SoLid: Search for neutrino oscillations using a Lithium-6 Detector at a nuclear reactor

University of Birmingham Seminar, 30th Nov 2016

Dan Saunders, on behalf of the SoLid collaboration

Outline

- Neutrino Oscillations (reminder).
  - Reactor based neutrino experiments (current gen & next gen).
  - Challenges at very short baselines.
- SoLid technology.
  - Detection principle.
  - Status of the project.
- Prototype results.
  - Reconstruction.
  - Searching for neutrinos.
- Phase I preparations:
  - Optimisations.
- Conclusions

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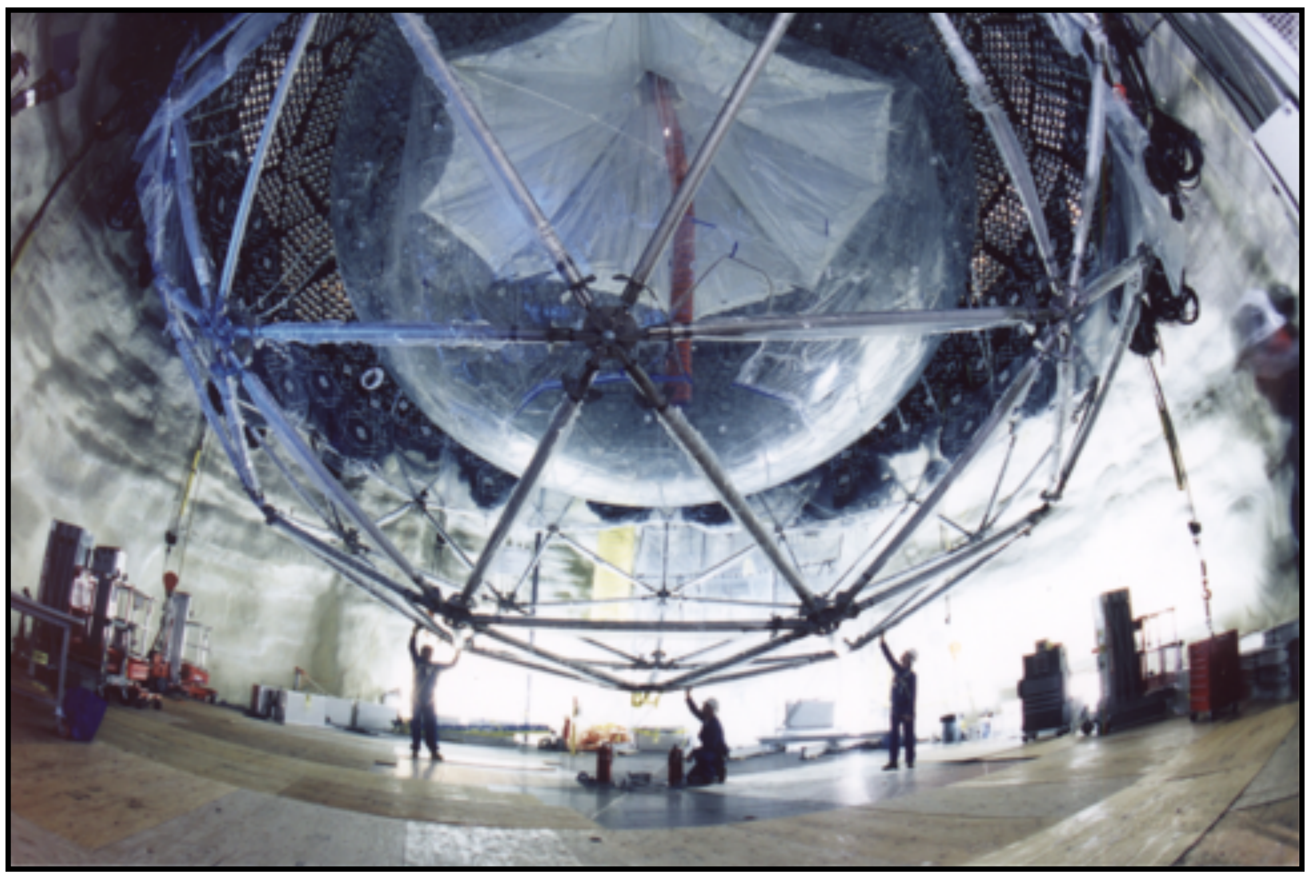
Neutrino Oscillations (reminder)

- 2015 Nobel prize for discovery of neutrino oscillations (solar):
  - Arthur McDonald (SNO) and Takaaki Kajita (Super K) experiments!
  - Flux measurements of solar electron and muon neutrinos.
  - Solves solar neutrino problem.
  - Requires neutrino's have mass.

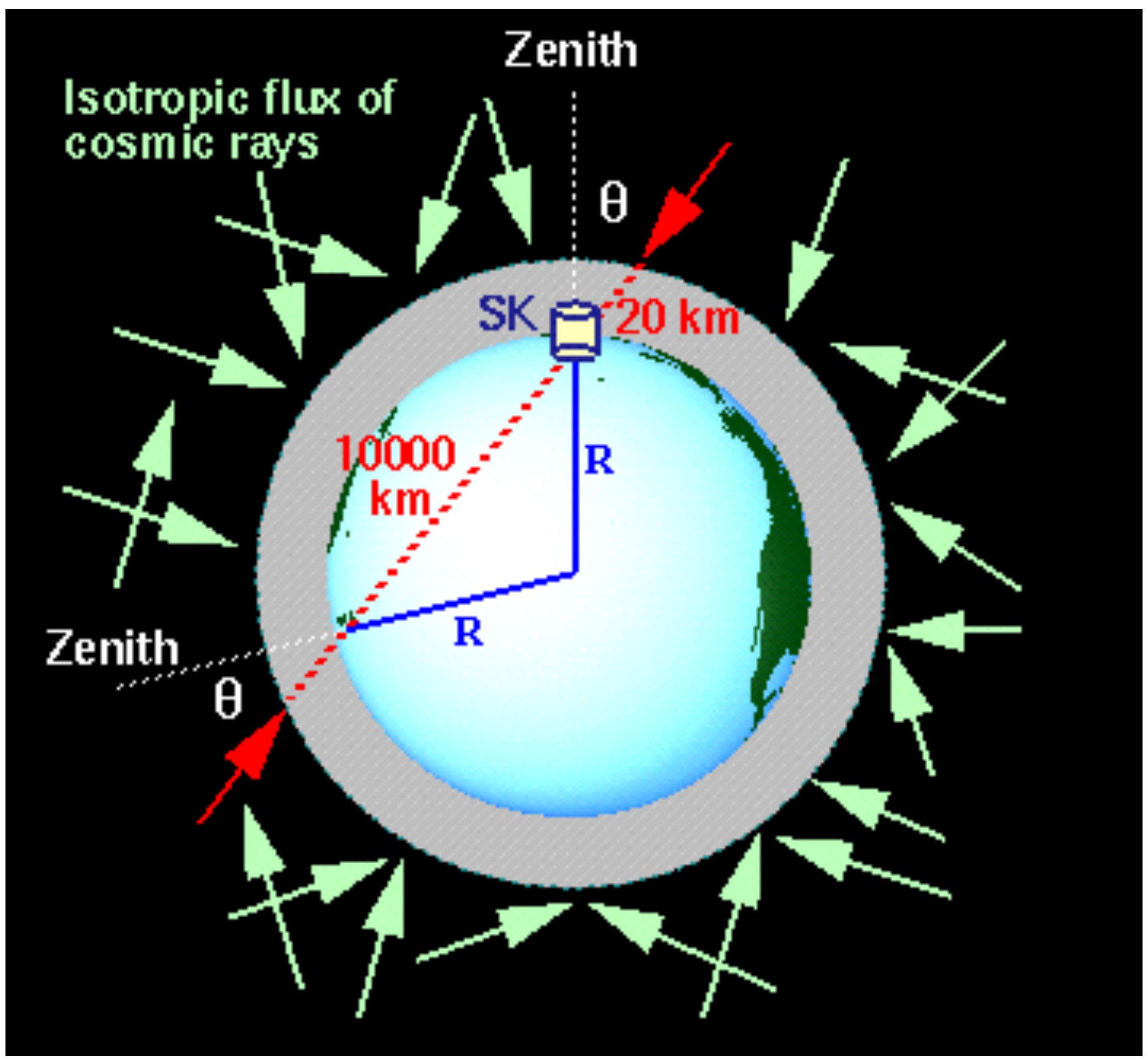


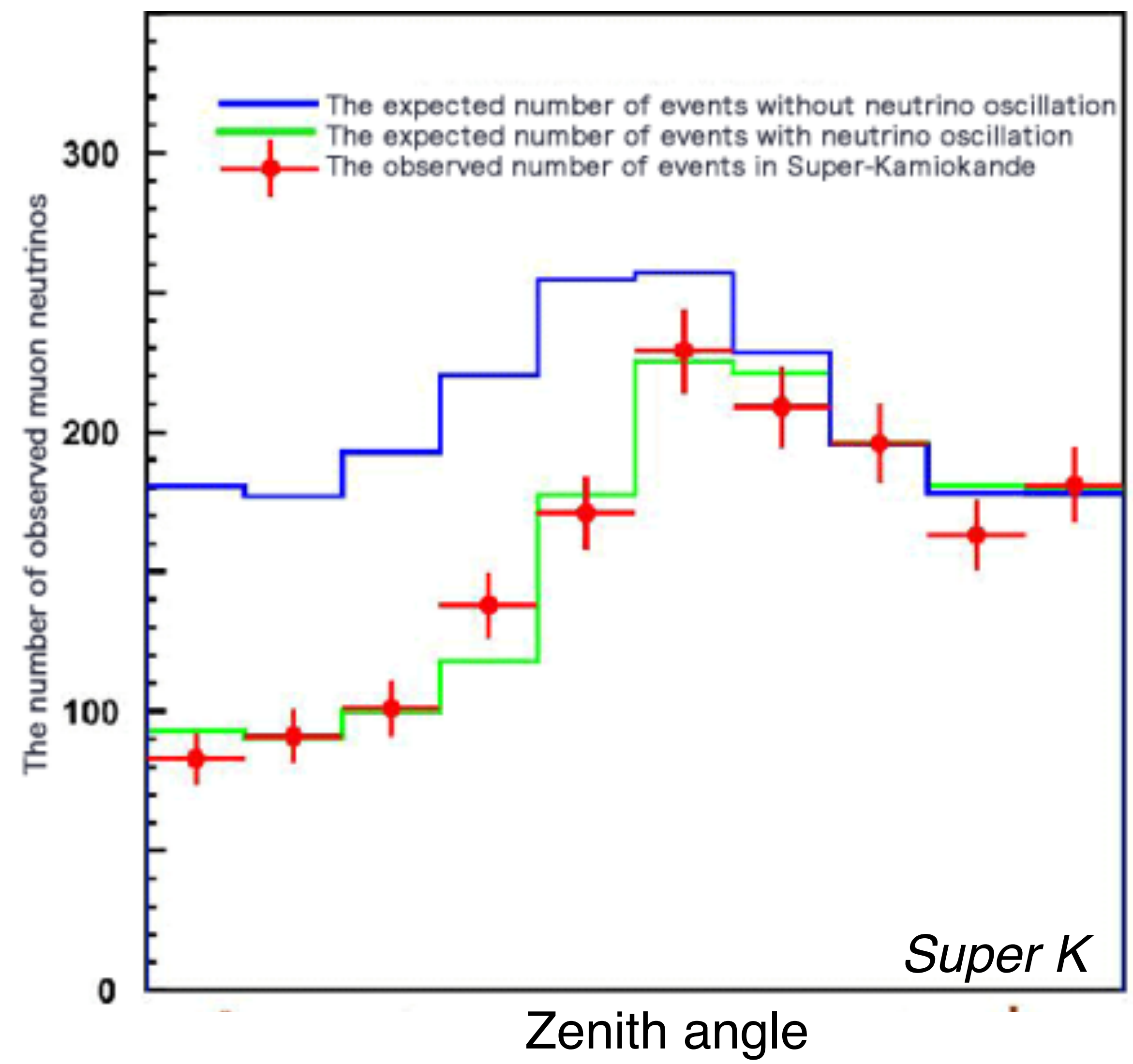
SNO Observatory

NGT at Super Kamiokande

Neutrino Oscillations - Atmospheric

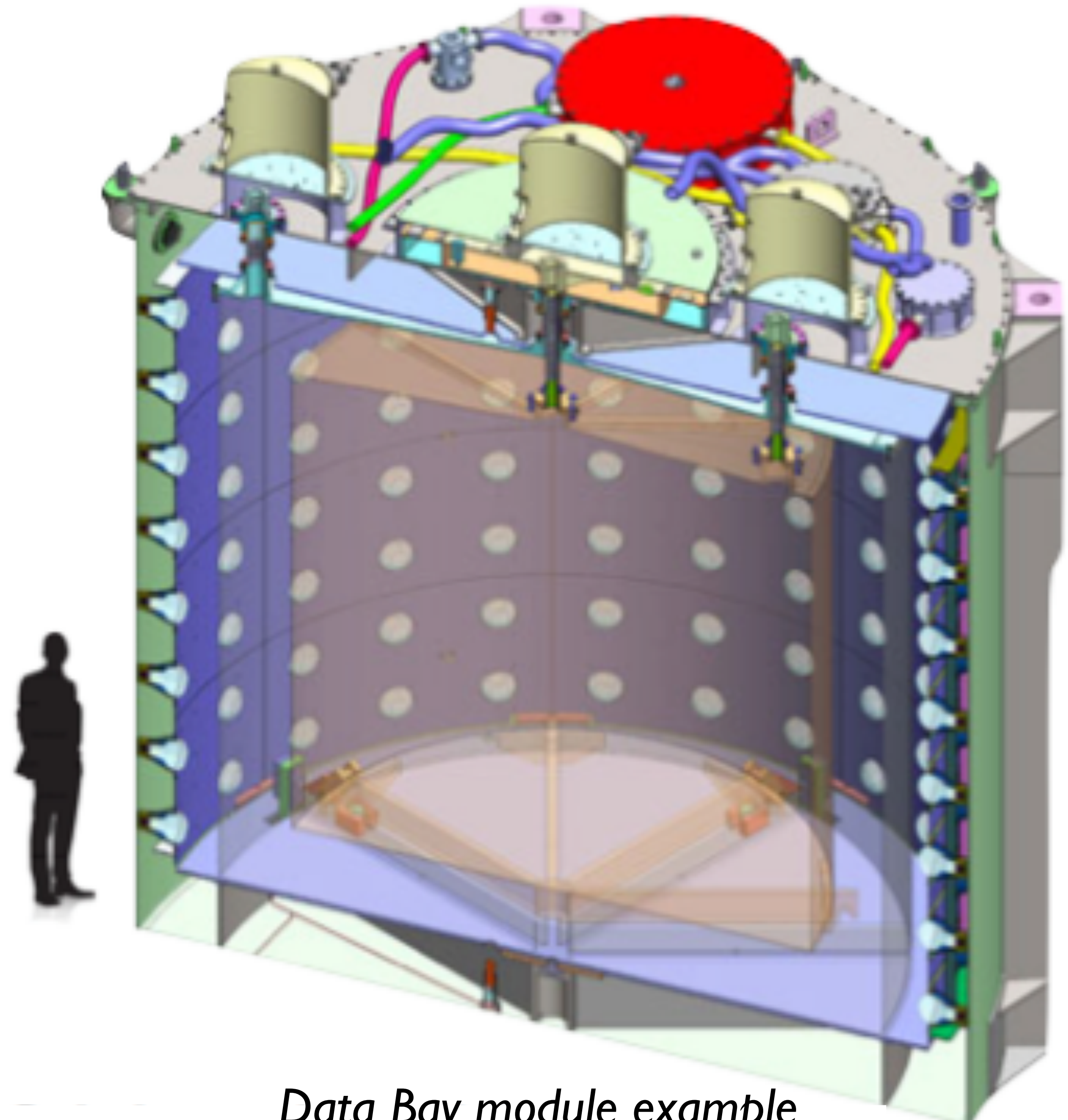
- Cosmic rays produce neutrinos uniformly in the atmosphere.
- Detector on the surface (with directionality) can observe neutrino oscillations by measuring ν flux as a function of zenith angle.





Short Baseline Experiments

- Reactor neutrino experiments well established:
  - First successfully attempted 1956 at Savannah River.
  - Multiple experiments since, with varying mass and distances from reactors.
- Take advantage of the enormous flux of neutrinos from reactors:
  - E.g. Daya Bay event rate: ~10 neutrinos per hour.



Data Bay module example

Current Generation

- Current generation experiments searching for oscillations at short baselines:
  - ~100m to ~1Km:
  - Daya Bay, RENO, Double-Chooz.

- Very successful physics campaigns:
  - Largely dedicated to measuring antineutrino electron disappearance (first time observed!). (independent of CP violating terms). First confirmed observation in 2012.
  - Use near and far detector to remove systematic errors in neutrino flux calculations.

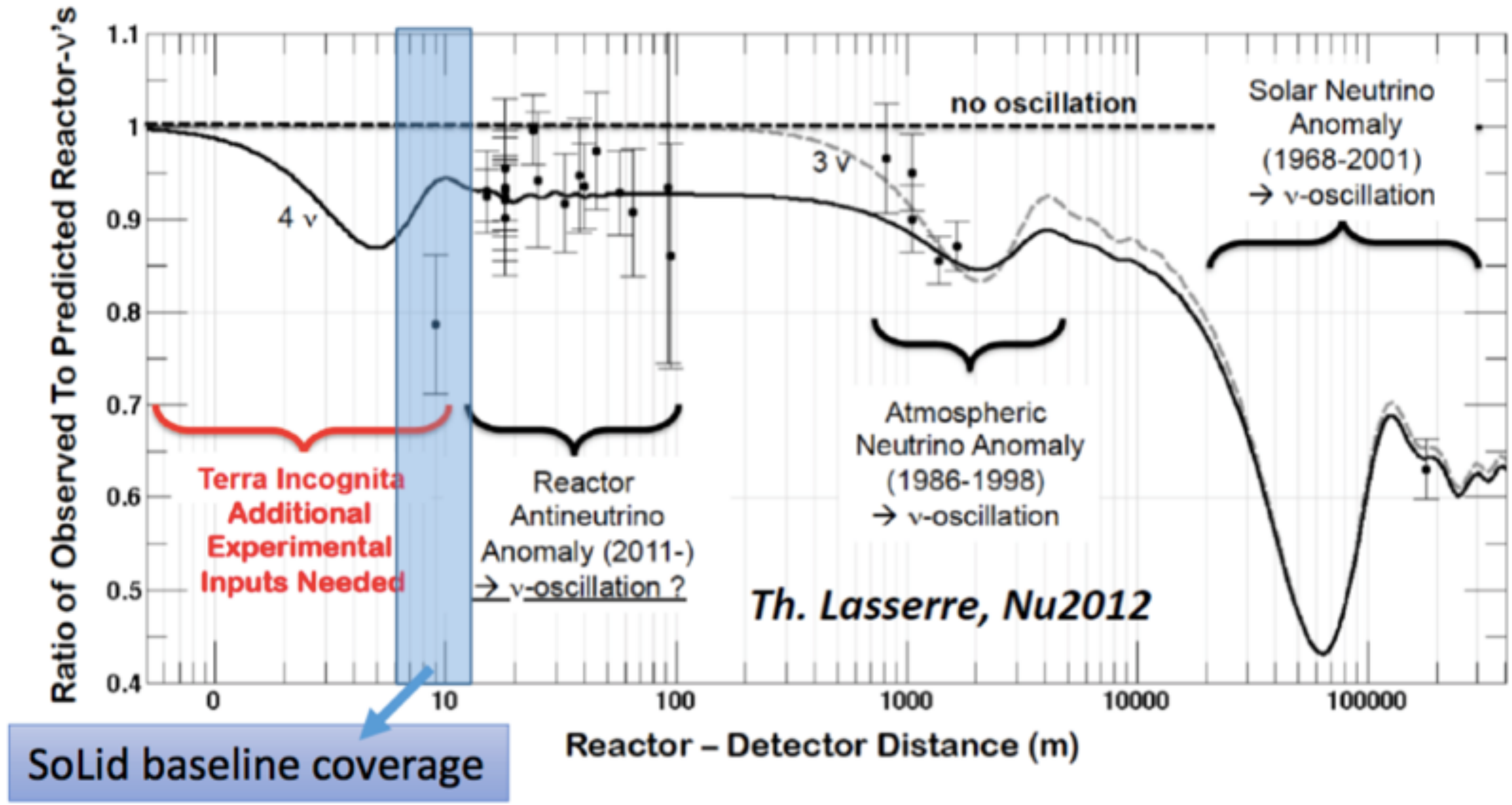
- Common characteristics:
  - Underground lab → reduced background.
  - Gd-doped liquid scintillator → flammable.
  - Large external shielding → non-compact.

    → *Difficult to use very short baselines.*

- Some anomalies…

Reactor Anomaly

- Re-evaluation of reactor flux calculations increased predicted rate - 2.7σ deficit.
- Proposed solution 4th 'sterile' neutrino (limits from LEP):
  - Analogous to logic used for solar and atmospheric deficits.

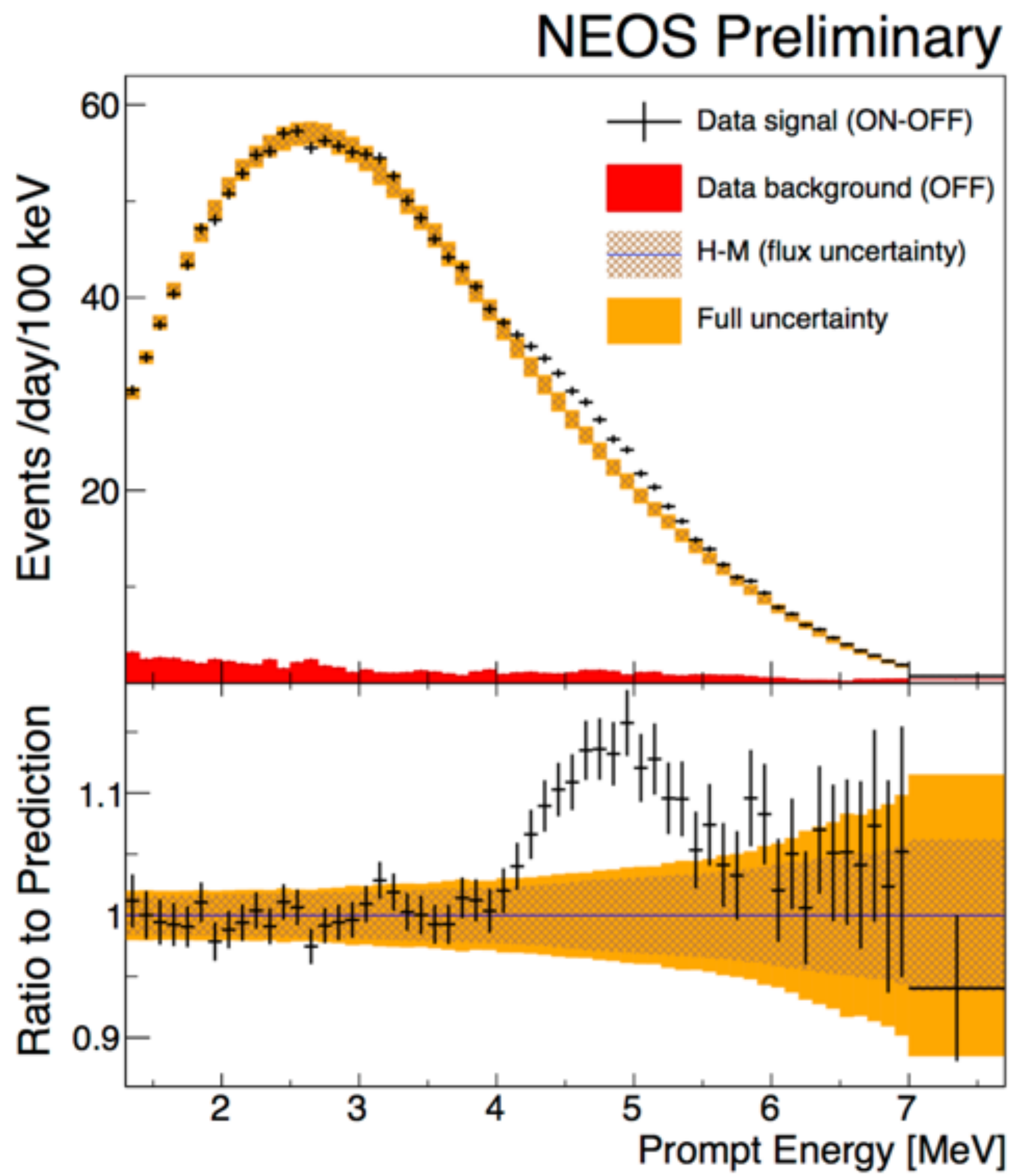


5 MeV Distortion

- Current generation observe unexpected distortion ('hump', or 'bump') around 5 MeV.

- Multiple explanations:
  - Errors in neutrino flux calculations from less understood isotopes.
  - Problems with tuning from other experiments.
  - Cannot be resolved exclusively by oscillations.

- Can be resolved by studying spectra from reactors with different energy spectra (such as ^{235}U).



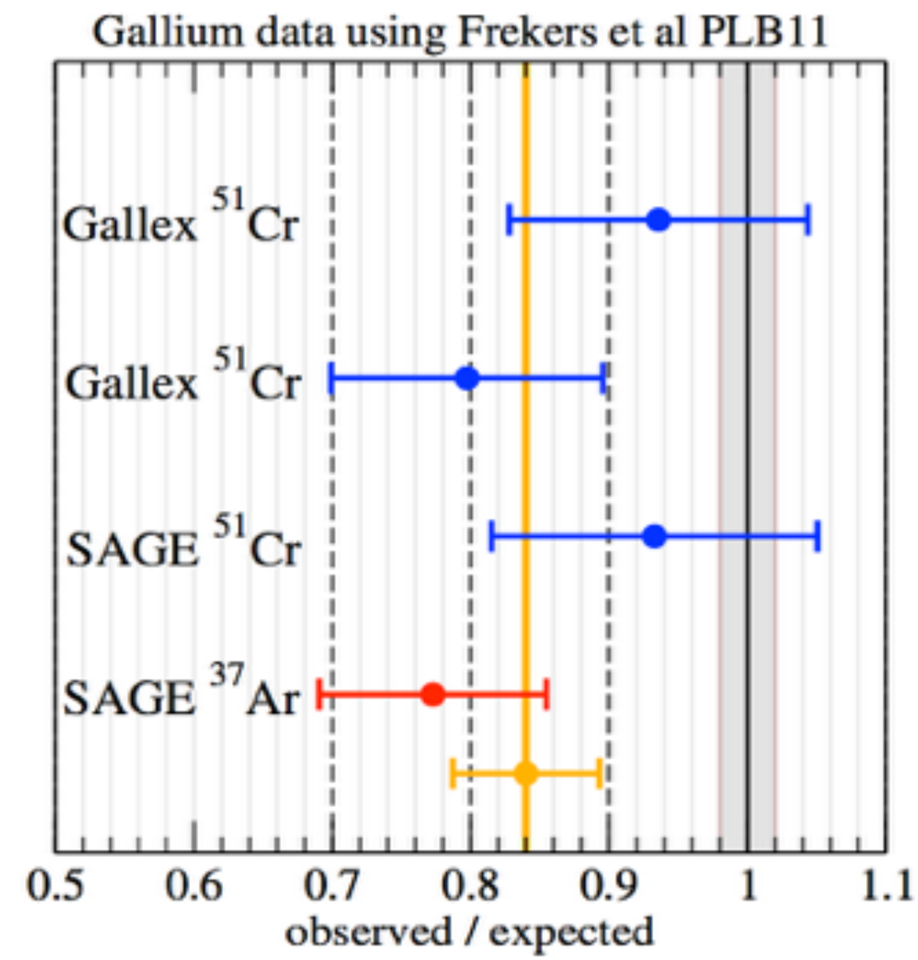
Gallium Anomaly

- Gallex and SAGE solar experiments tested with intense radioactive sources:
  - Rate deficit of 14 ± 6 %.
  - 2.8σ
- Could be explained by sterile oscillation.

→

Motivation to search at shorter baselines.

