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SMR.626 - 16

SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

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NEUTRINO PHYSICS

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leutrino Physics

- role of neutrinos
- Historical Introduction
- Neutrinos as a Test of The standard electroweak model
- Neutrinos as a probe of The nucleon, QCD, CKM
- Intrinsic Properties
  - motivations
  - basic properties
  - neutrino counting
  - electromagnetic moments
  - mass
    - models, mixing
    - laboratory
    - solar neutrinos
    - cosmology, decay
    - 17 keV

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Role of Neutrinos in particle physics, astrophysics, cosmology

- neutrinos central to most studies of weak interactions
  $\Rightarrow$ { Fermi Theory (β decay); electroweak theory, m_t (WNC) }
- sensitive probe of new physics:
  - β, μ, decay
  - WNC scattering
  - ν mass
- probe of structure of nucleon, QCD
- cosmology/astrophysics
  - ν (300/cm³) and γ (400/cm³) are most numerous inhabitants of Universe
  - Hot dark matter ($m_\nu = O(10\ eV)$) $\Rightarrow$ most of energy density
  - Solar ν: probes center of sun and ν properties
  - Supernova: 99% of energy emitted in ν's
  - nucleosynthesis:
    - primordial: $N_\nu \Rightarrow \frac{^4He}{H}$ ratio
    - heavy elements (stars, SN) $\leftrightarrow$ weak transitions

…st of standard model:

- U. Amaldi et al., PR D 36, 1385 (1987)
- P.L., A. Mann, M. Luo, RMP 64, 87 (92)
- "W and Z Physics" in "TeV Physics", ed. T. Huang et al (Gordon & Breach, 1991)

…eutrino Mass (General)

- "Neutrino Mass", in "Testing The Standard Model" (TASI-90), ed M. Cvetic, PL (World, 1991)
- "Scenarios For Neutrino mass", UPR-0511 T

…olar ν

- S.A. Bludman et al., UPR-0516T, PRD 45, 1810 (92); Nucl. Phys. B373, 498 (92)
- M. Cvetic and PL, UPR-0505T

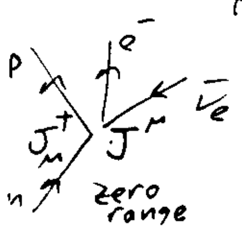
…7 keV

- D.O. Caldwell and PL, PRD 44, 823 (91)

Weak Interactions

- β decay (1896)
- neutrino (Pauli 1931)
  - ν_e Reines, Cowan, 1953
  - ν_μ Lederman, Schwartz, Steinberger, 1962
  - ν_τ ? (τ^-: 1975)
- Fermi Theory (1933)

$$H = \frac{G_F}{\sqrt{2}} J_\mu^{+} J^\mu$$



$$J_\mu^{+} \sim \bar p \gamma_\mu n + \bar\nu_e \gamma_\mu e^-$$

$n \to p$, $e^- \to \nu_e$

$$J_\mu \sim \bar n \gamma_\mu p + \bar e \gamma_\mu \nu_e$$

$p \to n$, $\nu_e \to e^-$ ($\times \to e^-, \bar\nu_e$)

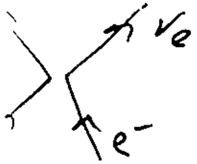
$G_F = 1.17 \times 10^{-5}\ \mathrm{GeV}^{-2}$ [Fermi constant]

- modified to include:
  - μ, τ
  - strangeness (Cabibbo)
  - quark model
  - heavy quarks (CKM)
  - parity violation (V−A) Lee, Yang, Wu ...
- correctly describes
  - μ, τ decay
  - β, K, hyperon, heavy quark decay
  - $\nu_\mu e \to \mu^- \nu_e$, $\nu_\mu n \to \mu^- p$, $\nu_\mu N \to \mu^- X$

However, Fermi Theory violates unitarity at high energy

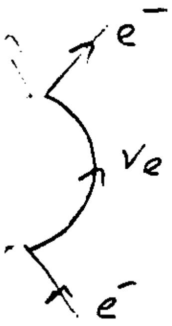
$$\sigma(\nu_e e^- \to e^- \nu_e) \longrightarrow \frac{G_F^2 s}{\pi}$$

$$s \equiv E_{cm}^2$$



Pure s-wave: unitarity $\Rightarrow \sigma < \frac{16\pi}{s}$

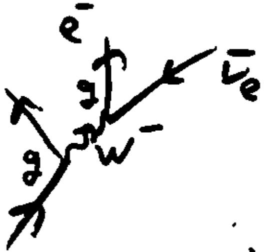
- Fails for $\frac{E_{cm}}{2} = \frac{\sqrt{s}}{2} \gtrsim \sqrt{\frac{\pi}{G_F}} \simeq 500$ GeV

