Precision Measurement of $\sin^2\theta_W$ at ν-Factory

ν-Factory 2-day Meeting

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Outline

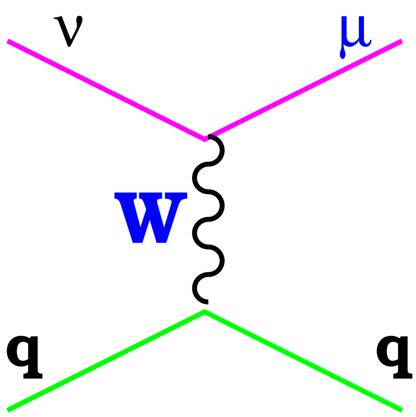
- Introduction
- Past and Present Measurements of $sin^2\theta_W$
- $sin^2\theta_W$ at the ν Factory
  - ▷ Measurement Technique
  - ▷ Sensitivity
  - ▷ Experimental & Theoretical Issues
- Conclusions and Work List for the Report

Electroweak Measurements - $\sin^2\theta_W$?

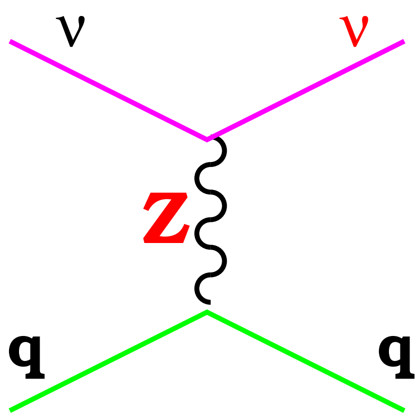
Opens a whole new era of Electroweak measurements using ν, thanks to high intensity $\Rightarrow$ In particular, using ν_e that we never had enough before, (see Kevin's talk)

- Comparable and complementary $M_W^{(on-shell)}$ to direct measurements within SM
- LHC Experiments will be vigorously looking for Higgs $\Rightarrow$ Need as much help as they can get, despite the $\Delta M_W < 30 MeV$ Tevatron & LEP-II measurements and $\Delta M_W \sim 15 MeV$ of their own
- Comparisons with direct M_W, Z^0 line-shape and $\sin^2\theta_W^{eff}$ $\Rightarrow$ sensitivity to new physics
- Measure light quark couplings $\Longrightarrow$ Extensions to SM coupling
- Sensitive to new heavy particles, such as extra Z bosons
- Comparison to SM prediction $\Rightarrow$ Neutrino Oscillations

Past $sin^2\theta_W$ Measurements in νN DIS



Coupling $\propto\ I^{(3)}_{\text{weak}}$



Coupling $\propto\ I^{(3)}_{\text{weak}} - Q_{\text{em}}\sin^2\theta_W$

At tree level for isoscalar targets : $\frac{\sigma^{\nu(\overline{\nu})}_{NC}}{\sigma^{\nu(\overline{\nu})}_{CC}} = \mathcal{F}(\sin^2\theta_W)$

Llewellyn Smith Formula :

$$R^{\nu(\overline{\nu})} = \frac{\sigma^{\nu(\overline{\nu})}_{NC}}{\sigma^{\nu(\overline{\nu})}_{CC}} = \rho^2\left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W\left(1 + \frac{\sigma^{\overline{\nu}(\nu)}_{CC}}{\sigma^{\nu(\overline{\nu})}_{CC}}\right)\right)$$

Extract $\sin^2\theta_W$ from the measured $R^{\nu(\overline{\nu})}$, comparing to MC

All νN DIS : $\sin^2\theta_W = 0.2268 \pm 0.0037$

$\Longrightarrow M_W = 80.18 \pm 0.19 GeV/c^2$(on-shell)

But suffered from systematic errors:

- Charged-Current Production of Charm
- ν_e Content of Beam

νN $\sin^2\theta_W$ Measurement at Present

- Charm Production $\Rightarrow$ Need techniques insensitive to Sea Quarks
  Paschos-Wolfenstein: $R^- = \frac{\sigma^{\nu}_{NC} - \sigma^{\overline{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\overline{\nu}}_{CC}} = \rho^2\left(\frac{1}{2} - \sin^2\theta_W\right)$

  Minimize sea quark contributions.
- Clever beam design $\Rightarrow$ Minimize uncertainties in N_{ν_e} by reducing neutral secondary contents, such as K_L

  But $\Longrightarrow$

- Still needed to understand the ν beam from the secondaries well.
- Statistical uncertainty dominates.
- Relies on statistical separation of NC and CC events based on longitudinal energy deposition in the calorimeter ("event length").
- Radiative correction a rather large theoretical uncertainty.

