CAU NEUTRINO LAB

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EXPECTED PERFORMANCE OF A WATER CHERENKOV DETECTOR FOR REACTOR ANTINEUTRINO–ELECTRON SCATTERING

NNN26 - Next-generation Nucleon Decay and Neutrino Detectors

S.H. Kim

Expected performance of a water Cherenkov detector for reactor antineutrino–electron scattering

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Abstract: We evaluate the expected performance of a 170 t water Cherenkov detector for reactor antineutrino–electron elastic scattering at the RENO near-detector site. The reactor-spectrum normalization is extracted from the reconstructed recoil-electron directional distribution using a constrained profile-likelihood fit for an exposure of 365.25 days. We define N_{prompt} as the number of distinct PMTs with hits within the 10 ns prompt timing window. For the idealized low-threshold $N_{\mathrm{prompt}} \geq 8$ scenario, in which PMT radioactivity is neglected, the total uncertainty on the reactor-spectrum normalization is $^{+1.08\%}_{-1.07\%}$. For the more restrictive $N_{\mathrm{prompt}} \geq 20$ scenario, used to suppress low-energy PMT backgrounds, the total uncertainty is $^{+1.49\%}_{-1.47\%}$. These results demonstrate that directional information from a water Cherenkov detector can provide percent-level sensitivity to the reactor elastic-scattering normalization.

Keywords: Cherenkov detectors, Neutrino detectors, Detector modelling and simulations I, Analysis and statistical methods

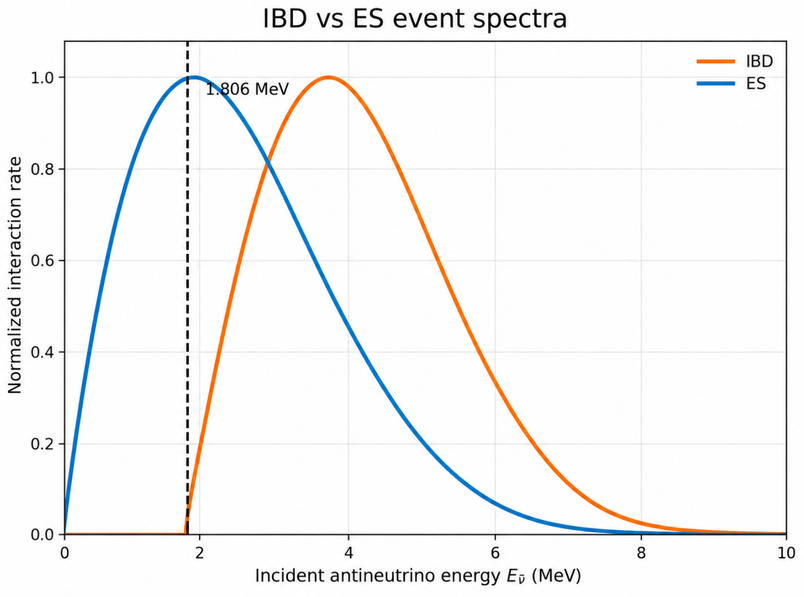
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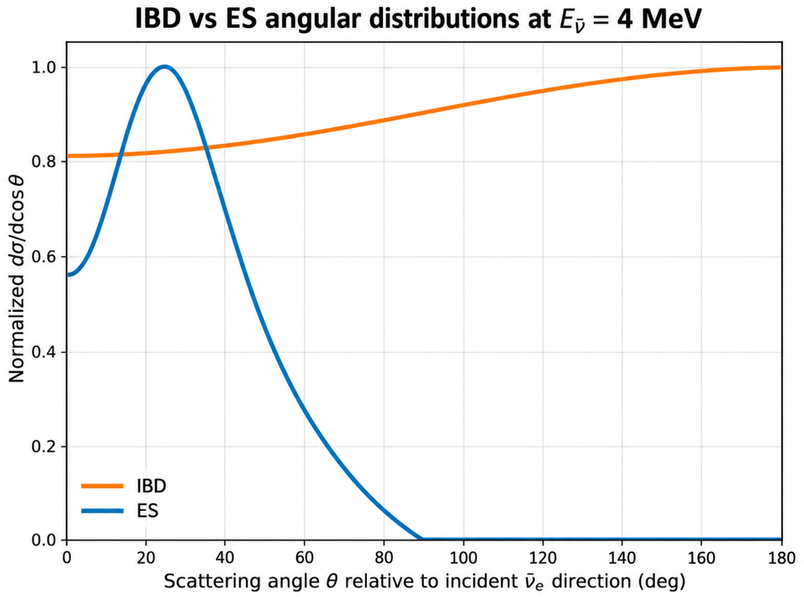
INTRODUCTION