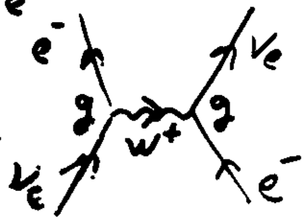


- higher order terms don't help
  - divergent integral $\int d^4k \, \frac{k + m_e}{k^2 - m_e^2} \, \frac{k}{k^2}$
  - non-renormalizable

Intermediate Vector Boson Theory

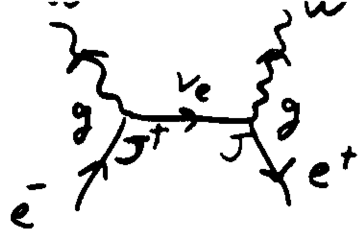
Yukawa 1935, Schwinger 1957





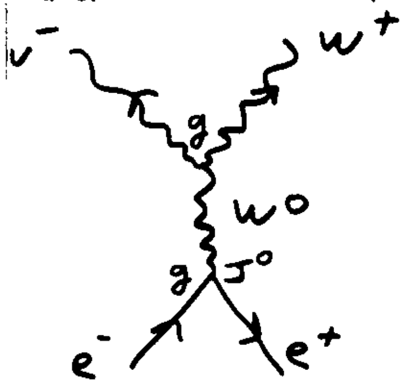
$\frac{G_F}{\sqrt{2}} \sim \frac{g^2}{8M_W^2}$ - for $M_W \gg |Q|$

- $\nu_e e^- \to \nu_e e^-$ better behaved [not s-wave]



- however, $e^+e^- \to W^+W^-$ violates unitarity for $\sqrt{s} \gtrsim 500$ GeV
- $A_\mu \sim \frac{k_\mu}{M_W}$ for longitudinal polarization
- non-renormalizable

Can Cancel:



- introduce W^0
- Fixes $W^0W^+W^-$ and $e^+e^-W^0$ vertices

$$[J, J^+] \propto J^0$$

$\Rightarrow$ Gauge theory couplings (SU_2)
- not realistic

Glashow model (1961):
- $W^\pm, Z, \gamma$
- no mechanism for M_W, M_Z

Weinberg, Salam (1967):
- applied Higgs mechanism $\Rightarrow M_W, M_Z$

Renormalizable (1971) ('t Hooft, ...)

Flavor-Changing Neutral Current:
- GIM mechanism (c quark) discovered 1974

weak neutral current discovered 1973

W, Z discovered 1983

The Z, The W, and The Weak Neutral Current

- weak neutral current: primary Test of unification part of $SU_2 \times U_1$

) mid 1970's: successful prediction of $SU_2 \times U_1$ discovery: 1973 Gargamelle

) late 1970's: 2^{ND} generation experiments ⇒ "model independent" fits ⇒ $SU_2 \times U_1$ correct To 1^{ST} approximation (Kim et al)

) 1980's: 3^{RD} generation experiments + (W, Z) (UA1, UA2: 1983)
- stringent limits on new physics
- rough Test of rad. corrections

pure weak: $\nu N \to \nu X$; $\nu p \to \nu p$, $\nu N \to \nu \pi X$; $\nu e \to \nu e$

weak-elm interference: $e^{\uparrow\downarrow} D \to e X$; atomic parity violation; $e^+e^- \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-, c\bar{c}, b\bar{b}, gg$

M_W, M_Z

SM correct; t exists; $m_t < 200$; $\sin^2\theta_W = .230 \pm .007$ (Amaldi et al; Costa et al)

) 1989 – 1990's ultrahigh precision Z-pole physics LEP (SLC)

$M_Z, \Gamma_Z, \Gamma_{\ell\ell}, \Gamma_{had}, N_\nu, A_{FB}, A_{pol}(\tau)$

later A_{LR}, A_{FB}^{pol}; M_W; A.P.V.; R_ν; ....

Neutrinos as a Test of The Standard Electroweak model

- WNC discovered in $\nu N \to \nu X$, $\nu e \to \nu e$
- primary quantitative Test of WNC prior To LEP

⇒ uniqueness of $SU_2 \times U_1$; $\sin^2\theta_W$; m_t limit ($\nu N \to \nu X$ very sensitive)

Present / Future

$\Delta \sin^2\theta_W|_{\nu N} \sim 0.005$ (present; mainly theory $\nu_\mu(d,s) \to \mu^- c$) ⟶ 0.002
- FNAL
- higher energy (c)
- new beam (ν_e bkg)
- higher intensity

$\sin^2\theta_W$ not competitive with LEP ($\Delta \sin^2\theta_W|_{M_Z} \sim 0.0003$ for fixed m_t, M_H)

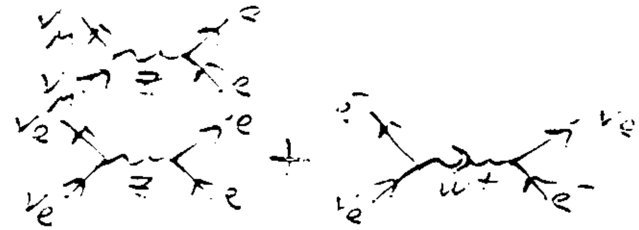
<u>but</u> (1) $\nu N \to \nu X$ still useful in m_t limit

