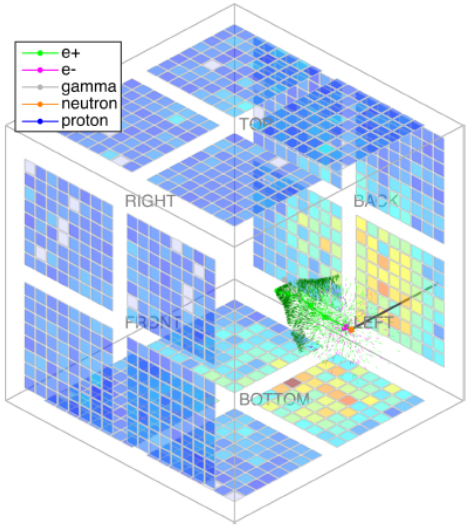
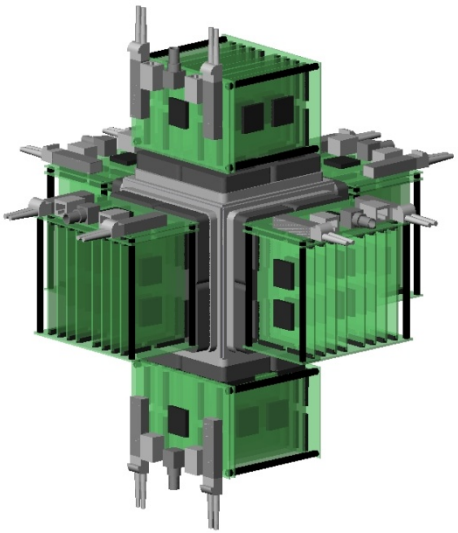


miniTimeCube

Applied Antineutrino Physics
Arlington, VA
December 7, 2015



University of Hawaii
R. Dorrill, M.J. Duvall, J. Koblanski, J.G. Learned, V.A. Li, L. Macchiarulo, S. Matsuno, J. Murillo, S. Negrashov, M. Rosen, M. Sakai, G.S. Varner

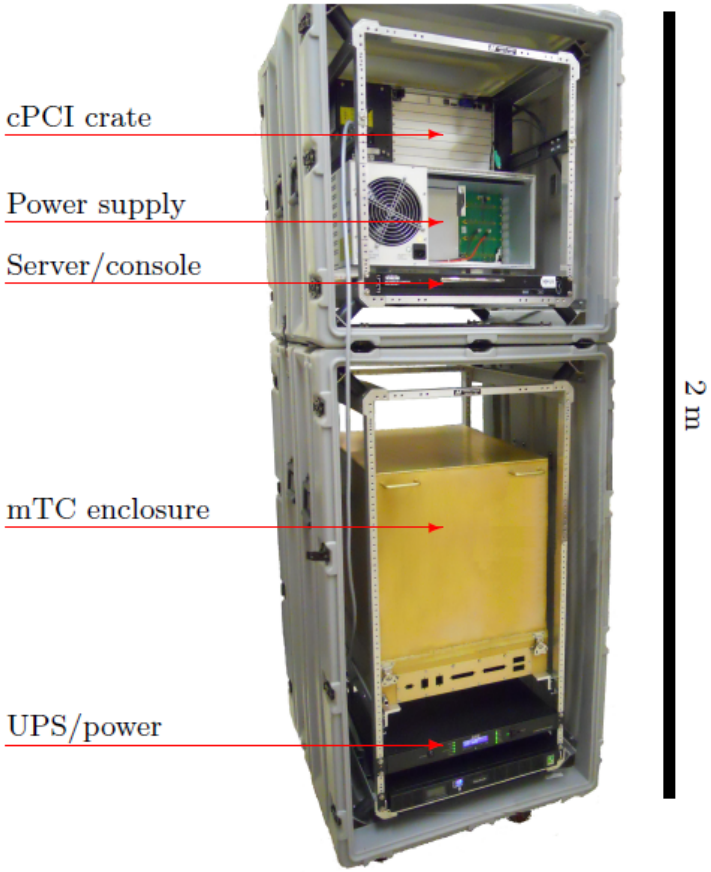
University of Maryland
W.F. McDonough, K. Engel, S.A. Wipperfurth

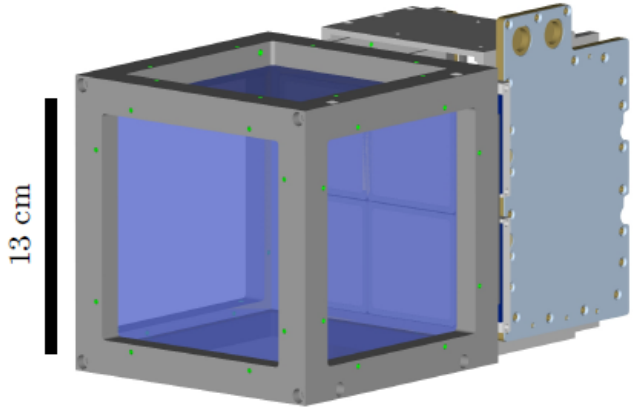
Ultralytics
G. Jocher, K. Nishimura

NIST
H.P. Mumm

NGA
S.M. Usman

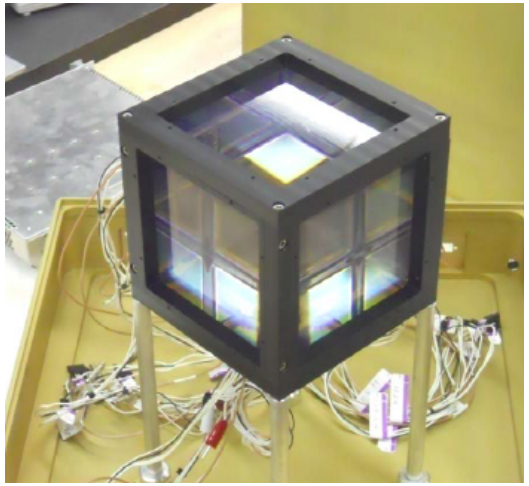
miniTimeCube (mTC) Concept

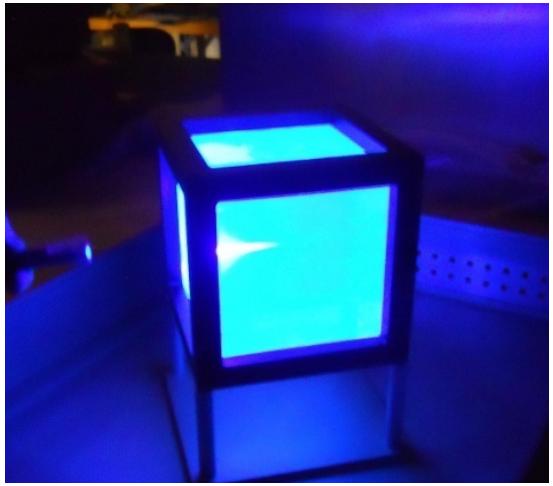




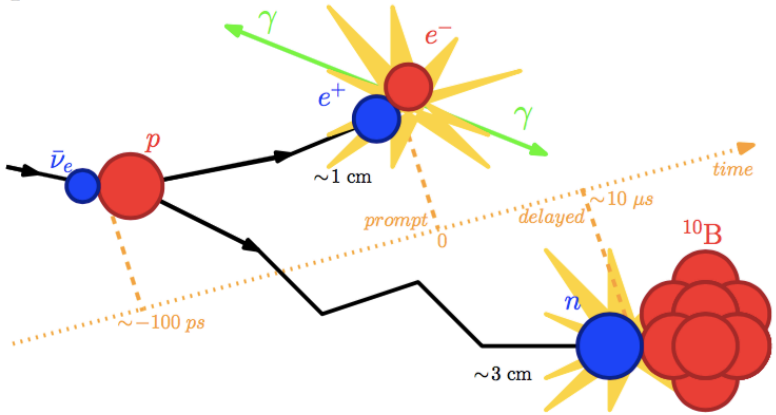
- Technology demonstrator:
  - Scintillator-based IBD detection.
  - Single compact detection volume (2.2 L).
  - Portable.
  - Fast timing (100 ps) for event reconstruction rather than optics.
    - Fast microchannel plate PMTs (MCP-PMTs).
    - Multi-GHz sampling electronics.

