Performance of the Reactor Neutrino Detector

SoLid

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On behalf of the SoLid collaboration

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

EUROPEAN PHYSICAL SOCIETY EPS HEP2019

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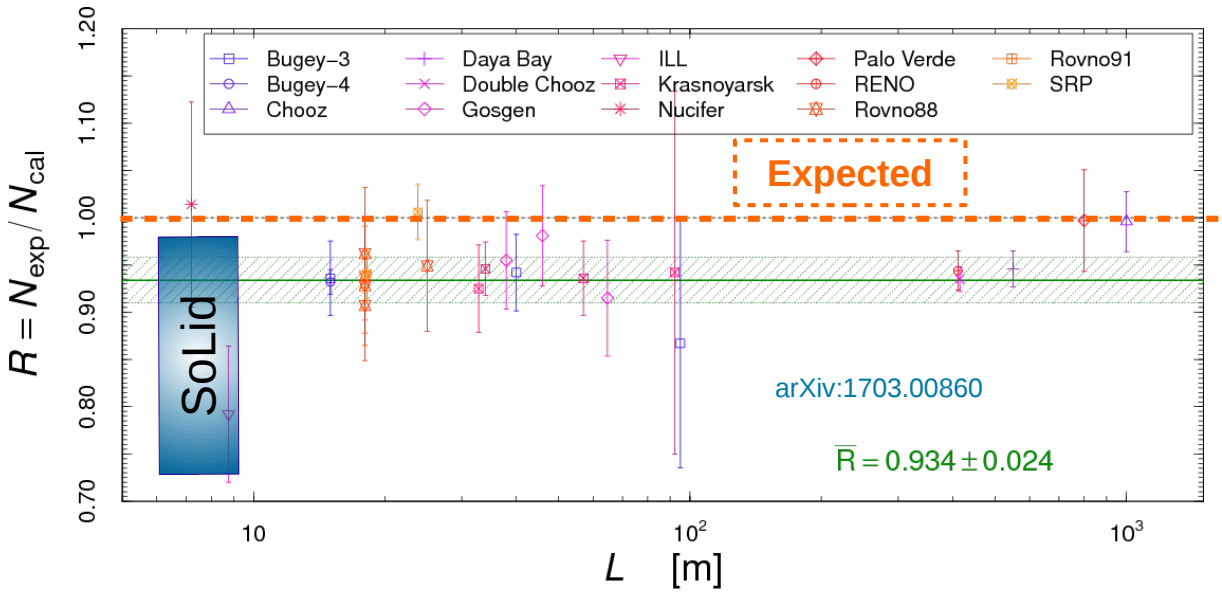
Outlook

- Physics motivations
- The SoLid experiment
- Construction – QA - Commissioning
- Calibration - Operation and performance
- Summary

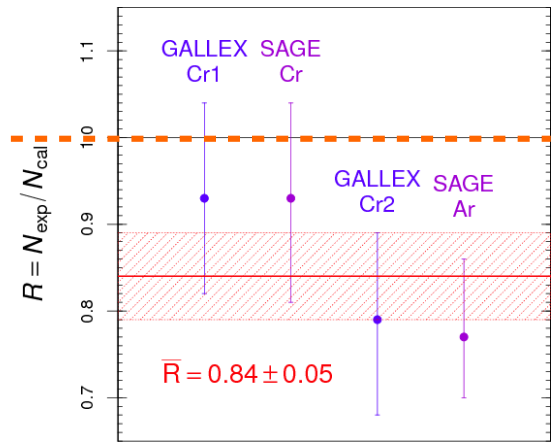
- ***Physics motivation***

Physics Motivations

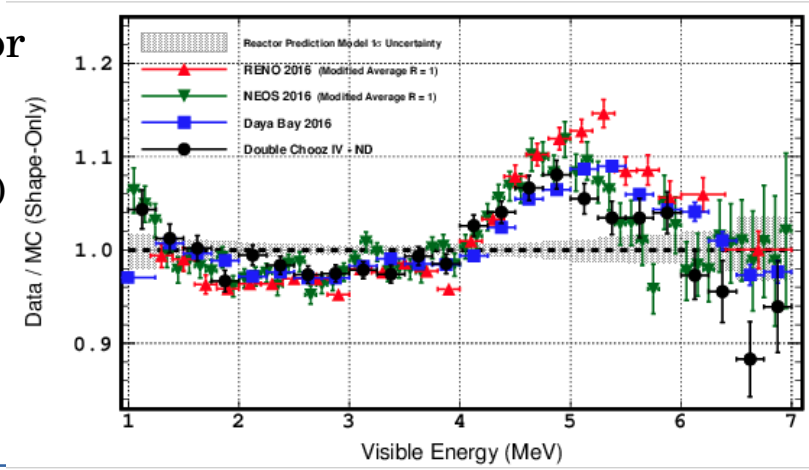
- **Anomalies:** The **reactor antineutrino anomaly (RAA)** and **gallium anomaly** both show discrepancies wrt expectations at ~3σ level
  - Oscillations into a **light sterile neutrino state** ($\Delta m^2 \sim 1$ eV^2) could account for such deficits



J.Phys. G43 (2016) 033001



- **Distortion** observed around **5 MeV** ("bump") in the reactor **antineutrino** energy **spectrum**
  - Hints point to $^{(235)}$**U** (arXiv: 1609.03910, 1608.04096, 1512.06656)
  - **Energy scale non-linearity** of LS (arXiv: 1705.09434) ?
- New experiments at SBL needed
  - → **SoLid experiment with new technology**

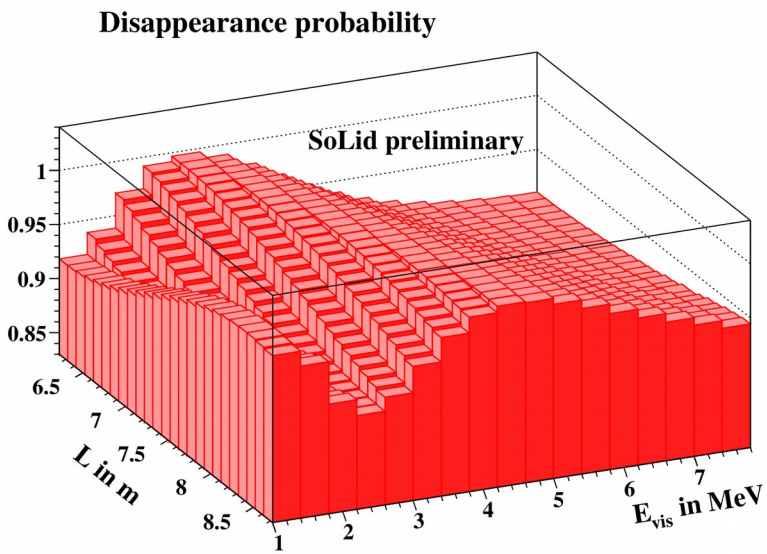


- ***The SoLid experiment***

SoLid goals

SoLid goals:

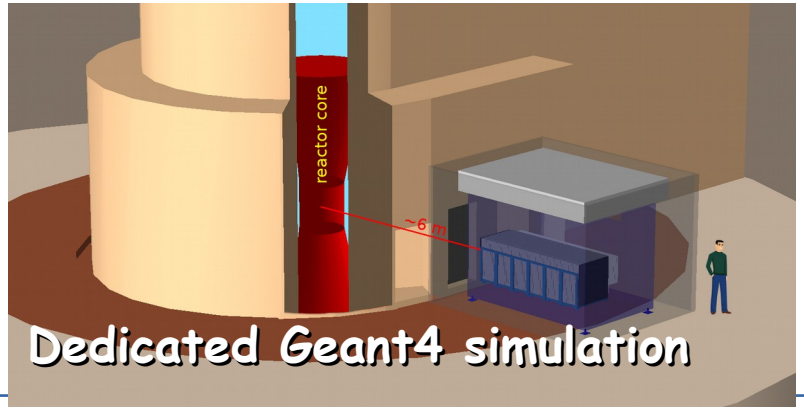
- Using a **different detection technology**
  - RAA: Search for an **energy and space oscillation** pattern at short baselines ([6-9] m)
  - 5 MeV "bump": Provide a **new** measurement of ^{235}**U** fuel **antineutrino energy spectrum**



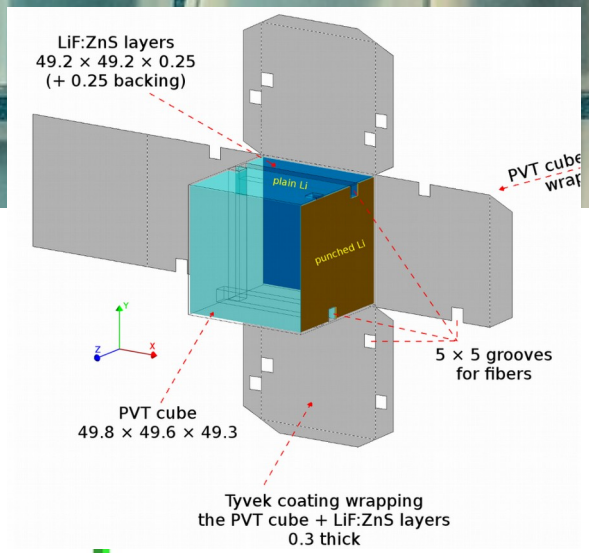
The BR2 site and reactor

Best fit RAA → Oscillation length of 3-4 m for 3 MeV ν 's ⇒ **Compact source**

- **Compact** reactor **core** Φ < 50 cm, h = 90 cm
  - Baselines : 6.5 → 9 m
- Thermal power: 45-80 MW
- Highly ^{235}**U enriched** (up to 93.5 %)
- 150 days per year duty cycle
  - Reactor off data for background estimation and subtraction
- **No nearby experiments**
- Overburden of ~10 mwe
- **Low background** (neutron, γ)
- **Excellent** collaboration with SCK•CEN

