A precision measurement of $\sin^2\theta_W$ at a Reactor

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with input from lots of people --- thanks!

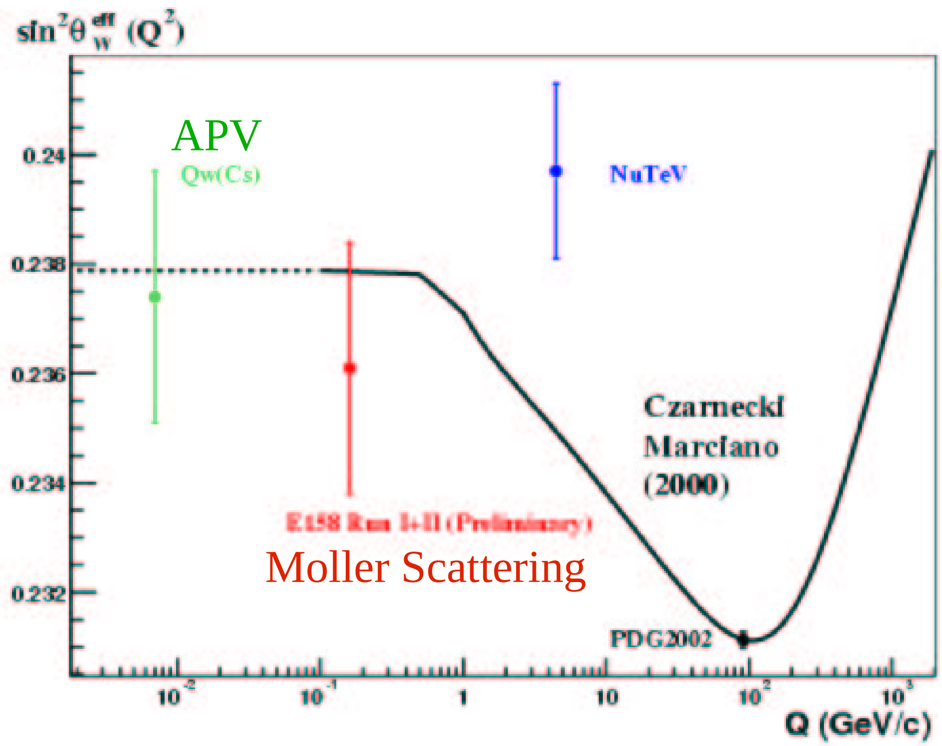
Midwest Reactor Collaboration Meeting, March, 12, 2004

Outline:

1. Why do this Measurement?
2. Issues which Drive the Design
3. Detector Design Specifics
4. Back to the issues again...

Bottom Line: $d(\sin^2\theta_W)=\pm 0.0019$

Motivation -- the NuTeV anomaly:

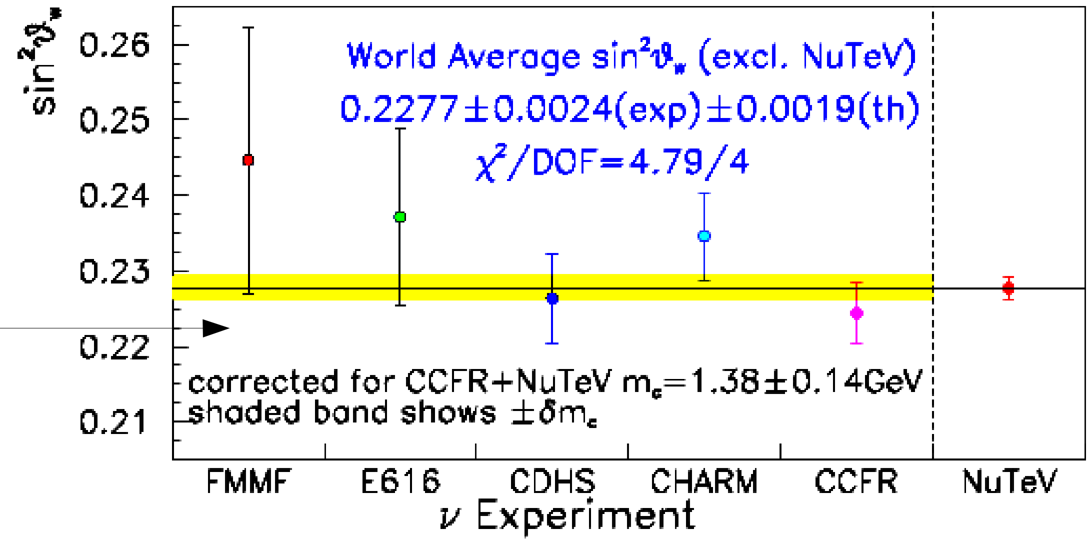


Standard Model Prediction

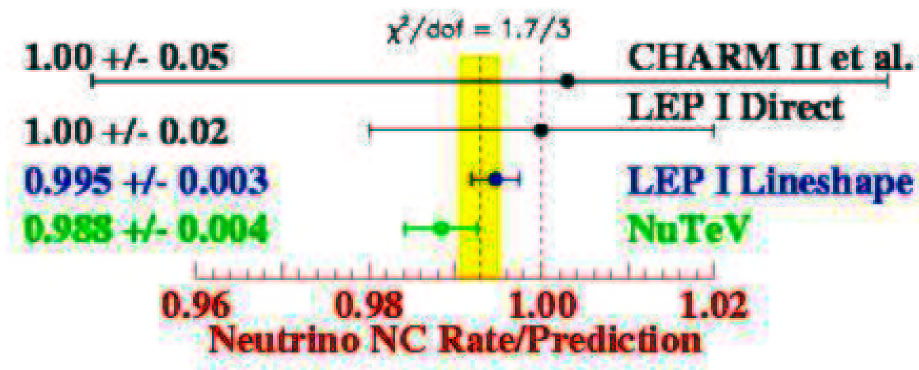
More about the NuTeV result:

Agrees with other DIS ν measurements, but with much smaller errors...