mTC Scintillator

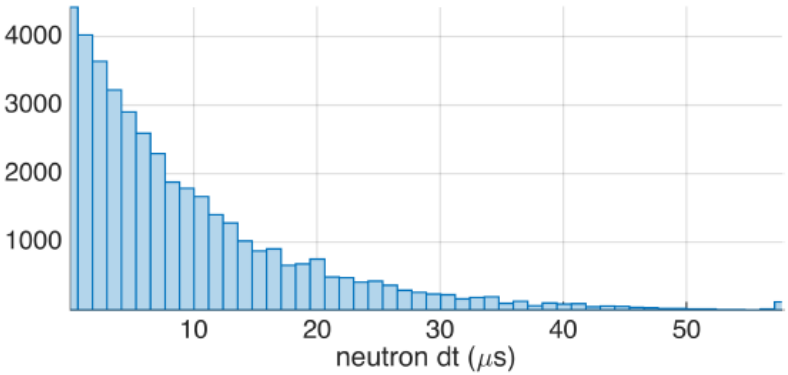


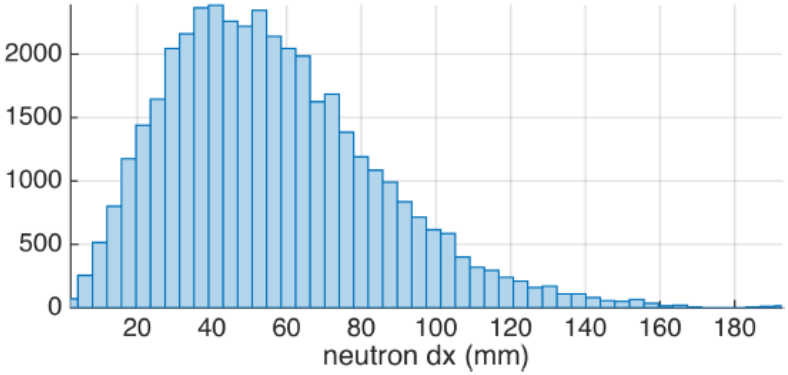


$$\bar{\nu}_e + p \rightarrow e^+ + n$$



$$n + {}^{10}\mathrm{B} \rightarrow {}^{7}\mathrm{Li}^* + {}^{4}\mathrm{He}(1471\ \mathrm{keV})$$
$$\hookrightarrow {}^{7}\mathrm{Li}^* \rightarrow {}^{7}\mathrm{Li}(839\ \mathrm{keV}) + \gamma(478\ \mathrm{keV})$$

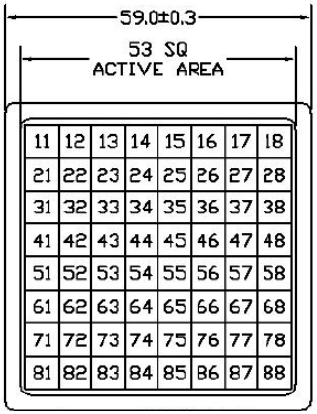


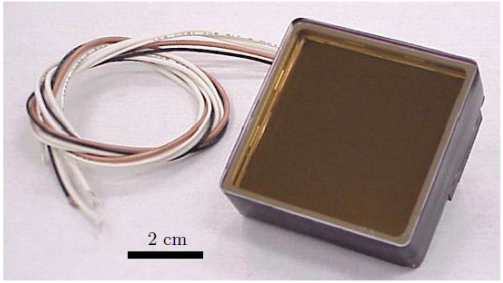


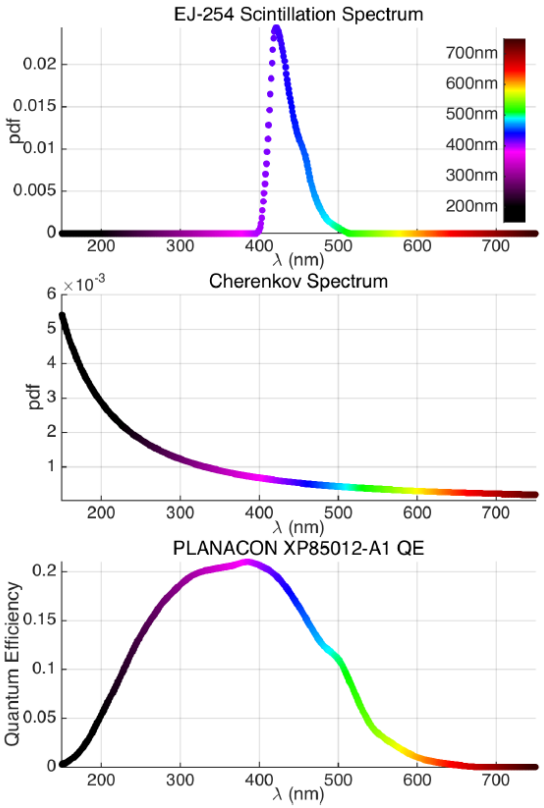
- Eljen Technology, EJ-254
- 1% boron-doped plastic scintillator.
  - 0.2% ^{10}B
- Fast: 2.2 ns decay time
- Dimensions: 13 cm x 13 cm x 13 cm
  - IBD neutrons: typically travel ~5 cm in ~10 us.
  - Efficiency for neutron interaction in the volume is ~50%.
  - Size is such that annihilation gammas deposit, on average, ~1/3 of their energy.

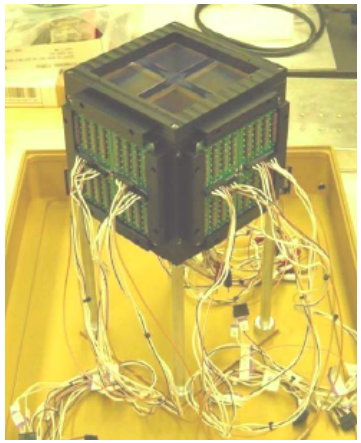
mTC Photodetectors: MCP-PMTs

- Photonis Planacon XPS85012
  - 25 µm pores.
  - 8x8 anode structure.
  - Active area ~28 cm^2.
  - Typical gain ~few x 10^6.
  - Transit time spread:
    - ~120 ps FWHM.
    - ~50 ps σ core.
- Total of 24 MCP-PMTs:
  - Photocathode area: 674 cm^2 (66%).
  - 1536 channels.

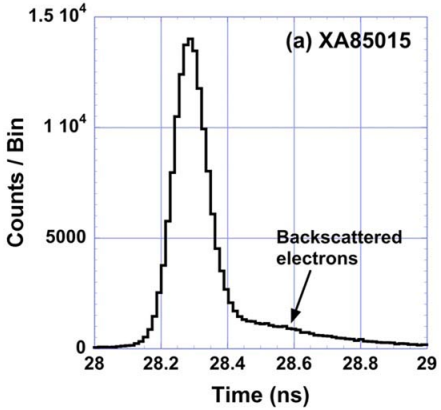








Partially populated mTC.

