Some Comments on the Physics of Neutrino–Electron Scattering

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On the Physics of Neutrino – Charged Fermion Scattering

Neutrino matter scattering provides a unique an clean environment to study purely weakly interacting processes. In the Standard Model, at low enough center of mass energies, $\nu_\mu + f$ eleastic scattering is governed by the following effective Lagrangian.

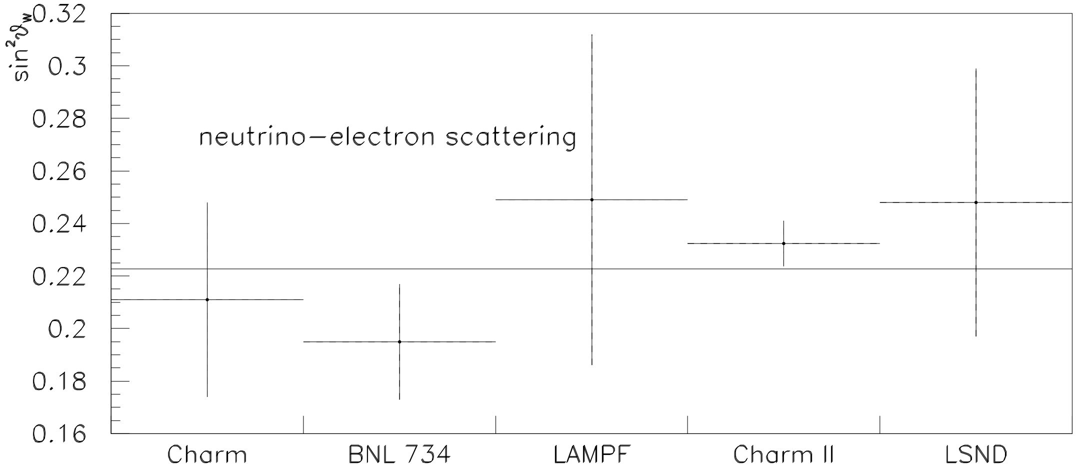
$$\mathcal{L} = -2\sqrt{2}G_F \left(g_L^\nu\, \bar{\nu}_L \gamma_\mu \nu_L\right) \times \left[g_L^f\, \bar{f}_L \gamma^\mu f_L + g_R^f\, \bar{f}_R \gamma^\mu f_R \right]$$

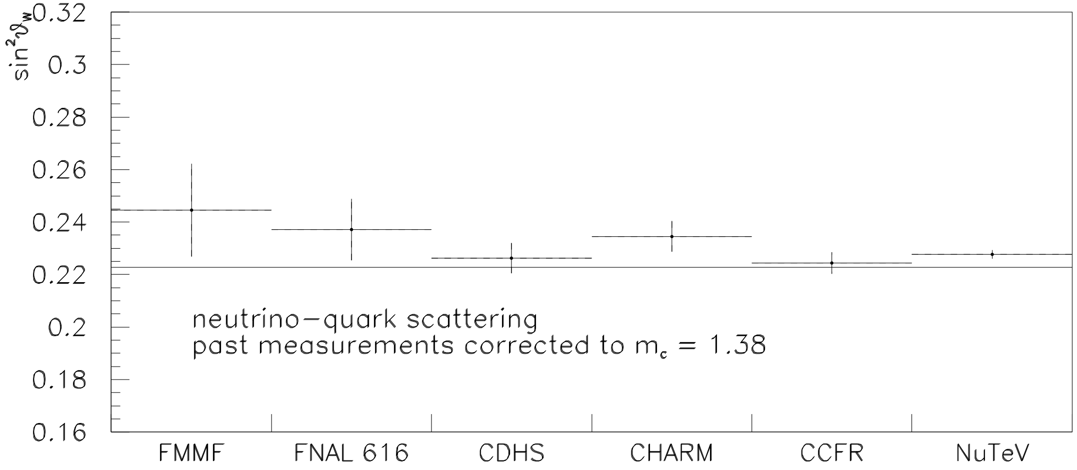
where

$$\begin{aligned} g_L^\nu &= \sqrt{\rho}\left(+\frac{1}{2}\right) , \\ g_L^f &= \sqrt{\rho}\left(I_3^f - Q^f \sin^2\theta_W\right) , \\ g_R^f &= \sqrt{\rho}\left(-Q^f \sin^2\theta_W\right) . \end{aligned}$$

At tree-level, $\rho = 1$. Loop corrections affect both ρ and what we mean by $\sin^2\theta_W$.