IBD vs ES

- Inverse beta decay(IBD), $\bar{\nu}_e + p \rightarrow e^+ + n$, restriction :
  - Incident antineutrino-energy threshold of approximately 1.806 MeV
  - The e+ direction is weakly correlated with the incident antineutrino direction

- Elastic scattering(ES), $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$:
  - no reaction threshold
  - the recoil electron is predominantly emitted in the forward direction



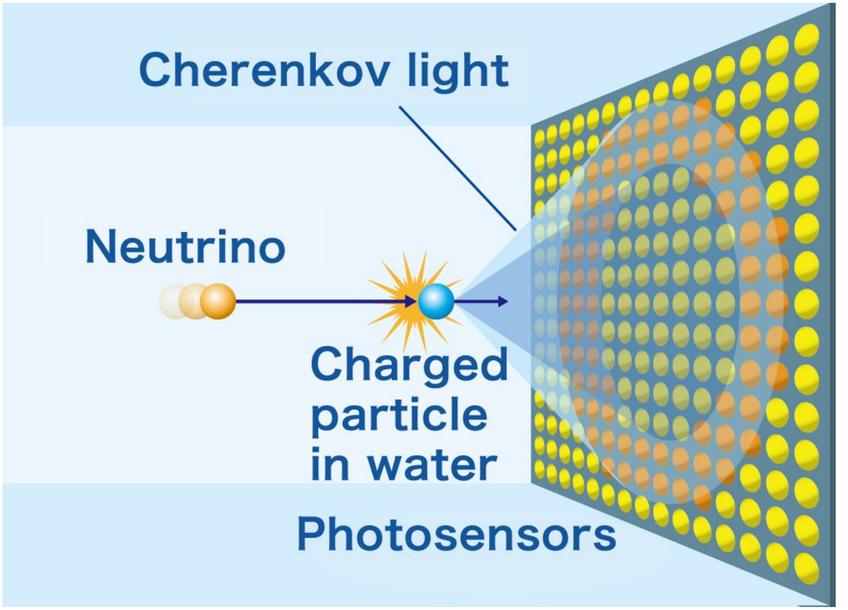


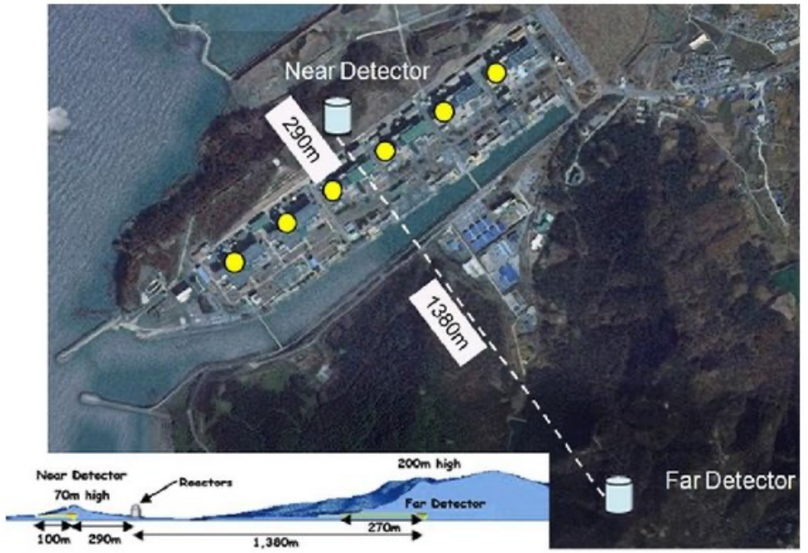
INTRODUCTION

Cherenkov Detector at RENO ND site

- A water Cherenkov detector is suited for exploiting this forward-scattering signature
  - Water provides a large number of target electrons at relatively low material cost
  - Cherenkov photons provides both the interaction vertex and the recoil-electron direction