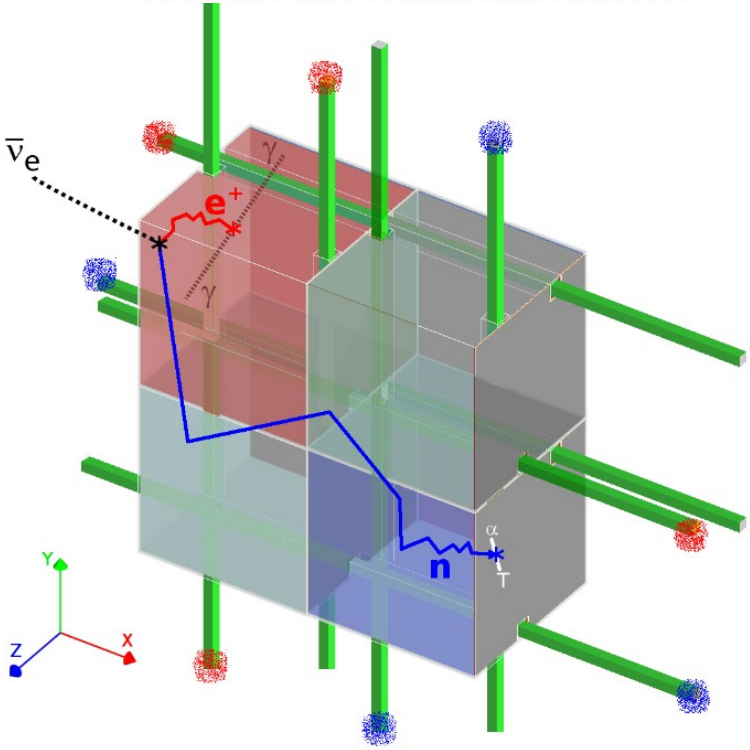


The SoLid technology

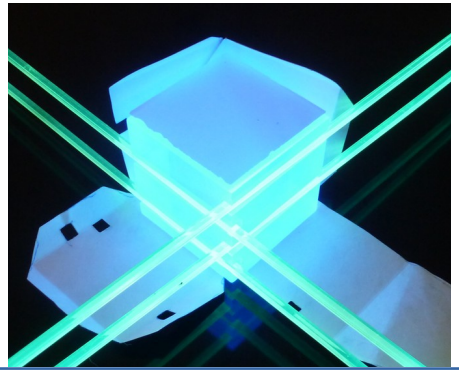


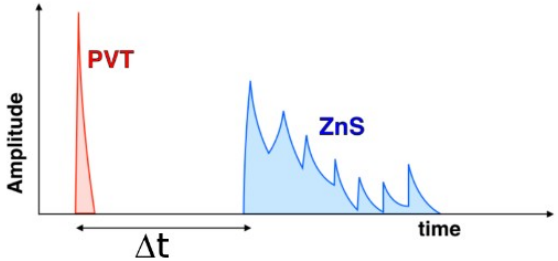
- Inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
- 3D highly **segmented composite detector**
  - 5 cm x 5 cm x 5 cm **PVT** scintillator cubes
    - $\bar{\nu}_e$ interaction
  - 2 layers / cube of **LiF:ZnS**(Ag) scintillator for neutron detection
    - Neutron capture on Li in ZnS layer :

      $n + {}^6Li \rightarrow {}^3H + \alpha$
  - Nuclear signals (**NS**) and electronic signals (**ES**) very different
    - → Waveform shape discrimination ("~PSD") + neutron trigger
- Cubes optically separated (Tyvek)
- WLS fibers + SiPM to read out signals



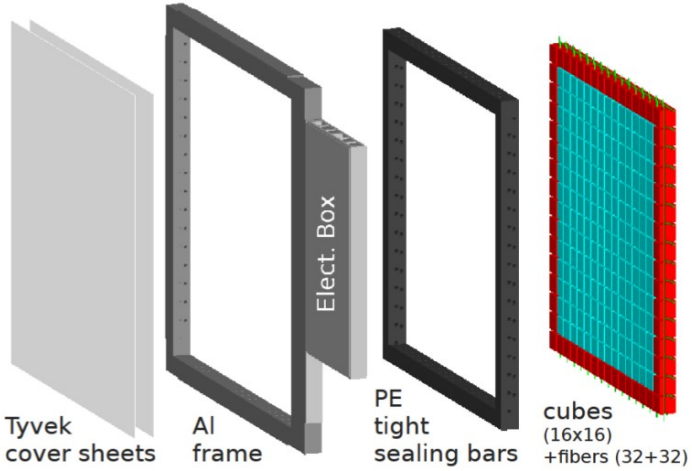
JINST, Vol. 12, 2017, arXiv:1703.01683

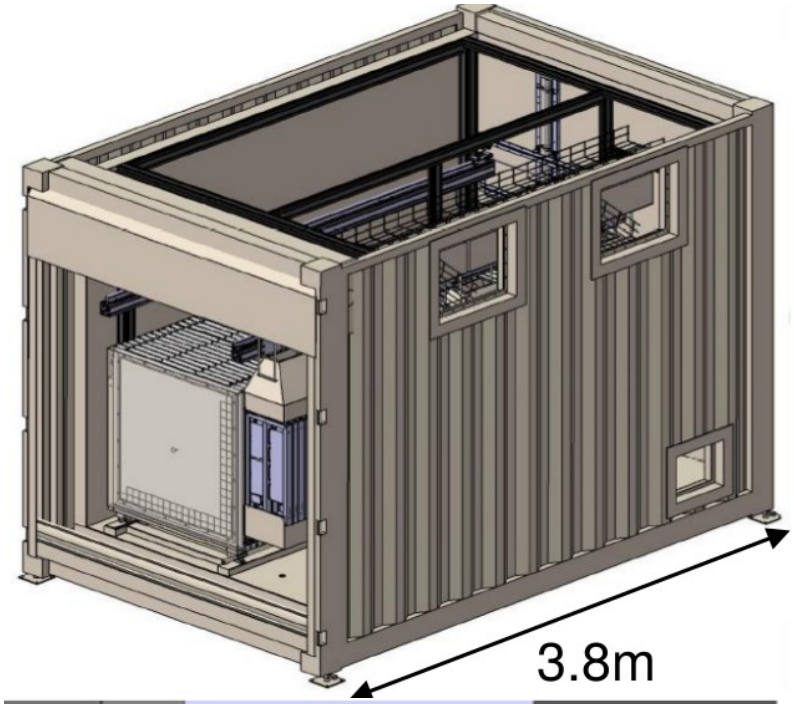


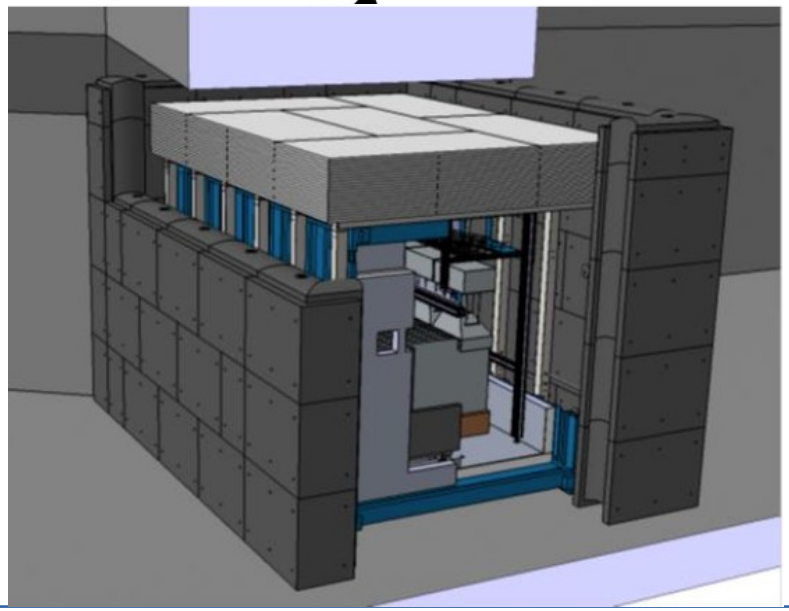


The SoLid (1600 kg) detector

- **5 Modules** of 10 planes
  - Planes of 16x16 cubes
- 4 x (fiber + SiPM + Mirror) per cube
- Automated calibration system (CROSS)
- Container (2.4⊗2.6⊗3.8 m) for **cooling at 10 °C**
  - Reduction of SiPM dark count rate
- **Shielding:**
  - Water wall: 50 cm thick, 3.4 m high, 28000 kg
  - Polyethylene ceiling: 50 cm thick, 6000 kg



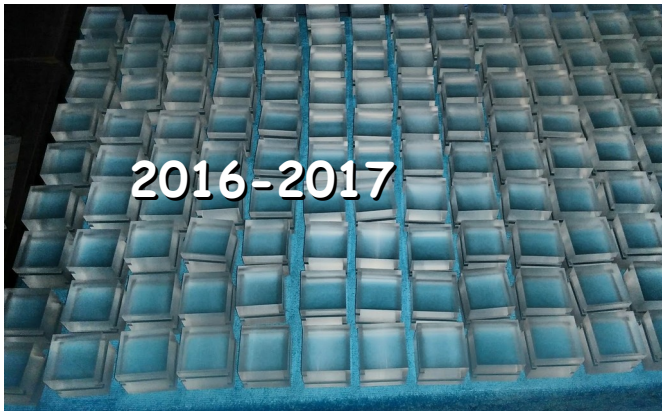


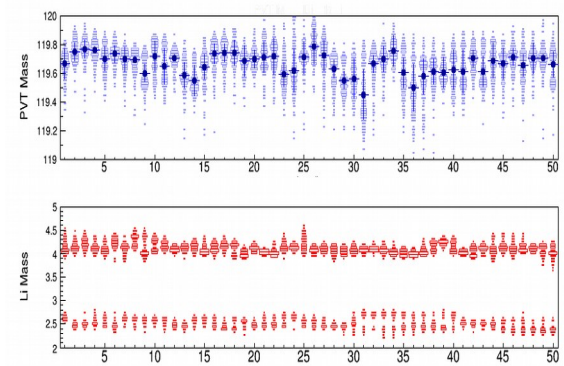


- ***From Construction and QA to commissioning***

From QA to commissioning

- ~13 000 cubes manually washed, weighted, wrapped, stacked, ...
- All cube components information stored in database



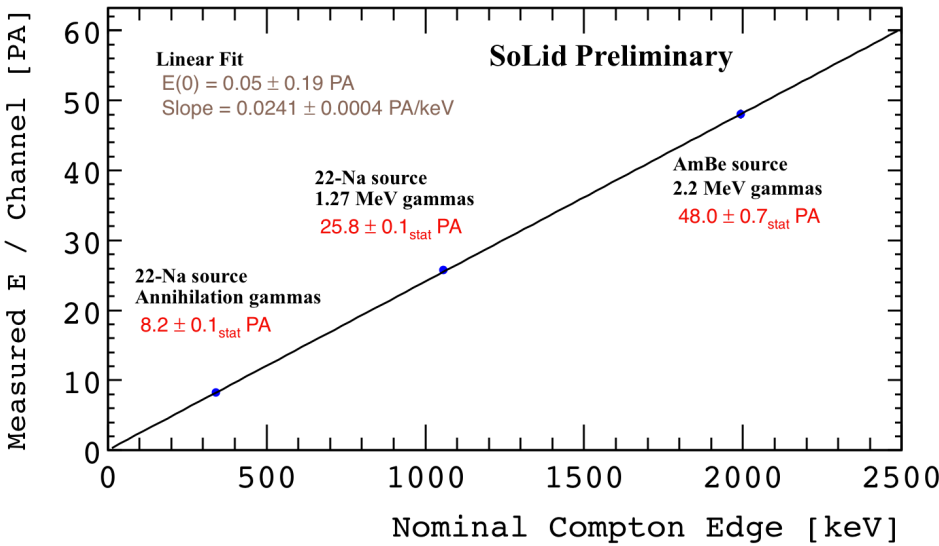


Planes, electronics and software qualified before installation with automated calibration robot CALIPSO

