Elastic scattering of electron -neutrinos and measurement of the weak mixing angle at a reactor

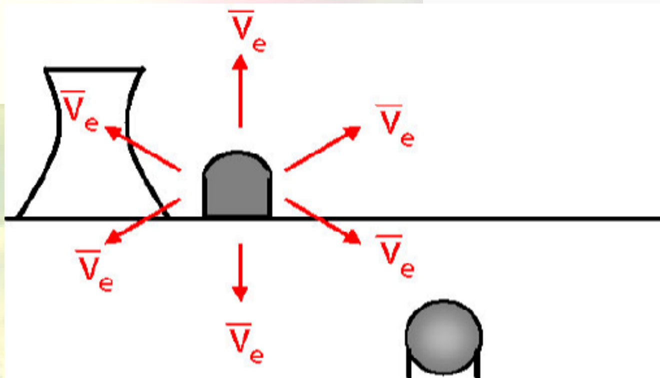
$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$$

See Janet's talk Tuesday!

- Standard model coupling constants
- DIS and the NuTeV anomaly
- Elastic scattering with reactor $\bar{\nu}$ s
- Backgrounds
- Motivation and physics

Braidwood Neutrino Experiment

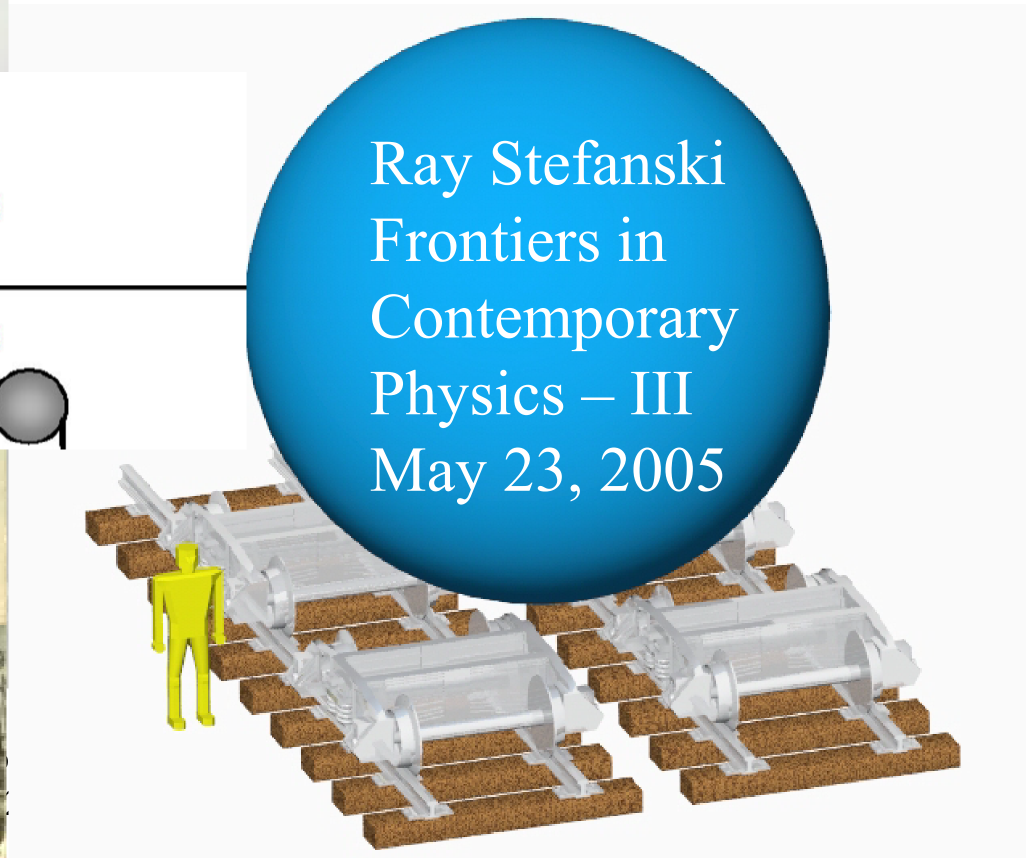
A new initiative at Krasnoyarsk.



Ray Stefanski

Frontiers in Contemporary Physics – III

May 23, 2005



The neutrino has mass. This implies the existence of right-handed neutrinos.

Hep-ph/0412099; R.N. Mohapatra *et al*.

The SM Lagrangian is:

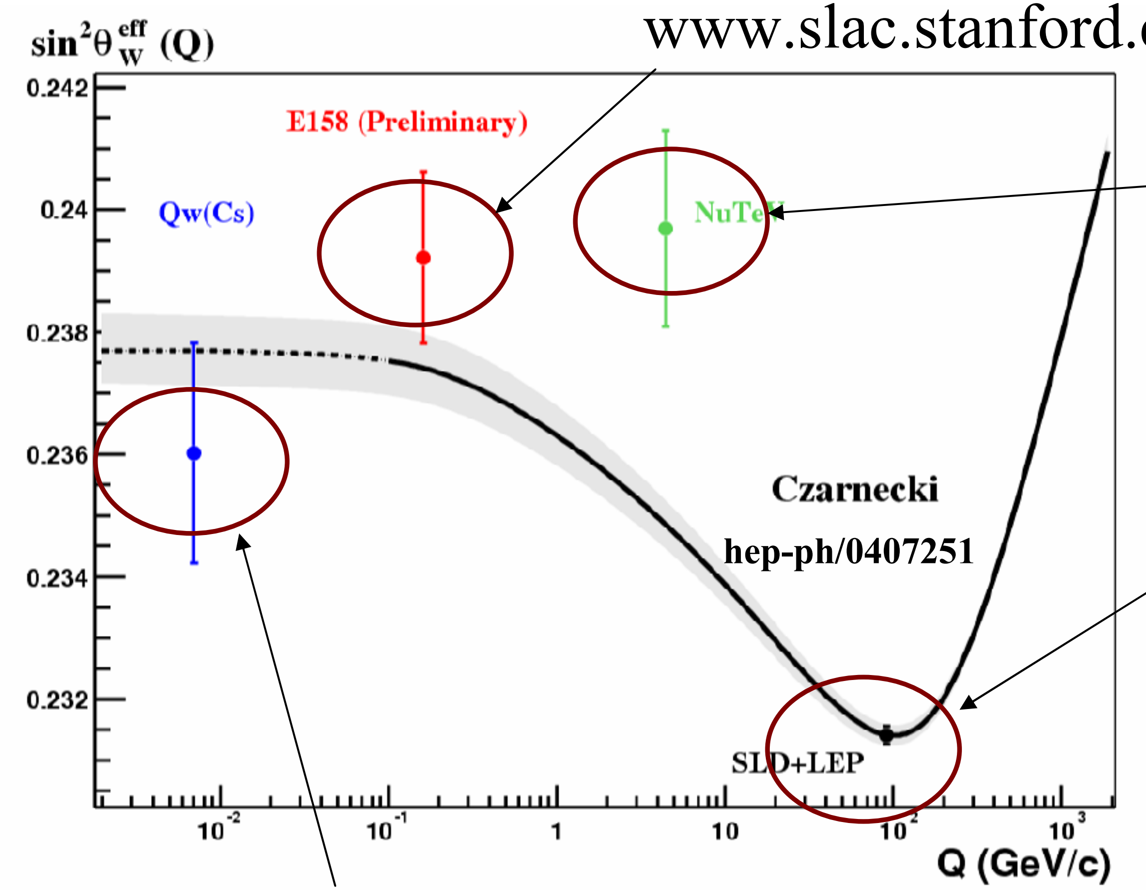
$$\mathcal{L}_{leptons} = \overline{R} i\gamma^{\mu}(\delta_{\mu} + \frac{ig'}{2}\mathcal{A}_{\mu}Y)R + \overline{L} i\gamma^{\mu}(\partial_{\mu} + \frac{ig'}{2}\mathcal{A}_{\mu}Y + \frac{ig}{2}\tau \cdot \mathrm{b}_{\mu})L$$

where the coupling constant associated with the $SU(2)_L$ and $U(1)_\gamma$ are g and g′ respectively. It is evident that *R* only interacts via $U(1)_\gamma$ gauge boson and *L* interacts via both $U(1)_\gamma$ and $SU(2)_L$ gauge bosons.

Direct measurements of g and g′ should provide good sensitivity to a possible departure from the conventional Standard Model. The neutrino is the particle that has a new property, so it seems a good idea to search in neutrino interactions.

$\tan\theta_W = g/g'$

Moller scattering is done with e + e reactions.
www.slac.stanford.edu/exp/E158



Measured with neutrinos; That may be a source of corrections in the SM.