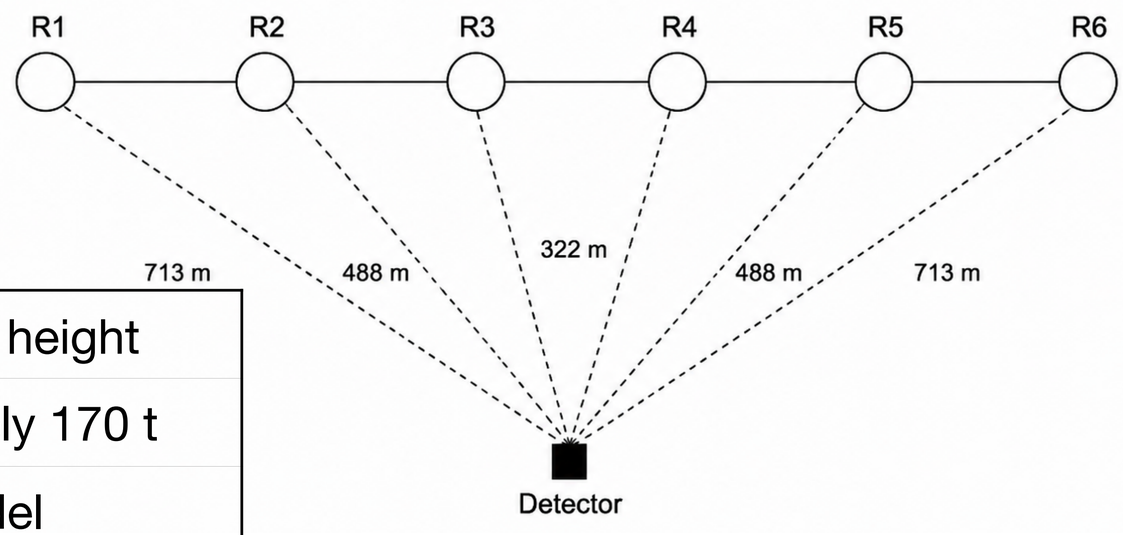
- We evaluate the expected performance of a 170 t pure-water Cherenkov detector located at the RENO near-detector site
  - The short baselines to the six Hanbit reactor cores
    -> high ES interaction rate



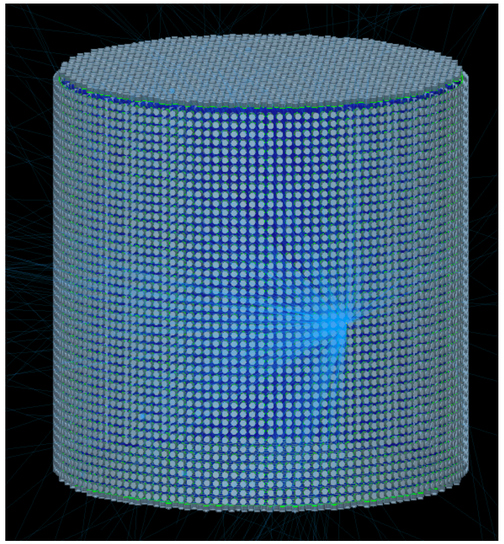


DETECTOR CONCEPT

Detector Geometry



Target geometry	Cylinder, 6 m diameter x 6 m height
Target medium and mass	Ultra-pure water, approximately 170 t
Photosensor model	Reference 4 in PMT model
PMT dimensions	102 mm outer diameter (95 mm active photocathode)
PMT arrangement	9,480 total 1,545 top, 1,545 bottom, 6,390 side
Photocathode coverage	39.6%
Photocathode efficiency	Wavelength dependent; 27% peak at 370 nm
Single-photoelectron timing resolution	1 ns