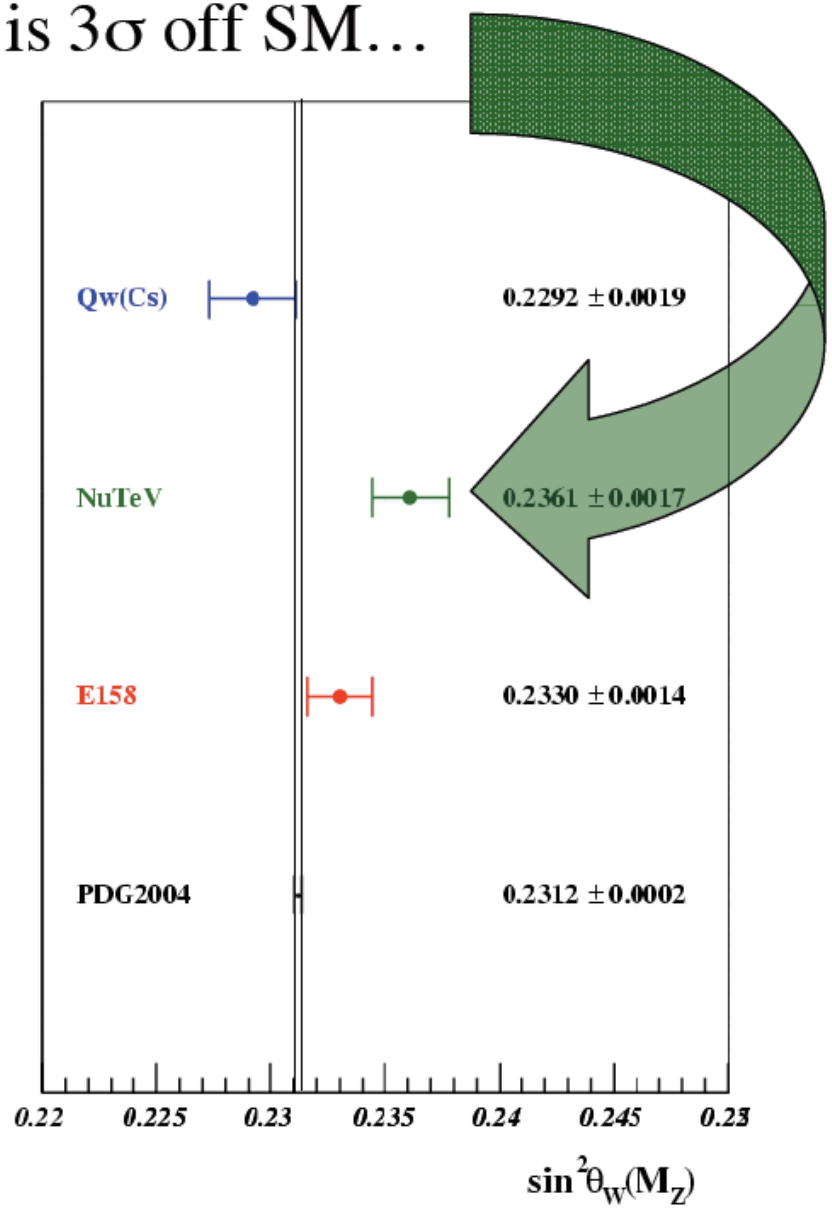
One can interpret $\nu + f$ as measuring the Weinberg angle …