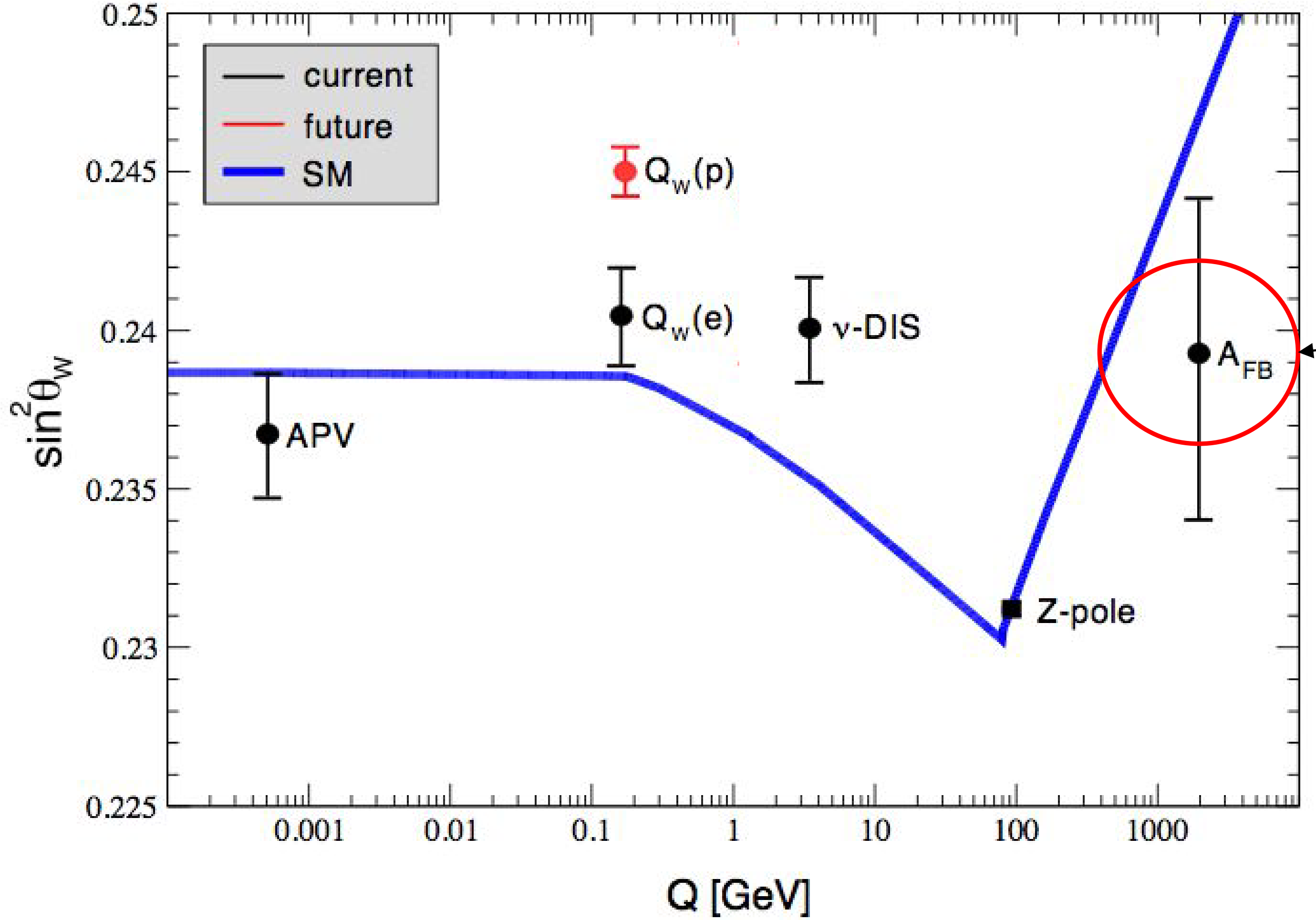
Measured above the Z mass; the ratio of the Z and W mass normalize the weak scale.

Atomic Parity Violation measurements test the photon's role in weak interactions.

Marciano and Rosner;
PRL Vol 65 No. 24, 2963; Dec 10, 1990

It may be the case that, except for neutrino DIS, the measurements agree with the SM. interactions.

From the Qweak proposal: the anticipated error in measurement of the weak charge of parity violating e-p scattering at JLAB.



LEP F-B asymmetry, as reported on the Qweak site gives an additional hint of a departure from the SM.

How do we measure deviations from the SM?

Conventionally this is broken into two parts. eviations caused by vacuum polarization; generally parameterized by the S, T, and U variables. These are called the oblique corrections. Additional corrections caused by physics BSM and require further corrections - ε_μ and ε_e. We'll make use of these later in the talk.

hep-ph/0403306 Loinaz, *et al.*
hep-ph/9603391;J.L. Hewett, *et al.*

$$\frac{\Gamma_{\rm lept}}{[\Gamma_{\rm lept}]_{\rm SM}} = 1 - 0.0021\,S + 0.0093\,T + 0.60\,\varepsilon_e + 0.60\,\varepsilon_\mu\ ,$$

$$\frac{\Gamma_{\rm inv}/\Gamma_{\rm lept}}{[\Gamma_{\rm inv}/\Gamma_{\rm lept}]_{\rm SM}} = 1 + 0.0021\,S - 0.0015\,T - 0.76\,\varepsilon_e - 0.76\,\varepsilon_\mu - 0.67\,\varepsilon_\tau\ ,$$

$$\frac{\sin^2\theta_{\rm eff}^{\rm lept}}{[\sin^2\theta_{\rm eff}^{\rm lept}]_{\rm SM}} = 1 + 0.016\,S - 0.011\,T - 0.72\,\varepsilon_e - 0.72\,\varepsilon_\mu\ ,$$

$$\frac{g_L^2}{[g_L^2]_{\rm SM}} = 1 - 0.0090\,S + 0.022\,T + 0.41\,\varepsilon_e - 0.59\,\varepsilon_\mu\ ,$$

$$\frac{g_R^2}{[g_R^2]_{\rm SM}} = 1 + 0.031\,S - 0.0067\,T - 1.4\,\varepsilon_e - 2.4\,\varepsilon_\mu\ ,$$

$$\frac{M_W}{[M_W]_{\rm SM}} = 1 - 0.0036\,S + 0.0056\,T + 0.0042\,U + 0.11\,\varepsilon_e + 0.11\,\varepsilon_\mu\ .$$

1. The electroweak gauge group is the standard SU(2)L × U(1)Y . The only electroweak gauge bosons are the photon, the W±, and the Z.
2. The couplings of new physics to light fermions are highly suppressed so that 'direct' corrections from new physics can be neglected (with the possible exception of processes involving the b quark). Only oblique corrections need to be considered.
3. The new physics scale is large compared to the W and Z masses.

We might expect that ε_l might be caused by the existence of the right-handed neutrino and could be directly related to the NuTeV result.

To minimize systematic effects, the Paschos – Wolfenstein Relation was used: Cross-section differences remove sea quark contributions, and reduce uncertainties from charm production and the sea.

NuTeV measured g_V in Deep Inelastic ν_μ scattering on nuclei.

Paschos - Wolfenstein Relation

$$R^- = \frac{\sigma^{\nu}_{NC} - \sigma^{\bar{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\bar{\nu}}_{CC}} = \rho^2\left(\tfrac{1}{2} + \sin^2\theta_W\right) = g_L^2 - g_R^2$$

$$g_{L,R}^2 = u_{L,R}^2 + d_{L,R}^2$$

$$\sigma\left(\nu_\mu d_{sea}\right) - \sigma\left(\bar{\nu}_\mu \bar{d}_{sea}\right) = 0 \Rightarrow \text{Only } d_{valence} \text{ contribute}$$

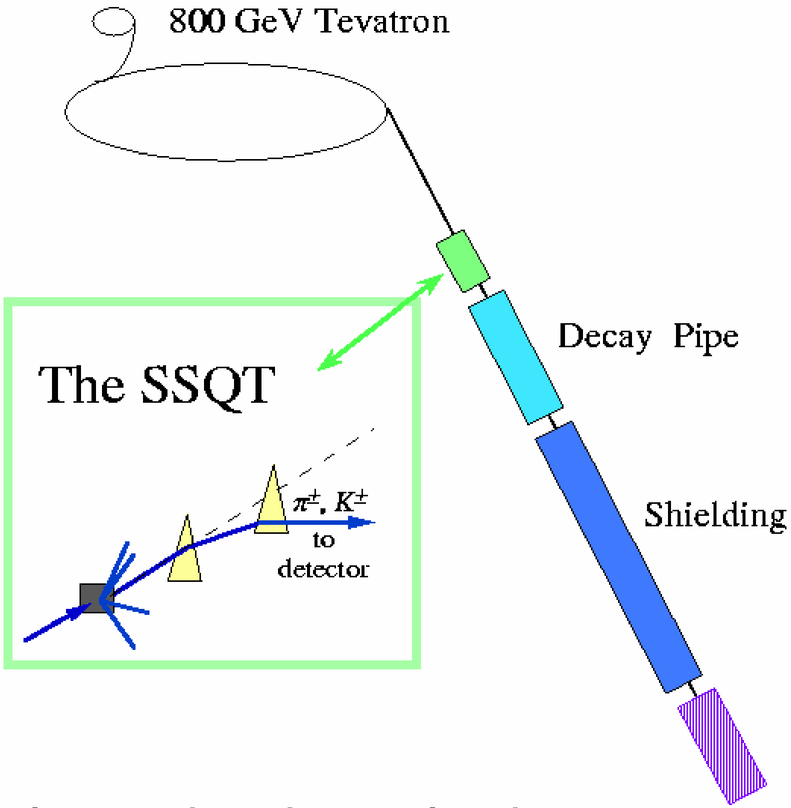
$$\sigma\left(\nu_\mu \bar{u}_{sea}\right) - \sigma\left(\bar{\nu}_\mu u_{sea}\right) = 0 \Rightarrow \text{Only } u_{valence} \text{ contribute}$$

$$\sigma\left(\nu_\mu s_{sea}\right) - \sigma\left(\bar{\nu}_\mu \bar{s}_{sea}\right) = 0 \Rightarrow \text{No } strange-sea \text{ contribution}$$

