Physics Potential of a Reactor Experiment

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- Why concentrate on measuring θ_{13} ?

$\Rightarrow$ *What $\sin^2 2\theta_{13}$ sensitivity is needed?*

- How do reactor measurements fit in with others?

- Measurement of the "Weak Mixing Angle"
  - Extra physics opportunity in combination with the oscillation measurements

Why Measuring θ_{13} is Important ?

- Theoretically:
  - Neutrino and Quark mixing matrices "must" be related
    - Grand Unified Theories ; See-saw Mechanism
  - The matrices look very different but these GUT models can relate them
    - ⇒ ***If θ_{13} is not too small (> 0.05 or $\sin^2 2\theta_{13}$ > 0.01)***
    - The relationship will give us a window on the GUT's at ~10^{16} GeV
  - If θ_{13} is very small, then will need to understand why? New symmetry….

MNS Neutrino Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} 0.7 & 0.7 & < 0.2e^{i\delta}\,? \\ -0.5 & 0.5 & 0.7 \\ 0.5 & -0.5 & 0.7 \end{pmatrix}$$

$$\begin{pmatrix} big & big & small? \\ big & big & big \\ big & big & big \end{pmatrix}$$

The relationship between neutrinos and quarks in GUTs may be the source of the matter-antimatter asymmetry in the Universe

(Leptogenesis)

CKM Quark Mixing Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} 0.97 & 0.22 & 0.003e^{i\delta} \\ -0.22 & 0.97 & 0.04 \\ 0.01 & -0.04 & 0.999 \end{pmatrix}$$

$$\begin{pmatrix} big & small & very\ tiny \\ small & big & tiny \\ tiny & tiny & big \end{pmatrix}$$

Why Measuring θ_{13} is Important ? (Contd.)

- Experimentally:
  - $\sin^2\theta_{13}$ sets the scale for further measurements of the neutrino mixing matrix
    - CP violation (δ) comes in combination with $\sin\theta_{13}\, e^{i\delta}$
    - Matter effects can tell us m_1 is less or greater than m_3 but again modulated by size of $\sin\theta_{13}$

$\Rightarrow$ Knowing the size of $\sin\theta_{13}$ is the next step and will set the roadmap for how to proceed

- What $\sin^2 2\theta_{13}$ sensitivity is needed?
  - Theoretically: $\sin^2 2\theta_{13} \approx 0.01$ seems to be a dividing line
  - Experimentally: Next step will need extreme measures if $\sin^2 2\theta_{13} < 0.01$

Comparing and Combining Reactors and Offaxis Measurements

(Reactor A) 90%CL = 0.01
$\Rightarrow \delta(\sin^2 2\theta_{13}) = 0.006$

(Reactor B) 90% CL = 0.02
$\Rightarrow \delta(\sin^2 2\theta_{13}) = 0.012$

Parameter	Value
Reactor	
E_ν	2.5 GeV
L	1250 m
δP_{osc}	0.006
JHF-SK	
E_ν	0.6 GeV
L	295 km
δP^{ν}_{osc}	0.0033
$\delta P^{\overline{\nu}}_{osc}$	0.0072
NuMI-Offaxis	
E_ν	2.3 GeV
L	820 km
δP^{ν}_{osc}	0.0014
$\delta P^{\overline{\nu}}_{osc}$	0.0029