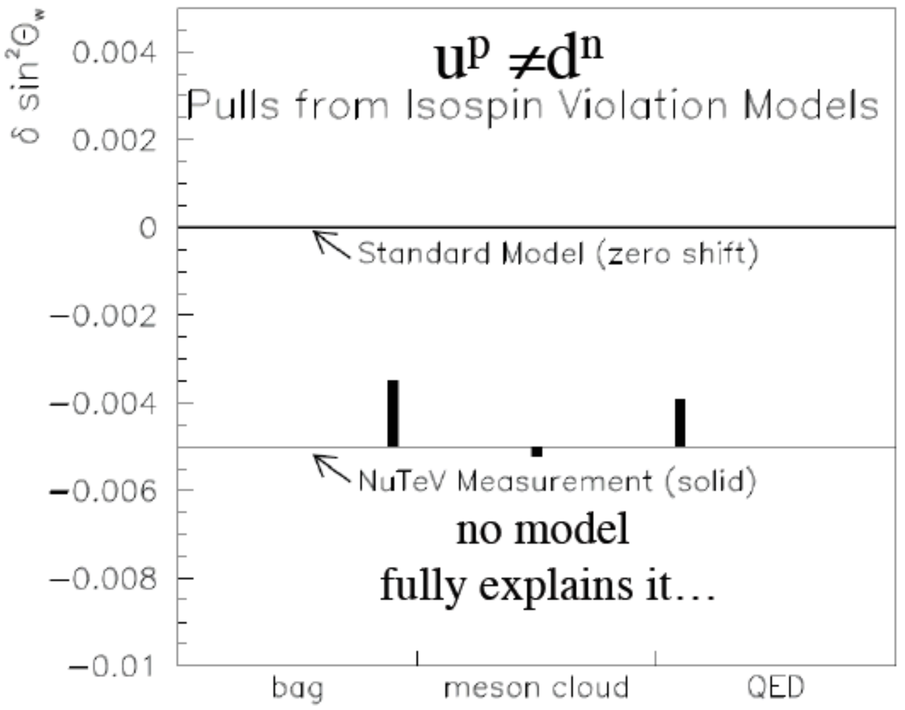


…but it measures $g_L^{\nu} g_L^{f}$ and $g_L^{\nu} g_L^{f}$ independently. Much more information.

NuTeV: νq scattering ("PW") is 3σ off SM…



New Physics, e.g. nonuniversality? or "Standard Model"?



no model
fully explains it…

An updated NuTeV analysis will be available spring/summer

Neutrino–Electron Elastic Scattering and New Heavy Physics

This is what one is able to measure:

$$\frac{d\sigma}{dT}(\nu_\ell e \to \nu_\ell e) = \frac{2G_\mu^2 m_e}{\pi E_\nu^2}\left[a^2 E_\nu^2 + b^2(E_\nu - T)^2 - abm_eT\right], \qquad (1)$$

Table 1: Standard model a and b parameter values for the differential cross-section. $s^2 \equiv \sin^2\theta_W \approx 0.23149 \pm 0.00015$ and $\ell = \mu, \tau$.

	$\nu_e e \to \nu_e e$	$\bar{\nu}_e e \to \bar{\nu}_e e$	$\nu_\ell e \to \nu_\ell e$	$\bar{\nu}_\ell e \to \bar{\nu}_\ell e$
a	$-\frac{1}{2} - s^2$	$-s^2$	$\frac{1}{2} - s^2$	$-s^2$
b	$-s^2$	$-\frac{1}{2} - s^2$	$-s^2$	$\frac{1}{2} - s^2$

$$a^2(\text{or } b^2) \to a^2(\text{or } b^2)\left[1 + \alpha F_{a(b)}(T, E_\nu)\right], \qquad (2)$$

$$\frac{d\sigma}{dy} = \frac{G_F^2 m_e E_\nu}{2\pi}\left[\left(g_V^{\nu e} \pm g_A^{\nu e}\right)^2 + \left(g_V^{\nu e} \mp g_A^{\nu e}\right)^2 (1-y)^2\right] ,$$

in the limit $m_e \ll E_\nu$, for $y = \frac{T_e}{E_\nu}$ for the recoil electron. Sign ambiguity for neutrino and antineutrino scattering, respectively.