- R^- manifestly insensitive to sea quarks
  - Charm and strange sea error negligible $\left(If\ xs(x) = x\bar{s}(x)\right)$
  - Charm production small since enters from d_V quarks only, which is Cabbibo suppressed and at high-x
- *But* R^- requires separate ν and beams so needed to develop a high-intensity separated beam $\bar{\nu}$

  ⇒ NuTeV SSQT (Sign-selected Quad Train)

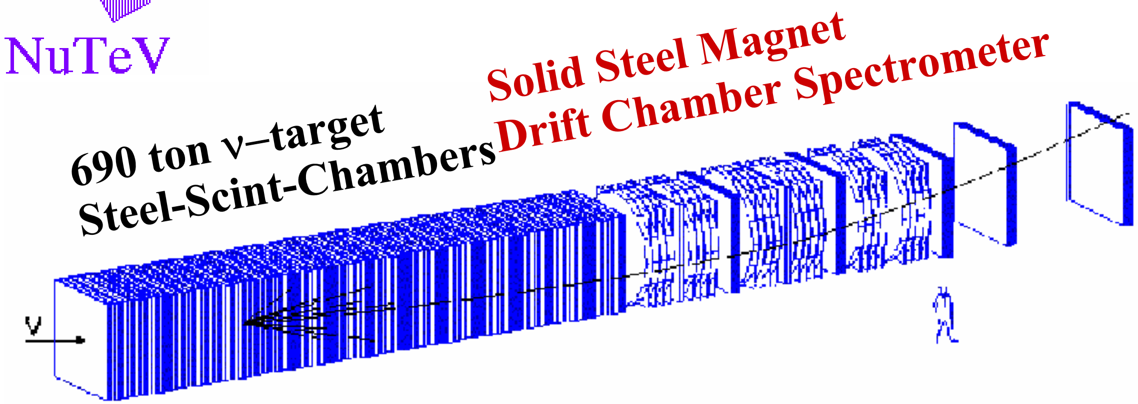
NuTeV Experimental Setup



- **The Quad Triplet Neutrino beam was an important innovation that made this measurement possible.**
- **Beam is almost pure ν or $\bar{\nu}$ ($\bar{\nu}$ in ν mode 3×10^{-4}, ν in $\bar{\nu}$ mode 4×10^{-3})**
- **Beam only has ~1.6% electron neutrinos**

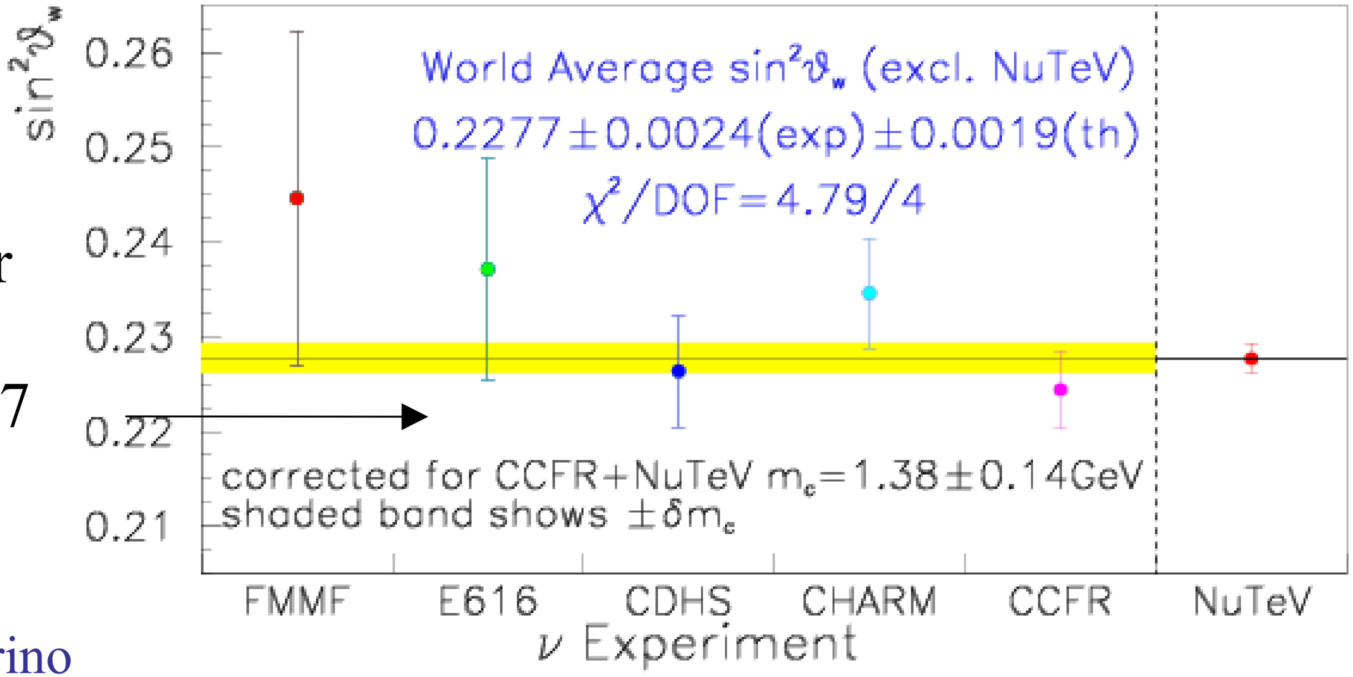
  $\Rightarrow$ Important background for isolating true NC event

Dipoles make sign selection
- Set ν / $\bar{\nu}$ type
- Remove ν_e from K_{long}



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

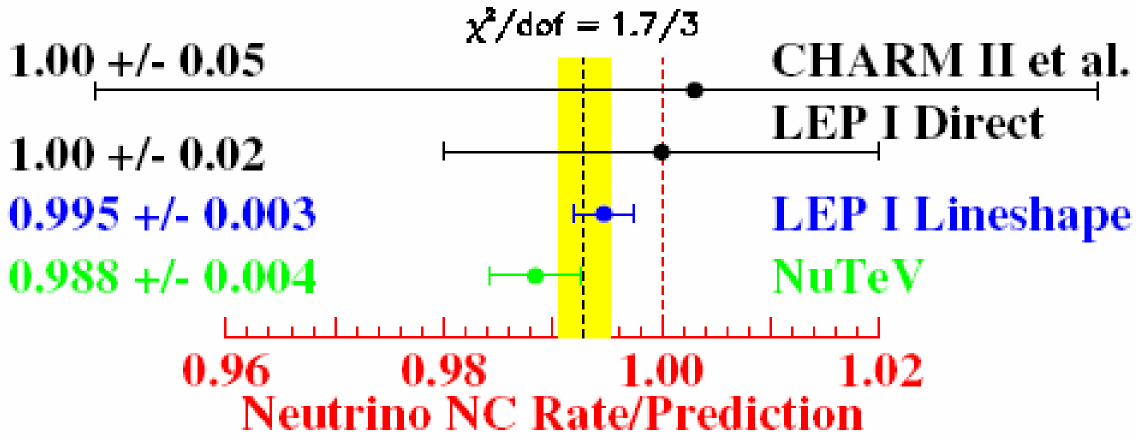
SM=0.2227



The number of light neutrino families is determined by comparing the Z width, as measured in the Breit-Wigner line-shape with the visible lepton and quark-decay channels. The difference determines the number of light neutrino species to be:

Nν = 2.985 ± 0.008.

2σ < 3



Measurements of the neutrino current coupling, interpreted as a neutrino neutral current interaction rate ($\propto \rho^{(\nu)}$). The precise measurements, $\Gamma(Z \rightarrow \nu\overline{\nu})$ at LEP I and the NuTeV data, interpreted as an overall deviation in the strength of the neutral current coupling to neutrinos, are both below expectation.

- Perhaps the explanation for the NuTeV effect may lie in the application of new results to the data.
  1. **Changes in quark distributions sets**
     Cross-section models:
     Leading Order (LO) vs Next to Leading Order (NLO)
  2. **Changes in standard model radiative-corrections**

- **Perhaps the explanation involves small effects due to physics we are already familiar with such as QCD :**

  1. Is there a Strange vs anti-strange quark asymmetry?
  2. Are there Shadowing and other nuclear effects involved?
  3. Are there small violations of "isospin" symmetry caused by EM effects in final state interactions?

Or perhaps the explanation lies in BSM Physics:

- **In a better understanding of neutrino properties (g g′)**
  1. **The existence of couplings to new particles (SUSY)**
  2. **Mixing and oscillation Effects (PNMS matrix)**
  3. **New Z′ or lepto-quark exchanges**
  4. **New particle loop corrections in neutrino interactions (seesaw and heavy neutrinos)**

• The deviations from the SM in neutrino DIS, and the Z decay to neutrino pairs, begs the question:

Can we exploit these effects to gain further insight into the nature of BSM physics?

• These measurements directly involve neutrinos in a way that is manifestly dependant on the coupling constants g and g′, and may thereby be giving us a hint of the dynamics of what is unknown in EW interactions.