Reactor A Scenario

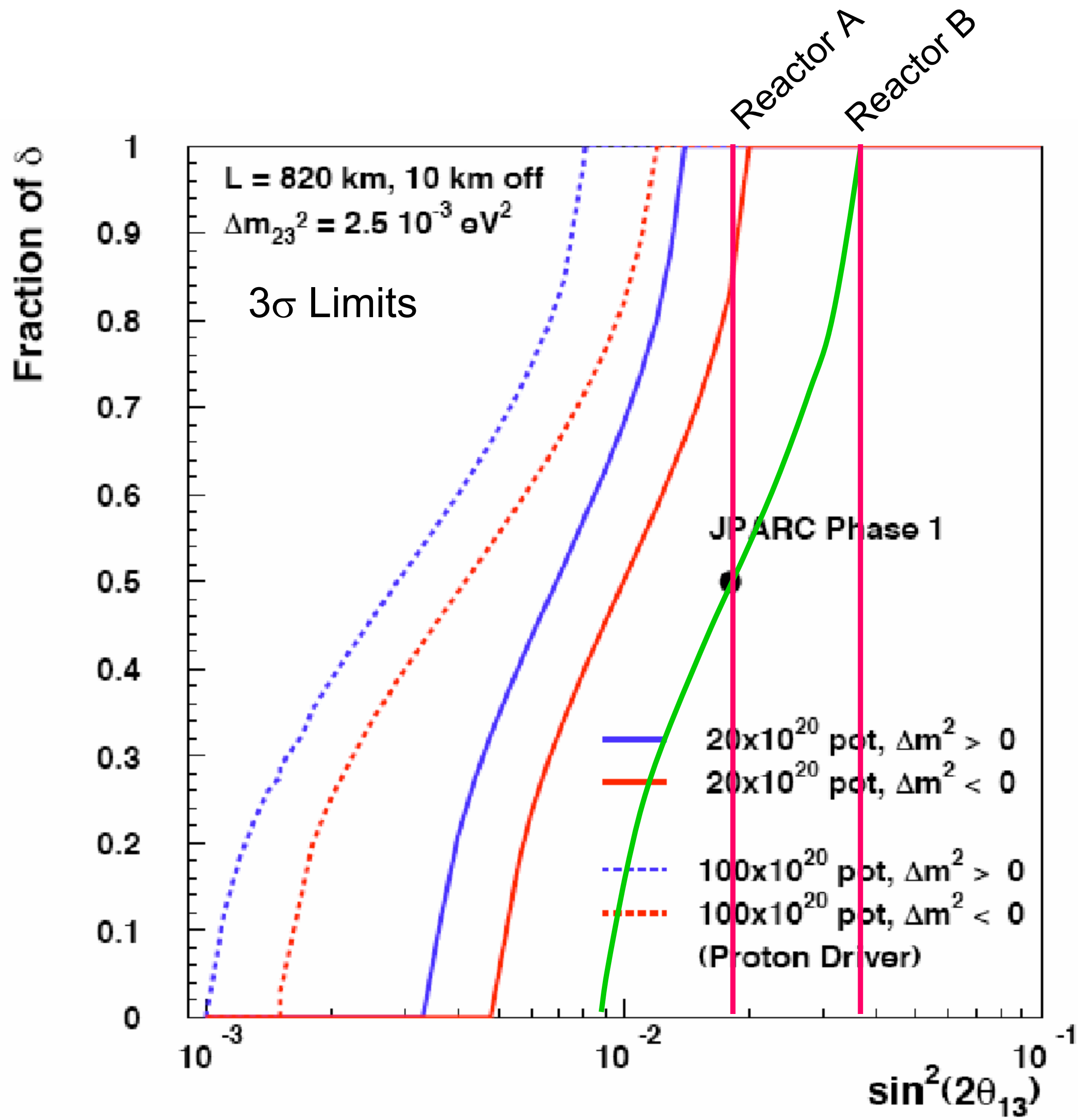
JHF-SK
3yr ν
3yr $\overline{\nu}$

NuMI-Off.
3yr ν
3yr $\overline{\nu}$

Parameter	Value
$\sin^2 2\theta_{13}$	0.058
$\sin^2 2\theta_{23}$	1 ± 0.06 ← NuMI 3yr
θ_{12}	30 deg.
δ_{CP}	45 or 270 deg.
Δm^2_{13}	2.5×10^{-3} eV^2
Δm^2_{12}	7.1×10^{-5} eV^2