New “heavy” physics will modify the coefficents

$$g_L^\nu g_L^e = g_V^{\nu e} + g_A^{\nu e}$$

$$g_L^\nu g_L^e = g_V^{\nu e} - g_A^{\nu e}$$

General effective Lagrangian one can probe with $\bar{\nu}_e + e$ scattering

$$\mathcal{L}^{e}_{\rm NSI} \quad = \quad +\frac{\sqrt{2}}{\Lambda^2}\left[\bar{\nu}_e\gamma_\sigma P_L \nu_\alpha\right]\left[\cos\theta\,\bar{e}\gamma^\sigma P_L e + \sin\theta\,\bar{e}\gamma^\sigma P_R e\right].$$

$\Lambda =$ New Physics scale.

θ parameterizes “handedness” of the new physics. Note: signs matter.

Assumption 1: no scalar–scalar interaction (“suppressed” by neutrino and electron masses)

Assumption 2: charged current – IMD – NOT modified. This is not true of specific models

Neutrino–Electron Scattering with Different Next-Generation Beams (Summary):

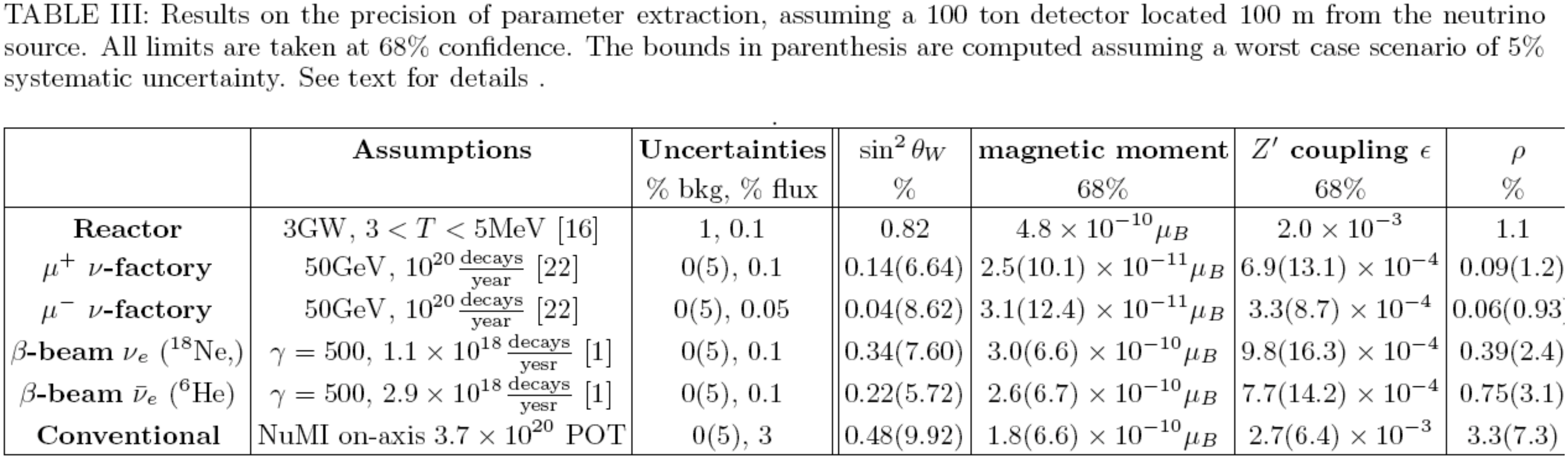


TABLE III: Results on the precision of parameter extraction, assuming a 100 ton detector located 100 m from the neutrino source. All limits are taken at 68% confidence. The bounds in parenthesis are computed assuming a worst case scenario of 5% systematic uncertainty. See text for details .