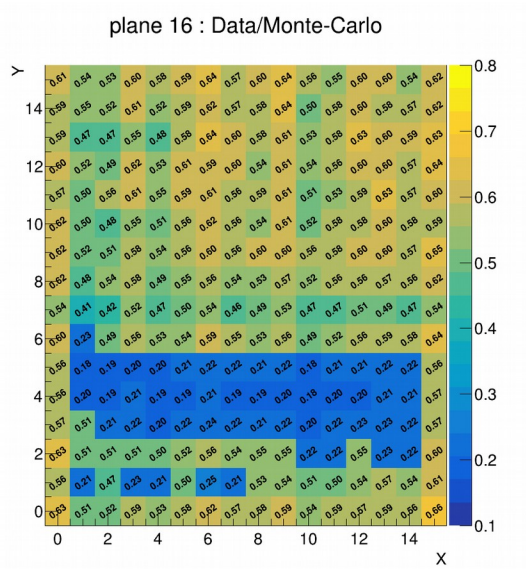
QA with CALIPSO

- Preliminary estimation of **LY and n eff** in all 12800 cubes
- **Exceeded** SoLid **requirements**
  - LY > 60 PA/MeV and n eff > 60%
- **Homogeneous** response
- Minor construction **problems identified and fixed**

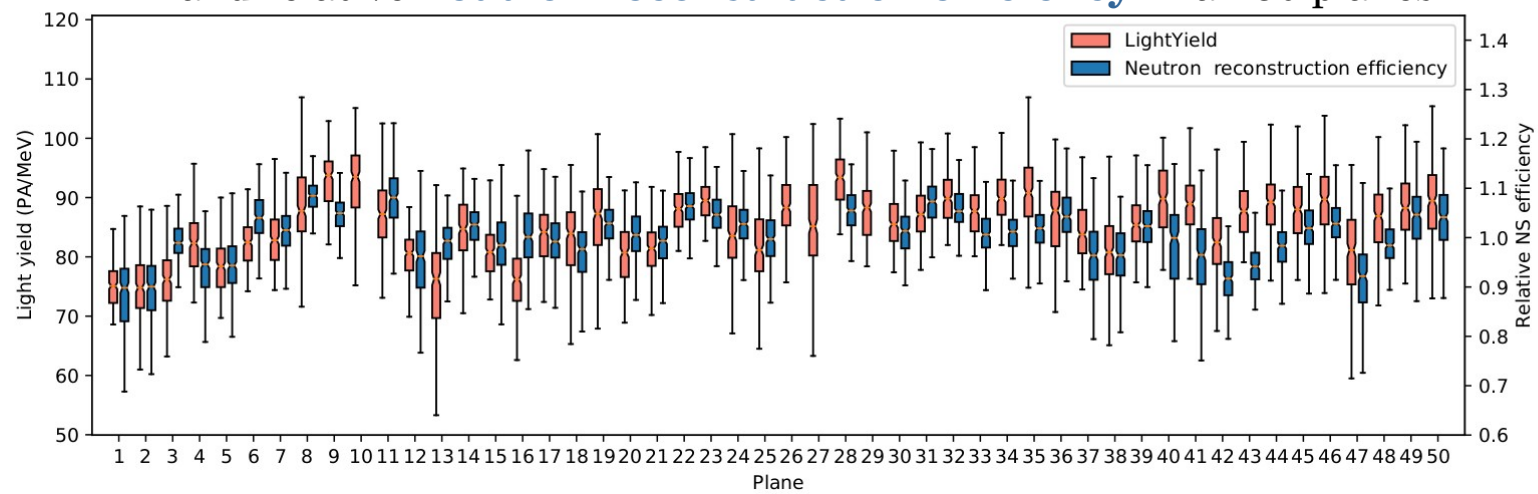
Very good linearity



One **bad** ^{6}LiF:ZnS **batch identified** and replaced



LY and relative **neutron reconstruction efficiency** in all 50 planes



Response all 50 planes (12800 cells) validated!

JINST 14 (2019) no.02 arXiv:1811.05244

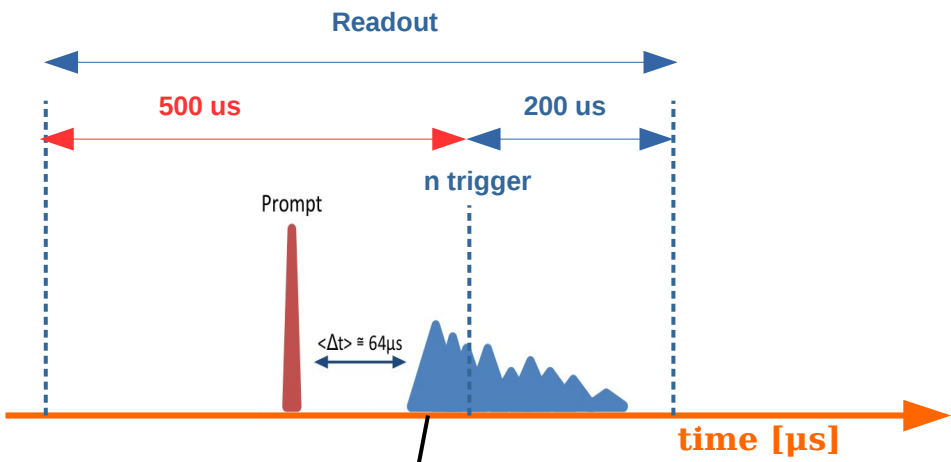
Commissioning at BR2

- **First modules deployed** at BR2 on November 2017
- **Commissioning** of the full detector **completed** beginning of February 2018
- Taking data in **stable conditions** since May 2018

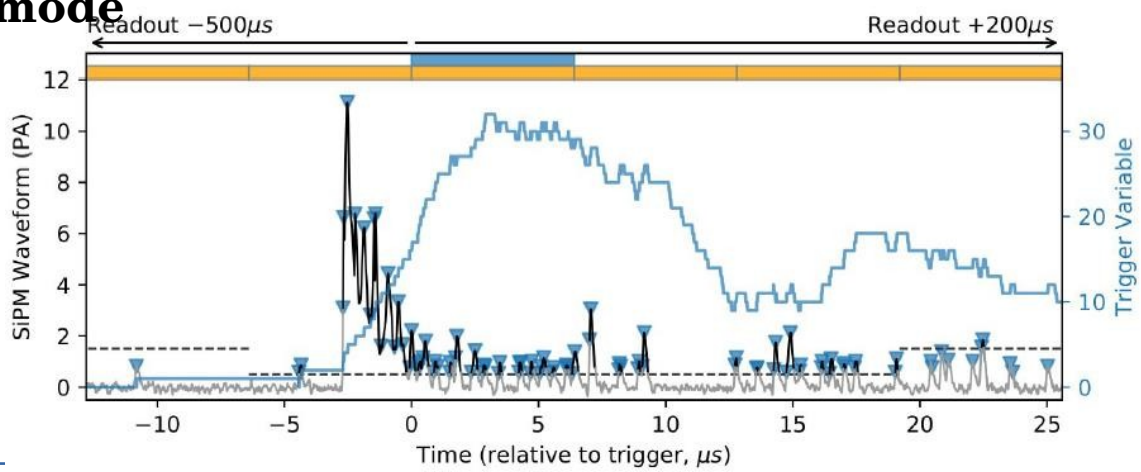
- ***Operation, calibration and performance***

DAQ and triggers

- **Random:** Full detector readout at 1 Hz
  - Non zero-suppressed waveforms for SiPMs monitoring
- **Threshold:** XY fibers coincidence > 2 MeV
  - Muon and high electromagnetic event tagger
- **Neutrino:** Algorithm for neutron trigger
  - **Neutron trigger** algorithm implemented in FPGA
    - Based on **peak counting**
    - Read out long time buffer around NS: [-500 µs, +200µs]
    - Multiplane readout (+/- 3 planes)
  - → **Unbiased prompt detection**
- **Triggers for data taking in physics mode optimized at OV of 1.8 V**