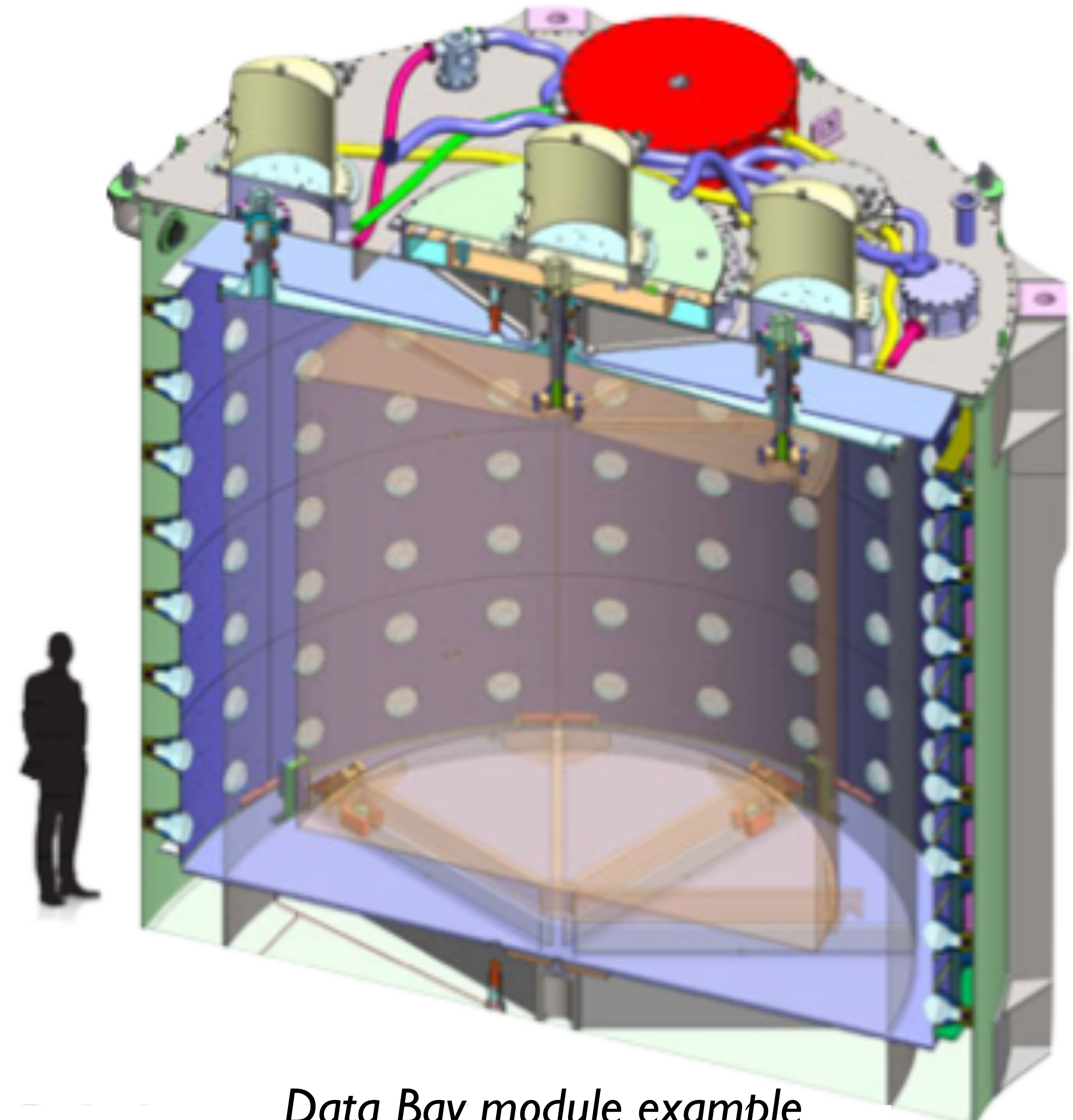
$$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$$



Giunti Laveder 1006.3244
J. Kopp et al., hep/ph:1303.3011

Very Short Baseline Experiments

- Next generation of reactor neutrino experiments study ***very short*** baseline:
  - Increased sensitivity for oscillation search.
  - Require compactness to be placed near reactor.



Data Bay module example

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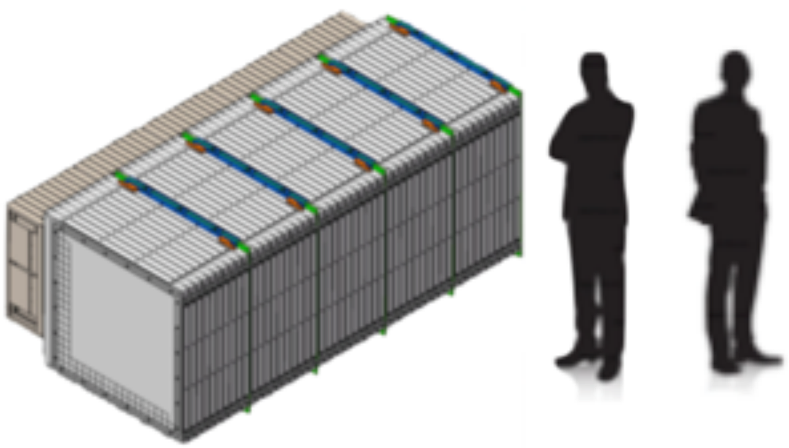
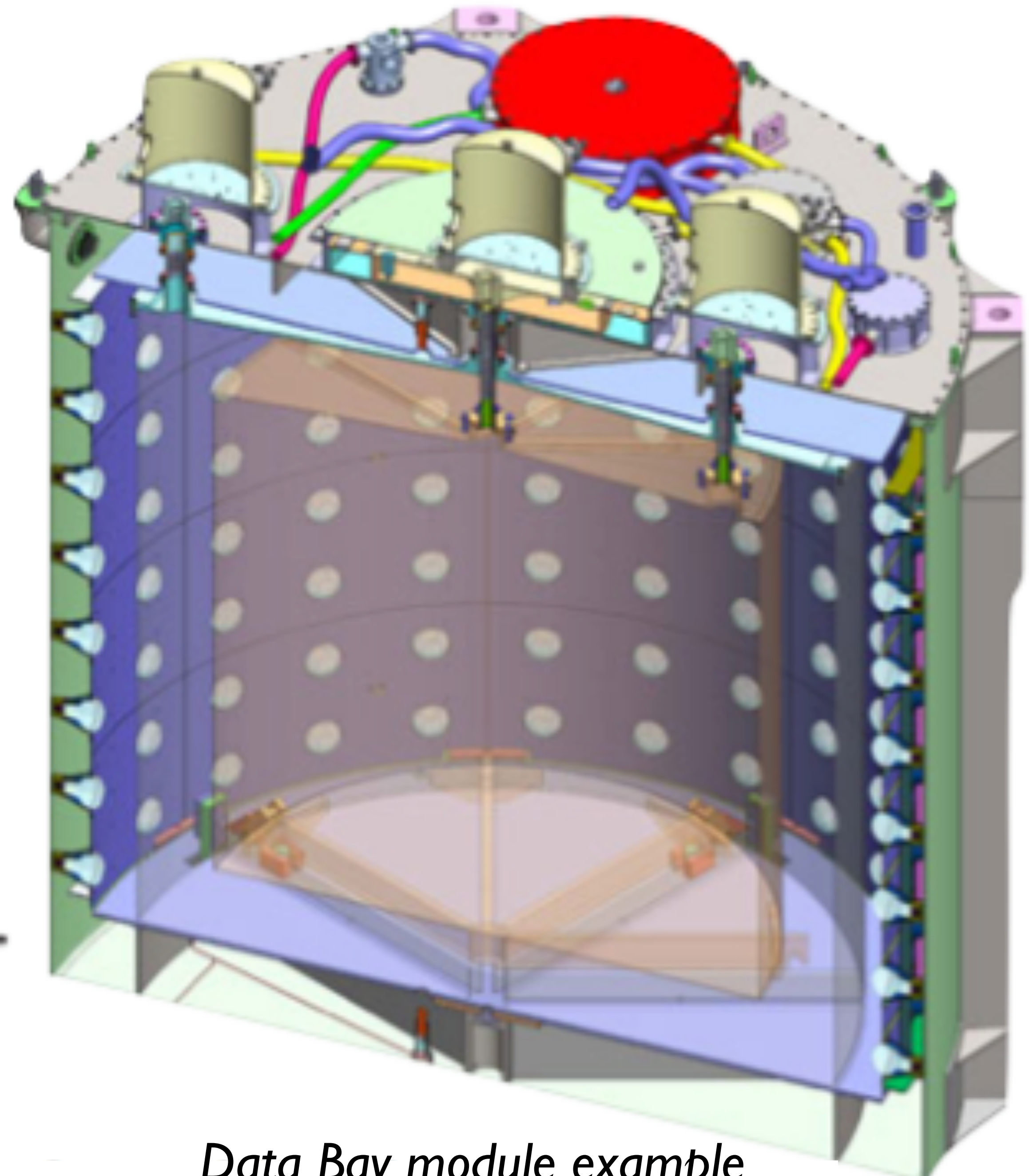


SoLid example



Data Bay module example

Challenges at VSBL

Detector

- High resolutions for oscillation search:
  - Spatial.
  - Energy.
- Effective background rejection:
  - Low overburden.
  - Reactor radiation.

Reactor

- Compact core
  - Understood fuel composition.
  - Access as close as possible.
- Security implications:
  - Reduce flammable liquids.

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SoLid Solutions

- Highly segmented detector:
  - Localisation of events.
  - (Quasi) 3D topological information.
- Suitable photo detector - SiPMs.
- Active and passive shielding.

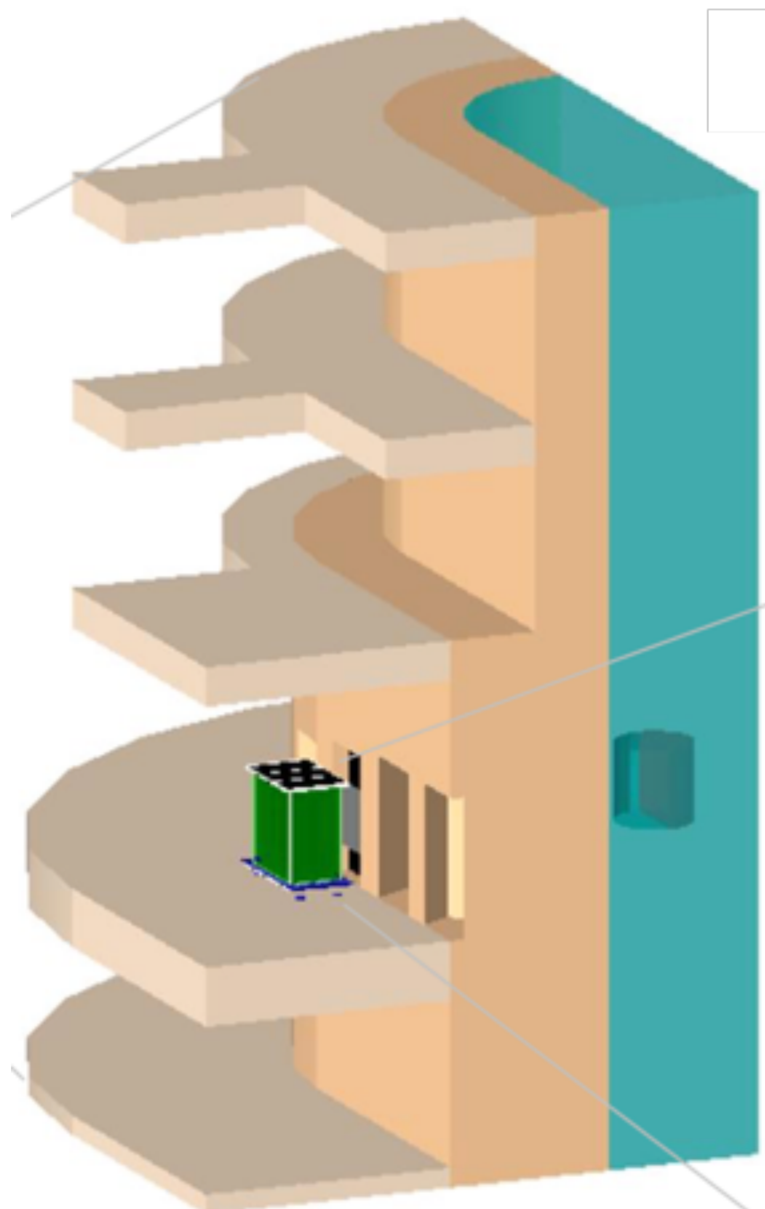
- Research reactor:
  - Belgian Reactor 2 (BR2) at SCK-CEN.
  - Core diameter 0.5m.
  - 95% Enriched 235U, 60MW.
  - Access ports for experiments.

SoLid Collaboration

The SoLid Collaboration at Brussels - ca 50 people

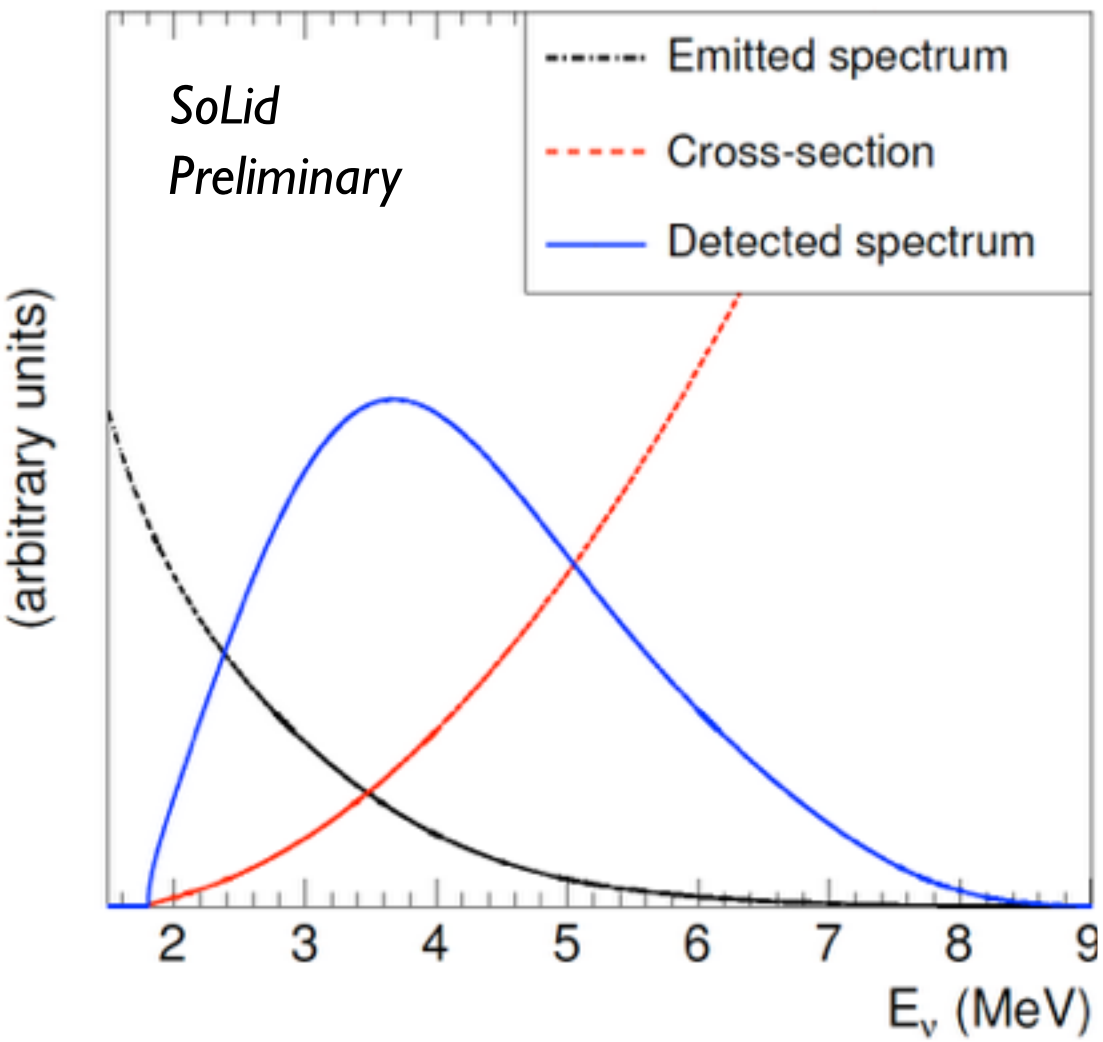
BR2 Reactor @ SCK · CEN

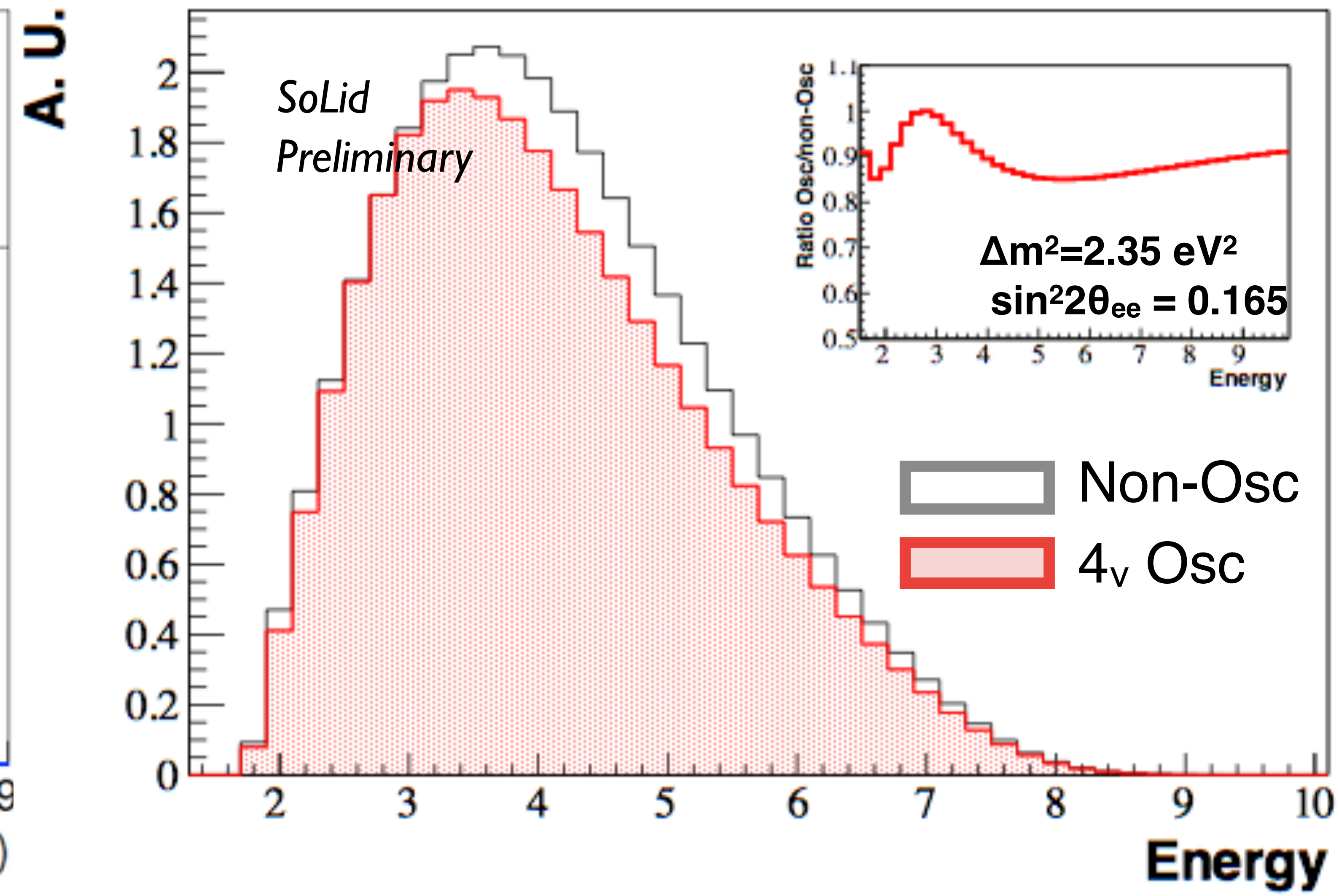
- Research reactor:
  - Belgian Reactor 2 (BR2) at SCK-CEN
  - 95% Enriched 235U
  - Core diameter 0.5m
  - Access ports for experiments
- Low vertical overburden (<10m WE).
- SoLid is on-axis with reactor core.
- No other users.



Searching for Oscillations

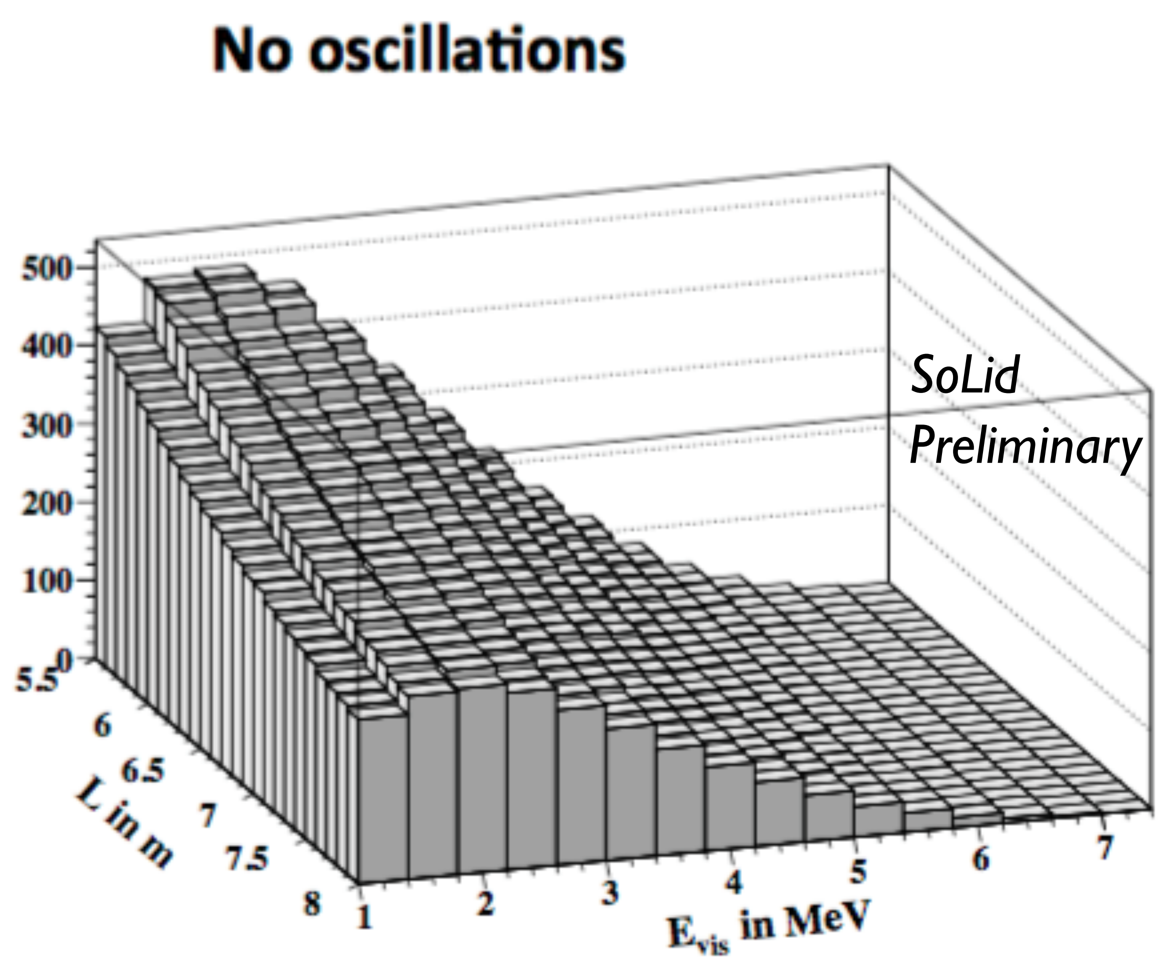
- Probability $\bar{\nu}_e$ disappearance proportional to E_ν/L (L=distance from reactor).
- Distorts E_ν spectrum.

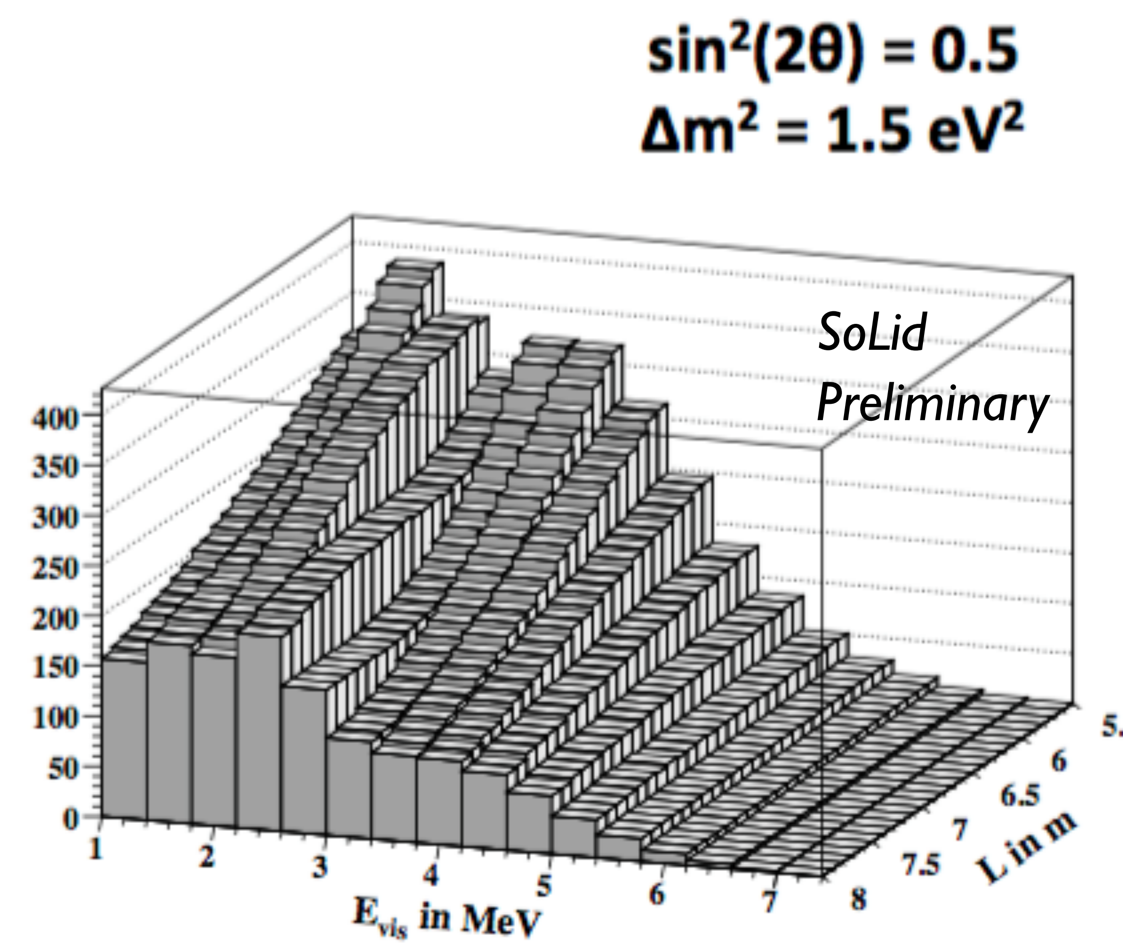




Searching for Oscillations

- Probability $\bar{\nu}_e$ disappearance proportional to E_ν/L (L=distance from reactor).
- Distorts E_ν spectrum.
- 2D shape fit to distribution of E_ν vs L (analogous to using near and far detector):
  - Careful about 5 MeV distortion.





SoLid Technology

Neutrino Channel

- Neutrinos seen via usual inverse beta decay (IBD) interactions:

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

- Proton from detector volume.

