Is it feasible to make a precision measurement of $\sin^2\theta_W$ at a reactor?

or

A New Angle on Reactors

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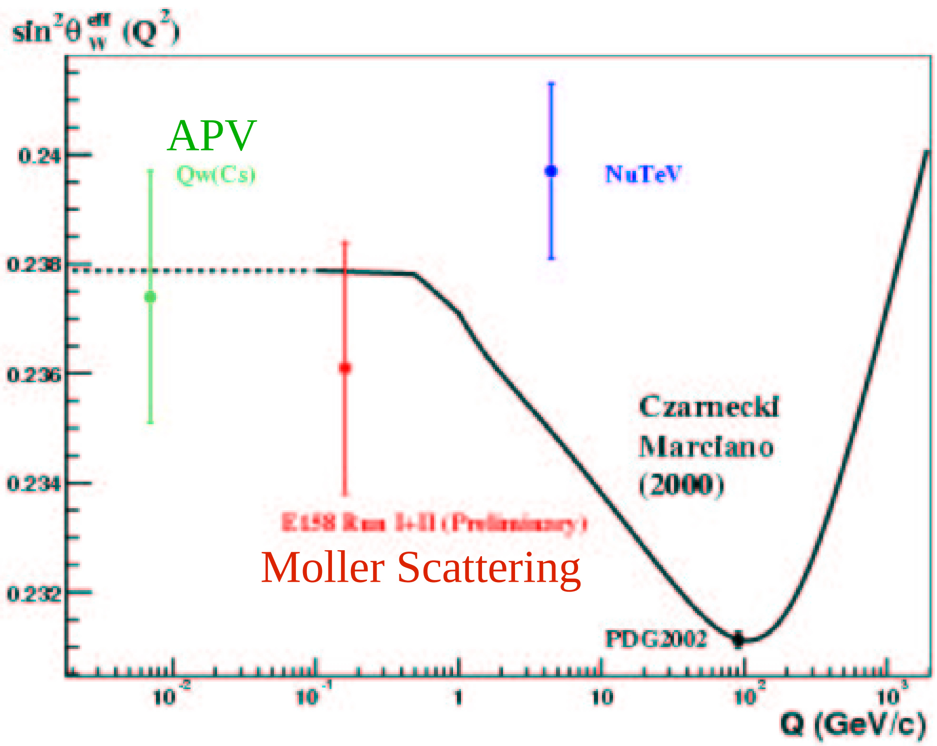
with help from Jon Link, Sam Zeller & the Columbia Neutrino Group

Janet Conrad, Columbia U.
APS Reactor Working Group Meeting, Feb. 7, 2004

Motivation -- the NuTeV anomaly:

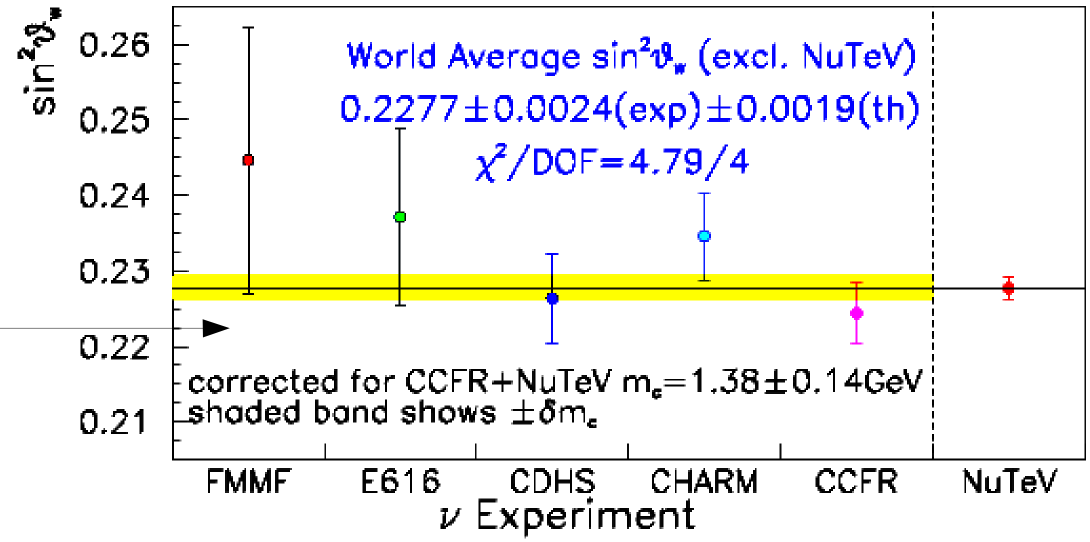


Standard Model Prediction

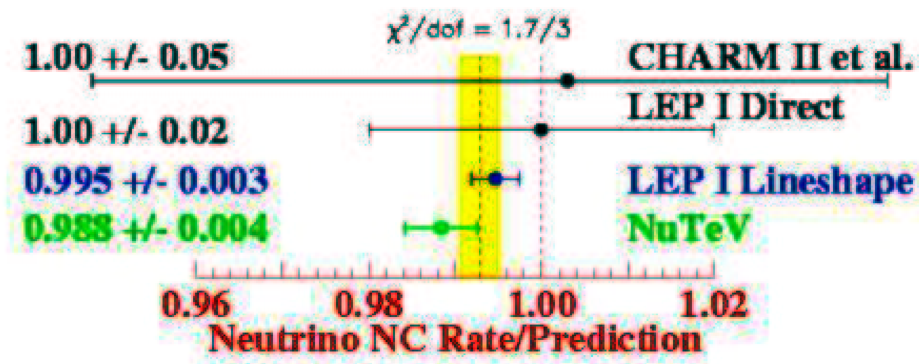
More about the NuTeV result:

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!

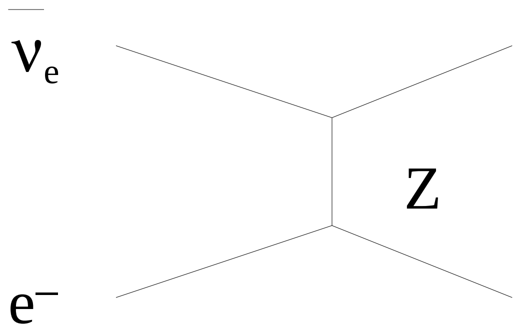
A Reactor-based measurement:

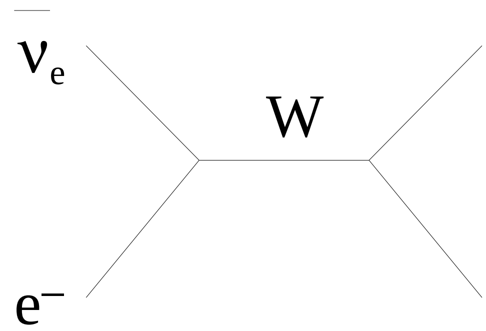
- Probes new physics in the neutrino sector (like NuTeV)
- Has low Q^2, comparable to APV (Qw)
- Has different systematics!
- Uses design similar to near detector proposals
- Can achieve errors less than APV and E158,
  & comparable to NuTeV ... $d(\sin^2\theta_W) = \pm 0.0017$

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)





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

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

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

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 $\sin^2\theta_W$

Outline:

1. 4 General Questions
   which Drive the Design
2. Detector Design Specifics
3. Event Rates Given this Design

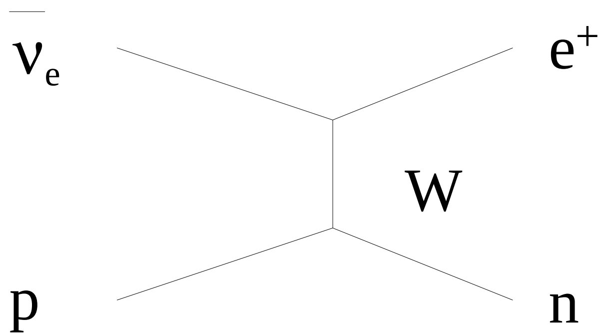
Bottom Line: $d(\sin^2\theta_W)=\pm 0.0020$!!!