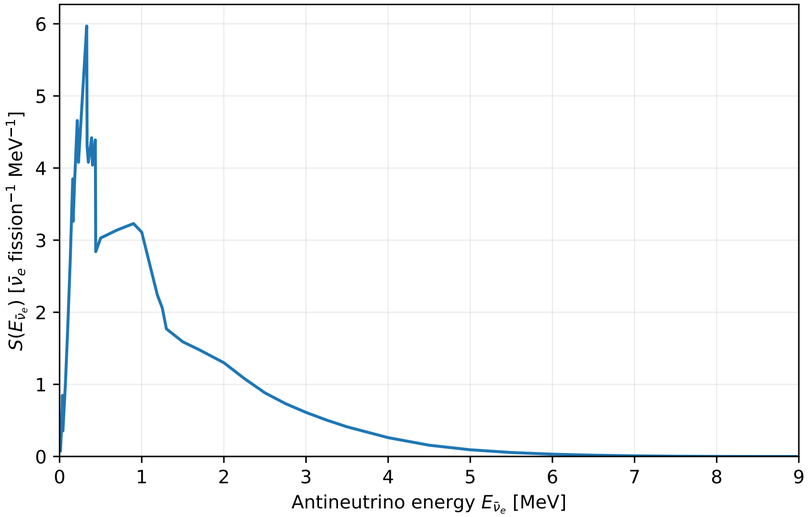


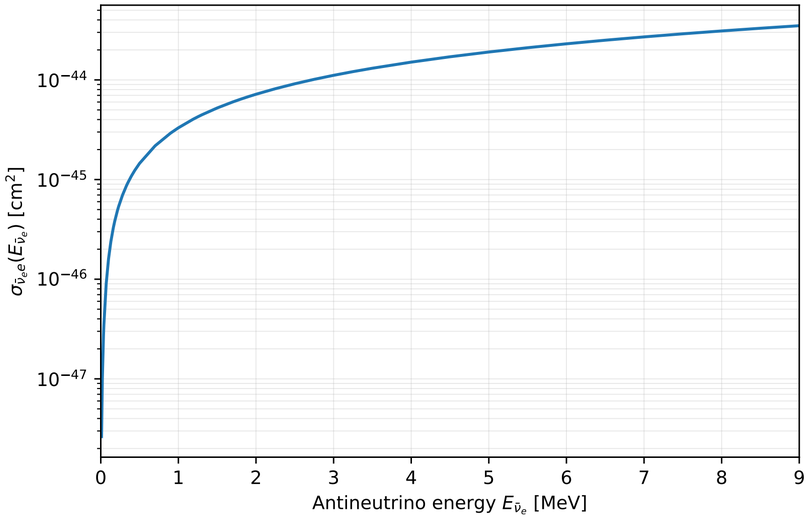
EXPERIMENTAL CONDITIONS

Hanbit Reactor Configuration and Expected Signal Rate

- A Thermal power of 2.8 GWth for each cores, an average energy release of 200 MeV per fission are assumed

Reactor cores	Baseline	Number of cores	Rate per core (/day)	Subtotal (/day)
3 and 4	322 m	2	1,050	2,090
2 and 5	488 m	2	456	912
1 and 6	713 m	2	214	427
Total	-	6	-	3,430





EXPERIMENTAL CONDITIONS

Expected Background Sources

- Any process producing a reconstructed electron-like event in the water can enter the selected sample

- The background model includes :
  PMT radioactivity (reference PMT model)
  Cosmogenic isotopes (muon rate of RENO ND)
  Water-borne radon (0.14 mBqm-3 (SK))

  Inverse beta decay
  (when the accompanying neutron is not identified)

Component	Nominal physical rate
PMT ^{214}Bi	(113 ± 21) day^{-1} PMT^{-1}
PMT ^{208}Tl	(31 ± 8) day^{-1} PMT^{-1}
PMT ^{40}K	$(2.60 \pm 0.42) \times 10^3$ day^{-1} PMT^{-1}
PMT ^{60}Co	(161 ± 21) day^{-1} PMT^{-1}
^{12}B	$(1.60 \pm 0.13) \times 10^3$ day^{-1}
^{12}N	$(2.00 \pm 0.22) \times 10^2$ day^{-1}
^{16}N	$(3.30 \pm 0.41) \times 10^3$ day^{-1}
^{8}Li	$(7.00 \pm 0.60) \times 10^2$ day^{-1}
Water ^{214}Pb	2.1×10^3 day^{-1}
Water ^{214}Bi	2.1×10^3 day^{-1}
Reactor IBD	1.26×10^4 day^{-1}