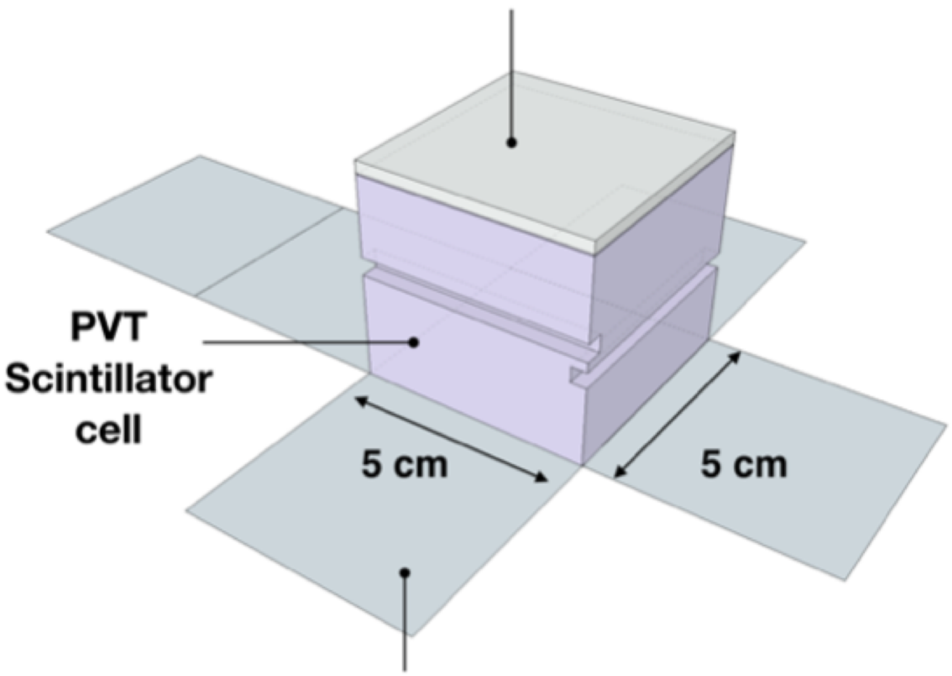
- Positron briefly travels through detector before annihilating to two annihilation γ:
  - Energy in the range of 1-8 MeV - highly correlated with $\bar{\nu}_e$ energy.
  - γs typically travel ~30cm away before absorption.

- Neutron needs to thermalise before capture:
  - Initially spatially near the positron (unlike background).

Neutrino Signal
Positron and neutron correlated in space and time.

Detector Technology

- Novel technology developed to take advantage of spatial correlation - composite cubes.



<u>*Polyvynil-Toluene (PVT)*</u>

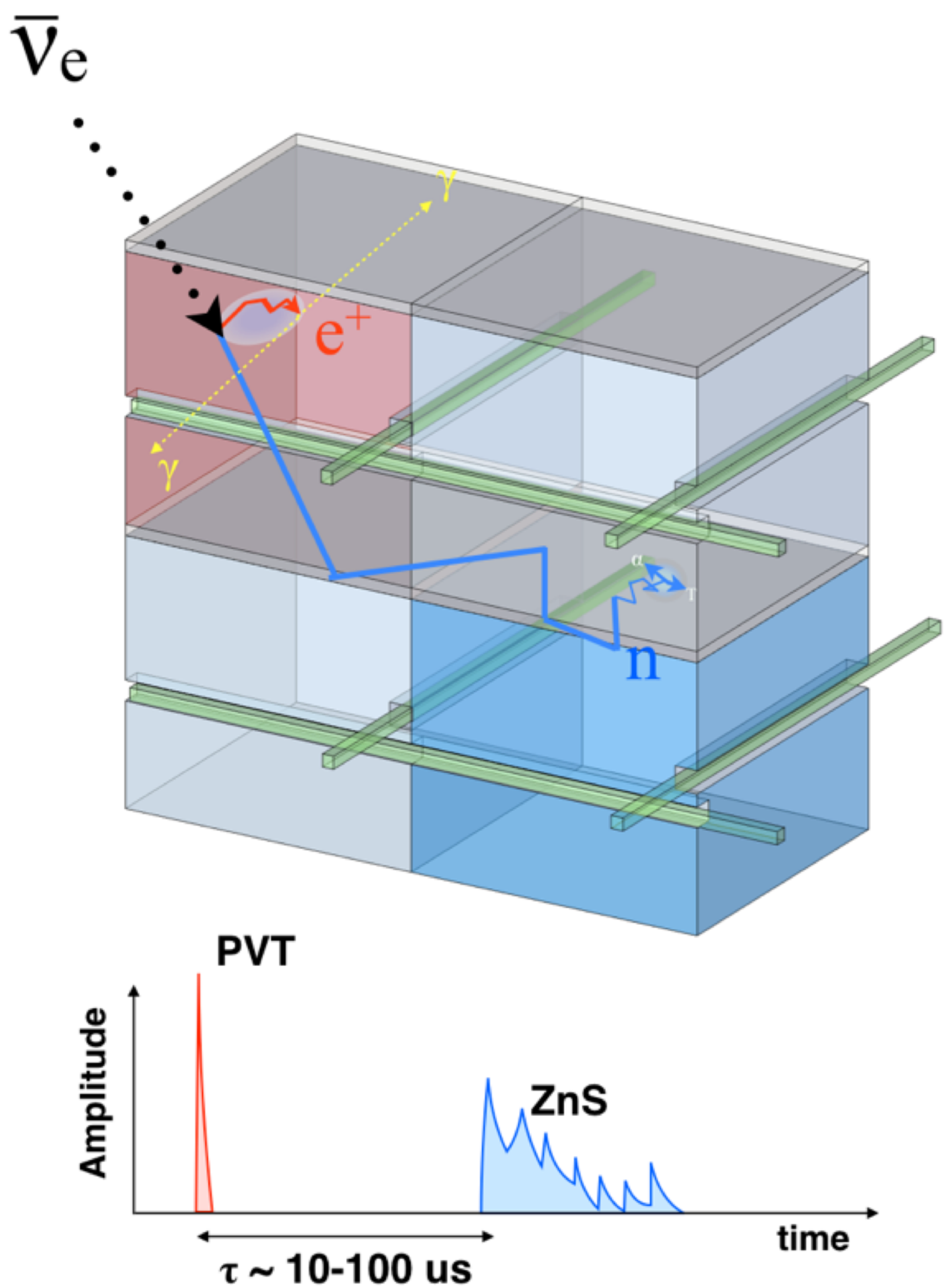
- Scintillator for ionising particles. Light out proportional to positron energy.
- Light detected within a ***few ns***.

<u>*Sheet of ^{6}LiF:ZnS(Ag)*</u>

- Neutron scintillator using the reaction: n + Li → α + T
- Alpha and triton scintillates in ZnS(Ag) with a ***few μs***.

Neutron ID
Scintillation light from neutrons emitted much slower than EMs.

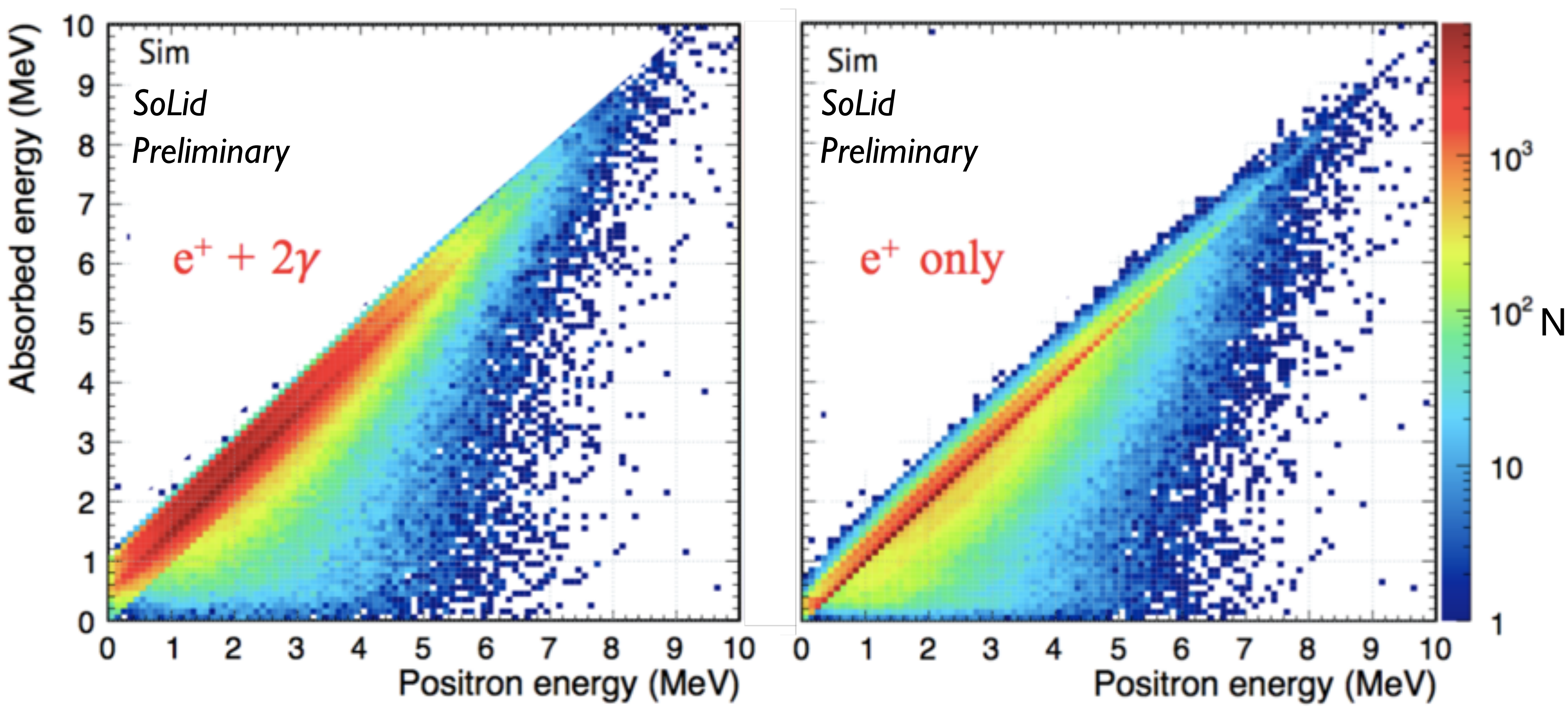
Detector Technology



- Cubes are stacked to form detector.
- PVT acts as neutron moderator:
  - Positron and neutron typically separated by less than two cubes.
  - Topologically different to backgrounds!
  - Average time separation ~100μs.
- Each cube (PVT + Li) is wrapped in Tyvek for light tightness:
  - Positron and neutron signals localised to specific cubes → high spatial resolution.
- Positron energy can be reconstructed independently of annihilation gammas.

Detector Technology

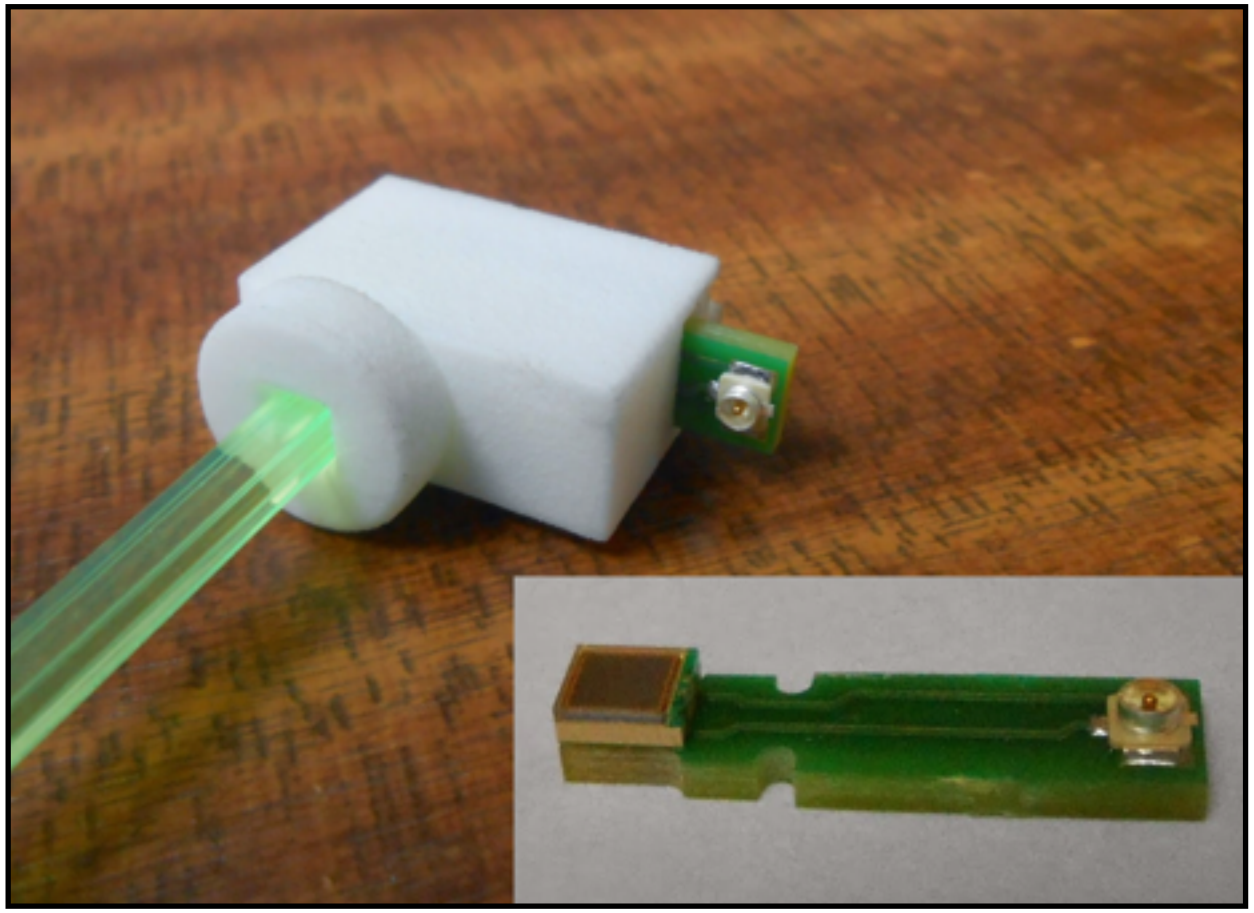
- Positron energy can be reconstructed independently of annihilation gammas:
  - Gamma leakage not a problem.



e+ energy reconstruction. Left: including gamma energy. Right: only cubes near the positron. RO effects not included.

Readout

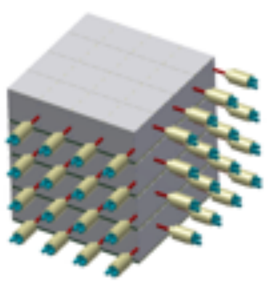
- Light from cubes is read-out using a 2D array of wavelength shifting fibres:
  - Typically 3x3mm^2 square fibres sitting in 5x5mm^2 grooves.
- Each end of a fibre optically coupled to a silicon photomultiplier.
- SiPMs readout by custom electronics:
  - Typically 14bit ADC range.
  - Sample period of 25ns - fast enough to show neutron shape.



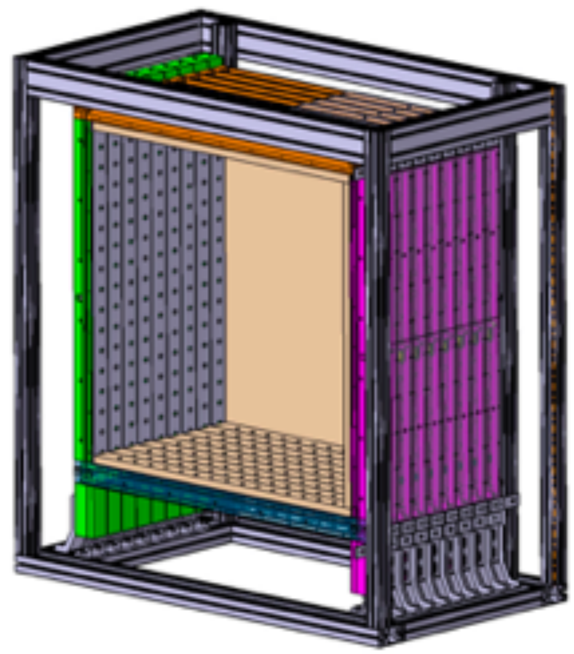
Example SiPM fibre connector

Experiment Status

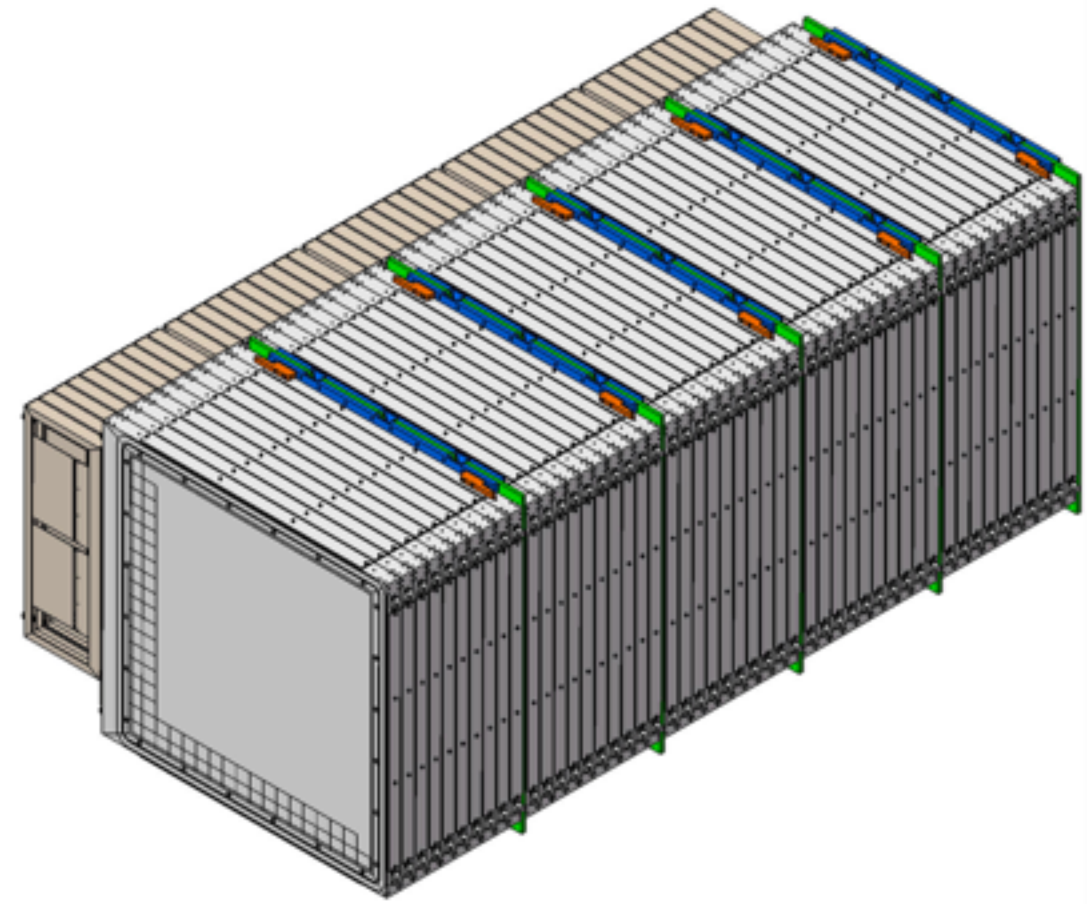
2013



2014-15



2016-17



Nemenix (8kg)

- Proof of concept.
- Demonstrate PID.

SM1 Prototype (288kg)

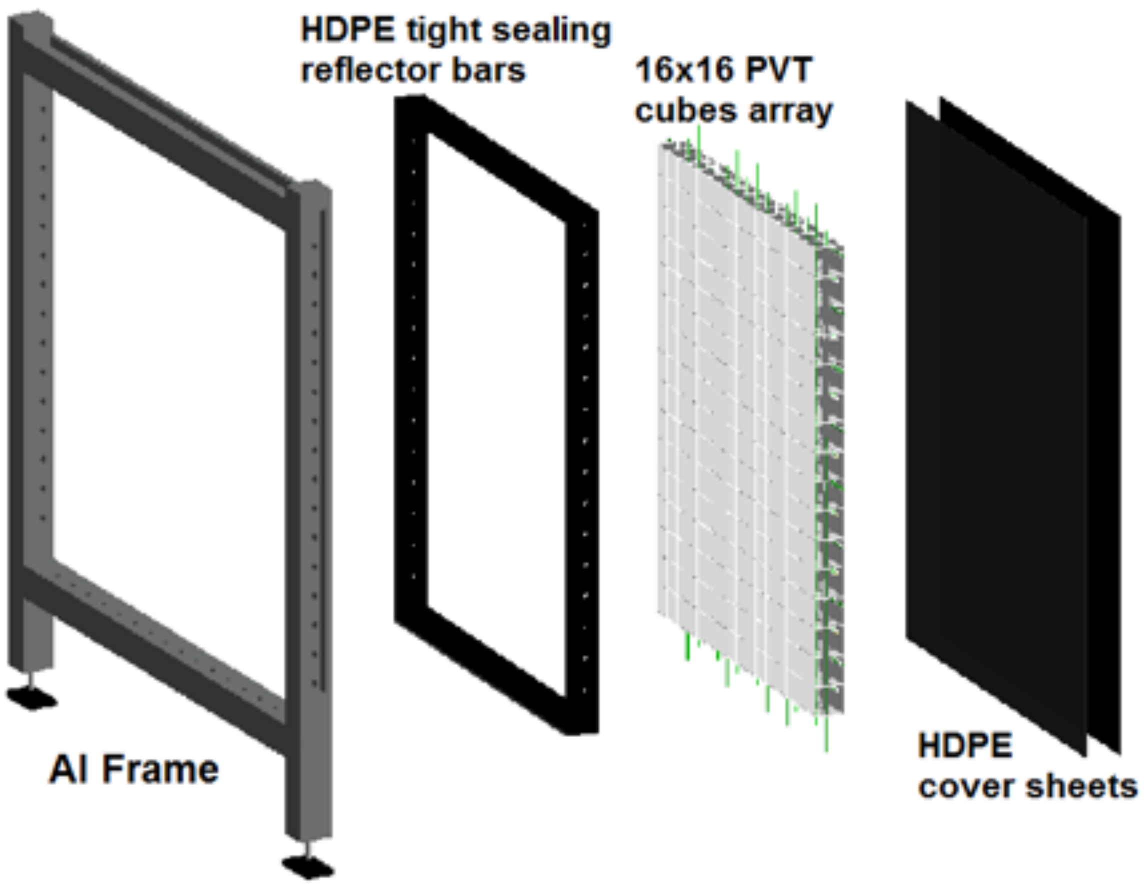
- Test scalability and production.
- Prove power of segmentation.

SoLid Phase I (1.6 T)

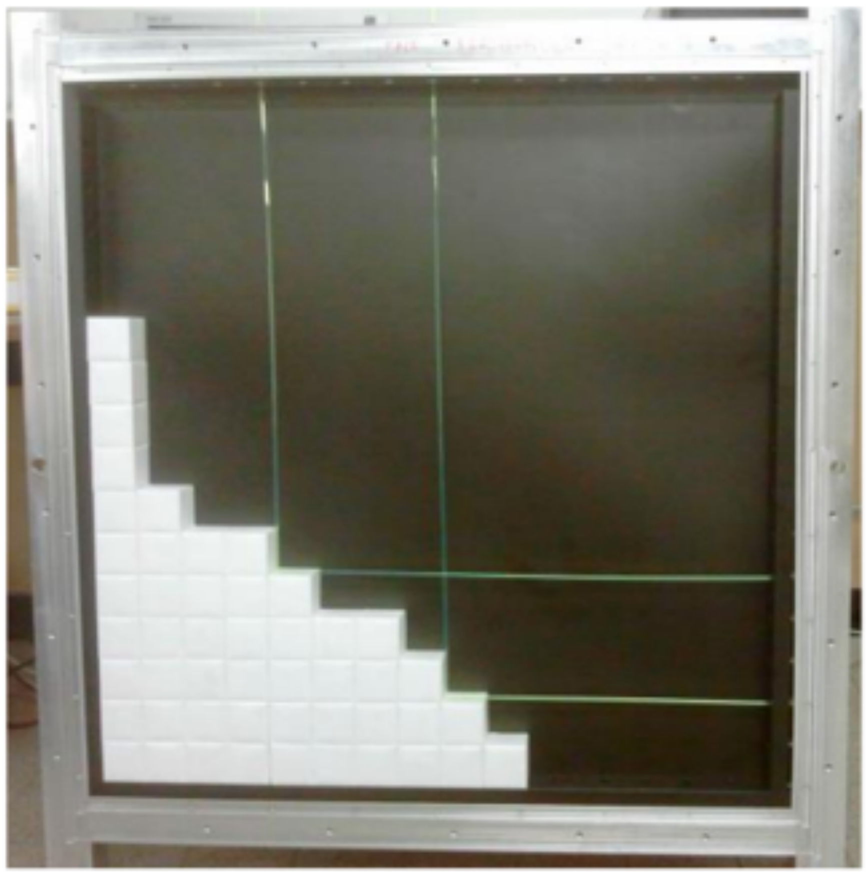
- 12k cubes with 3.2k channels, ~300 events/day.
- Perform first oscillation search.

Prototype SoLid Module 1 (SM1)

- First large scale demonstration of technology.
- Cubes placed in an arrangement of 16x16x9 cubes (~20% planned mass).
- Assembled late 2014 and deployed at the reactor site prior to 1 year reactor refit.

