The Standard Model:

Current Status & Open Questions

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Fermilab

Parity violation in weak decays

1956 Wu *et al.*: correlation between spin vector $\vec{J}$ of polarized ^{60}Co and direction $\hat{p}_e$ of outgoing β particle

Parity leaves spin (axial vector) unchanged $\mathcal{P} : \vec{J} \to \vec{J}$

Parity reverses electron direction $\mathcal{P} : \hat{p}_e \to -\hat{p}_e$

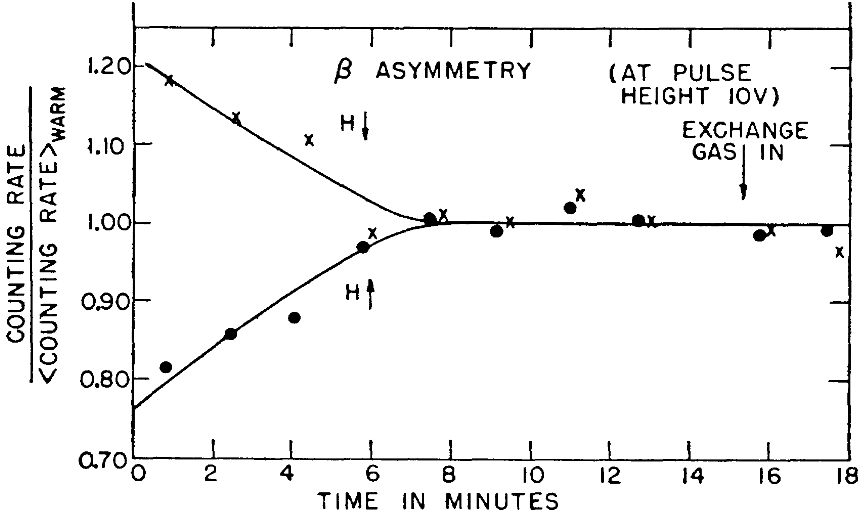
Correlation $\vec{J} \cdot \hat{p}_e$ is *parity violating*

Parity links left-handed, right-handed ν,

$$\nu_L \overset{\Leftarrow}{\longrightarrow} \mathcal{P} \overset{\Leftarrow}{\longleftarrow} \not{\nu}_R$$

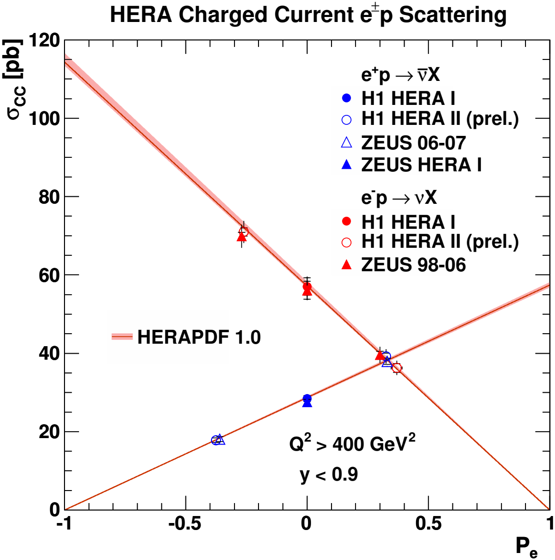
$\Rightarrow$ build a manifestly parity-violating theory with only ν_L.

Parity violation in ^{60}Co decay



Left-handed Charged-current Interaction

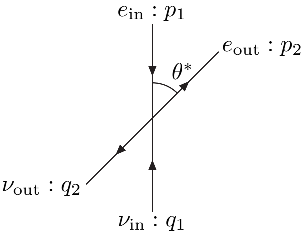
Polarized $e^{\pm}p \to (\bar{\nu}, \nu) + \text{anything}$ — no RHCC



Effective Lagrangian for the Weak Interactions

$$\mathcal{L}_{\mathsf{V-A}} = \frac{-G_{\mathsf{F}}}{\sqrt{2}} \bar{\nu}\gamma_\mu(1-\gamma_5)e\,\bar{e}\gamma^\mu(1-\gamma_5)\nu$$

with $G_{\mathsf{F}} = 1.166\,378\,7(6) \times 10^{-5}\ \mathsf{GeV}^{-2}$. $\bar{\nu}e$ scattering:



$$\mathcal{M} = -\frac{iG_{\mathsf{F}}}{\sqrt{2}} \bar{v}(\nu, q_1)\gamma_\mu(1-\gamma_5)u(e, p_1)\bar{u}(e, p_2)\gamma^\mu(1-\gamma_5)v(\nu, q_2)$$