SM=0.2227



Implies Nν<3, consistent with LEP I lineshape



A neutrino experiment is the right place to pursue this!

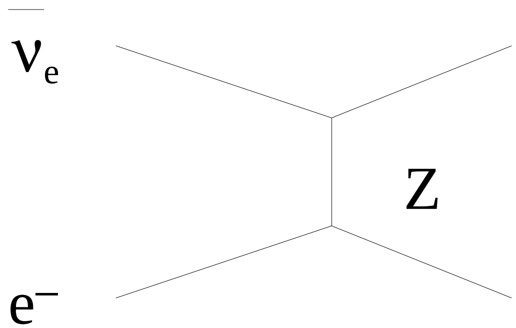
A Reactor-based measurement:

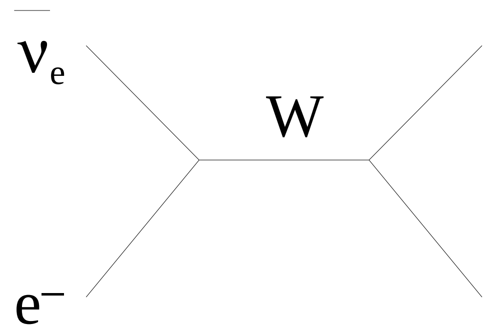
- Probes new physics in the neutrino sector (like NuTeV)
- Has low Q^2, comparable to APV (Qw)
- Has different systematics!
- Uses design similar to near detector proposals
- Can achieve errors less than APV and E158,
  & comparable to NuTeV ... $d(\sin^2\theta_W) = \pm 0.0017$

It looks like this is well-worth pursuing!

How to measure $\sin^2\theta_W$ at a reactor:

Use the antineutrino-electron **elastic scattering** (ES)





$$\frac{d\sigma}{dT} = \frac{G^2 m}{2\pi}\left\{(C_V+C_A)^2 + (C_V-C_A)^2\left(1-\frac{T}{E}\right)^2 + (C_A^2-C_V^2)\, m\frac{T}{E^2}\right\}$$

$C_V = \tfrac{1}{2} + 2\,\mathbf{\sin^2\theta_W}$

$C_A = \tfrac{1}{2}$

T = electron KE energy
E = neutrino energy
m= mass of electron
This assumes $\mu_\nu=0$

The total rate for this process is sensitive to $\sin^2\theta_W$

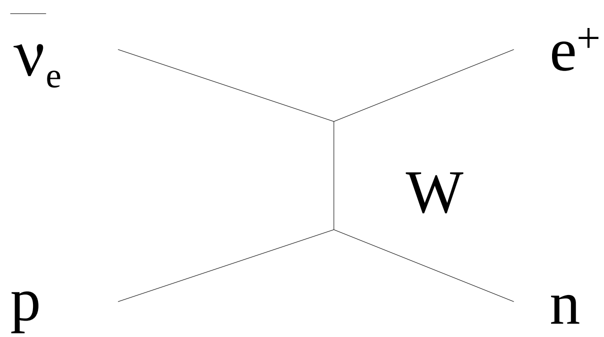
Starting points for design:

To match NuTeV, the total error (sys+stat) must be about 1.2% on the ES rate.

1. Are the statistics high enough? We will need > 10k events

2. Are environmental backgrounds (cosmics, radioactivity) low enough?
   #1 issue: high-energy-muon (HEμ) induced isotopes ... Go Deep!

3. Can the background from *inverse beta decay* (IBD) be controlled?



Yes, as long as the detector has high neutron detection efficiency

4. Is the normalization known well enough to make a precise measurement?

Yes, we use the IBD events.

The plan:

Use the near detectors in the oscillation experiment

Scintillation oil-based with Gd Doping.

Why this type of detector?

