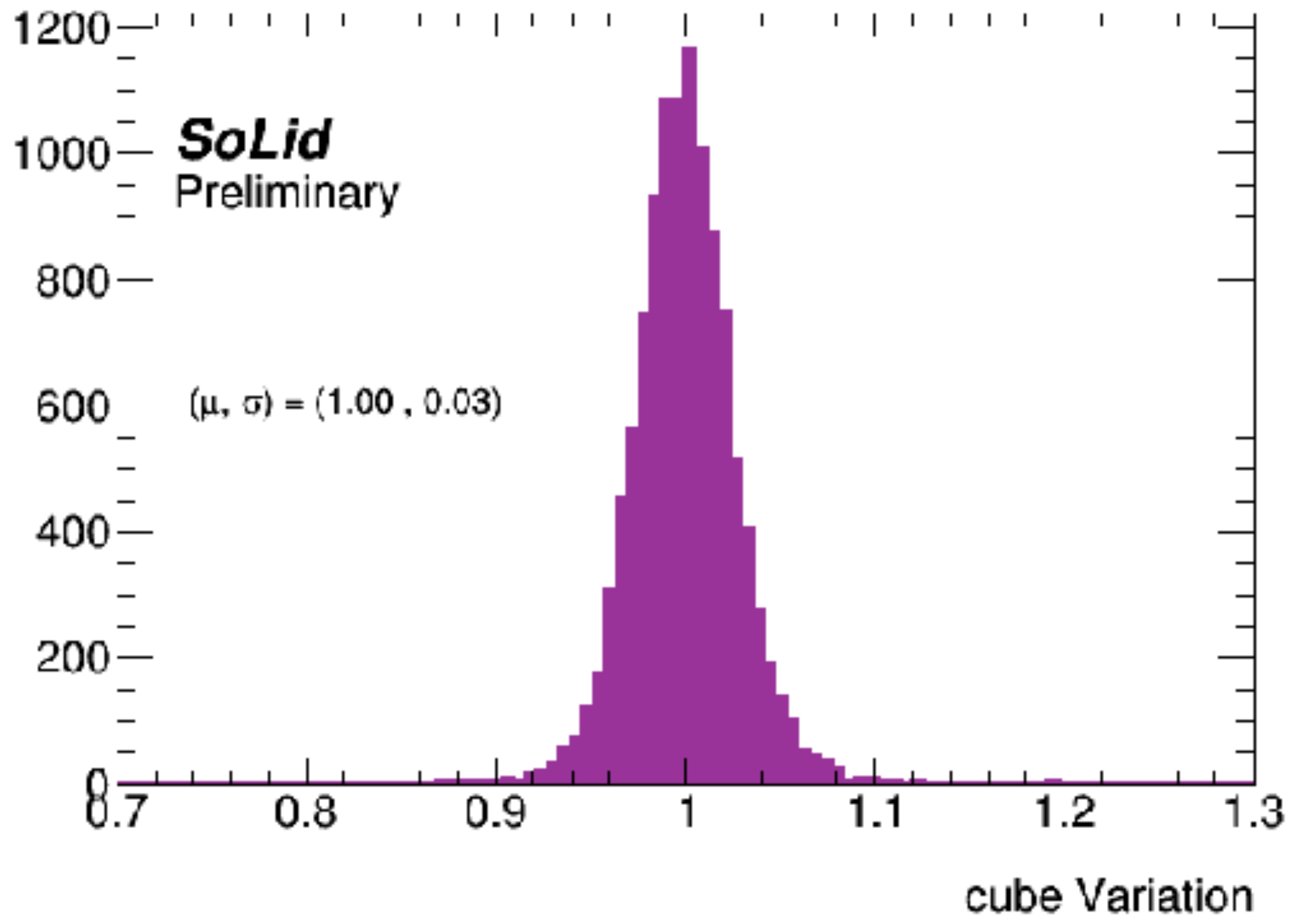




Fibres



After correction