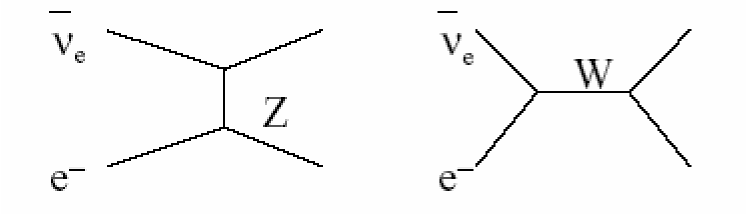
• Wouldn't it be interesting to search for similar effects in other systems? We propose taking a look at: $\bar{\nu}_e + e^- \longrightarrow \bar{\nu}_e + e^-$ at the Braidwood reactor near Joliet Illinois.

Let's look at Braidwood, then get back to NuTeV and compare results.

Conrad, Link, and Shaevitz, hep-ex/0403048

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$$

More and better measurements are needed!!
Elastic scattering in a reactor generated neutrino beam may provide another opportunity.



The differential cross-section:

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}[(g_V + g_A)^2 + (g_V - g_A)^2(1 - \frac{T}{E_\nu})^2 + (g_A^2 - g_V^2)\frac{m_e T}{E_\nu^2}] + \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\frac{(1 - T/E_\nu)}{T}$$

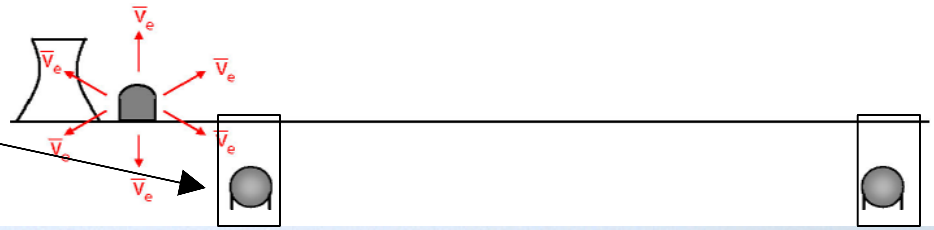
T = electron recoil KE
μ_ν = neutrino magnetic moment, generally assumed small.

- tag recoil events with 3 < T < 5 MeV
- use $\bar{\nu}_e + p \rightarrow e^+ + n$ to normalize
- U/Th contamination
- calibrate the energy scale
- test of NuTeV measurement !

$g_A = -½$
$g_V = ½ + 2\sin^2\theta_W$

$\tan\theta_W = g/g'$

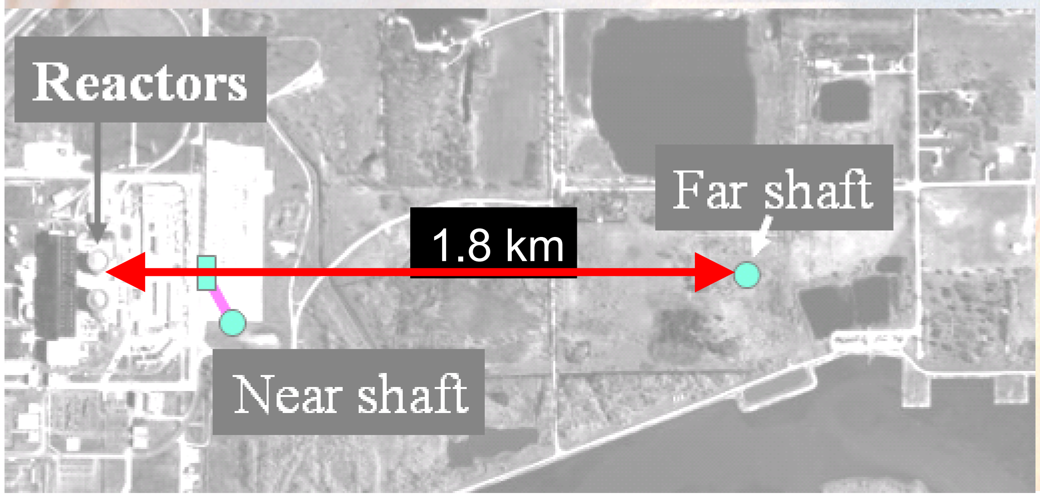
Use the near detector



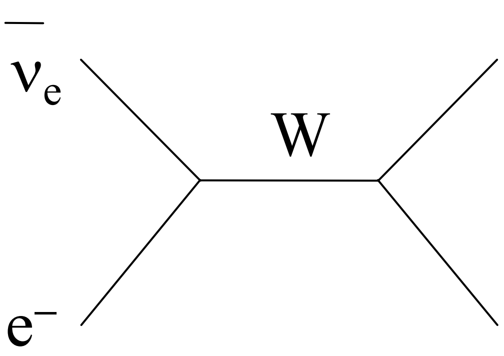
The Braidwood Design:

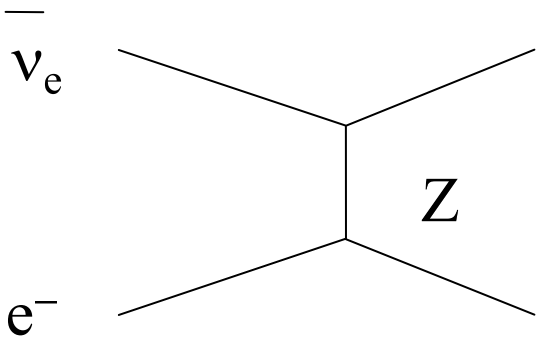
- 2 reactors @ 3.6 GW
- 224 m from reactors to near detectors
- ~1000 to 2000m to far detectors
- 900 live-days of running
- detectors are in two 600′ deep shafts

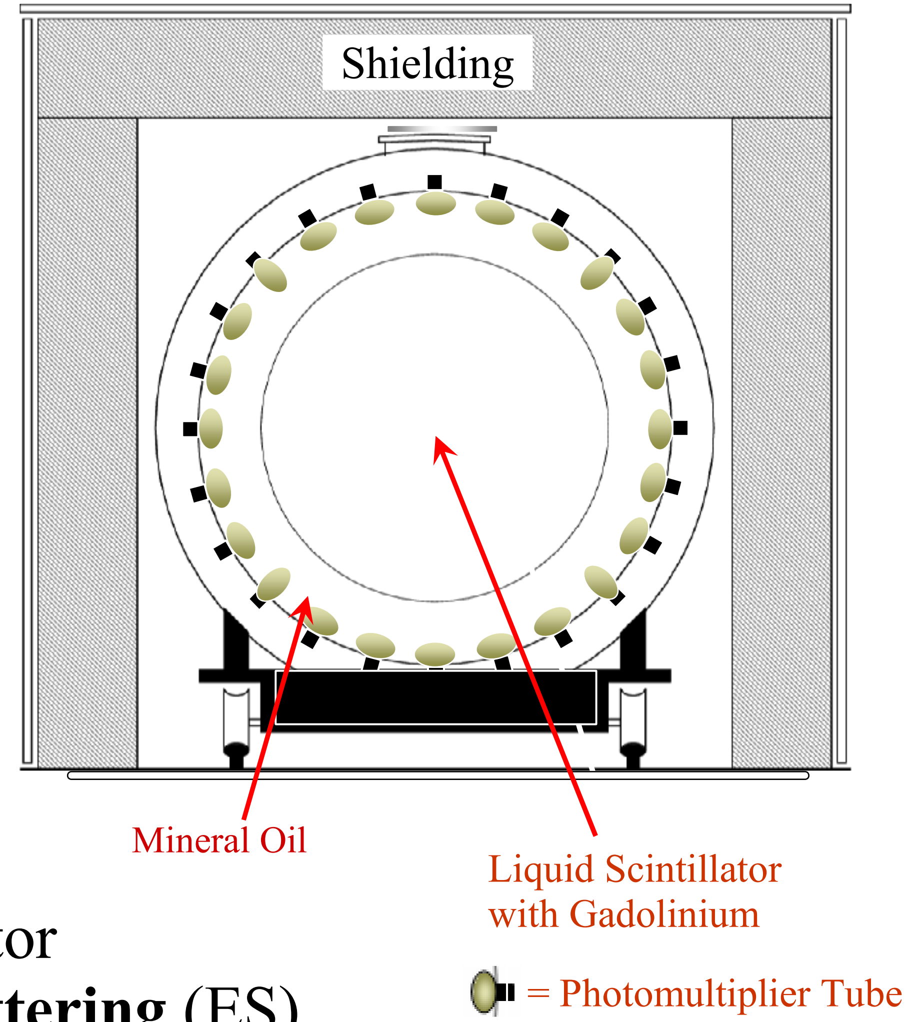
The elastic scattering experiment is a rate-limited measurement, so you need to be as close as possible to the reactor while maximizing overburden.