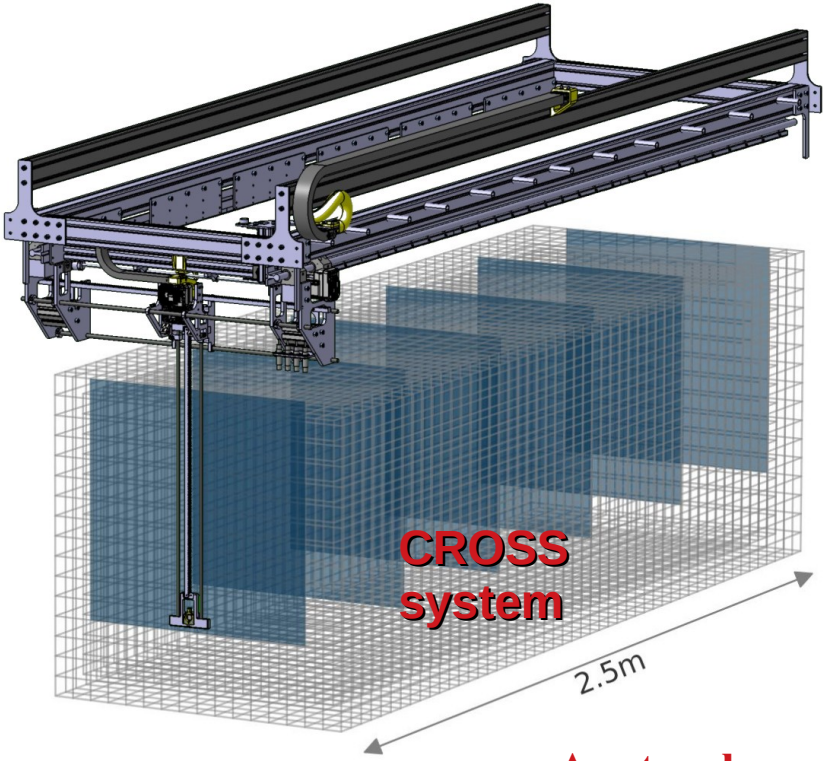
A real waveform

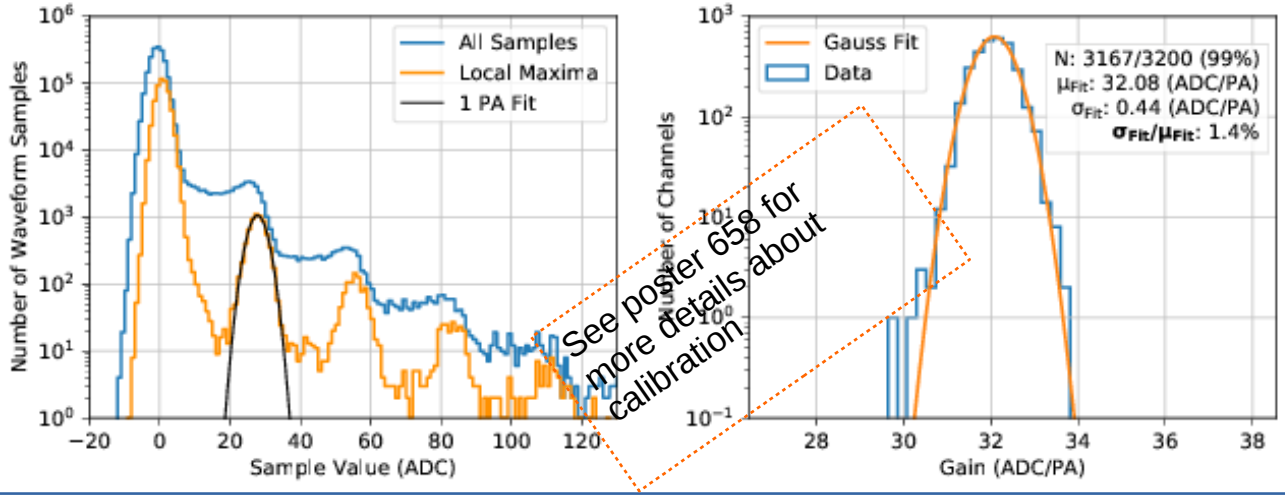


ArXiv:1812.05425 Submitted to JINST

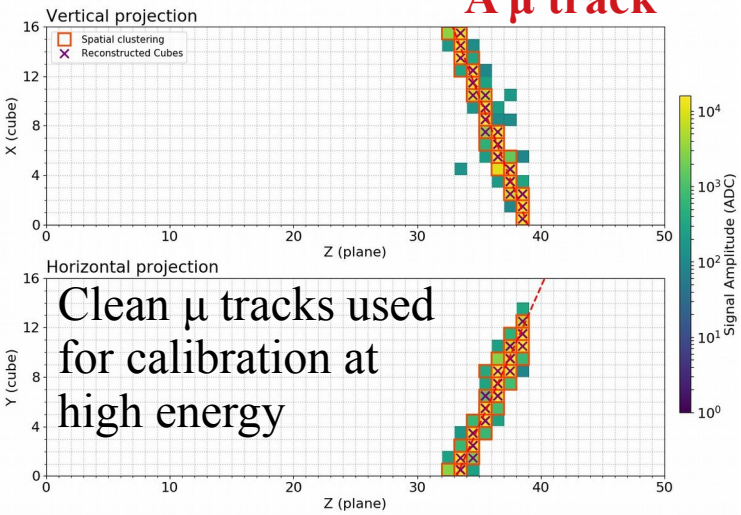
Calibration

- Automated robot (CROSS) for **full detector calibration**
- **Periodic calibration** campaigns with ^{22}Na and AmBe sources every reactor OFF period
  - Full ^{22}Na scan in ~22 hours
  - Full AmBe scan in ~72 hours
  - Dedicated calibration campaigns with ^{137}Cs, ^{207}Bi, ^{252}Cf
  - **100% of cubes** have been **calibrated**
  - **SiPMs equalization at the ~1% level**





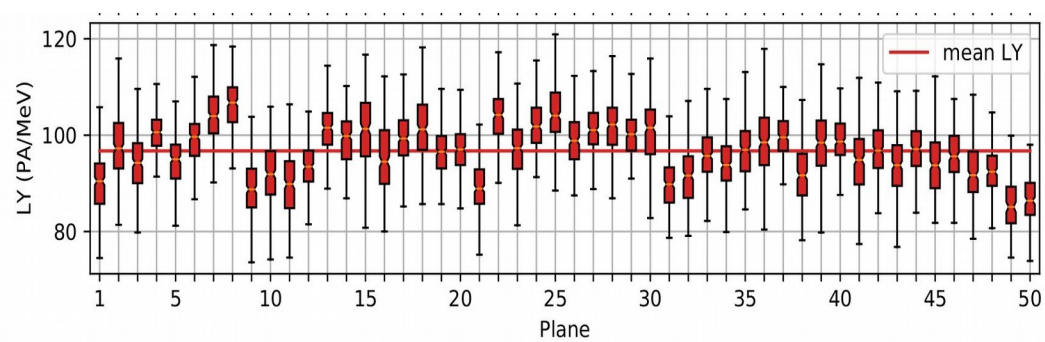
A μ track

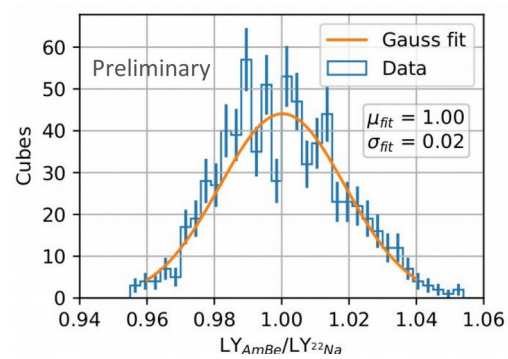


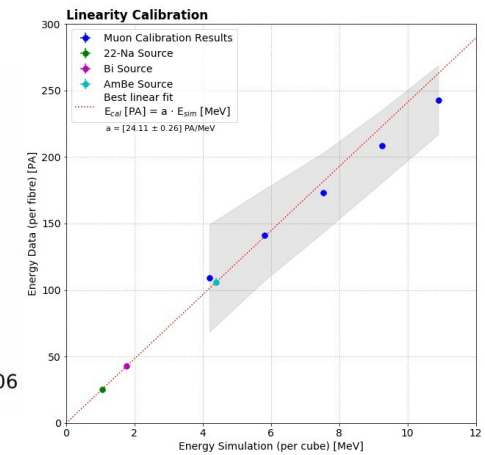
Energy scale calibration

$\bar{\nu}_e + p \rightarrow e^+ + n$

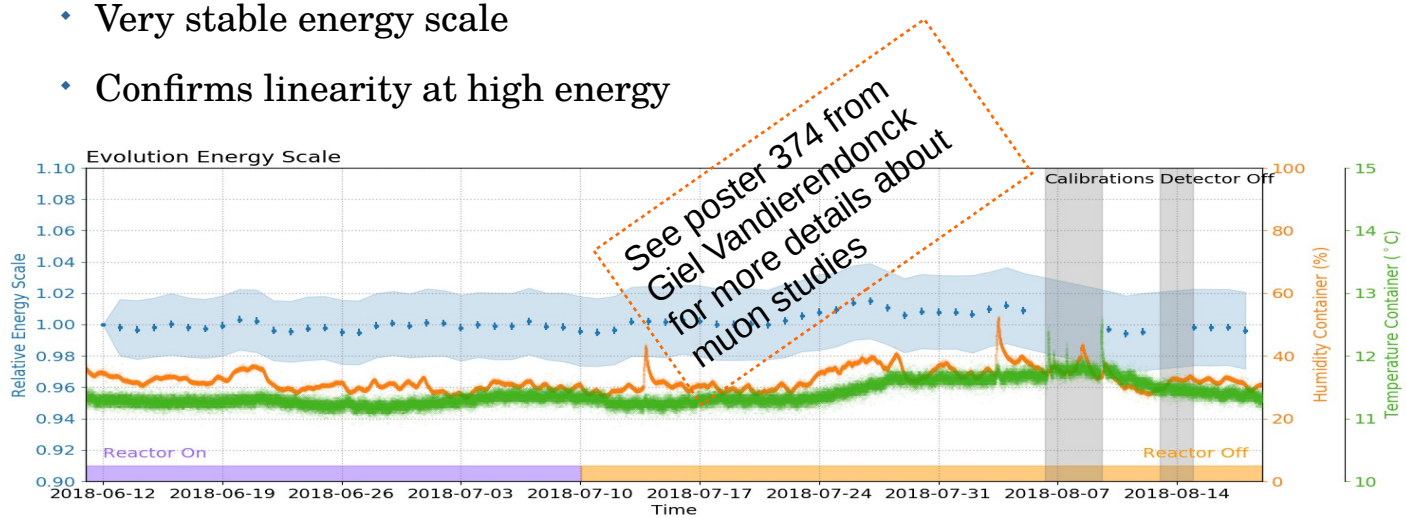
- LY of about 96 PA/MeV (w/o x-talk subtraction) with good homogeneity
- Excellent **agreement between ^{22}Na** (1.27 MeV) **and AmBe** (4.4MeV) / **^{207}Bi** (1.7 MeV)
  - **Confirms PVT energy linearity**

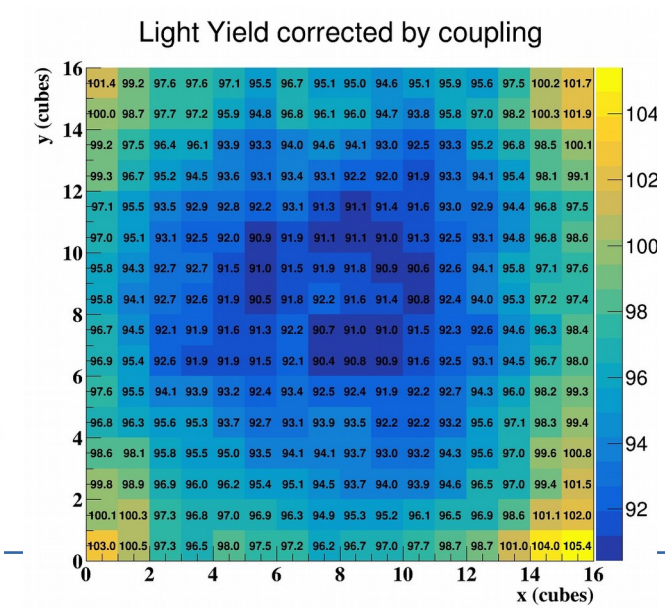






- Muons used at high energy and for daily monitoring of energy scale
  - Very stable energy scale
  - Confirms linearity at high energy

