Double Chooz

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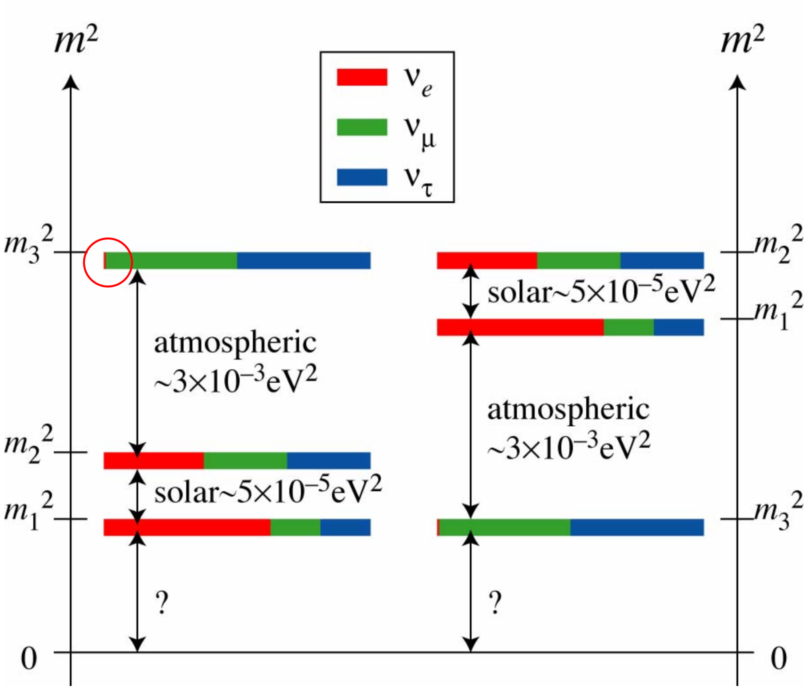
Neutrino Mixing

- $\theta_{12} \approx 30°$ (solar)
- $\theta_{23} \approx 45°$ (atmospheric)
- $\sin^2 2\theta_{13} < 0.2$ (reactor)
- what is ν_e component of ν_3?

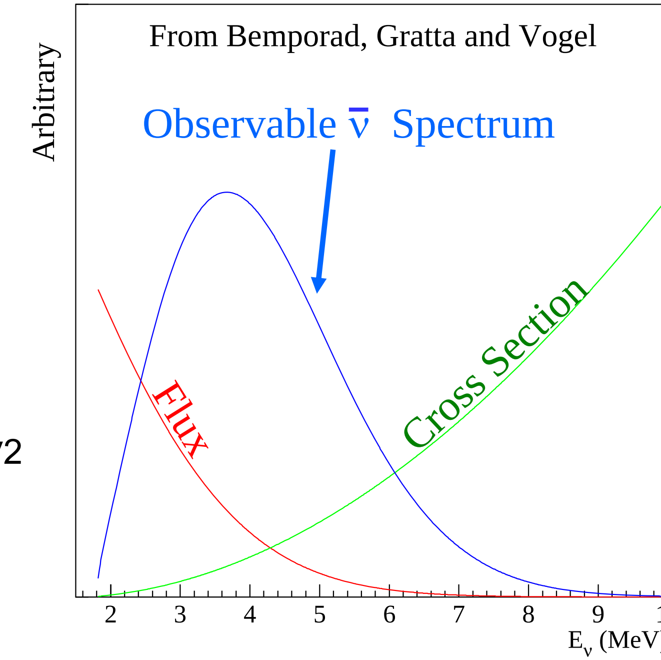


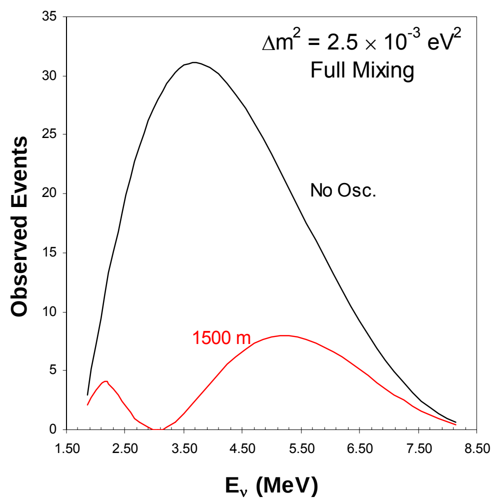
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} Big & Big & Small? \\ Big & Big & Big \\ Big & Big & Big \end{pmatrix}$$

$$= \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

Reactor Neutrinos

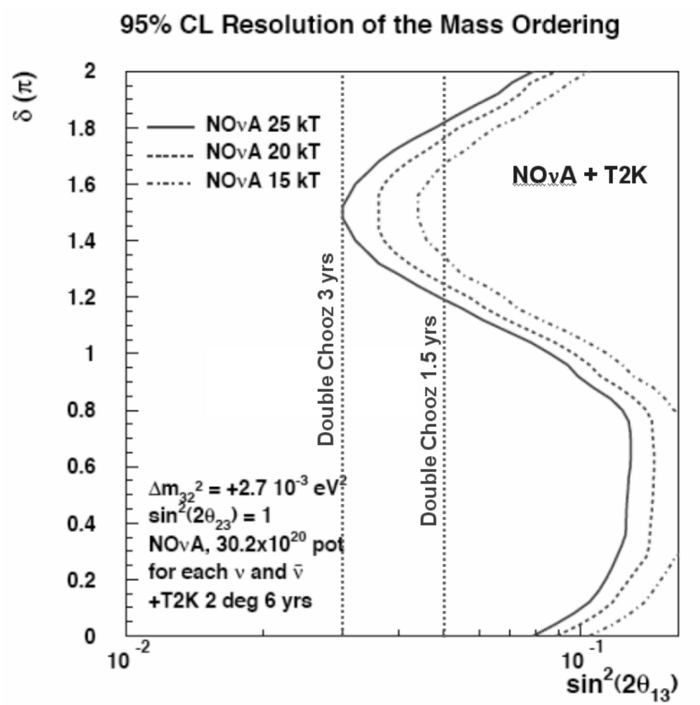
- Nuclear reactors are intense $\bar{\nu}_e$ sources with a well–measured flux and spectrum
  - 3 GW → 6×10^{20} $\bar{\nu}_e$/sec
    700 events /year/ton at 1500 m
  - visible spectrum peak at ~ 3.7 MeV
  - oscillation max. for $\Delta m^2=2.5\times10^{-3}$ eV^2 at L ~1500 m





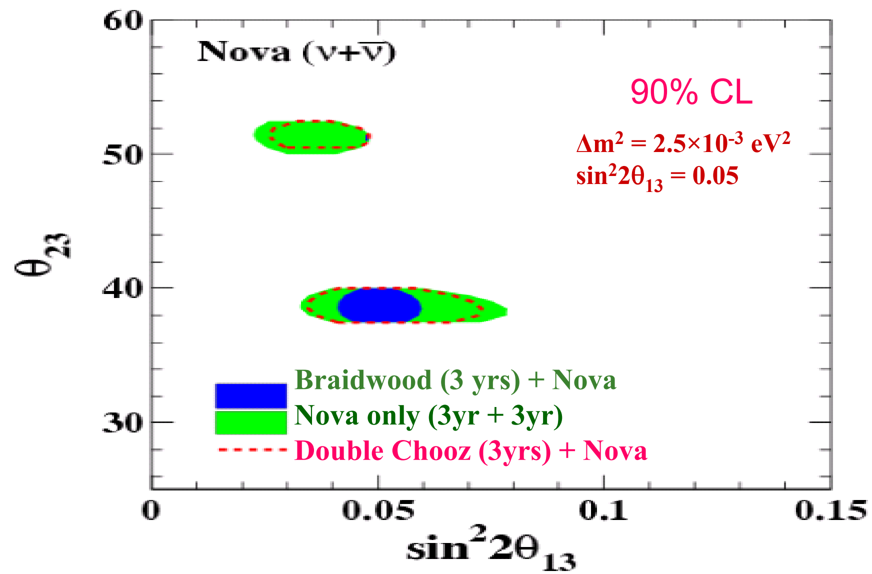
- Disappearance measurement:
  - look for small rate deviation from $1/r^2$ measured at near and far detectors:
    - Counting: number of events
    - Shape: energy spectra

Motivation



- Reactor experiment provides clean measurement of θ_{13}:

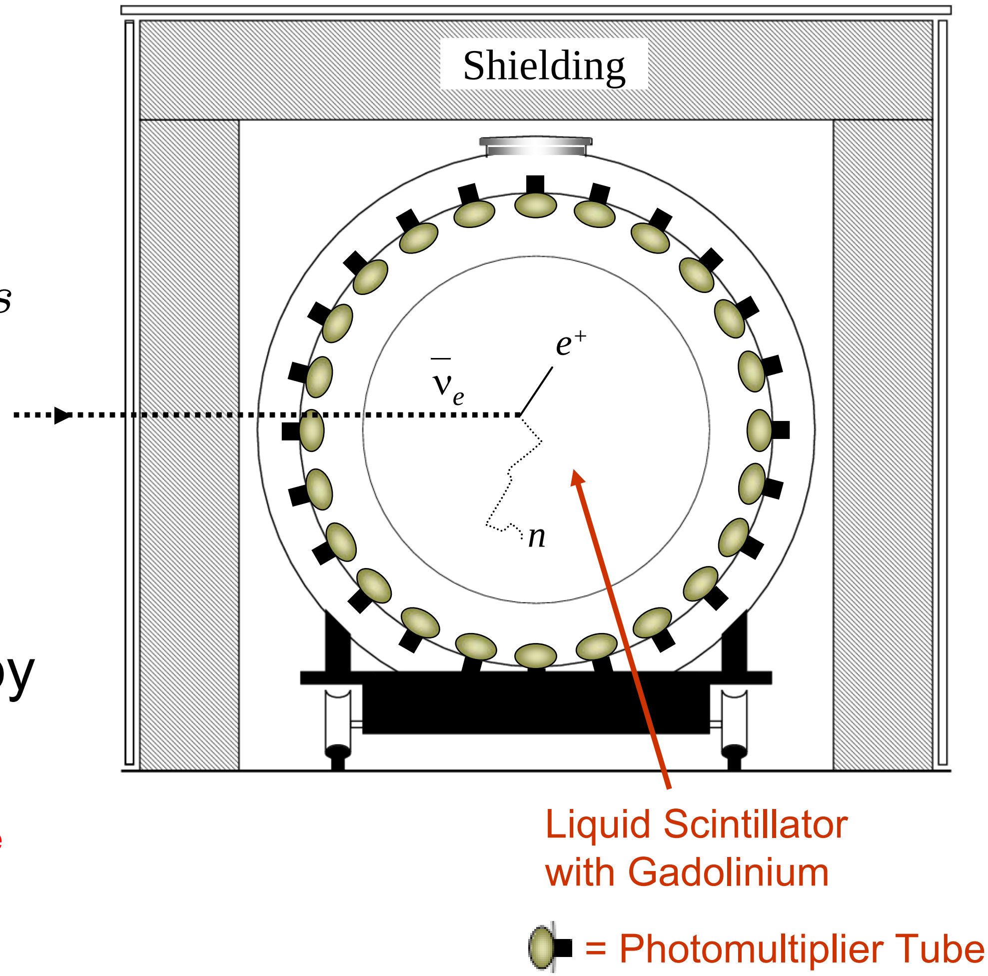
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m_{13}^2 L}{E_\nu}\right)$$



- Reactor experiment can lift θ_{23} degeneracy
- $\sin^2 2\theta_{13} \approx 0.01$ seems to be dividing line for theory and experiment

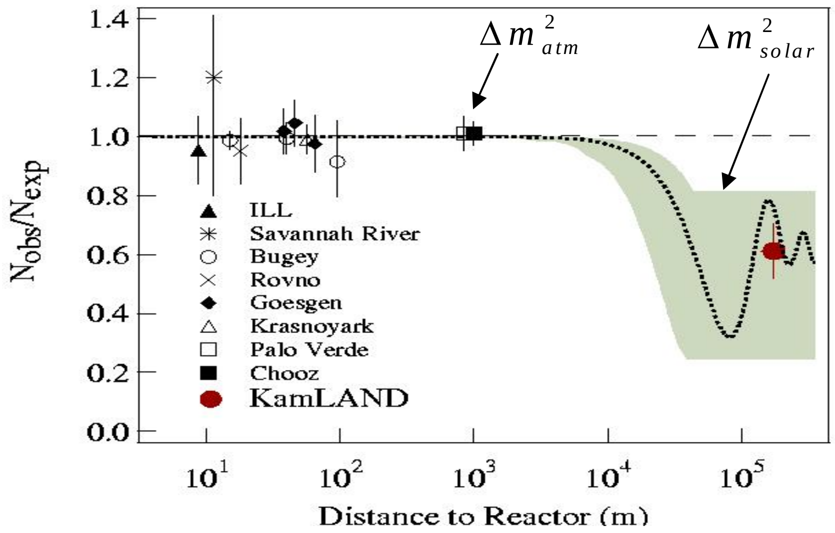
Detection

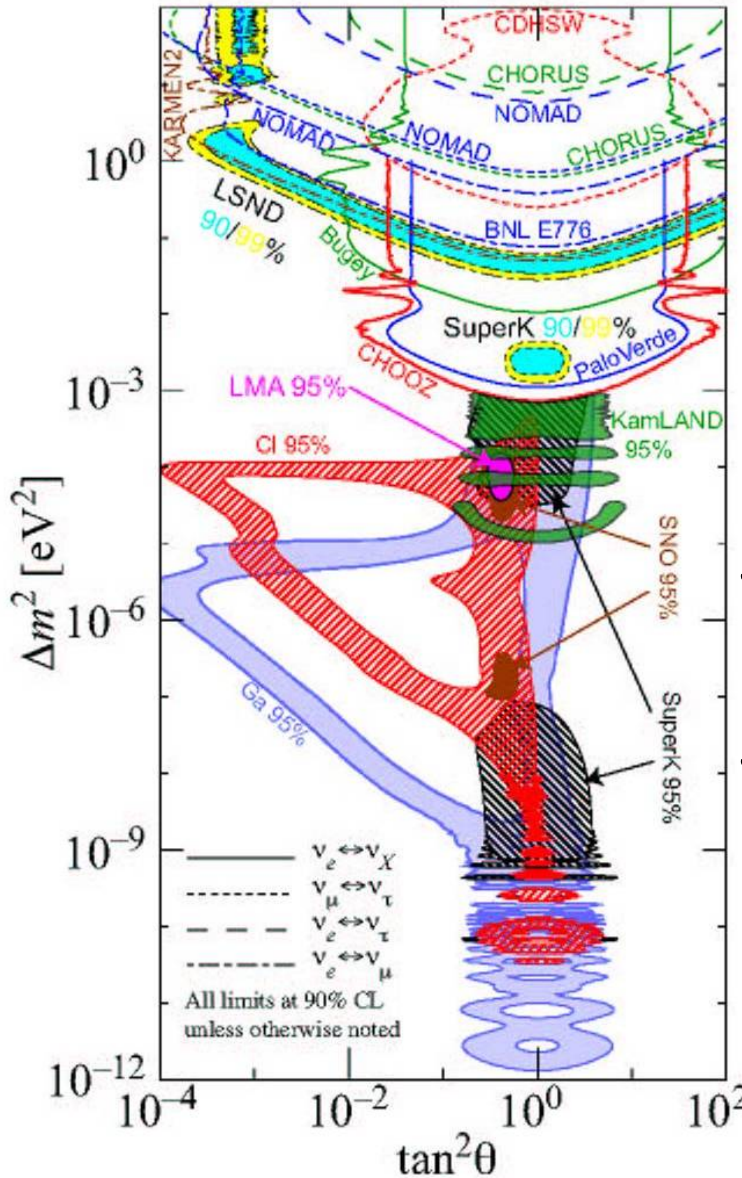
- Inverse β–decay:
  - $\bar{\nu}_e + p \rightarrow e^+ + n$
- ^{155}Gd,^{157}Gd capture:
  - $n + Gd \rightarrow$ 8 MeV of γs
  - τ ~ 30 μsec (0.1% Gd concentration)
- Events selected by coincidence
- ν energy spectrum given by visible e^+ energy:
  - $E_\nu = E_{vis} + 1.8 \text{ MeV} - 2m_e$



Previous Results

- CHOOZ, Palo Verde:
  - single detector with baseline ≈ 1 km
  - $\sin^2 2\theta_{13} < 0.2$ at 90% CL

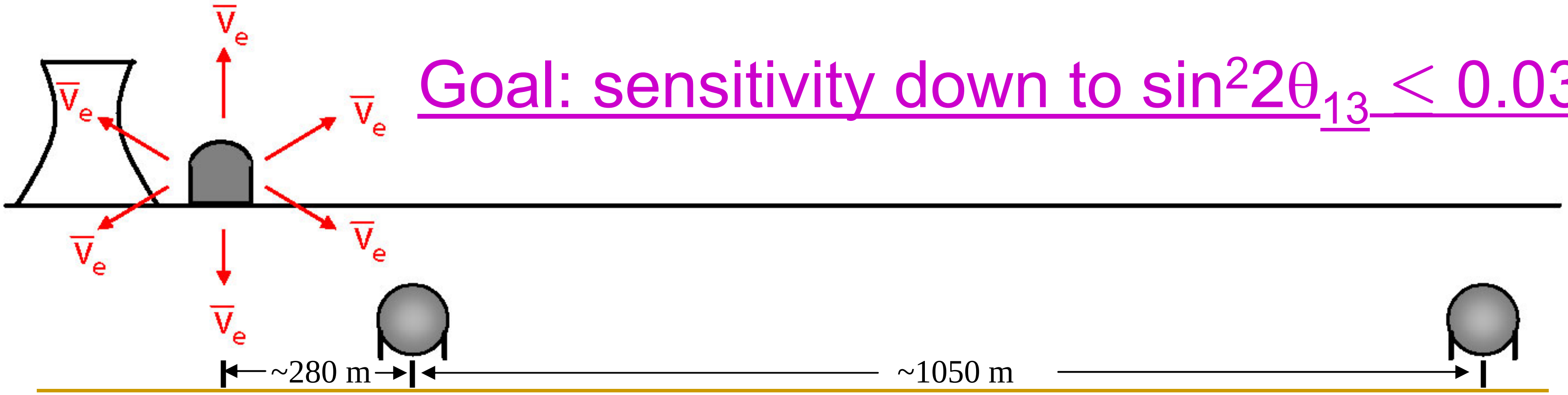




contributed by H. Murayama to PDG

Improve Limits

- CHOOZ limit:
  - $\sin^2 2\theta_{13} < 0.15$ at 90% CL for $\Delta m^2_{23} = 2.5\times10^{-3}$ eV^2
- Add identical near detector
  - need only relative acceptance
  - remove systematics from reactor neutrino flux, energy
- New Gd scintillator mixture
  - instability in CHOOZ scintillator attenuation
- Reduce cosmogenic backgrounds: add outer detectors