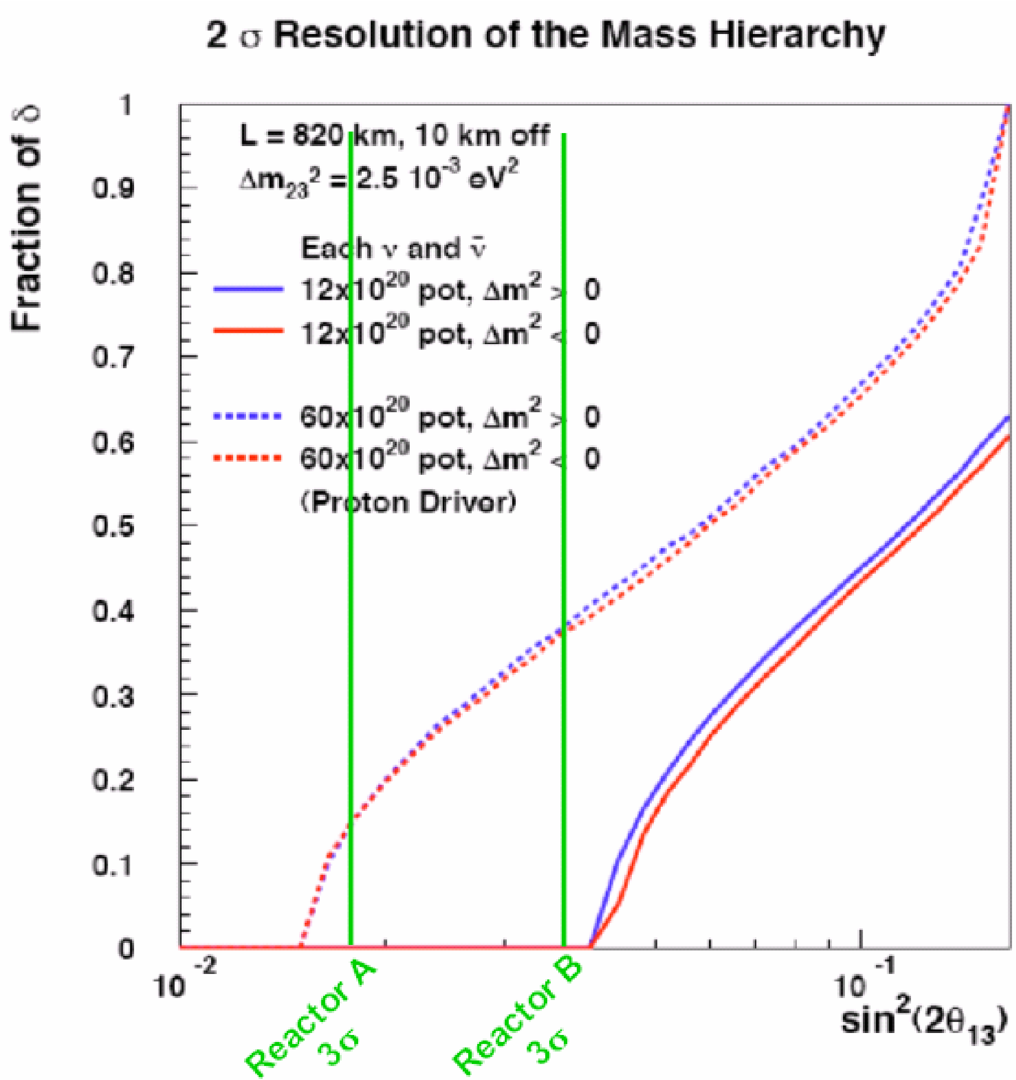
Question 1: What is $\sin^2 2\theta_{13}$?

- Both reactor and offaxis experiments have sensitivity here
  $\Rightarrow$ But offaxis measurements have ambiguities



Question 2: What is the mass hierarchy?

- Determine if m_1 is less or greater than m_3
  - NuMI offaxis experiment has sensitivity but only for large $\sin^2 2\theta_{13}$

