Optical simulation of the SABRE veto system

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One of the most important aspects of direct detection dark matter experiments is a low background. One way of achieving this (implemented by both COSINE and SABRE) is by using an active veto system to identify and reject background signals, reducing the total background by nearly an order of magnitude in some cases. The efficacy of this veto system depends strongly on the optical properties of the liquid scintillator, the physical geometry, and the characteristics of the detectors (PMT quantum efficiency, for example). These must all be carefully modelled to understand the veto power of a system.

In order to understand the thresholds available for veto cuts in SABRE, we require detailed optical simulations. We present here the methodology used to understand how optical photons propagate through the liquid scintillator, and how their probability of detection scales with scintillator properties, energy, and position of deposition in the detector.

Basic approach

Based on energy deposition in liquid scintillator

1. Simulate radioactive decays in various detector components
2. Record any deposition in crystal and liquid veto
3. Remove any events with deposition >100 keV in veto

Result is a total veto efficiency of 56% (84% for ^{40}K decay, as shown in Fig. 1)

Issues

Simulation uses only energy deposition produced in liquid scintillator, not detected by the system. Does not account for:

- Detector geometry (e.g., PMT number and position)
- Scintillator properties (e.g., Light yield, decay time)
- Deposition location

Likely a position related limit on the realistic energy threshold not accounted for here. Requires light propagation simulation that is unfeasible to run for typical statistics required.

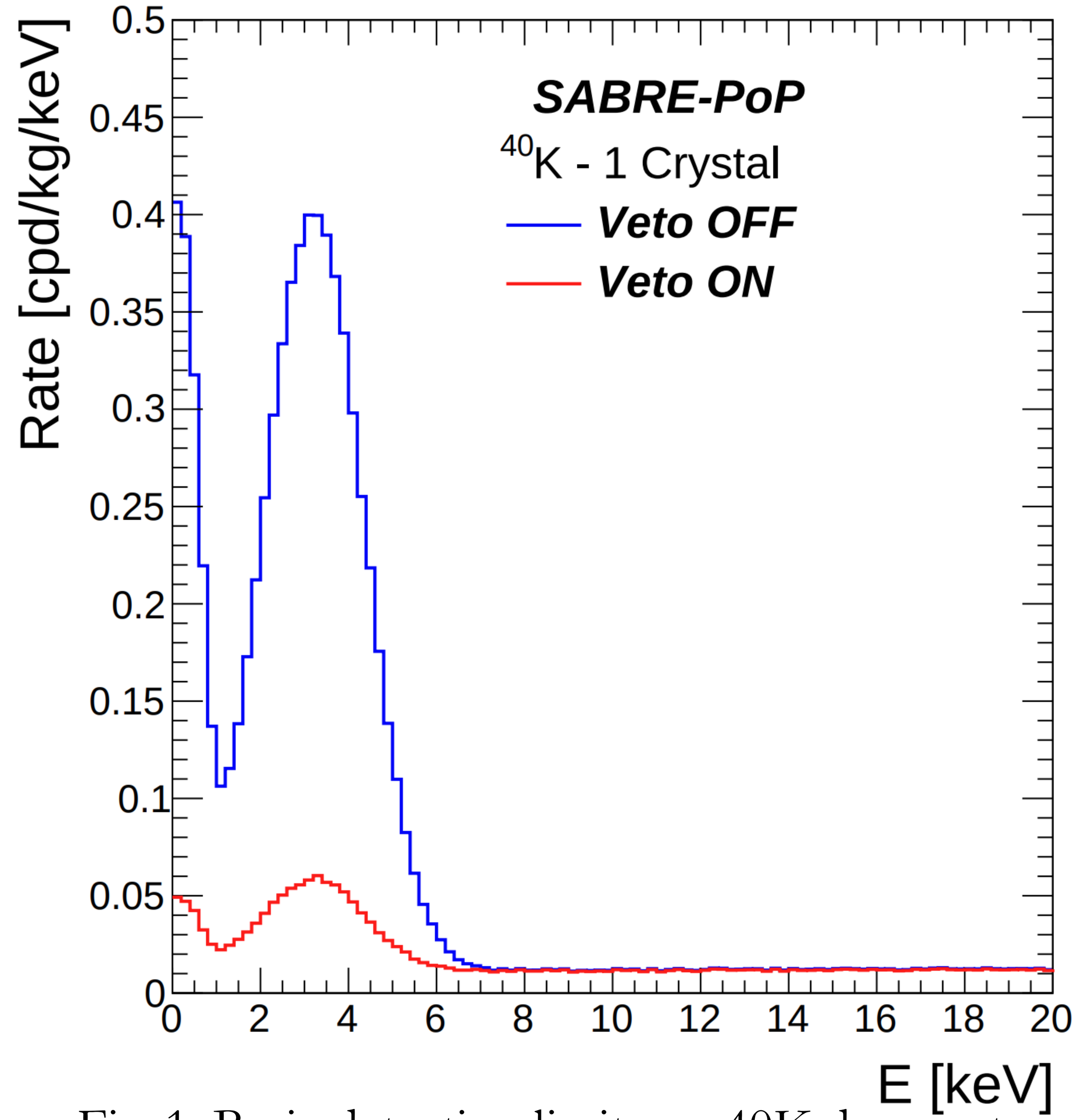

Fig. 1: Basic detection limits on 40K decay rate

Optical veto approach

Instead create a detection probability map that can be applied to results after simulation. Allows for limits to be set based on number of detected photons.