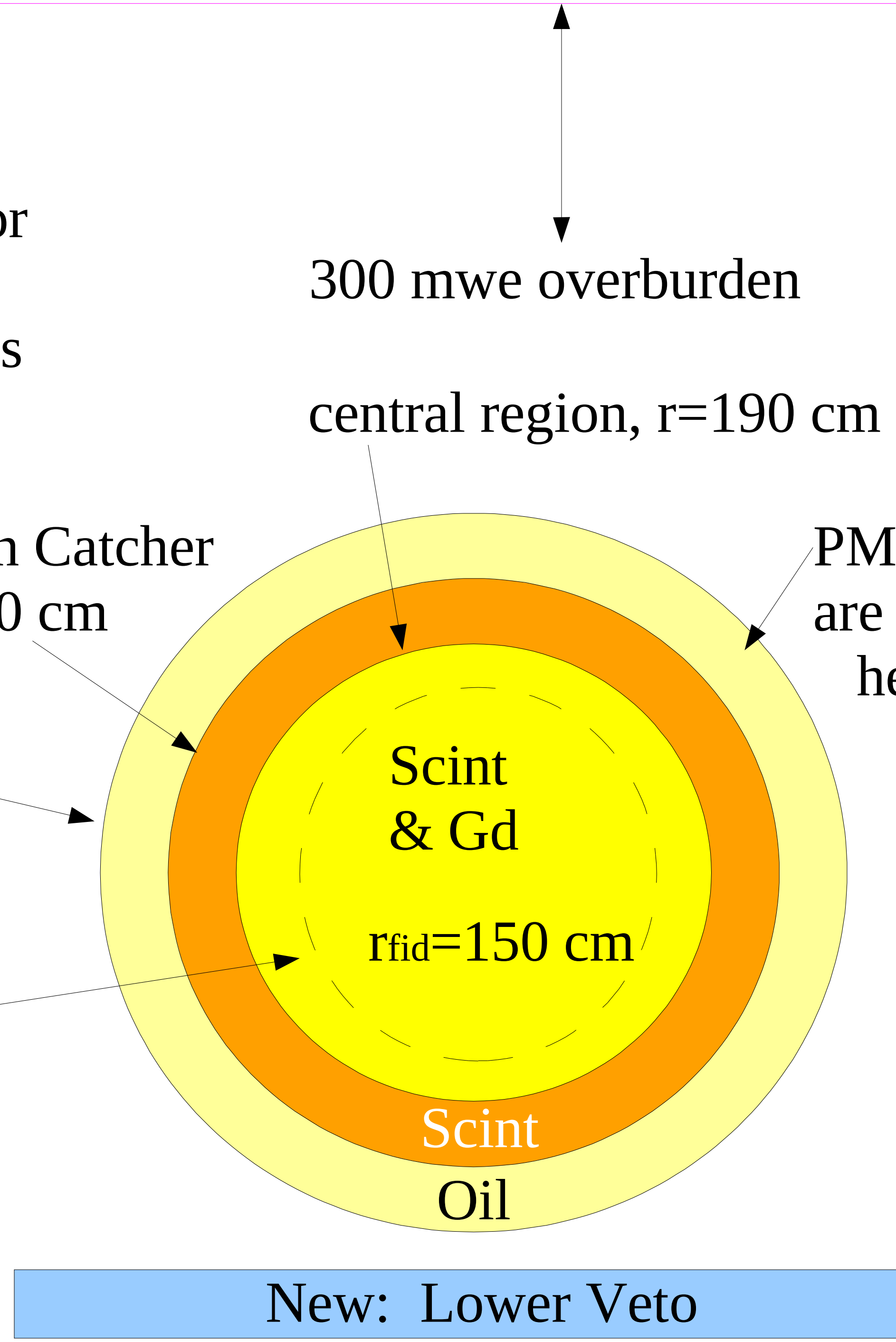
We need to make the ES and IBD measurements with the same detector (reduce systematics from fiducial volume, deadtime, etc.)

This style of detector is ideal for this.

The one drawback of a C-based detector will be HEμ interactions, but these are easily controlled by depth of overburden.

Use Braidwood as the model:
2 reactors @ 3.6 GW
224 m from reactors to detector
900 live-days of running
2 near detectors, 4 far detectors

Detector surrounded
by shielding
and active veto



The tricks we will use:

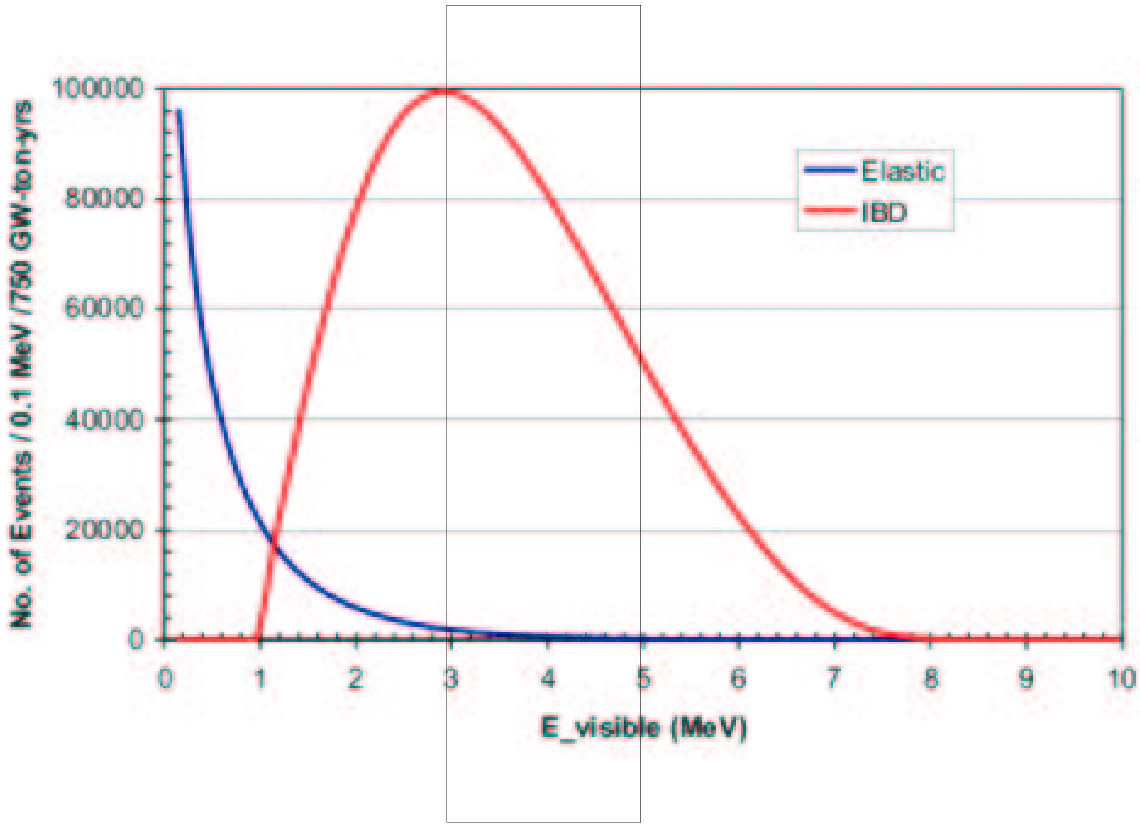
- Normalize to IBD
- Choose a window where signal is high and backgrounds are low...