(2) still sensitive to new physics (e.g. Z′)

(LEP only sensitive To Z properties)

$\overset{(-)}{\nu}_\mu e^- \to \overset{(-)}{\nu}_\mu e^-$

$\overset{(-)}{\nu}_e e^- \to \overset{(-)}{\nu}_e e^-$



$\nu N \to \ell X$ } deep inelastic

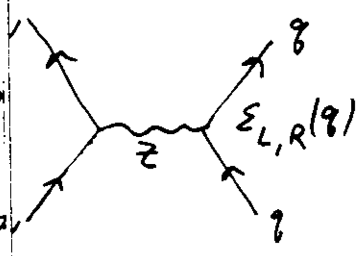
$\nu p \to \nu X$

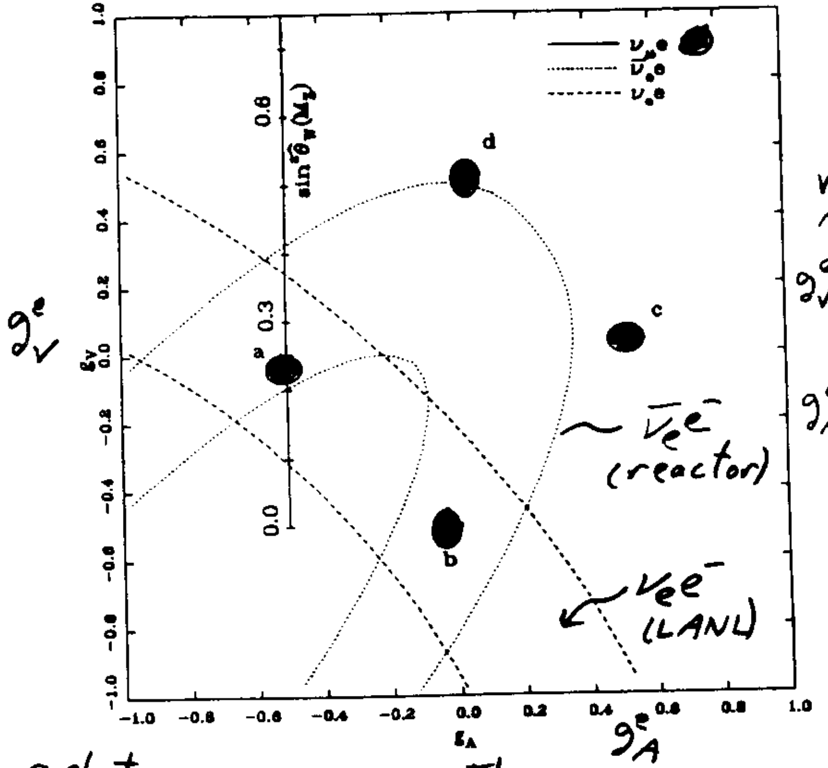
$\nu n \to \nu X$

$\nu p \to \nu p$

$\nu N \to \nu \pi^0 N$ (coherent)