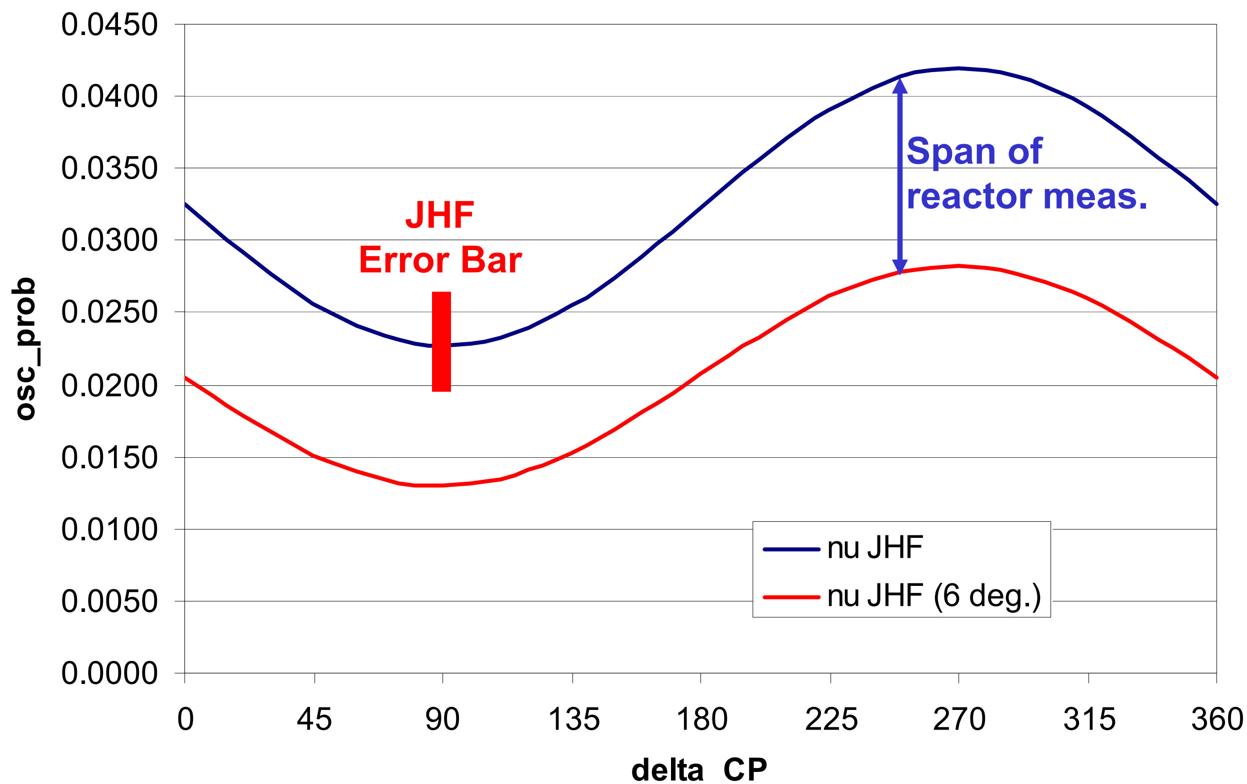


From NuMI-Offaxis Progress Report

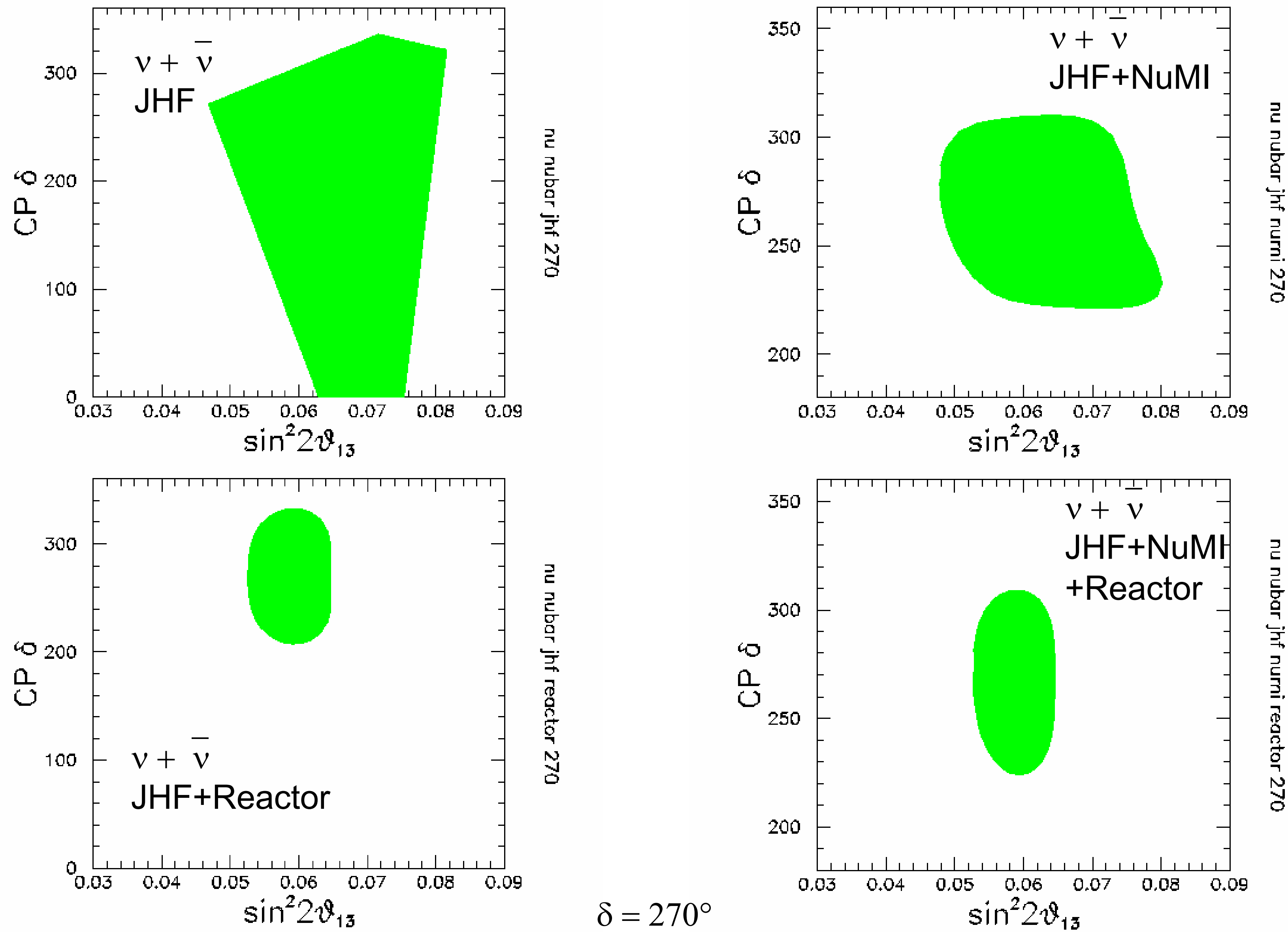
Question 3: Is there CP Violation? ⇒ Measure δ

-Combine JHF nu-only with