$3 < E_{vis} < 5$ MeV

Aside for the people who were at the APS Workshop in February ... a few things that have changed

- Analysis is now done without using event topology
- Far detectors are used to understand environmental backgrounds
- Some new analysis-level vetos have been introduced.

ES Event Rates (e/free p is 4.3!!!)



Above 3 MeV, the ES to IBD event rate is about 100:1
Most near detectors are designed to collect ~ 1E6 IBD events
so > 10,000 ES events, or a 1% stat error, looks feasible

Environmental Backgrounds: Part I: the straightforward ones....

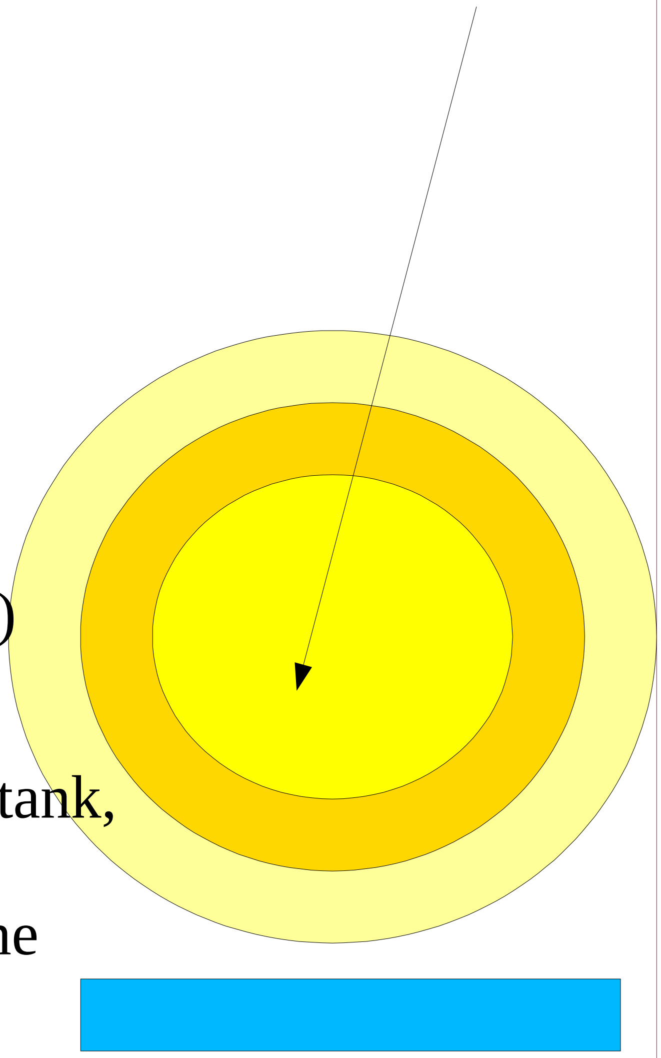
Cosmic Ray Muons: 3.5 Hz/detector

Most will fire the veto
high energy deposited in detector
separable from other events due to energy.
Will not fall into visible energy range

Stopping Muon Related Backgrounds

- Electrons from Muon Decay (Michel electrons)
- ^{12}B from muon capture (½ life ~ 20 ms)