EVENT RECONSTRUCTION

Hit Preprocessing and Prompt-hit Selection

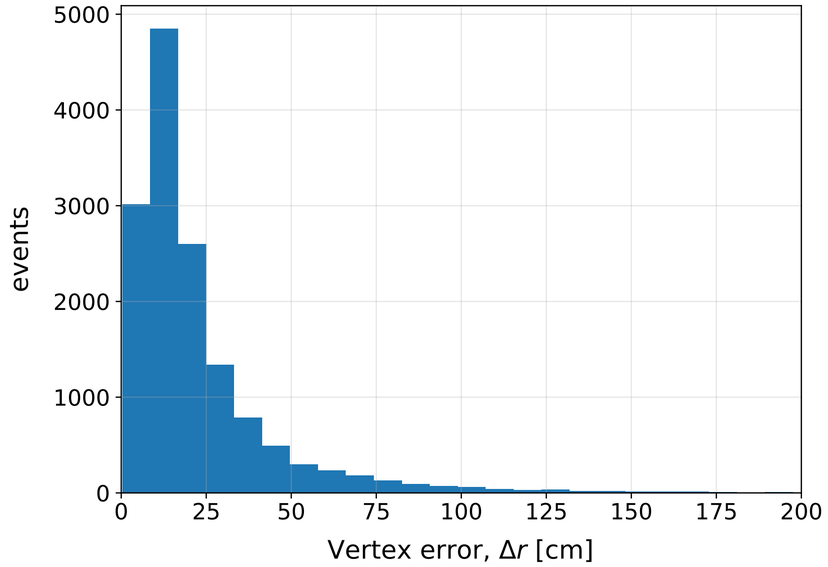
- The signal and background samples used in this study were generated with RAT-PAC

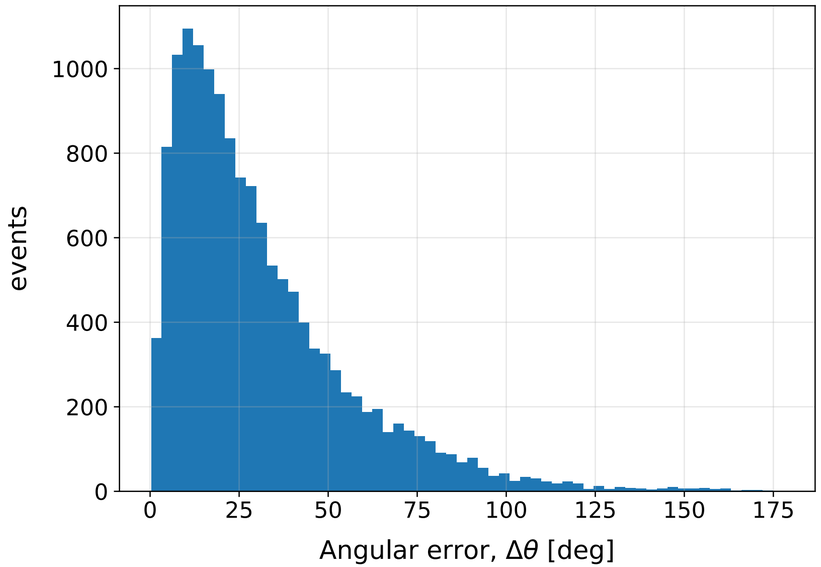
- We defined the earliest representative PMT hit time, t_{min},
  a prompt-hit set was formed relative to the earliest PMT time in each event,
  $\Delta t_i = t_i - t_{min}$
- Events were required to contain at least 8 distinct PMTs satisfying
  $\Delta t_i < 10\ ns$
- The number of PMTs satisfying this condition is denoted N_{prompt}
  -> This selection helps to improve reconstruction performance and analysis

EVENT RECONSTRUCTION

Reconstruction Performance

- The vertex/direction reconstruction was adapted from the method developed for Super-Kamiokande.