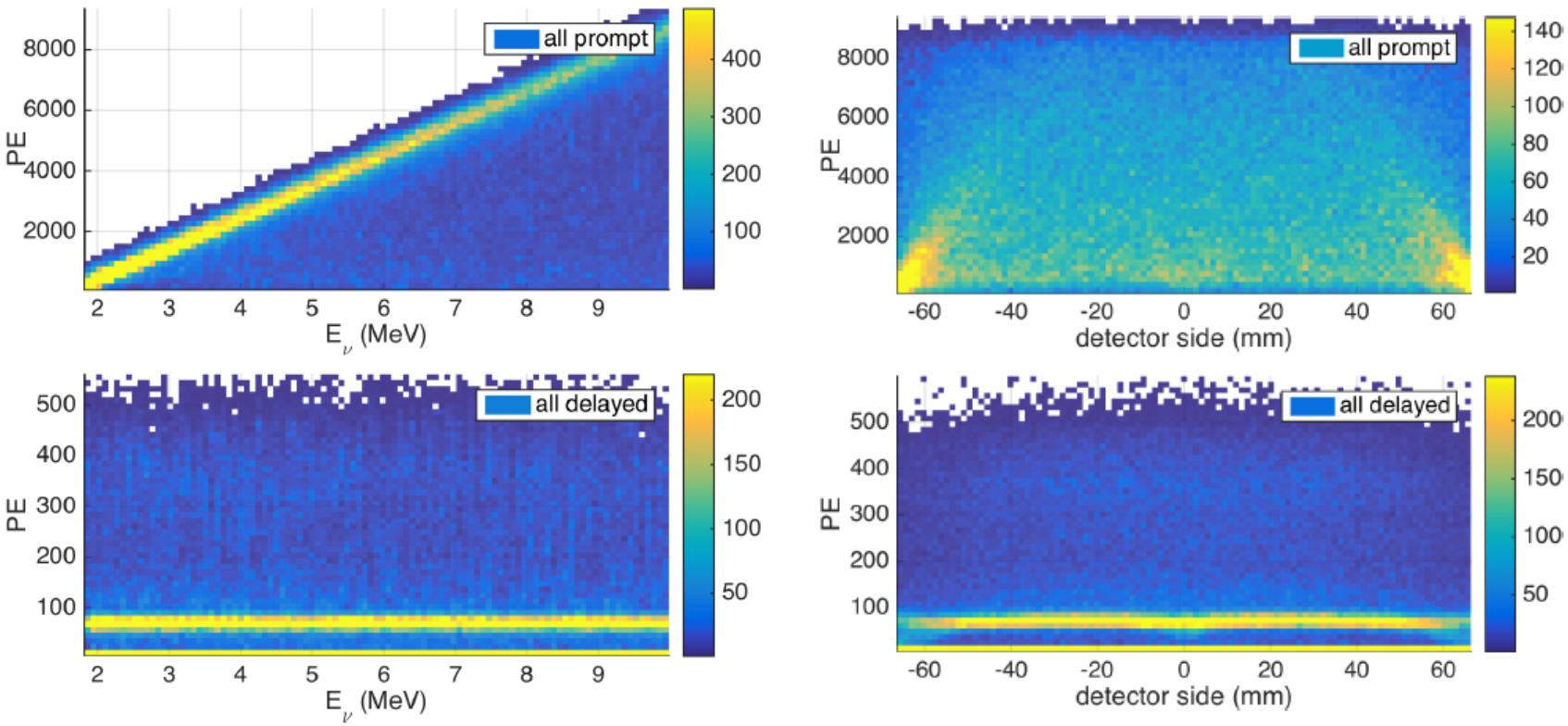


Timing distribution from IEEE Trans Nucl Sci. 2010 Sep 13; 57(5): 2417–2423.

Expected IBD Prompt & Delayed Signals

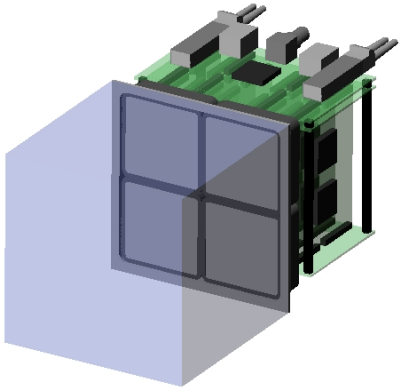
- Simulated prompt and delayed PE distributions, including:
  - Scintillator optical properties.
  - Optical couplings and optical properties of MCP-PMT glass.
  - MCP-PMT quantum efficiency.

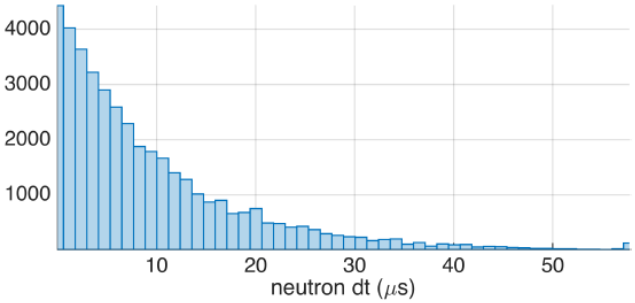
- Prompt signal:
  - Generally thousands of PE (many per channel).
  - Long-tail of "missing PE":
    - Escaping positrons increasingly likely at high E.
- Delayed signal:
  - Typically < 100 PE (<< 1 PE per channel).

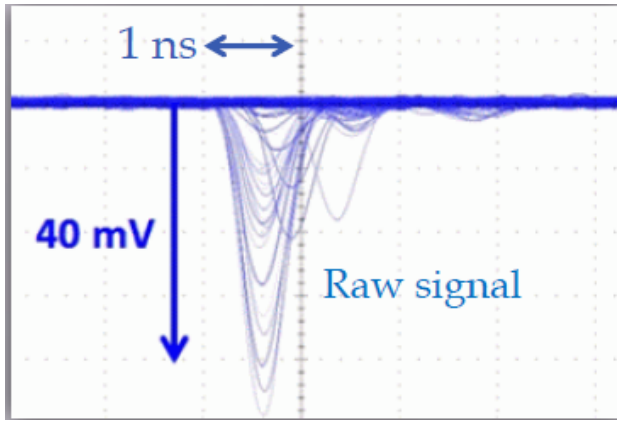


Readout Electronics Requirements

- High channel density:
  - 1536 channels in a small volume.
- Deep buffering to accommodate long potential delay between prompt and delayed IBD signals.
  - Many tens of microseconds.
- Self-triggering capabilities.
  - Delayed signal requires channel-level triggering on single PE signals.
- Must preserve fast timing information from MCP-PMTs.
  - Waveform information desired to correct for crosstalk, properly analyze multi-PE events, etc.





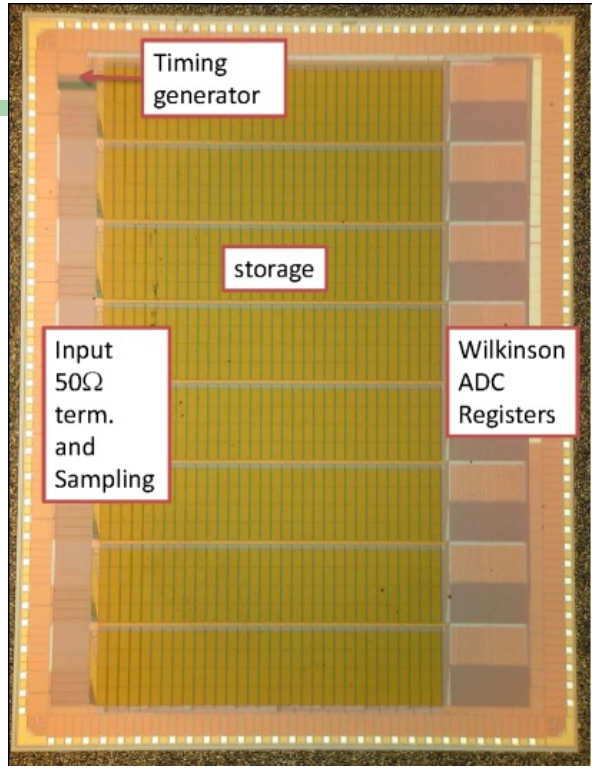


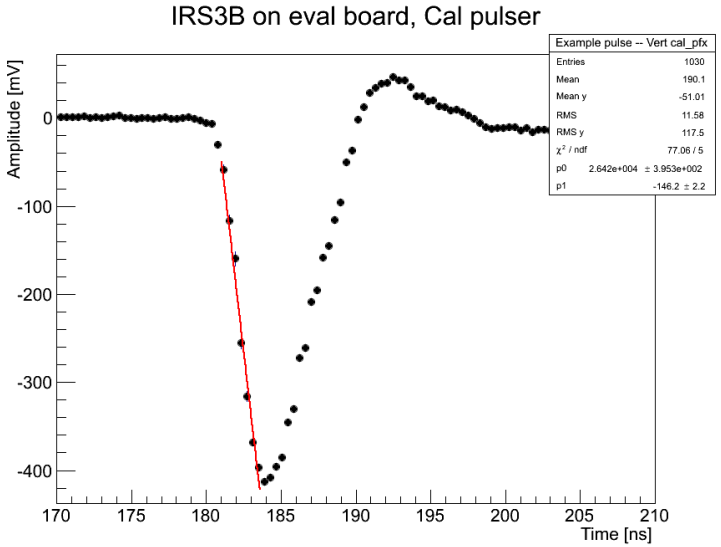
*Example MCP-PMT pulse (not Planacon)