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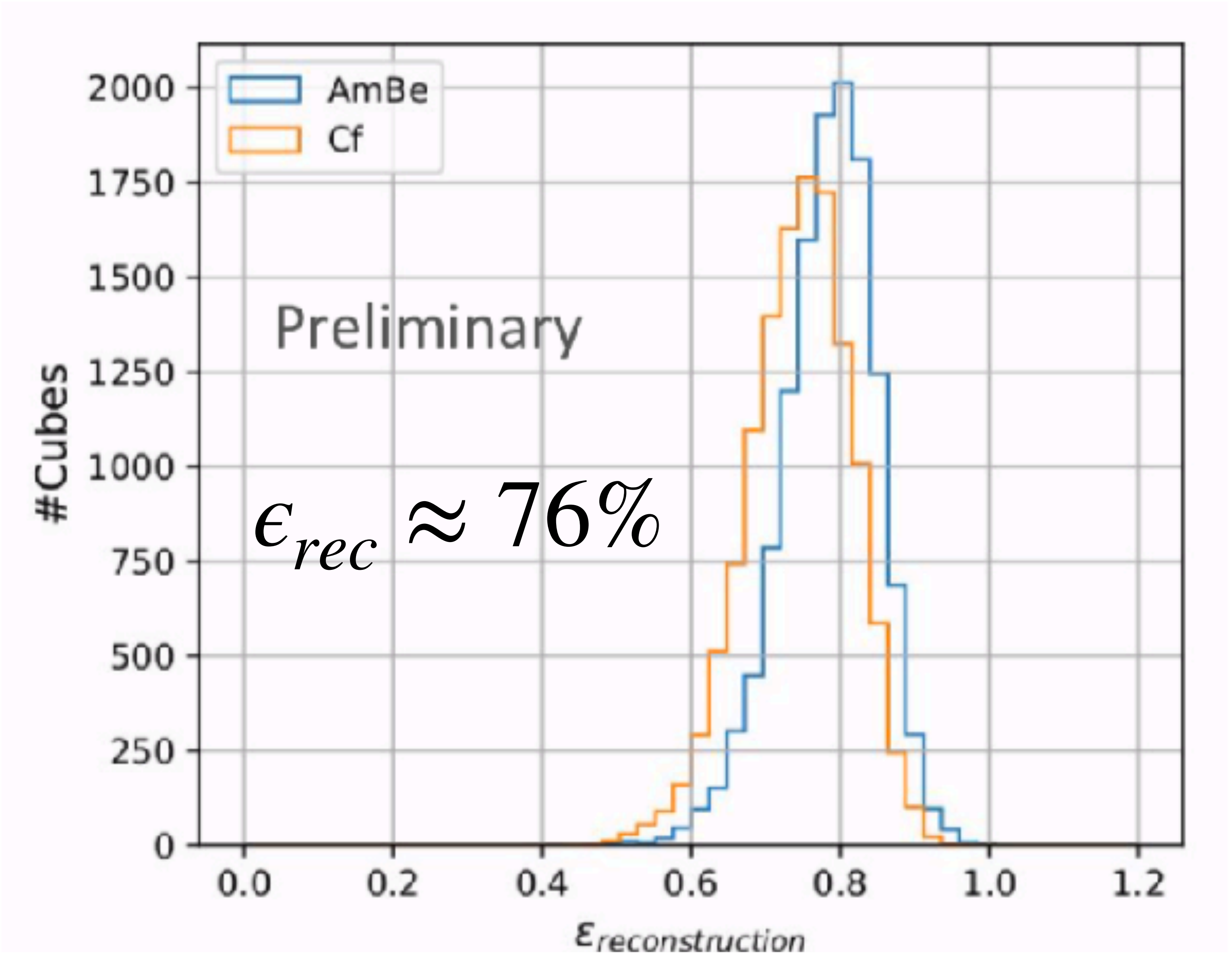