- The median vertex error was 15.33 cm, the 68% containment was 22.00 cm
- The median angular error was 24.15˚, the 68% containment was 35.79˚

DIRECTIONAL ANALYSIS

Analysis Strategy

- Two minimum prompt-hit multiplicity requirements,
  $N_{prompt} \geq 8$ and $N_{prompt} \geq 20$, are considered.
  - For $N_{prompt} \geq 8$, only ~60 of the 1M simulated PMT 40K decays survived
    -> limited surviving sample does not provide sufficient statistical precision
    -> the PMT-radioactivity components are not included
    -> idealized low-threshold scenario

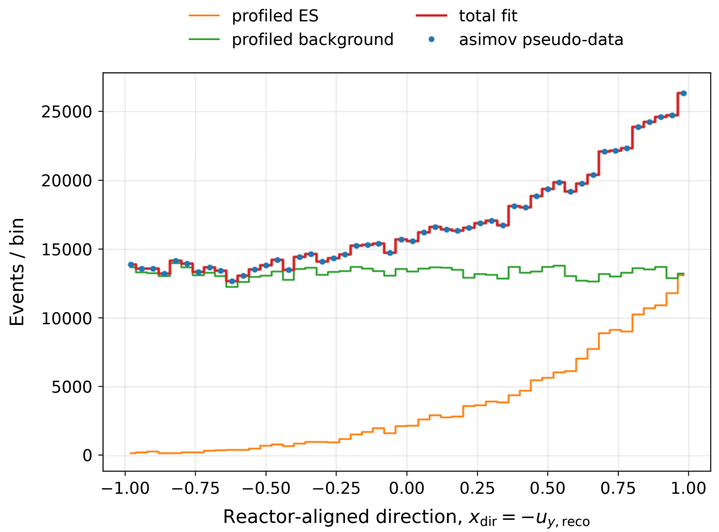
  - For $N_{prompt} \geq 20$, no event survives (PMT 40K, 60Co)
    -> 208Tl and 214Bi components are retained
    -> low-energy PMT backgrounds suppression scenario

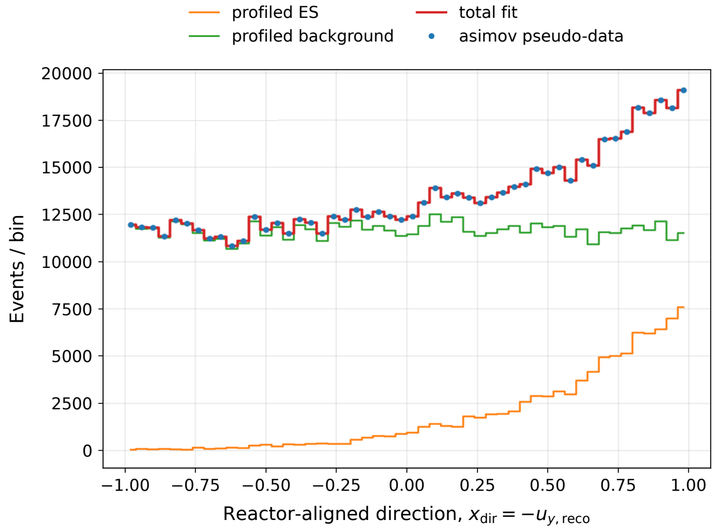
PROJECTED PERFORMANCE

Reactor-flux Normalization Extraction

- Signal and background templates were constructed
  -> The reactor-flux normalization was extracted
  using a constrained profile-likelihood fit
  by minimizing the NLL.

- The expected yields are obtained from the physical interaction rates, the simulated selection efficiencies, and the 365.25-day exposure.





PROJECTED PERFORMANCE

Uncertainty Summary

Statistical and signal-normalization inputs		
Poisson event counts	Determined by the expected yield	Included through the binned Poisson likelihood.
ES selection efficiency	Finite-Monte-Carlo binomial uncertainty	Included as a constrained signal-normalization nuisance.
Spectrum-averaged ES cross section	0.5%	Included as a constrained signal-normalization nuisance in the reactor-flux fit.
Background-normalization inputs		
^{8}Li production rate	8.57%	Combined with the finite-Monte-Carlo efficiency uncertainty and profiled.
^{12}B production rate	8.13%	
^{12}N production rate	11.0%	
^{16}N production rate	12.42%	
Residual IBD normalization	Tagging scenarios: 0, 50, 90, and 100%	The residual IBD yield is treated as an additional background component. No additional physical-rate uncertainty is assigned; the finite-Monte-Carlo selection-efficiency uncertainty remains active when IBD is present.
PMT ^{40}K activity	16.15%	PMT sources are excluded from the idealized reference $N_{\text{prompt}} \geq 8$ scenario. For $N_{\text{prompt}} \geq 20$, the central ^{40}K yield is set to zero because no simulated event survives.
PMT ^{208}Tl activity	25.81%	
PMT ^{214}Bi activity	18.58%	
PMT ^{60}Co activity	13.04%	For $N_{\text{prompt}} \geq 20$, the central ^{60}Co yield is set to zero because no simulated event survives.
Radon-daughter rates	No physical-rate uncertainty assigned	The radon concentration is fixed to the adopted value; finite-Monte-Carlo efficiency uncertainties remain active.