- 450 mwe shielding
- Shaft ~200 m from Reactor
  20-30 m at Krasnoyarsk
- 2 Detectors, 7 m radius







To measure coupling constants at a reactor
use the antineutrino-electron **elastic scattering** (ES)

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}\left[(g_V + g_A)^2 + (g_V - g_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 + (g_A^2 - g_V^2)\frac{m_e T}{E_\nu^2}\right] + \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\frac{(1 - T/E_\nu)}{T}$$

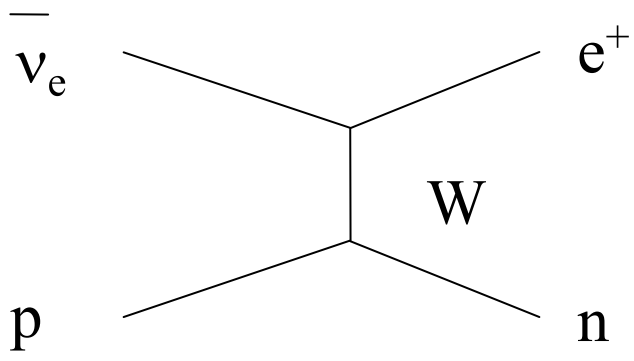
$g_V = ½ + 2\ \mathbf{sin^2}\ \theta_W$

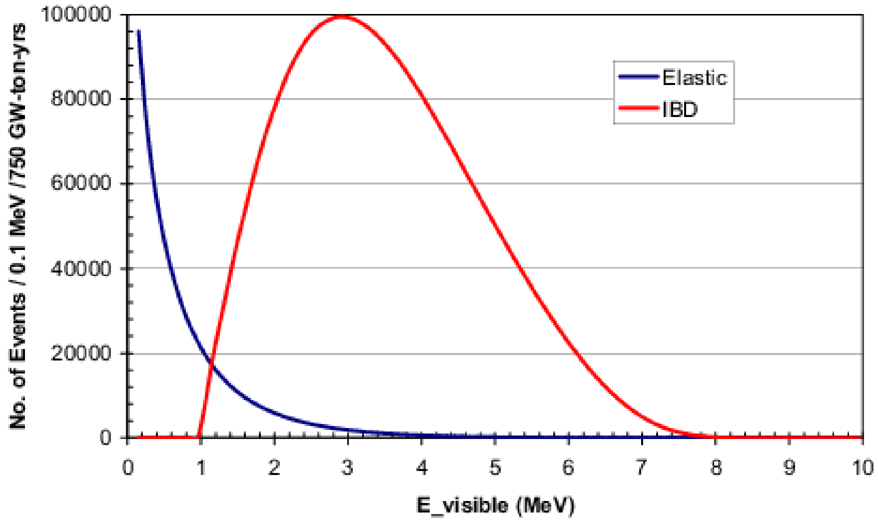
$g_A = ½$

T = electron KE energy
E = neutrino energy
m= mass of electron
This assumes μ_ν=0

• Why can this experiment do better than past reactor-based WMA measurements?

Remove the reactor flux uncertainty by normalizing to inverse beta decay (IBD)



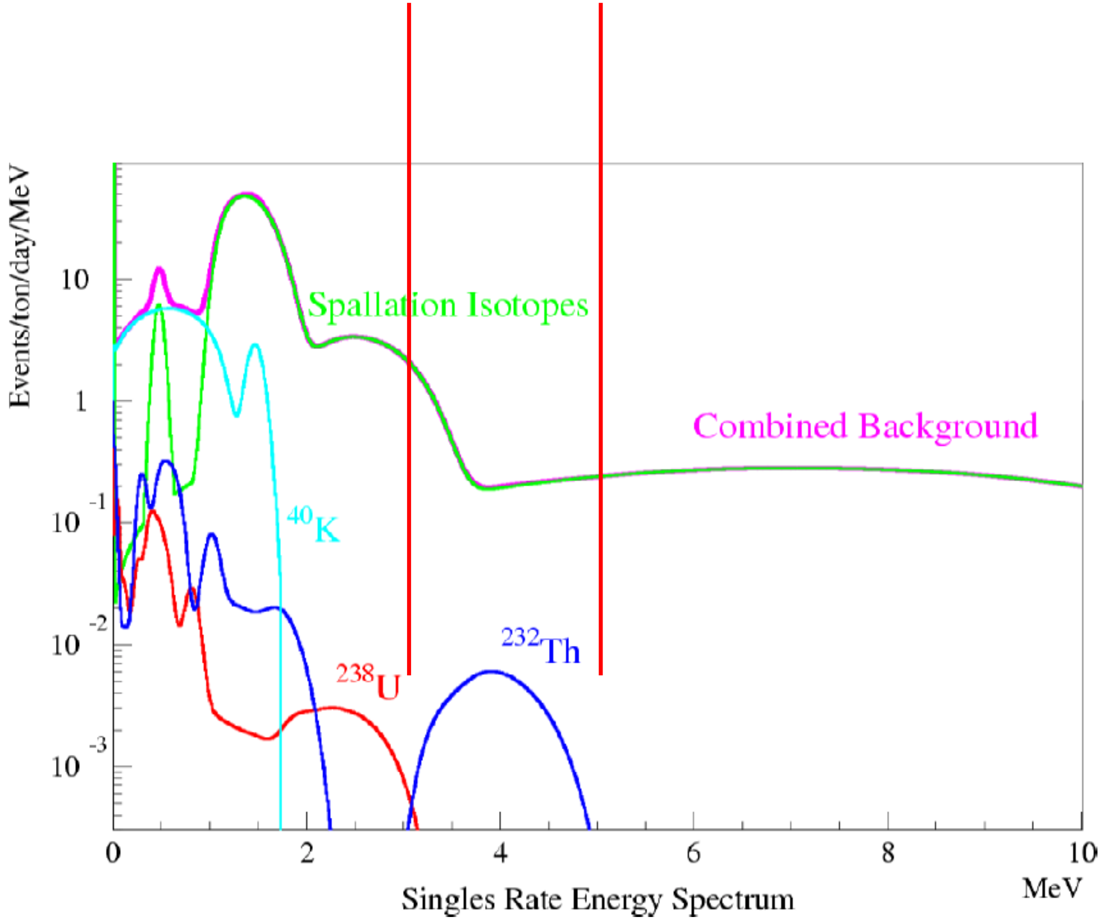


This cross section is known to 0.2%
because of recent precision measurements of the neutron lifetime.

This reduces the flux error from 2%
... A crucial improvement over past experiments!

- Why can this experiment escape the problems faced by neutrino magnetic moment measurements?

Use the window from 3-5 MeV to reduce backgrounds



This window is substantially higher than that needed by magnetic moment experiments

Contamination:

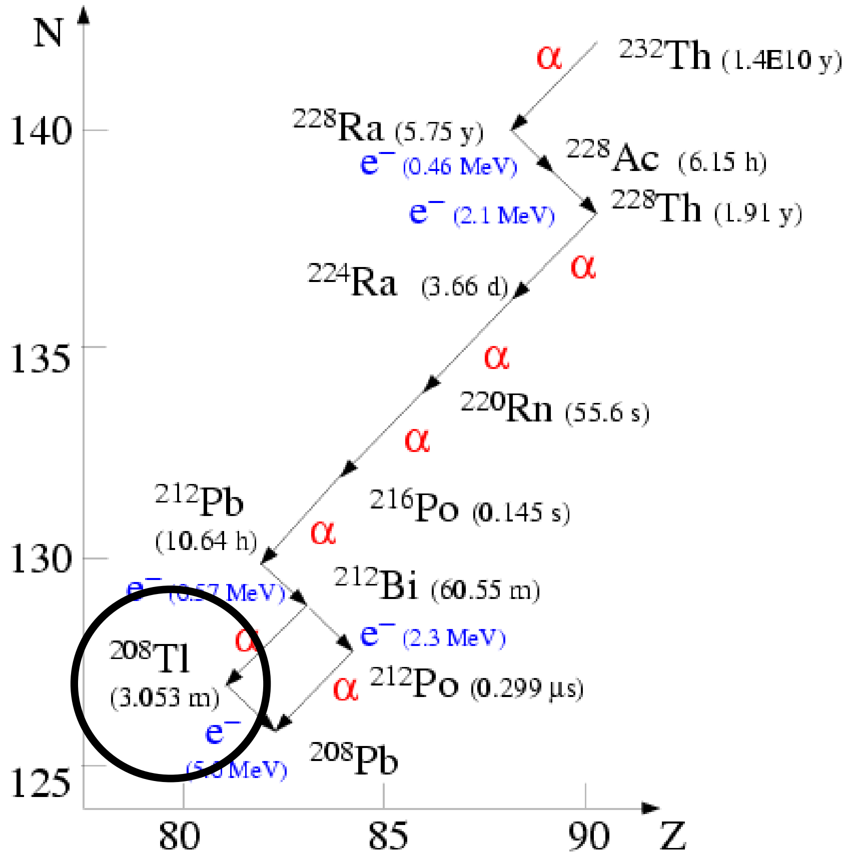
Basically only the Th chain

Spallation

Reduce by going deep,
by trigger/analysis methods

Reduce error by using far detectors to get accurate measurement

Contamination: ^{208}Tl



In pure scintillator, the required contamination rate is already demonstrated (Kamland, Borexino-CTF)

What about the Gd doping?

Looks like we can achieve 10^{-12} g/g of Th in Gd, which is then diluted to 0.1% in scintillator oil

All About ^{208}Tl...