⇒ Reactor A ($\sin^2 2\theta_{13} = 0.06 \pm 0.006 \Rightarrow \theta_{13} = 7.0° \pm 0.4°$)



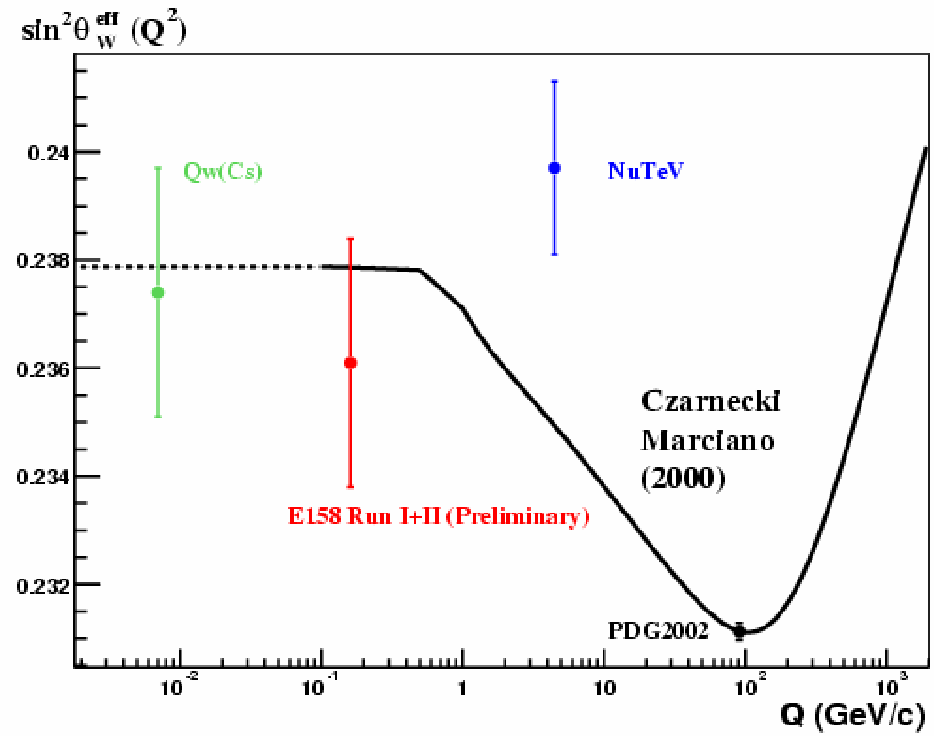
δ_{CP} Measurement (with / without Reactor)

