An antineutrino-based detection concept for non-intrusive site-wide reactor monitoring

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LLNL-PRES-854357

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

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Non-intrusive site monitoring

NuTools thoughts:

NuTools: Use-case findings…“There is interest in the policy community in neutrino detection as a possible element of future nuclear deals involving cooperative reactor monitoring or verifying the absence of reactor operations”

E.g. An antineutrino detector could potentially be useful to monitor a ~few km^2 area, or a site non intrusively

A non intrusive antineutrino detector situated ”outside-the-fence” could have some utility here.

Example: A site ~1-10 km^2 in size and an antineutrino detector

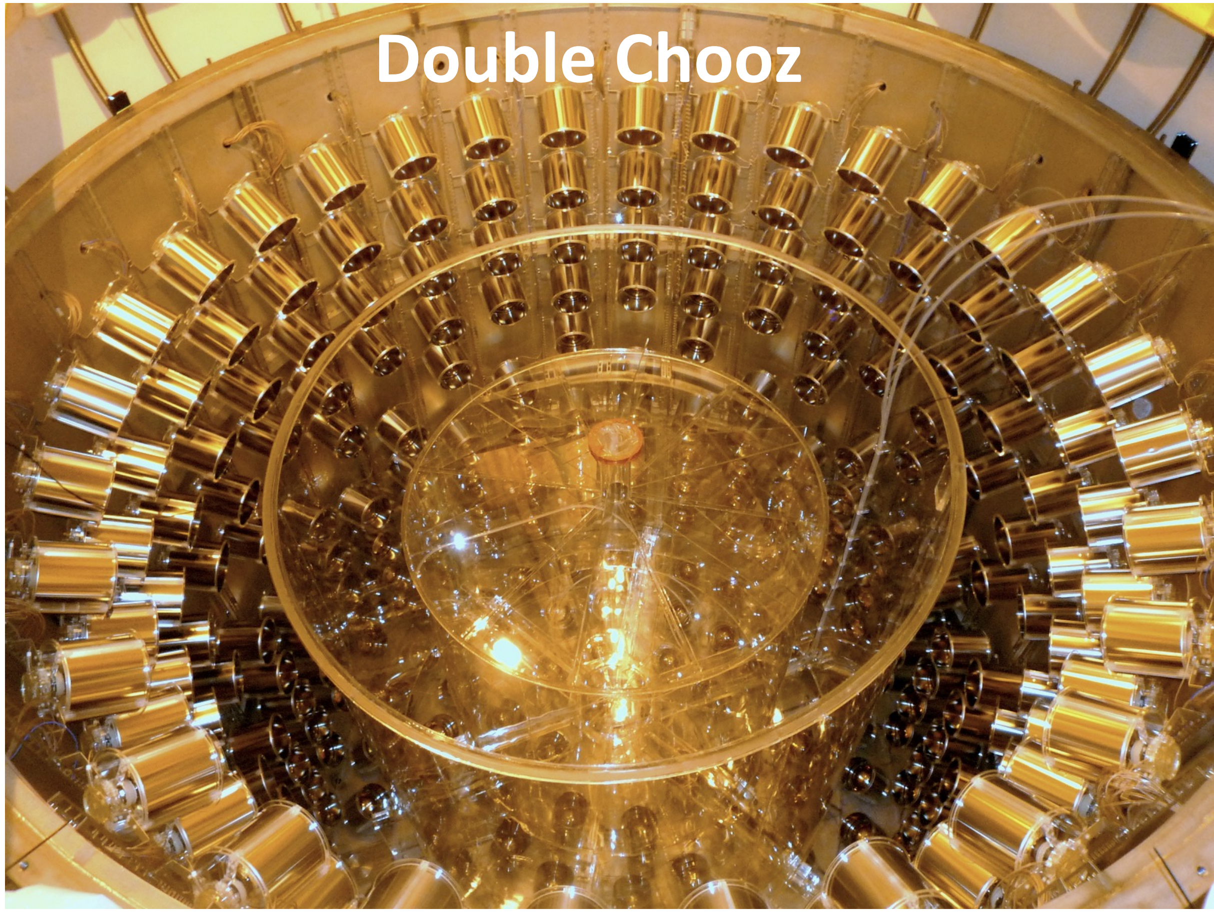
- Baseline anywhere between 100-2000m
- Size - ~10-100 m^3 fiducial
- Will need to be underground, but only Palo Verde-like overburden (10-50m)

New scintillators: have been developed since Double Chooz/Daya Bay/Palo Verde. Can we exploit these materials for:

- PSD ^{6}Li-doped liquid scintillator - PROSPECT-like. Has the potential to permit shallow deployments
- Water-based liquid scintillator
  - Particle ID via Cherenkov/scintillation separation
  - Particle ID via PSD

Design goals:

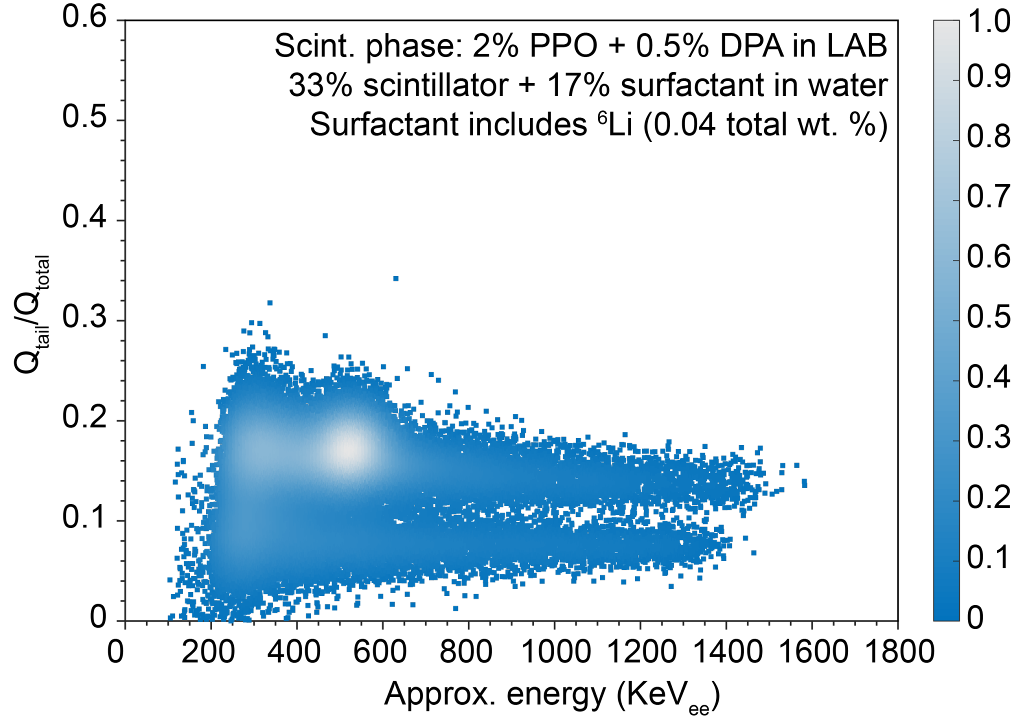
- Shallower deployment capability
- Higher fiducial/total ratio?
- Simpler design, easier to engineer



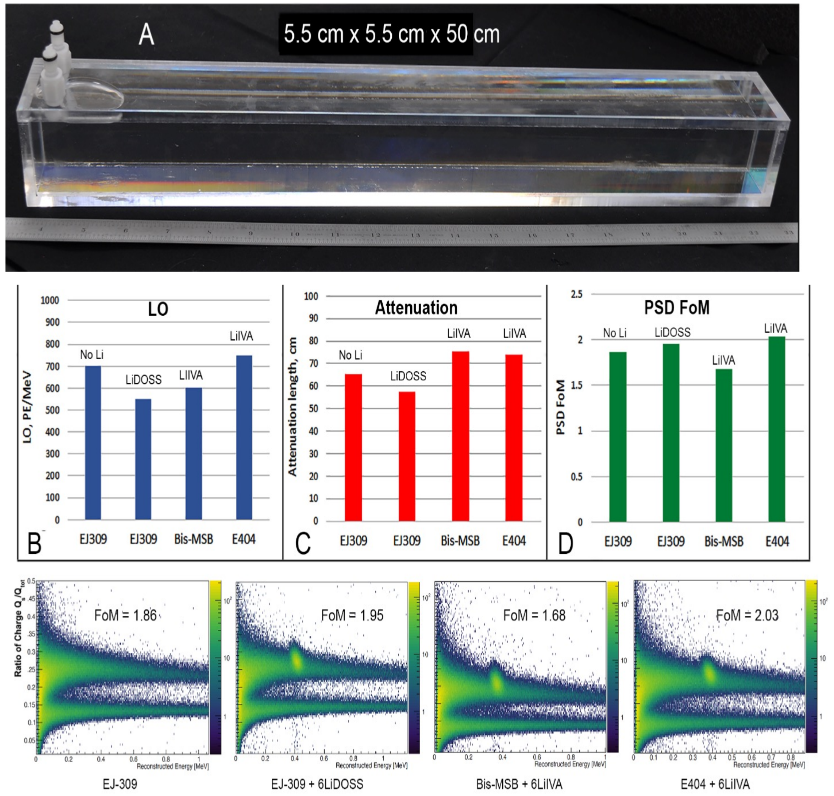
Pulse shape sensitivity in new liquids

WbLS (33% scintillator)

Note: small vial



^{6}Li-doped PSD liquid scintillator



In principle we have a tool for particle ID which could help with enabling shallow deployments
But sensitivity may degrade as detectors get larger

What happens if we sacrifice everything on the altar of energy and PSD sensitivity?

What does such a detector look like?

^{6}Li-doped PSD liquid scintillator Detector Idea:

Aim:
Capitalize on PSD and energy resolution provided by the scintillator.
Collect as much light as possible:

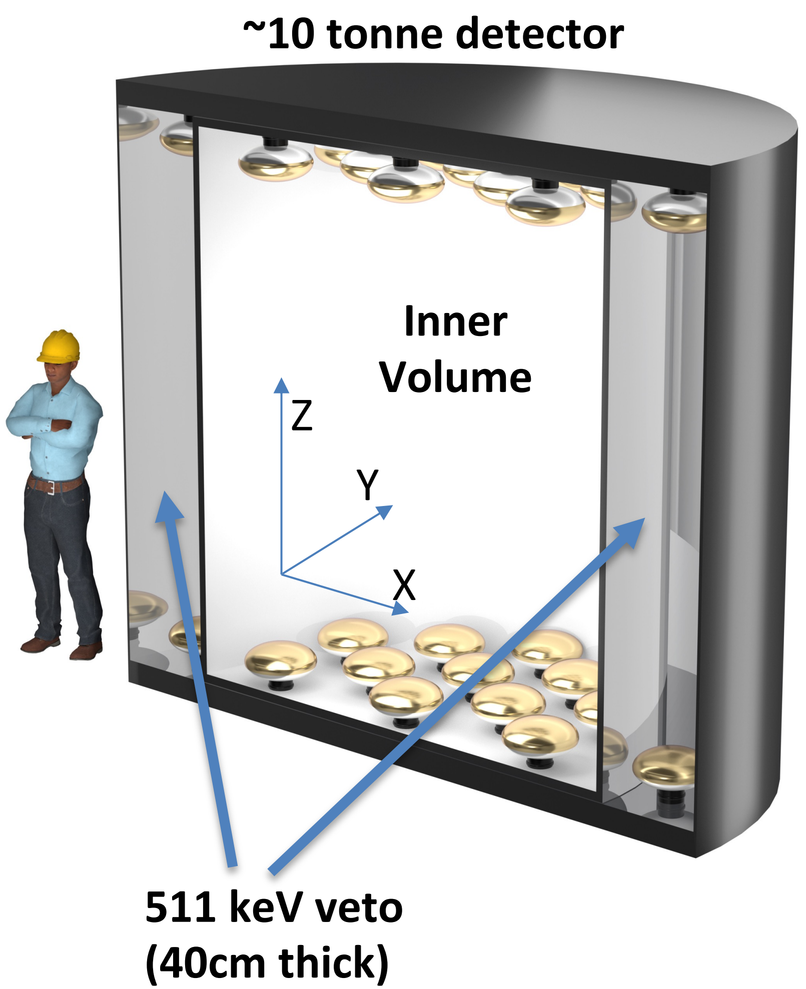
Method:
PMTs top and bottom, white reflective walls.

- We maximize PSD and energy resolution, while giving up position sensitivity

Note: a traditional detector (black walls + PMTs on all walls) would also work, I suspect white walls are likely to maximize PSD sensitivity

Note: we can claw back some position sensitivity by:

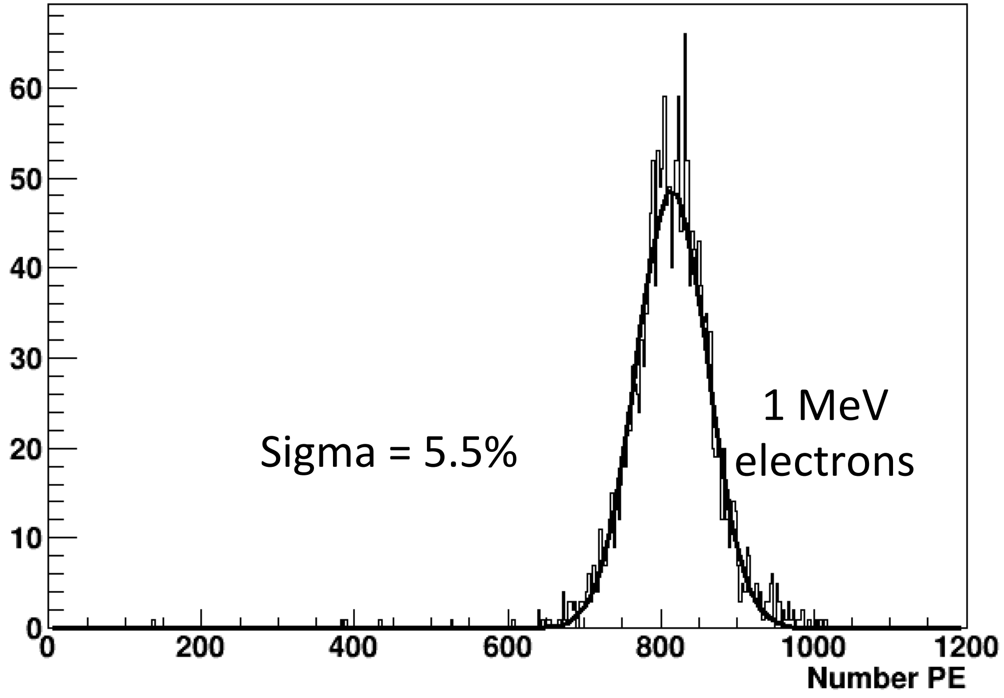
1. Timing of first photon signal (top versus bottom) gives z sensitivity
2. Put a veto volume around the sides of the detector. Positron related 511 keV gamm as that escape fiducial can be tagged with veto.