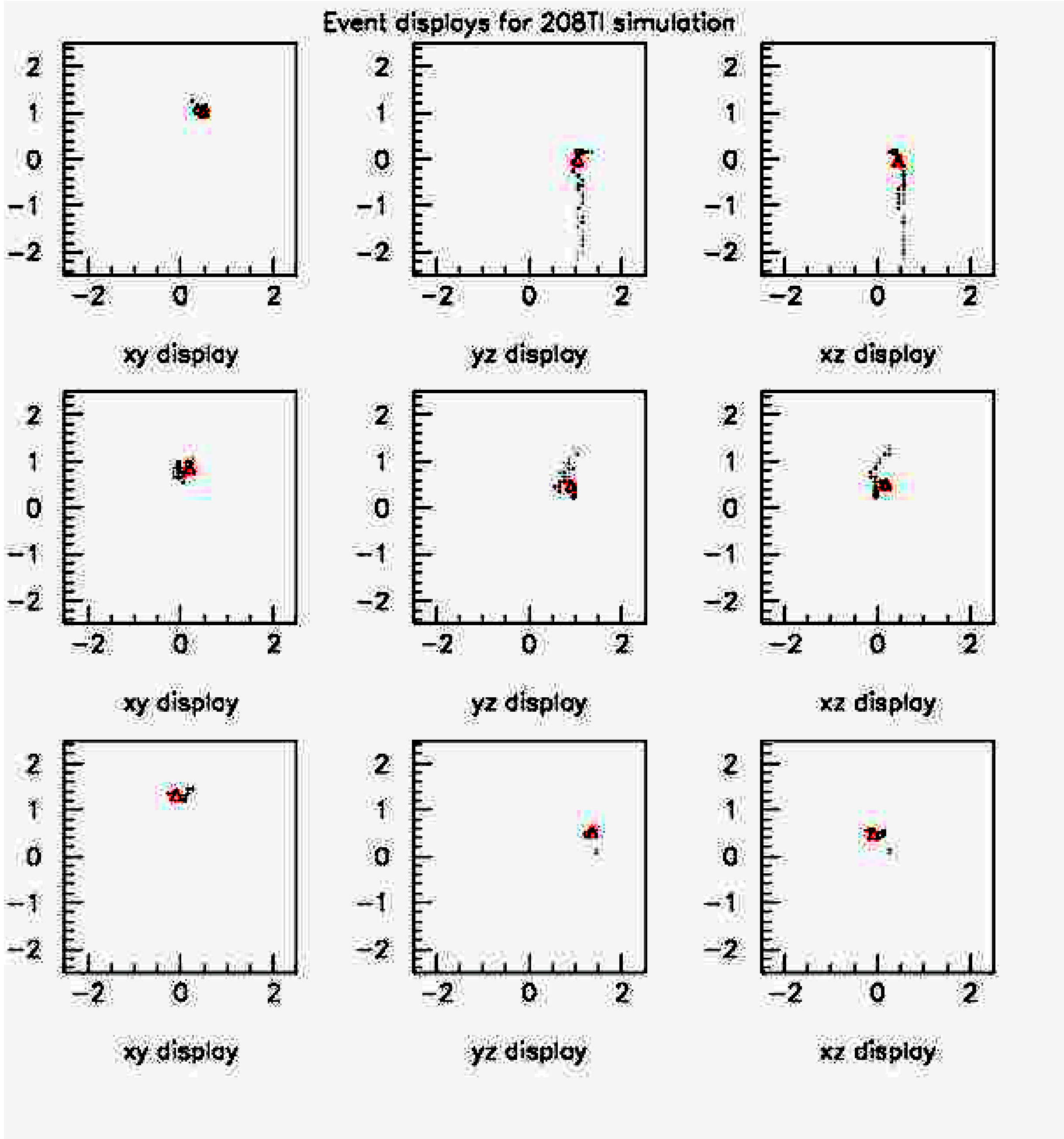
% Decay	Mode	Type
49%	1.8 MeV β + 0.6 MeV γ + 2.6 MeV γ	1
22%	1.5 MeV β + 0.3 MeV γ + 0.6 MeV γ + 2.6 MeV γ	2
25%	1.2 MeV β + 0.3 MeV γ + 0.3 MeV γ + 0.6 MeV γ + 2.6 MeV γ	3
	1.2 MeV β + 0.3 MeV γ + 0.9 MeV γ + 2.6 MeV γ	4
	1.2 MeV β + 0.6 MeV γ + 0.6 MeV γ + 2.6 MeV γ	5
	1.2 MeV β + 1.2 MeV γ + 2.6 MeV γ	6
4%	1.0 MeV β + 0.2 MeV γ + 0.3 MeV γ + 0.3 MeV γ + 0.6 MeV γ + 2.6 MeV γ	7
	1.0 MeV β + 0.5 MeV γ + 0.3 MeV γ + 0.6 MeV γ + 2.6 MeV γ	8
	1.0 MeV β + 0.5 MeV γ + 0.9 MeV γ + 2.6 MeV γ	9
	1.0 MeV β + 0.3 MeV γ + 0.5 MeV γ + 0.6 MeV γ + 2.6 MeV γ	10
	1.0 MeV β + 0.8 MeV γ + 0.6 MeV γ + 2.6 MeV γ	11
	1.0 MeV β + 1.4 MeV γ + 2.6 MeV γ	12

The decay modes of ^{208}Tl. The "event type" number designates the Type of decay as noted in the Table.

Each event type contains a 2.6 MeV γ and a 1.0 to 1.8 MeV β
These EM interactions in the scintillator leave an identifiable signature.

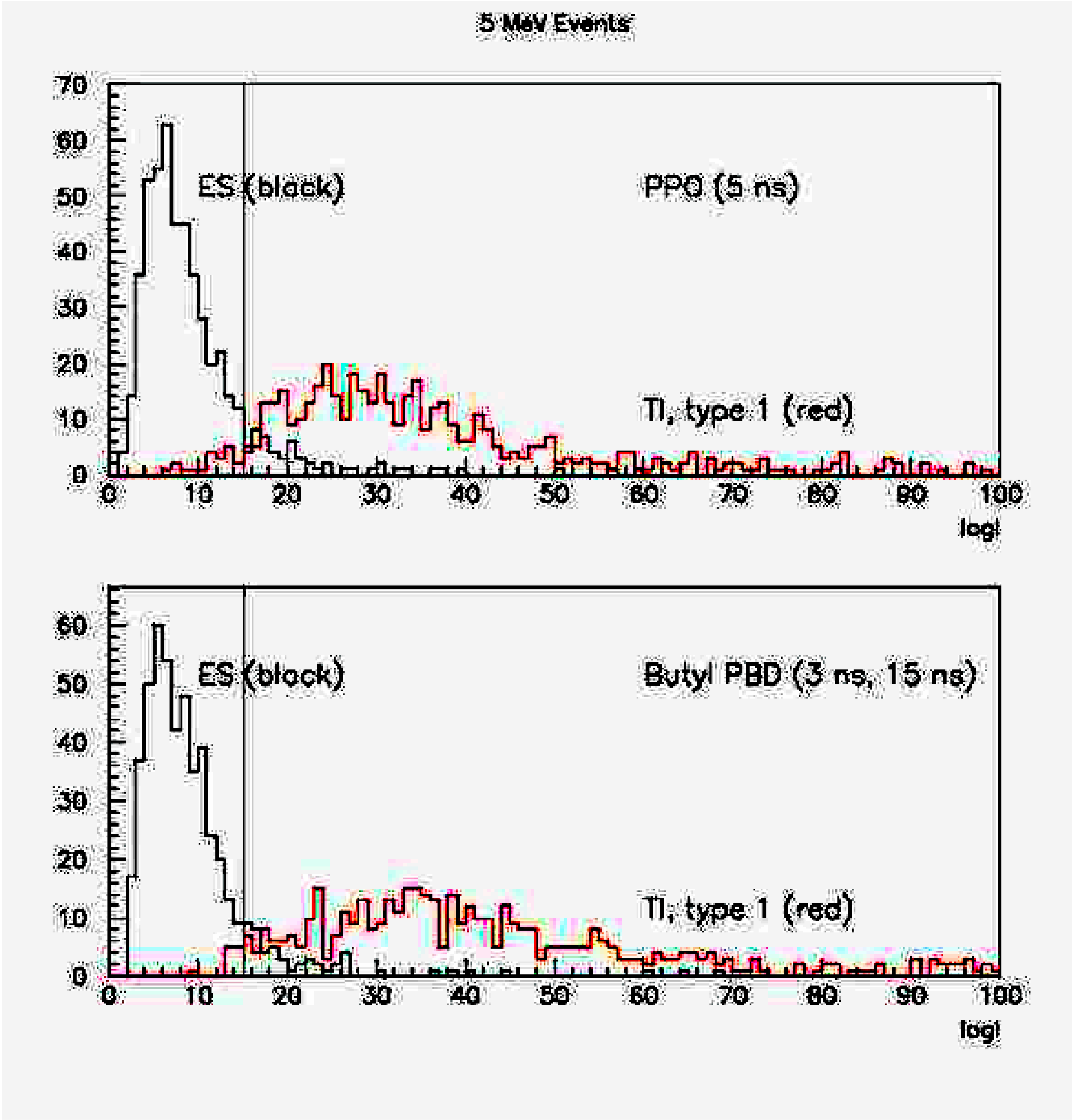
From a Monte Carlo study it appears that the events form patterns, with some of the energetic gammas migrating as far as the detector wall.