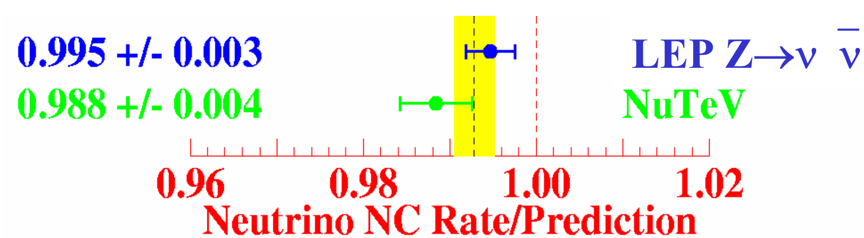


$\delta = 270°$

Measurement of the Weak Mixing Angle at a Reactor

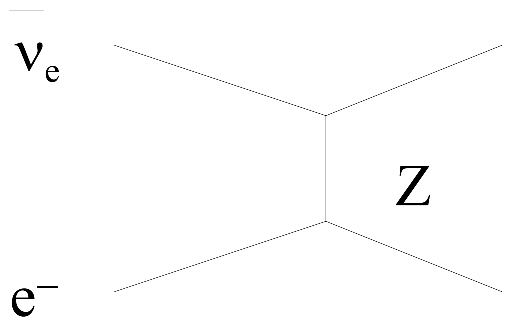
- Extra physics opportunity in combination with the oscillation measurements
- Probes neutrino electroweak physics in new low Q^2 regime
- Some indications from previous measurements of a discrepancy
  - NuTeV measurement
  - LEP invisible line shape

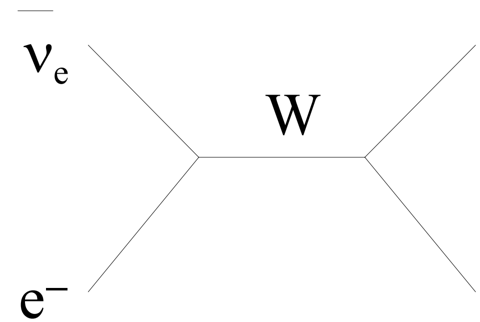




How to measure $\sin^2\theta_W$ at a reactor

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





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

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

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

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

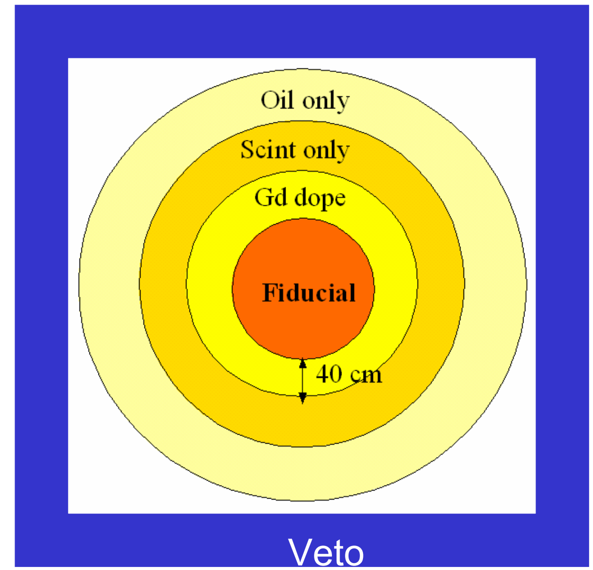
The total rate for this process is sensitive to $\sin^2\theta_W$