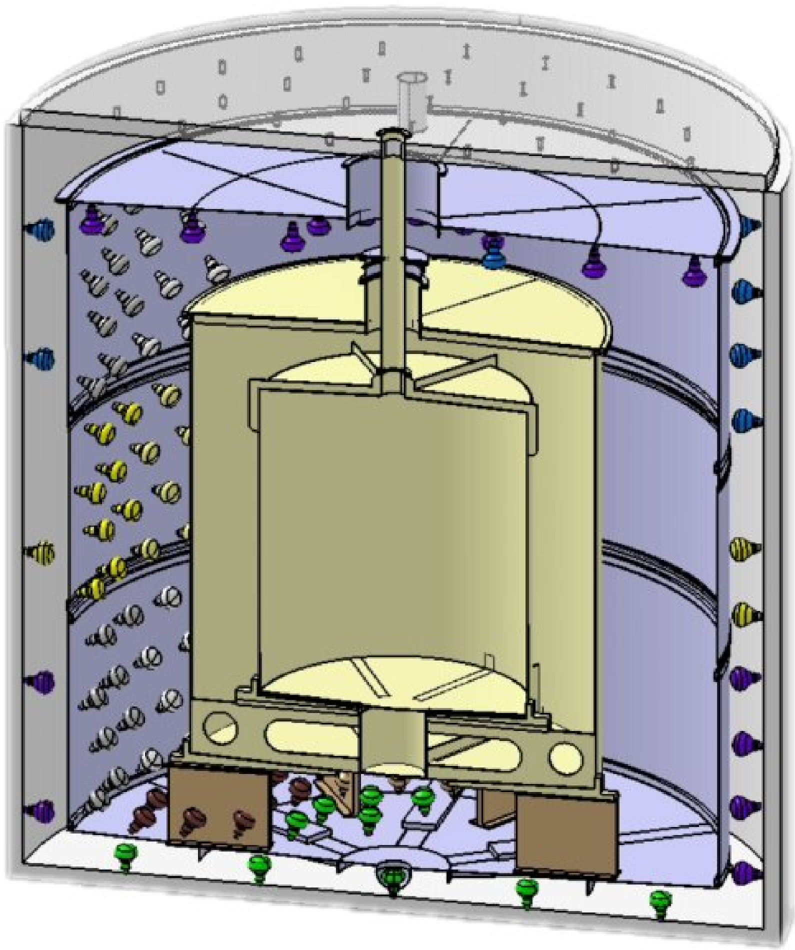
Goal: sensitivity down to $\sin^2 2\theta_{13} \leq 0.03$

Double Chooz

Features of Double Chooz site:

- 2×4.27 $GW_{thermal}$ reactors – 8.54 GW maximum power
- Far site hall reusable from original CHOOZ with 300 m.w.e. mountain overburden at 1050 m baseline
- Near site: ~30 m rock (75 m.w.e.) overburden at 280 m baseline

"3 Zone" Detectors



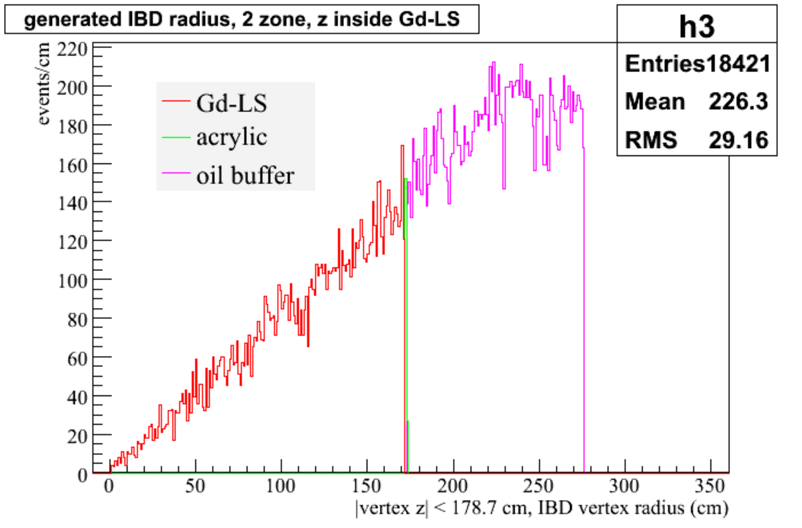
- Target
  - 10.3 m^3 (8.8 tonnes) of 0.1% Gd-doped LS
- Gamma-catcher
  - 55 cm of unloaded LS
- Buffer
  - 105 cm of nonscintillating organic liquid
- Photomultipliers
  - 534 8" Hamamatsu PMTs for 13% coverage

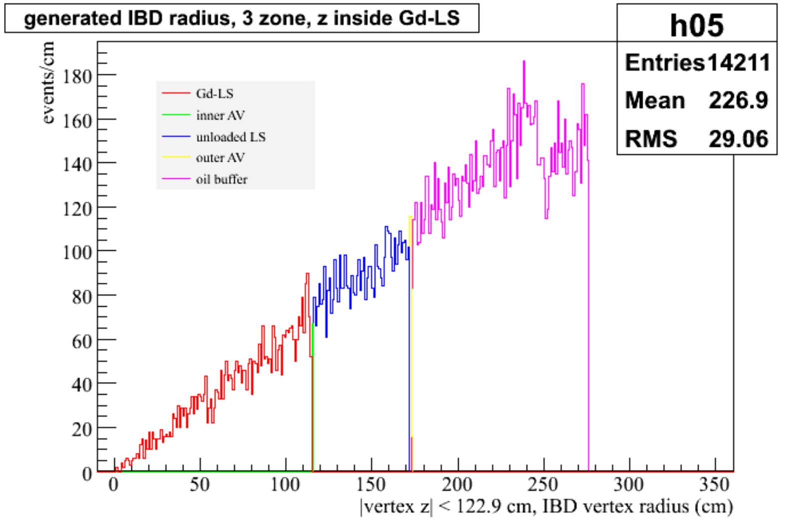
Shielding and Vetos

- 14 cm thick steel shield outside of buffer
- Inner veto: 50 cm of unloaded LS instrumented with PMTs
- Outer veto: flat, large-coverage muon system above the main detector

Detector Simulation

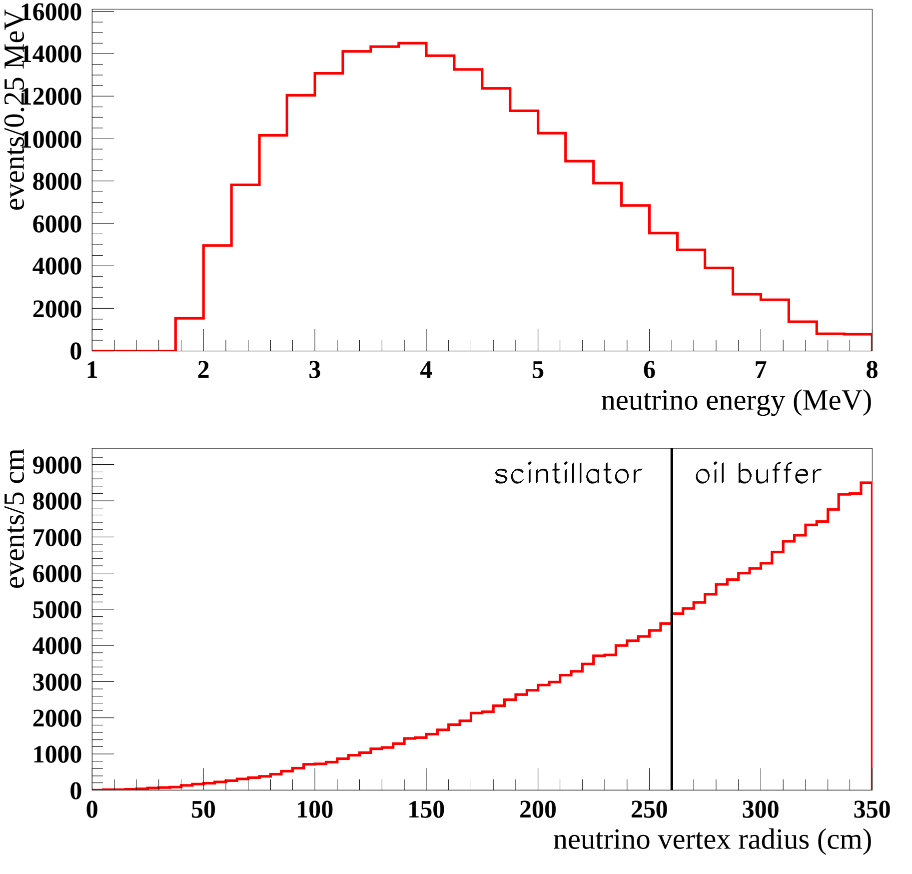
- Geant4-based simulation: RAT+GLG4sim
  - added own Gd capture cross-sections
  - added ~3 highest BR decays: n+Gd → 8 MeV of gammas
- Two detector configurations
  - 2 zone (fill GC volume with Gd-loaded LS): 12,000 events in target
  - 3 zone: 4,000 events in target