pure NC





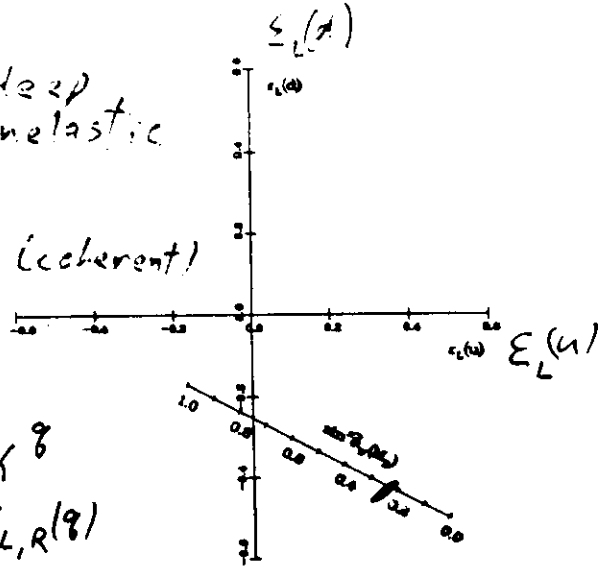
new CHARM II

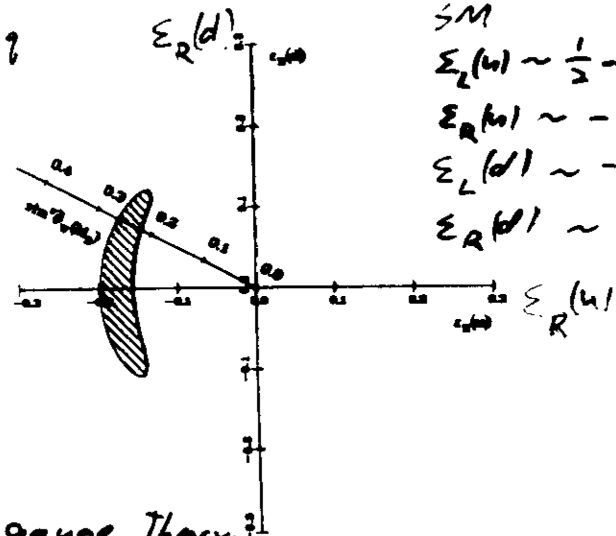
$g_V^e = -.025 \pm .020$

SM: $-.037 \pm .001$

$g_A^e = -.503 \pm .017$

SM: $-.506 \pm .001$





SM

$\epsilon_L(u) \sim \frac{1}{2} - \frac{2}{3}\sin^2\theta_W$

$\epsilon_R(u) \sim -\frac{2}{3}\sin^2\theta_W$

$\epsilon_L(d) \sim -\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$

$\epsilon_R(d) \sim \frac{1}{3}\sin^2\theta_W$

arbitrary gauge theory

$$-L^{\nu e} = \frac{G_F}{\sqrt{2}}\bar\nu\gamma^\mu(1-\gamma^5)\nu\,\bar e\gamma_\mu[g_V^e - g_A^e\gamma^5]e$$

$SU_2 \times U_1$: $g_V^e \sim -\frac{1}{2} + 2\sin^2\theta_W$, $g_A^e \sim -\frac{1}{2}$

$$\sigma^{NC}_{\nu,\bar\nu e} \simeq \frac{G_F^2 m_e E_\nu}{2\pi}\left[(g_V^e \pm g_A^e)^2 + \frac{1}{3}(g_V^e \mp g_A^e)^2\right]$$

$\nu_e e$: $g^e_{V,A} \to g^e_{V,A} + 1$

arbitrary gauge theory:

$$-L^{\nu N} = \frac{G_F}{\sqrt{2}}\bar\nu\gamma^\mu(1-\gamma^5)\nu\sum_{i=u,d}\left[\epsilon_L(i)\bar q_i\gamma_\mu(1-\gamma^5)q_i + \epsilon_R(i)\bar q_i\gamma_\mu(1+\gamma^5)q_i\right]$$

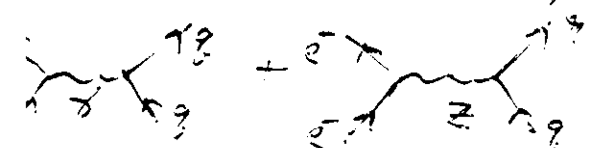
rton odel

$R_\nu = \frac{\sigma_{\nu N\to\nu X}}{\sigma_{\nu N\to\mu^- X}} \sim g_L^2 + g_R^2 r$ $\qquad R_{\bar\nu} \sim g_L^2 + \frac{g_R^2}{r}$

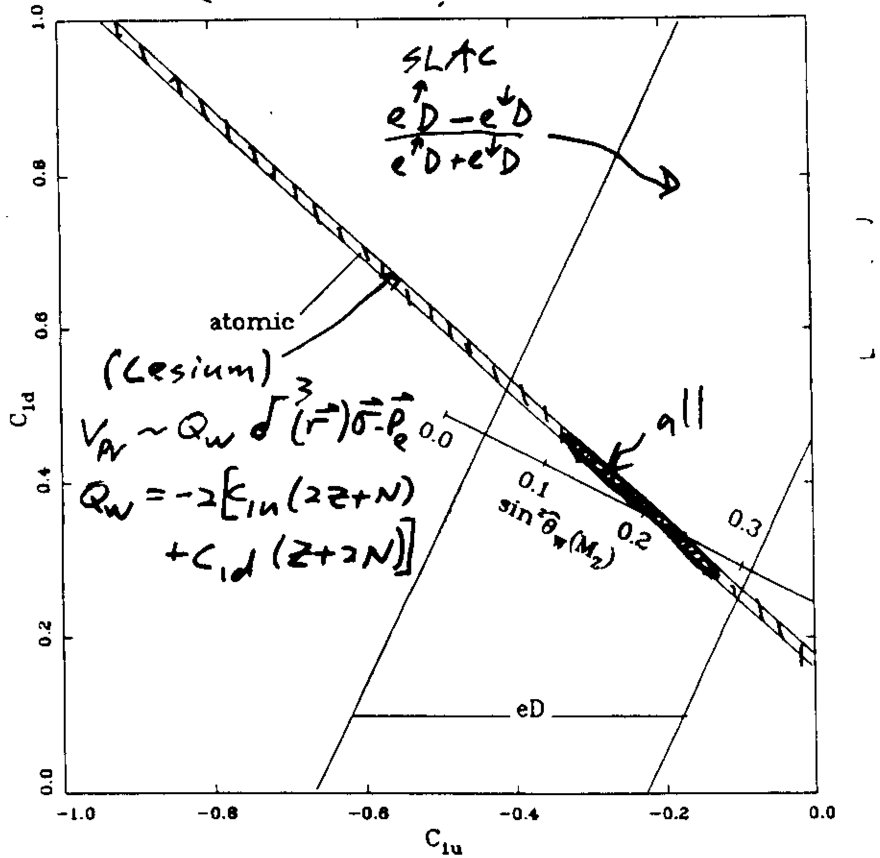
$r = \frac{\frac{1}{3}+\epsilon}{1+\epsilon} = \frac{\sigma^{cc}_{\bar\nu N}}{\sigma^{cc}}$