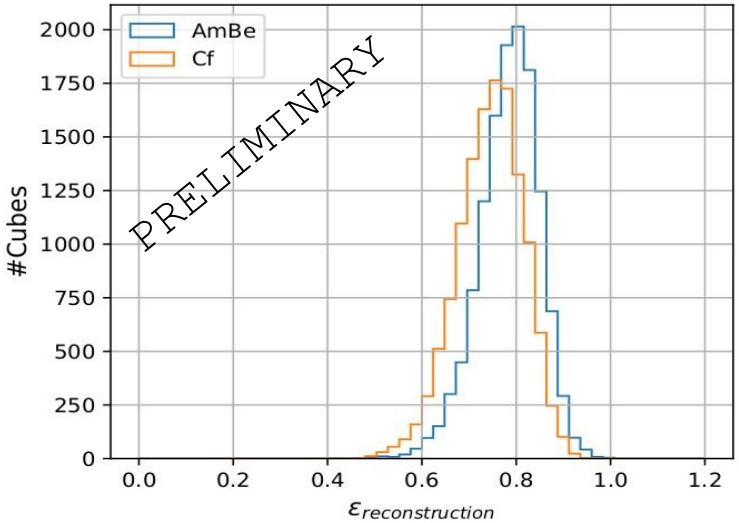


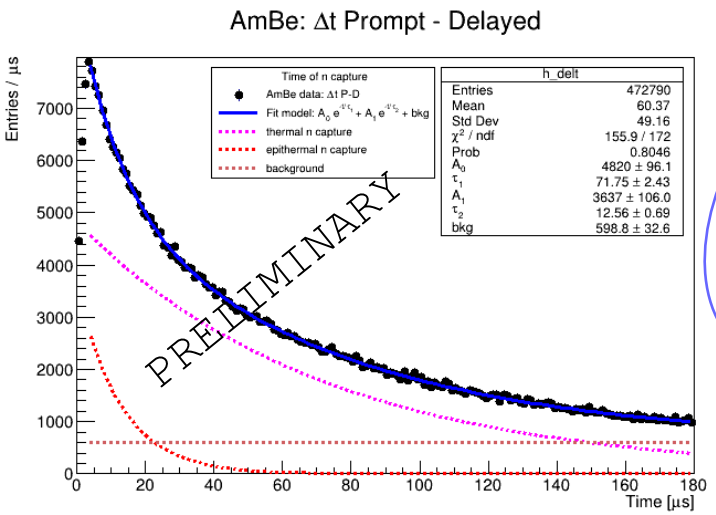


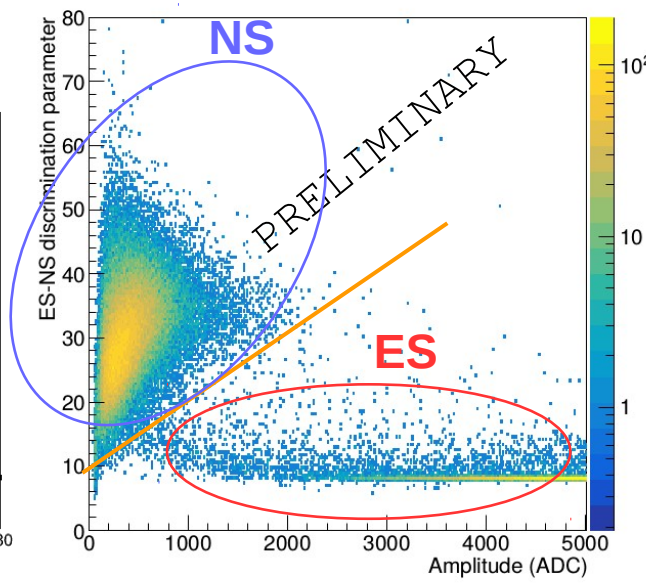
Neutron calibration

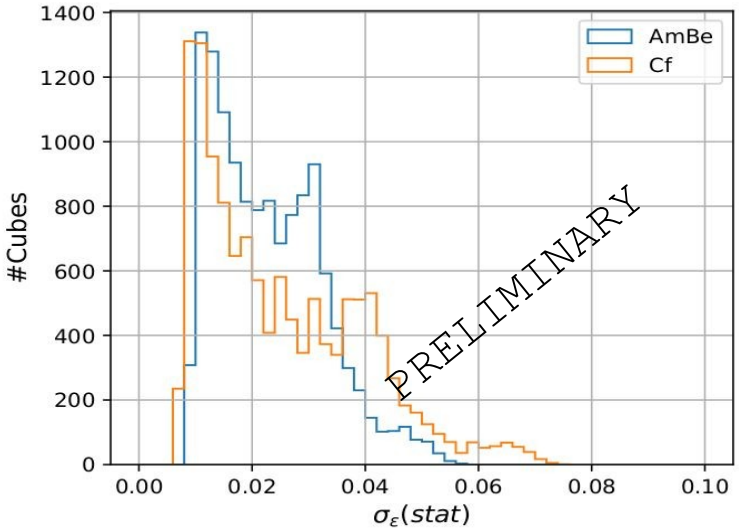
$\bar{\nu}_e + p \rightarrow e^+ + n$

- Calibration with AmBe (~4 MeV) and ^{252}Cf (~2 MeV)
  - Able to calibrate **n efficiency per cube** with both sources!
  - **Agreement at the ~3% level**
- Neutron reconstruction efficiency > 75%!
- Statistical error ~2.5%
  - Dominated by cubes far from the source
  - Will decrease using data from other calibration campaigns (ongoing)
- Time of neutron capture for AmBe n's ~ 71.8± 2.4 μs



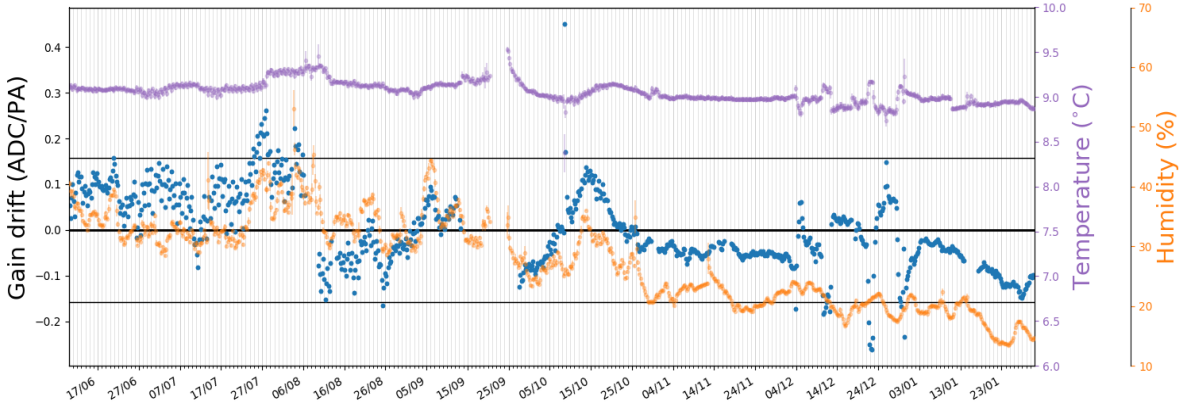


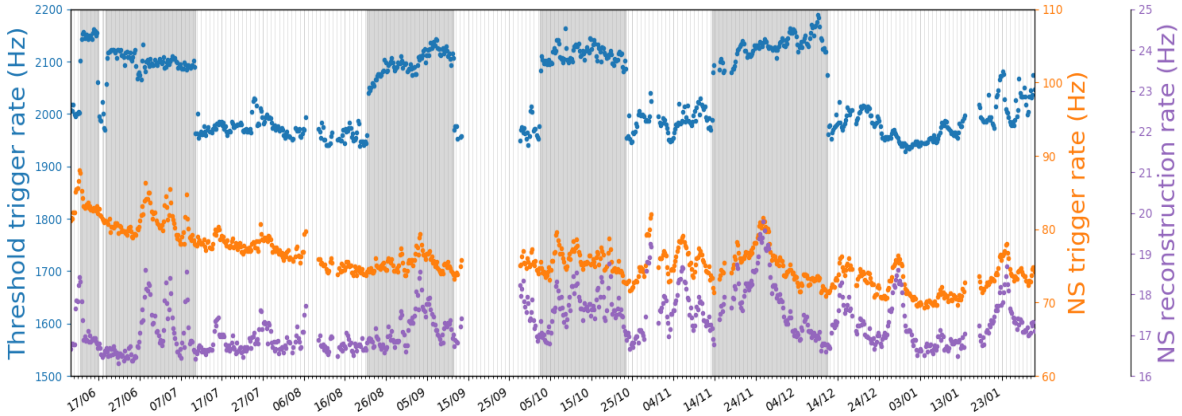


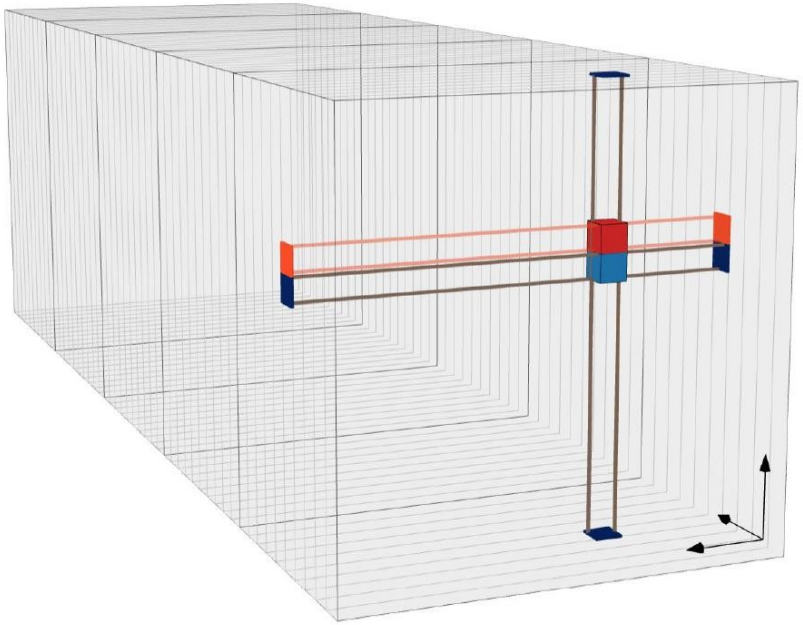


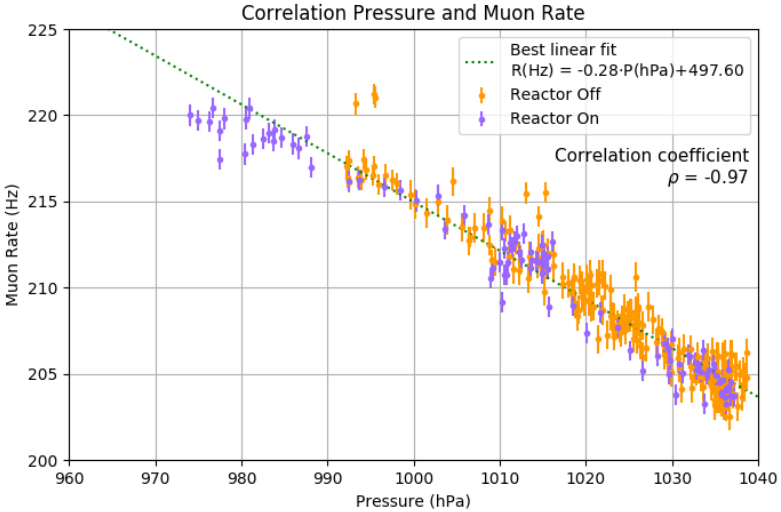
Data taking and stability

- **Stable** data taking since May 2018 → Stable for both reactor on and off
- **Online**, live, remote **detector monitoring**
- Online event reconstruction for subsample of data
- **Physics variables available online**









Summary

- **New detector concept for $\bar{\nu}_e$ detection**
  - ArXiv:1703.01683 1802.02884 1806.02461 1811.05244 1812.05425
- **Construction of full detector (1600 kg) completed**
- **Commissioning** at BR2 research reactor **finished in February 2018**
- **Data taking** in physics mode **in stable conditions** since May 2018
- Calibration results indicate **excellent detector performance**
  - LY > 70 PA/ MeV → stochastic energy resolution of ~12%
  - Neutron trigger efficiency > 70 %
  - **Linear energy response**
- Analysis of unblinded data sample for first **physics results ongoing**
  - See dedicated talk by Ianthe Michiels (Sat. on Neutrino session)