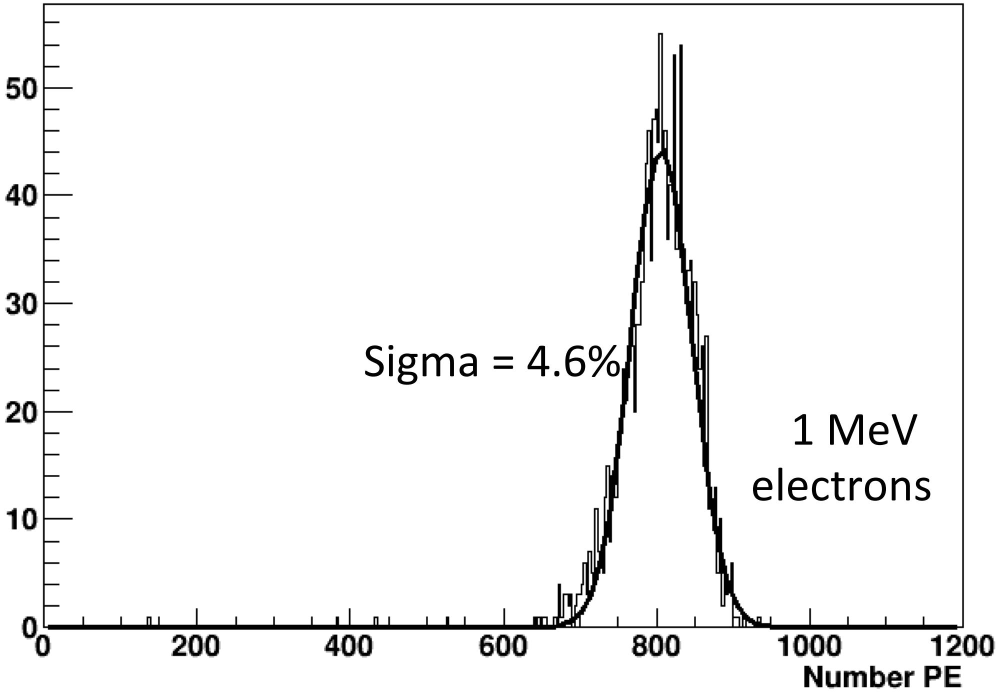
GEANT4 Simulations: Energy resolution

1 MeV electrons distributed throughout whole detector – PSD liquid scintillator (10k photons/MeV)

Whole volume

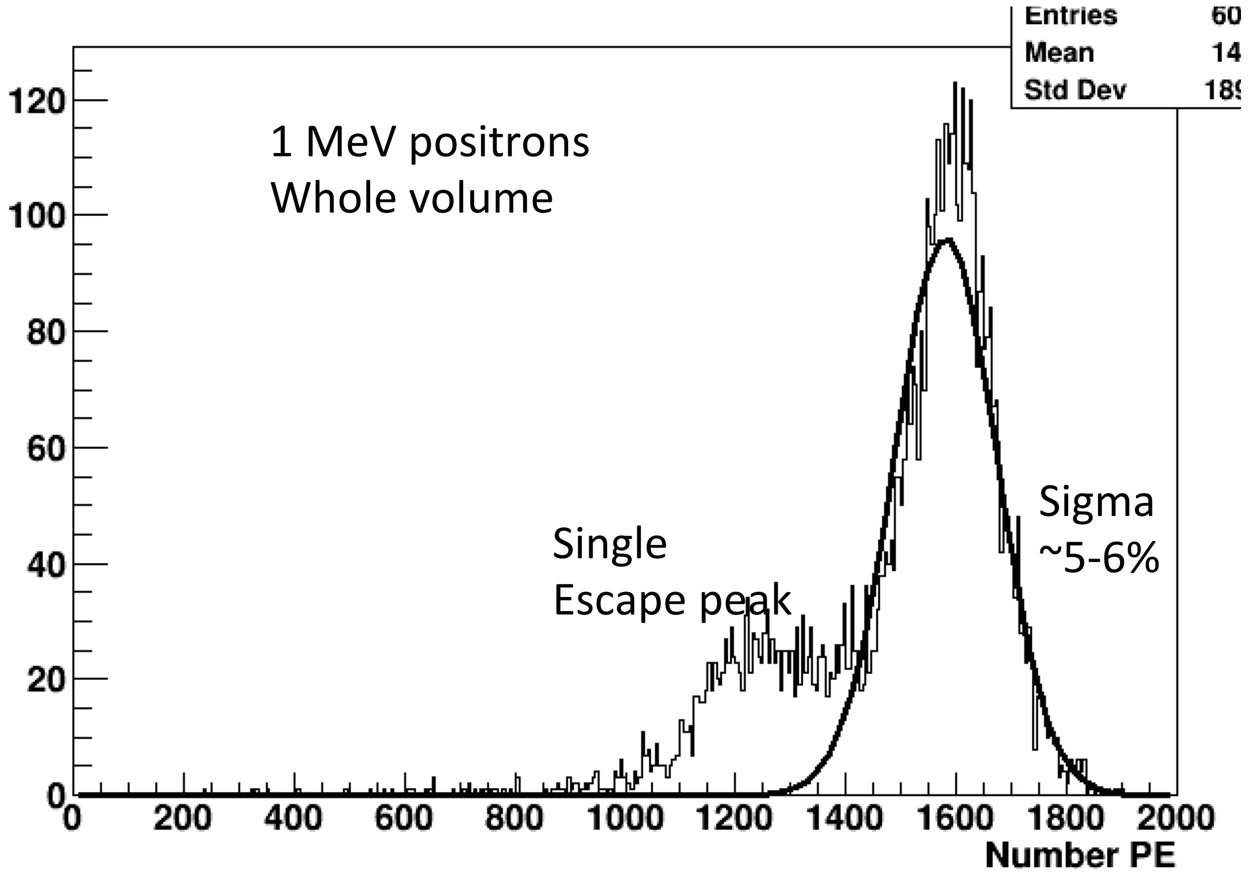