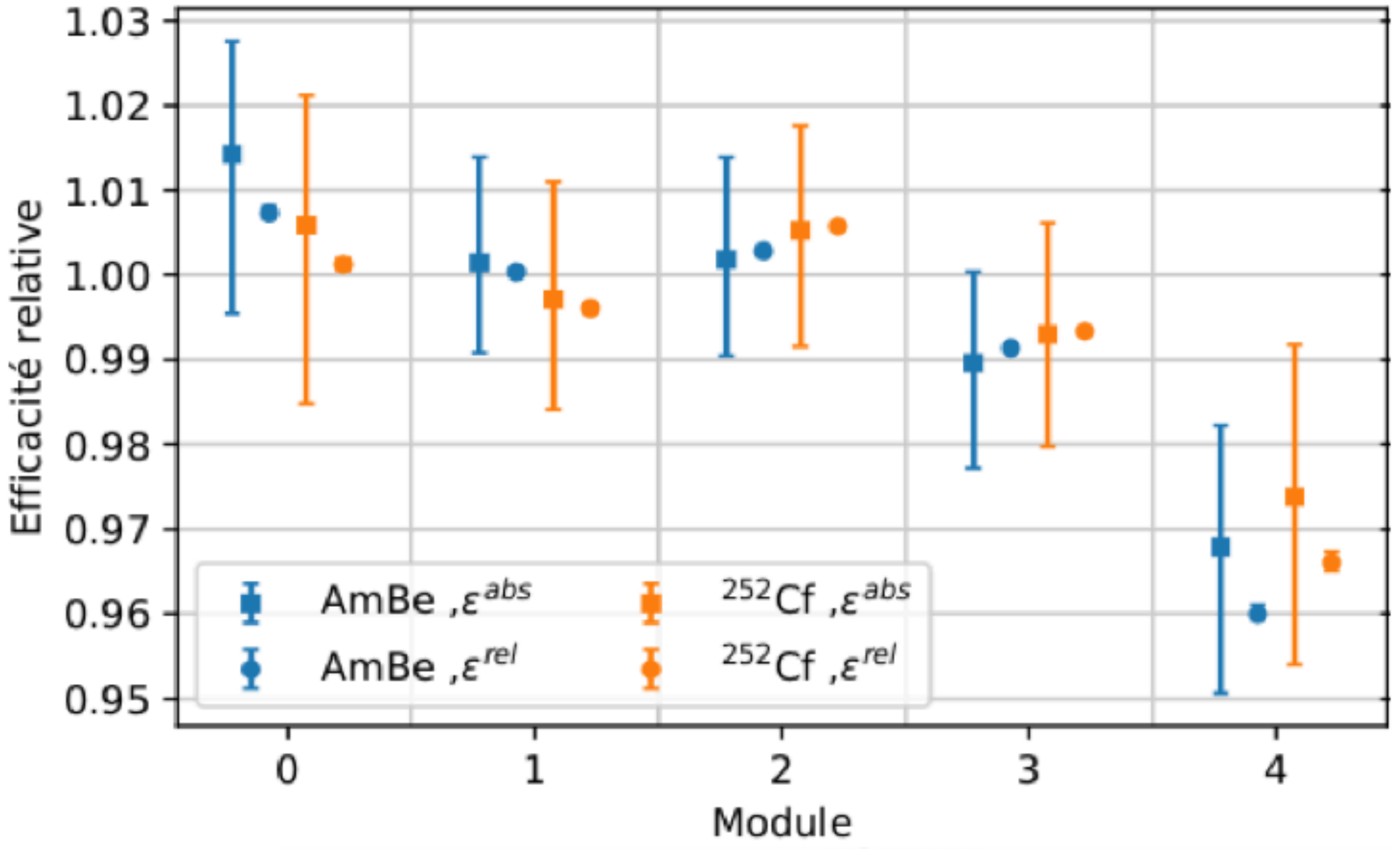
Neutron calibration