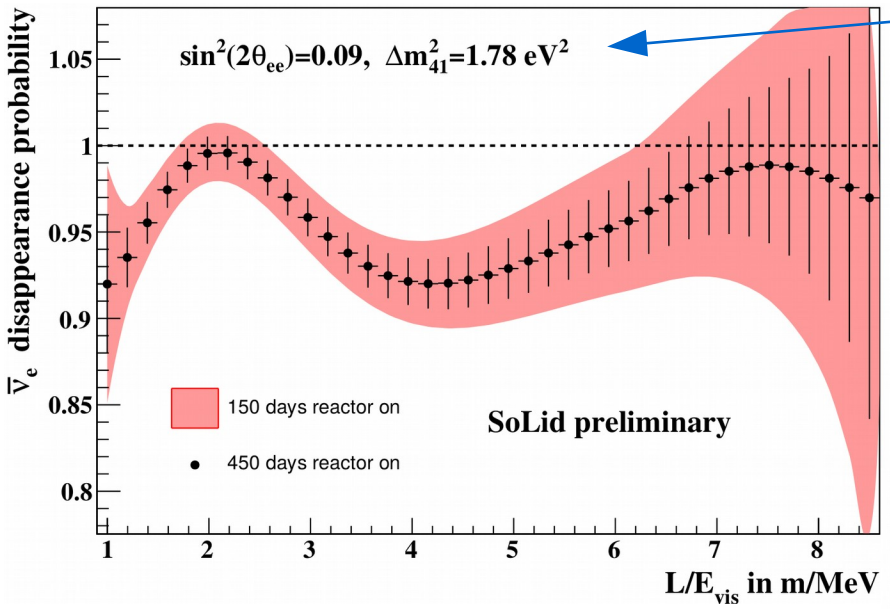
Thanks for your attention

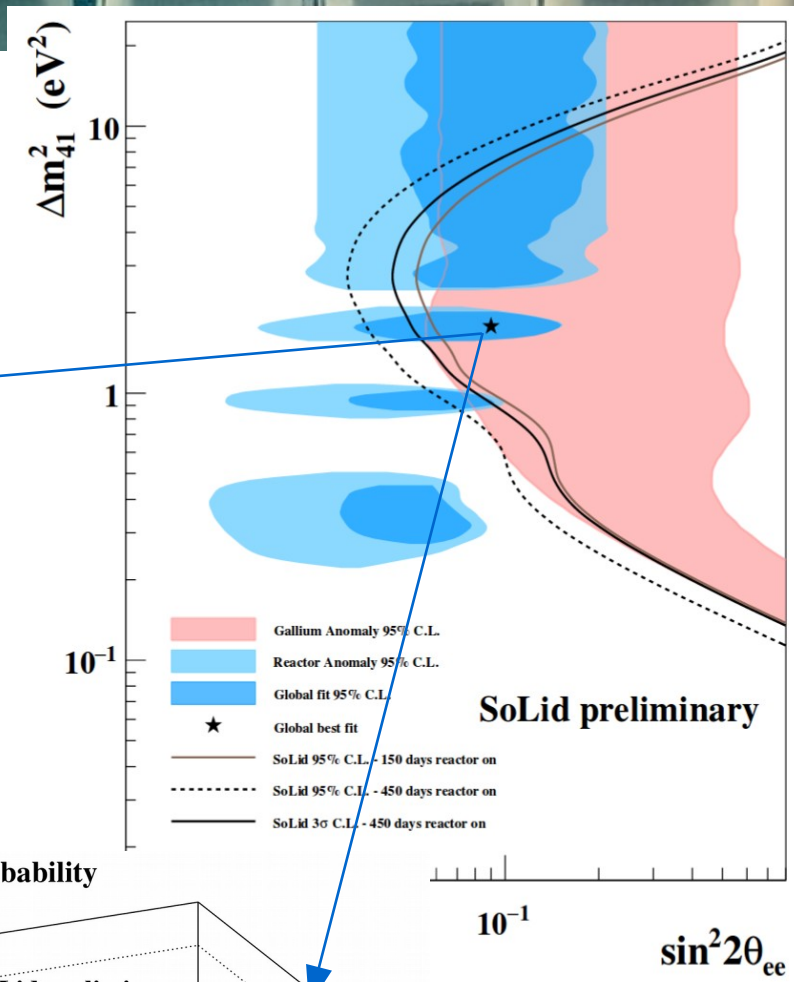
Stay tuned !

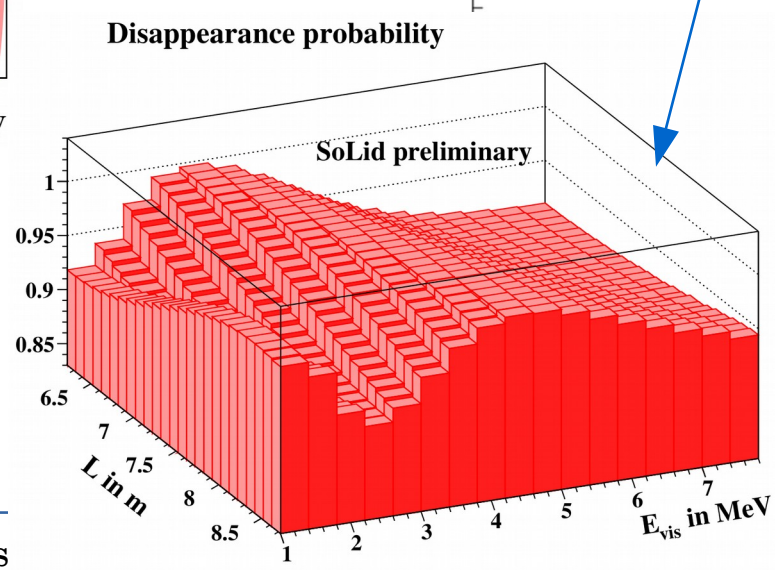
BACK UP

Expected physics results

- Baselines: 6 – 9 m
- Energy resolution 14% / √E
- IBD eff: 30%
- Thermal power: 60 MW
- S:B of 3:1 5 Modules
- 450 days of reactor ON



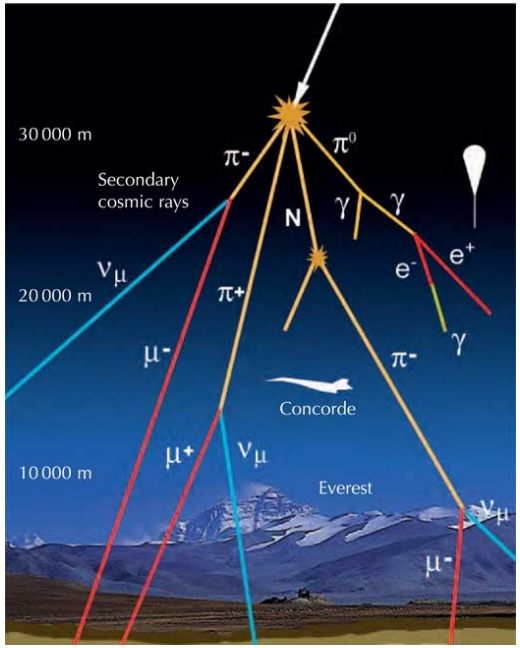


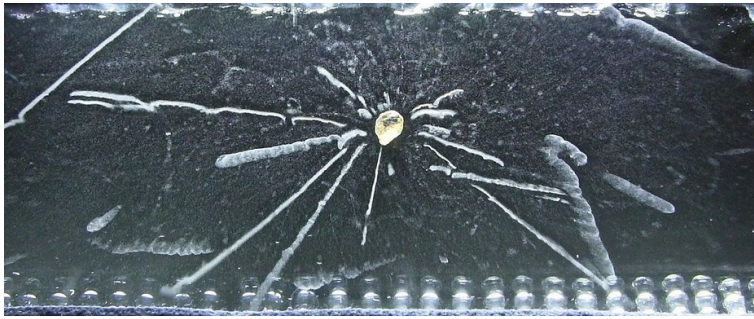


New measurement of **ν spectrum** of ^{235}U

On track for first physics result around the end of the year, beginning of next year

Backgrounds





Muon induced

- Fast neutrons from spallation
- Stopping μ's (with Michel e^-)
- Cosmogenic isotopes (e.g. ^{9}Li, ^{8}He)

Countermeasures:

- ✓ Shielding/underground lab
- ✓ Active veto
- ✓ Pulse Shape Discrimination (PSD)

Reactor induced

- Neutrons (fast & slow)
- γ's from n captures

Countermeasures:

- ✓ Shielding
- ✓ PSD
- ✓ **Topology**

Radioactivity

- Thorium/Uranium
- Radon/Argon
- Potassium

Countermeasures:

- ✓ Material radiopurity
- ✓ **Topology**

SoLid Calibration systems

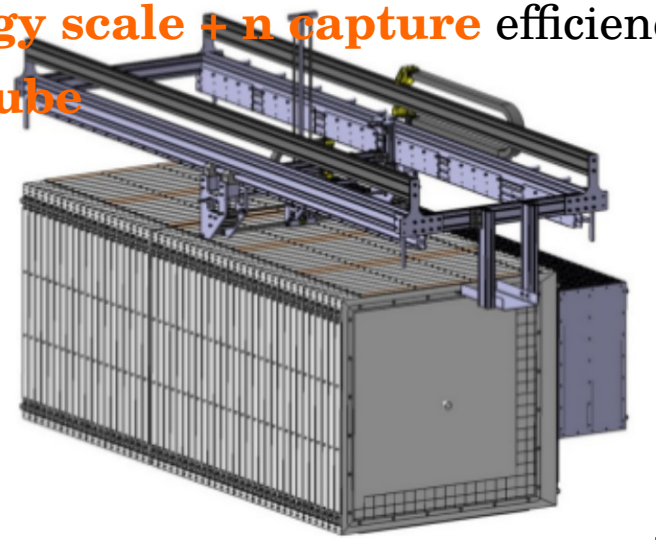
Double calibration: **during construction** and **in-situ**

CALIPSO system

- **Individual** plane calibration
- Automated robot to place **radioactive sources in front of each cube**
- Calibration during detector construction
- Preliminary detector performance
- **Used for quality assurance**

CROSS system

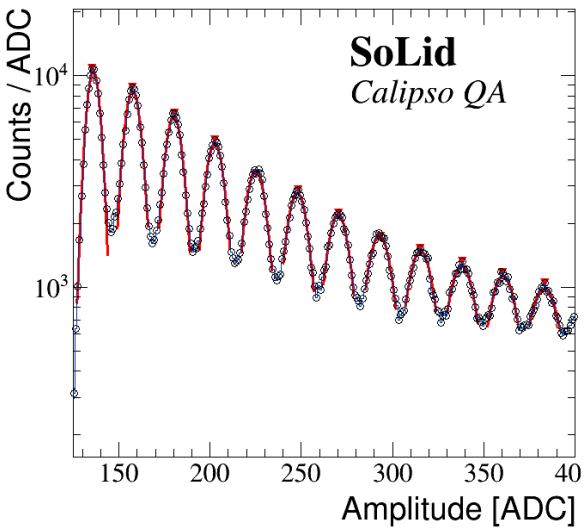
- **Global** detector calibration
- Automated robot to place **radioactive source between modules**
- Calibration during reactor OFF periods
- Detailed detector performance
- **Energy scale + n capture** efficiency **per cube**