Goal: do the analysis in sufficient detail to check if this
is worth pursuing further.

in other words: at the end there will still be open questions
but we hope the main issues are addressed.

Starting points:

1. Are the statistics high enough?
2. Are the rates from environmental backgrounds (cosmics, radioactivity) low enough?
3. Can the background from *inverse beta decay* (IBD) be controlled?

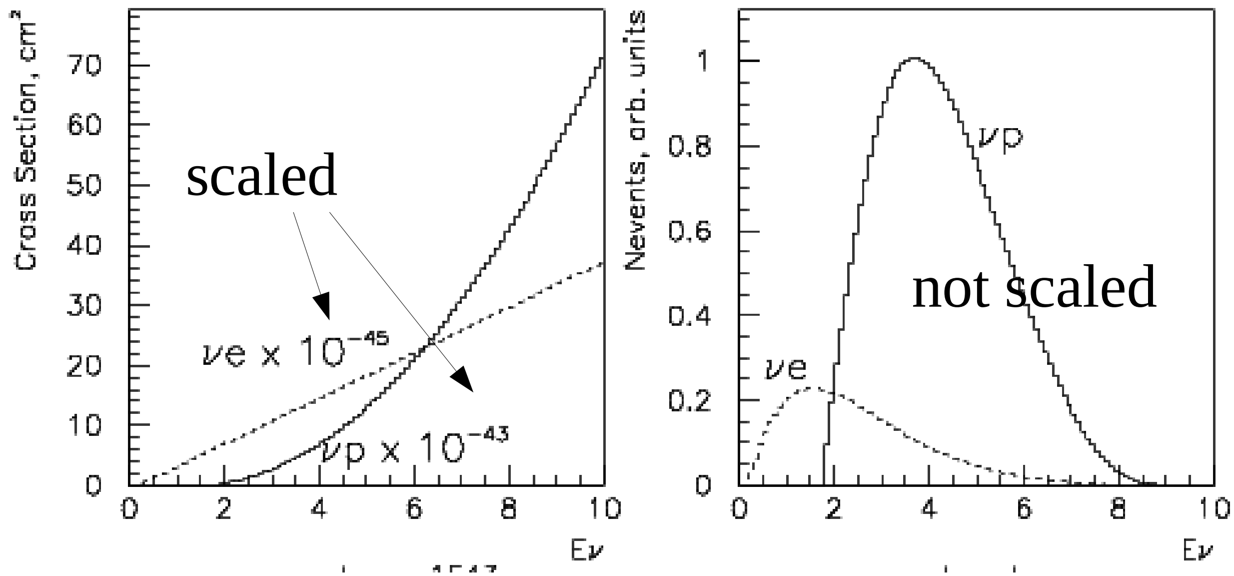


4. Is the normalization known well enough to make a precise measurement?

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

Question 1: Is the ES event rate high enough?

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

Question 2: Are the Environmental Backgrounds Controllable?

Yes if you introduce a cut: $3<E_{vis}<5$ MeV

<u>Radioactivity:</u>

Energy deposited by
Natural Radioactivity cuts off
at about 3 MeV

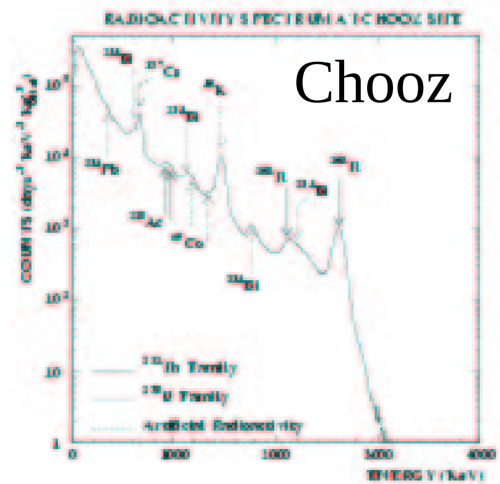


Fig. 11. Natural radioactivity spectrum recorded by a NaI crystal in the well hosting the detector.