- Neutron detection efficiency obtained with AmBe and fission neutrons sources (precision calibration to 2%)

$$\epsilon_{det} = \epsilon_{capture} \cdot \epsilon_{rec}$$

- Capture efficiency $\epsilon_{capture}$
  - determined with MC: 65%
- Reconstruction efficiency ϵ_{rec}
  - ^{6}Li break up detection probability
  - Data vs MC
- Results
  - Average reconstruction efficiency ~ 76 %
  - Module relative efficiency ~ 3% (<1% for 4 modules)
  - Cube level uncertainty at percent level





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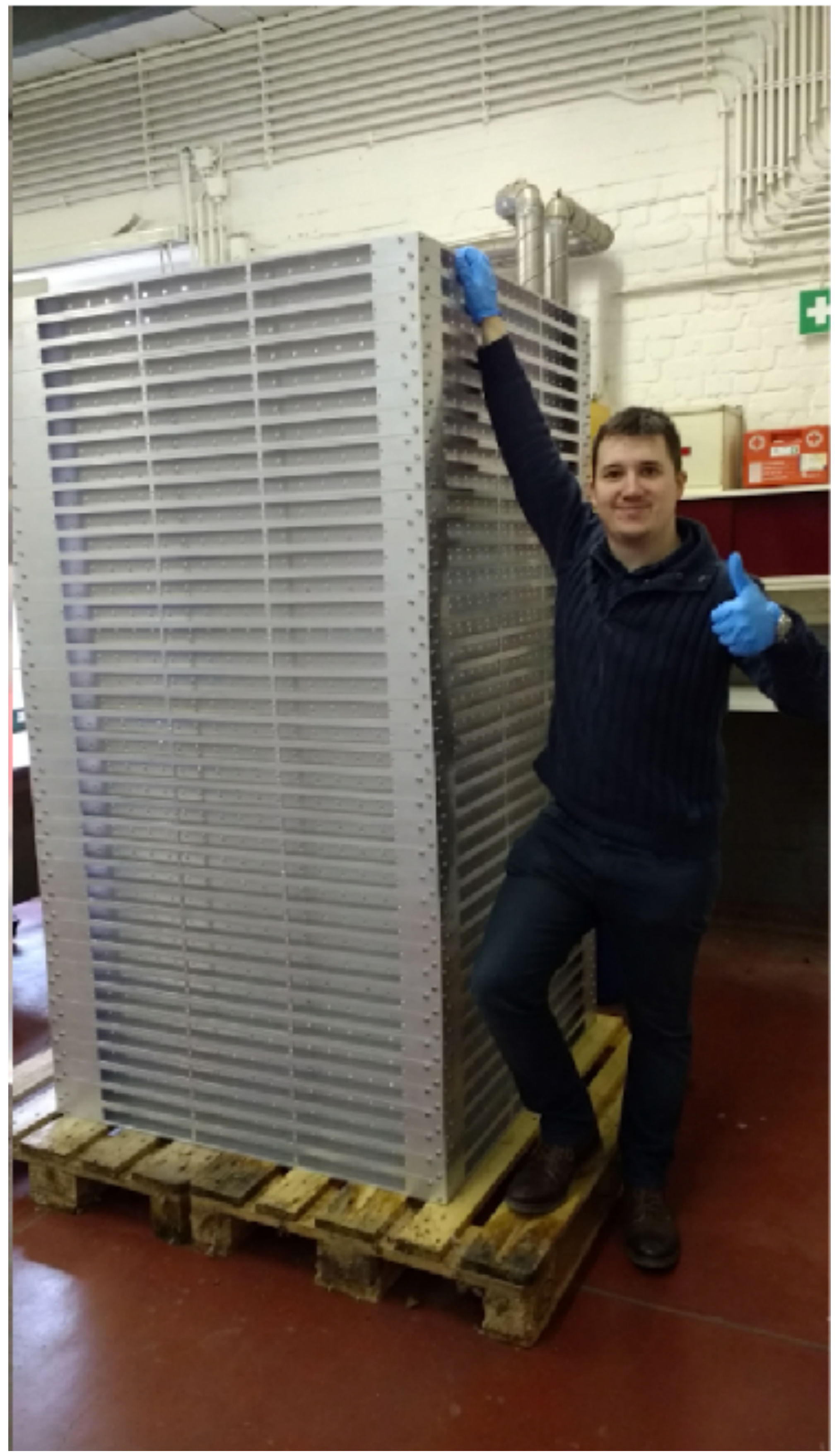
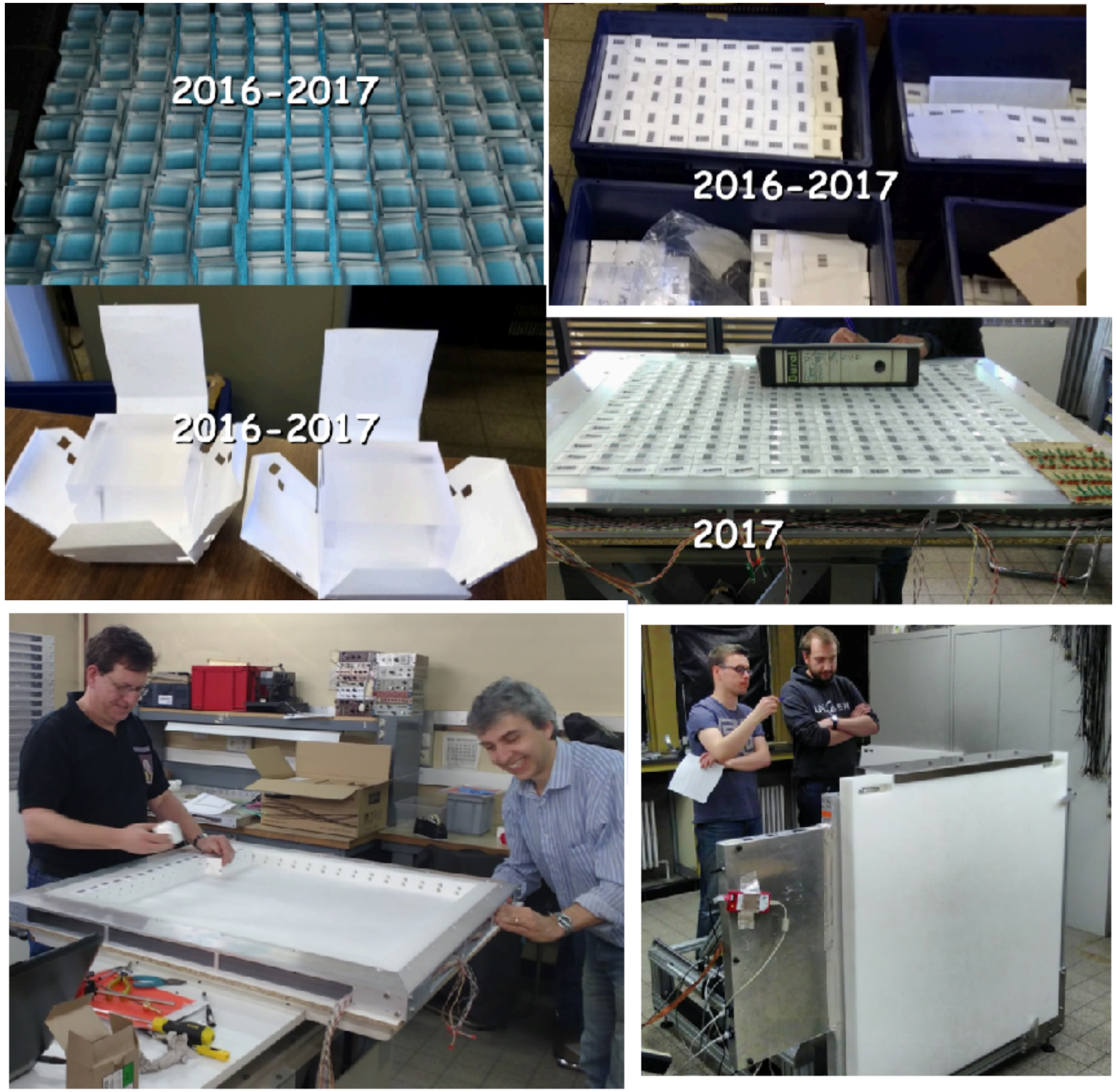
Construction