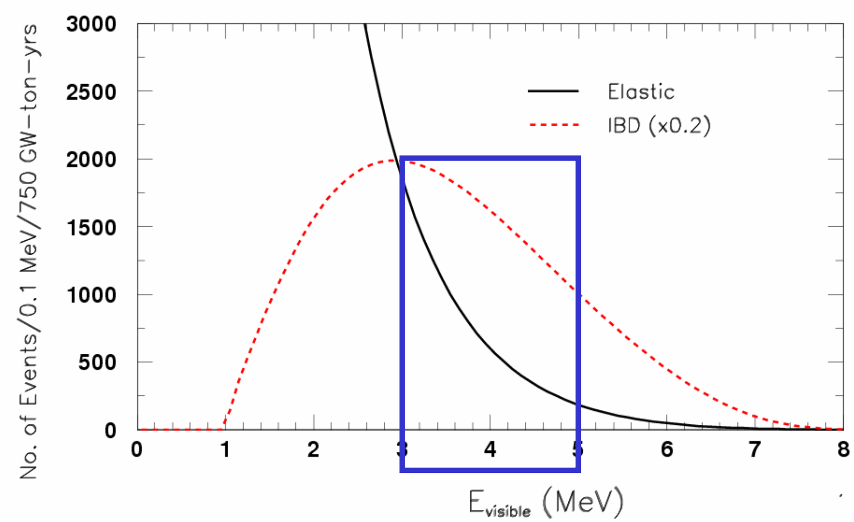
Reactor WMA Measurement

- Use near detector to make measurement
  - Needs to be as close as possible to reactor for statistics (~200m)
  - Needs to be as deep as possible to reduce backgrounds (>300 mwe)
  - Measure elastic rate between 3 – 5 MeV

- Use reduced fiducial volume at center of Gd region and 4π veto system to reduce environmental backgrounds

- Use far detector to measure background levels
  - Overburden near and far should be very similar





Outline of a Reactor WMA Measurement

- Precision Requirements:
  - NuTeV: $\sin^2\theta_W = 0.2274 \pm 0.0017$ (0.75%)
  - Reactor Exp: Need to measure $\bar{\nu}_e e$ rate to 1.2% between 3 to 5 MeV

Questions:

1. Are the statistics high enough?
   - A 3 yr run with 25 ton detector at 200m
     $\Rightarrow$ ~10,000 events

2. Are the rates from environmental backgrounds (cosmics, radioactivity) low enough?
   - Main background is beta-decay from muon induced long-lived isotopes
     $\Rightarrow$ ~1500 event background

3. Can the background from *inverse beta decay* (IBD) be controlled?
   - Neutron veto using fiducial volume inside Gd region
     $\Rightarrow$ ~2000 event background

4. Is the normalization known well enough to make a precise measurement?
   - Yes, using the observed IBD events to measure the ν_e flux
     $\Rightarrow$ IBD cross section known to 0.3% and $1.8\text{x}10^6$ event sample to set normalization

Measurement Sensitivity

- Required sensitivity looks possible
  - Measurement is statistics limited
  - Systematics on the backgrounds are fairly large
    $\Rightarrow$ Would like to use far detector to measure these

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%

$\Rightarrow \delta(\sin^2\theta_W) = 0.0019$
(compare to NuTeV = 0.0017)

- Bottom Line
  - Need close (~200m) and deep (>300 mwe) near detector
  - Good cross check if near and far at same depth

Conclusions

- $\sin^2 2\theta_{13}$ is a key parameter in trying to understand neutrino masses and mixings
  - Could give a new window on physics at the GUT energy scale

- Reactor measurements of $\sin^2 2\theta_{13}$ set the scale for pursuing *CP* violation and mass hierarchy.
  - If $\sin^2 2\theta_{13}$ is too small they will be out of reach for the currently proposed offaxis experiments even with increased intensity proton sources

- Ambiguities make measuring *CP* violation and the mass hierarchy difficult with only offaxis measurements
  - Adding a reactor measurement makes a significant improvement in extracting the physics parameters

- Measurements of the weak mixing angle using elastic scattering in the near detector could add another physics opportunity for reactor experiments