removed by an analysis level veto with very small deadtime

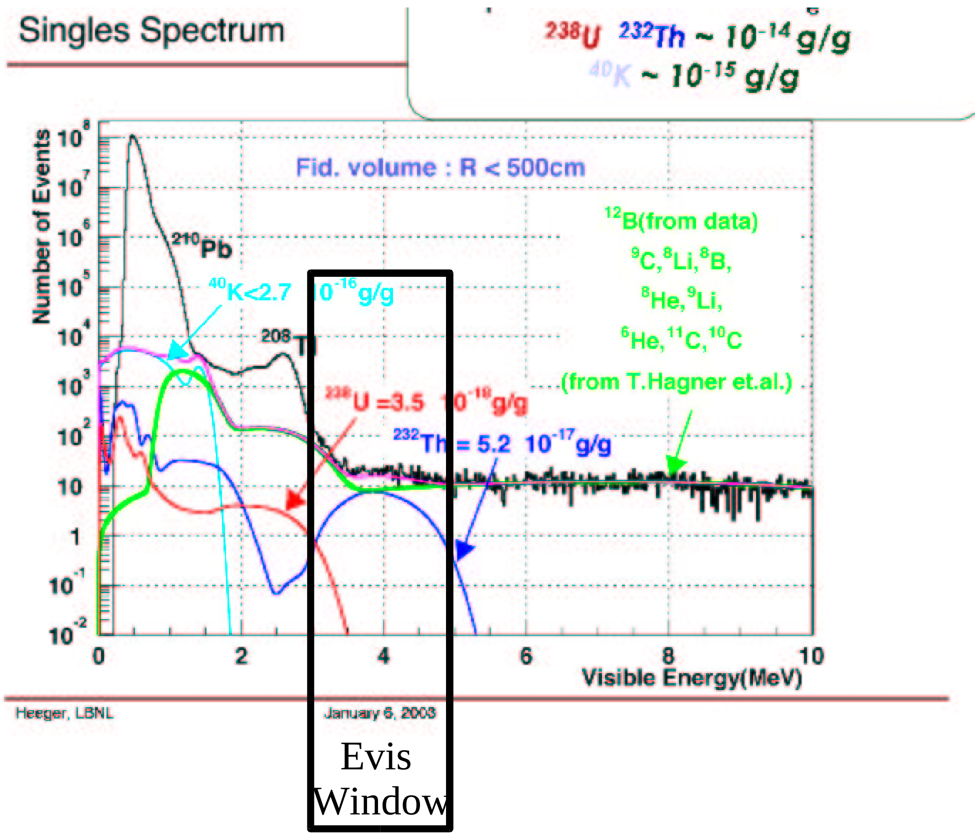


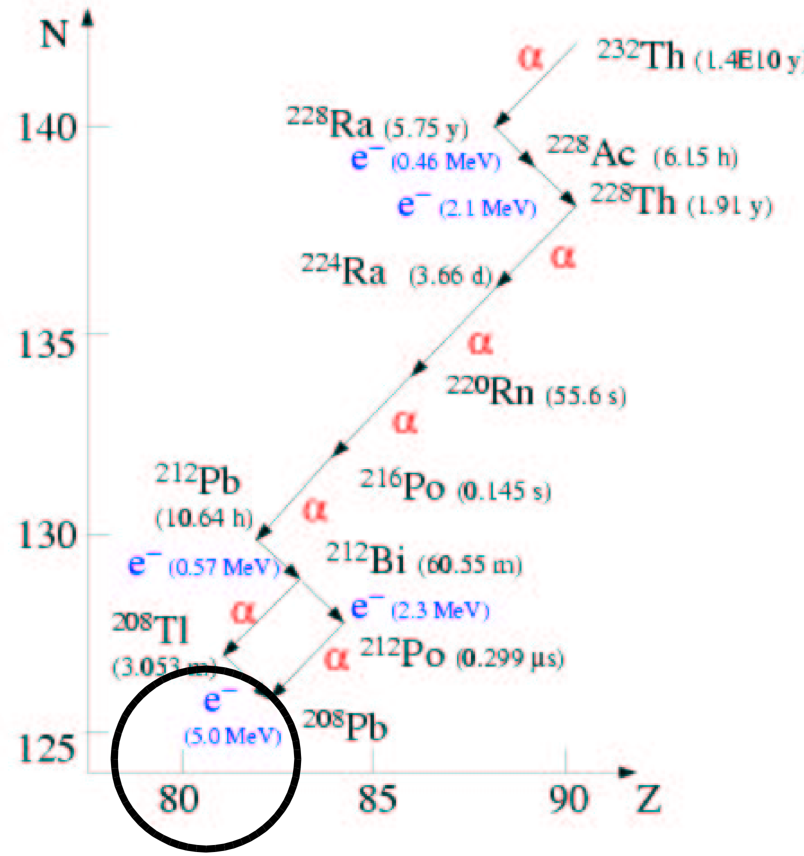
Cosmic in tank,

No hit in the lower veto

Environmental Backgrounds: Part II: more difficult case...

Contaminants

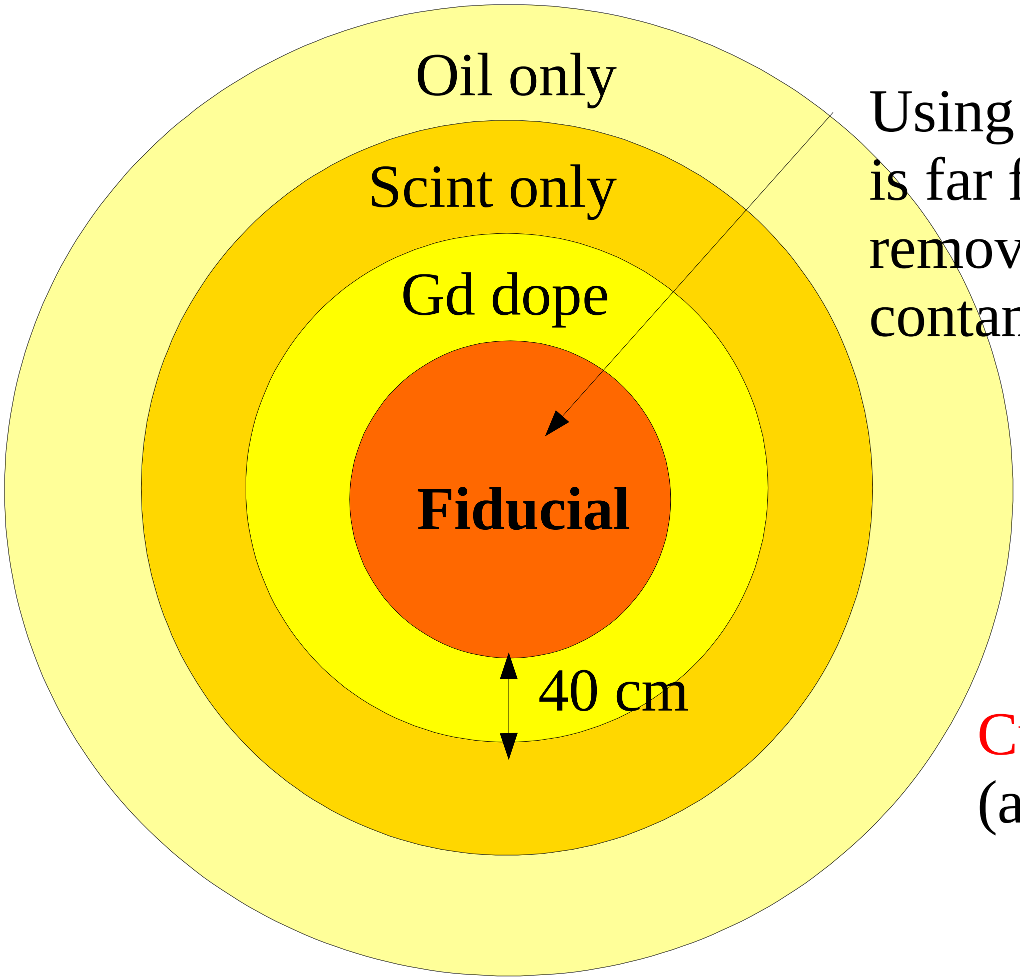




α's quench, producing < 1 MeV of visible E

It is the β's that are producing the background

(no γ's are produced w/ energy in the window)



Using a fiducial volume which is far from the acrylic vessel removes background from contaminants on balloon.