Front-end Readout ASIC

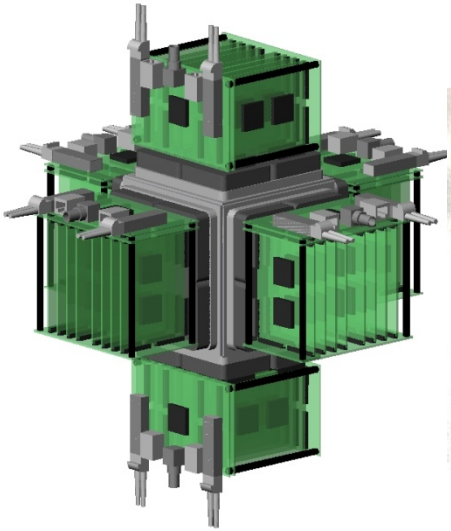
- MCP-PMT signals digitized by waveform sampling electronics:

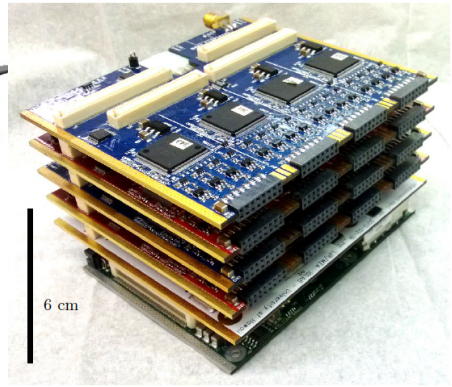
- "IRS" series ASICs - switched capacitor array with deep buffering.
  - 8 channels per ASIC.
  - Sampling rate up to 4 GSa/s.
    - Nominal operation at 2.7 GSa/s.
  - Buffer depth of 32,768 samples.
    - 12 µs at nominal sampling rate.
  - Channel-level triggers allow identification of regions-of-interest in analog storage memory.
  - On-chip ADC (Wilkinson) digitizes 64-sample blocks in ~few µs.

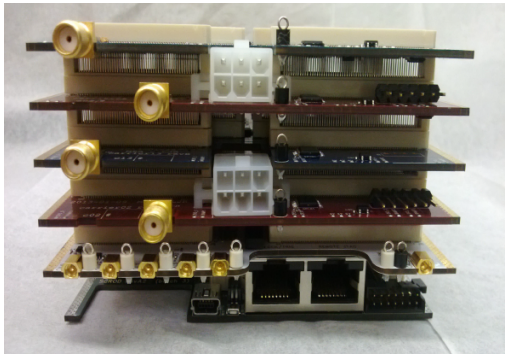


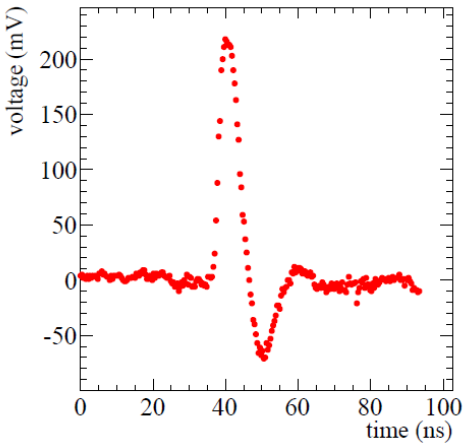


Front-end Electronics Packages









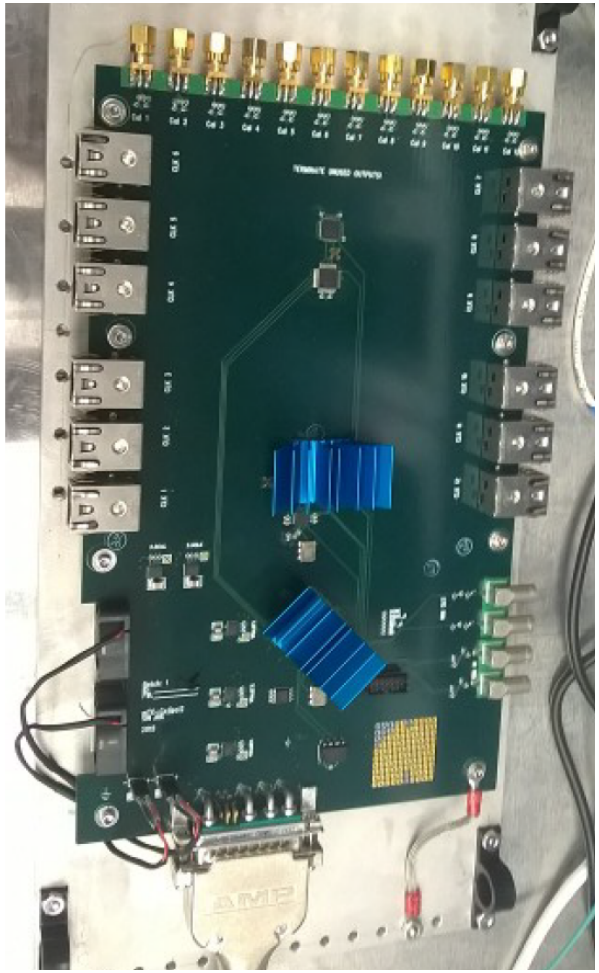
- IRS ASIC serves 8 channels.
- 4 x ASICs per “carrier board” (32 channels).
- 4 x carrier boards per “boardstack” (128 channels).
- One control board w/ FPGA per boardstack.
- One boardstack serves 2 Planacon MCP-PMTs.
- 12 boardstacks required to instrument 24 Planacons.
- Total envelope per boardstack ~10 cm x 10 cm x 8 cm.

- Cabling and interface requirements:
  - 2x CAT7, RJ45:
    - Trigger and clock.
    - Remote JTAG programming.
  - 2x LV power cable bundles: 3,4,5 V.
  - 1x fiberoptic interface to DAQ system.
  - MMCX, SMA for electrical calib signal.
  - Input/output cooling connections to chiller plates on boardstack housing.

System Electronics

- Central clock and trigger board:
  - Distributed clock synchronizes sampling on all ASICs in the system.
  - Receives lower-level trigger primitives from all boardstacks.
  - Issues system trigger to all boardstacks.
  - Fast calibration pulser with programmable delay for timing calibrations, verifications.

- Other custom PCBs:
  - High voltage distribution card.
  - JTAG programming card to reconfigure front-ends.

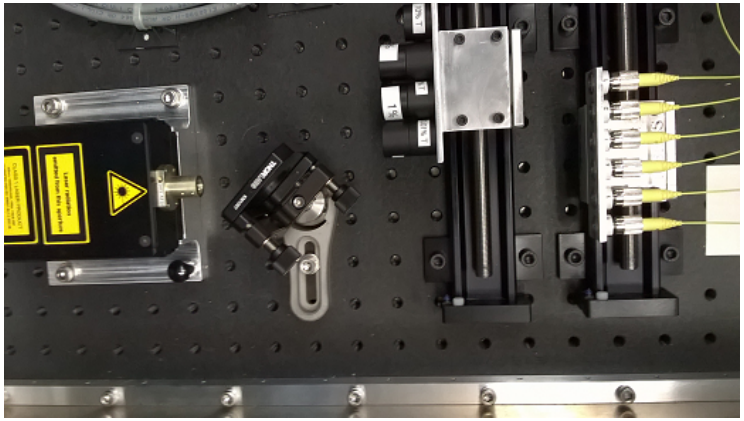


Clock and trigger distribution board

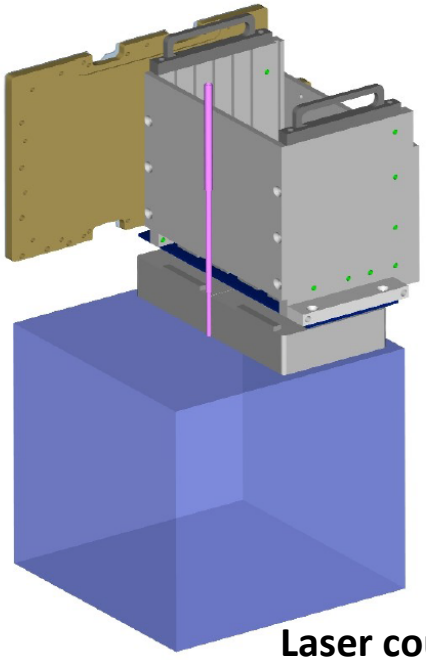
Auxiliary Systems

- Fast laser diode system:
  - Variable attenuation for single/multi PE studies.
  - Fiberoptic steering to inject at any of 6 faces.
- Data acquisition server.
  - Connections to front-end through commercial fiberoptic gigabit Ethernet PCI cards.
- Commercial LV and HV supplies.
- Cooling (required inside radiation shielding cave) provided by external chiller.
- UPS system.