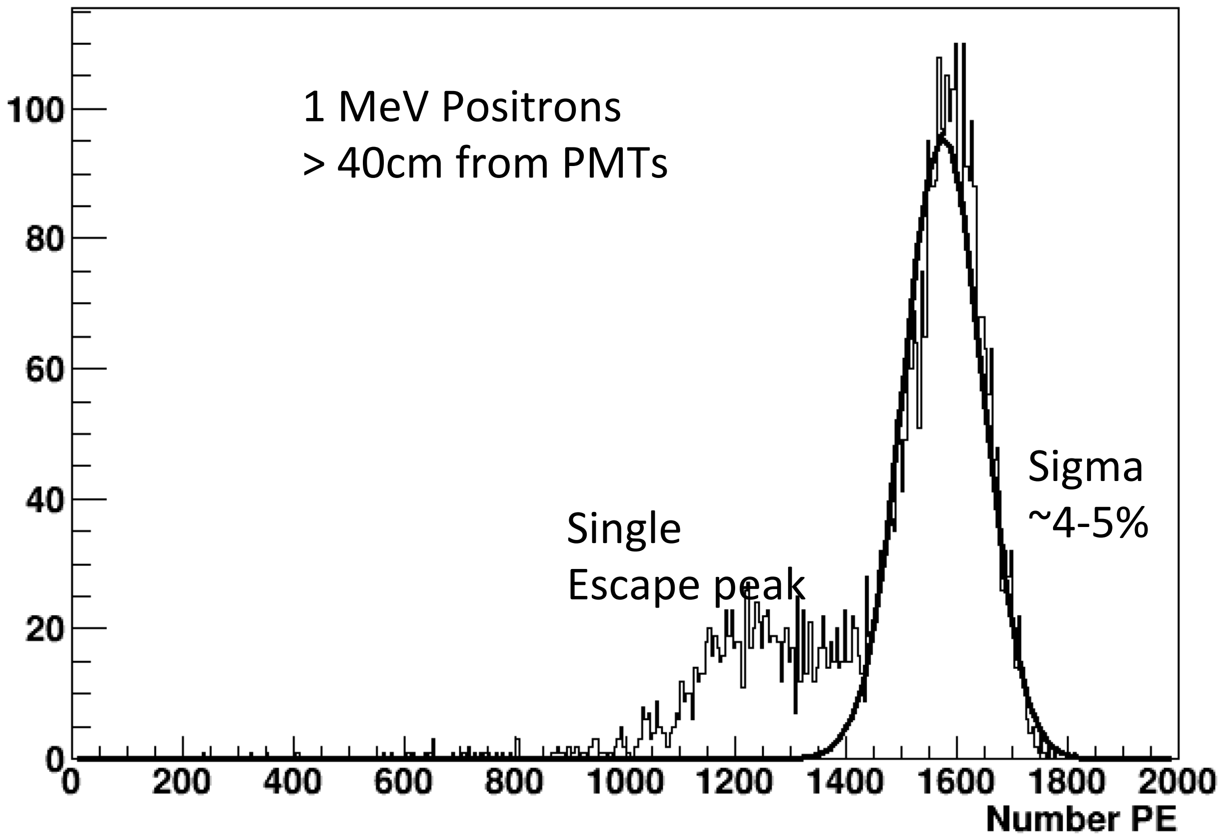
de-select events within 40 cm of PMTs



Take away – some position sensitivity relative to PMTs is required to improve energy resolution

Positrons throughout volume (1 MeV positrons)