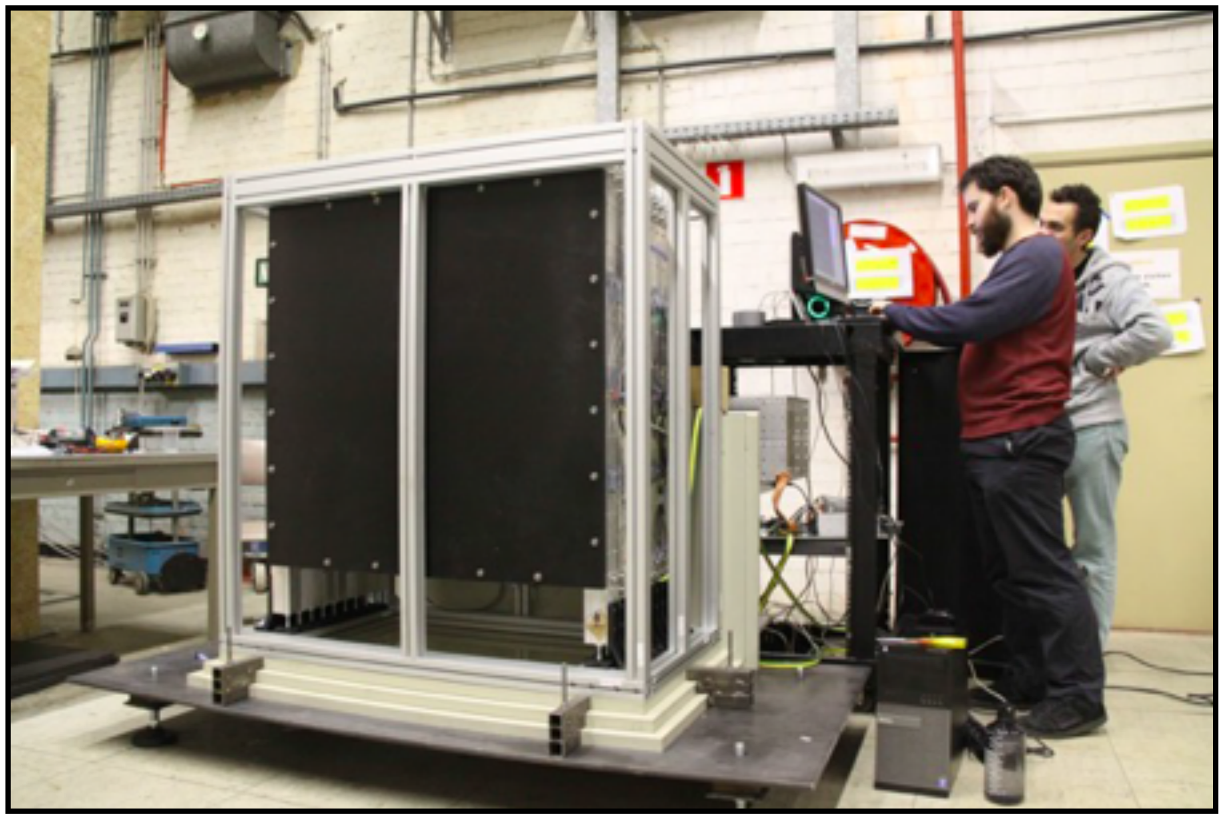


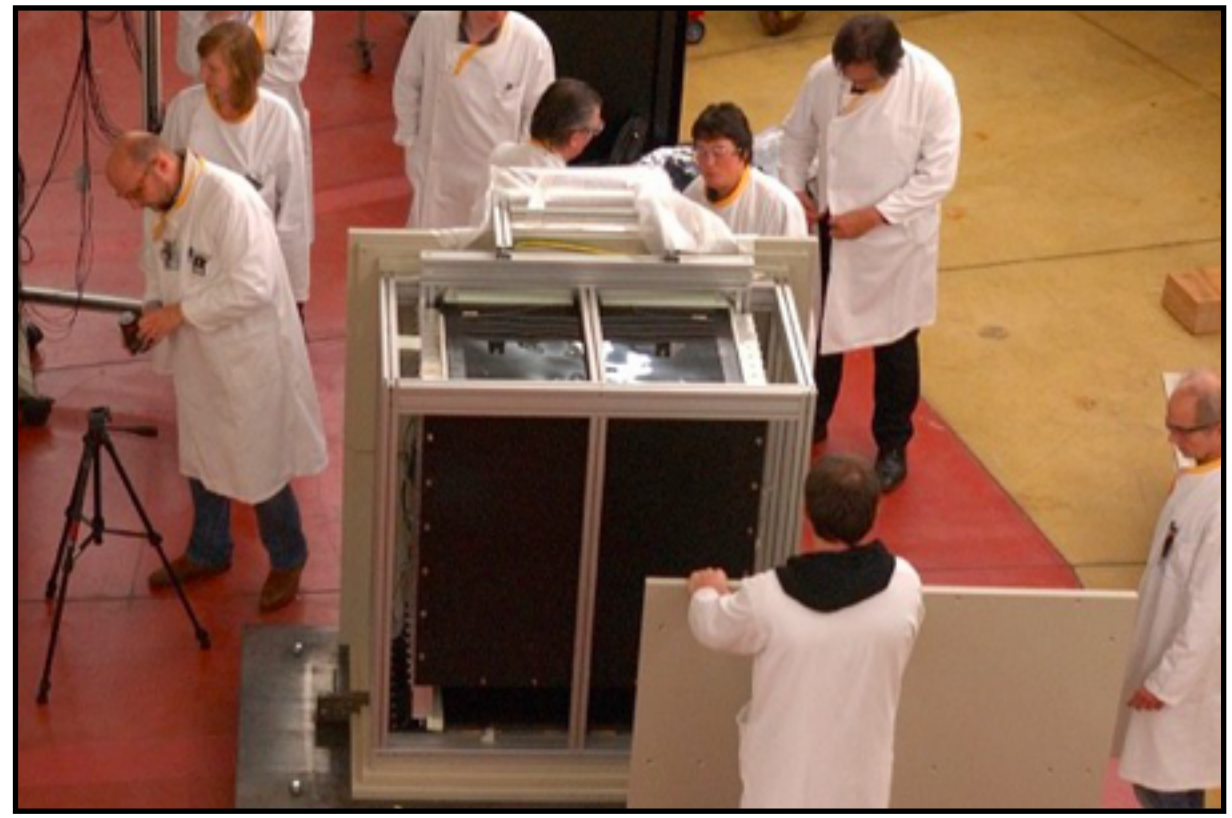
Plane Diagram



Plane Assembly

Prototype SoLid Module 1 (SM1)

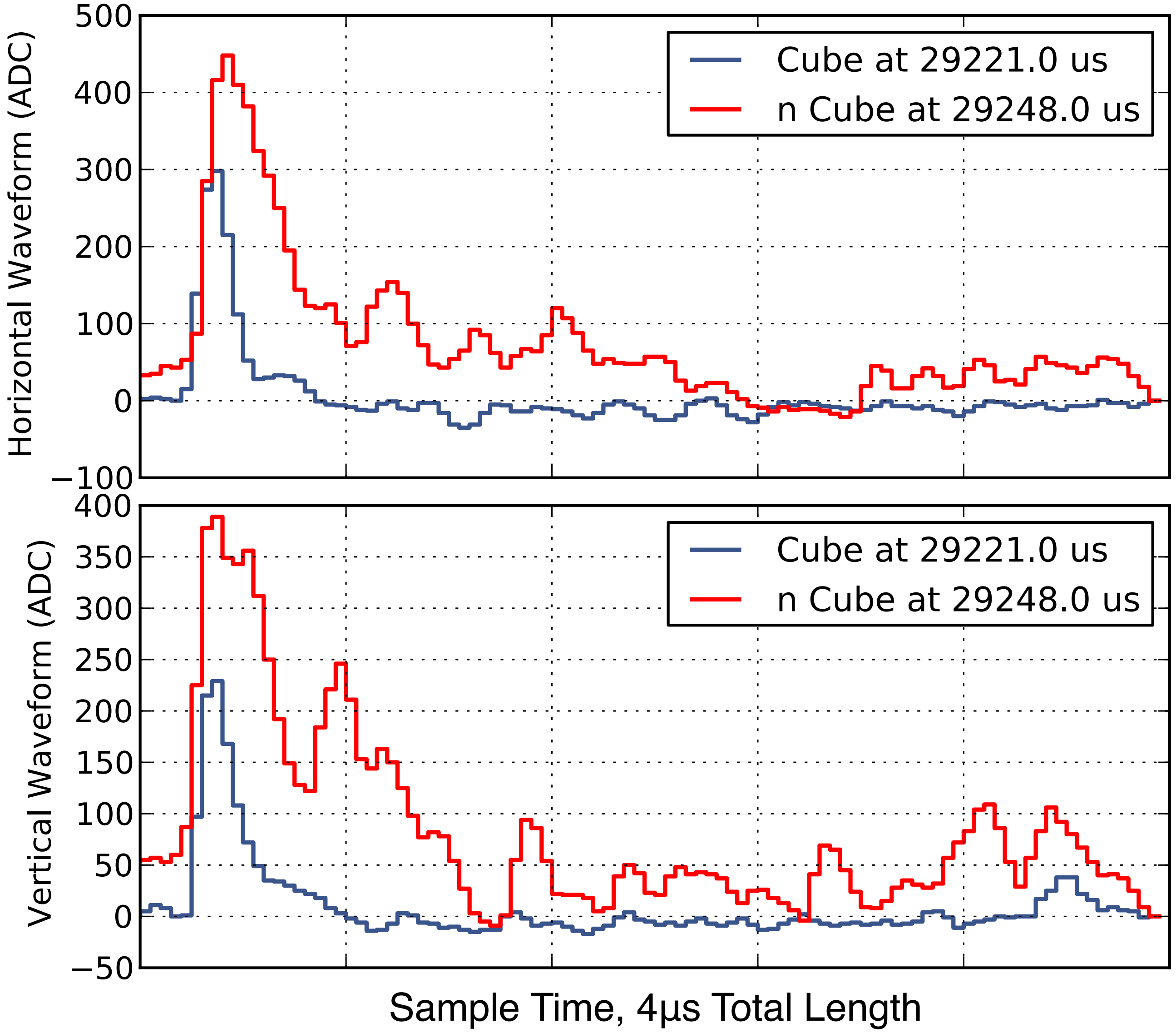

Commissioning at Gent, Nov 2014


Deployment at BR2, Dec 2014

- 50hr reactor on run. Long reactor off and source calibration runs.
- Simple trigger and no passive shielding: statistically limited to see ν_e signal.

Prototype Results

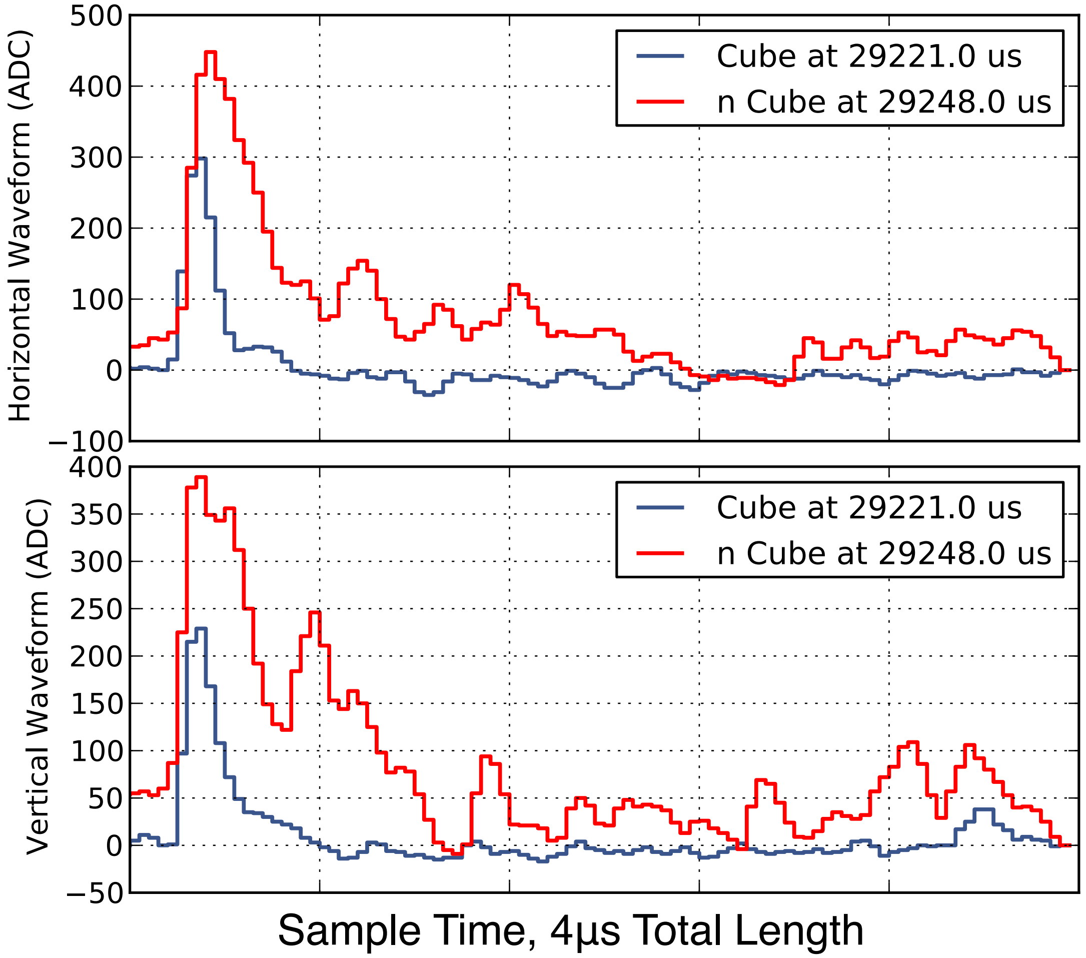
Neutron Identification

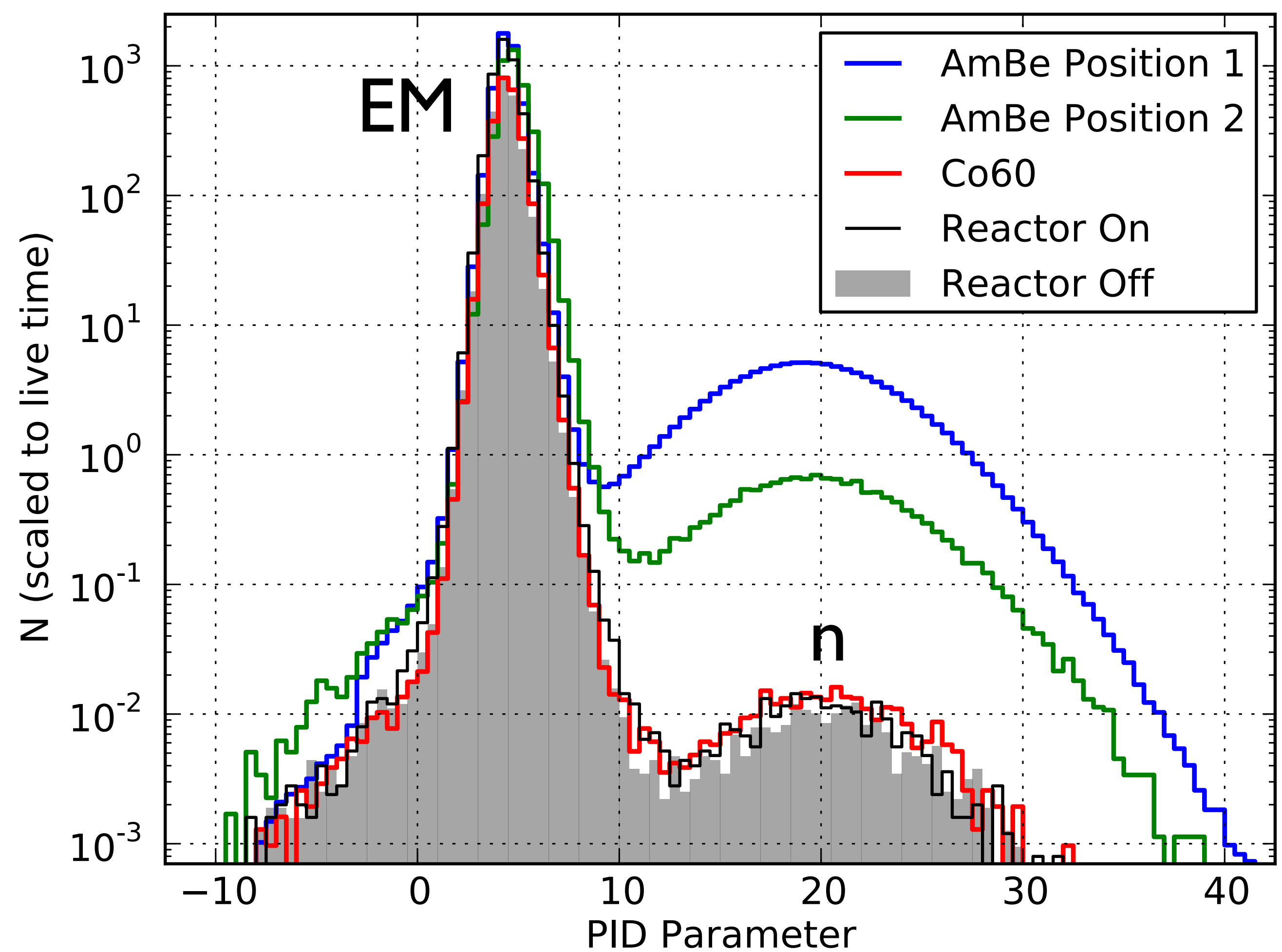


*Example IBD candidate SiPM waveforms - **Data***
EM signal** and **Neutrons

- Prototype module used a simple trigger design for all signals:
    - Threshold trigger with co-incidence between vertical and horizontal fibre.
- 256 samples of written to disk for SiPMs above trigger threshold.

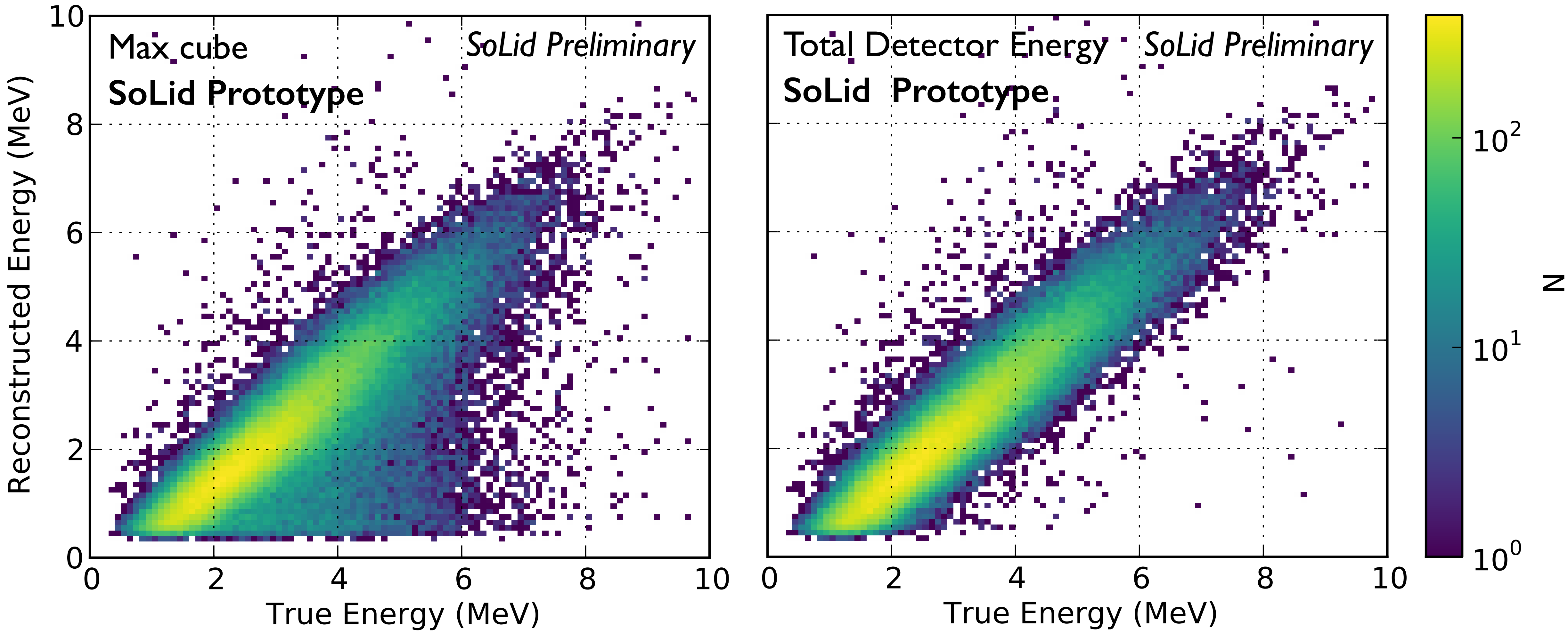
Neutron Identification





- Pulse shape discrimination algorithms developed (e.g. ratio of integral to amplitude)
  - Source runs demonstrate good population separation, despite large background environments.
- Neutrons well separated despite enormous EM background.

Positrons Reconstruction

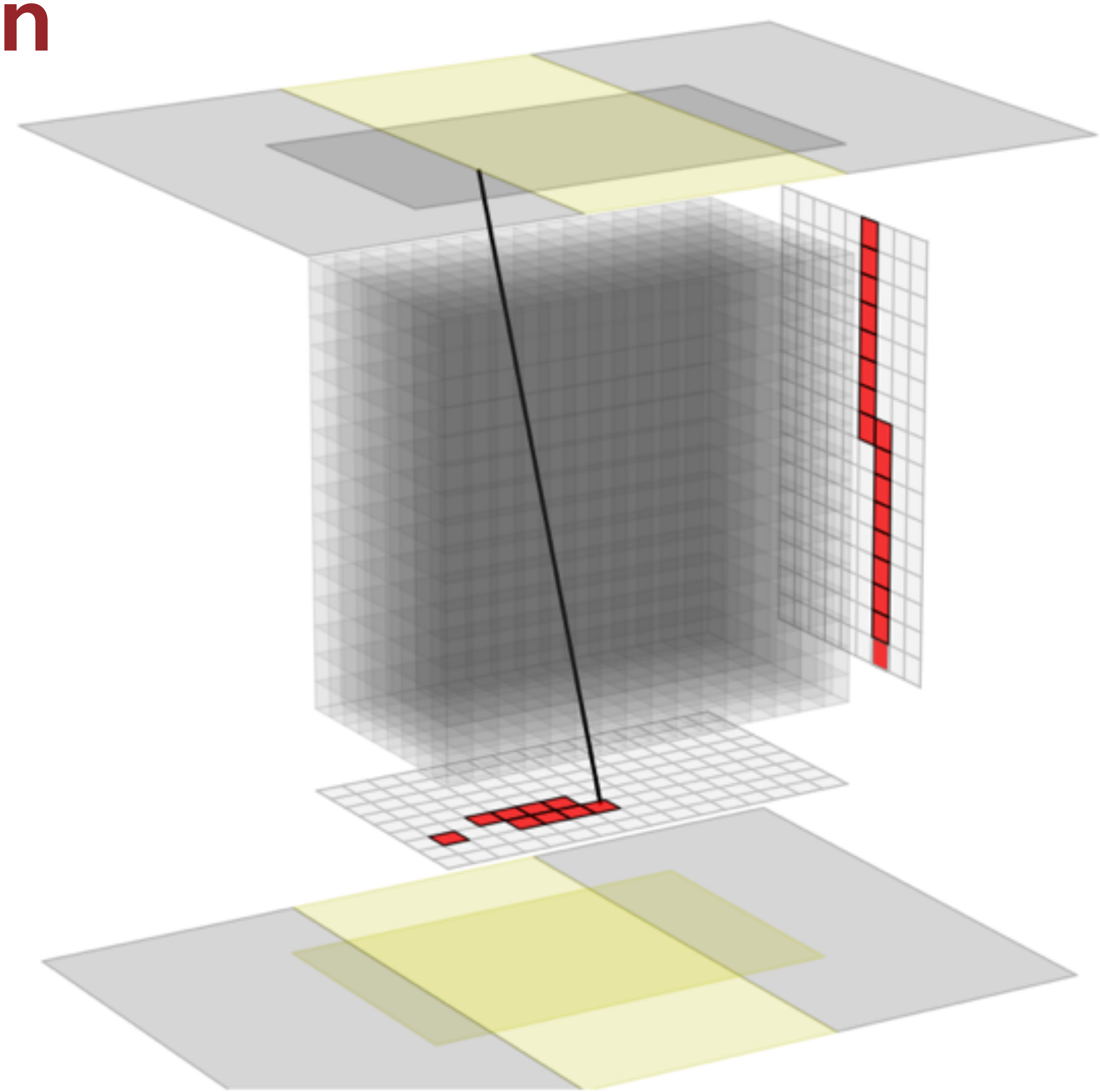


*Positron reconstruction algorithm comparison for SM1 configuration - **Sim.** Readout effects included*

- Demonstration of positron energy reconstruction algorithms:
  - Nb negligible γ detection efficiency for SM1.

Muon Identification

- Effective muon identification is critical for SoLid:
  - Source of IBD backgrounds.
  - Useful for commissioning and calibration studies.
- Can be identified by:
  - Large energy deposits.
  - High channel multiplicity.
  - Position in detector.



Muon event display

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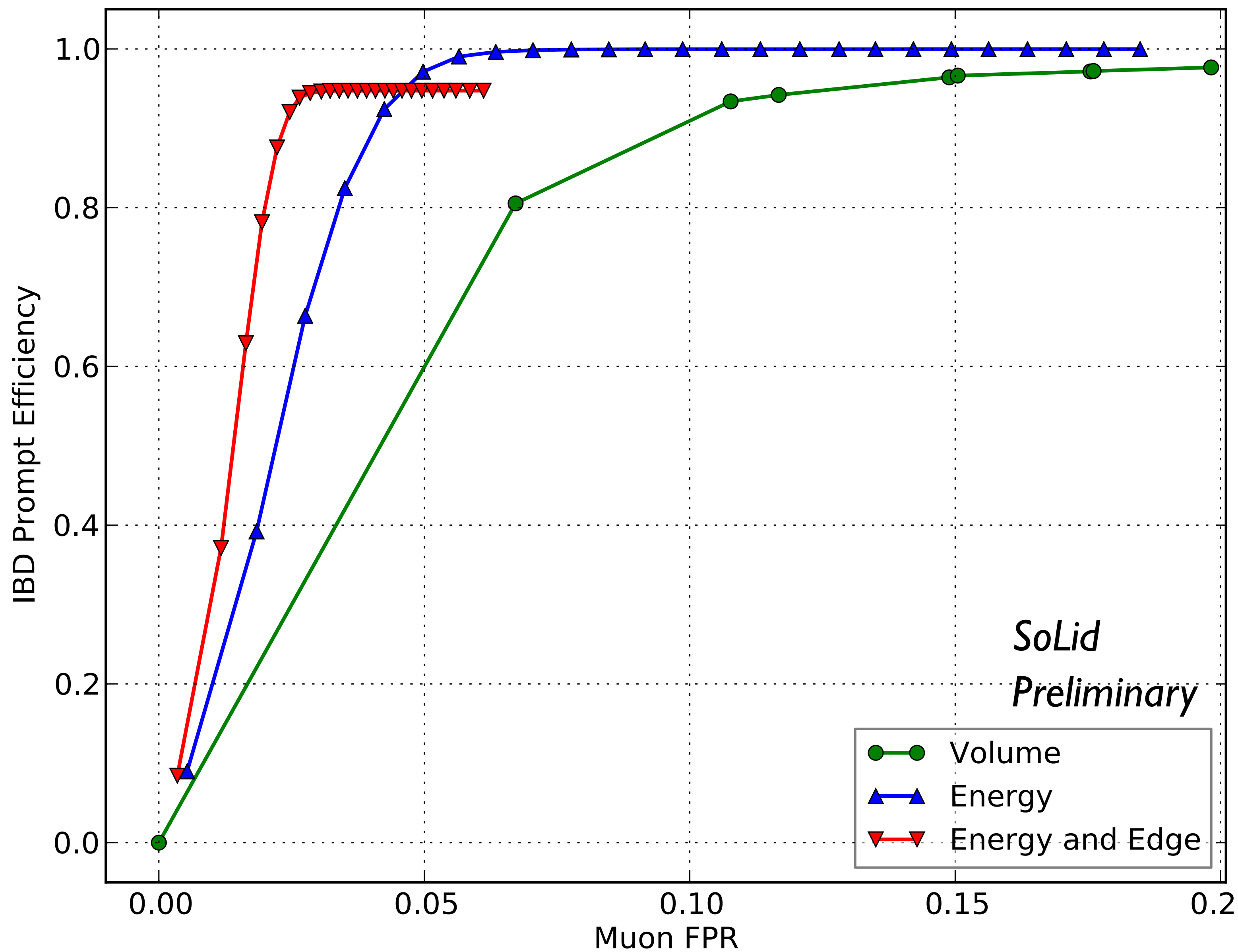
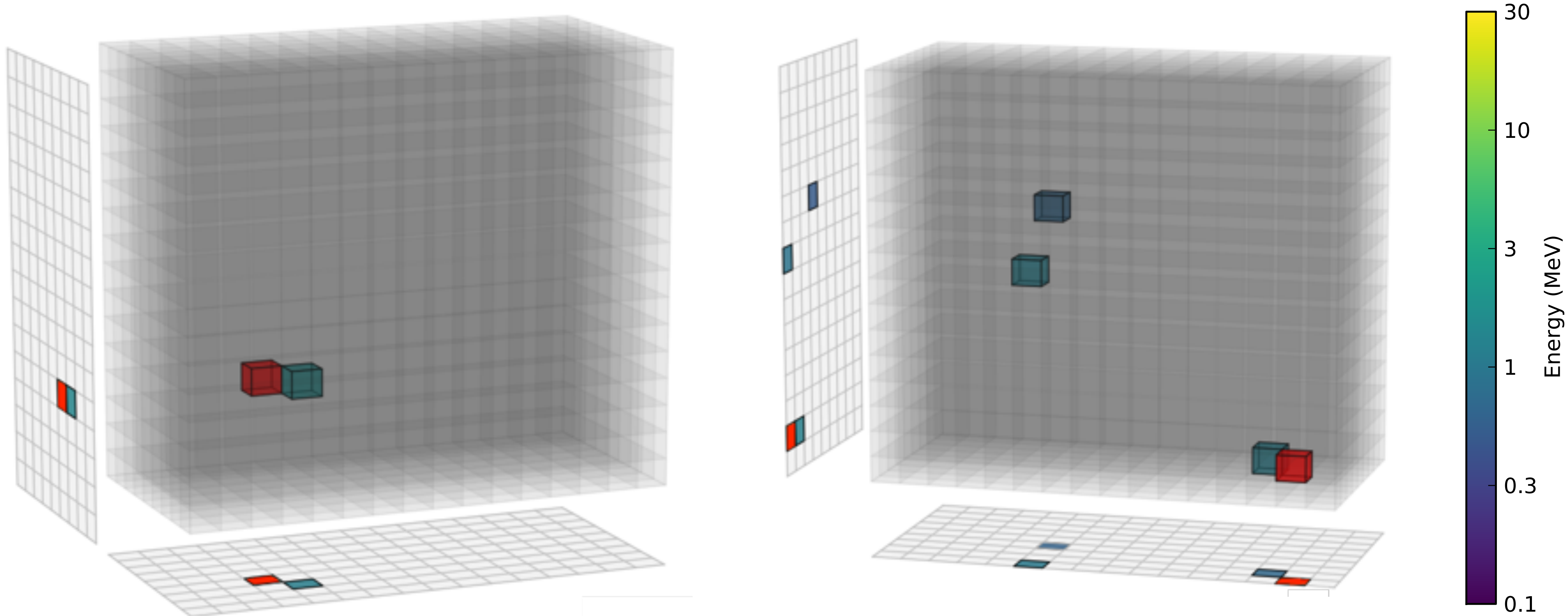


ROC curves demonstrating positron-muon separation.