1. Simulate radioactive decays in various detector components
2. Record number of optical photons that reach PMTs
3. Remove any events with #PE above signal threshold

Probability of detection a combination of:

- Probability of a single optical photon generated at (x,y,z) reaching PMT$_i$: $P_{Di}(x,y,z)$
- Quantum efficiency of PMT$_i$: QE_i
- Number of optical photons generated by energy deposition E: $\mathrm{Poiss}(n; LY \times E)$

So the probability distribution function for detection of an event is:

$$\mathrm{Poiss}(n; LY \times E) * \mathrm{Bi}(n, QE_i \times P_{Di}(x,y,z))$$

For simulated events, just need energy deposited and deposition position to find fraction of photons that will be detected. This allows for better estimations of backgrounds that pass the threshold requirements.

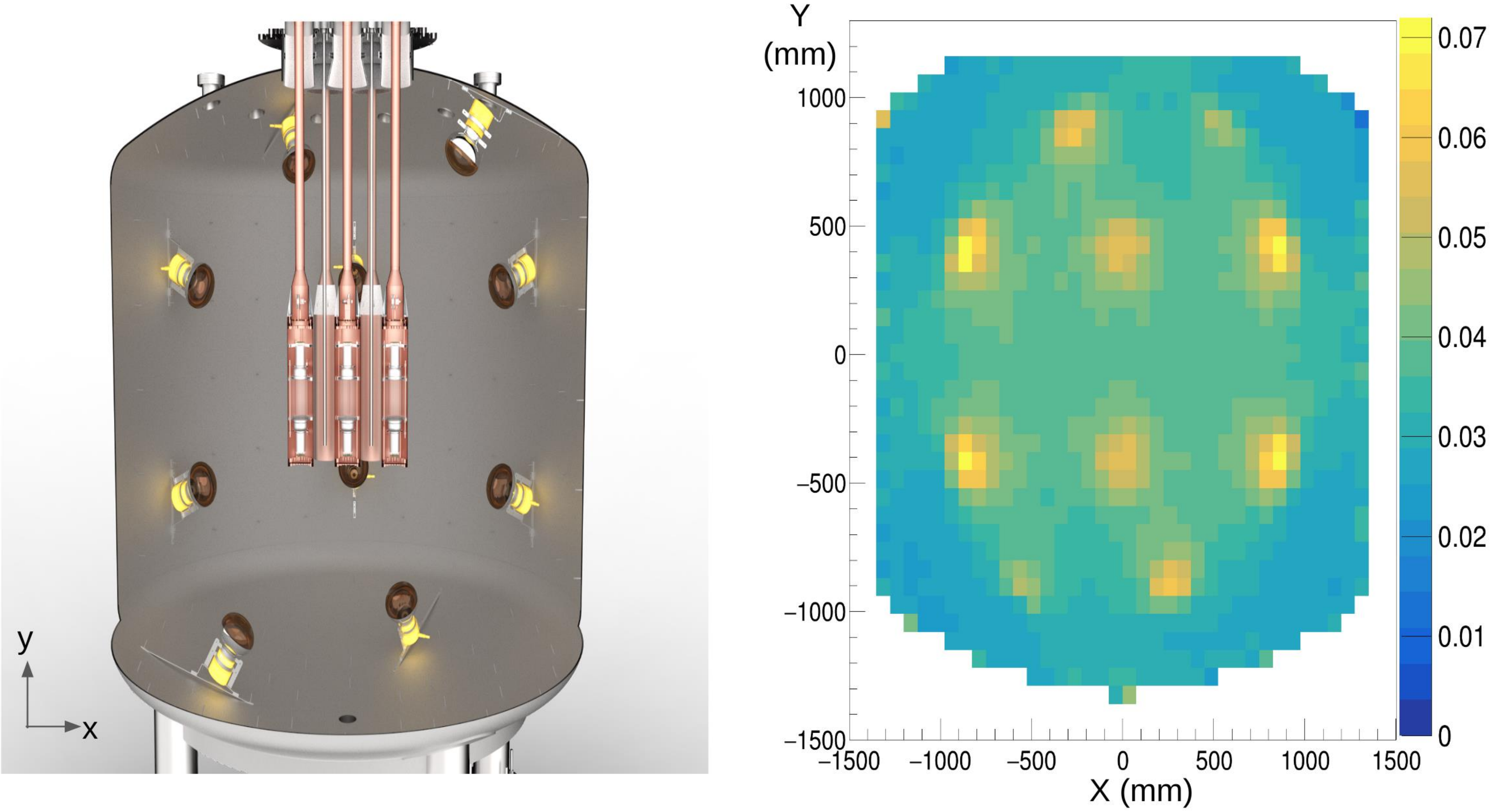

Fig. 2: (L) Cut away rendering of SABRE vessel demonstrating PMT positioning, (R) probability of optical photons reaching a PMT based on generation position.