Laser diode, attenuators, face selection



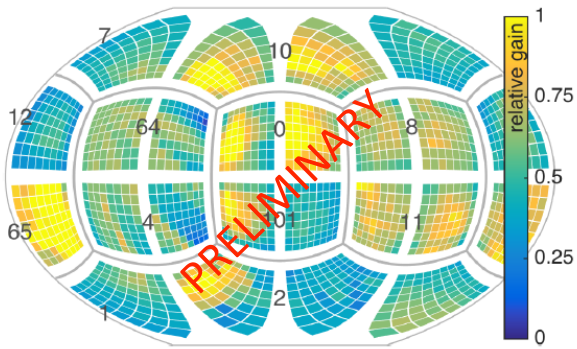
mTC chiller



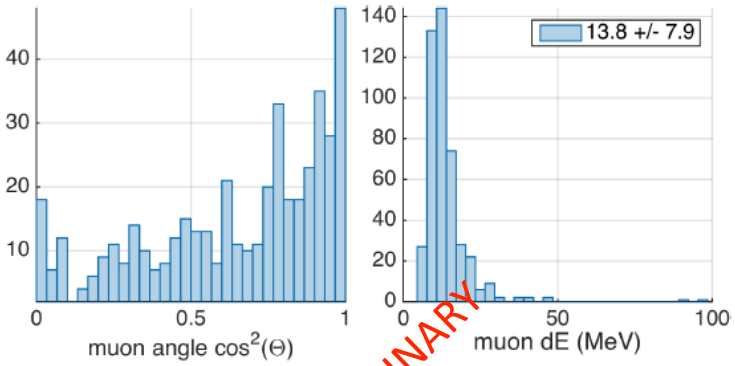
Laser coupling to mTC

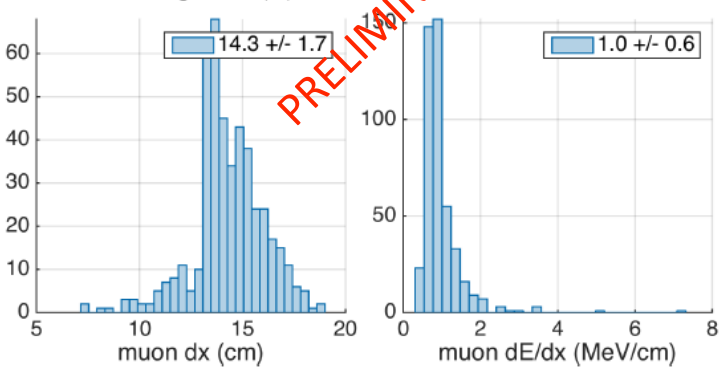
Ongoing Calibrations

- Calibrations required:
  - ASIC-level timing calibrations.
    - Waveform sampling technique results in non-uniform delays
  - Channel-level gain maps.
    - Laser injection at single PE levels.
  - Cosmic ray muons:
    - Calibrate light yields.
    - Validate timing calibrations and MC optical models.

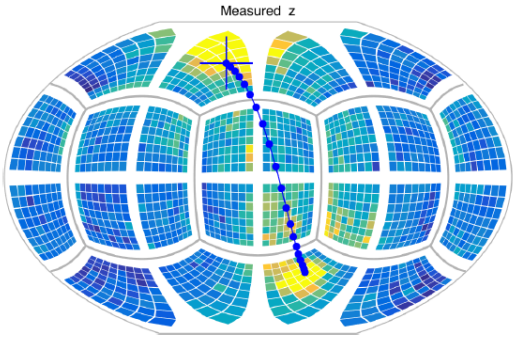


Preliminary relative gain map

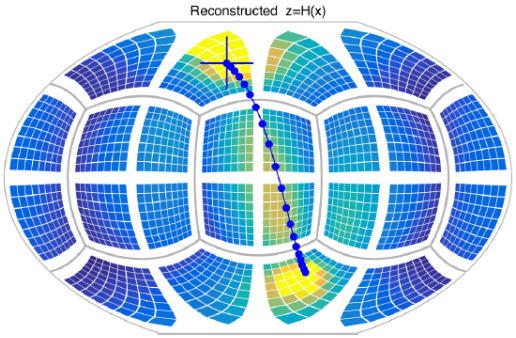




Reconstructed muon parameters



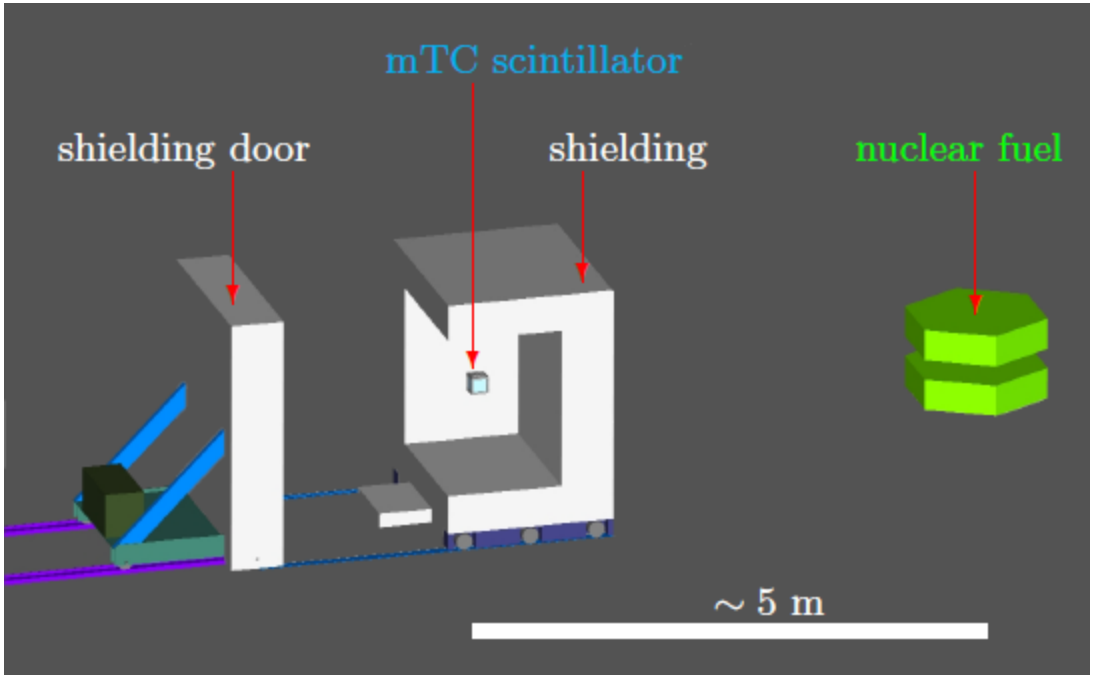
Measured muon event



Best fit reconstruction

Deployment at NCNR

- mTC will be deployed at NIST Center for Neutron Research (NCNR).
  - 20 MW research reactor.
  - ~5 meters from split-core.
  - ➔ ~1 detected neutrino per day.
  - Shielding cave required to limit neutron, gamma backgrounds.