Neutrino Candidates

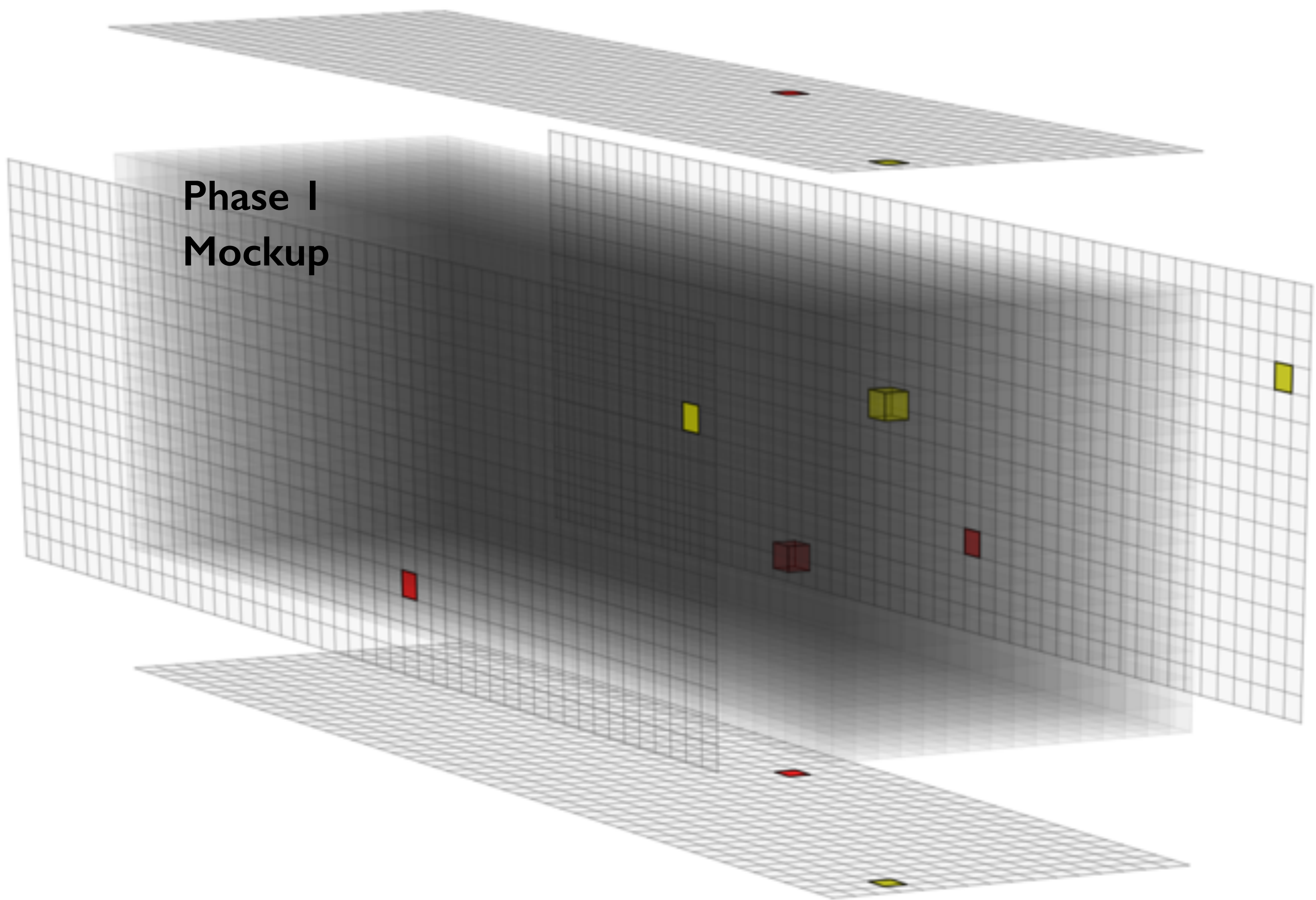
- Inverse beta decay (IBD) analysis techniques developed.
- Granularity of the detector allows detailed topological studies.



IBD candidates from SM1. Neutrons in ***red****, EM signals use colour scale*
Left: isolated candidate (waveforms above). Right: candidate with accidental gammas - can be used in analysis

Backgrounds - Accidental

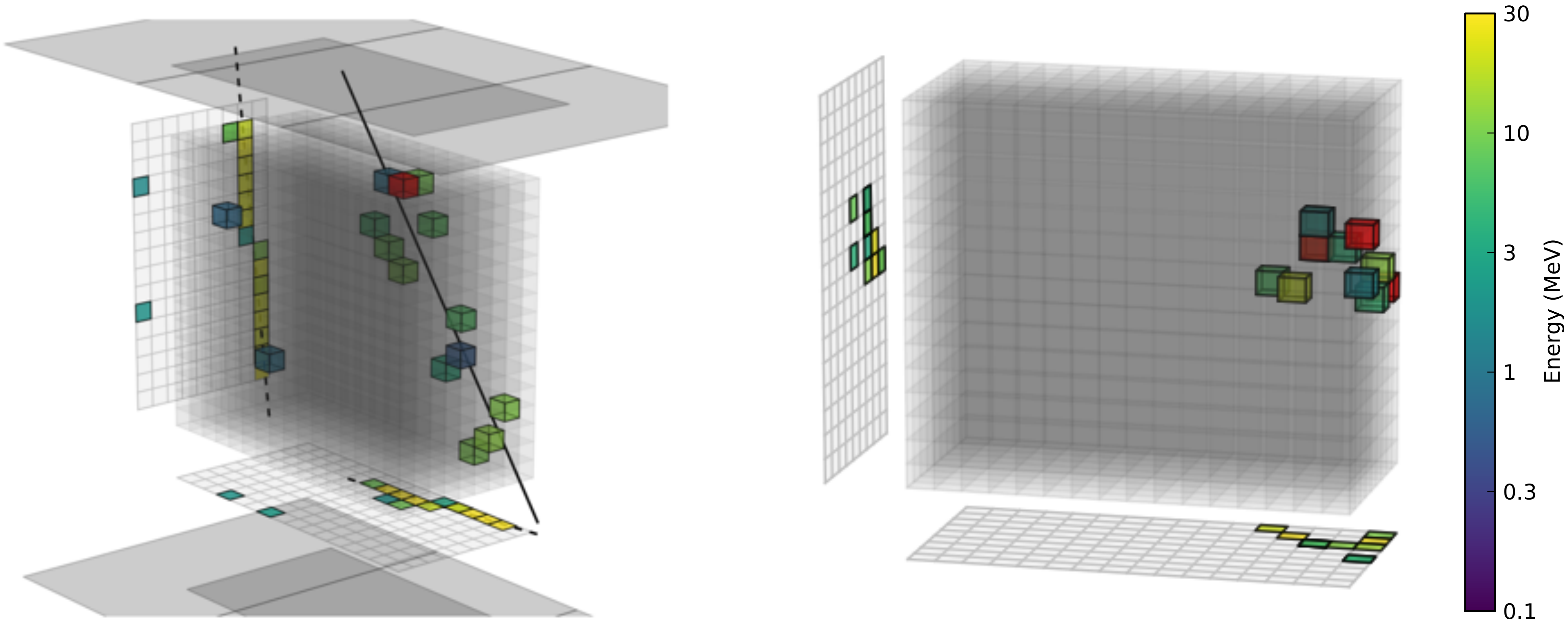
- Random EM event (e.g. reactor ɣ) associated to a random neutron (e.g. reactor neutron).
- Studied using off-time windows (reactor on and reactor off separately).
- Combated with topology and energy selections.



Accidental Background candidates example using phase I configuration

Backgrounds - Correlated

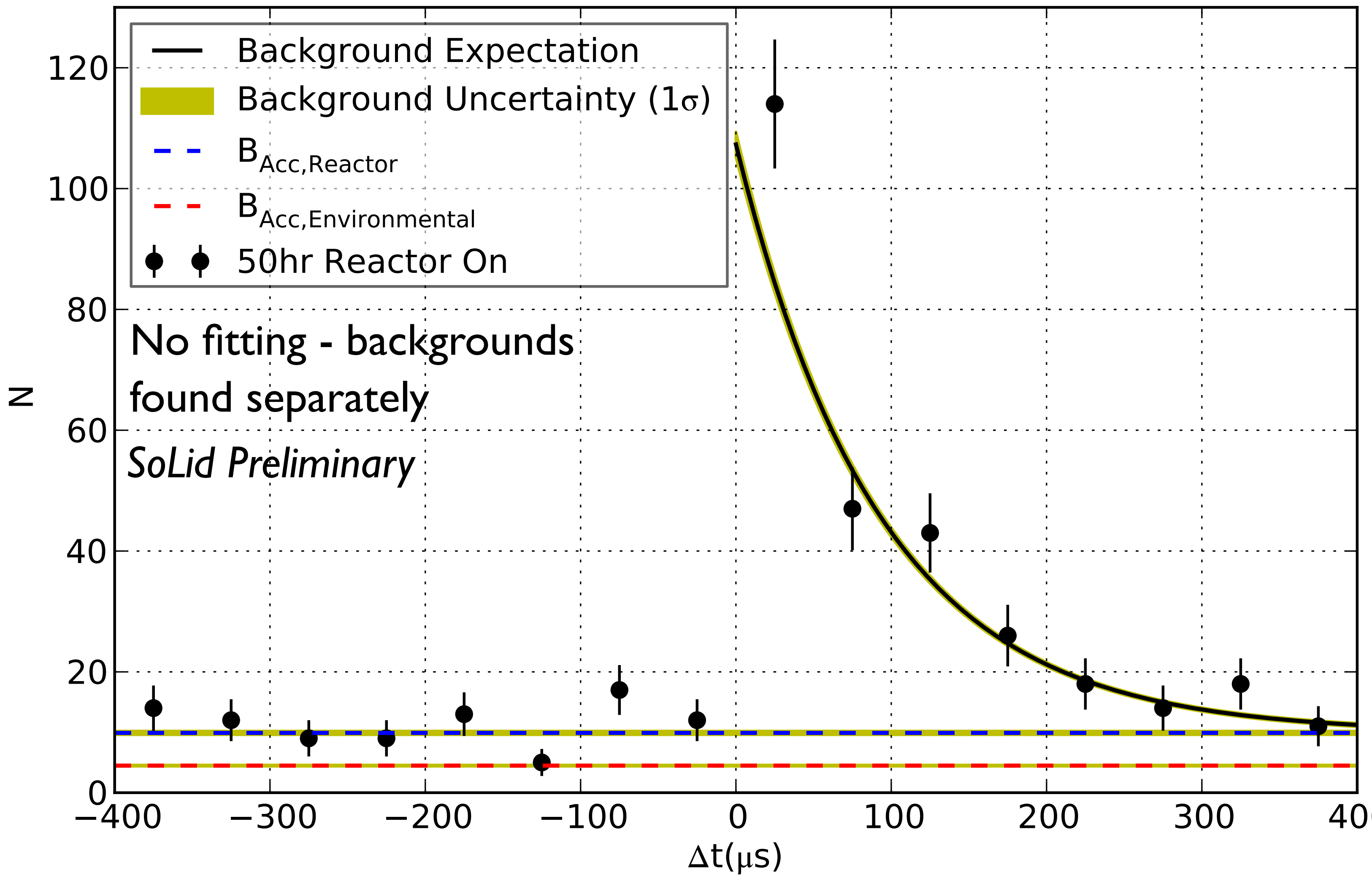
- EM event and neutron produced in same process. Studied using reactor off data, e.g:
  - Muon spallation in the detector - combat with muon ID.
  - High energy neutron - combat with multiplicity selections against proton recoils.



*Background candidates. Neutrons in **red**, EM signals use colour scale.*
*Left: muon spallation event **(Data)**. Right: cosmic neutron event **(Sim)**.*

IBD Features

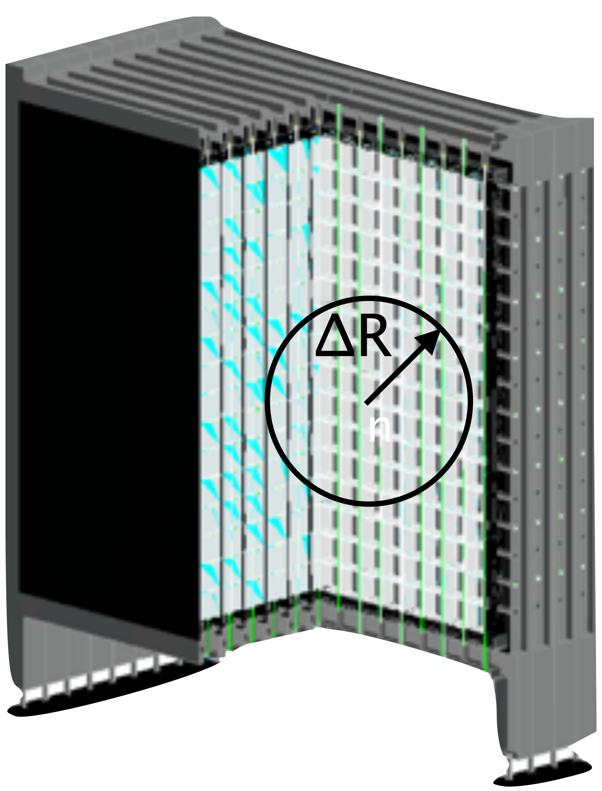
- Reconstruction parameters for each IBD:
    - $\Delta t = t_{Prompt} - t_{Delayed}$

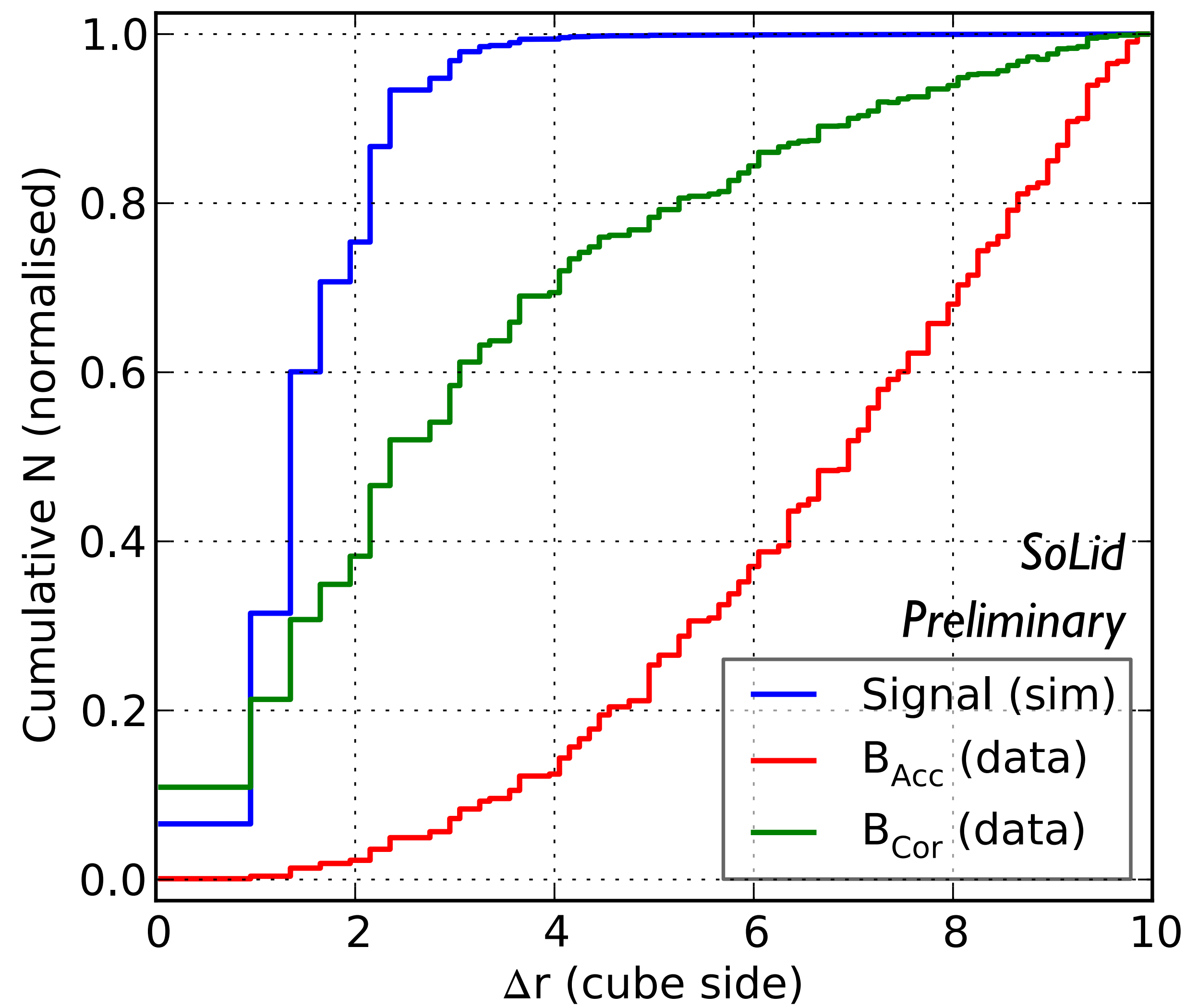


Reactor on-off comparison for time separation between prompt and delayed events. Background components shown (data driven)

IBD Features

- Reconstruction parameters for each IBD:
  - $\Delta t = t_{Prompt} - t_{Delayed}$
  - $\Delta r = | \underline{r}_{Prompt} - \underline{r}_{Delayed} |$

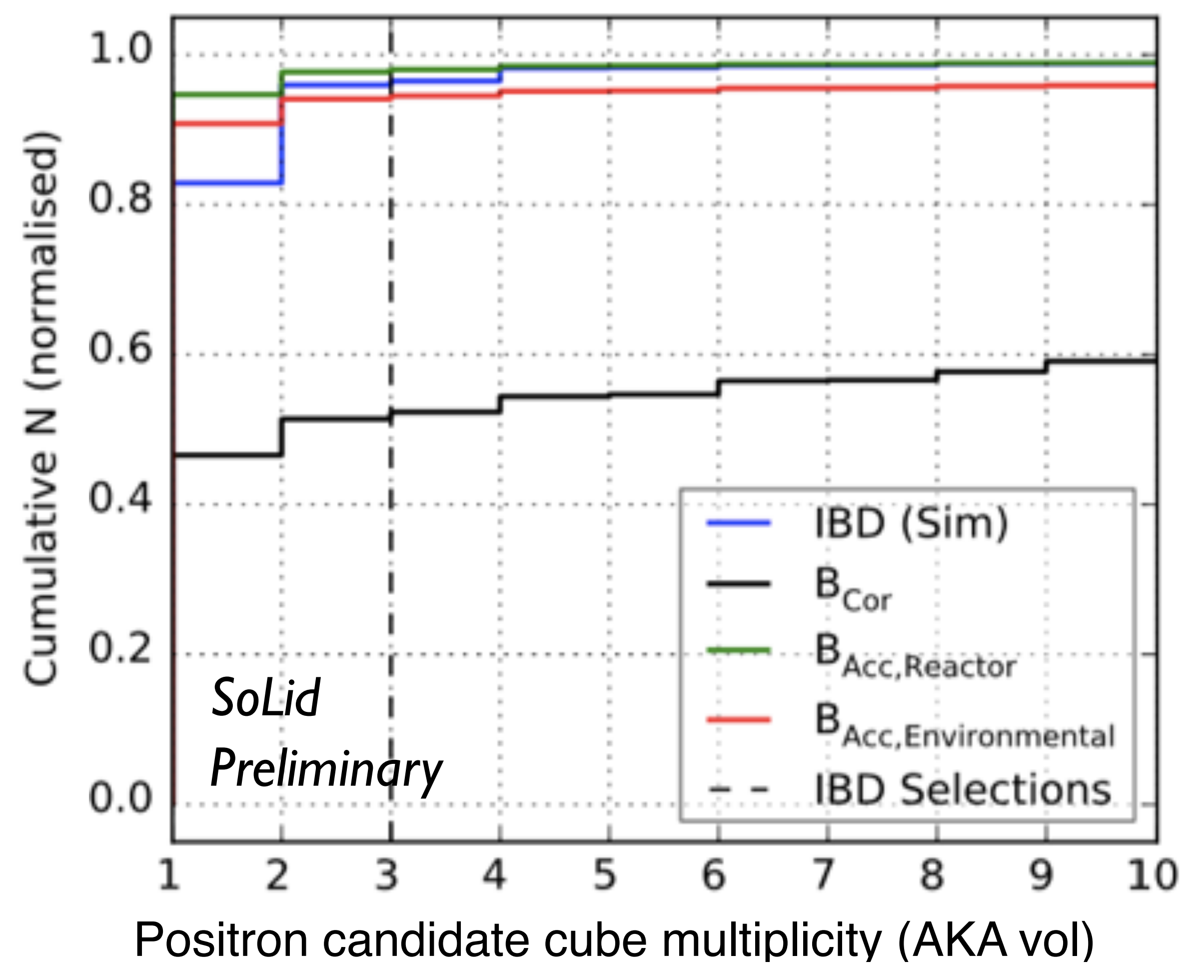


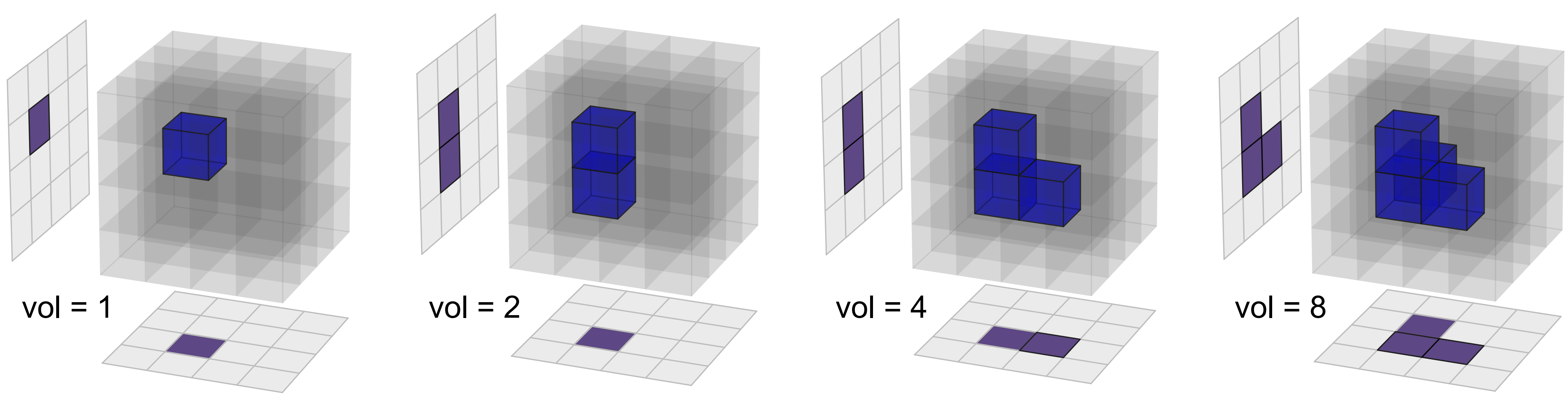


Radial separation between prompt and delayed events for signal and background IBD candidates

IBD Features

- Reconstruction parameters for each IBD:
  - $\Delta t = t_{Prompt} - t_{Delayed}$
  - $\Delta r = | \underline{r}_{Prompt} - \underline{r}_{Delayed} |$
  - Positron multiplicity

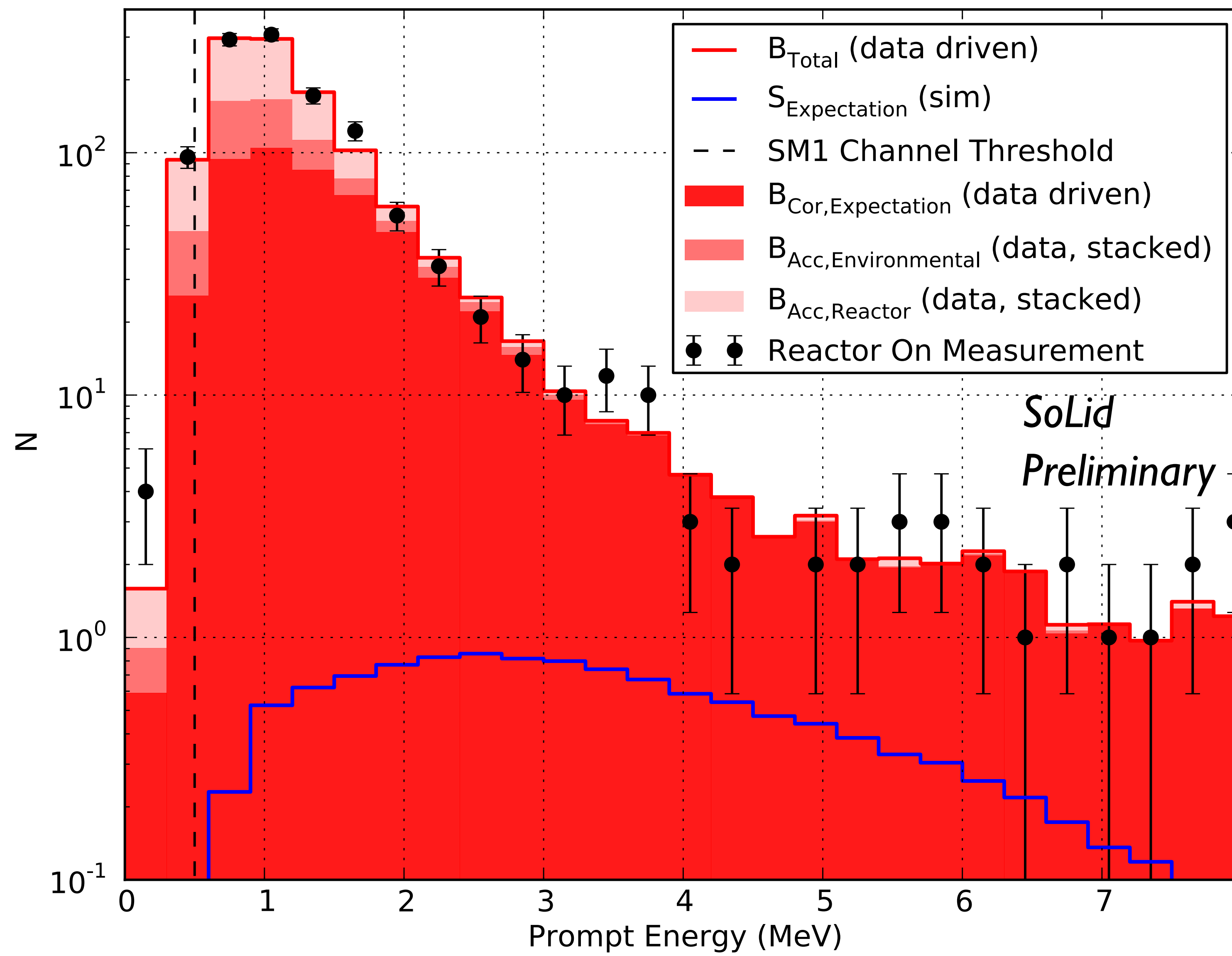




IBD Features

- Reconstruction parameters for each IBD:
  - $\Delta t = t_{Prompt} - t_{Delayed}$
  - $\Delta r = | \underline{r}_{Prompt} - \underline{r}_{Delayed} |$
  - Positron multiplicity
  - Positron energy

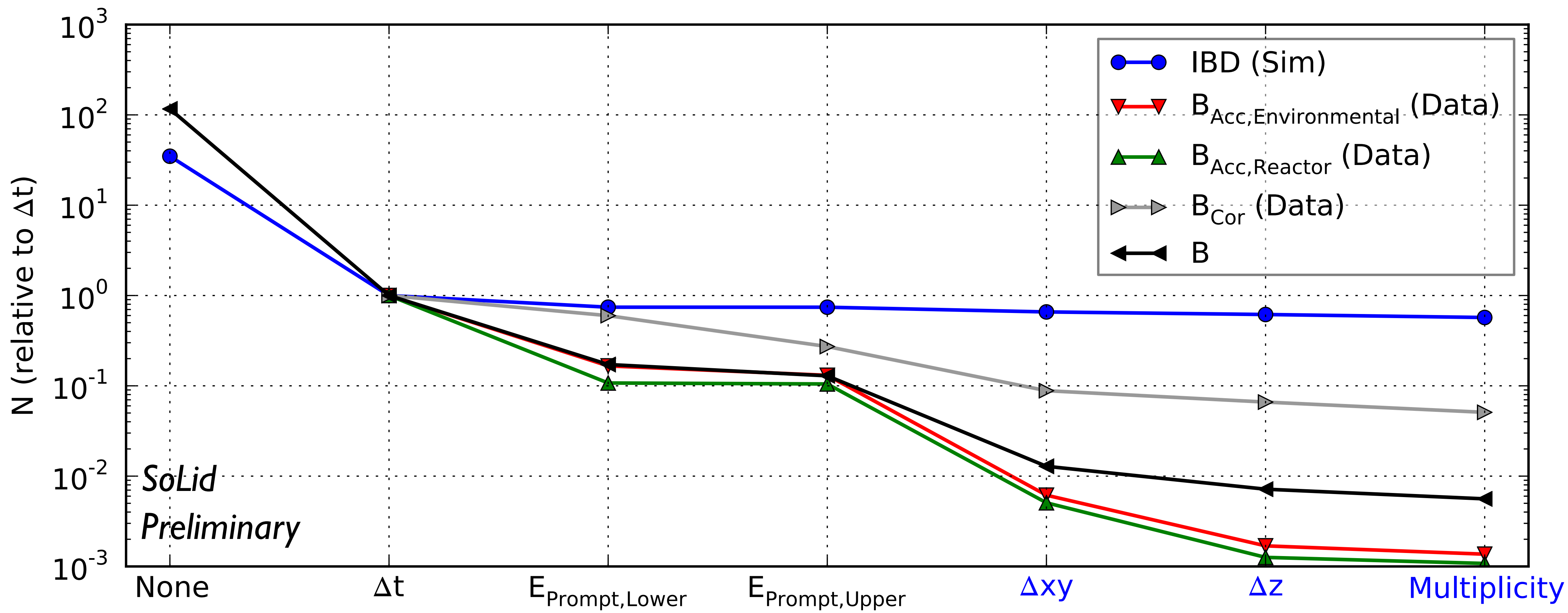
- Good agreement between reactor on data and expectation:
  - Validation of background understanding.