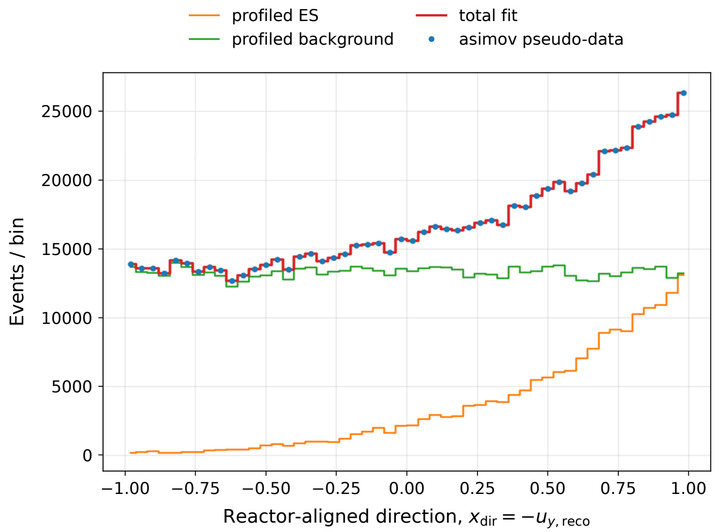
PROJECTED PERFORMANCE

All-energy Reactor-flux Projection

- For $N_{prompt} \geq 8$, the projected reactor flux is

$$\Phi_{\bar{\nu}_e} = 1.449 \times 10^{11}\ cm^{-2}s^{-1}$$
$$^{+5.95 \times 10^{8}}_{-5.94 \times 10^{8}}\ (stat.)$$
$$^{+1.56 \times 10^{9}}_{-1.54 \times 10^{9}}\ (total)$$

the statistical uncertainty is $^{+0.411\,\%}_{-0.410\,\%}$, the total uncertainty is $^{+1.08\,\%}_{-1.07\,\%}$.

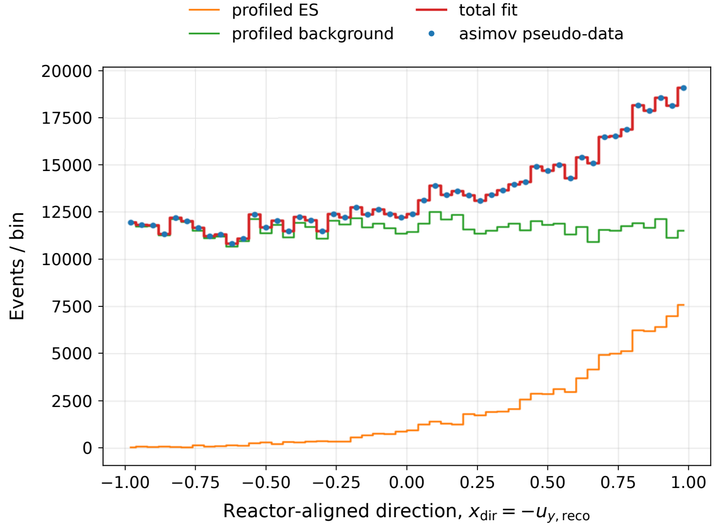


$N_{prompt} \geq 8$

- For $N_{prompt} \geq 20$, the projected reactor flux is

$$\Phi_{\bar{\nu}_e} = 1.449 \times 10^{11}\ cm^{-2}s^{-1}$$
$$^{+9.38 \times 10^{8}}_{-9.37 \times 10^{8}}\ (stat.)$$
$$^{+2.16 \times 10^{9}}_{-2.13 \times 10^{9}}\ (total)$$

the statistical uncertainty is $^{+0.648\,\%}_{-0.647\,\%}$, the total uncertainty is $^{+1.49\,\%}_{-1.47\,\%}$.