$\mathcal{L}_{\mathsf{V-A}}$ Consequences

$$\frac{d\sigma_{\mathsf{V-A}}(\bar{\nu}e \to \bar{\nu}e)}{d\Omega_{\mathrm{cm}}} = \frac{\overline{|\mathcal{M}|^2}}{64\pi^2 s} = \frac{G_{\mathsf{F}}^2 \cdot 2mE_\nu(1-z)^2}{16\pi^2}; \quad z = cos\theta^*$$

$$\sigma_{\mathsf{V-A}}(\bar{\nu}e \to \bar{\nu}e) = \frac{G_{\mathsf{F}}^2 \cdot 2mE_\nu}{3\pi} \approx 0.574 \times 10^{-41} \text{ cm}^2 \left(\frac{E_\nu}{1 \text{ GeV}}\right)$$

Repeat for νe scattering:

$$\frac{d\sigma_{\mathsf{V-A}}(\nu e \to \nu e)}{d\Omega_{\mathrm{cm}}} = \frac{G_{\mathsf{F}}^2 \cdot 2mE_\nu}{4\pi^2}$$

$$\sigma_{\mathsf{V-A}}(\nu e \to \nu e) = \frac{G_{\mathsf{F}}^2 \cdot 2mE_\nu}{\pi} \approx 1.72 \times 10^{-41} \text{ cm}^2 \left(\frac{E_\nu}{1 \text{ GeV}}\right)$$

Problem 6

Trace the origin of the factor-of-three difference between the νe and $\bar{\nu} e$ cross sections, which arises from the left-handed nature of the charged-current weak interaction. Analyze the spin configurations for forward and backward scattering for the two cases, and show how angular momentum conservation accounts for the different angular distributions.

The Two-Neutrino Experiment

Lederman, Schwartz, Steinberger, 1962

- Make a beam of high-energy ν from $\pi \to \mu\nu$
- Observe $\nu N \to \mu + X$

  not $\nu N \to e + X$

$\Rightarrow$ neutrino produced in $\pi \to \mu\nu$ decay is ν_μ

Suggests family structure

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_{\mathrm{L}} \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_{\mathrm{L}}$$

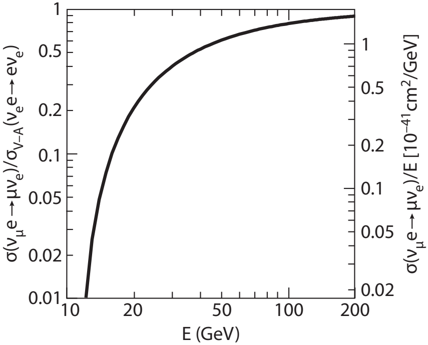
Generalize the effective Lagrangian:

$$\mathcal{L}_{\mathrm{V-A}}^{(e\mu)} = \frac{-G_{\mathrm{F}}}{\sqrt{2}} \bar{\nu}_\mu \gamma_\mu (1 - \gamma_5) \mu \; \bar{e} \gamma^\mu (1 - \gamma_5) \nu_e + \mathrm{h.c.}$$

(Inverse) Muon Decay

$$\Gamma(\mu \to e\bar{\nu}_e\nu_\mu) = \frac{G_F^2 m_\mu^5}{192\pi^3}$$

$$\sigma(\nu_\mu e \to \mu\nu_e) = \sigma_{V-A}(\nu_e e \to \nu_e e)\left[1 - \frac{(m_\mu^2 - m_e^2)}{2m_e E_\nu}\right]^2$$



Partial-wave Unitarity (Probability Conservation)

PW unitarity constrains the modulus $|\mathcal{M}_{J=0}| < 1$ for an s-wave amplitude.

Equivalently, the contribution to the cross section is bounded by $\sigma_0 < \pi/p_{\mathrm{cm}}^2$.

$$\mathcal{M}_0 = \frac{G_\mathrm{F} \cdot 2m_e E_\nu}{\pi\sqrt{2}} \left[1 - \frac{(m_\mu^2 - m_e^2)}{2m_e E_\nu}\right]$$

Satisfies unitarity constraint for

$$E_\nu < \pi/G_\mathrm{F} m_e \sqrt{2} \approx 3.7 \times 10^8 \text{ GeV},$$

or $E_{\mathrm{cm}} \lesssim 300$ GeV

Physics must change before $\sqrt{s} = 600$ GeV

Problem 7

Using the measured lifetimes of the muon and the tau lepton, $\tau_\ell = \hbar/\Gamma_\ell$, and the branching fractions into the $e\bar{\nu}_e\nu_\ell$ channel to determine the Fermi couplings for muon and tau interactions, G_μ and G_τ. Compare these two values with each other and with the standard value of G_F.