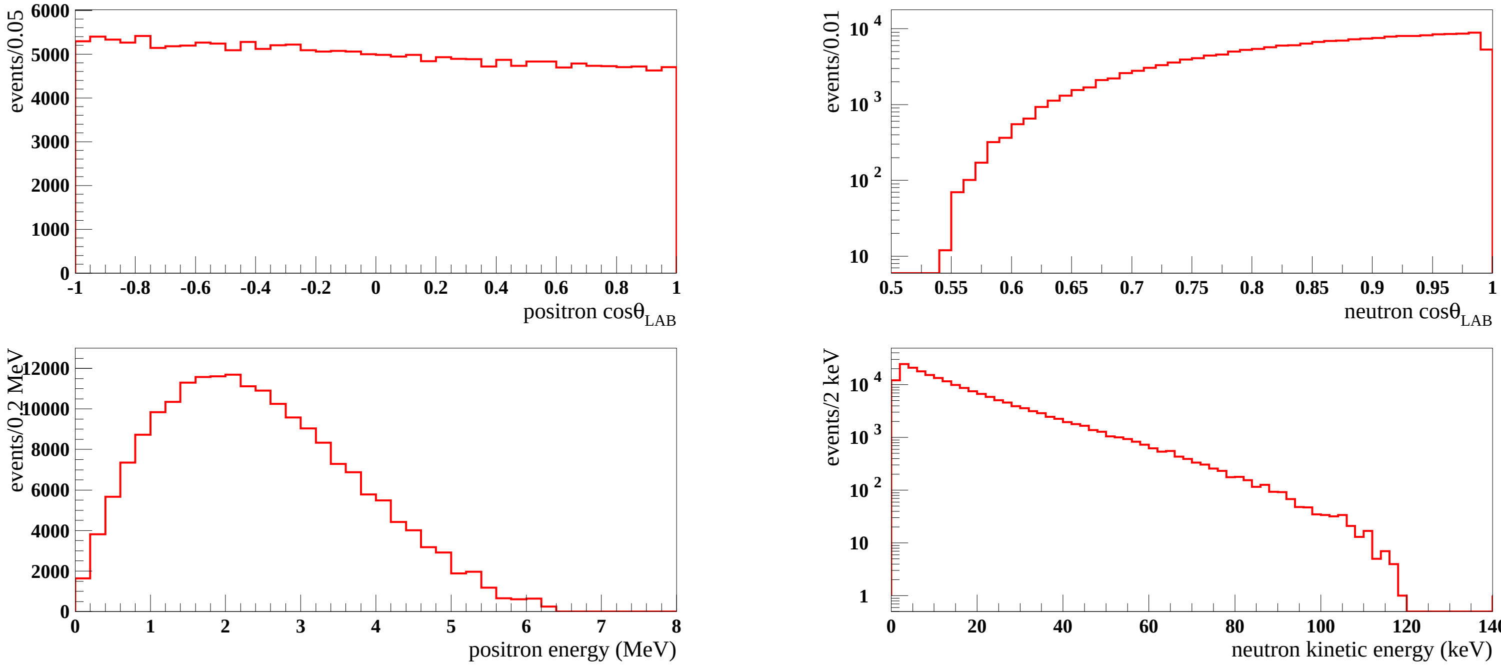


Inverse β-decay Events

- Beacom/Vogel cross-section with:
  - order $(\Delta/M)^1$ corrections ($\Delta = M_n - M_p$)
  - final state neutron kinematics
  - inner radiative corrections
- neutrino flux from Bemporad, Gratta, and Vogel RMP



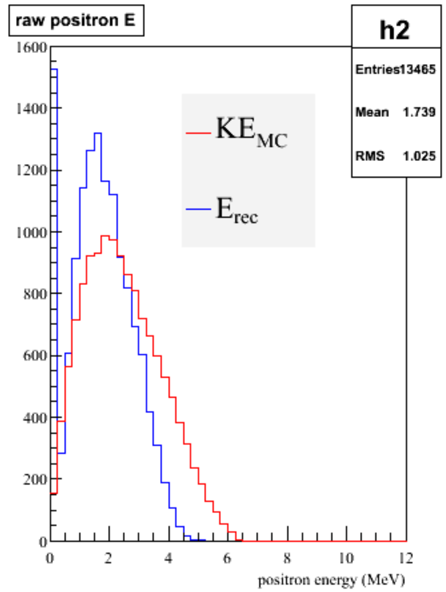
e^+ and n Properties

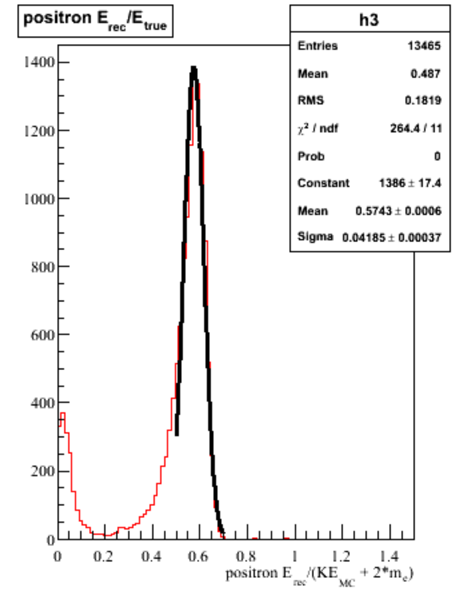


- Slight negative asymmetry in $\cos\theta_{LAB}(e^+)$
- Positron energy: $KE(e^+) = E(\nu) - \Delta - m_e - KE(n)$
- Maximum $\theta_{LAB}(n) \approx 57°$
- Maximum $KE(n) \approx 120$ keV

Reconstruction

- Use only hit–level information
- Sum PH from all PMT with hits in time window
  - threshold = 0.2 MeV
  - no *a priori* knowledge of particle generating light (e^+ or n)
  - allows energy from n elastic scatter into e^+ PH
- Reconstruction
  - positions with charge–weighted sum
  - assume straight line from position to PMT, apply QE, attenuation to get energy

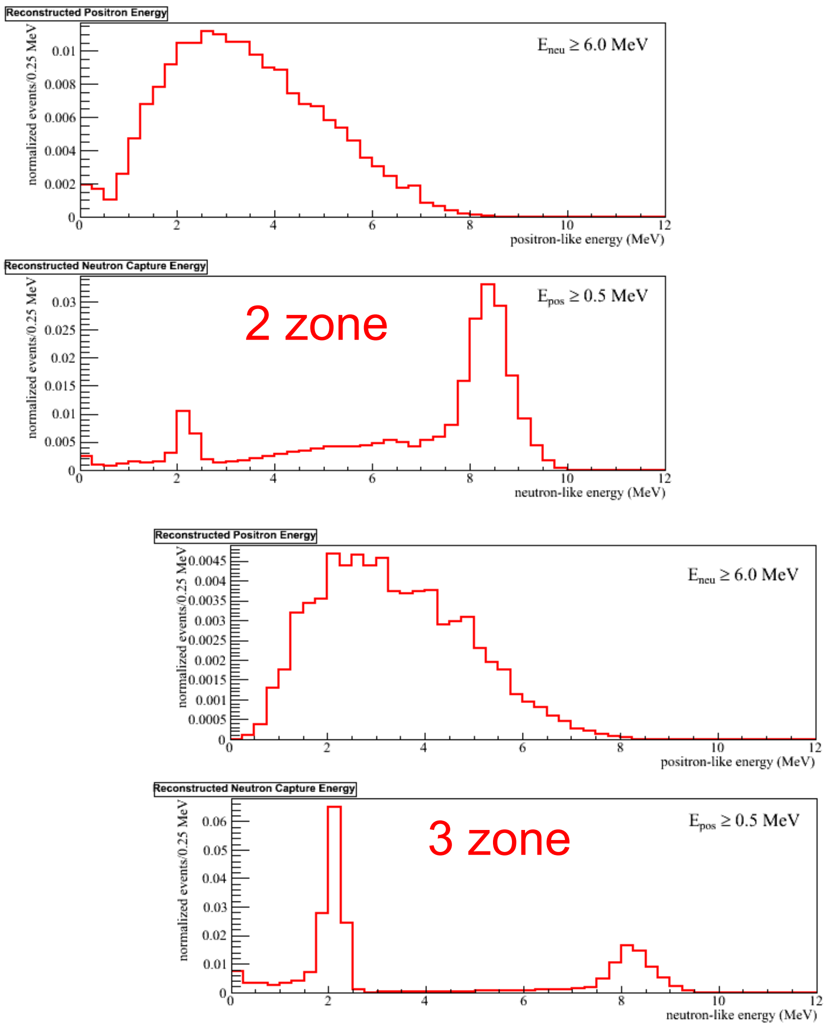




- Calibrate energy scale with reconstructed e^+-like energy and KE $_{e+}$ from MC:

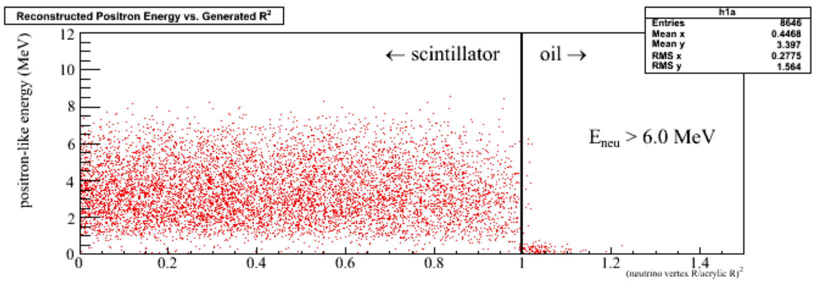
$$E_{rec} = KE_{MC} + 2m_e$$

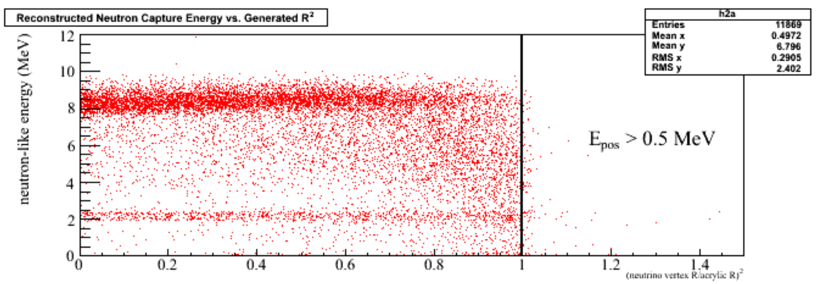
Neutrino Signal



- Two reconstructed events within a 100 μsec coincidence window
- Prompt positron-like event
  - E_{pos} > 0.5 MeV
  - gives neutrino energy
- Delayed neutron-like event
  - E_{neu} > 6 MeV
  - 8 MeV peak from Gd capture well above natural radioactive backgrounds
- Coincidence signal suppresses accidentals

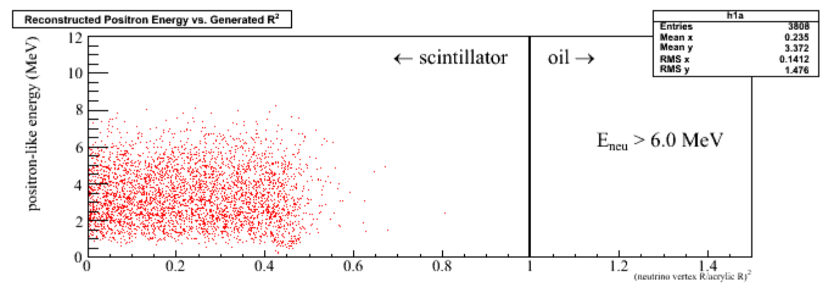
Energy vs. Position

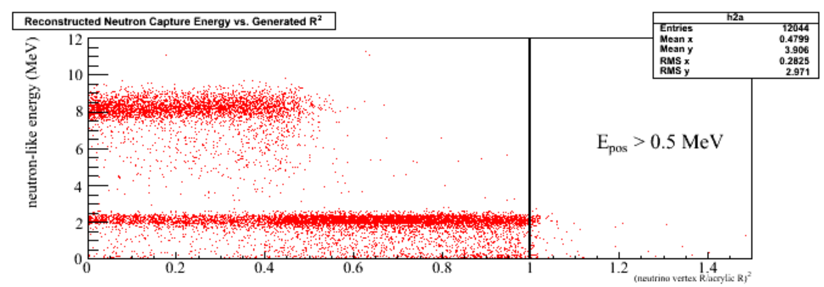




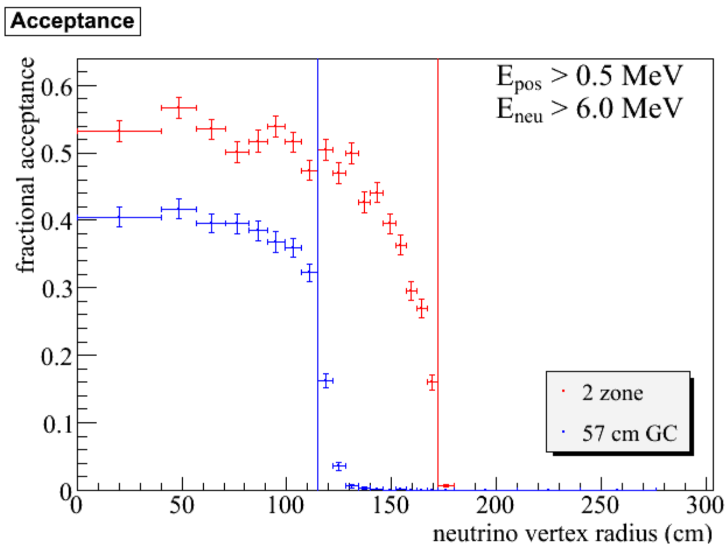
- 2 zone detector
  - Gd-LS filling entire acrylic vessel
  - gamma leakage near AV causes Gd peak tail

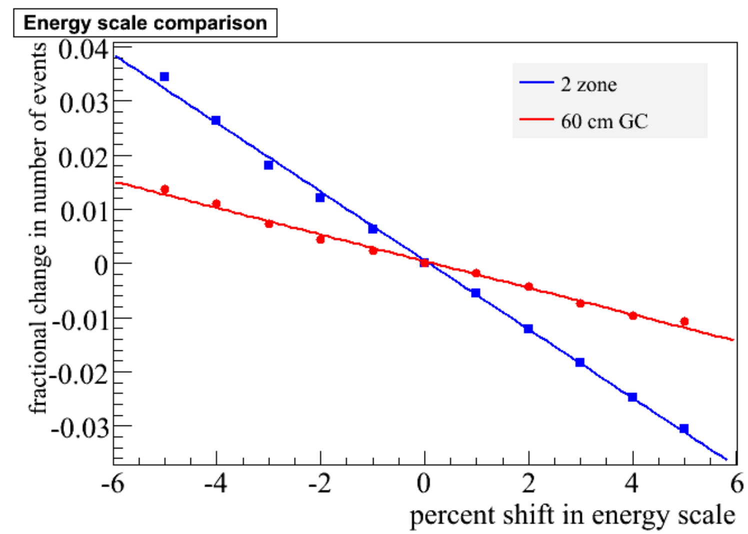
- 3 zone detector
  - GC region contains gammas from e^+ annihilation and Gd capture
  - no leakage near AV





Acceptance





- 3 zone design has lower acceptance than 2 zone but a better defined Gd-LS target volume
  - reduces Gd peak tail near 6 MeV energy cut
  - systematic uncertainty on acceptance driven by energy scale uncertainty at the 6 MeV cut
- can calibrate *in situ* shift in energy scale in <u>each</u> detector with fit to well-understood Gd peak

Backgrounds

- Accidental
  - random coincidences between two different events (*e.g*. radioactive decay plus cosmogenic neutron) together fake IBD signal
- Correlated
  - fast neutron – from muon showers near detector. A single neutron can elastically scatter in the target and subsequently capture on Gd
  - muon capture – on nuclei in dead material along muon track can produce several high-energy neutrons
  - 9Li – production by muon spallation inside target. Production mechanism not well-understood. About 50% of β decays produce a neutron. 178 ms half life causes prohibitive deadtime if vetoed by muon track in target.

Detector	Site		Background				
			Accidental		Correlated		
			Materials	PMTs	Fast n	μ-Capture	^{9}Li
Double Chooz		Rate (d^{-1})	0.1 ± 0.1	0.3 ± 0.2	0.11 ± 0.11	< 0.1	1.0 ± 0.5
(69 ν/d)	Far	bkg/ν	0.1%	0.4%	0.2%	< 0.1%	1.4%
		systematics	<0.1%	<0.1%	0.2%	<0.1%	0.7%
Double Chooz		Rate (d^{-1})	0.5 ± 0.3	1.7 ± 0.9	0.15 ± 0.15	0.4	9 ± 5
(1012 ν/d)	Near	bkg/ν	< 0.1%	0.2%	< 0.1%	< 0.1%	0.9%
		systematics	<0.1%	<0.1%	<0.1%	<0.1%	0.5%

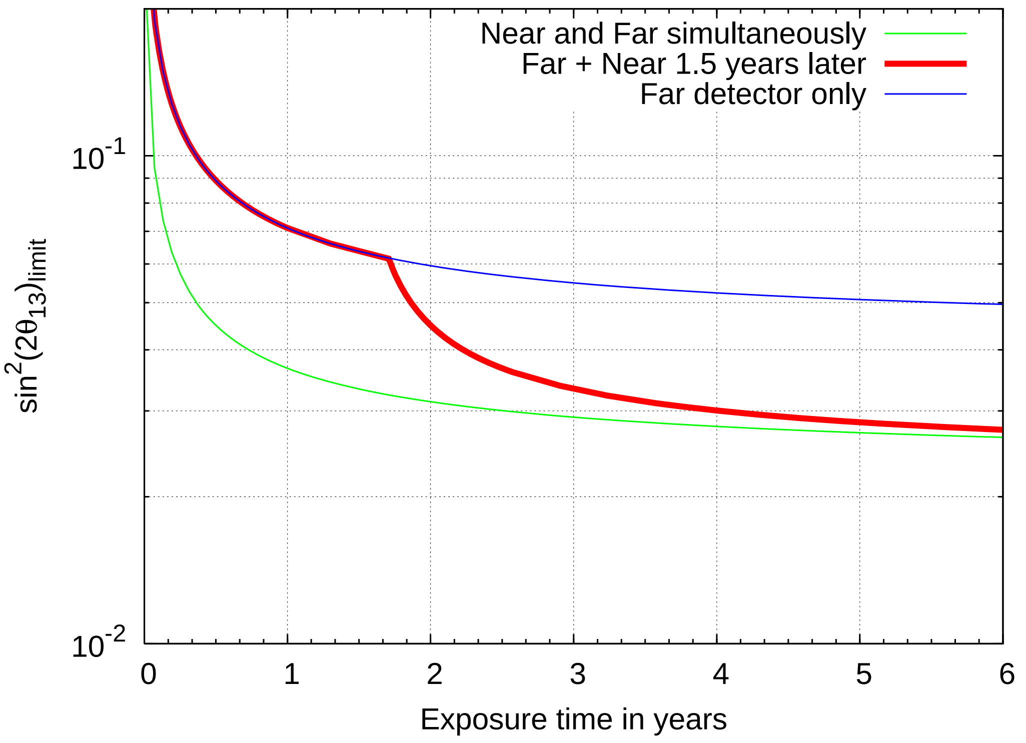
Uncertainties

- 45,000 signal events at far site after 3 years data-taking
  - 0.5% statistical uncertainty
- Total systematic on the normalization between the detectors:

			CHOOZ	Double Chooz
Reactor		Solid Angle	—	0.2%
Detector	H nuclei in Target	Volume	0.3%	0.2%
		Fiducial Volume	0.2%	0
		Density		0.1%
		H/C	0.8%	0
Detector	Electronics	Dead Time	—	0%
Particle Identification	Positron	Escape	0.1%	0
		Capture	0	0
		Identification Cut	0.8%	0.1%
Particle Identification	Neutron	Escape	1.0%	0
		Capture (% Gd)	0.85%	0.3%
		Identification Cut	0.4%	0.1%
Particle Identification	Antineutrino	Time Cut	0.4%	0.1%
		Distance Cut	0.3%	0
		Unicity	0.5%	0
Total			1.5%	0.5%

- 0.9% systematic uncertainty expected from background

Goals



- Schedule
  - late 2007 – install far detector in existing hall
  - summer 2008 – begin data-taking at far site
  - late 2008 – finish near hall construction
  - summer 2009 – begin data-taking at near site

- Compare counts and shape in identical, large, cylindrical detectors at two distances that have $\Delta L \sim 770$ m:
  - Sensitivity (90% CL) down to the $\sin^2 2\theta_{13} = 0.03$ level

Outer Veto Project

- Tasked to build outer muon systems at both near and far sites
  - extruded plastic scintillator detectors
  - 64 channel PMTs + front-end electronics
  - control and clock-fanout electronics
- Groups
  - University of Chicago: Ed Blucher, Matt Worcester, Daniel Silverstein, Nathan Whitehorn
  - Columbia University: Janet Conrad, Zelimir Djurcic, Mike Shaevitz
  - Barnard College: Reshmi Mukherjee
- Proposal submitted to NSF

Muon Backgrounds

- All correlated backgrounds are associated with cosmic muons
- Muon flux and energy estimated with MUSIC
  - near detector (75 m.w.e.): $\Phi = 5.9 \times 10^{-4}$ $cm^{-2}s^{-1}$ with <E> = 30 GeV
  - far detector (300 m.w.e.): $\Phi = 6.2 \times 10^{-5}$ $cm^{-2}s^{-1}$ with <E> = 61 GeV
- Muons traversing the target and buffer easily identified
- Expected background rates after removing central detector tagged muons:

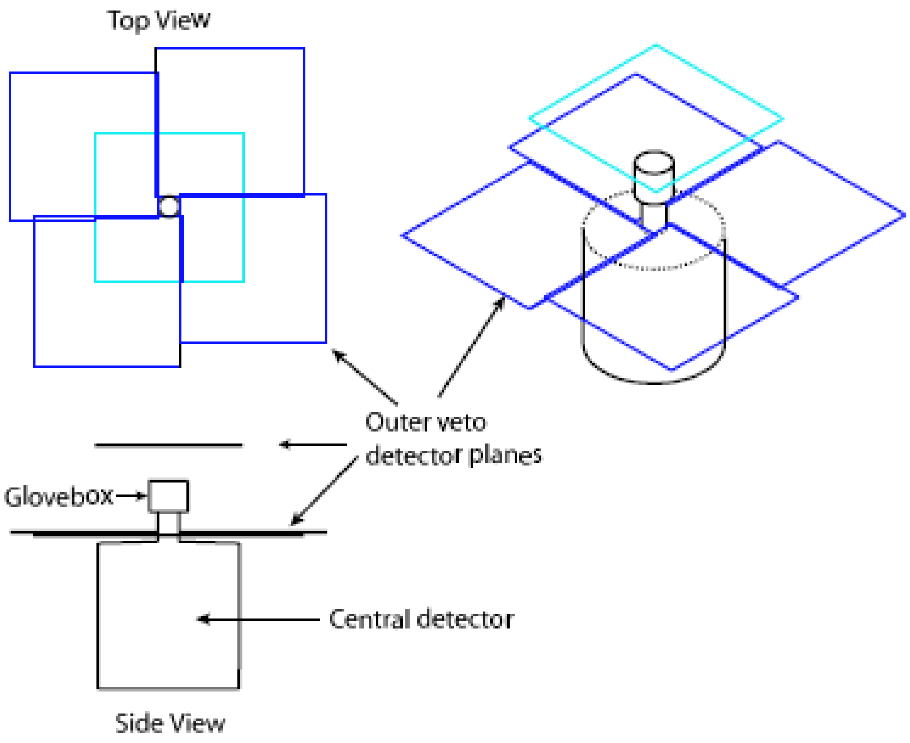
Detector	Site		Background				
			Accidental		Correlated		
			Materials	PMTs	Fast n	μ-Capture	^{9}Li
Double Chooz		Rate (d^{-1})	0.5 ± 0.3	1.5 ± 0.8	2.0 ± 2.0	28	1.0 ± 0.5
(69 ν/d)	Far	bkg/ν	0.7%	2.2%	2.9%	40%	1.4%
Double Chooz		Rate (d^{-1})	5 ± 3	17 ± 9	9.1 ± 9.1	266	9 ± 5
(1012 ν/d)	Near	bkg/ν	0.5%	1.7%	0.8%	26%	0.9%

- Veto systems designed to tag and reject "near-miss" muons which produce most of these backgrounds

Outer Veto Functions

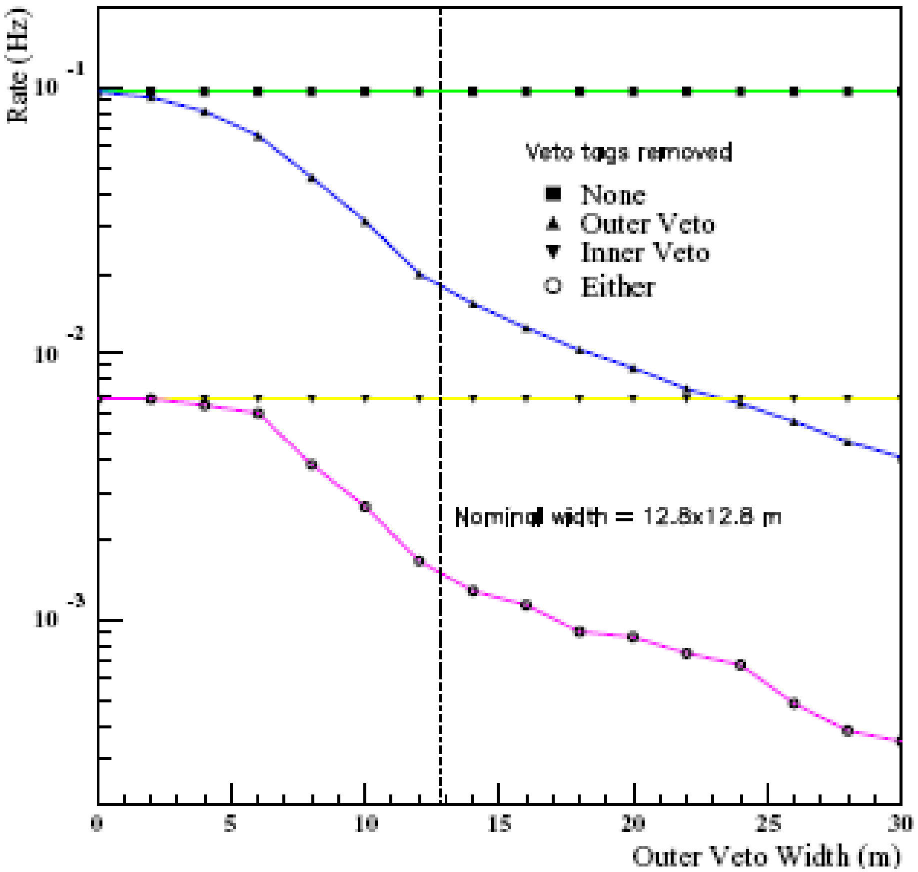
- Reduce fast neutron background in the near (far) detector by a factor of 5 (2) over inner veto alone
- Measure efficiency of inner veto
- Select samples of cosmic muons hitting uninstrumented regions (*e.g*. rock, steel shield, support structure) to study neutron background
- Provide a tracked sample of muons in and near the target to study ^{9}Li background
- Cover dead areas on top of inner veto
- Eliminate muon capture in the steel shield
- Reduce accidental background where at least one signal is cosmic muon originated