	Assumptions	**Uncertainties**	$\sin^2\theta_W$	**magnetic moment**	Z' **coupling** ϵ	ρ
		% bkg, % flux	%	68%	68%	%
Reactor	3GW, $3 < T < 5$MeV [16]	1, 0.1	0.82	$4.8 \times 10^{-10}\mu_B$	2.0×10^{-3}	1.1
μ^+ ν**-factory**	50GeV, $10^{20}\,\frac{\text{decays}}{\text{year}}$ [22]	0(5), 0.1	0.14(6.64)	$2.5(10.1) \times 10^{-11}\mu_B$	$6.9(13.1) \times 10^{-4}$	0.09(1.2)
μ^- ν**-factory**	50GeV, $10^{20}\,\frac{\text{decays}}{\text{year}}$ [22]	0(5), 0.05	0.04(8.62)	$3.1(12.4) \times 10^{-11}\mu_B$	$3.3(8.7) \times 10^{-4}$	0.06(0.93
β**-beam** ν_e (^{18}Ne,)	$\gamma = 500$, $1.1 \times 10^{18}\,\frac{\text{decays}}{\text{yesr}}$ [1]	0(5), 0.1	0.34(7.60)	$3.0(6.6) \times 10^{-10}\mu_B$	$9.8(16.3) \times 10^{-4}$	0.39(2.4)
β**-beam** $\bar{\nu}_e$ (^{6}He)	$\gamma = 500$, $2.9 \times 10^{18}\,\frac{\text{decays}}{\text{yesr}}$ [1]	0(5), 0.1	0.22(5.72)	$2.6(6.7) \times 10^{-10}\mu_B$	$7.7(14.2) \times 10^{-4}$	0.75(3.1)
Conventional	NuMI on-axis 3.7×10^{20} POT	0(5), 3	0.48(9.92)	$1.8(6.6) \times 10^{-10}\mu_B$	$2.7(6.4) \times 10^{-3}$	3.3(7.3)

[AdG, J. Jenkins, PR**D74**, 033004 (2006)]

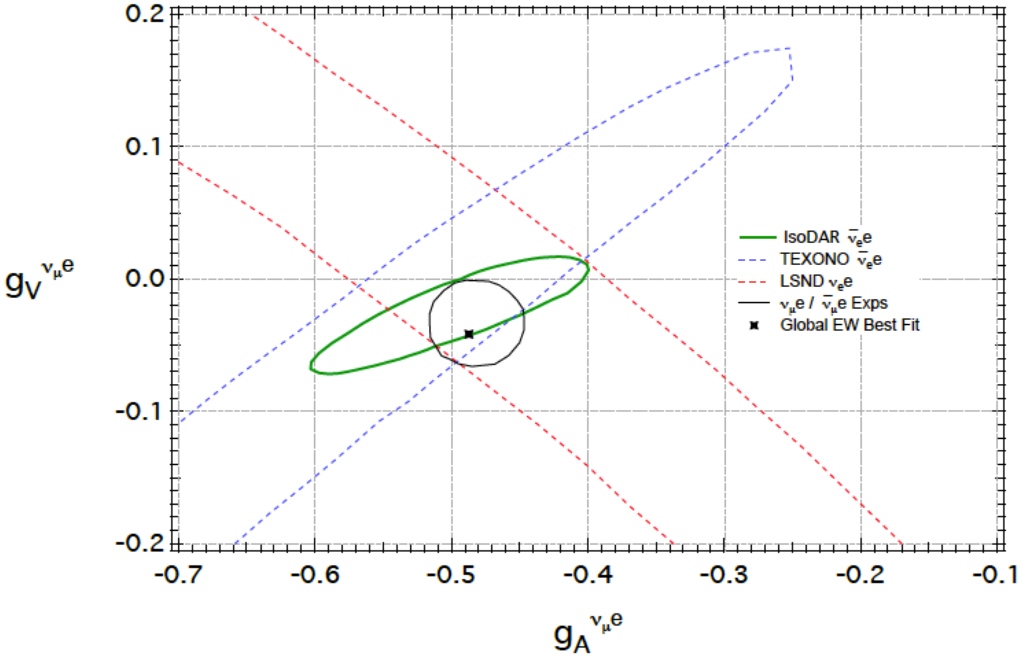


FIG. 2: IsoDAR's sensitivity to g_V and g_A along with allowed regions from other neutrino scattering experiments and the electroweak global best fit point taken from Ref. [37]. The IsoDAR, LSND, and TEXONO contours are all at 1σ and are all plotted in terms of $g_{V,A}^{\nu_\mu e} = g_{V,A}^{\nu_e e} - 1$ to compare with ν_μ scattering data. The $\nu_\mu e/\bar{\nu}_\mu e$ contour is at 90% C.L.