Reactor on-off comparison of prompt energies

Signal Selection

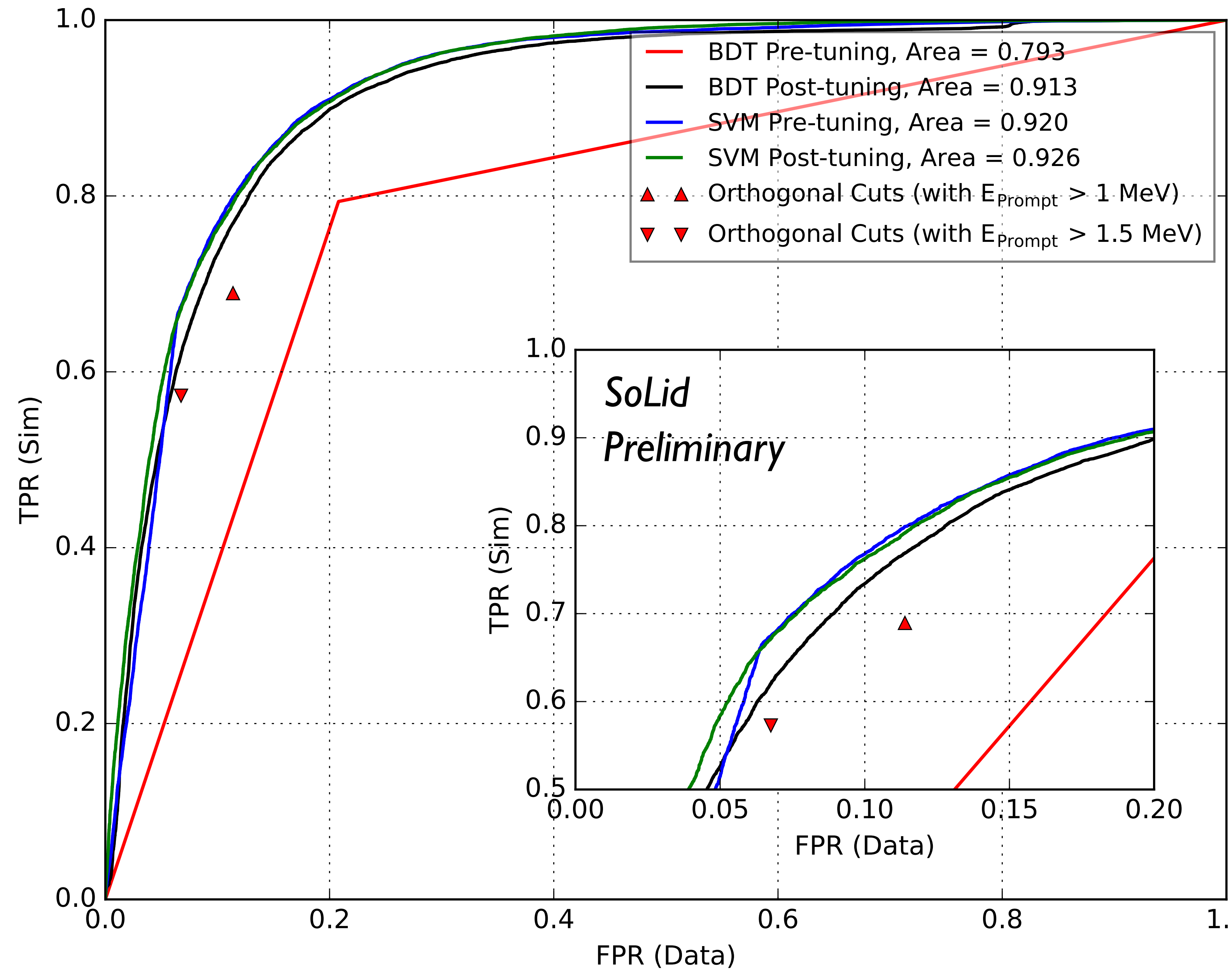
- S:N critical in sterile search:
- Cut based analysis shows significant reductions in backgrounds:



- **Segmentation** provides many handles for tackling backgrounds:
  - Spatial separation, directionality, multiplicity.

Signal Selection

- Beginning to explore machine learning analysis techniques:
    - Likelihood discriminators and SVM.
- Initial results show further factor ~1.5 reduction in background rate.
- Starting to also look at deep learning methods (e.g. tensor flow) for PID and IBD selections.



ROC curves for various MVA techniques (scikit learn). Reactor off dataset used for training.

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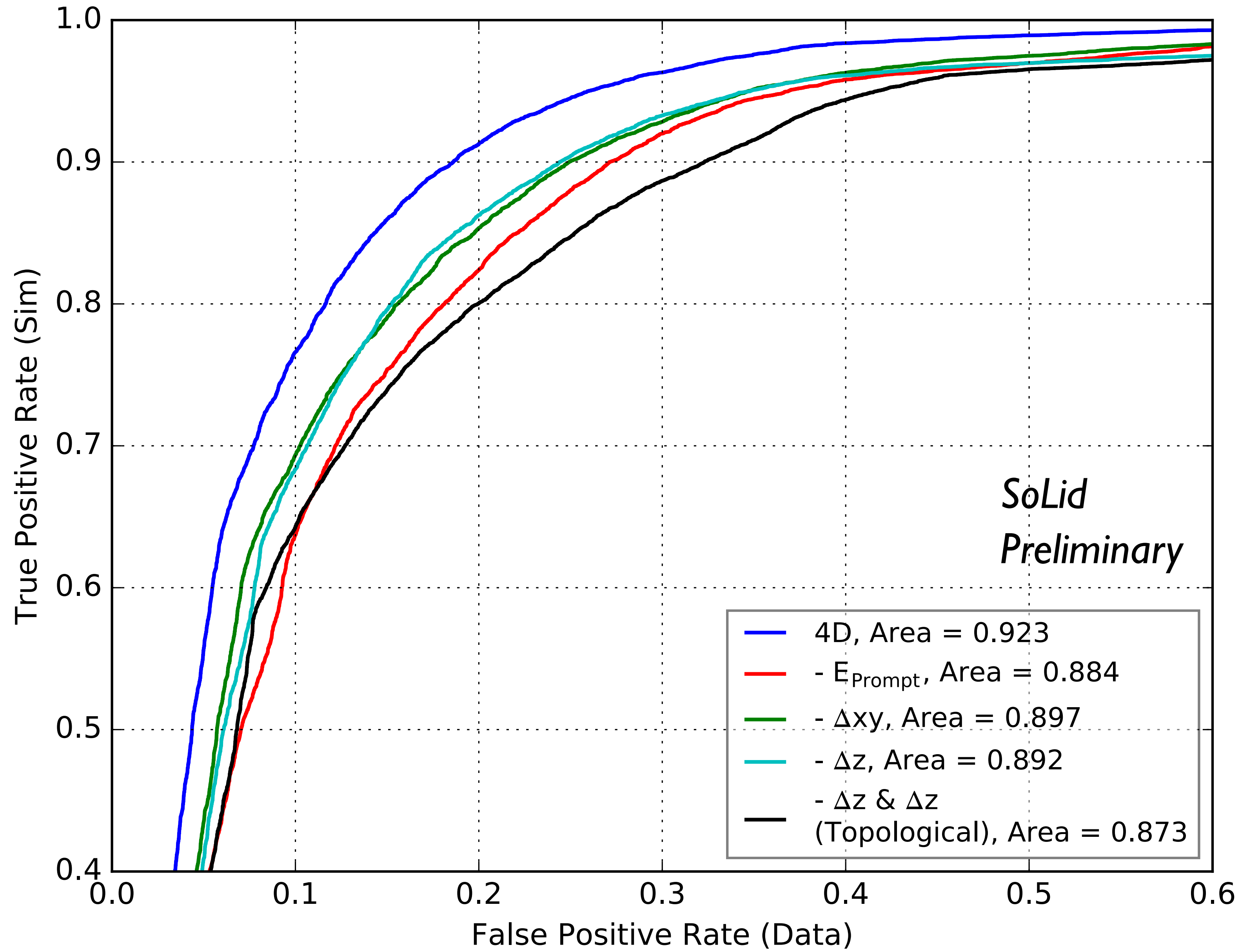
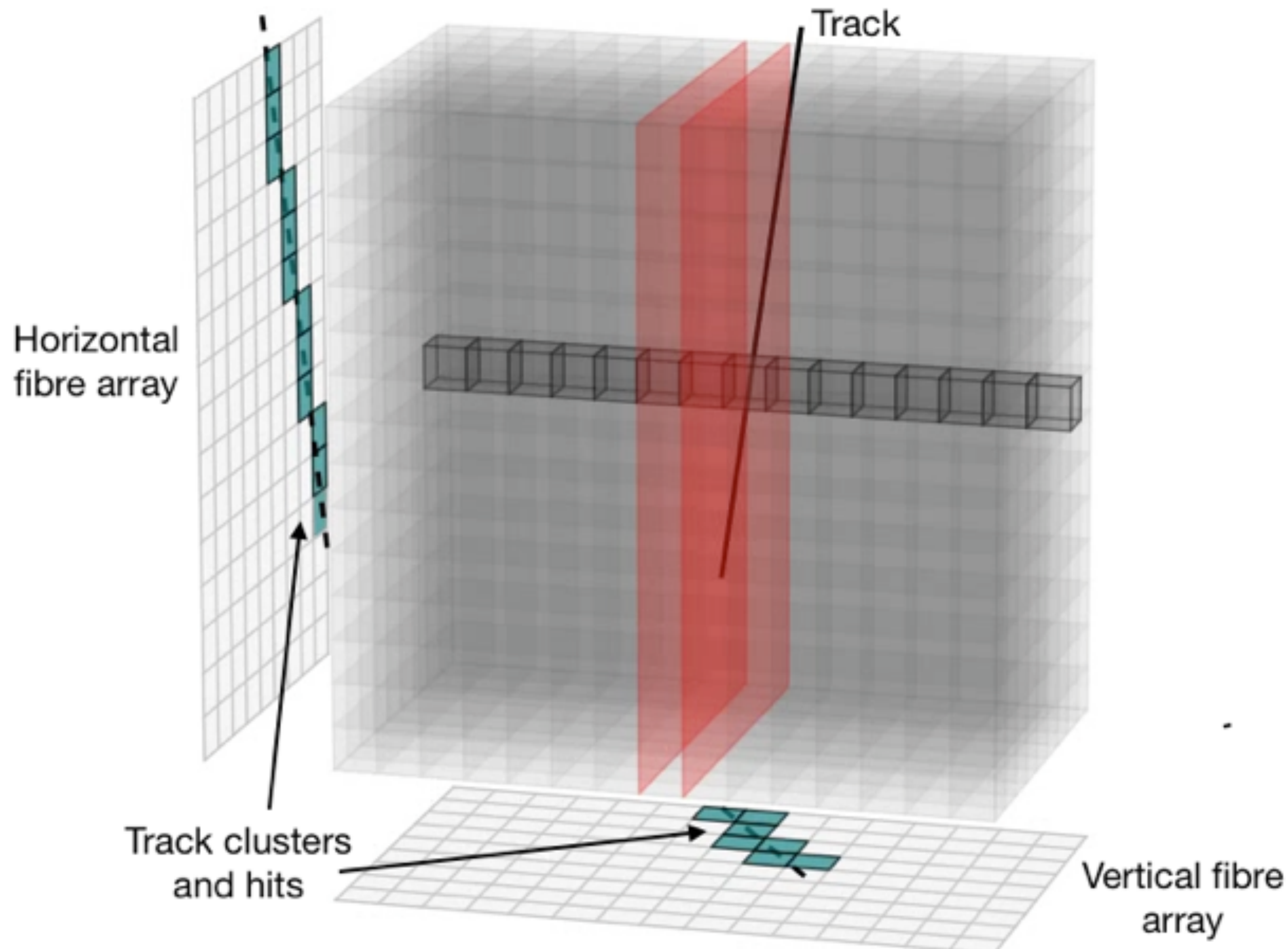
- Starting to also look at deep learning methods (e.g. tensor flow) for PID and IBD selections.



ROC curves using SVM technique, popping different training features. Topology is the most effective.

Muon Energy Calibration

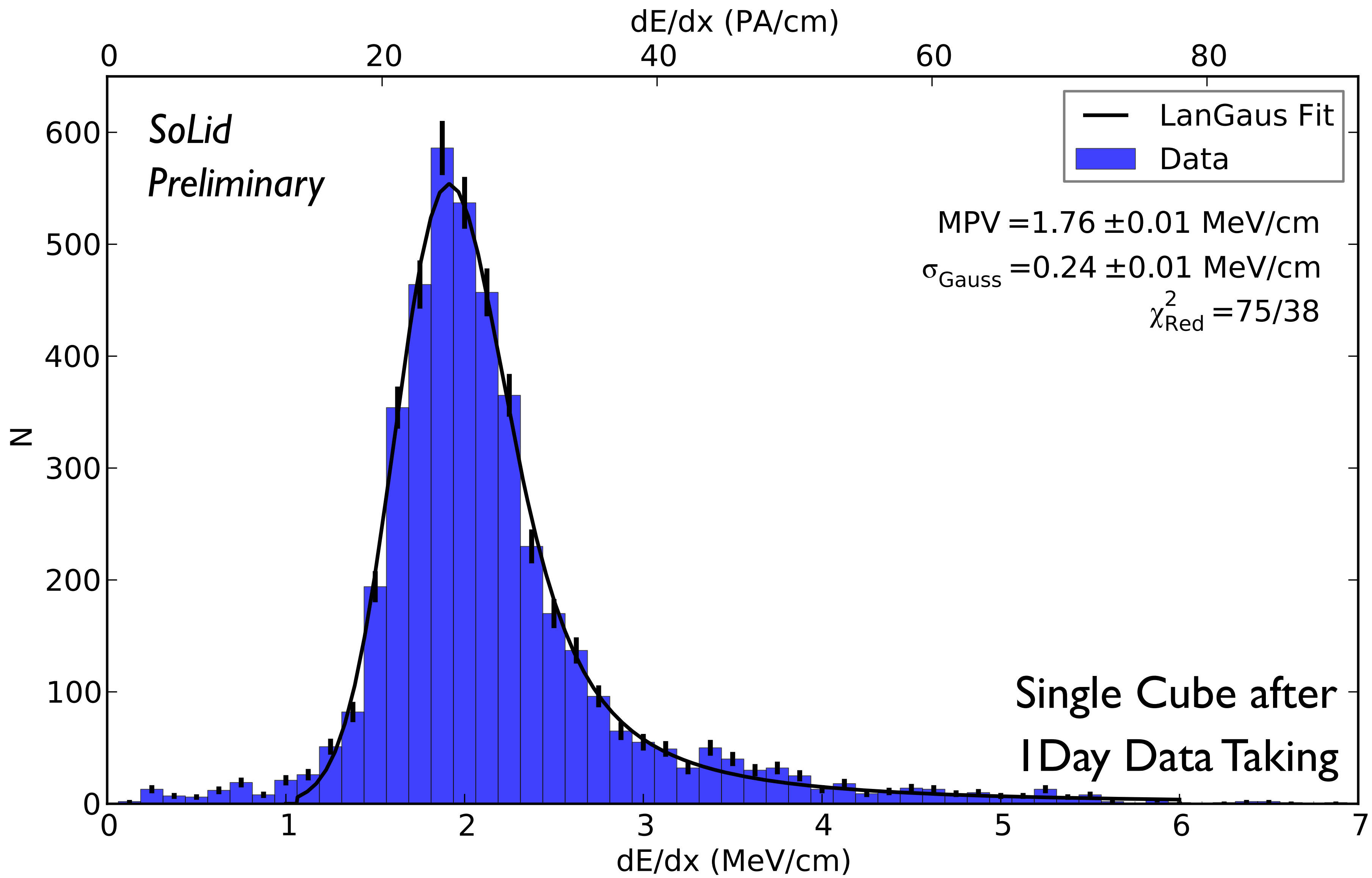
- Muons are not only a source of background - can be used for calibration.
- With tracking algorithms and geometrical selections, can find dE/dx distribution for each cube.
- Can be used to extract absolute scale and perform cube equalisation.



Muon calibration example event

Muon Energy Calibration

- Can be used to extract absolute scale and perform cube equalisation:



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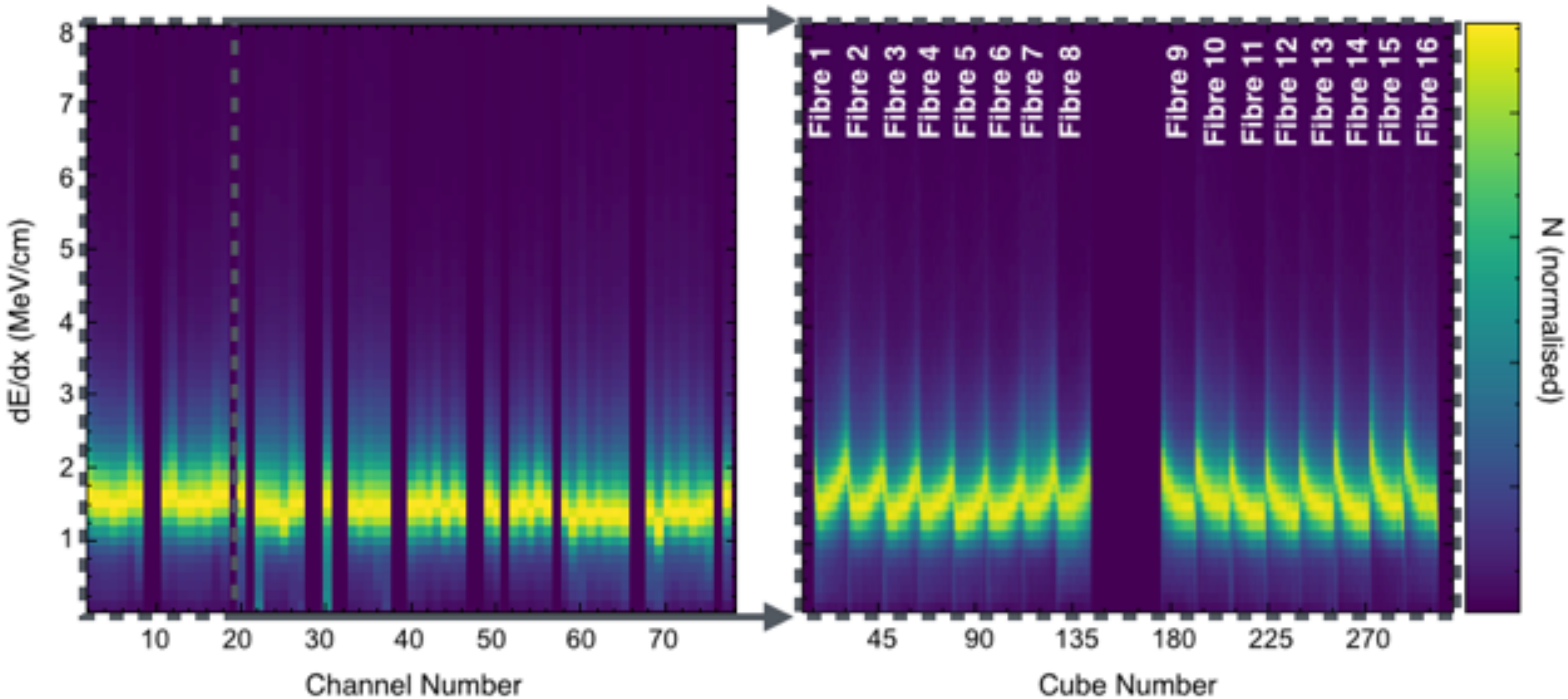
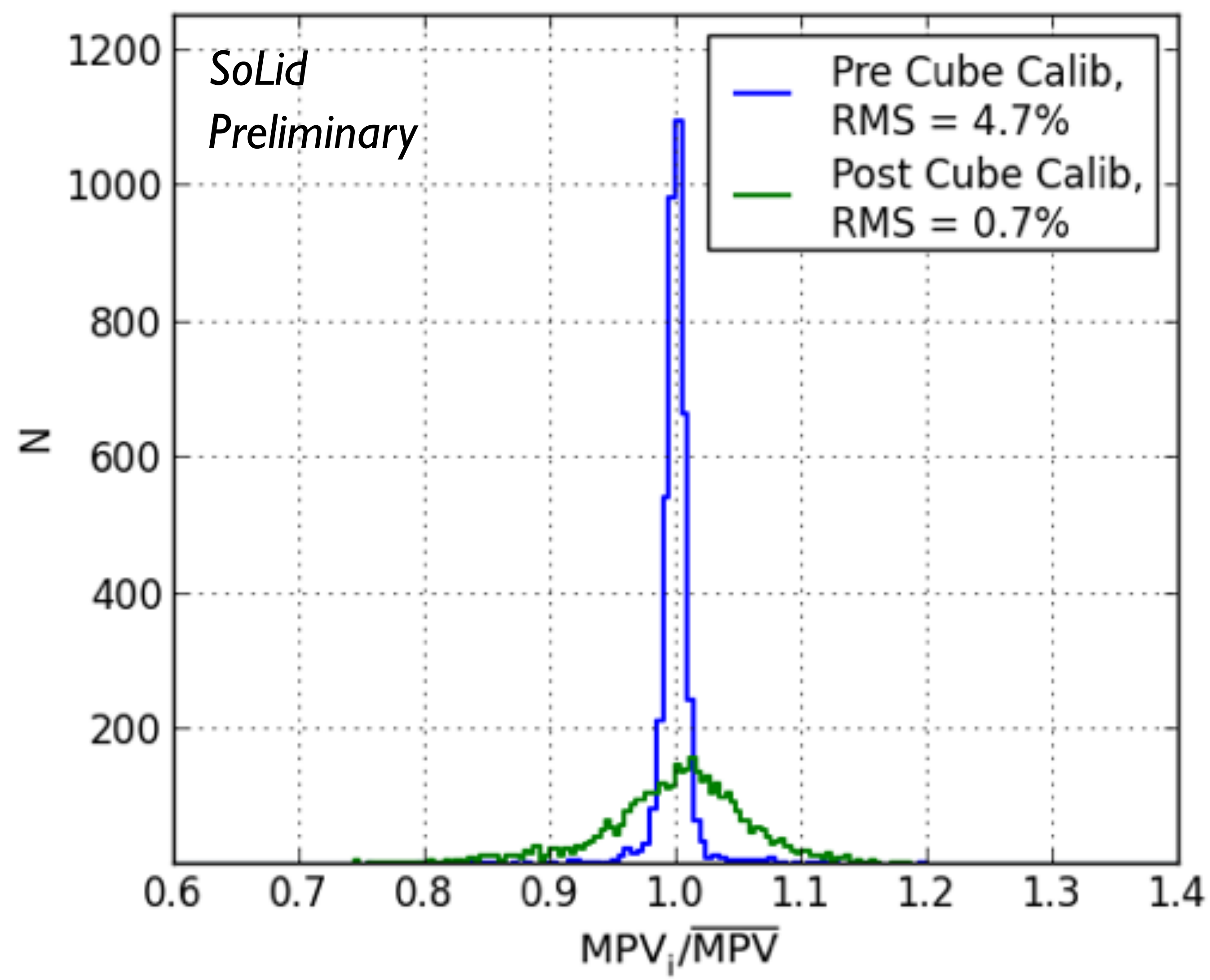


dE/dx as a function of position along multiple fibres

Muon Energy Calibration

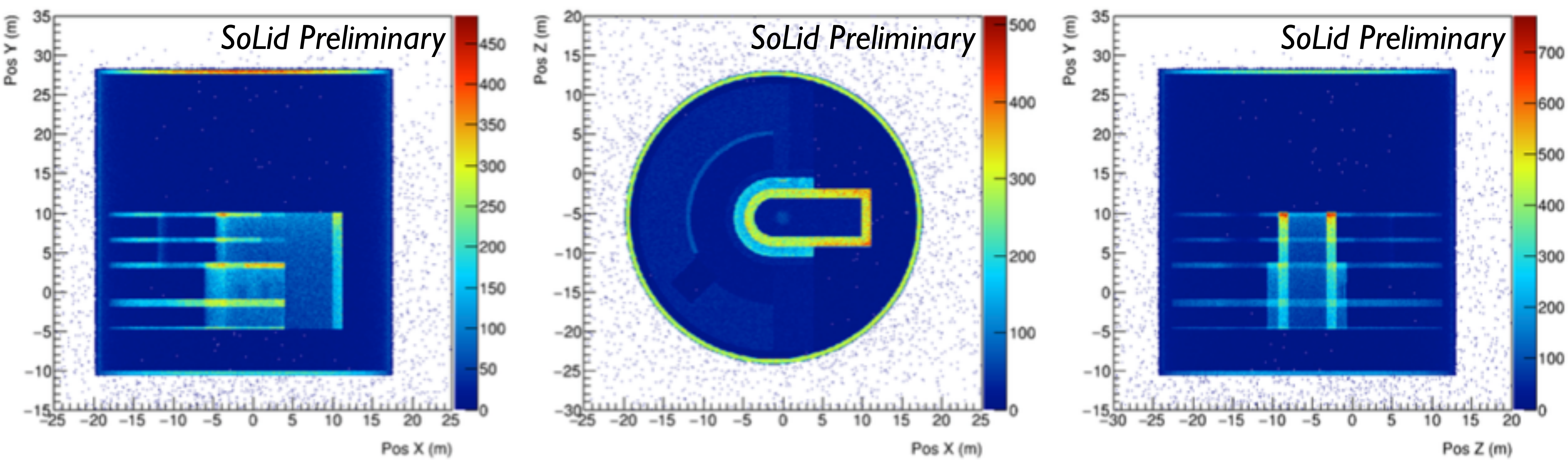
- Cube equalisation can be achieved to the ~1% level.
- Absolute energy scale measured to the ~5% level.