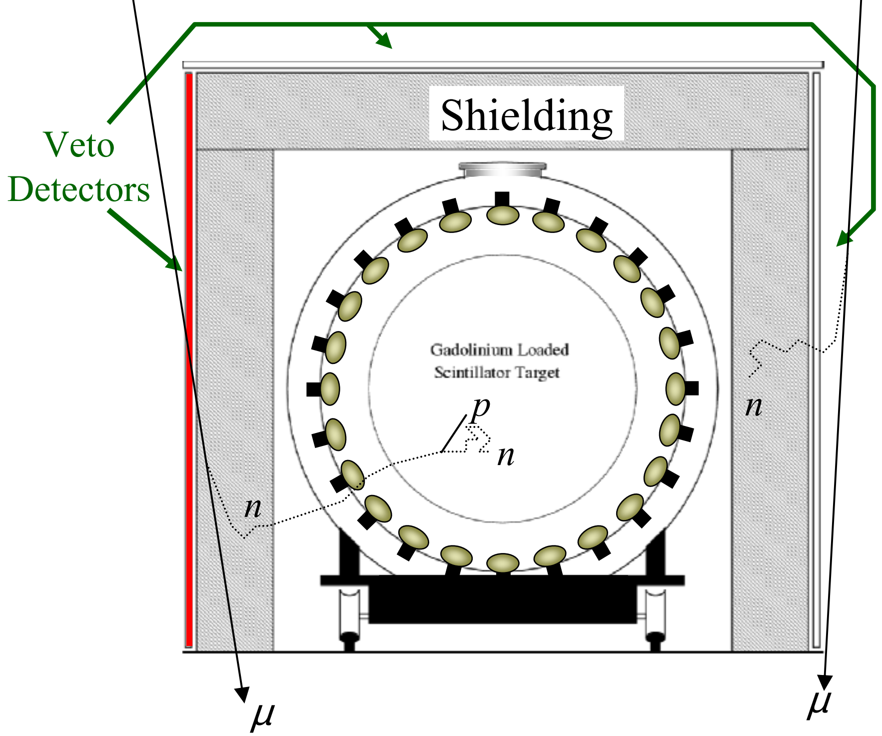
The events evolve in time, so that the timing information provides a way to cut on the data and exclude this background with minimal loss of signal



Event display of 5 MeV ^{208}Tl type 1 decays.

A comparison of the log likelihood of the reconstructed timing distribution for 500 ES (black) and Tl type 1 (red) events.
The proposed cut is at logl=20(line). Top: PPO. Bottom: Butyl PBD.





Spallation products that contain two alpha particles:

$$^{8}B \rightarrow \beta^{+} + \beta^{-} + 2\alpha$$

$$^{9}C \rightarrow \beta^{+} + \beta^{-} + 2\alpha + {}^{1}H$$

$$^{8}Li \rightarrow \beta^{-} + 2\alpha$$

$$^{8}He \rightarrow {}^{8}Li \rightarrow \beta^{-} + 2\alpha$$

Backgrounds generated as spallation products of muon interactions:

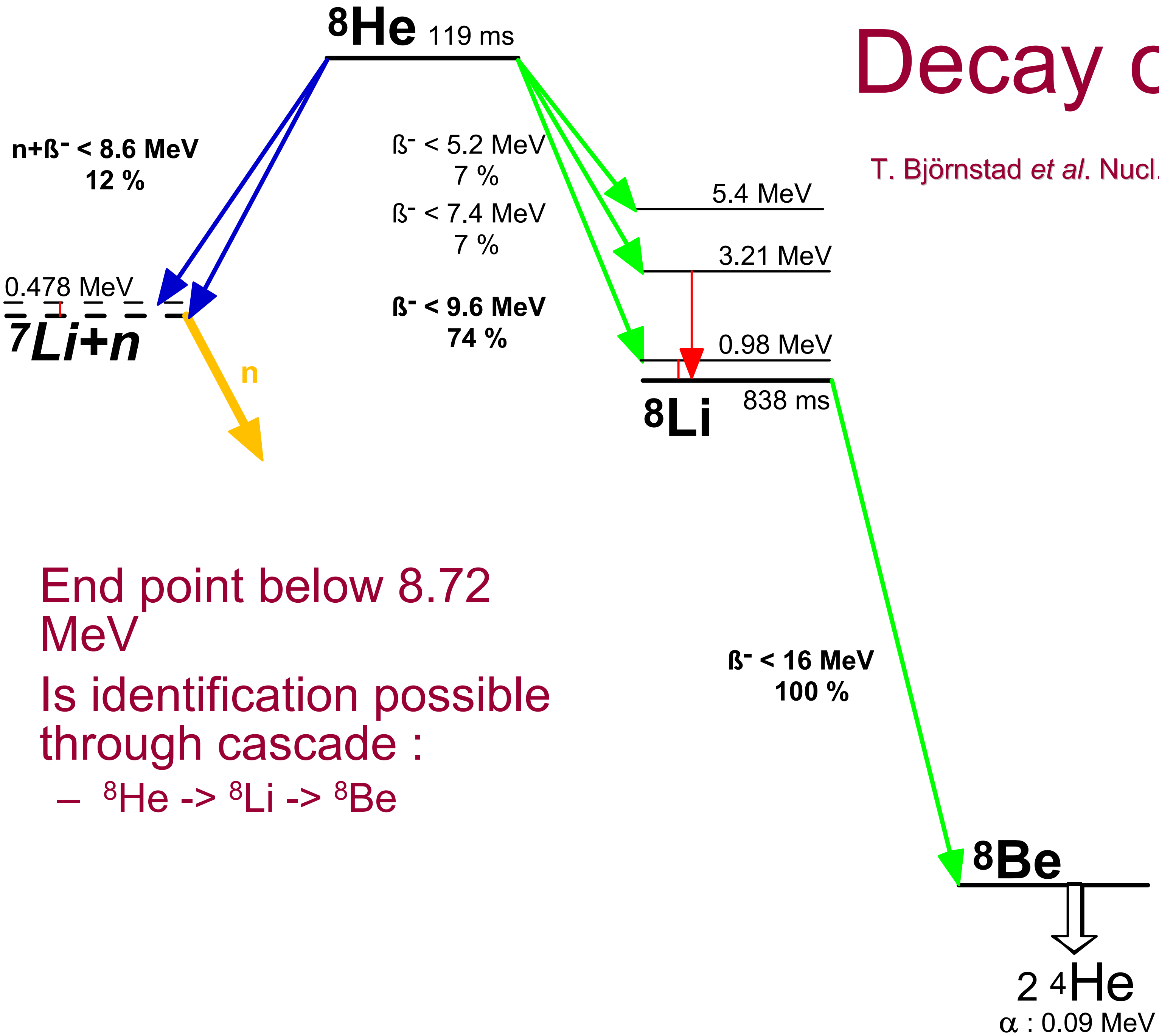
- Most spallation-produced isotopes have accompanying α's that can be observed. (CTF) Reduces the spallation backgrounds by 55%.

- Many have accompanying neutrons that are detected.

- The remainder are cut by a muon-hadron veto, which cuts out a window following a high energy shower.

Decay of ^{8}He

T. Björnstad *et al*. Nucl.Phys. A366 (1981)461



- End point below 8.72 MeV
- Is identification possible through cascade :
  - ^{8}He -> ^{8}Li -> ^{8}Be

The goal to shoot for:

dN/N = 1.3%....... Looks like we can do that
= 1.0%....... May be attainable
= 0.7%...... Hard!