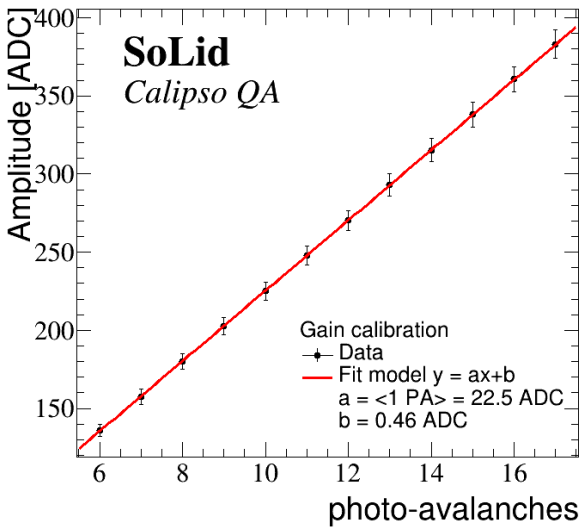


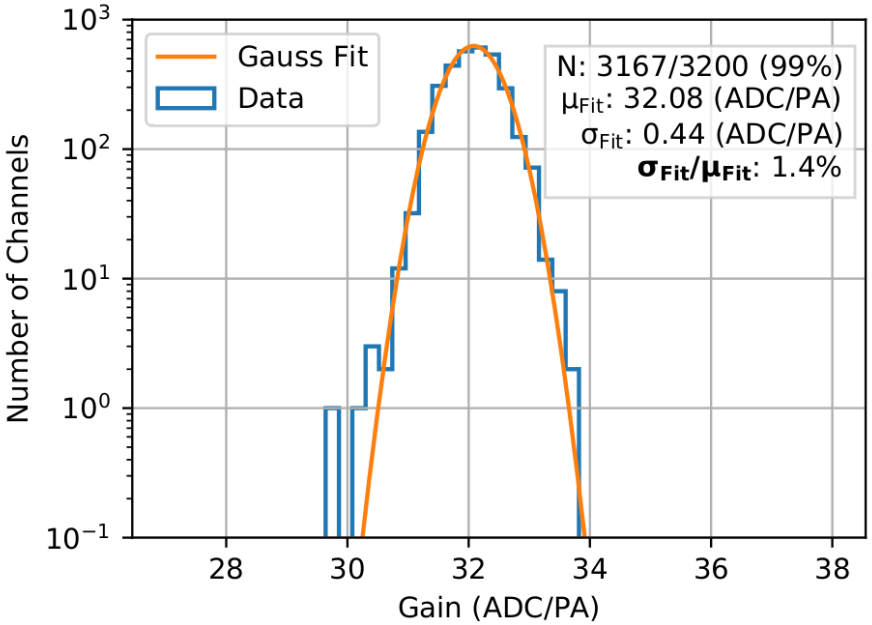
+ Muon calibration

Energy scale with ^{22}Na source

- SiPMs are **equalized** (gains) at **the 1 % level**!
  - Crosscheck with data: ADC → PA







Individual PA arrivals can be identified

SiPM response is very linear!

- The total amplitude per cube (A_{ij}) is found summing the amplitudes of the 4 SiPMs associated to each cube

$$A_{ij} = \frac{A_i^t}{g_i^t} + \frac{A_i^b}{g_i^b} + \frac{A_j^l}{g_j^l} + \frac{A_j^r}{g_j^r}$$

t,b,l,r for the position of the SiPM in the frame

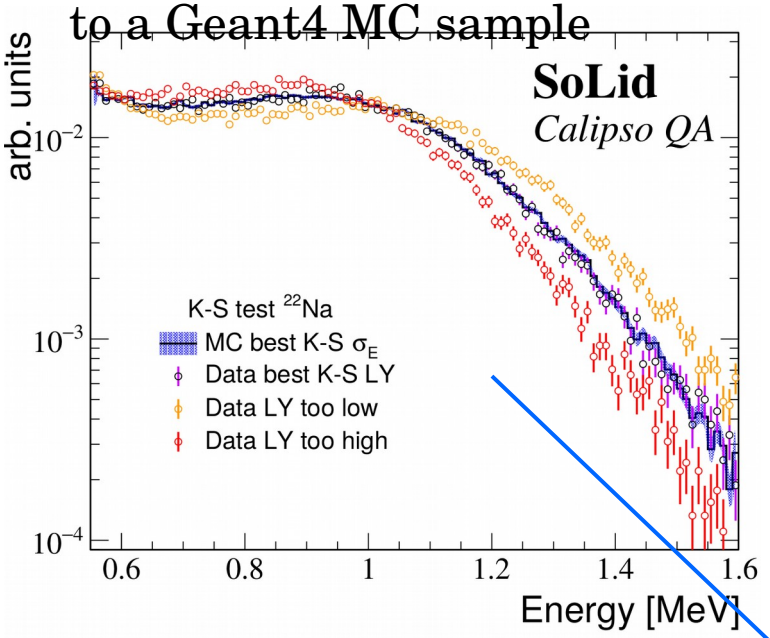
g the gain of each SiPM

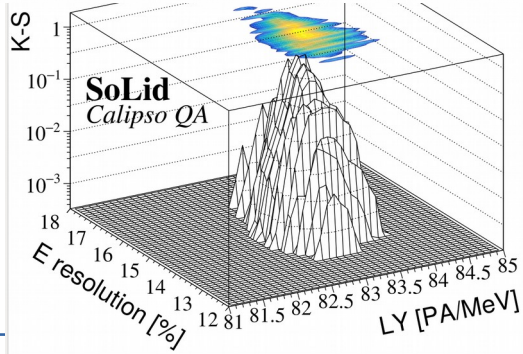
Energy scale with ^{22}Na source

- No photo-peak in PVT cubes → using Compton edge
  - **Two** independent **approaches** to assess the energy scale

Kolmogorov S test (KS)

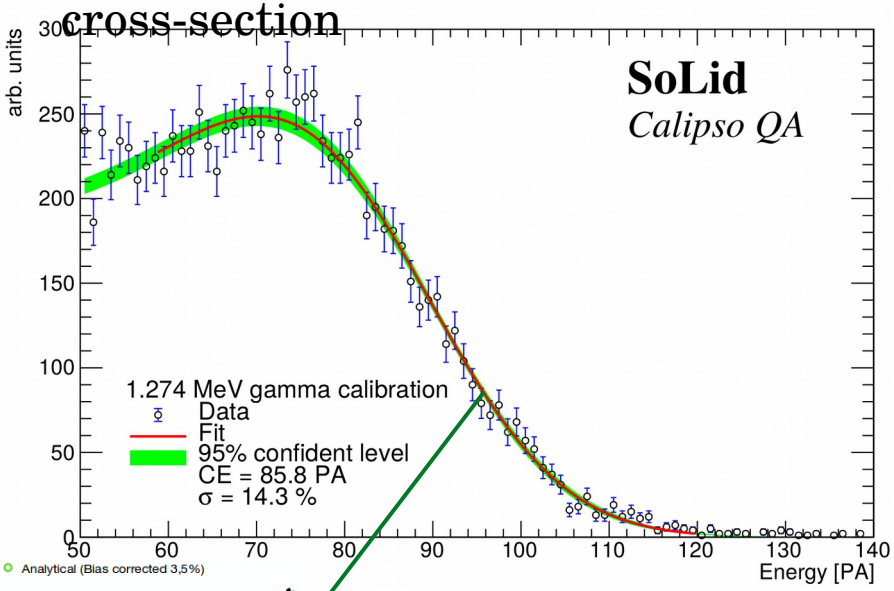
Compare measured sample to a Geant4 MC sample

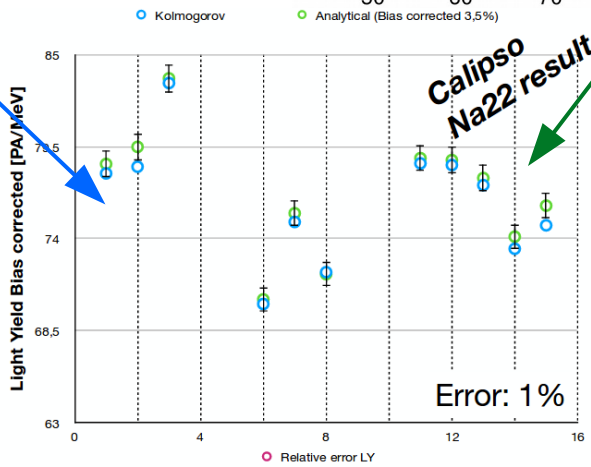




Analytical fit

Use pdf based on Klein-Nishina cross-section

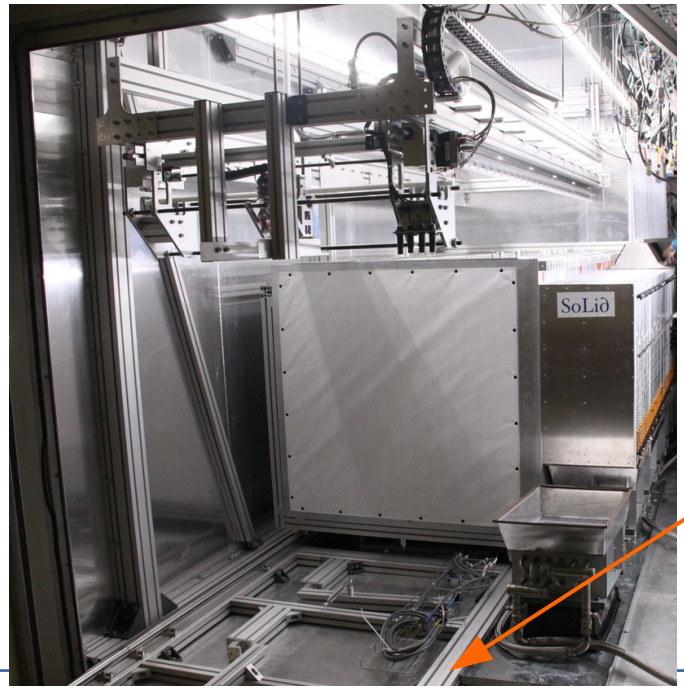




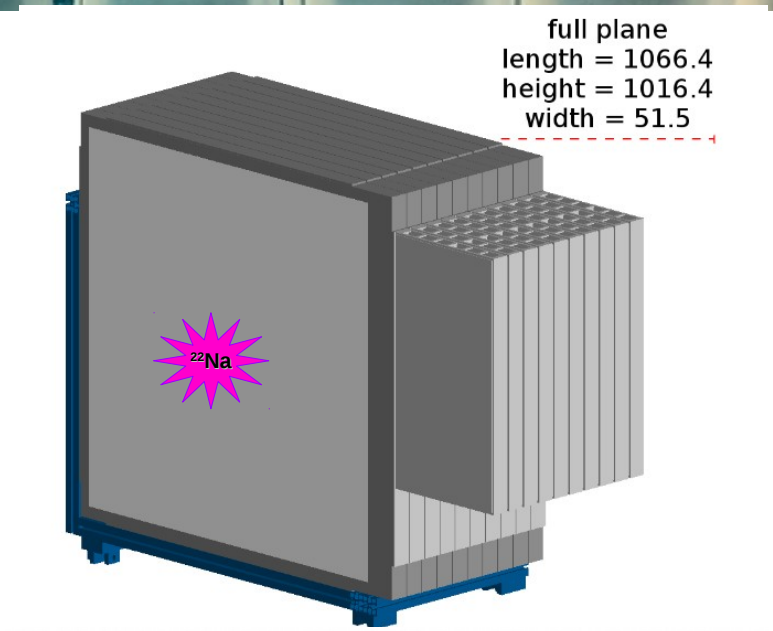
Agreement between both methods at the 1% level!