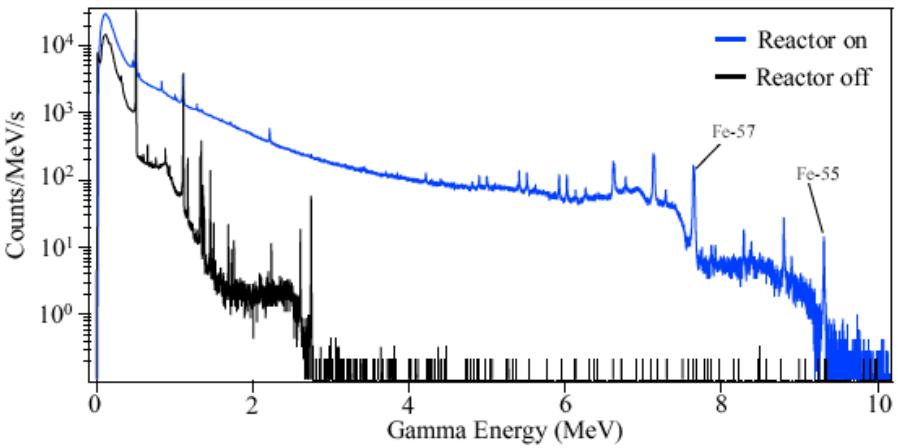
mTC in various venues

Parameter	NIST	TPR	Ship
Power, GW_{th}	0.02	3	1.1
⟨Baseline⟩, m	5	25	10
Fuel	HEU	mixed	HEU
Fuel cycle, on/off days	38/10	400/10	–
Compact core	☑	☐	☑
⟨Event rate⟩, $\bar{\nu}_e$/ day	~ 1	~ 10	~ 20

Background Simulations

- Geant4 simulations used to model muon, neutron, and gamma backgrounds.
  - With and without shielding enclosure:

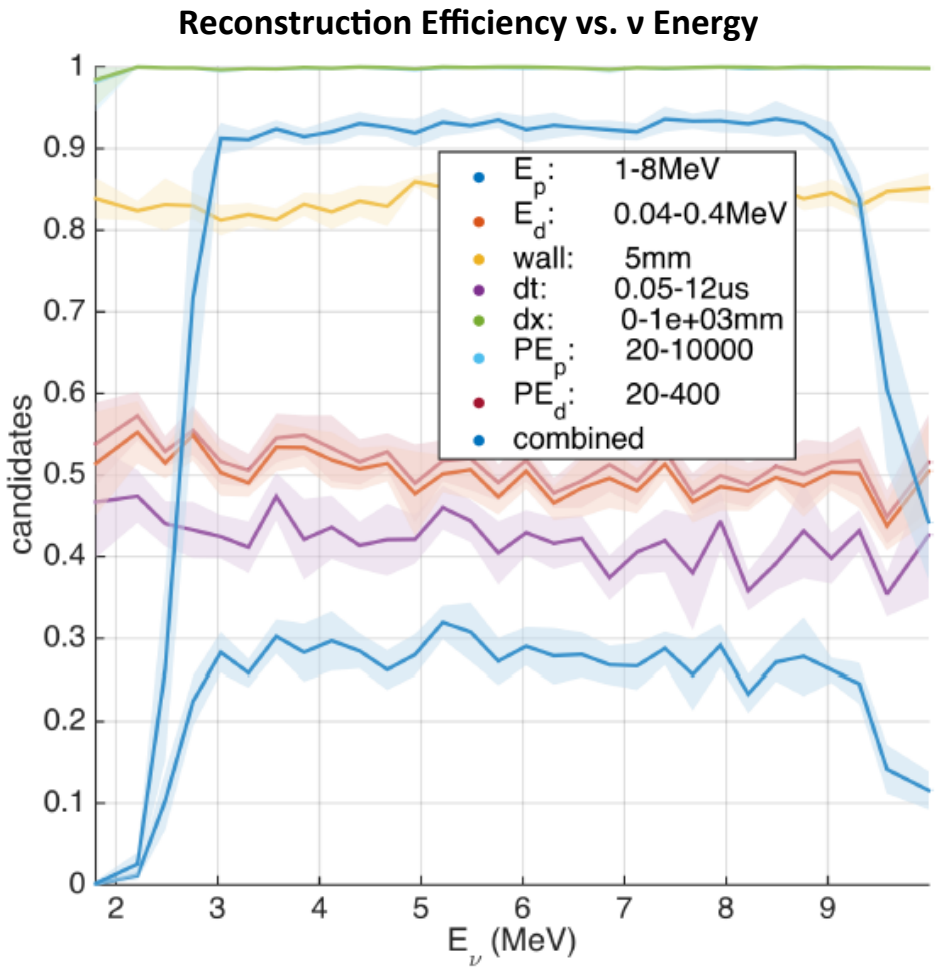
Type	normal	shielded	normal	shielded	attenuation
	#/mTC/s		#/cm^2/s		%
Muon	15	1.72	.017	2.0×10^{-3}	88.2%
Neutron	10151	0.082	12	9.7×10^{-5}	99.9%
Gamma	860	9.03	1.0	1.1×10^{-2}	98.9%



Unshielded HPGe gamma background spectra

- Shielded rates are used to estimate accidental coincidences that can fake our IBD signal:
  - ➔ Accidental rate estimated from simulation: ~1 / day
- This corresponds to an SNR of ~1:1.
- Correlated backgrounds need further study.

Reconstruction & Efficiency



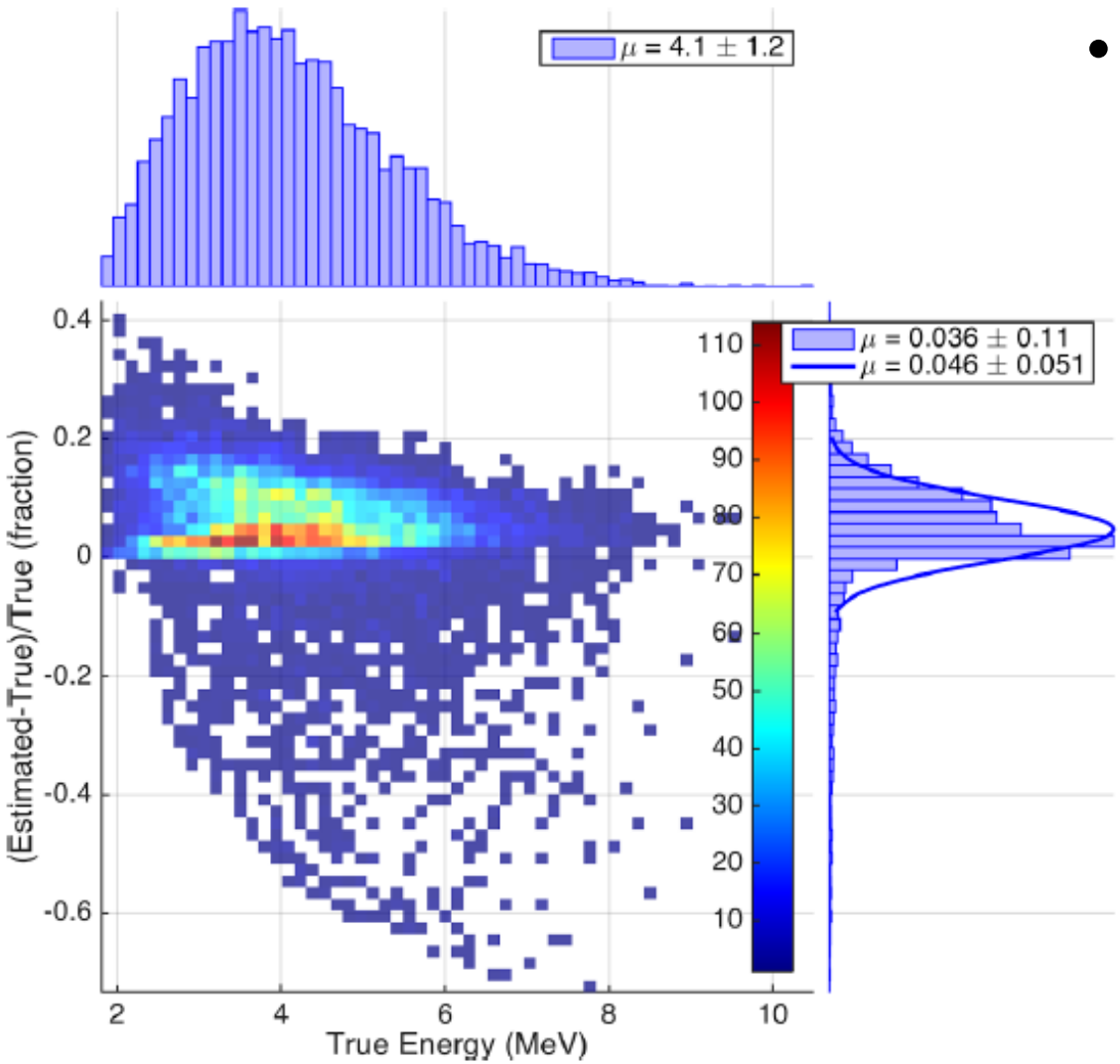
Preliminary reconstruction criteria developed to study performance on simulated IBD events:

- Both prompt and delayed vertices must be > 5 mm from any wall.
  - Reduces effective volume by 20%, from 2.2 L to 1.7 L.
- Time between prompt, delayed signals:
  - Minimum: 50 ns.
  - Maximum: 12 μs.
- Energy:
  - Prompt: 1 – 8 MeV.
  - Delayed: 40 – 400 keV.
- Detected PE:
  - Prompt: 20 – 10,000
  - Delayed: 20 – 400

*Results shown in this talk are for a maximum likelihood fit to two point sources to the prompt, delayed vertices.

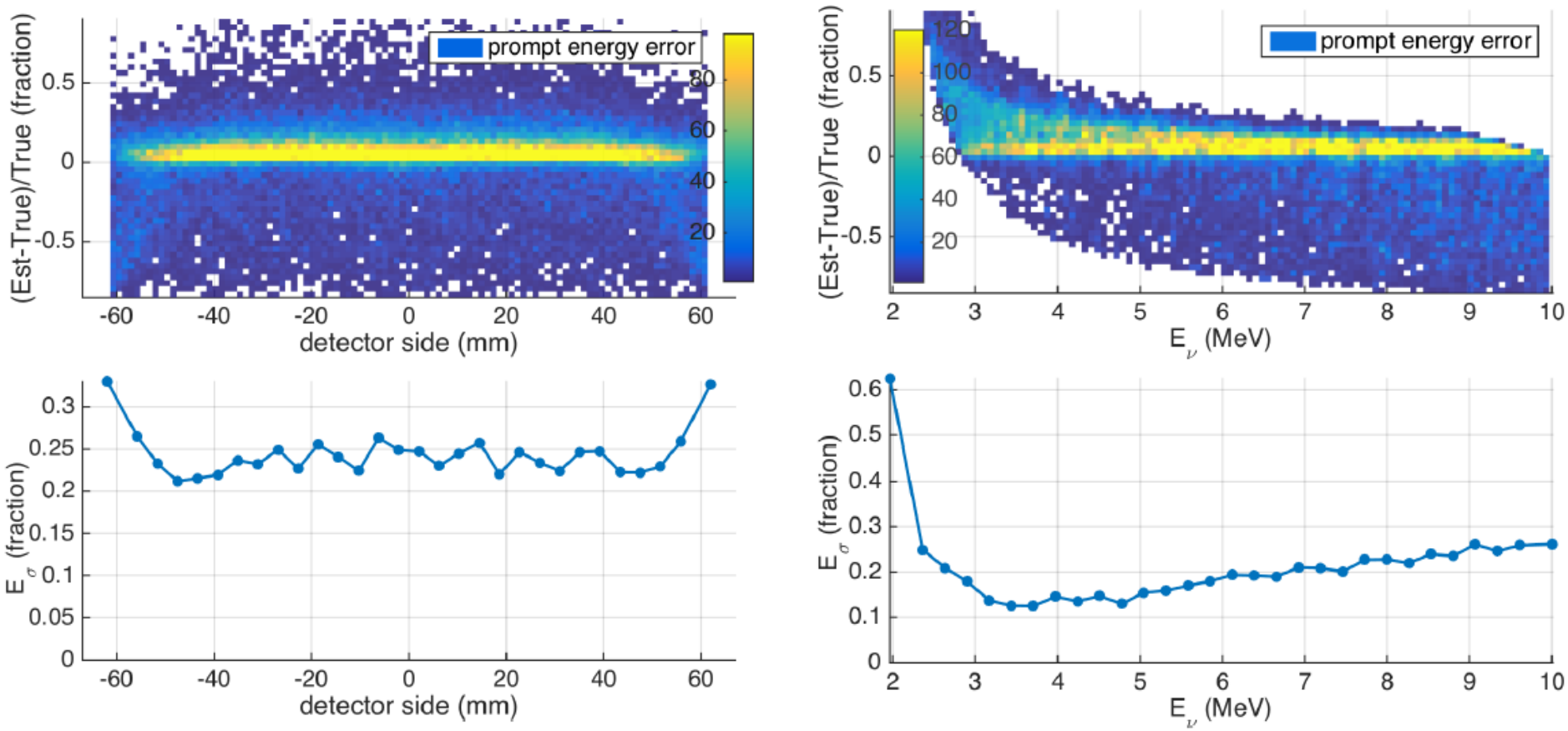
➔ Overall efficiency ~30%.

Simulated Energy Resolution (1)



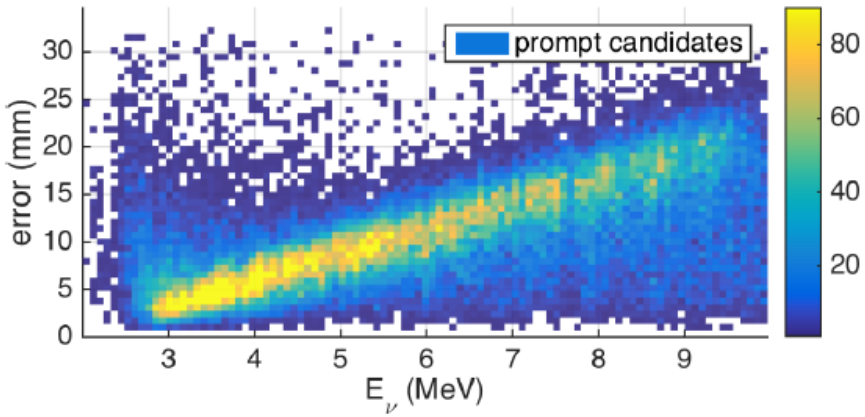
- Expected energy resolution, weighted by reactor spectrum:
  - ~11% including tail.
  - Tail largely correlated with higher energy events where positron is not fully contained.

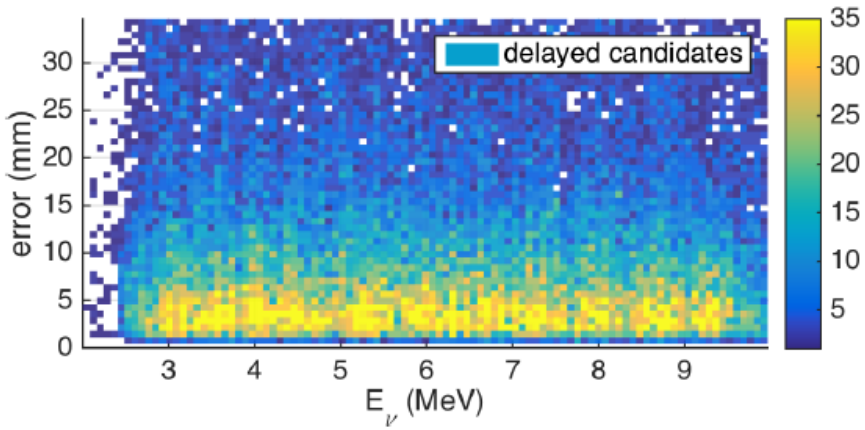
Simulated Energy Resolution (2)



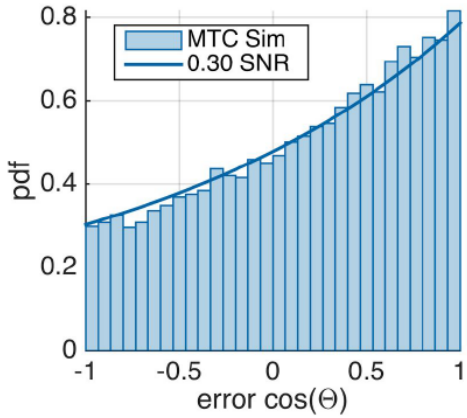
- Poorer energy resolution observed with reconstructed vertices near wall.
- Best energy performance is ~11% at 3-4 MeV.