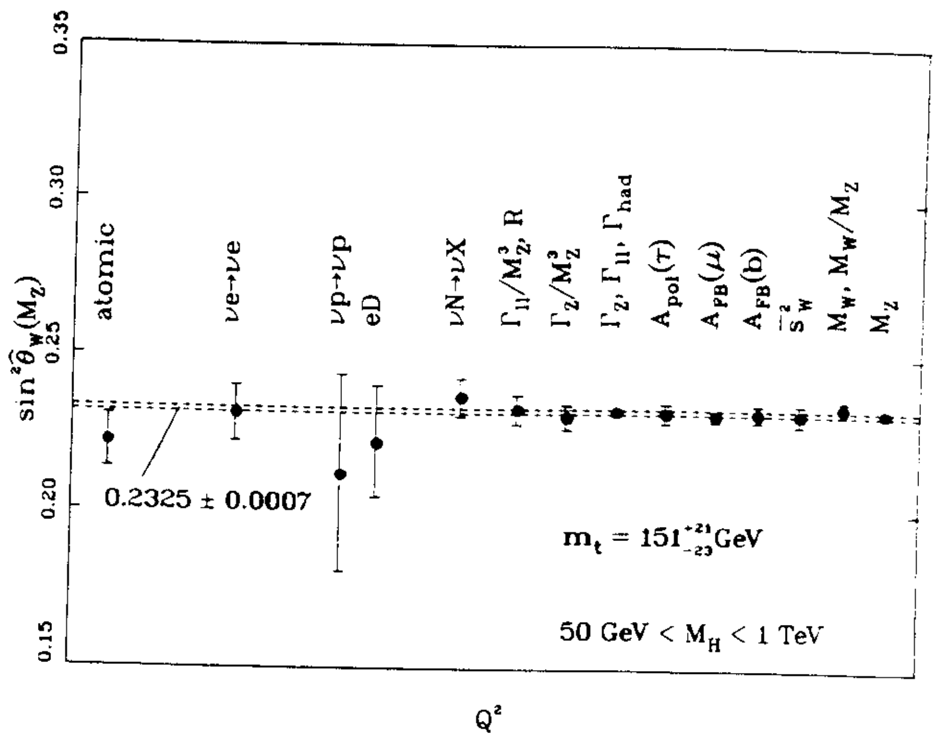
$g_{L,R}^2 = \epsilon_{L,R}(u)^2 + \epsilon_{L,R}(d)^2$

arity violation in eq system



weak-elm interference





itrary gauge theory:

$$\mathcal{L}^{eq}_{PV} = \frac{G_F}{\sqrt{2}} \sum_{i=u,d} \left[C_{1i}\, \bar e \gamma^\mu \gamma^5 e\, \bar q_i \gamma_\mu q_i + C_{2i}\, \bar e \gamma^\mu e\, \bar q_i \gamma_\mu \gamma^5 q_i \right]$$

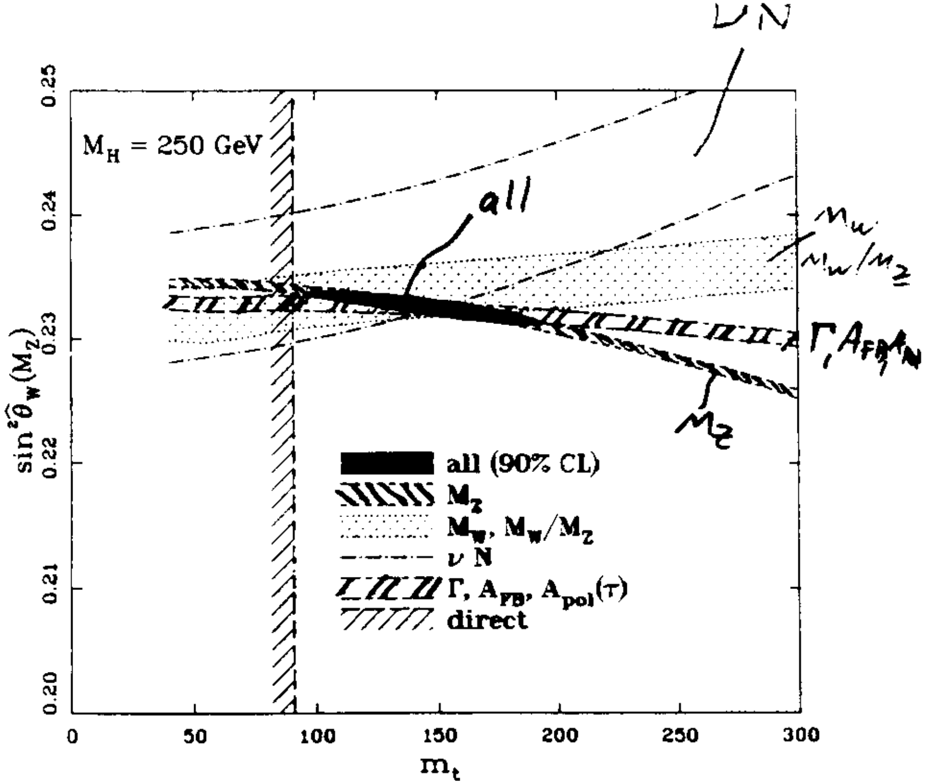
$SU_2 \times U_1$:

$$C_{1u} \sim -\tfrac{1}{2} + \tfrac{4}{3}\sin^2\theta_W$$
$$C_{1d} \sim \tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W$$
$$C_{2u} = -C_{2d} = -\tfrac{1}{2} + 2\sin^2\theta_W$$

4/92

Z_ψ

P.L., Lao, Mann



TS: $\sin^2\hat{\theta}_W(M_Z) = 0.2325 \pm .0007$

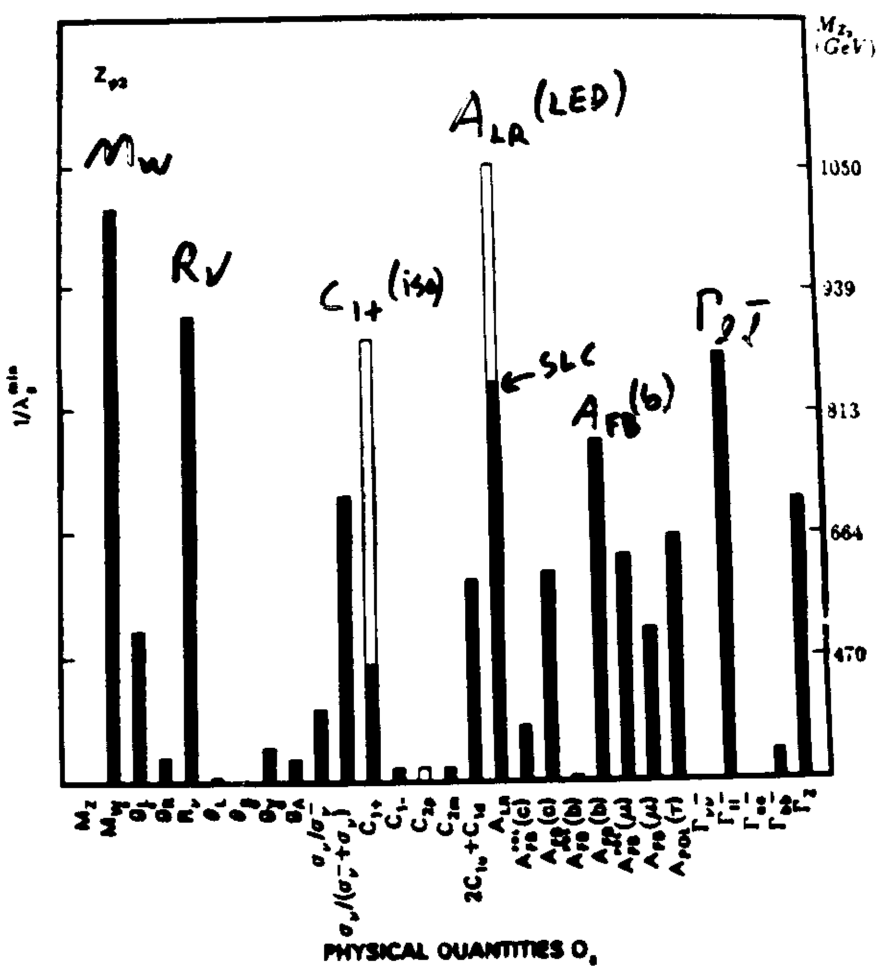
on-shell $1 - \frac{M_W^2}{M_Z^2} = 0.2257 \pm .0026$

$m_t = 151^{+21}_{-23}{}^{+18}_{-14}$ GeV

$m_H = 250 \nearrow 1000 \searrow 50$ GeV

$\cdot\, m_t < 193\ (199)$ GeV at 90 (99)% CL
For $m_H \leq 1$ TeV 4/92

Figure 5.4: The new physics of Z_ψ with $C = -(2/3)^{1/2}$
solid bar for C_{1+}, C_{2p}, and $A_{LR}(SLC)$;
open bar for $C_{1+}(iso)$, $C_{2p}(1)$, and $A_{LR}(LEP)$.