<u>Cosmic Ray Muons:</u>

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

<u>Electrons from Muon Decay (Michel electrons):</u>

Can be vetoed by a 10 lifetime look-back system,
Small fraction in visible energy range. ... *negligible background*

Muon-induced isotopes (Part 1):

Muon capture: ^{12}B

- 8% of the μ^- stopping rate
- lifetime 20 ms

Rate reduced by ~20% by 3<Evis<5 MeV ... not enough!

Introduce a 40 ms look-back.

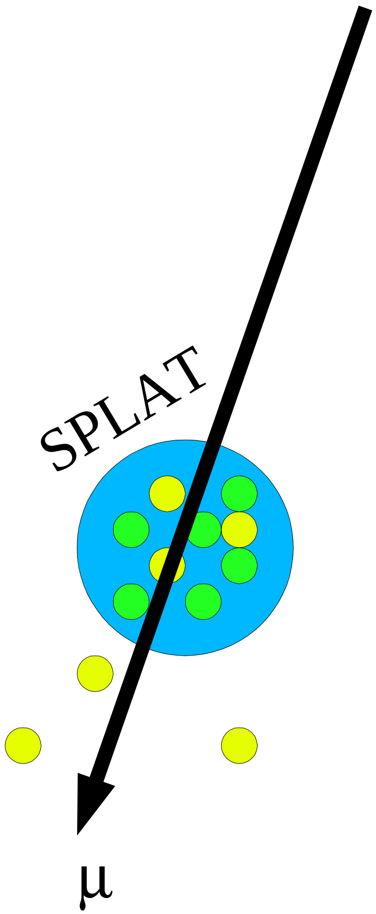
This will produce an 11% deadtime.
When I talk about days-of-running, I mean live-days.

This is still going to be a significant background

Muon-induced isotopes (Part 2):

From T. Lasserre's talk at Munich Mtg.,
Isotope production rates measures by
NA54 on 12C

High energy production (spallation)



Isotope	1/2 life (s)	Endpoint	Rate (1/d)	with Cut (1/d)
^{11}Be	13.80	11.5	< 2	< 0.4
^{9}Li+^{8}He	0.18 & 0.12	13.6 & 10.6	2	< 0.4
^{8}Li	0.84	16.0	4	< 0.5
^{6}He	0.81	3.5	14	< 2.0
^{9}C	0.13	16.0	4	< 0.5
^{8}B	0.77	13.7	4	< 0.6

Lifetimes are too long for a simple cosmic look-back

Perhaps a look-back for cosmic+spallation n's ???
Horton-Smith, Munich Mtg

Introducing
3<Evis<5 MeV
(assumes flat dist)

This will result in a rate as large as the signal.

This was at 300 mwe.

37.5 mwe is more than $\times$10 worse!

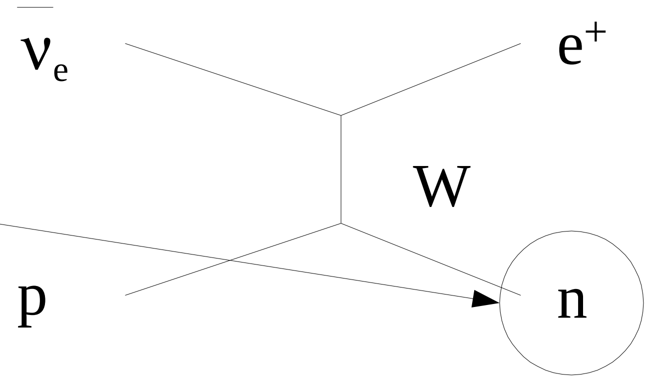
DEEPER IS MUCH MUCH BETTER
FOR THIS ANALYSIS

CAN WE GO DEEPER?

for now we assume 300 mwe...