J. Conrad *et al.* arXiv:1307.5081

Neutrino Electromagnetic Properties

Nonzero neutrino masses imply that neutrinos have a nonzero electromagnetic moment, i.e., the couple to photons.

$$\mathcal{L} \propto \mu_{\alpha\beta}\bar{\nu}_\alpha \sigma_{\mu\nu}\nu_\beta F_{\mu\nu} + d_{\alpha\beta}\bar{\nu}_\alpha \sigma_{\mu\nu}\nu_\beta \tilde{F}_{\mu\nu}$$

If the neutrinos are Majorana fermions, $\mu_{\alpha\beta} = -\mu_{\beta\alpha}$ (same for d) so only the transition moments are not zero. This is irrelevant for the discussion here!

(For CEνES – for neutrino electron scattering it is about the same),

$$\left(\frac{d\sigma}{dT}\right)_{\rm EM} = \frac{\pi\alpha_{\rm em}^2 {\mu_{eff}}^2 Z^2}{m_e^2}\left(\frac{1-T/E_\nu}{T}\right)F_Z^2(q^2)\,,$$

which adds incoherently to the SM expectation. μ_{eff} is a combination of the appropriate $\mu_{\alpha\beta}$ and $d_{\alpha\beta}$.

The best laboratory bounds are from $\nu + e$ elastic scattering

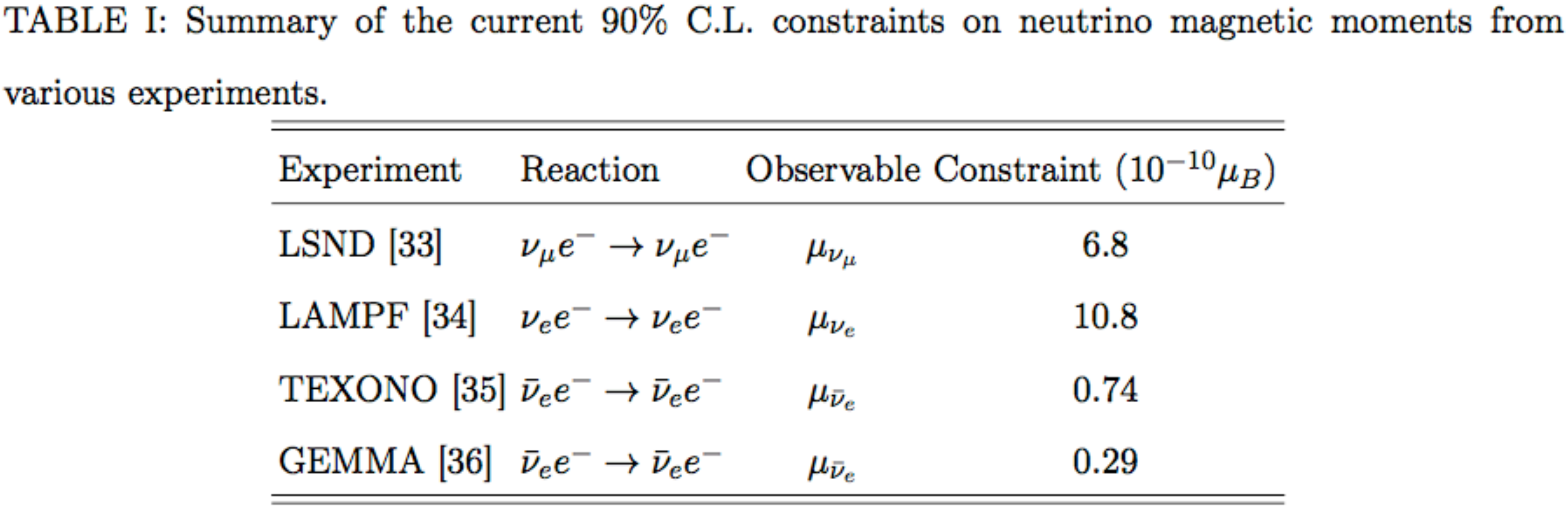


TABLE I: Summary of the current 90% C.L. constraints on neutrino magnetic moments from various experiments.