NuTeV $\sin^2\theta_W$ and Uncertainties

$$\sin^2\theta_W^{(\text{on-shell})} = 0.2253 \pm 0.0019(\text{stat}) \pm 0.0010(\text{syst})$$
$$M_W = 80.26 \pm 0.11 \text{ GeV}$$

	SOURCE OF UNCERTAINTY	$\delta\sin^2\theta_W$
Statistics:	Data	0.00188
	Monte Carlo	0.00028
TOTAL STATISTICS		0.00190
$\nu_e/\overline{\nu}_e$ *Flux*:	$K^\pm$ (1.1%)	0.00024
	Other sources of ν_e's	0.00048
Energy Measurement:	Calibrations (0.5%)	0.00043
	Muon Energy Deposition (3%)	0.00004
	Energy Resolution	0.00004
Event Length:	Hadron Shower	0.00015
	Longitudinal Vertex Determination	0.00015
	Counter Edge Location	0.00010
	Counter Efficiency and Noise	0.00016
TOTAL EXP. SYST.		0.00075
Sea Quarks:	Strange Sea	0.00034
	V_{cd}	0.00004
	Charm Sea	0.00009
	Charm Mass	0.00009
Other $\nu/\overline{\nu}$ *Cross-Section Differences*:	$\sigma^\nu/\sigma^{\overline{\nu}}$	0.00023
	Non-Isoscalar Target	0.00013
	Radiative Corrections	0.00051
Non-QPM Cross-Section:	Higher Twist	0.00013
	Longitudinal Structure Function	0.00007
TOTAL PHYSICS MODEL		0.00070
TOTAL UNCERTAINTY		0.0022

Advantages and Concerns of ν Factory for $\sin^2\theta_W$

- Neutrinos come from the μ decays
  $\Rightarrow$ Good understanding of the beam (narrow band).
- Better collimated than conventional neutrino beam
- Large neutrino flux
  Resulting from $\sim 10^{19} - 10^{21}\mu -$ decays/yr

But one needs to be careful...

Two neutrinos per each μ decay ($\overline{\nu}_e + \nu_\mu$ or $\overline{\nu}_\mu + \nu_e$)

- Traditional Heavy target detector won't work.
  $\Rightarrow$ Will screw up NC counting due to ν_e CC events.
  $\Rightarrow$ Needs light weight detector (Can afford to do this).

- Needs new technique for NC to CC ratio.

Experimental Technique

Indistinguishable NC events prohibits R^- Style measurements $\Rightarrow$ But we could measure $R^{\nu(\overline{\nu})}$ Style

Linear combinations of Llewellyn-Smith ratios:

For $\nu_\mu\overline{\nu}_e$ beam

$$R_\nu^{\mu^-} = \frac{\sigma(\nu_\mu, NC) + \sigma(\overline{\nu}_e, NC)}{\sigma(\nu_\mu, CC) + \sigma(\overline{\nu}_e, CC)} = \frac{R^\nu + grR^{\overline{\nu}}}{1+gr} \qquad (1)$$

For $\nu_e\overline{\nu}_\mu$ beam

$$R_{\overline{\nu}}^{\mu^+} = \frac{\sigma(\overline{\nu}_\mu, NC) + \sigma(\nu_e, NC)}{\sigma(\overline{\nu}_\mu, CC) + \sigma(\nu_e, CC)} = \frac{R_{\nu_\mu} + g^{-1}rR_{\overline{\nu}_\mu}}{1+g^{-1}r} \qquad (2)$$

where,

$$r = \frac{\sigma(\overline{\nu}, CC)}{\sigma(\nu, CC)} \simeq 0.5$$

and

$$g \equiv \frac{\int \Phi(E_{\overline{\nu}_e})E_{\overline{\nu}_e}dE_{\overline{\nu}_e}}{\int \Phi(E_{\nu_\mu})E_{\nu_\mu}dE_{\nu_\mu}} = \frac{\int \Phi(E_{\nu_e})E_{\nu_e}dE_{\nu_e}}{\int \Phi(E_{\overline{\nu}_\mu})E_{\overline{\nu}_\mu}dE_{\overline{\nu}_\mu}}. \qquad (3)$$