Question 3: Is IBD Misidentification controllable?

Most events are identified
via the neutron



We require high efficiency
for identifying capture on H

We need a 40 cm Gd buffer to prevent n escape!   Big Fid Vol Cut!

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

Events with neutrons outside of the window...

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

Ecapture + Tpositron + Eannihilation = Etotal

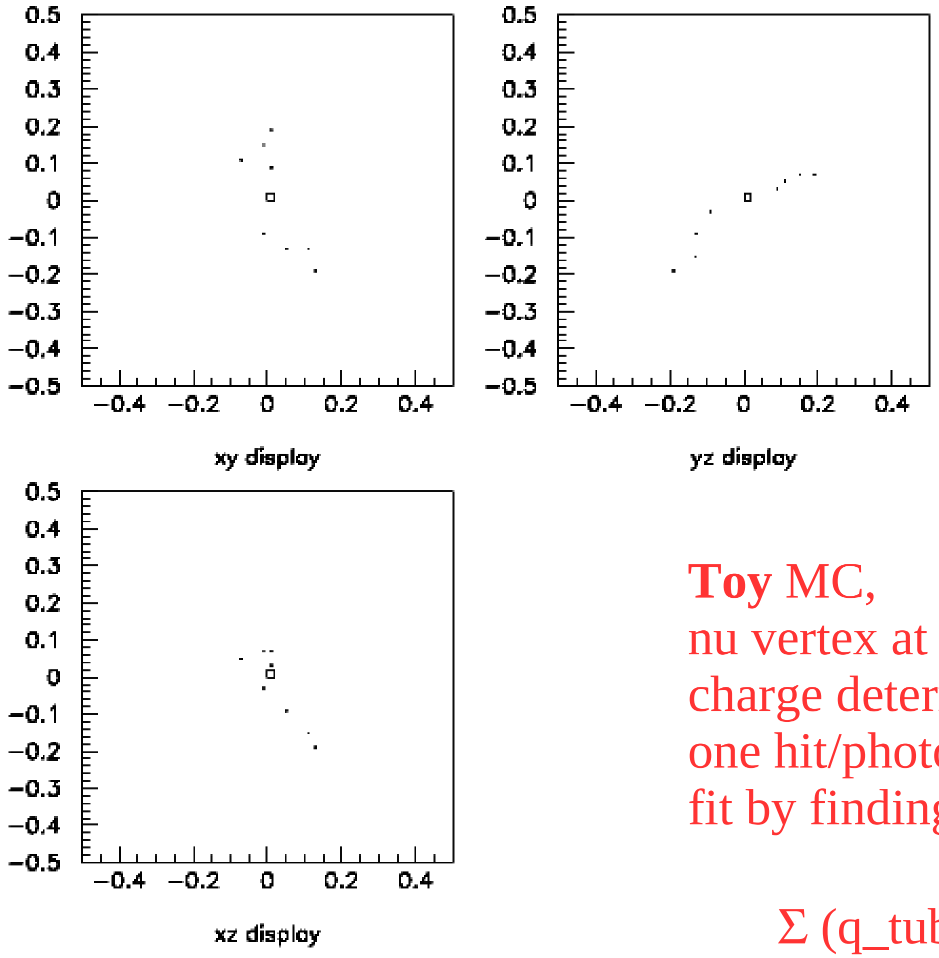
> 5 Mev for Gd or =2.2 for H | 0 to Enu-1.8 | 1 MeV | > 5 for Gd, always and Only 20% have < 5 MeV for H

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)

The IBD background is tolerable so far,
but better to beat it down...