Outer Veto Design



- Large, flat “umbrella” style detector made from strips of extruded plastic scintillator
  - space constraints at existing far hall allow top-only design with 13x6.5 m coverage
  - 13x13 m top-only design at near hall sufficient for background reduction and tracking
  - significantly lower cost than 4π coverage with additional passive shield
- Deadtime
  - 1 kHz (50 Hz) muon rate in near (far) hall outer veto
  - 250 μsec veto = 25% deadtime at near site
  - independently monitored by flashers in each detector

Fast Neutron Study



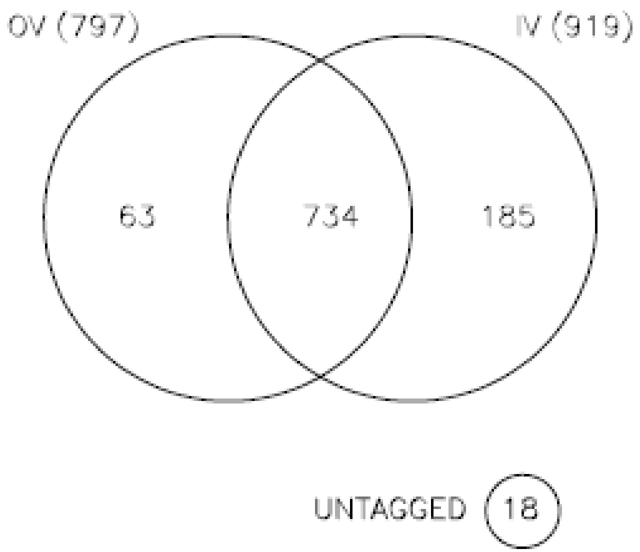
Near site, 100% efficient detectors

- Dave Reyna (ANL) used FLUKA to generate a sample of muons which produce at least one neutron entering the GC
- Remove muons which traverse central detector
- Study the rate of near-miss muon produced neutrons entering the GC as a function of outer veto width

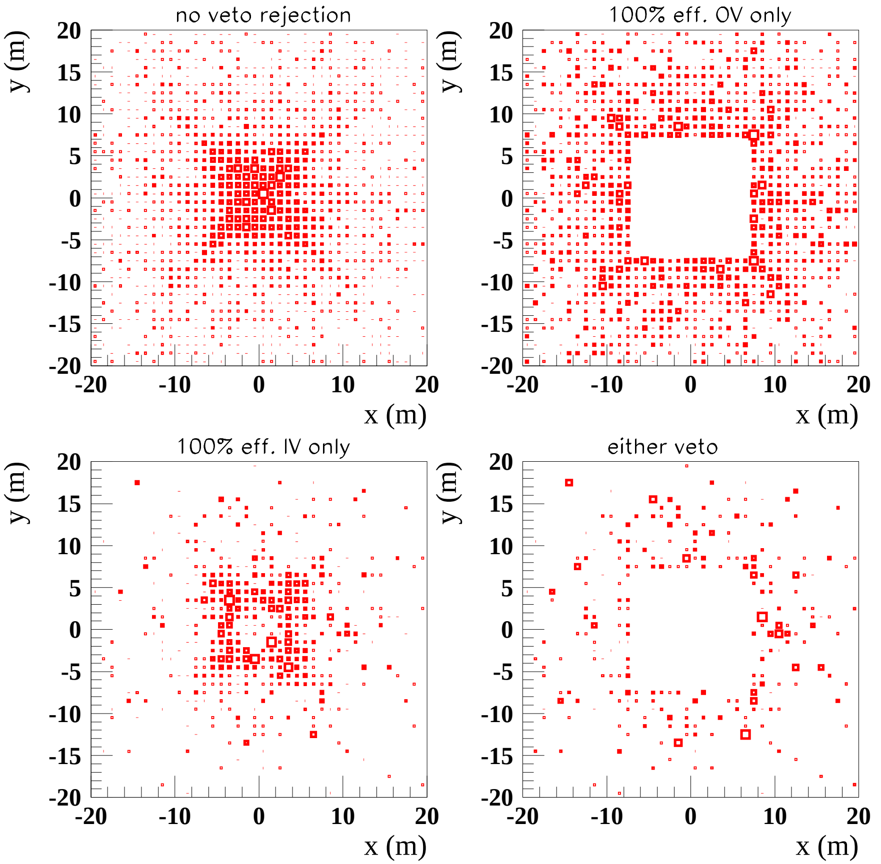
Veto Tag	Rate (Hz)	
	Near	Far
none	0.086	0.018
OV alone	0.017	0.0086
IV alone	0.0067	0.0014
either	0.0014	0.00095

Fast Neutron Study

Out of 1000 muons at the near site which produce neutrons that enter the GC but do not traverse the central detector:



Near site
100% efficient detectors at outer veto depth:



- After removing target-tagged muons, assuming 100% efficient detectors:
  - 80% are tagged by OV
  - 92% are tagged by IV
  - 98% are tagged by either

Background Rates

- The inner and outer veto together reduce:
  - accidental rates by a factor of 10 (5) at the near (far) site
  - fast neutron rates by 60 (20) at the near (far) site
  - muon capture rates by >99% at both sites
- ^{9}Li rate is not expected to be reduced, tracking in the veto will be an important tool to measure the ^{9}Li background level

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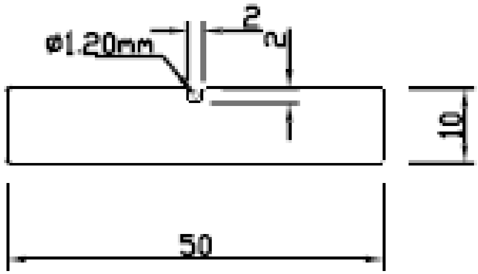
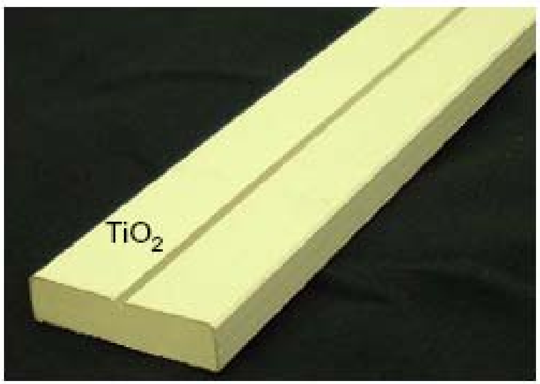
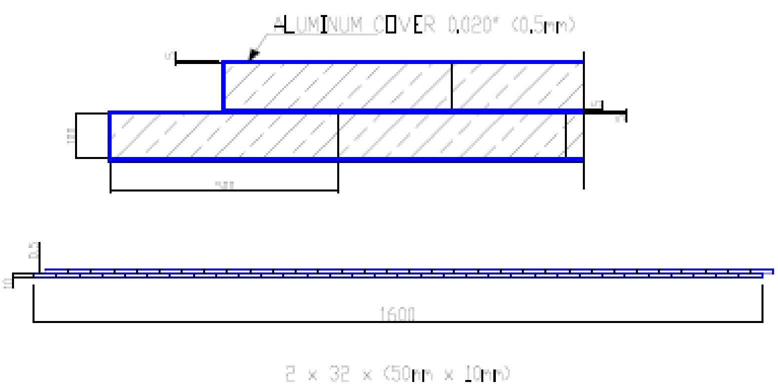
		systematics	<0.1%	<0.1%	<0.1%	<0.1%	0.5%