Simulations

- Full cosmic simulation of BR2 reactor environment (geometry, detector, shielding etc)
  - Multiple generators: Guang, Cry, Gordon

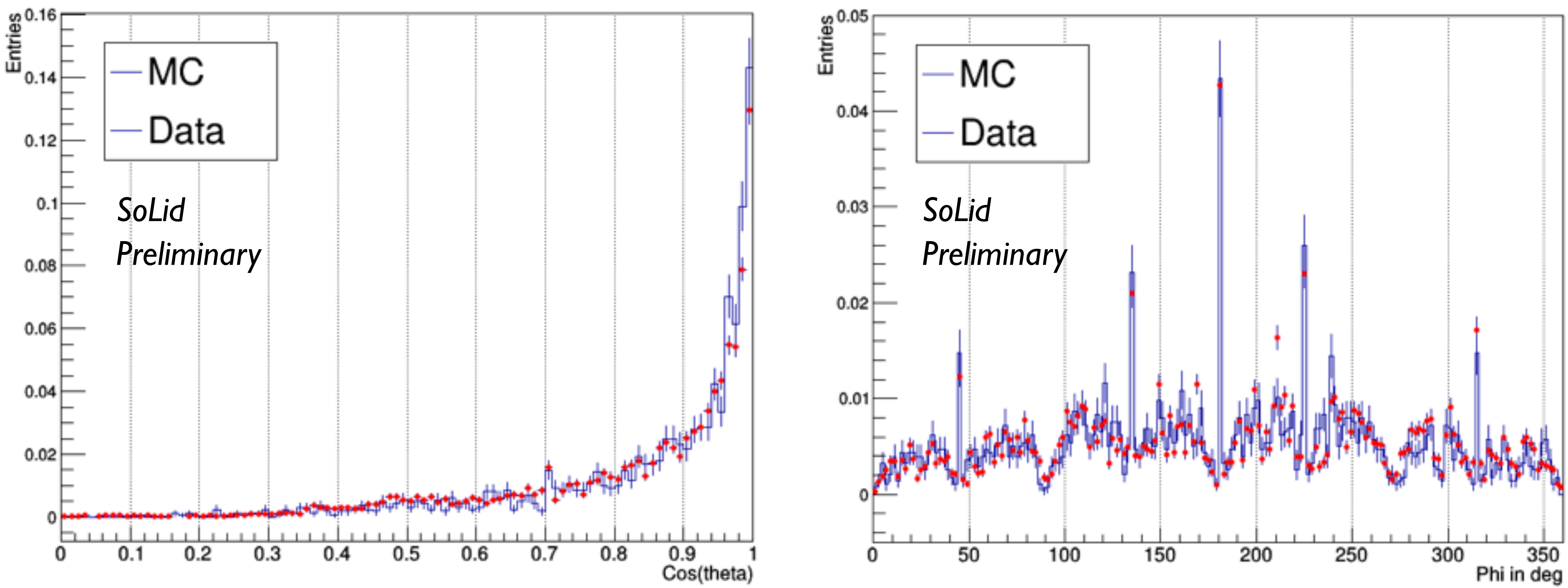
- Neutron transport validated using G4 and MCNP - agreement ~2%.
- Good agreement between sim and prototype data → key SM1 results:
  - Background shapes, neutron capture time, muon angular distributions etc.



Cosmic simulation of the BR2 reactor hall - example showing muon induced neutron production locations

Muon Angular Distributions

- Excellent agreement between cosmic track angle distribution sim and data.
- Sensitive to building geometry.
- *(Spikes due to discretised detector)*

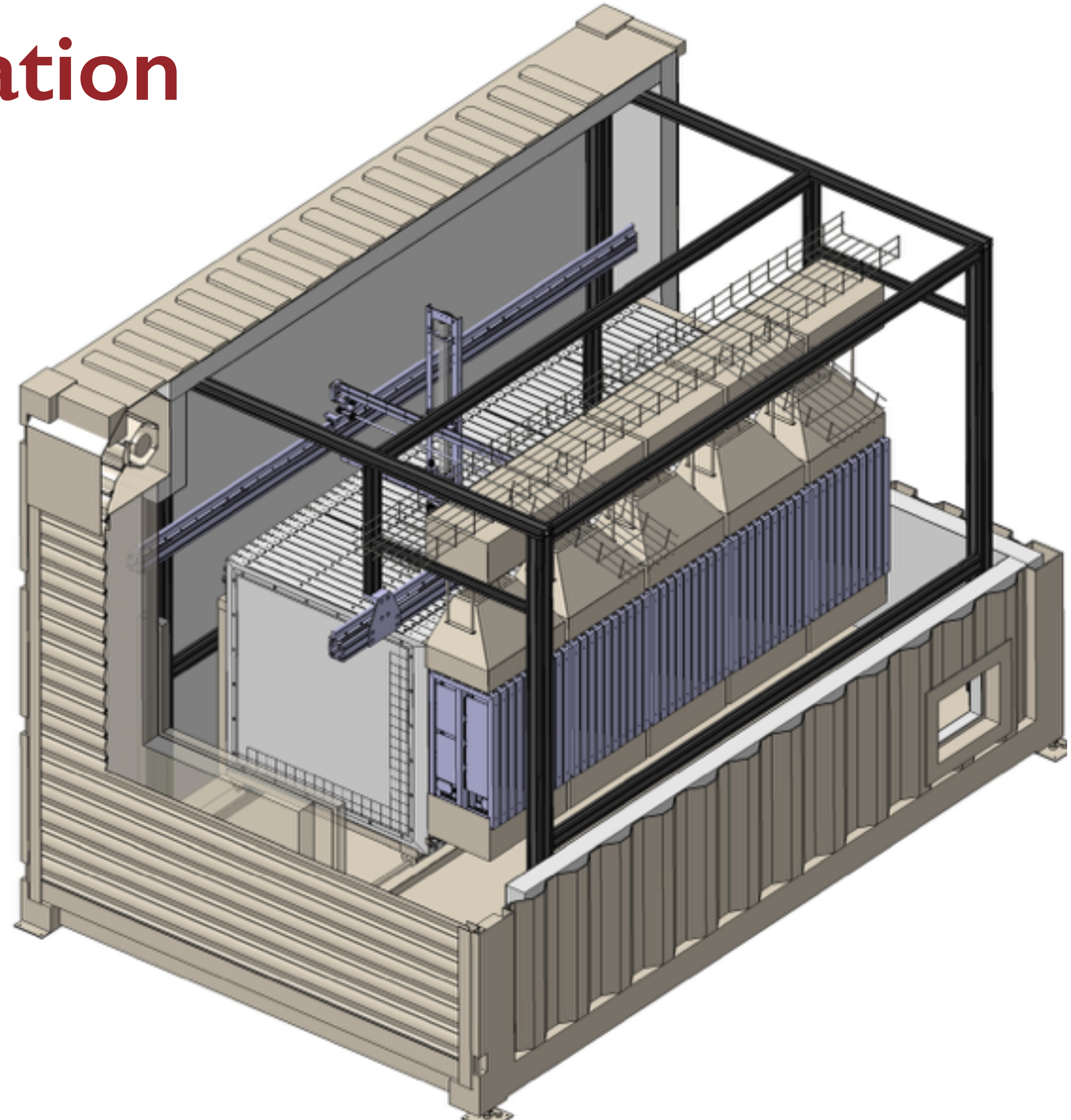


Sim-data comparison for track angular distribution

Phase I Preparations

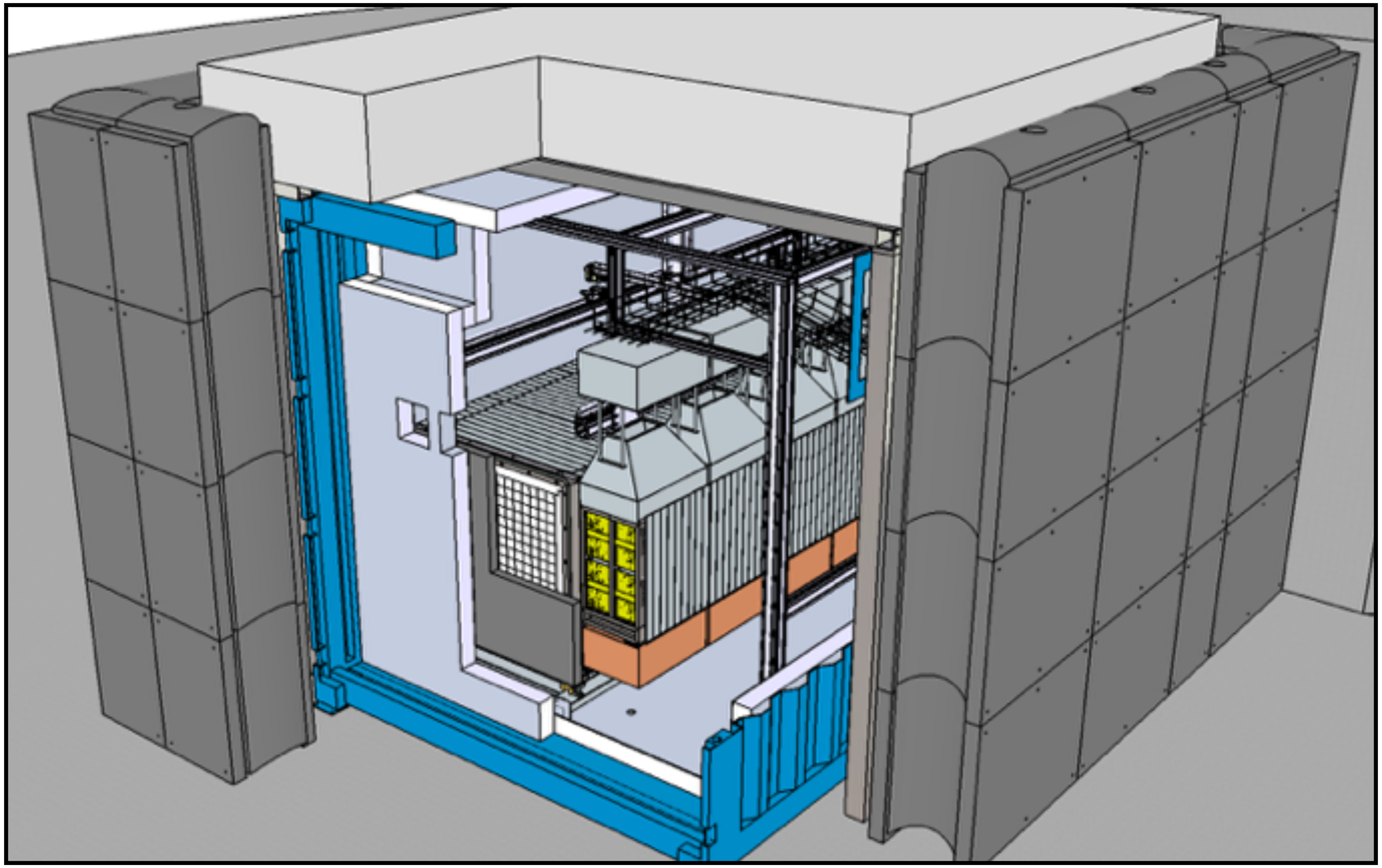
Phase I Configuration

- First phase of the experiment currently being built:
  - Initially 1.6 T.
  - 50 planes of 16 x 16 cubes.
- Commissioning expected at the reactor hall May 2017.
- Many enhancements compared to prototype…



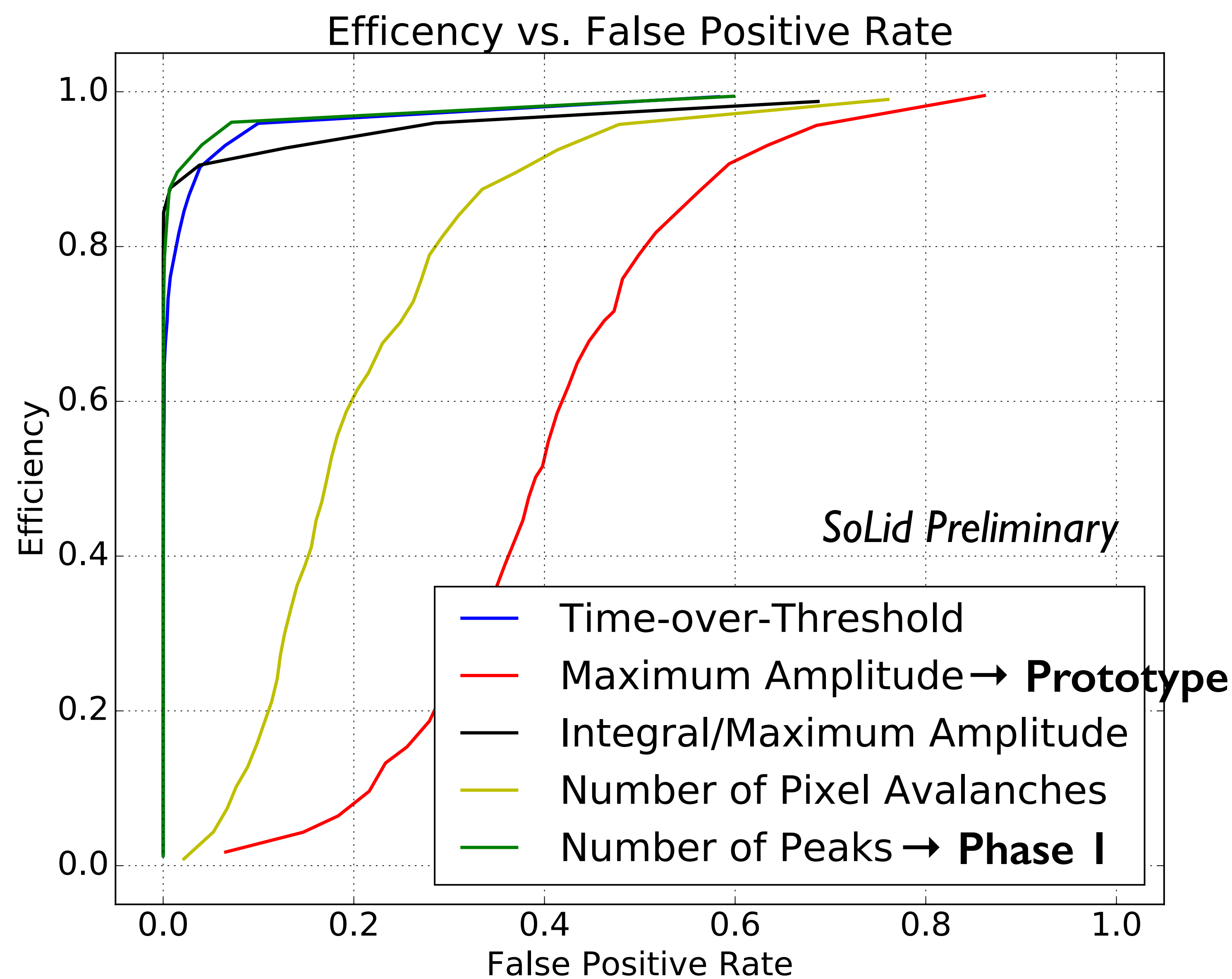
Passive Shielding

- Entire detector to be surrounded by 50cm water walls. HDPE on the root.
- Shield against backgrounds (e.g. highly energetic neutrons): expect ~10x reduction.



Neutron Trigger

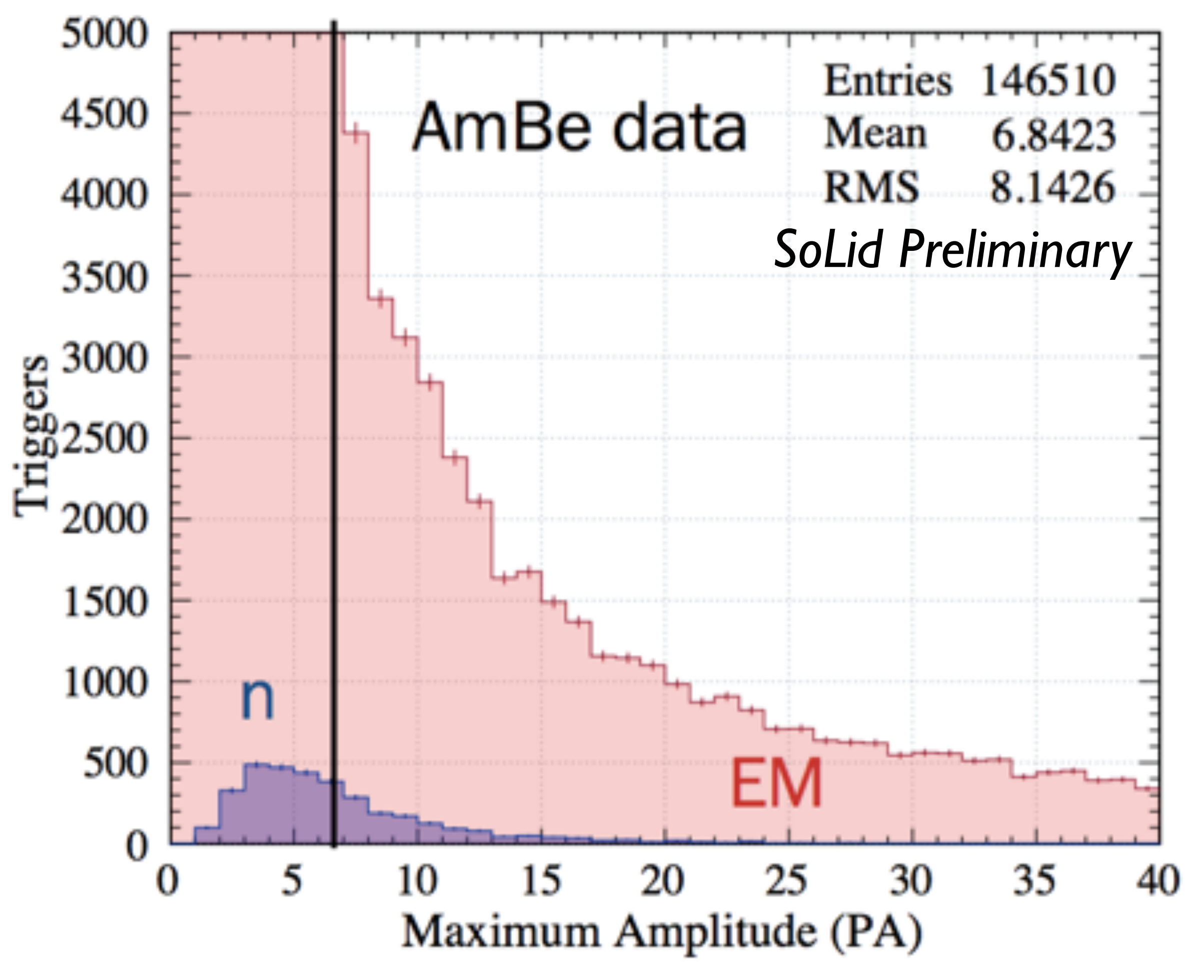
- New algorithms for electronic neutron trigger:
  - Neutron ID algorithms to be migrated into FPGAs.
- Combined with buffer (~1ms) readout for positron detection (±2 planes around n):
  - Very high prompt detection efficiency.
  - Further handles for discriminating background prompt events.

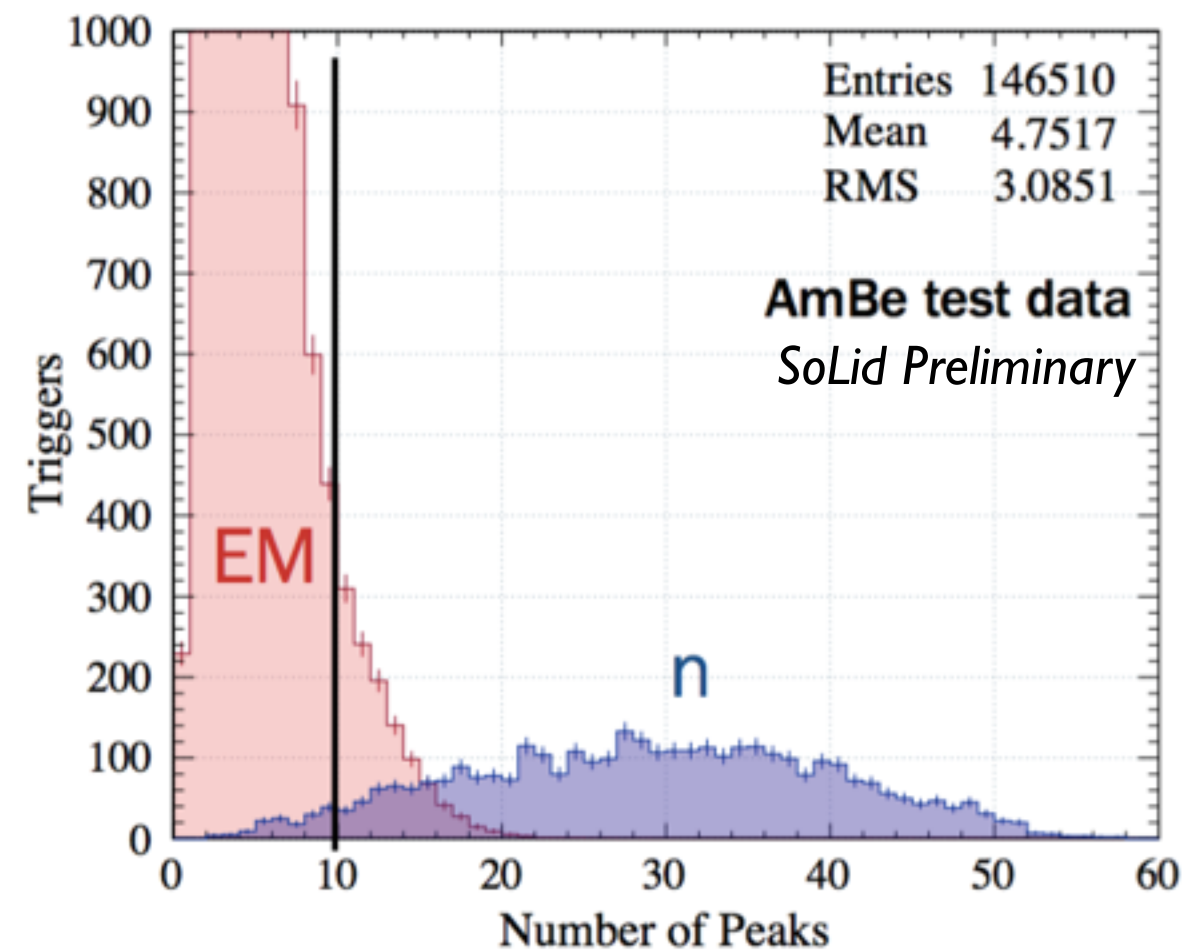


Neutron trigger ROC curves for various PID algorithms

Neutron Trigger

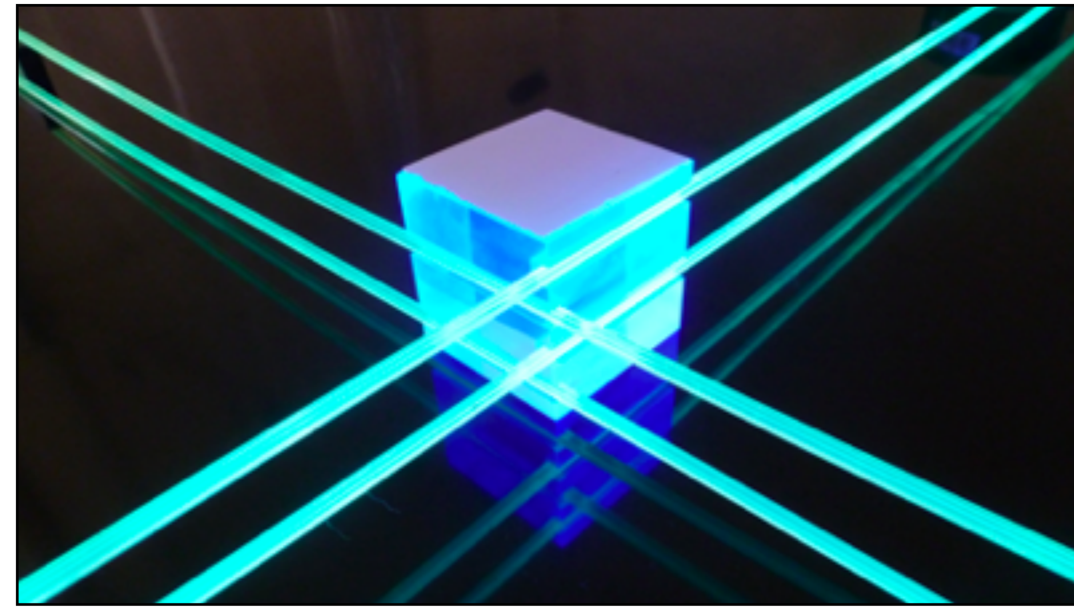
- Prototype used simple trigger due to time constraints.
  - High threshold set to manage data rates: neutron trigger efficiency ~5%
- Number of peaks in neutron waveform (rolling calculation) gives far better separation



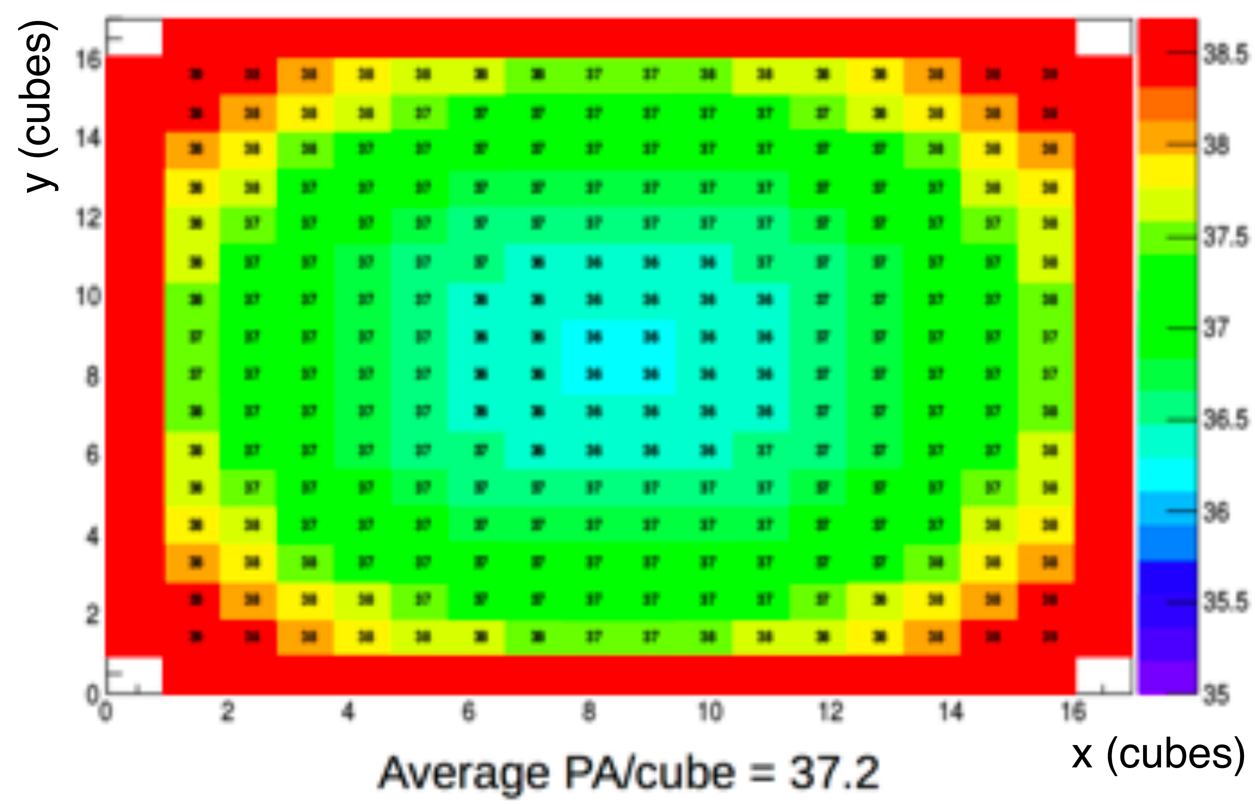


Readout

- Number of fibres and SiPMs doubled:
  - Each cube readout by 4 fibres.
- Light yield increased ~1.6x:
  - Material choice (tyvec, fibres)
  - Energy resolution ~14%/√E
  - Improves background separation and increases sensitivity in oscillation search.
- Entire container cooled to ~5℃:
  - Increased stability for SiPMs.
  - Signifncalty reduces dark counts (and hence fake trigger) rate.