An event topology analysis



IBD events have a nu vertex
and a series of compton scats

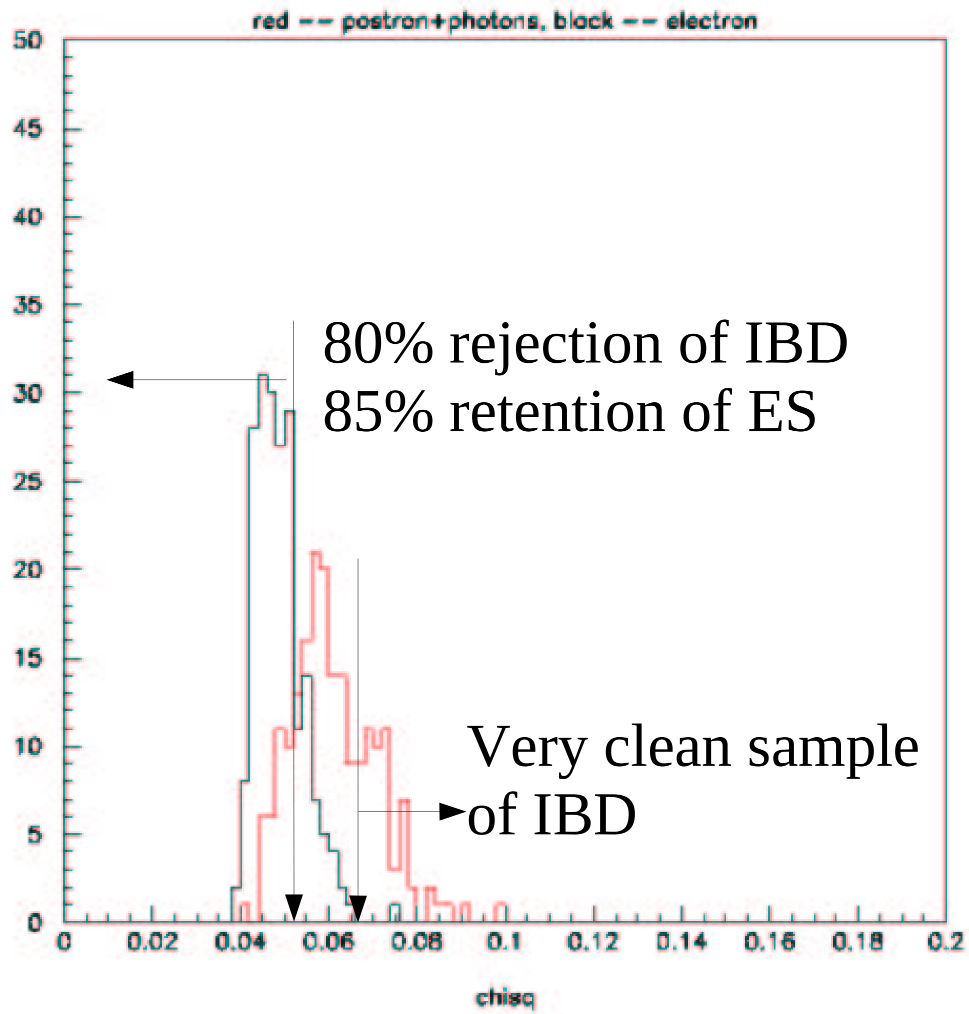
Can we differentiate this from
ES events (only 1 vertex)?

Toy MC,

(Thanks, Byron Roe!)

nu vertex at (0,0,0)
charge determined by solid angle w/ attenuation
one hit/phototube
fit by finding vertex which minimizes

$$\Sigma\ (q\_tube\text{-}i\ \ -\ q\_predicted\text{-}i)^2$$



Conclusion:
Looks promising!

Needs to be developed
beyond the toy-stage

For now, show results
without and with
a shape analysis cut...

The clean sample of
IBD events will be useful!