eutrinos as a probe of QCD, nucleon, CKM

k' (E) charged current:

$$\begin{cases} \nu_\mu N \to \mu^- X \\ \bar{\nu}_\mu N \to \mu^+ X \\ \ell^\mp N \to \ell^\mp X, \quad \ell = e, \mu \end{cases}$$

$q = E - E'$

$\overset{(-)}{\nu}_\mu N$: parity violation and flavor change $\Rightarrow \bar{Q}/Q$, etc

$\frac{\nu}{E}$, $x = \frac{Q^2}{2M\nu}$, $Q^2 = -q^2 > 0$

$^\mp N \to \ell^\mp X$

$$\frac{d^2\sigma}{dx\,dy} \sim \frac{4\pi\alpha^2 s}{Q^4}\left[(1-y)F_2^{\ell N} + y^2 x F_1^{\ell N}\right]$$

spin-$\frac{1}{2}$

$$F_2^{\ell N}(x,Q^2) = 2xF_1^{\ell N}(x,Q^2)$$

quark parton: $\simeq \frac{4}{9}x(u+\bar{u}) + \frac{1}{9}x(d+\bar{d})$

QCD ($\Rightarrow \alpha_s$): $+ \ln Q^2$ terms

$+ (s, c, b, t)$

$\to \mu^\mp X$

$$\frac{d^2\sigma}{dx\,dy} \sim \frac{G_F^2 s}{2\pi}\left[(1-y)F_2^{\overset{(-)}{\nu}N} + y^2 x F_1^{\overset{(-)}{\nu}N} \pm \left(y - \frac{y^2}{2}\right)F_3^{\overset{(-)}{\nu}N}\right]$$

spin-$\frac{1}{2}$; parity violation

$$\left.\begin{aligned} F_2^{\nu N} &= 2xF_1^{\nu N} \simeq 2x[u+\bar{d}] + \ln Q^2 \\ F_2^{\bar{\nu}N} &= 2xF_1^{\bar{\nu}N} = 2x[d+\bar{u}] + \text{''} \\ F_3^{\nu N} &= 2x[u-\bar{d}] + \text{''} \\ F_3^{\bar{\nu}N} &= 2x[d-\bar{u}] + \text{''} \end{aligned}\right\} \text{QCD } (\alpha_s)$$

QPM $\qquad + (s, c, b, t)$

probe:
- quark distributions
- scaling violation (QCD)
- quark charges:
  - For isoscalar target (eg C):
    $u = d \equiv q, \quad \bar{u} = \bar{d} \equiv \bar{q}$

$$\Rightarrow F_2^{\nu N} = F_2^{\bar{\nu}N} = 2x(q+\bar{q})$$
$$F_2^{\ell N} = \frac{5}{9}x(q+\bar{q}) = \frac{5}{18}F_2^{\nu N}$$

- $\bar{Q}/Q$ of nucleon: $\bar{Q} = \int_0^1 x\,\bar{q}(x)\,dx$
  $Q = \int_0^1 x\,q(x)\,dx$

$$\frac{d\sigma^{\nu N}}{dy} = \frac{G_F^2 s}{\pi}\left[Q + (1-y)^2\bar{Q}\right]$$

$$\frac{d\sigma^{\bar{\nu}N}}{dy} = \frac{G_F^2 s}{\pi}\left[\bar{Q} + (1-y)^2 Q\right]$$

- charm production
  $\overset{(-)}{\nu}_\mu N \to \mu^\mp \mu^\pm X$

$\nu_\mu (d, s) \to \mu^- c X_1$, $\; c \to \mu^+ X_2$

$\bar{\nu}_\mu (\bar{d}, \bar{s}) \to \mu^+ \bar{c} X_1$, $\; \bar{c} \to \mu^- X_2$

$\Rightarrow d \to c$: $|V_{cd}|^2$

$s \to c$: $S|V_{cs}|^2$

- also, threshold for $R_{\nu,\bar{\nu}}$

Future(?): $\nu p \to \nu p$ sensitive to s content of proton

Intrinsic Properties of Neutrinos

(and implications for grand unification, large scale structure of universe, nucleosynthesis, stellar astrophysics, ...)

- motivations for ν mass
- basic properties
- neutrino counting
- electromagnetic moments
- neutrino mass
  - models
  - mixing
  - experimental constraints
  - cosmology, decay
  - solar neutrinos
  - 17 keV

Motivations

- New physics
  - $m_\nu \neq 0$ in most SM extensions
  - usually, $m_\nu \sim \frac{v^2}{M}$ $\quad v$ = weak scale, M = new scale
- Solar ν spectrum / deficit

$$r = \frac{\varphi_{observed}}{\varphi_{SSM}} = \begin{cases} 0.28 \pm 0.04, & Cl \\ 0.49 \pm 0.08, & Kam. \end{cases}$$