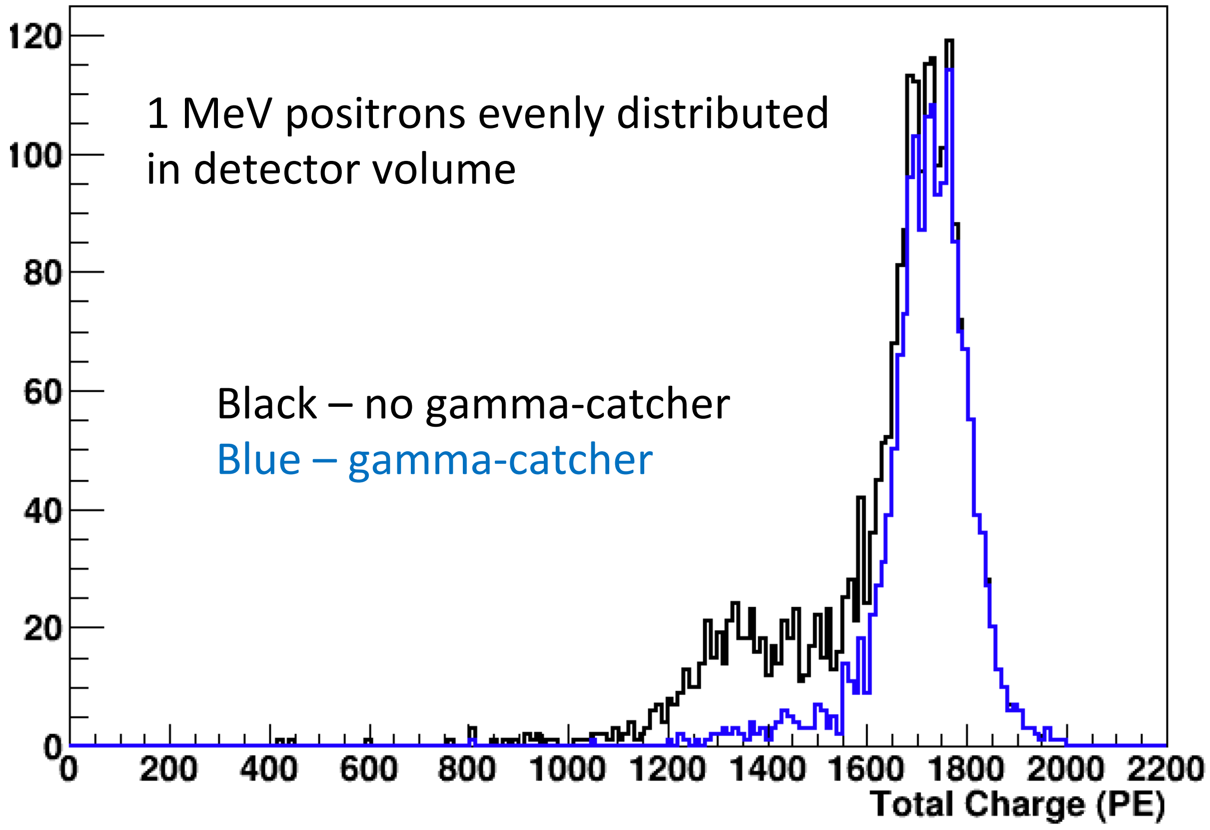




Note: Positrons near the edge of the detector have a single escape feature which will impact spectral sensitivity

Effect of 511 keV veto - positron energy resolution improves

We can remove most of the escape peak by vetoing events that produce charge in both volumes



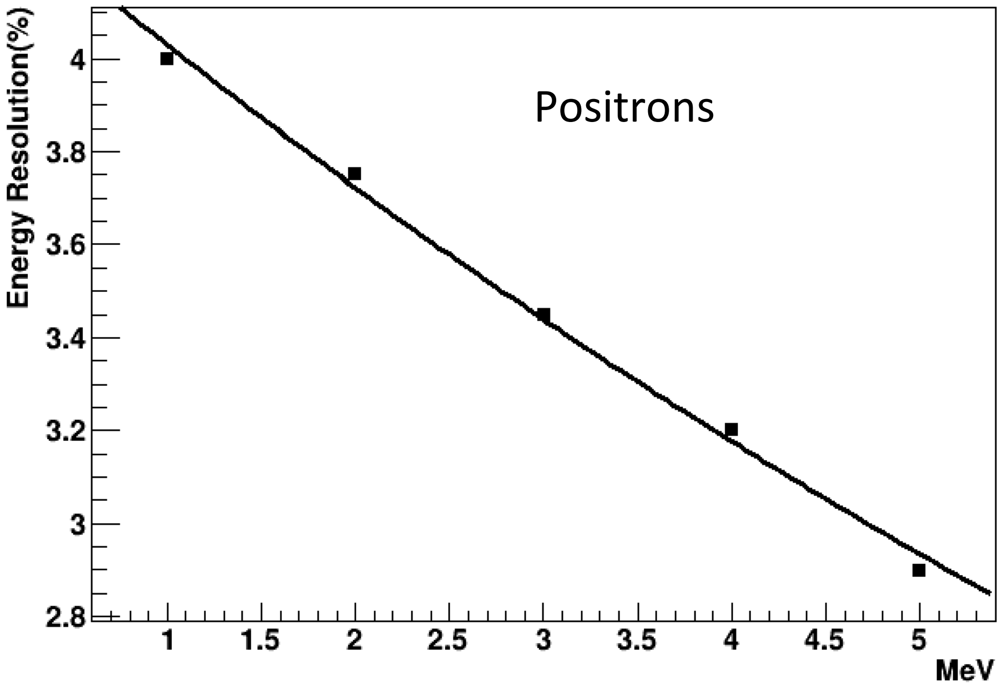
Positron energy resolution (after escape peak veto)

Positron energy resolution is good – and gaussian.

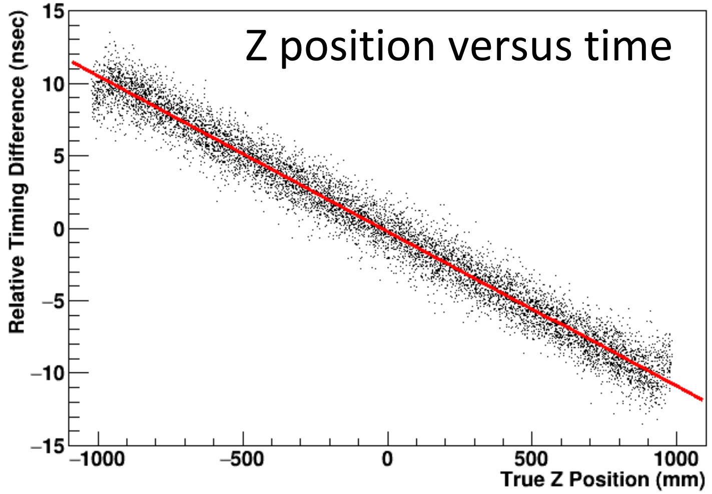
Some position dependency inside the detector volume remains.