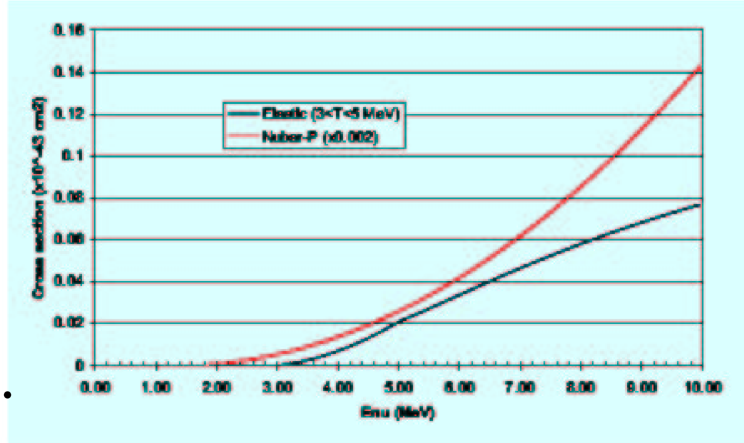
Question 4: How to normalize the sample?

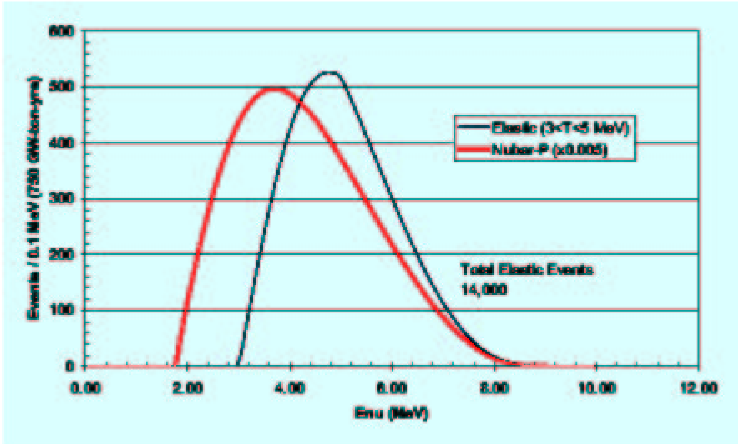
Use IBD to nail down the flux (xsec known to ~0.2%!!!)
Use that flux to get the ES event rate within 3<Evis<5 MeV

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.
Negligible bkgd in sample but 0.7% error on Gd fraction.
Would well-identified sample from shape analysis help???

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...

in light of the answers to the general questions...

Here are the CUTS:

40 cm Gd surrounding the fiducial region

3 < Evis < 5 MeV

0.5 < Δt < 200 μs

Shape chisq < 0.0525 for signal

Shape chisq > 0.0650 for norm sample Gd capture study

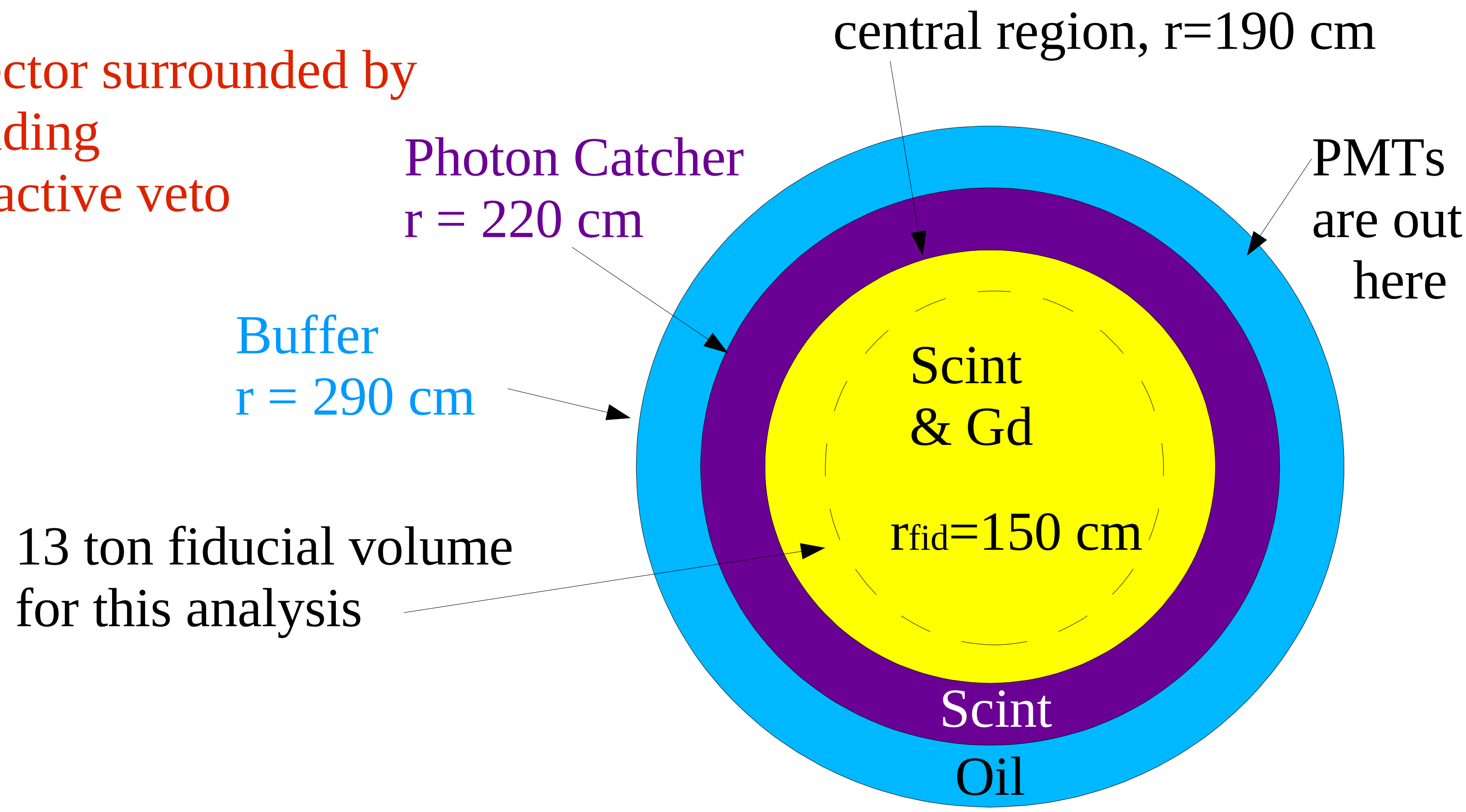
plus the look-back windows (applied in software)

And here is a feasible experimental design...

Use Braidwood as the model:
2 reactors @ 3.6 GW
224 m from reactors to detector
900 live-days of running
(or 1035 if using topology analysis)
2 detectors

300 mwe overburden

Detector surrounded by shielding
and active veto



Rates for this design (assumes a topology analysis)

13,155 ES events

1,408,049 IBD events (potential bkgd)
704 IBD events background given a 0.05% ineffic.
systematic error turns out to be negligible

11,000 beta decays from muon-induced isotopes.
other environmental sources are negligible after cuts.

1,334,930 IBD events in the normalization sample

Assume Gd ratio error on norm
improved by $\times 2$ from topology analysis ... 0.35%

error on $\sin^2 \theta_W$: 0.0020 Comparable to NuTeV!

If one does not use a Topology Analysis....

11,000 events from muon-induced isotopes
inefficiency for IBD increases by $\times 5$
Gd capture ratio without topology analysis 0.7%

error on $\sin^2\theta_W$: 0.0022 Still close to NuTeV!

Event Topology Analysis and spallation neutron veto: 0.0017

If we were at 37.5 mwe overburden
> 1,100,000 events from muon-induced isotopes
error on $\sin^2\theta_W$: 0.0040
Unacceptable

Possible Problems with our Arguments:

Systematic errors on environmental backgrounds not evaluated
Energy resolution has not been considered

Possible ways to improve this analysis

Run longer
Reduce the muon-induced isotope bkgds w/ clever look-back scheme
Make a more realistic shape analysis
Consider using all IBD events rather than Gd scatter events for normalization.

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.