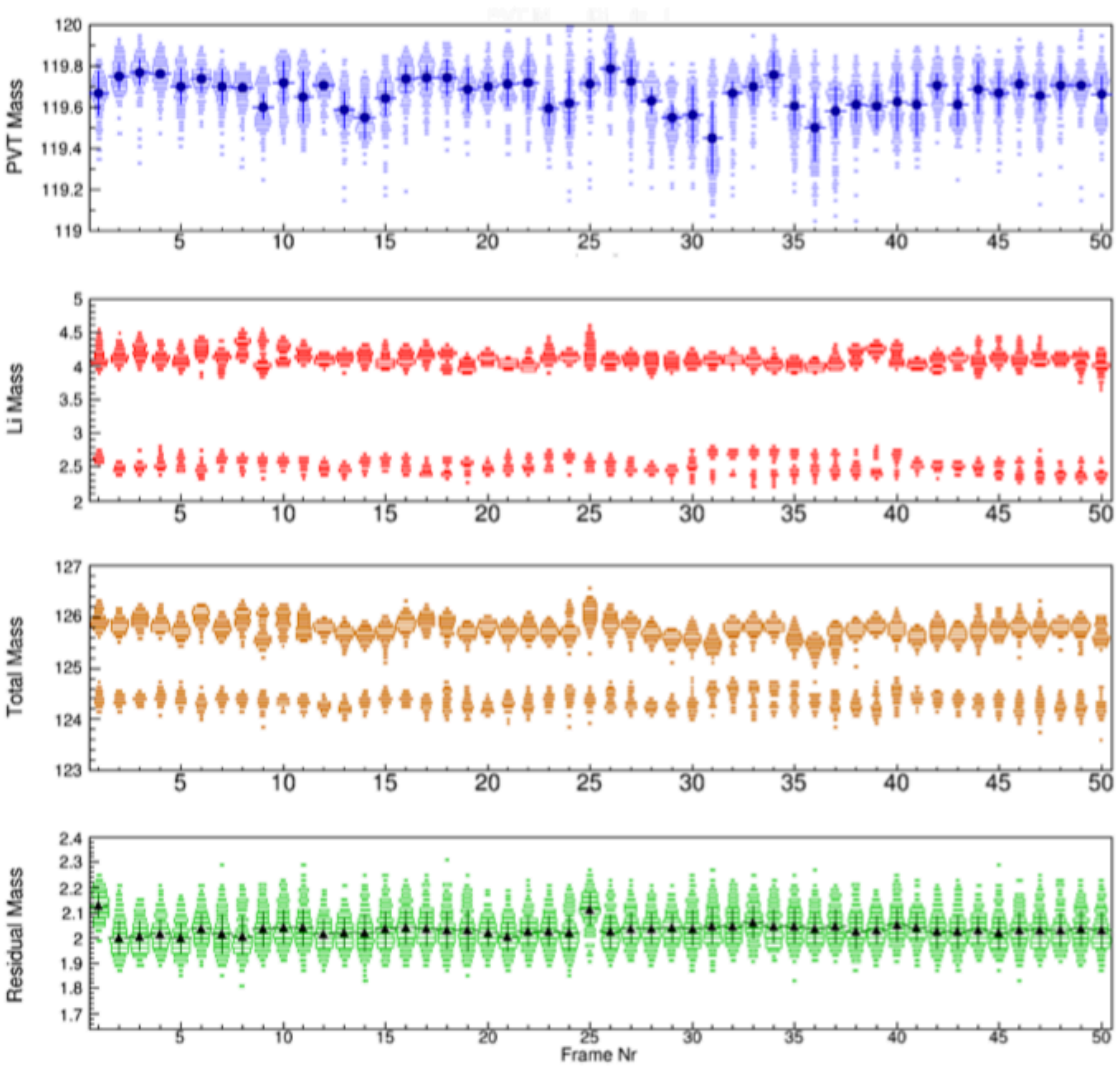
- Construction started in December 2016
- Plane assembly May to July 2017
- Quality asssurance tests using X-Y scanner summer 2017
- Plane and module assembly summer 2017