$N_{prompt} \geq 20$

PROJECTED PERFORMANCE

Impact of Residual Inverse-beta-decay Background

Prompt-hit requirement	Assumed IBD tagging	Residual IBD	Total background	S/B	Statistical $\delta\Phi/\Phi$	Total $\delta\Phi/\Phi$
$N_{\text{prompt}} \geq 8$	0%	2,136,686.2	2,801,955.9	0.0643	$^{+0.698\%}_{-0.698\%}$	$^{+1.346\%}_{-1.333\%}$
$N_{\text{prompt}} \geq 8$	50%	1,068,343.1	1,733,612.8	0.1039	$^{+0.573\%}_{-0.573\%}$	$^{+1.219\%}_{-1.207\%}$
$N_{\text{prompt}} \geq 8$	90%	213,668.6	878,938.3	0.2049	$^{+0.448\%}_{-0.448\%}$	$^{+1.107\%}_{-1.096\%}$
$N_{\text{prompt}} \geq 8$	100%	0.0	665,269.7	0.2707	$^{+0.410\%}_{-0.410\%}$	$^{+1.076\%}_{-1.066\%}$
$N_{\text{prompt}} \geq 20$	0%	1,434,536.2	2,017,671.6	0.0465	$^{+1.054\%}_{-1.053\%}$	$^{+1.879\%}_{-1.856\%}$
$N_{\text{prompt}} \geq 20$	50%	717,268.1	1,300,403.5	0.0722	$^{+0.875\%}_{-0.874\%}$	$^{+1.697\%}_{-1.675\%}$
$N_{\text{prompt}} \geq 20$	90%	143,453.6	726,589.0	0.1292	$^{+0.699\%}_{-0.698\%}$	$^{+1.535\%}_{-1.514\%}$
$N_{\text{prompt}} \geq 20$	100%	0.0	583,135.4	0.1610	$^{+0.647\%}_{-0.647\%}$	$^{+1.491\%}_{-1.471\%}$

PROJECTED PERFORMANCE

Idealized Projections with Event-level True-energy Selections

Prompt-hit requirement	True-energy selection	PMT radioactivity	N_{ES}	N_{bkg}	S/B	Statistical $\delta\Phi/\Phi$	Total $\delta\Phi/\Phi$
$N_{\mathrm{prompt}} \geq 8$	$T_e^{\mathrm{true}} < 3\,\mathrm{MeV}$	Excluded	136,434.8	139,049.2	0.981	$^{+0.350\%}_{-0.350\%}$	$^{+1.133\%}_{-1.120\%}$
$N_{\mathrm{prompt}} \geq 8$	$T_e^{\mathrm{true}} \geq 3\,\mathrm{MeV}$	Subdominant	43,684.7	526,220.5	0.083	$^{+1.177\%}_{-1.175\%}$	$^{+2.304\%}_{-2.260\%}$
$N_{\mathrm{prompt}} \geq 20$	$T_e^{\mathrm{true}} < 3\,\mathrm{MeV}$	Included	52,577.2	43,962.7	1.196	$^{+0.538\%}_{-0.537\%}$	$^{+1.732\%}_{-1.703\%}$
$N_{\mathrm{prompt}} \geq 20$	$T_e^{\mathrm{true}} \geq 3\,\mathrm{MeV}$	Subdominant	41,326.8	539,172.7	0.077	$^{+1.249\%}_{-1.247\%}$	$^{+2.399\%}_{-2.353\%}$

- T < 3 MeV, backgrounds from PMTs are dominant
- T > 3 MeV, backgrounds from muons/radons are dominant

CONCLUSION

Future Plans

- Directional information from a water Cherenkov detector can provide percent-level sensitivity to the reactor elastic-scattering normalization

- Validated recoil-energy reconstruction and improved background characterization are the principal requirements for extending the physics reach of this approach.
- A future analysis could incorporate the known reactor geometry and the time-dependent contributions of the individual cores into a joint likelihood or unfolding framework combining recoil-energy and directional information.