The equality of G_μ, G_τ, and G_F and supports the notion that the leptonic (charged-current) weak interactions are of universal strength.

Introduction: J. R. Patterson, "Lepton Universality," SLAC *Beam Line* (Spring 1995).
Recent BaBar study, *Phys. Rev. Lett.* **105**, 051602 (2008).

Electroweak theory antecedents

Lessons from experiment and theory

- Parity-violating $V - A$ structure of charged current
- Cabibbo universality of leptonic and semileptonic processes
- Absence of strangeness-changing neutral currents
- Negligible neutrino masses; left-handed neutrinos
- Unitarity: four-fermion description breaks down at $\sqrt{s} \approx 620$ GeV $\qquad \nu_\mu e \to \mu \nu_e$
- $\nu\bar{\nu} \to W^+W^-$: divergence problems of *ad hoc* intermediate vector boson theory

Formulate electroweak theory

Three crucial clues from experiment:

- Left-handed weak-isospin doublets,

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \qquad \begin{pmatrix} c \\ s' \end{pmatrix}_L \qquad \begin{pmatrix} t \\ b' \end{pmatrix}_L \; ;$$

- Universal strength of the (charged-current) weak interactions;
- Idealization that neutrinos are massless.

First two clues suggest $SU(2)_L$ gauge symmetry

A theory of leptons

$$\mathsf{L} = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_{\mathsf{L}} \qquad \mathsf{R} \equiv e_{\mathsf{R}}$$

weak hypercharges $Y_{\mathsf{L}} = -1,\ Y_{\mathsf{R}} = -2$

Gell-Mann–Nishijima connection, $Q = I_3 + \frac{1}{2}Y$

$\mathsf{SU(2)_L} \otimes \mathsf{U(1)}_Y$ gauge group $\Rightarrow$ gauge fields:

- weak isovector $\vec{b}_\mu$, coupling g

$$\boxed{b_\mu^\ell = b_\mu^\ell - \varepsilon_{jk\ell}\alpha^j b_\mu^k - (1/g)\partial_\mu \alpha^\ell}$$

- weak isoscalar $\mathcal{A}_\mu$, coupling $g'/2$ $\quad \boxed{\mathcal{A}_\mu \to \mathcal{A}_\mu - \partial_\mu \alpha}$

Field-strength tensors

$$F_{\mu\nu}^\ell = \partial_\nu b_\mu^\ell - \partial_\mu b_\nu^\ell + g\varepsilon_{jk\ell} b_\mu^j b_\nu^k\ ,\ \mathsf{SU(2)_L}$$

$$f_{\mu\nu} = \partial_\nu \mathcal{A}_\mu - \partial_\mu \mathcal{A}_\nu\ ,\ \mathsf{U(1)}_Y$$

Interaction Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{leptons}}$$

$$\mathcal{L}_{\text{gauge}} = -\tfrac{1}{4}F^{\ell}_{\mu\nu}F^{\ell\mu\nu} - \tfrac{1}{4}f_{\mu\nu}f^{\mu\nu},$$

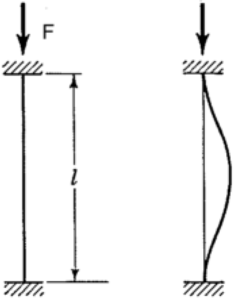
$$\begin{aligned}\mathcal{L}_{\text{leptons}} &= \overline{\mathsf{R}}\, i\gamma^{\mu}\left(\partial_{\mu} + i\frac{g'}{2}\mathcal{A}_{\mu}Y\right)\mathsf{R} \\ &+ \overline{\mathsf{L}}\, i\gamma^{\mu}\left(\partial_{\mu} + i\frac{g'}{2}\mathcal{A}_{\mu}Y + i\frac{g}{2}\vec{\tau}\cdot\vec{b}_{\mu}\right)\mathsf{L}.\end{aligned}$$

Mass term $\mathcal{L}_e = -m_e(\bar{e}_{\mathsf{R}}e_{\mathsf{L}} + \bar{e}_{\mathsf{L}}e_{\mathsf{R}}) = -m_e\bar{e}e$
would violate local gauge invariance