$$dN/N=1.3\% \Leftrightarrow d(\sin^2 \theta_W)=\pm 0.0019$$

Compare to NuTeV: ±0.0016

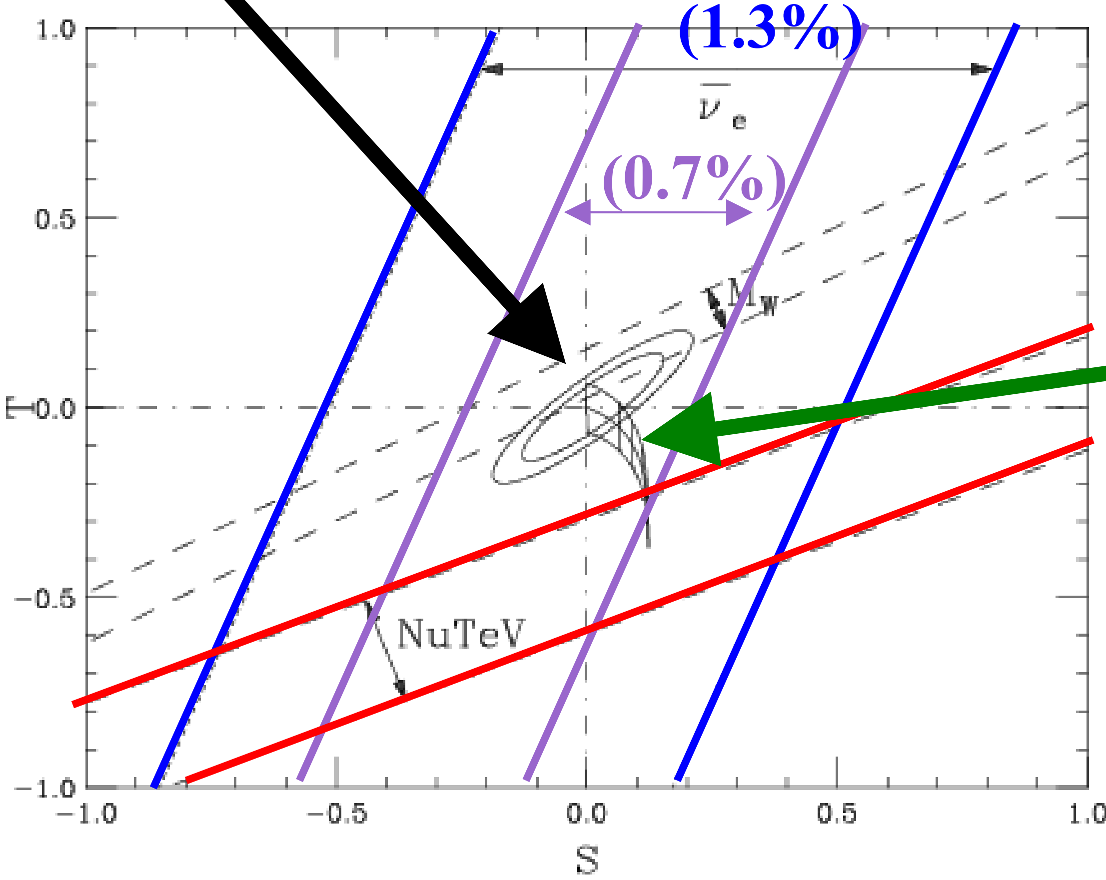
Rosner, hep-ph/0404264

Sensitivity to S and T

Fit which does not include NuTeV and uses a light Higgs...

Unusual in strong S-dependence

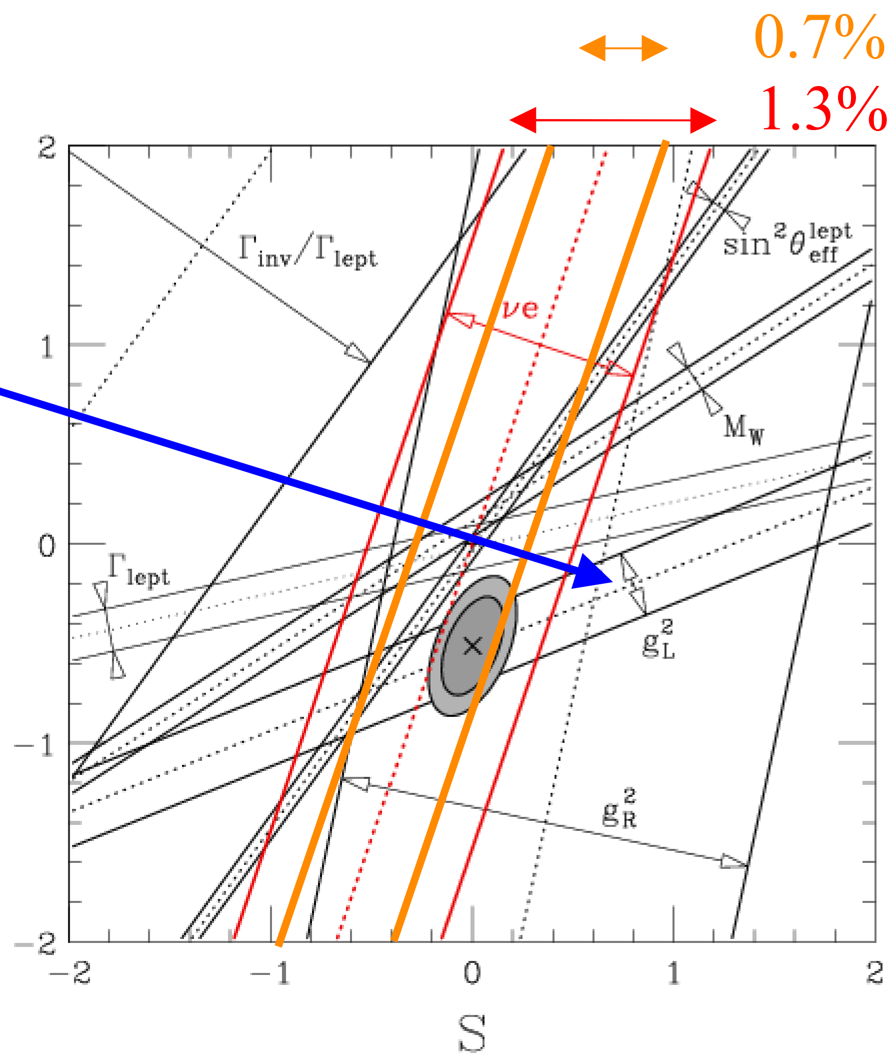
indicates Higgs dependence



Include NuTeV in the fit (expressed as g_L and g_R)

Solution without NuTeV is about here.

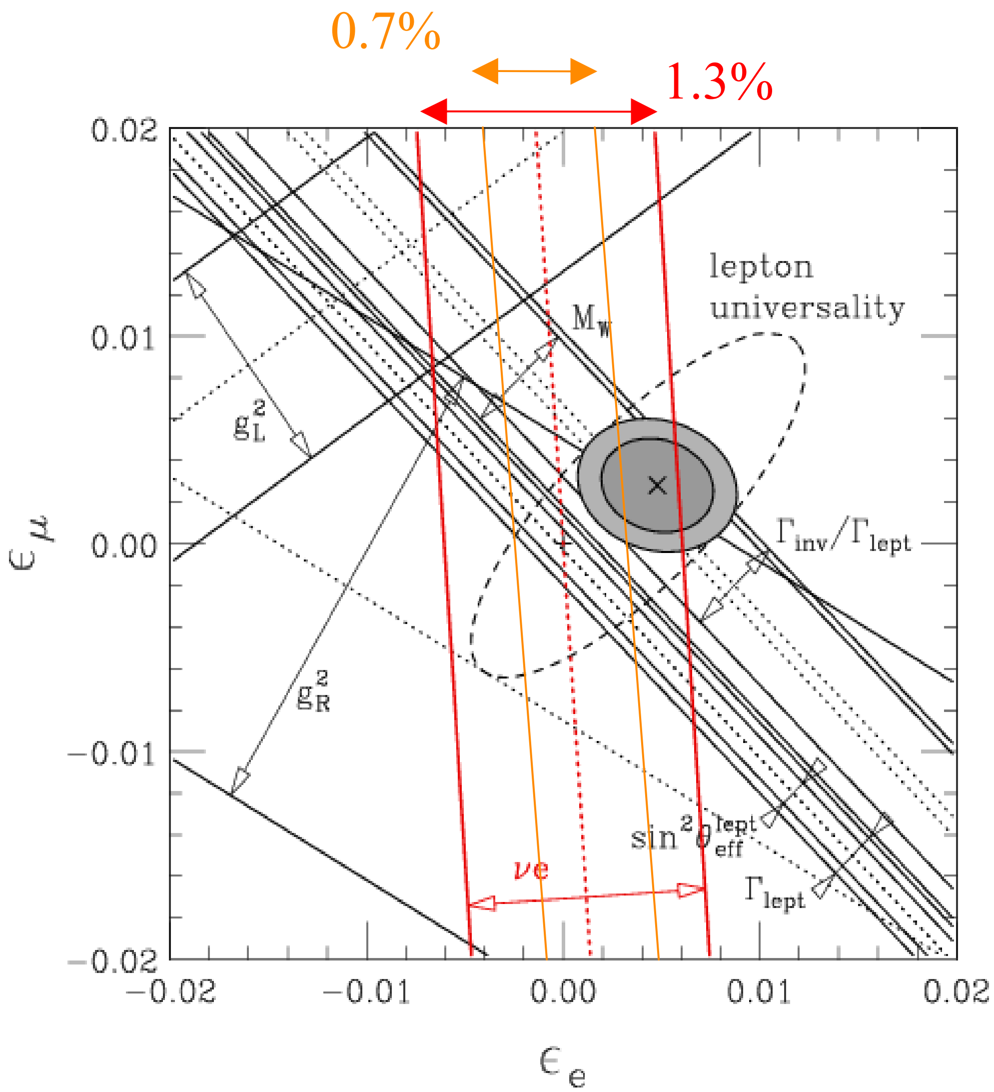
Downward shift is consistent with a <u>heavy</u> Higgs



<u>Loinaz,</u> *et al*, hep-ph/0403306

Sensitivity to ε

A better fit is obtained if neutrinos are allowed to have non-oblique corrections (adjusted by ε~0.3%). Idea has now been expanded to consider flavor dependence, with fits to world's data on lepton couplings...



- The NuTeV result provides information on ε_μ.
- Reactor experiments provide information on ε_e, although there is slight ε_μ sensitivity that comes through G_F and muon decay.

$$G_F = G_\mu(1 + \frac{\varepsilon_e + \varepsilon_\mu}{2})$$

Loinaz, *et al*, hep-ph/0403306

$$M_{top} = 178 GeV \quad M_{Higgs} = 115 GeV$$

Summary:

The discovery of neutrino mass, and neutrino right-handedness
May be an indication of departrure from Standard Model physics.

Elastic scattering should provide a additional source of information regarding the Standard Model coupling constants.

Two initiatives are being studied: at Braidwood and more recently at Krasnoyarsk.

The proposals are in the formative state, so please give us your input.

See also...

http://braidwood.uchicago.edu/
http://faculty.washington.edu/josephf/beyond_theta13.html

Thanks!