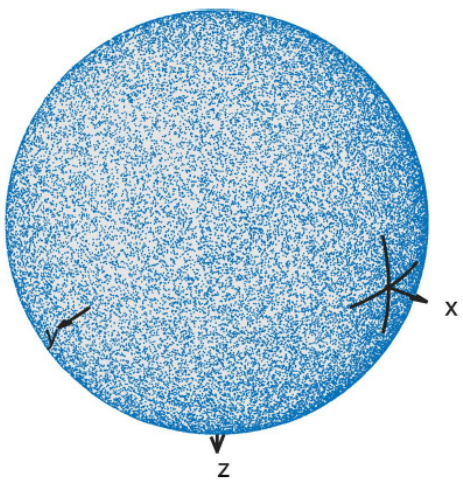
Simulated Vertex Resolution & Pointing





- Distributions of error on reconstructed prompt, delayed vertices.
  - Prompt vertex resolution can suffer due to low light at low energies, incorrectly modeled positron track length at higher energies.

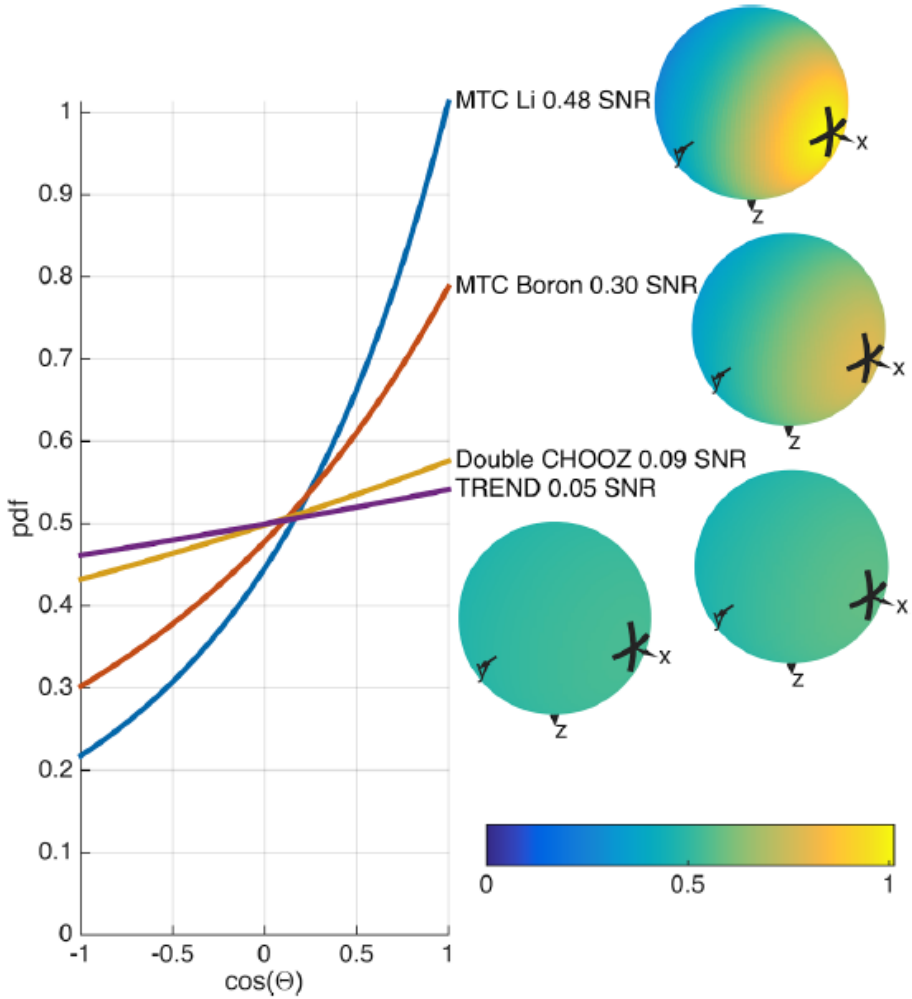




- Reconstructed vertices are used to point back to incoming neutrino and study angular resolution.
  - σ not well defined, so study distributions over cos(θ).
  - We also define vector SNR:
    - Mean displacement between vertices / uncertainty in one of the dimensions.

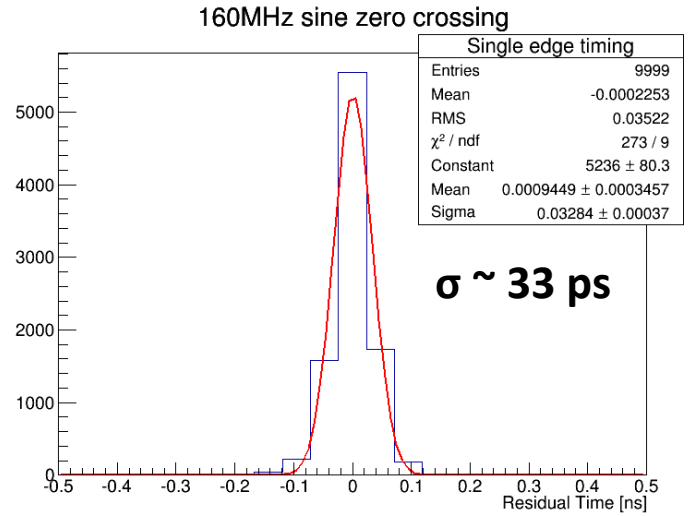
Directionality Performance Comparisons

- Comparison of directionality performance with other simulated detectors:
  - Double CHOOZ and (hypothetical) TREND directionality from: arXiv:1307.2832.
  - mTC shows good potential for directional reconstruction.
  - Initial study with Li-doped mTC shows promise for further investigation.

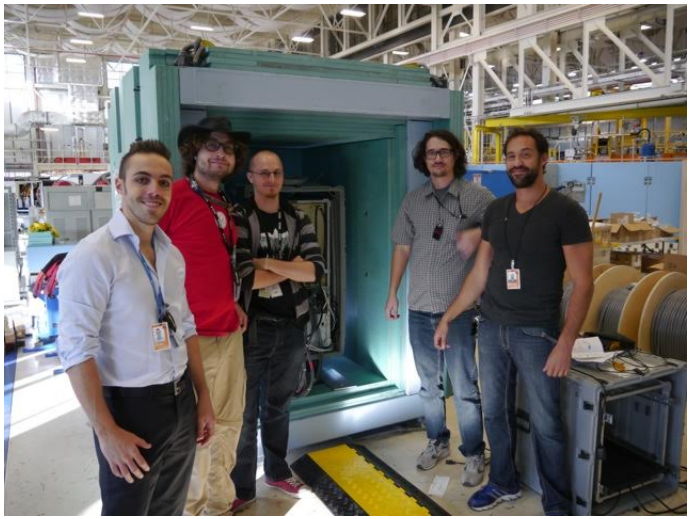


mTC Schedule and Outlook

- mTC electronics are presently being upgraded.
  - Upgraded amplifier chains and ASICs address SNR, trigger efficiency, timing precision and stability.
- Construction of shielding cave is nearly complete.
  - All but door is finished.
- Scheduled to install mTC inside the shielding cave and begin operations in early-mid January.
  - A dry run of this was conducted last month in the guide hall.
  - Initial checks will assess background rates, compare to simulation & other detectors.
  - First physics data following soon.
- Look for Rev. Sci. Instrum. paper on detector (presently under review), first ν-data next year.



Upgraded electronics timing distributions



mTC in (mostly) assembled cave