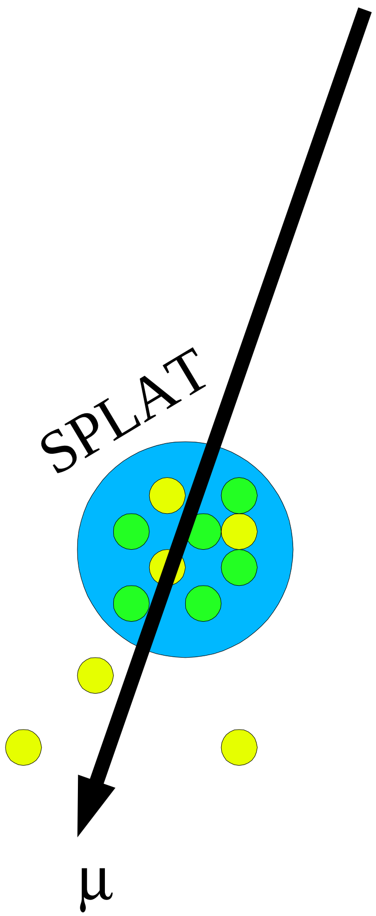
(Position of β is well localized)

Cut 40 cm from inner balloon
(also addresses IBD bkgds)

This leaves contamination of the oil.
We need to achieve purity levels for U, Th equivalent to KamLAND

Environmental Backgrounds: Part III: the largest background...

High-Energy-Muon-induced isotopes:

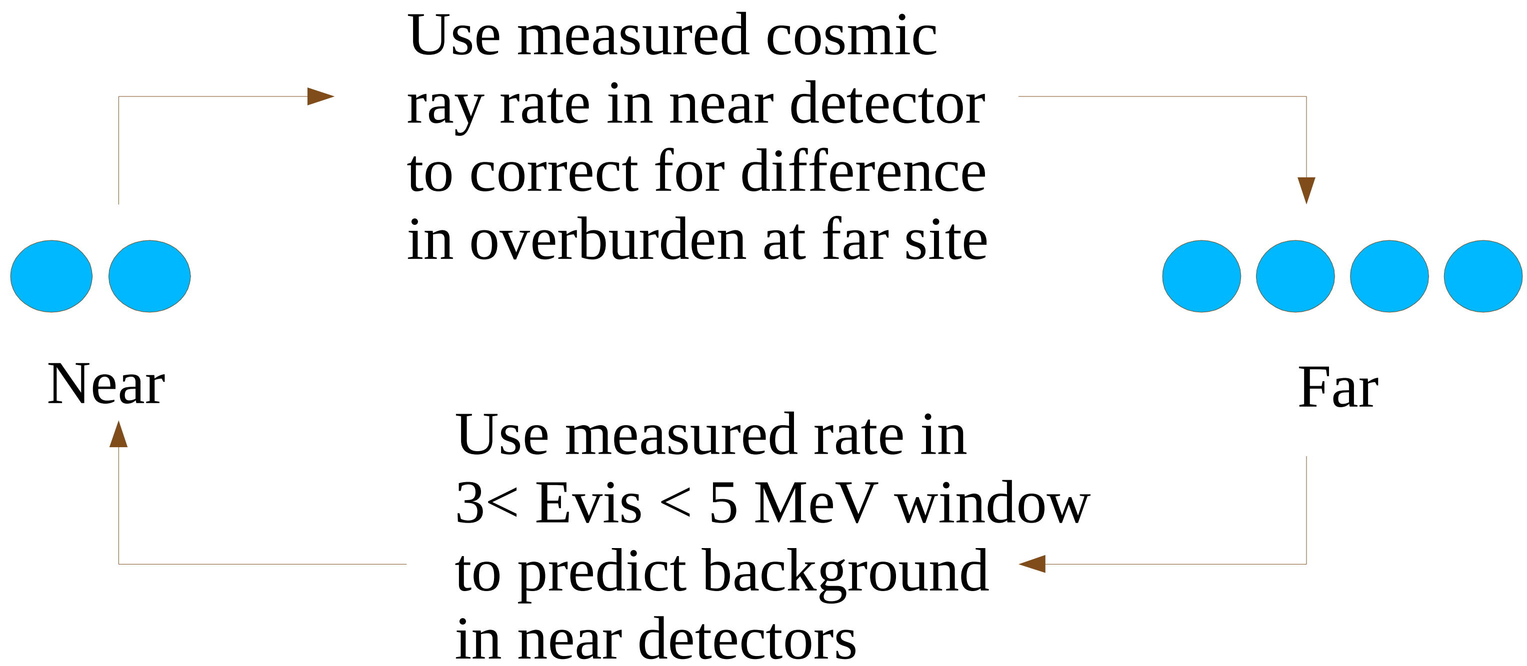


Going deep reduces the rate substantially.
minimum to achieve NuTeV error: 300 mwe

Lifetimes are too long for a simple cosmic veto

We propose a veto for cosmic+spallation n's
Horton-Smith, Munich Mtg

Most important:
We can use the far detectors to measure the background rate in the near detectors...