the energy-weighted flux ratio between ν_μ and ν_e

The above assumes lepton universality and no beam polarization

Sensitivity of the Technique

Since for unpolarized beam:

$$g = \frac{< x >^e}{< x >^\mu} = \frac{6}{7}.$$

$R_\nu^{\mu^-}$ and $R_{\overline{\nu}}^{\mu^+}$ become

$$R_\nu^{\mu^-} \simeq 0.70 R^\nu + 0.30 R^{\overline{\nu}}$$

and

$$R_{\overline{\nu}}^{\mu^+} \simeq 0.63 R^\nu + 0.37 R^{\overline{\nu}}.$$

Sensitivity of Llewellyn-Smith ratios R^ν and $R^{\overline{\nu}}$ to $\sin^2\theta_W$:

$$\frac{dR_\nu}{dsin^2\theta_W} = -1 + \frac{10}{9} sin^2\theta_W(1+r) \simeq -0.625 \tag{4}$$

and

$$\frac{dR_{\overline{\nu}}}{dsin^2\theta_W} = -1 + \frac{10}{9} sin^2\theta_W \frac{(1+r)}{r} \simeq -0.250, \tag{5}$$

giving the corresponding sensitivities:

$$\frac{dR_\nu^{\mu^-}}{d\sin^2\theta_W} = -0.513$$

and

$$\frac{dR_{\overline{\nu}}^{\mu^+}}{d\sin^2\theta_W} = -0.487$$

Experimental and Theoretical Issues

Experimental Issues

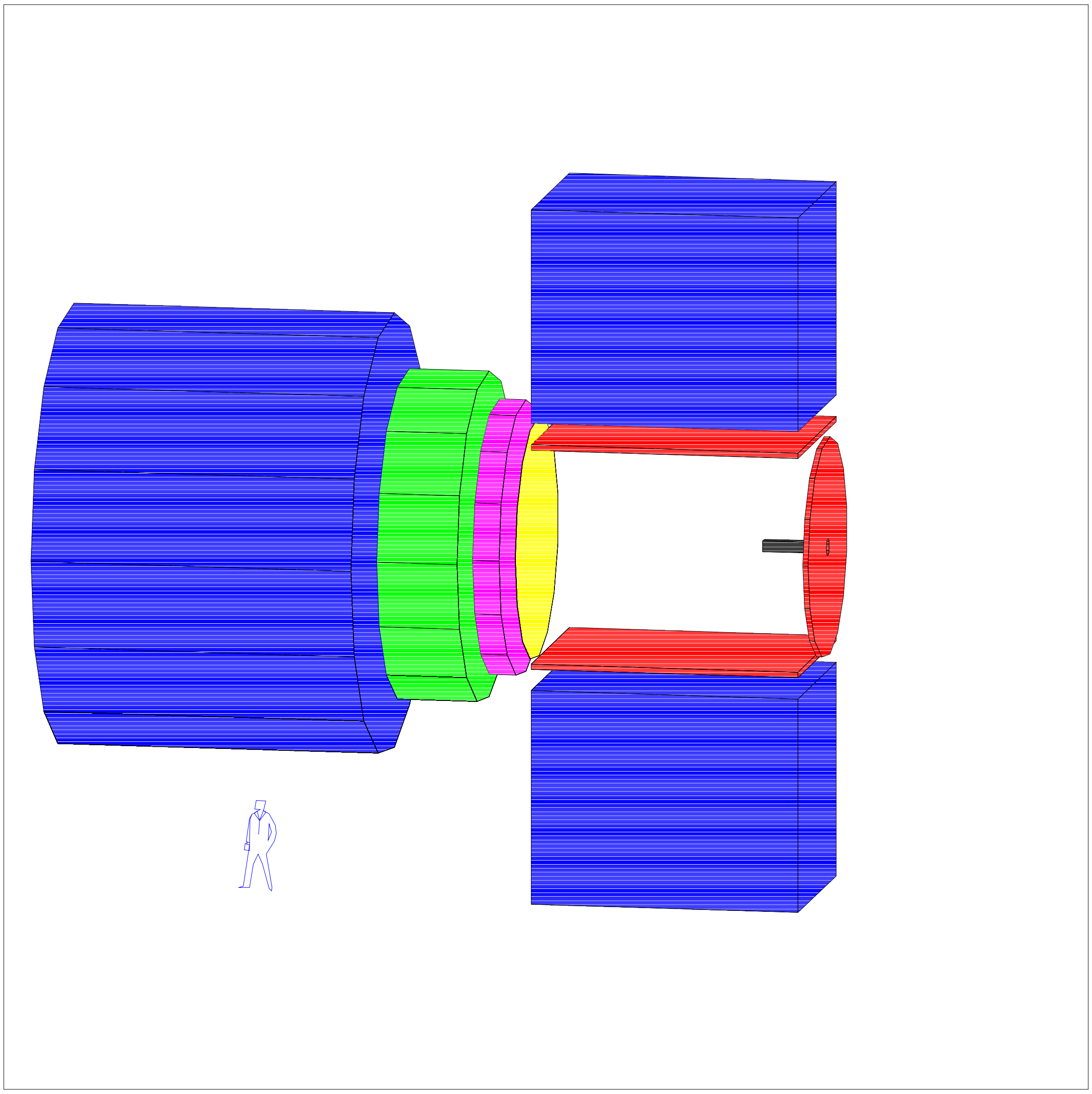
- Must be able to reverse beam polarity
- Too long a straight section won't help too much.
- The detector must be light weight.
- Must be able to distinguish primary e from μ from π
  Need to control overall p-ID efficiency to better than 10^{-3}