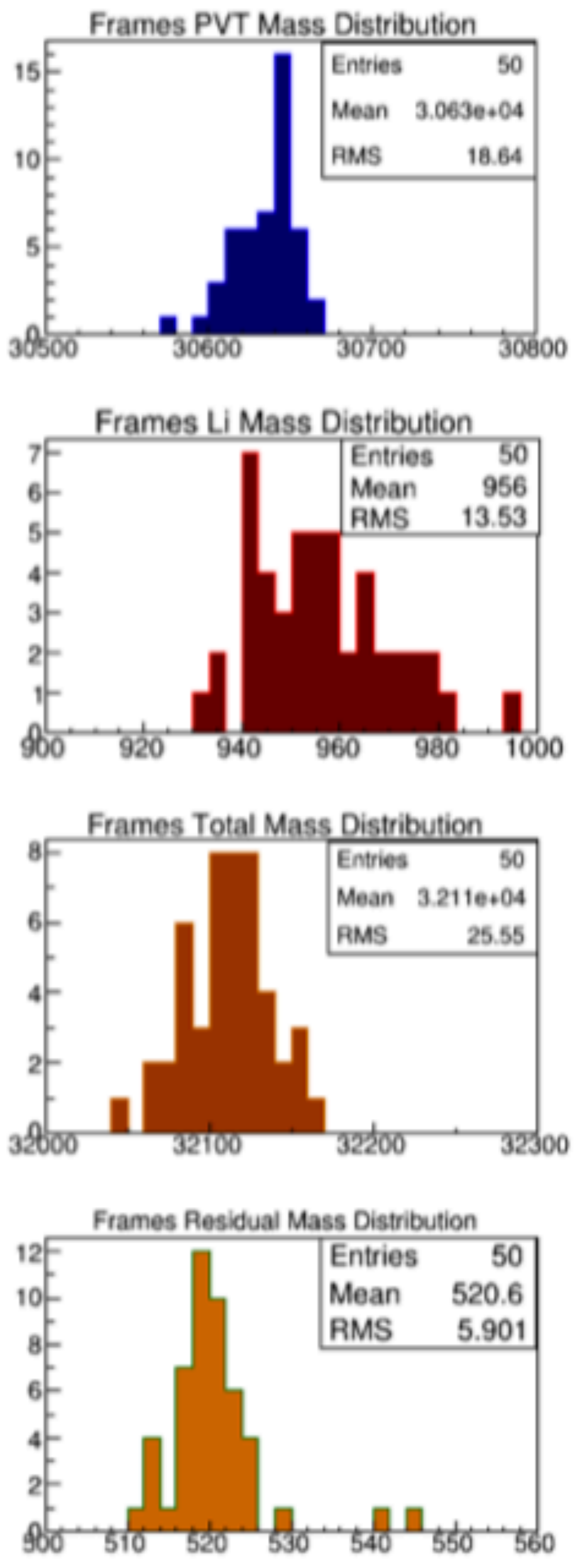


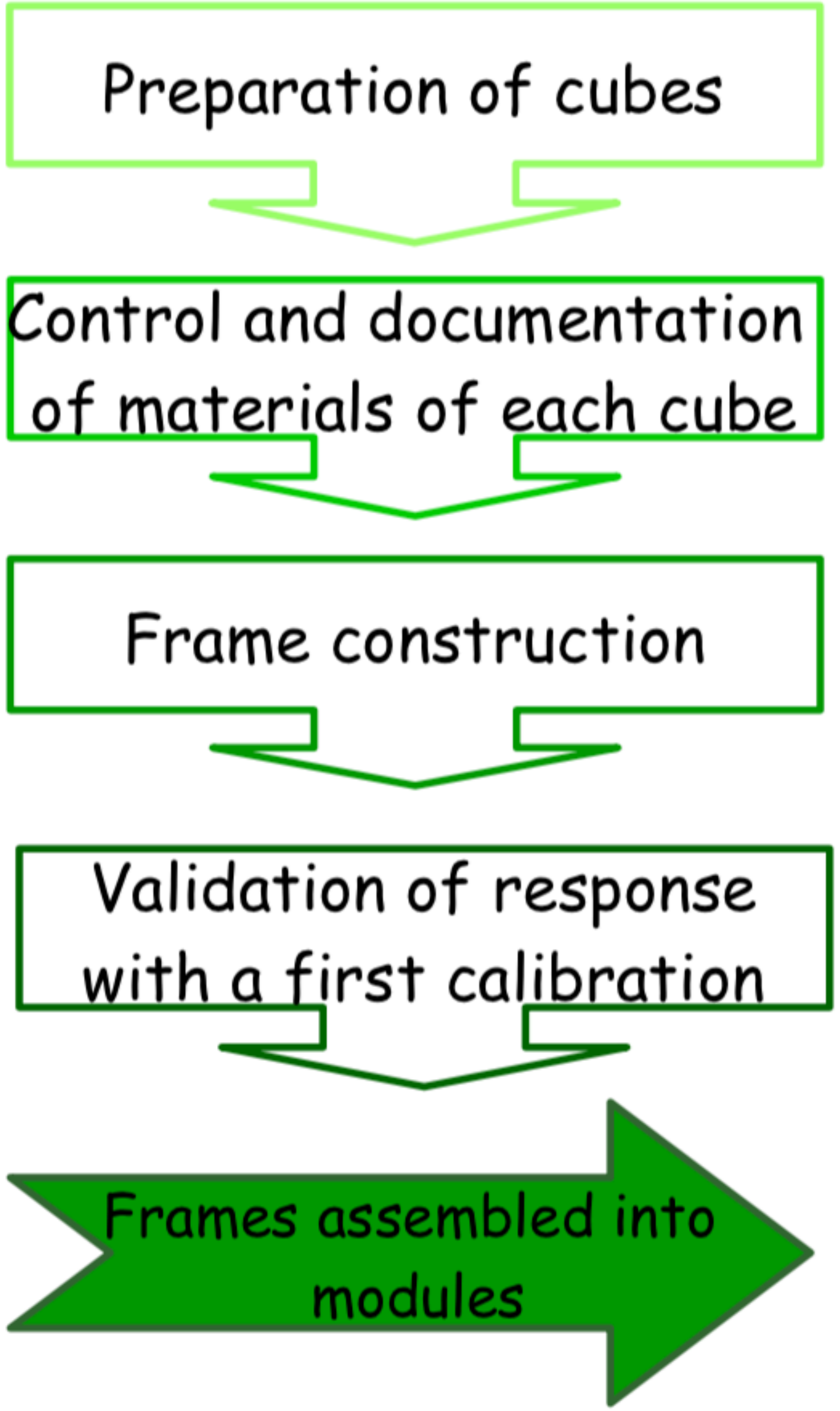


SoLiđ

Weigh and quality assurence







- All elements from target were weighted to account for
  - the number of hydrogen atoms
  - The number of Lithium-6 atoms for neutron capture estimation

SoLid

Commissioning at Ghent University

- Main commissioning was done at Ghent
  - CROSS installation
  - Module testing
  - Module deployment and alignment in container
- Four module system tested for two weeks
- Removed and shipped separately to SCK•CEN