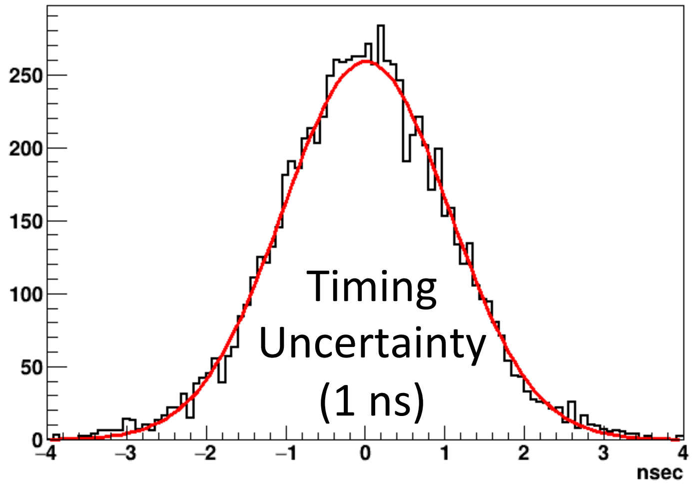
Results are a little degraded relative to statistical variation you would expect given the number of detected photons.

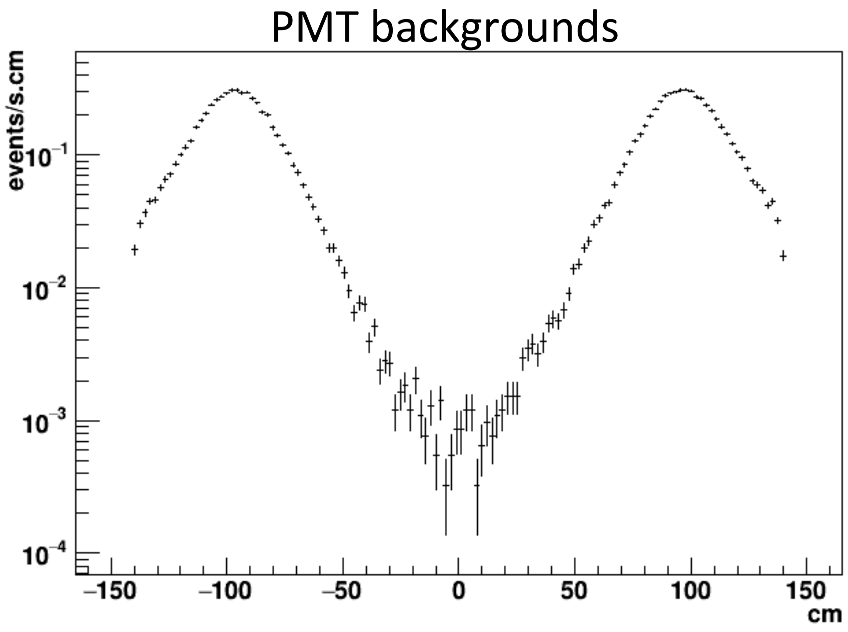
Note: 3% energy resolution is Juno-level. So 4% (@ 1 MeV) is pretty good.



Timing – PMT background removal







Use the relative time difference (top versus bottom PMTs) to determine Z position

Z position resolution ~10 cm

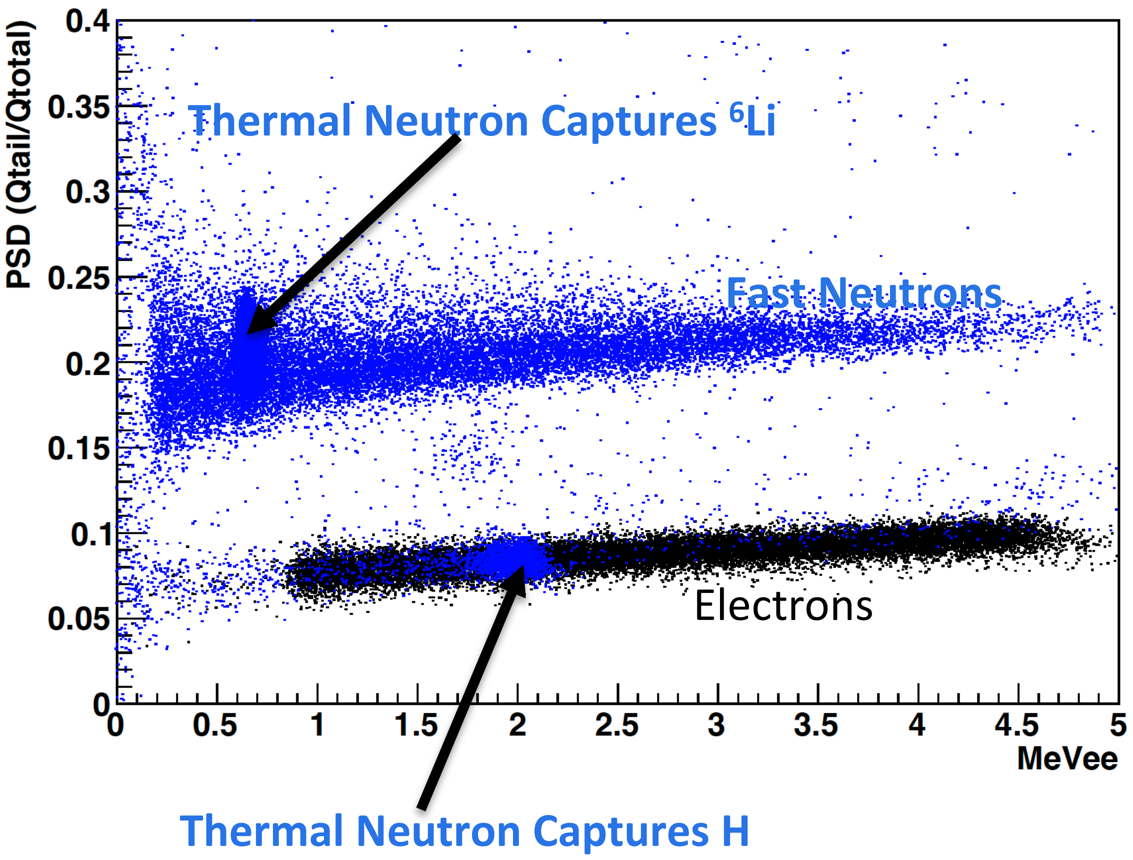
Enables discrimination against PMT backgrounds

Pulse Shape Sensitivity of a large detector with reflective walls

Significant PSD difference between neutrons (1-10 MeV) and electrons (1-5 MeV).