  - excludes cool sun at $>99\%$ CL — Bahcall, Bethe, Bludman, (Hata), Kennedy, PL

GALLEX: $83 \pm 19 \pm 8$ SNU

(SAGE 12/91: $20^{+15}_{-20} \pm 30$ SNU)

- SSM: 132^{+7}_{-6} SNU

nonstandard SM: > 80 SNU

$\Rightarrow \nu_e \to \nu_x$, $\Delta m^2 = m^2_{\nu_x} - m^2_{\nu_e} \sim 10^{-5}\, eV^2$

- 17 keV
  - scenario: $m_{\nu_\tau} = 17$ keV $\leq m_{\nu_\mu}$
  - $\nu_e \to \nu_s$ in sun, $\Delta m^2 \sim 10^{-5}\, eV^2$ (ν_s: light sterile)
- atmospheric ν_μ / ν_e deficit

$$\frac{(\mu/e)_{data}}{(\mu/e)_{MC}} = \begin{cases} 0.65 \pm 0.06 \pm 0.06, & \text{Kamiokande} \\ 0.64 \pm 0.09 \pm 0.12, & \text{IMB} \end{cases}$$

(single ring)

$\nu_\mu \to \nu_x$, $\Delta m^2 \sim (10^{-3} - 1)\, eV^2$, large mixing

- hot dark matter (?)
  - $m_{\nu_\tau} \sim (1 - 28)\, eV$ (1: irrelevant; 28: closure)
  - need galaxy seeds { cosmic strings / decaying ν

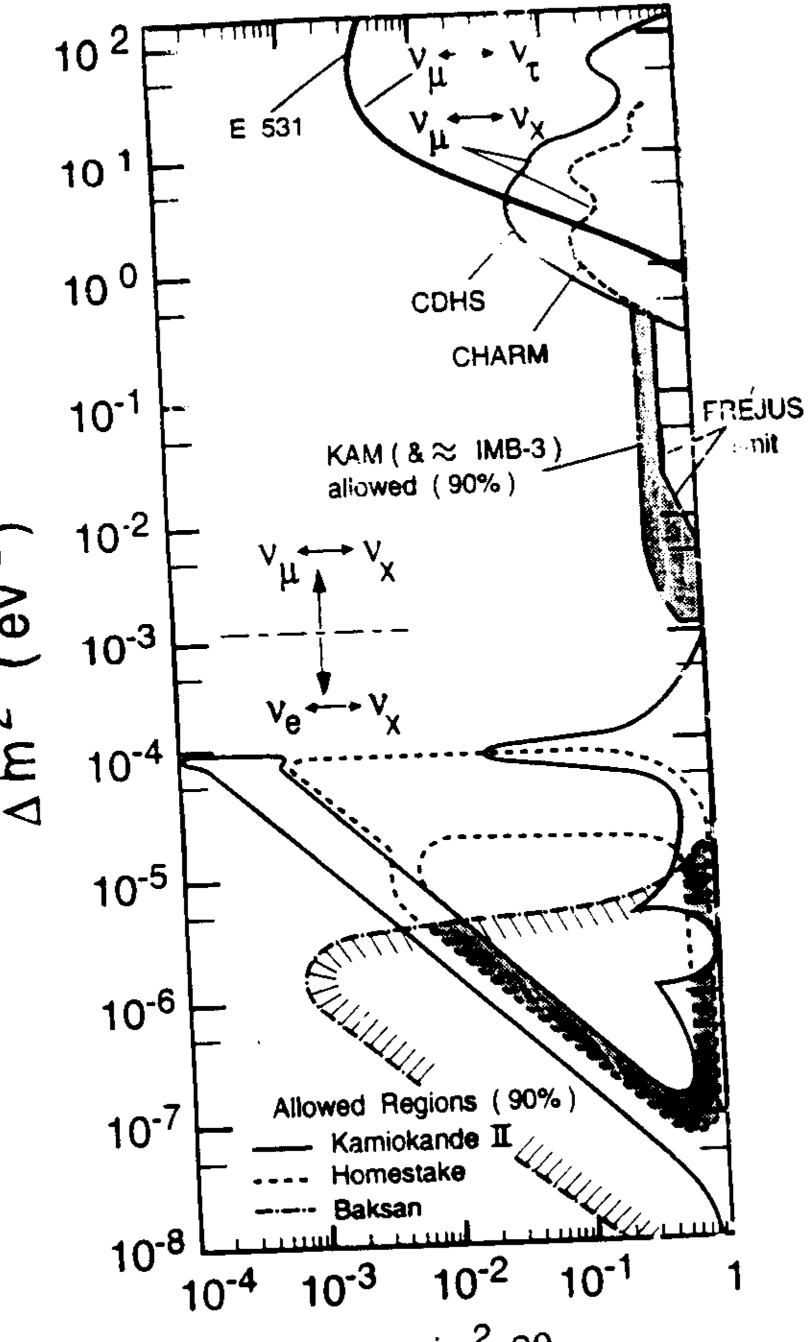


Fig. 6

Hirata et al