Experiment	Reaction	Observable	Constraint ($10^{-10}\mu_B$)
LSND [33]	$\nu_\mu e^- \to \nu_\mu e^-$	μ_{ν_μ}	6.8
LAMPF [34]	$\nu_e e^- \to \nu_e e^-$	μ_{ν_e}	10.8
TEXONO [35]	$\bar{\nu}_e e^- \to \bar{\nu}_e e^-$	$\mu_{\bar{\nu}_e}$	0.74
GEMMA [36]	$\bar{\nu}_e e^- \to \bar{\nu}_e e^-$	$\mu_{\bar{\nu}_e}$	0.29

Somewhere in between: Light Mediators

Nothing to report, other than there are people working on it, AdG, P. Machado, L. Necib, A. Ridgeway, Y. Zhang.

Interesting issues:

- What is this good for?
- Do you solve any other outstanding issues (muon $g-2$)?
- New observable: shape distortion.

Modifying the Neutrino Coupling to the Heavy Gauge Bosons:

- **neutrino mixing with heavy gauge-singlet leptons**

$$\begin{aligned} \nu &= \nu_{\rm light}\cos\theta + \nu_{\rm heavy}\sin\theta \\ \chi &= -\nu_{\rm light}\sin\theta + \nu_{\rm heavy}\cos\theta \end{aligned}$$

$$\begin{aligned} Z\nu\nu &= Z\nu_{\rm light}\nu_{\rm light}\cos^2\theta \\ &\quad +2Z\nu_{\rm light}\nu_{\rm heavy}\sin\theta\cos\theta \\ &\quad +Z\nu_{\rm heavy}\nu_{\rm heavy}\sin^2\theta \\ W\ell\nu &= W\ell\nu_{\rm light}\cos\theta + W\ell\nu_{\rm heavy}\sin\theta \end{aligned}$$

$$Z\nu_\ell\nu_\ell\,(1-\epsilon_\ell) \qquad W\ell\nu_\ell\left(1-\frac{\epsilon_\ell}{2}\right)$$