Preliminary results and conclusions

From Fig. 2, clear there is position dependence on veto efficiency: events with an energy deposition close to a PMT have nearly double the average probability of being detected.

BUT! Likely that we can cut on a lower energy. Assuming:

- Average $P_{Di}(x,y,z)=0.04$
- Average $QE_i = 0.3$
- Light yield of LAB = 12 PE/keV

Expect average number of detections to be 0.144 PE/keV.

Depending on PMT signal thresholds, we can reduce veto cuts further:

- 8 PE threshold ⇒ 56 keV veto cut
- 6 PE threshold ⇒ 42 keV veto cut

These probability maps can also be used to inform position reconstruction and particle ID within the veto detector (I.e., compute the probability that a detected event was generated at a given position)

Initial results suggests this can be reconstructed to within ±25 cm even with very basic reconstruction algorithms.

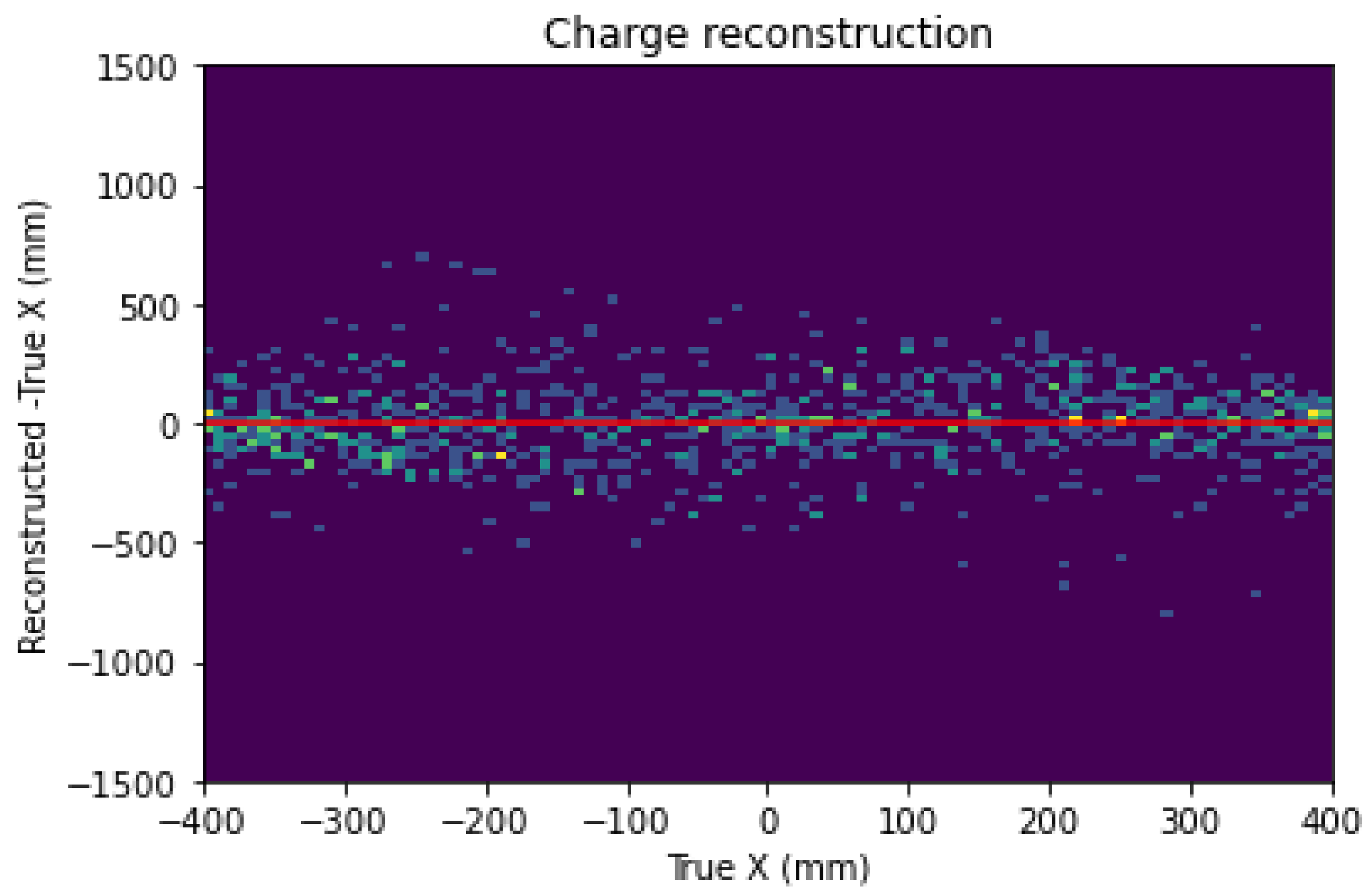

Fig. 3: Basic charge reconstruction on the position of a 1 MeV deposition within the liquid scintillator

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