- High electron detection efficiency
- Good EM and Hadronic Shower identification
- Good charged particle momentum measurement
- Good vertex measurement w/ triggering capability at the target

Theoretical Issues

- Charm CC cross section needs to be well measured
- Need to control Radiative correction uncertainty to limit the error due to this source to $\Delta M_W \sim 1MeV$ (*eg., Bardin-Dokuchaeva calculations has explicit quark mass dependence; JINR-E2-86-260 (1986)*)
- Better understanding of higher twist effects
- ...

An Example Light Weight Detector



Uncertainty Comparisons

For $E_\mu = 50GeV$ and 10^{20} μ-decays/yr, 40m straight section, on a 1m long CCD (iso-scalar) target would yield $\sim 30M$events/yr, assuming 100% fiducial coverage

SOURCE of UNCERTAINTY	NuTeV	νMC
Data Statistics	0.0019	$\sim 3.5 \times 10^{-4}$
ν_e flux	0.00045	**Irrelevant**
Transverse Vertex	0.0004	negl.
Energy Measurement		
Energy Scale	0.00049	negl.
Muon Energy Loss in Shower	0.00012	negl.
Energy Resolution	0.00006	negl.
Primary lepton ID	N.A.	negl.?
Event Length		**Irrelevant**
Hadron Shower Length	0.00022	
Counter Fiducial Size	0.00024	
Counter Efficiency & Noise	0.00011	
Vertex Determination	0.00012	
TOTAL EXP. SYST.	0.00078	negl.?
Charm Production, $\overline{s}$ ($m_c = 1.31 \pm 0.24$ GeV)	negl.	negl.?
Higher Twist	0.00011	negl.?
Longitudinal Cross-Section	0.00004	negl.
Charm Sea, (±100%)	0.00002	negl.
Non-Isoscalar Target	0.00017	0 (D_2 Target)
		9×10^{-5} (CCD + Al Circuit)
Structure Functions	0.0001	negl.
Rad. Corrections	0.00051	< 0.0005
$\sigma^{\overline{\nu}}/\sigma^{\nu}$	0.00021	negl.
TOTAL PHYSICS MODEL	~0.00069	< 0.0005
TOTAL UNCERTAINTY	0.0022	< 0.0006
ΔM_W	$\mathbf{0.11}GeV/c^2$	$< 0.030GeV/c^2$

Conclusions and Work list

- Add valuable information to understanding SM
- Contribute significantly to LHC's Higgs search
- Can measure $\sin^2\theta_W$ or M_W to a very comparable precision (in 10 years?), thanks to the high flux ($\Delta M_W = 20 \sim 30$MeV possible, though need to control Theoretical error)

Work List for the report

- Recompute the uncertainties, using more realistic MC:
  - ▷ More studies on cuts to minimize uncertainties
  - ▷ Straight Section Length Dependence
  - ▷ E_μ Dependence
  - ▷ Target Material Dependence (D_2 and CCD)
- Detector consideration into the appropriate section
- Take the existing document and re-write the relevant sections of the report