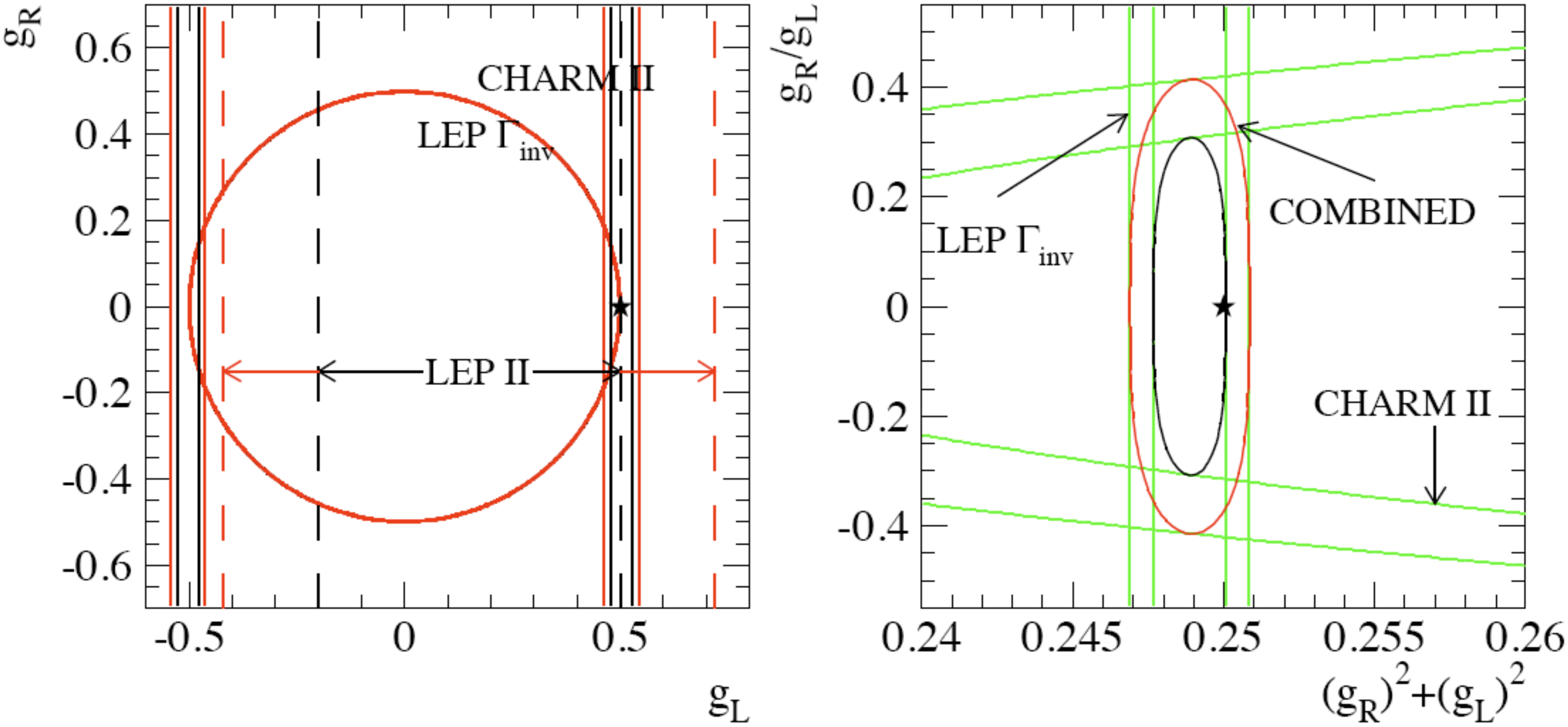
Another Example: The "Nature" of the $\nu - Z$-boson Coupling

In the Standard Model, the neutrino coupling to the Z-boson is purely left-handed. It is interesting to ask "how well do we know that?"

The most precise information we have regarding the neutrino–Z-boson coupling comes from the invisible Z-width at LEP. However, LEP does not measure g_L^ν: it measures $(g_L^\nu)^2 + (g_R^\nu)^2$.

On the other hand, we know a lot about the nature of the neutrino W-boson coupling. That one is known to be purely left-handed

This means that neutrino beam experiments measure only g_L^ν: Complementary to LEP.



CHARM II – neutrino electron scattering – plays a fundamental role!

Competitive with E158 (Moller scattering)

$$\mathcal{L}_{\rm new} = \pm\frac{4\pi}{2\Lambda_{LL}^{\pm 2}}\left(\bar{e}_L\gamma_\mu e_L\right)\left(\bar{e}_L\gamma^\mu e_L\right) \ .$$

$$\Lambda_{LL}^{+} \geq 7\,\text{TeV}\ , \qquad \Lambda_{LL}^{-} \geq 16\,\text{TeV}\ .$$

[E158 only sensitive to parity-violating physics, unlike NuSOnG]

… and LEP2 $\mathcal{L} = \pm\frac{4\pi}{\Lambda_{eP}^{\pm 2}}\left(\bar{e}_P\gamma_\sigma e_P\right)\left(\bar{\mu}_L\gamma^\sigma \mu_L\right)\ ,\qquad P = L, R.$

	Λ_{eL}^{-}	Λ_{eL}^{+}	Λ_{eR}^{-}	Λ_{eR}^{+}
L3	3.8 TeV	8.5 TeV	2.0 TeV	6.5 TeV
OPAL	7.3 TeV	8.1 TeV	6.3 TeV	6.3 TeV
DELPHI	7.6 TeV	7.3 TeV	2.0 TeV	6.3 TeV
ALEPH	9.5 TeV	6.6 TeV	2.0 TeV	6.1 TeV