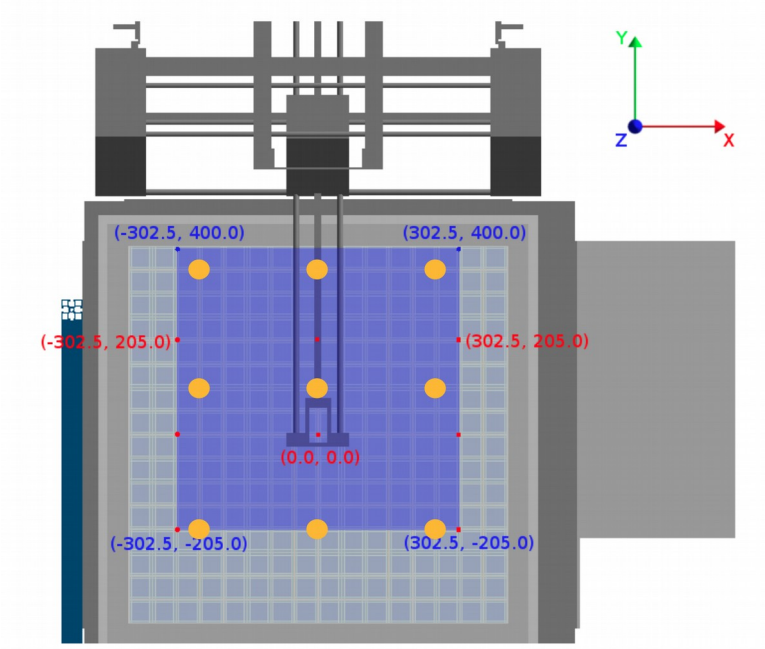
Calibrating with CROSS system

- **In situ** calibration
- Sits above detector planes
- Mechanically open gap between sets of ten planes (Module)
  - Source free to move in gap
  - 9 positions per gap used
  - 6 gaps in total → modules irradiated from two sides



Rails to move modules





Resources for calibration

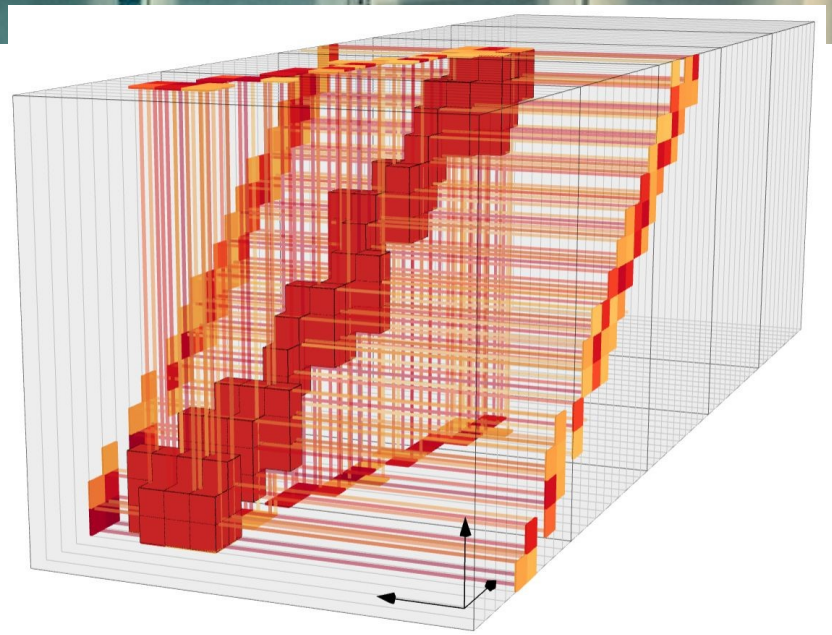
- Neutron sources: AmBe (~4 MeV) +^{252}Cf (~2MeV)
  - Neutron rate **calibrated at the 1% level** at the National Physical Laboratory (UK)
- Gamma sources:

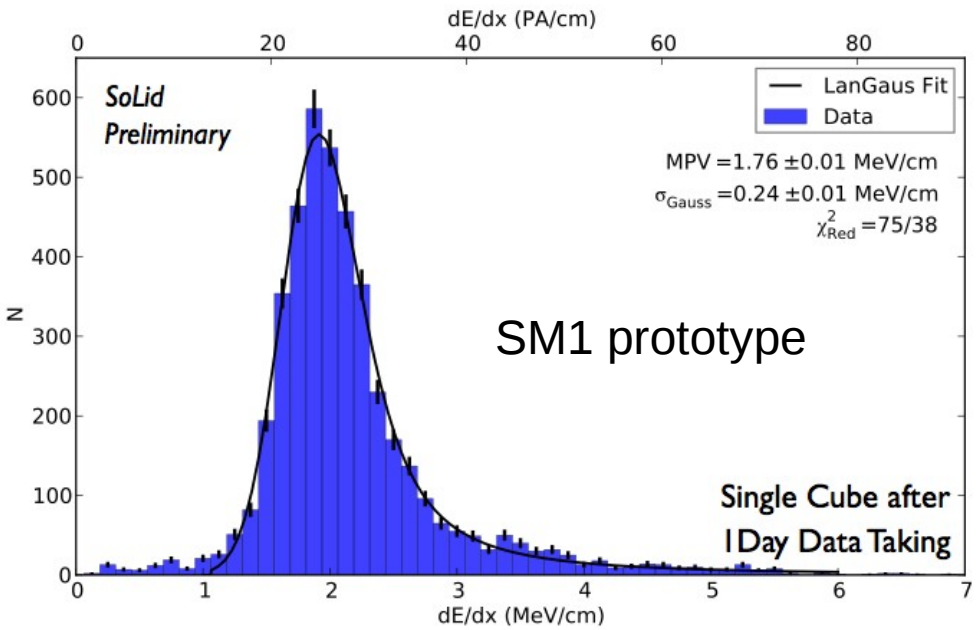
Source	^{22}Na	^{137}Cs	^{207}Bi	^{60}Co	n-H (AmBe/Cf)	AmBe
Energy [MeV]	2x0.511 1.27	0.667	0.57 1.064 1.77	1.17 1.33	2.2	4.44

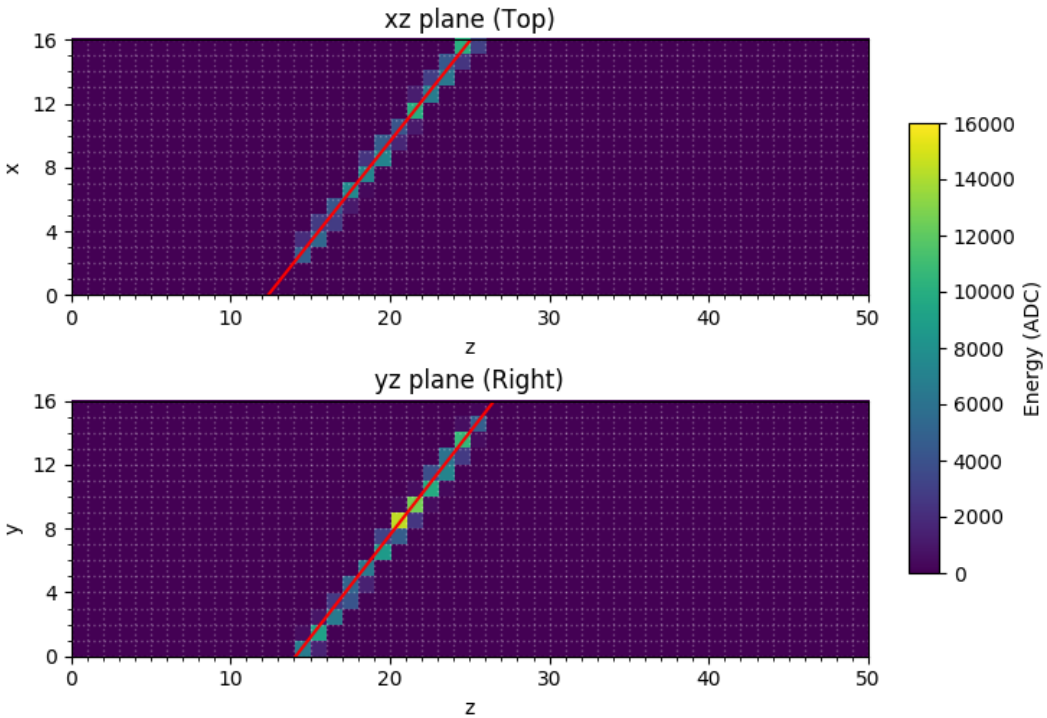
- Muons at high energy

Muon calibration

- Reconstruct muon tracks
  - → Edep / cube using well known dE/dx
  - Monitoring detector stability
  - Linearity at high energ





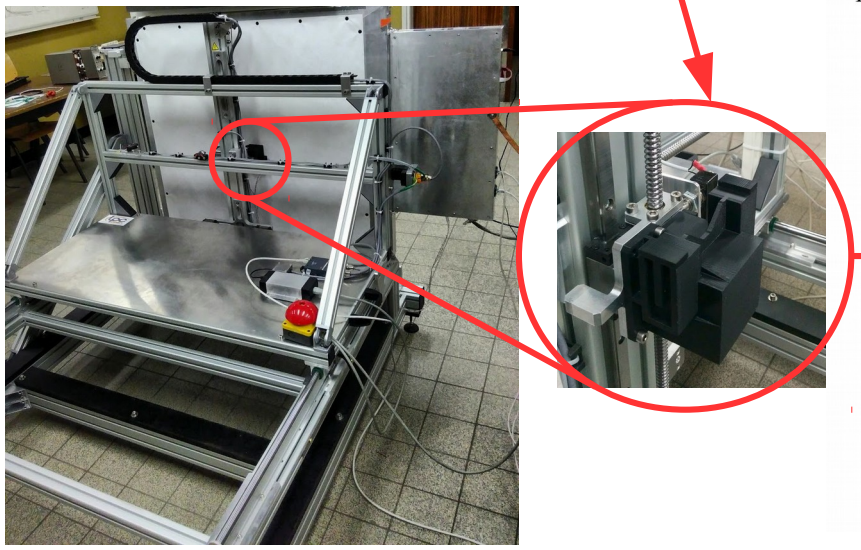


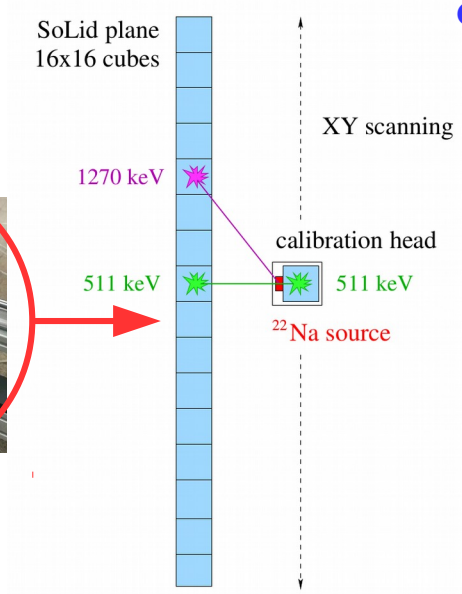
QA II

- **Automated** system to place radioactive sources in front of **each cube**
  - Gamma and neutron mode
- Check **quality** and **uniformity** of the SoLid planes
  - → **Early identification of defective components**
- Gave a good **knowledge** of the detector response **before installation** at BR2
- Allowed calibration of 1 plane / day

Gamma mode

^{22}Na source with **external trigger**





Neutron mode

^{252}Cf source with **polyethylene collimator**