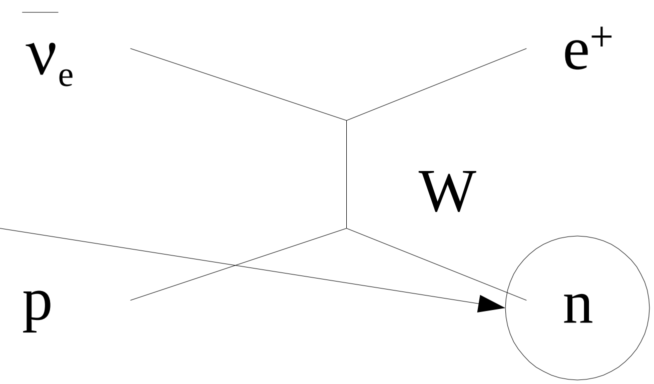


Measures both HEμ and contamination backgrounds at once

This works as long as...

1) The contamination of oil is same in near/far
2) The overburden is not very different
   (cosmic ray correction addresses normalization but not shape)

Question 3: Is IBD Misidentification controllable?



Most events are identified
via the neutron

We require high efficiency
for identifying capture on H

We need that 40 cm Gd buffer to prevent n escape!

We require a neutron window which opens earlier than CHOOZ
and closes later: $0.5 < \Delta t < 200\ \mu s$

This leaves:
events which escape because neutron is early
events which escape because neutron is late.
events which escape because of inefficiency on H capture

Events with neutrons outside of the window...

Early:
The neutron capture energy will be added to the neutrino vertex energy:

Ecapture + Tpositron + Eannihilation = Etotal

> 5 Mev for Gd or =2.2 for H | 0 to Enu-1.8 | 1 MeV | > 5 for Gd, always and Only 20% have < 5 MeV for H

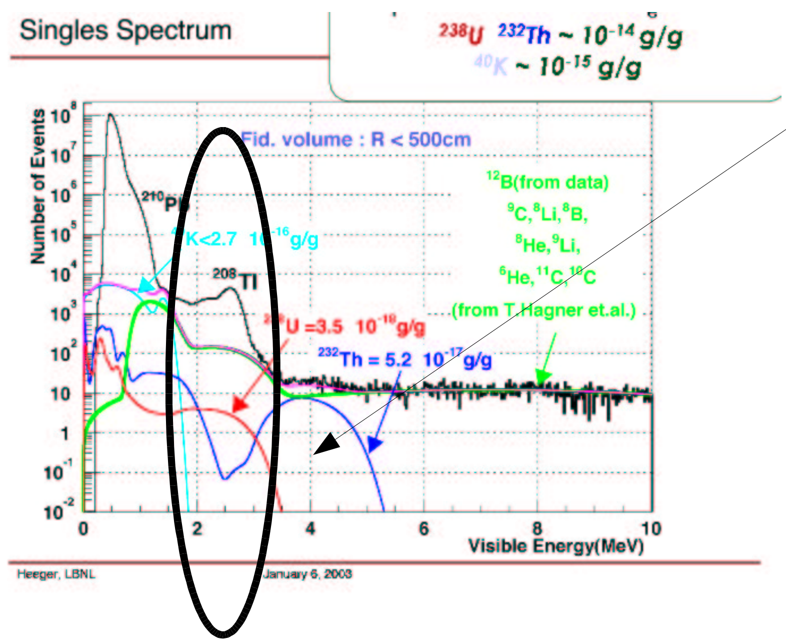
Only a small fraction will pass the Evis cut

Late:
Only the positrons with energy in the 3<Evis<5 window
Neutrons never pass cuts (2.2 MeV too small, >5 MeV too large)

This analysis requires using H captures

Question: how efficient can we be? We assume 99.4%

tradeoff of false trigger rate vs. efficiency.



False rate come from many sources:

Contaminants

Michel electrons

(veto is applied at analysis level)

etc.

trigger only on n signals in limited spatial region near e^+ signal?

A few things to note:

fake rate from tubes & tank walls reduced by inactive oil buffer

KamLAND-level purity will reduce fake rate

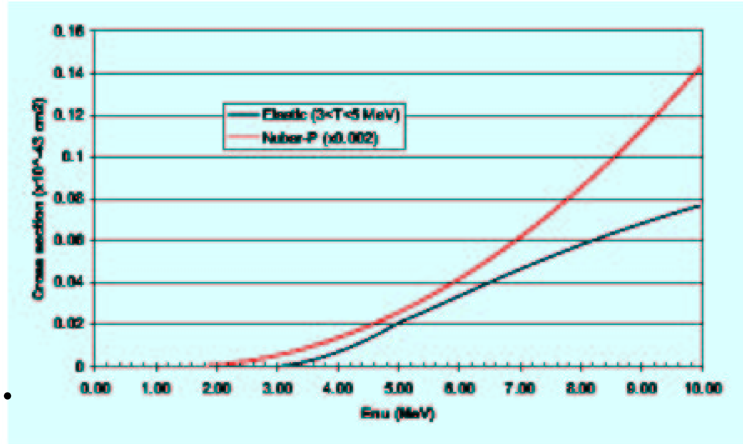
Question 4: How to normalize the sample?