Upgrade cube - 4 fibres and 2 Li screens

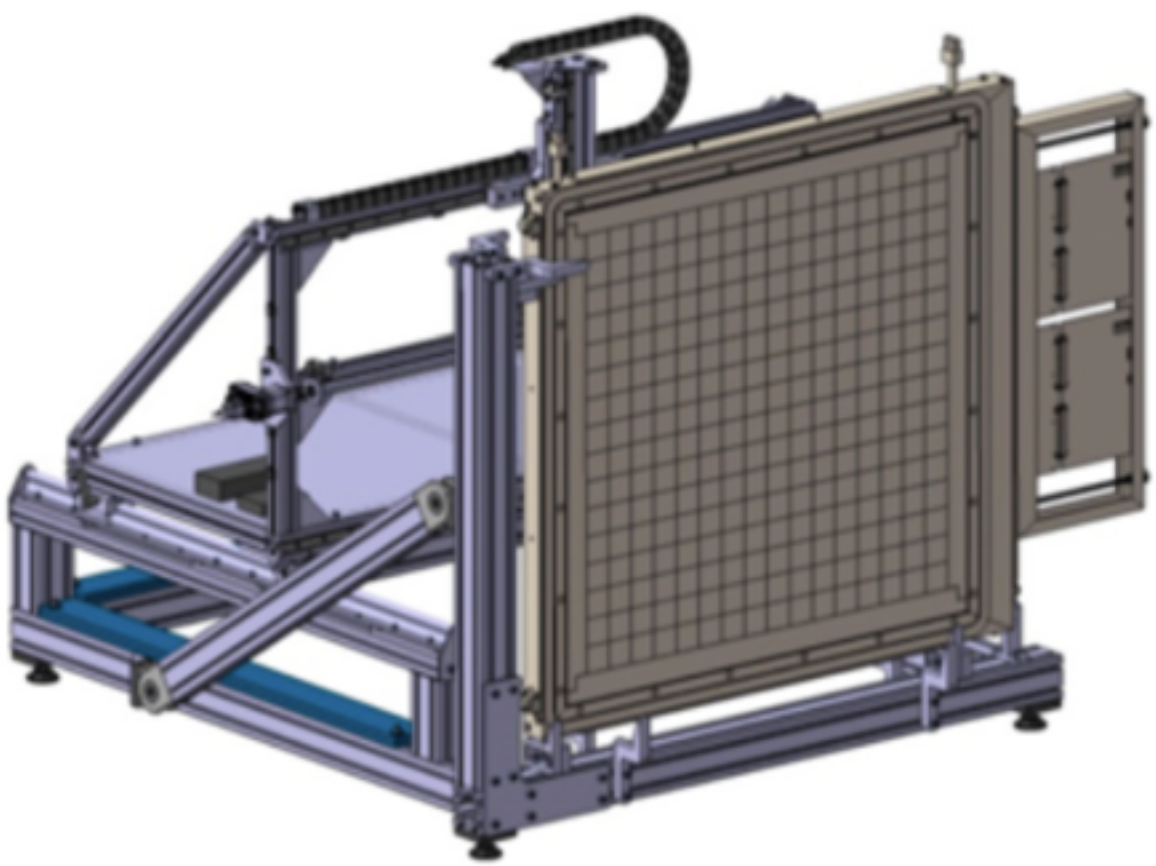


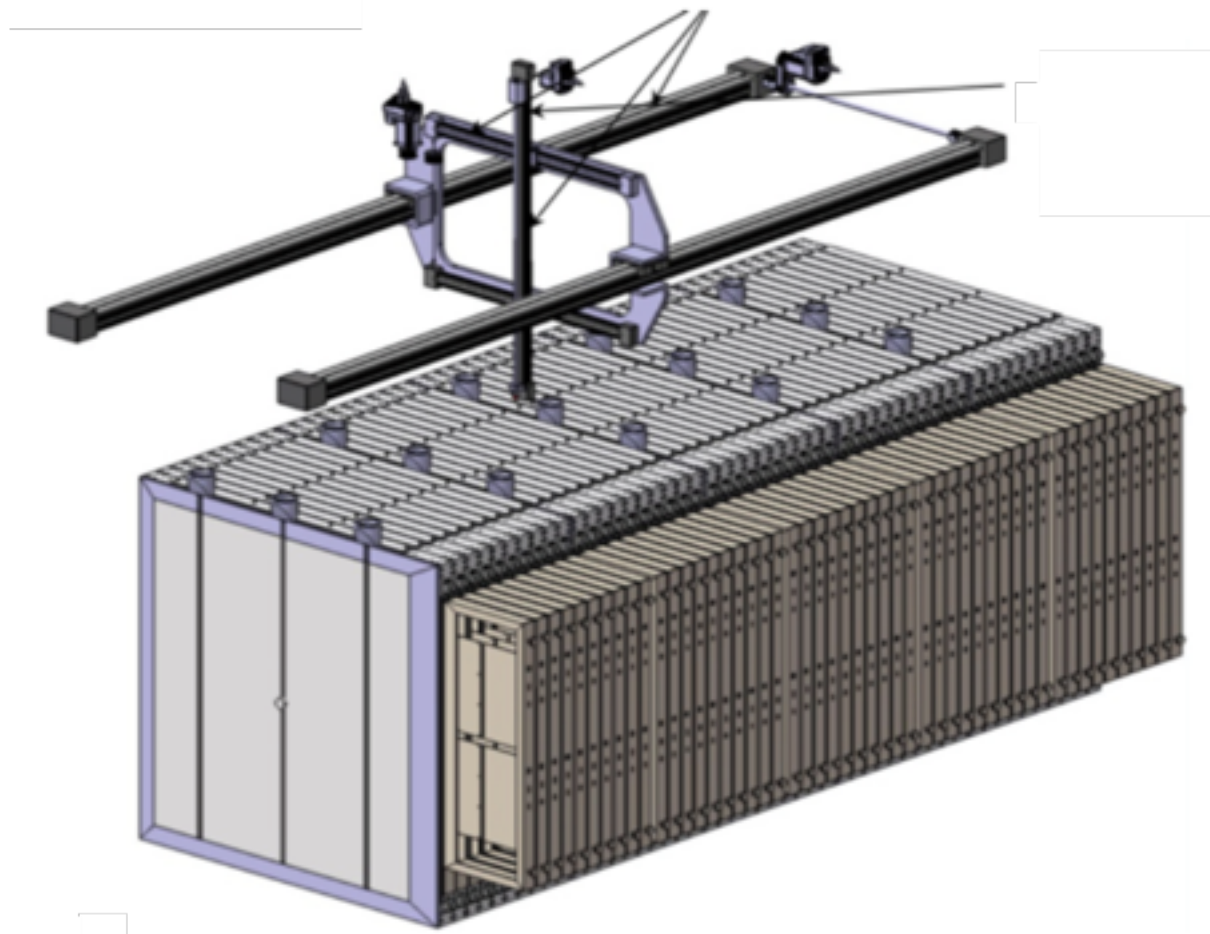
Light yield of Phase I cubes for a single plane

Calibration

- Off-site calibration system (CALIPSO)
  - Plane characterisation
  - Neutrons and EM sources used to allow precise cube to cube equalisation

- In-situ calibration system (CROSS)
  - Energy scale determination (~1% level)
  - Absolute neutron detection efficiency (target ~3% precision)





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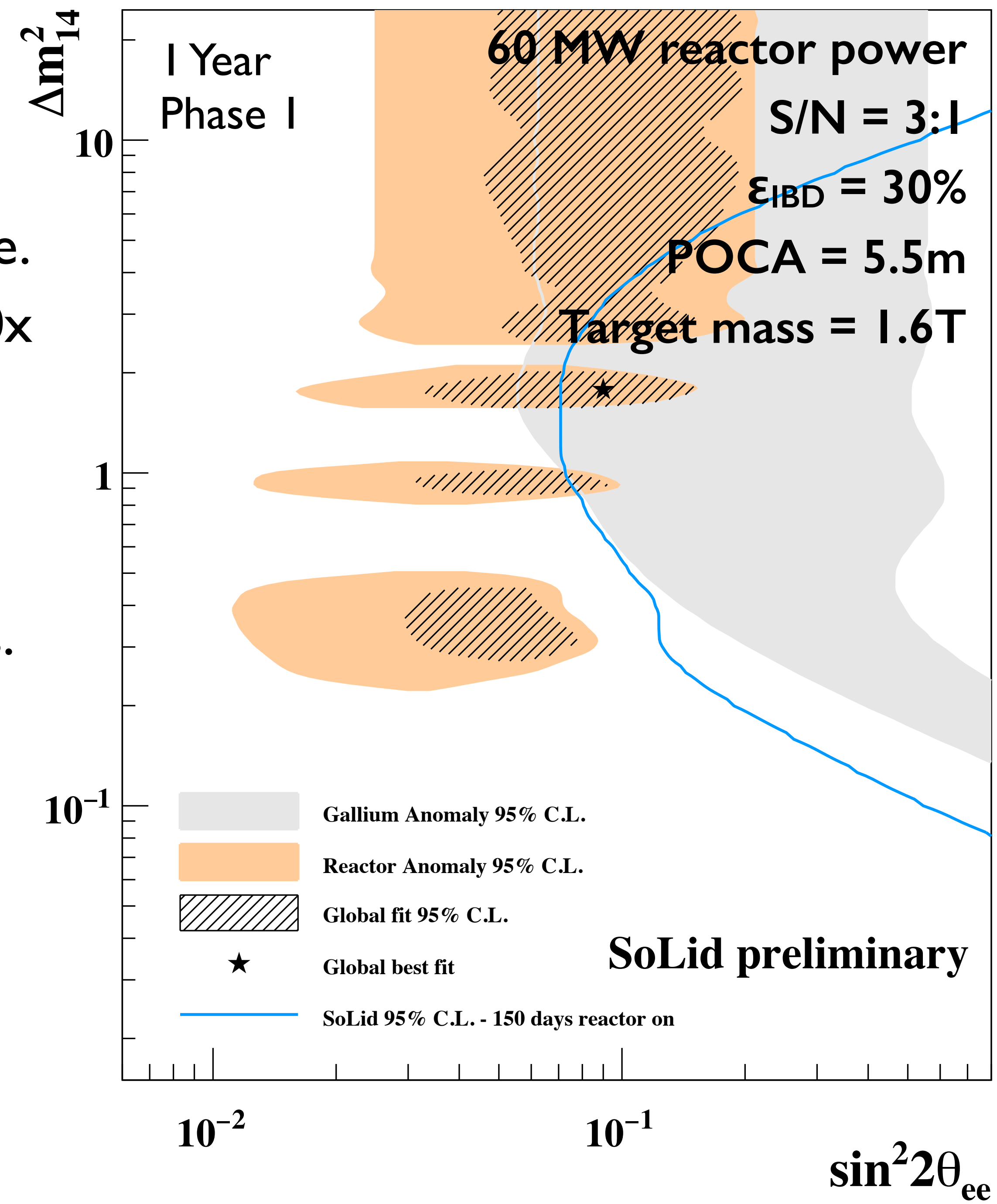
Conclusions

- Deployment and analysis of prototype complete:
  - Experience running technology at large scale.
  - Power of segmentation demonstrated: ~100x reduction B_{Acc}, ~10x reduction B_{Cor}.
  - Validation of simulation and data driven background studies.
  - Developed software and analysis techniques.
- Construction of phase I SoLid began:
  - 1.6T, to perform initial sterile search.
  - Upgrades for reduced background, energy resolution and trigger efficiency.
  - Deployed early 2017.
  - On track for S:N ~ 3:1 with ε_{IBD} ~ 30%.



References

[1] B. Kayser @ Moriond EW 2012:arXiv: 1207.2167

[2] K. N. Abazajian et al., arXiv:1204.5379 [hep-ph]

[3] Kopp,Machado,MaltoniandSchwetz,JHEP05(2013)050

[4] Mention et al., Phys. Rev. D 83 073006 (2011)

Backup

Sim/Data Comparison

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  - Multiple generators: Guang, Cry, Gordon

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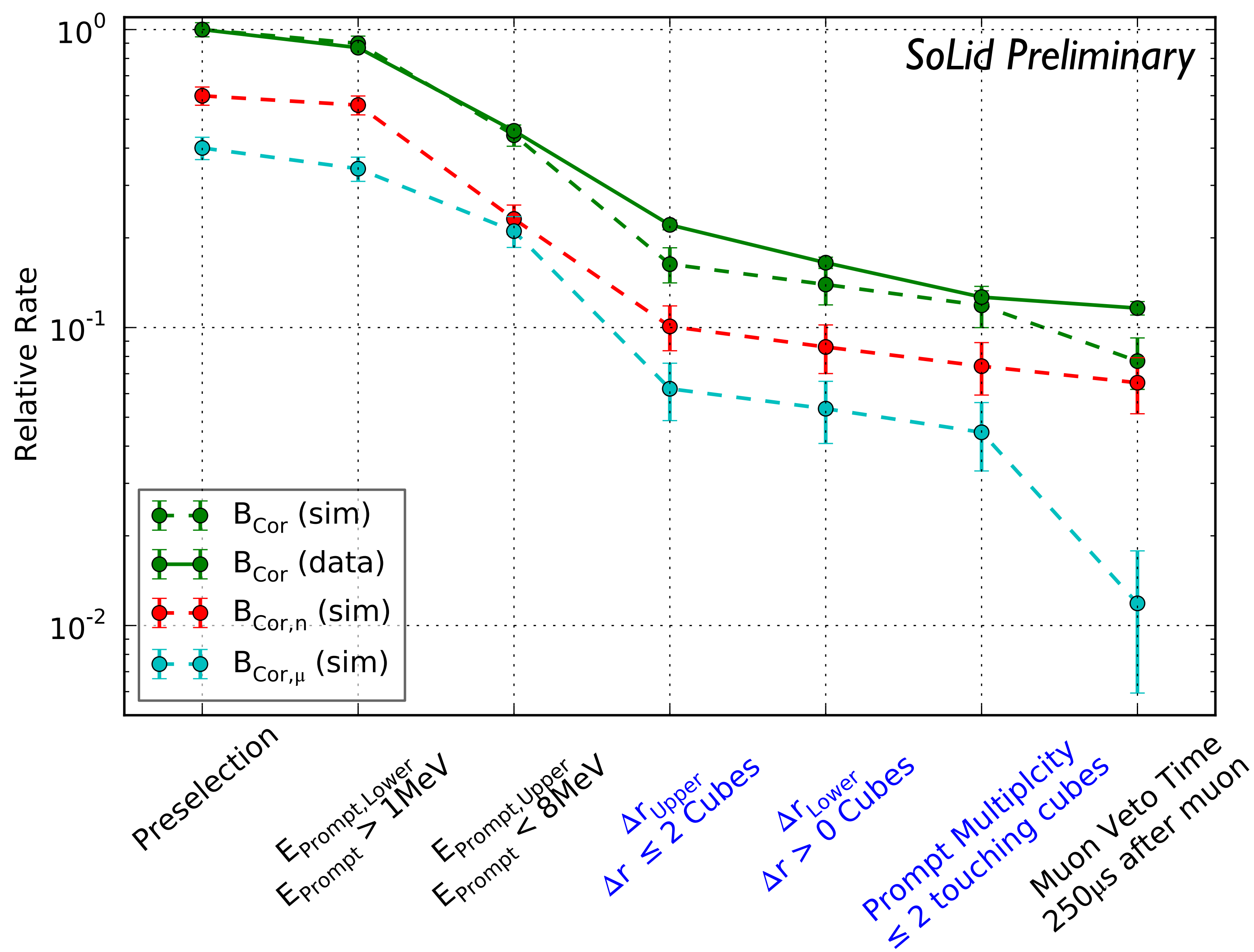
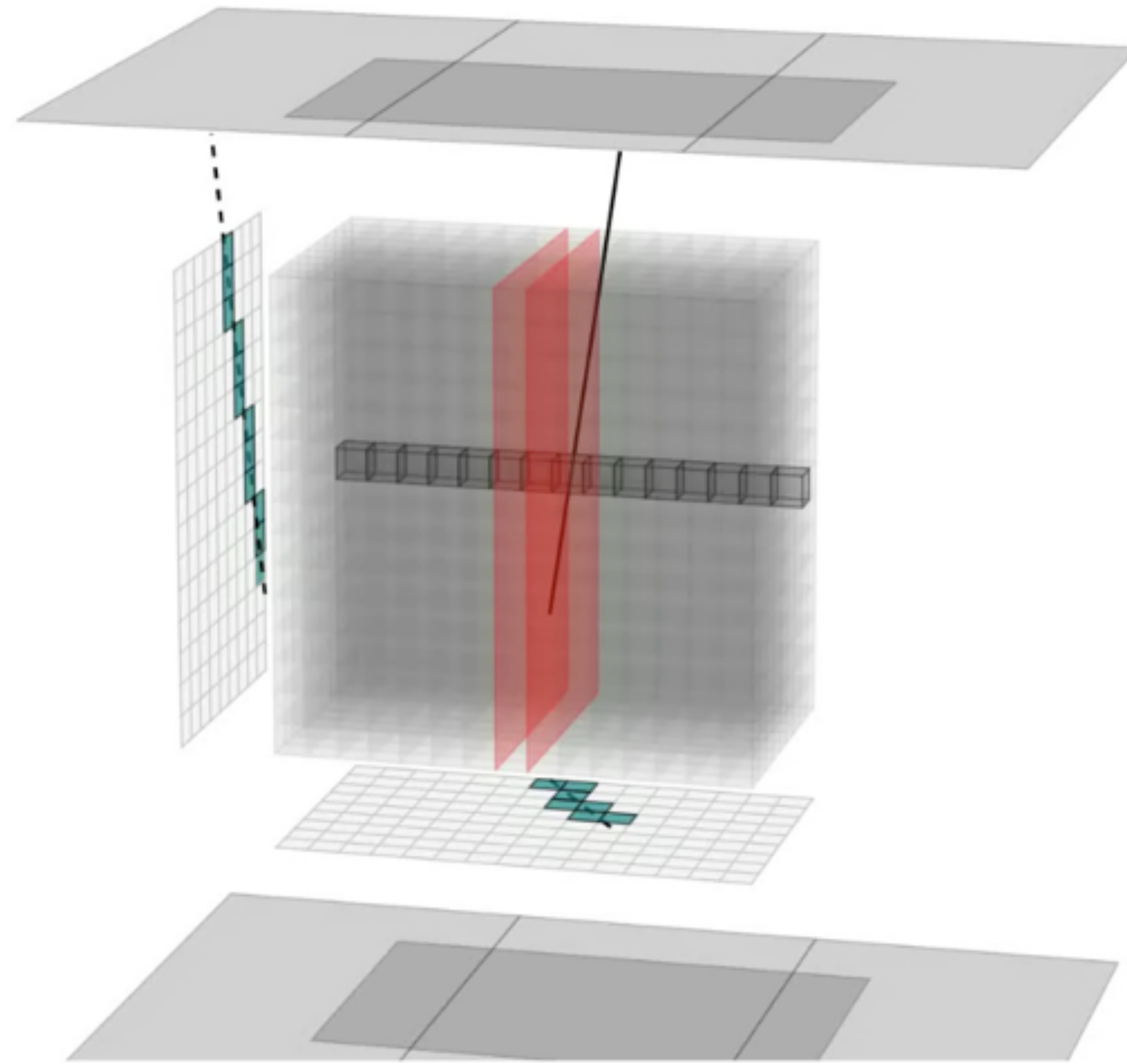


Energy Calibration

- SM1 EM calibration performed using comic muons:
  - High quality reconstruction tracks
  - dE/dx distribution found for each cube
  - Selection criteria applied to remove non-degenerate cases
  - Allows for equalisation signal and energy scale estimation



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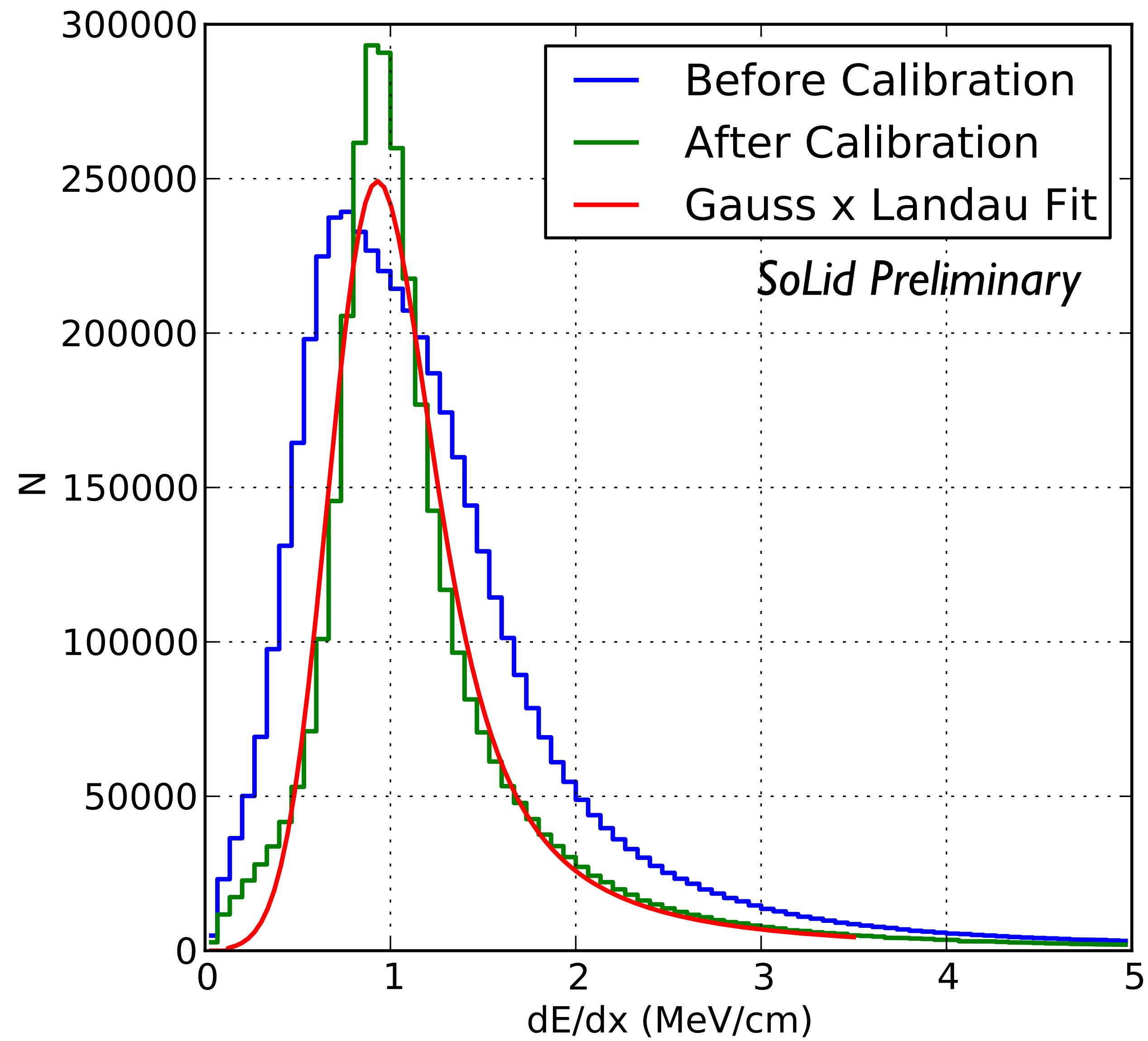


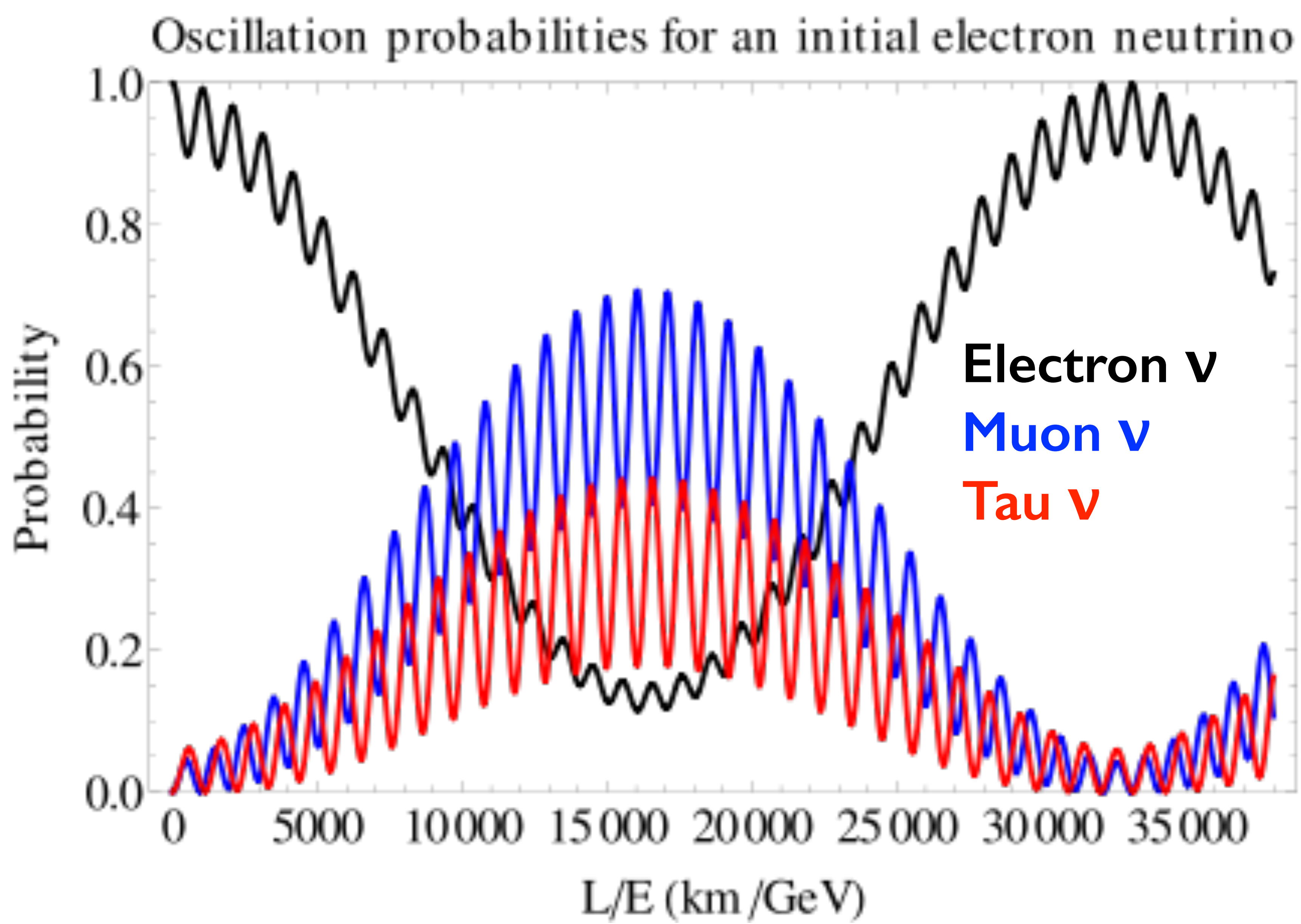
Oscillation Formalism

- Neutrino oscillations (hence masses) are not part of the standard model, but can be modified to incorporate.

- Mixing of the flavour eigenstates can be parameterised by the PMNS mixing matrix (analogous to CKM):

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}$$

- Four free parameters:
  - Three 'mixing angles': θ_{13}, θ_{12}, θ_{23}
  - CP violating angle delta.


Oscillation probabilities for an initial electron neutrino
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
5000
10000
15000
20000
25000
30000
35000
L/E (km/GeV)
Electron ν
Muon ν
Tau ν