Outer Veto Modules



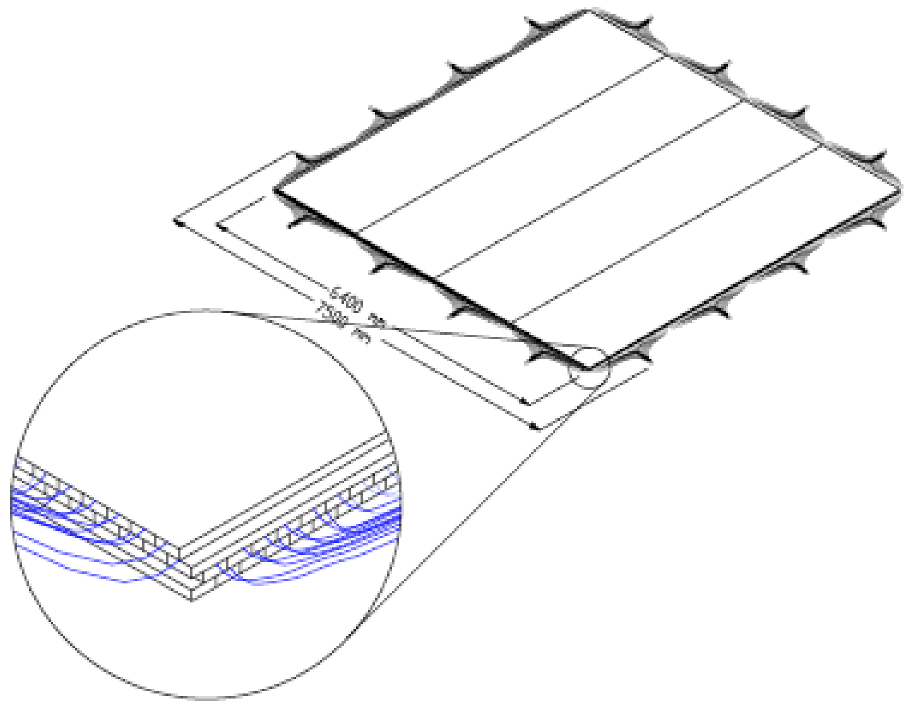




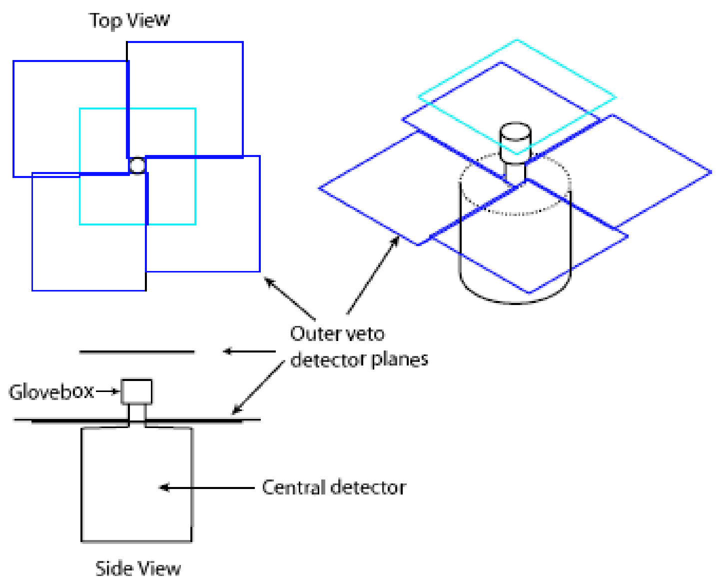
- Based on MINOS and OPERA designs
  - 5x1 cm cross-section strips of coextruded plastic scintillator and TiO_2 reflective coating
  - strips are 6.4 m long
  - 1.2 mm wavelength shifting fiber read out by Hamamatsu M64s
- One module has 2 layers of 32 strips, offset by 2.5 cm
  - one module is 1.6 m wide
  - each has one M64 on each end

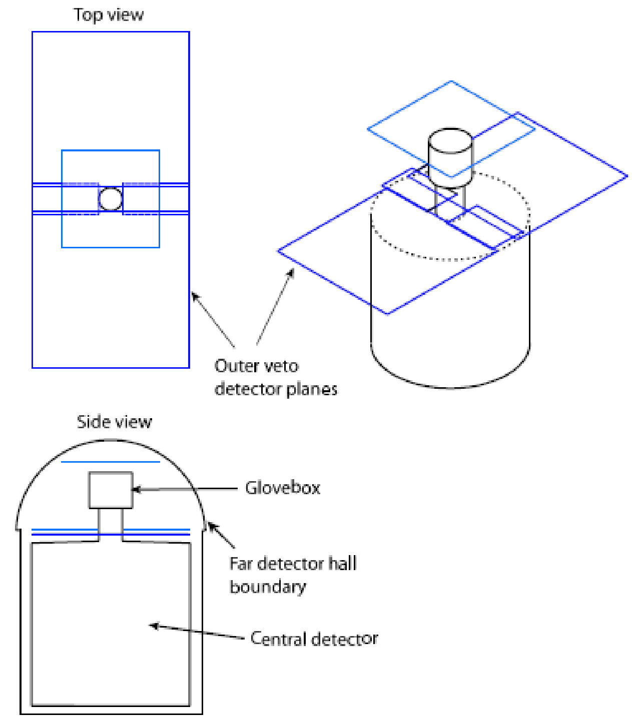
Outer Veto Panels

- 4 of these double-layer modules are laid side by side to form a 6.4x6.4 m plane
- Finally, a second plane rotated 90 degrees is added to form a panel
- Each panel will have 16 M64s for readout



Site Layouts



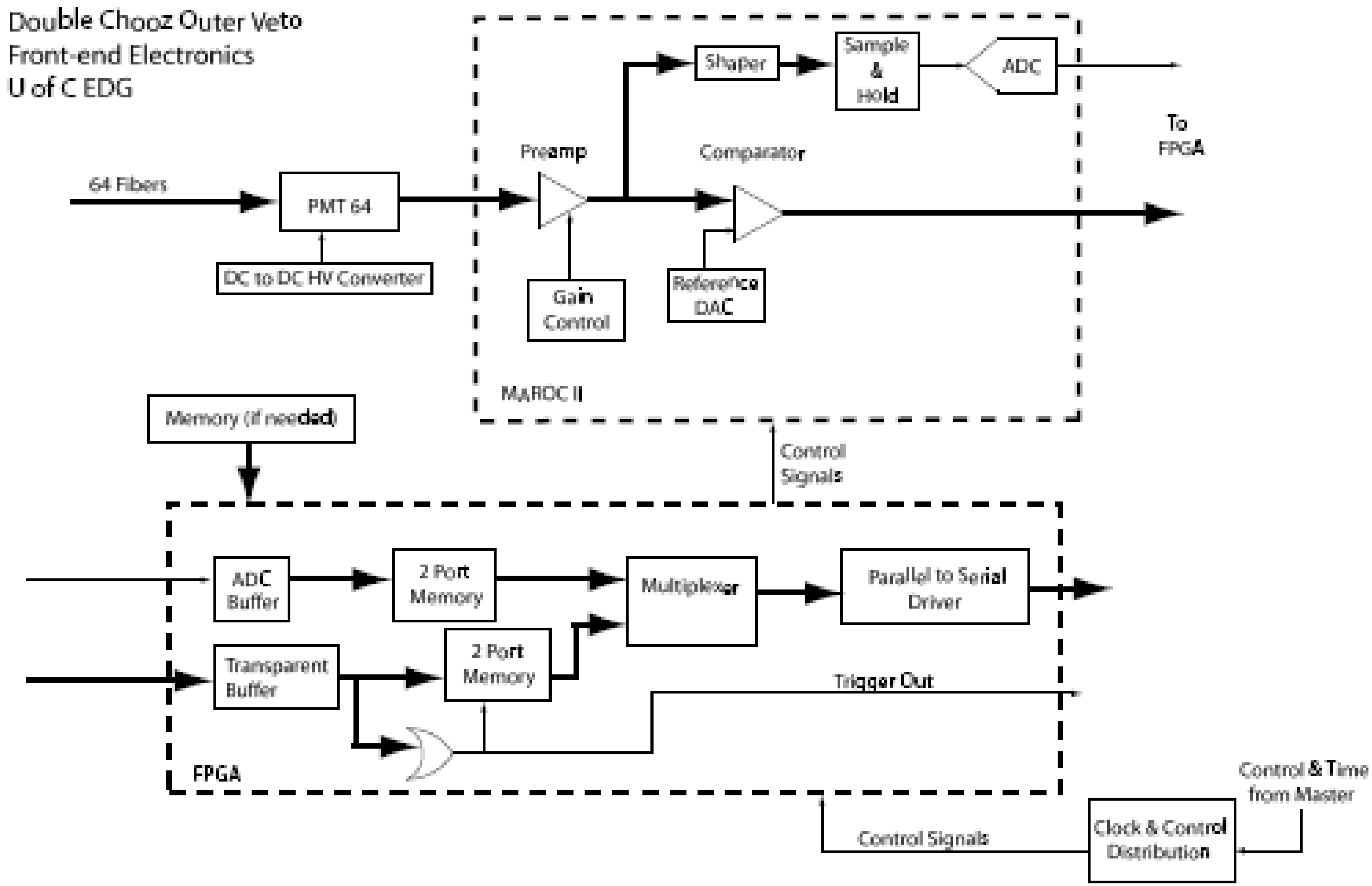


- Near site
  - 4 panels ~1 m above the central detector for 12.8x12.8 m coverage
  - 1 full panel ~4 m above for tracking
- Far site
  - 2 panels ~1 m above the central detector
  - 1 smaller panel above for limited tracking

Data Acquisition

- Save the time and location of hits in the veto
- MAROC2
  - ASIC to discriminate PMT signals
  - designed at LAL (Orsay) for ATLAS luminosity monitor
  - up to 64 channels, one per M64
  - adjusts gain for each channel – expect x3 pixel-to-pixel gain variation in M64
  - 3 discriminator thresholds
  - separate multiplexed ADC output and analog trigger path
- Output from MAROC2 sent to FPGA
  - records time stamp of hit from 62.5 MHz DC central distributed clock
  - buffers channel data
  - passes control signals to MAROC2 and flags to control boards

Front-end Card



Schedule and Funding

- Prototypes for summer 2007 beginning immediately
- Begin fabrication of far site outer veto in 2007 to match central detector schedule
- $250k NSF supplement awarded August 2006
- $2.3M (including 30% contingency) proposal submitted to NSF in November

Target Date	Milestone
December 2006	Extrude scintillator for prototype modules
July 2007	Run prototype modules in Double Chooz far hall
September 2007	Begin Extrusion for Far Detector Modules
July 2008	Install Outer Veto system in Far Hall
September 2008	Begin Extrusion for Near Detector Modules
September 2009	Install Outer Veto system in Near Hall

Category	Request in thousands of dollars			
	Year 1	Year 2	Year 3	Total
Module Construction	399.2	517.4	134.0	1050.6
Electronics	308.9	235.1	53.1	597.1
Shipping and Installation	0	43.7	53.7	97.4
Contingency (on above items)	109	100	300	509
Education and Outreach	47.5	10.3	10.3	68.1
Total	864.6	906.5	551.1	2322.1