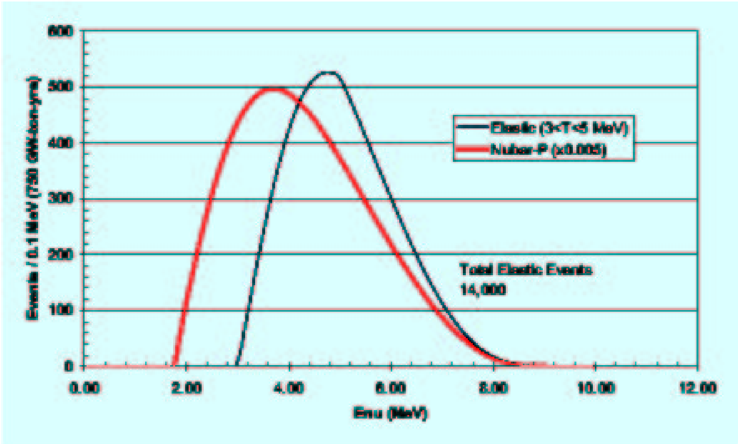
Use IBD to nail down the flux (xsec known to ~0.2%!!!)
Use that flux to get the ES event rate within 3<Evis<5 MeV

Two points:

1) Don't apply 3<Evis<5 MeV
to the normalization sample!!!

2) Correct for the fact that you applied
a cut to one window and not the other.





There will be
>1E6 normalization events
stat error is not an issue
but there are systematics...

Systematics 1: number of target electrons for ES and
number of target protons from IBD.
these are correlated.

Using CHOOZ free proton error and correcting for correlation: 0.6%

Systematics 2: isolating your IBD sample

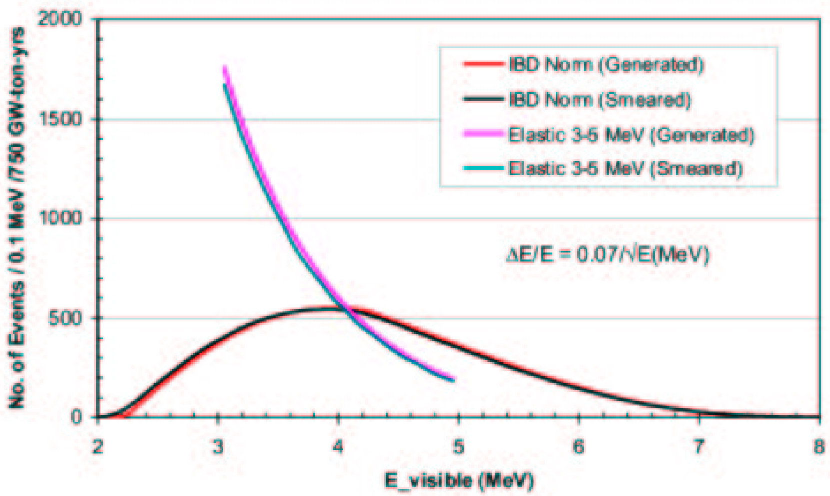
Option 1: Use only Gd-identified events.
May needs a specialized small detector to allow measure of
Gd fraction to 0.3% using Am/Be source.

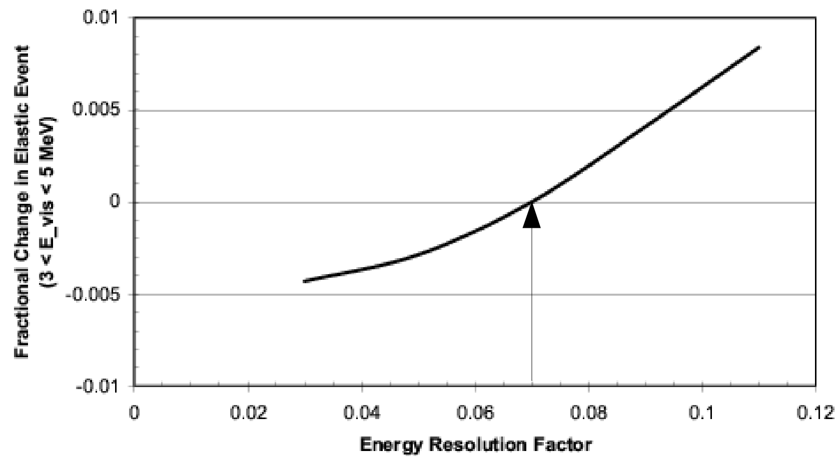
Option 2: Use both H and Gd identified events,
Difficult for me to estimate background
Error on Gd fraction no longer a big issue

We'll use option 1 because we don't know how to estimate
option 2 errors...

Does energy smearing matter? ... can we can reach < 10%/ $\sqrt{E}$??

(KamLAND achieved 7%)





If we are in the 7-10% range the effect is negligible.
We do not consider it here.

Rates for this design

11,440 ES events

1,224,391 IBD events (potential bkgd)
1959 IBD events background given a 0.16% ineffic.
systematic error turns out to be negligible

1458 beta decays from muon-induced isotopes.
100 contamination-induced events
other environmental sources are negligible after cuts.

1,160,809 IBD events in the normalization sample

Statistical error on the signal	0.95%
Statistical error $\bar{\nu}p$ background subtraction	0.40%
Systematic error $\bar{\nu}p$ background subtraction	0.0%
Statistical error on U and Th background	0.08%
Systematic error on U and Th background	0.0%
Statistical error on muon-induced isotopes	0.34%
Systematic error on muon-induced isotopes	0.61%
Statistical error on the normalization	0.10%
Systematic error on electron-to-free-proton ratio	0.60%
Systematic error on the Gd capture fraction	0.30%
Total error	1.3%

error on $\sin^2 \theta_W$ 0.0019

Comparing to NuTeV 0.0017

Conclusions:

An error comparable to NuTeV can be achieved
using a realistic design

I think we should add this to the arguments for
building a reactor-based neutrino experiment
in the near future.

We are passing out a final draft of the paper.
We will put this on the web in a week.
Comments welcome! conrad@nevis.columbia.edu