Note: PSD sensitivity is not significantly nullified by white walls (which causes ~10s of ns delay in photon detection in ~10 m^3 sized detector)

Q: How does PSD sensitivity evolve with detector size?
A: I'd like a tuned simulation for this prediction



Summary and next steps

We have simulated a detector optimized for energy resolution (3-4%), high (fiducial:total) volume ratio, and simple design (relative to Double Chooz, Daya Bay, RENO, etc)

Position sensitivity is sufficient to remove large fraction of PMT backgrounds

High photon collection efficiency → ^{6}Li capture will likely be detectable

Gamma-catcher (as a veto) appears to work well – positron escape peak can be removed

Known unknowns:

- ^{9}Li veto requires either muon tracking or identification of showering muons. Tracking muons will be difficult in this style detector.

Next Steps:

Predict antineutrino sensitivity of a real detector in a use-case of interest to DNN

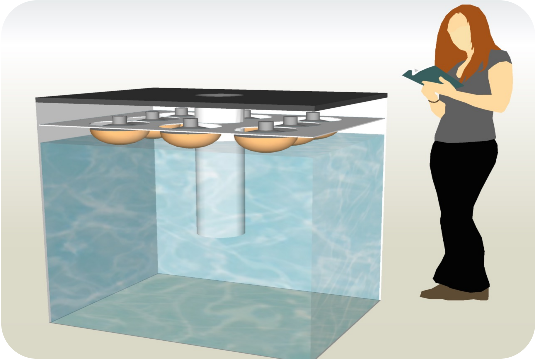
Test accuracy of simulation prediction of PSD sensitivity with the LLNL 1-tonne detector filled with EJ-309 (White Teflon-coated walls, PMTs at top)

Predict PSD sensitivity as function of detector size

Test ^{9}Li identification via showering muons in 1-tonne

Top view

LLNL 1-ton



Inside view

Backups

2 options for ^{6}Li-doped PSD liquid – 1) PROSPECT liquid and 2) Fully dissolved ^{6}Li-doped PSD liquid scintillator

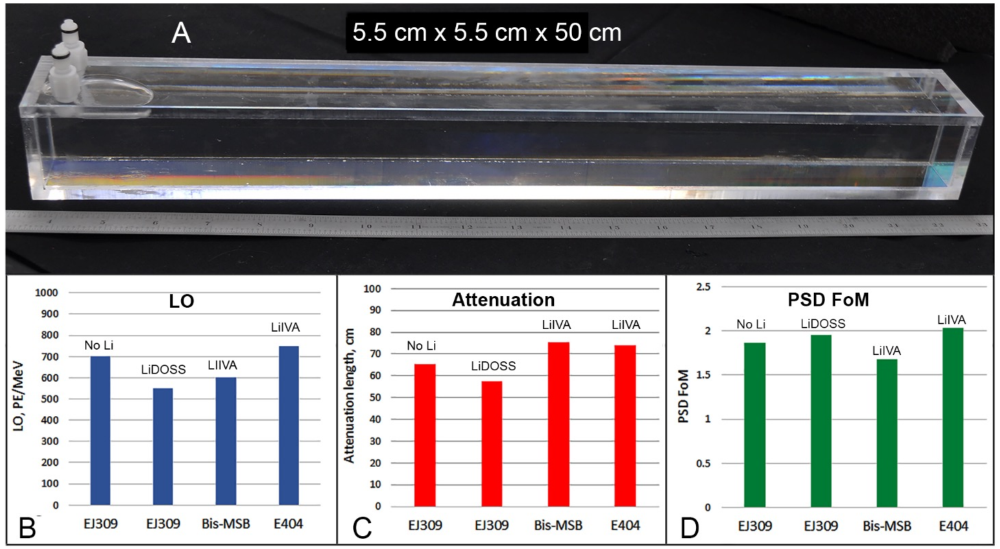
New formulations of ^{6}Li-doped PSD liquid scintillator (Natalia Zaitseva and Michael Ford, LDRD funded work at LLNL) (Submitted to Nucl. Inst. And Meth. A – March, 2023)

- Fully dissolved ^{6}Li in organic solvent, in turn dissolved in PSD liquid scintillator
- PSD performance is competitive with EJ-309
- Light output ~65% of EJ-309
- Long term stability tests are ongoing. Good reason to believe these formulations might be more stable than the PROSPECT version.

Stability:

- Lithium is fully dissolved in organic solvent. Doesn't use reverse micelles (PROSPECT).
- Hope is that materials compatibility might be easier to achieve (not tested yet)

N. P. Zaitseva, M. L. Carman, M. J. Ford, et al., Submitted to NIMA, March (2023)



Light output and PSD performance of new liquids are competitive with EJ-309 standard.