Theory: 4 massless gauge bosons ($\mathcal{A}_{\mu}$ b^1_{μ} b^2_{μ} b^3_{μ});
Nature: 1 (γ)

Symmetric law need not imply symmetric outcome

Buckling rod (L. Euler) *spontaneous symmetry breaking*



radius R, moment of inertia $I = \pi R^2/4$, elastic modulus E

Critical point: $F_{\text{cr}} = \pi^2 IE/\ell^2$

symmetric solution unstable, ground state degenerate

Symmetric law need not imply symmetric outcome

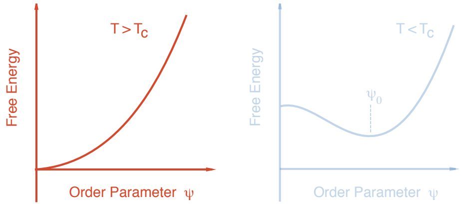
Massive Photon? *Hiding Symmetry*

Recall 2 miracles of superconductivity:

- No resistance . . . . . . Meissner effect (exclusion of **B**)

Ginzburg–Landau Phenomenology (not a theory from first principles)

normal, resistive charge carriers . . . . . . + superconducting charge carriers



$$\mathbf{B} = 0: \qquad G_{\text{super}}(0) = G_{\text{normal}}(0) + \alpha\,|\psi|^2 + \beta\,|\psi|^4$$

$$T > T_c: \quad \alpha > 0 \quad \langle|\psi|^2\rangle_0 = 0$$

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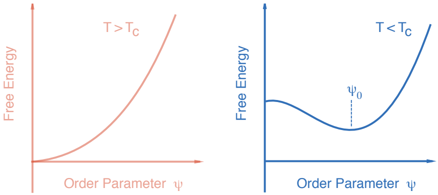

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$$T < T_c: \quad \alpha < 0 \quad \langle|\psi|^2\rangle_0 \neq 0$$

In a nonzero magnetic field . . .

$$G_{\text{super}}(\mathbf{B}) = G_{\text{super}}(0) + \frac{\mathbf{B}^2}{8\pi} + \frac{1}{2m^*}\left|-i\hbar\nabla\psi - \frac{e^*}{c}\mathbf{A}\psi\right|^2$$

$$\left.\begin{array}{c} e^* = -2 \\ m^* \end{array}\right\} \text{of superconducting carriers}$$

Weak, slowly varying field: $\psi \approx \psi_0 \neq 0$, $\nabla\psi \approx 0$

Variational analysis $\rightsquigarrow$

$$\boxed{\nabla^2\mathbf{A} - \frac{4\pi e^{*2}}{m^* c^2}\left|\psi_0\right|^2\mathbf{A} = 0}$$

wave equation of a *massive photon*

Photon – *gauge boson* – acquires mass
within superconductor

origin of Meissner effect

Hiding EW Symmetry

Higgs mechanism: relativistic generalization of Ginzburg-Landau superconducting phase transition

- Introduce a complex doublet of scalar fields

$$\phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad Y_\phi = +1$$

- Add to $\mathcal{L}$ (gauge-invariant) terms for interaction and propagation of the scalars,

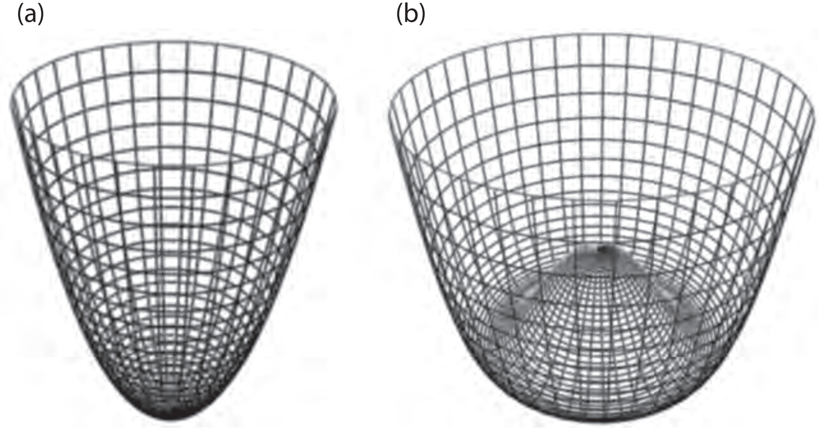
$$\mathcal{L}_{\text{scalar}} = (\mathcal{D}^\mu \phi)^\dagger (\mathcal{D}_\mu \phi) - V(\phi^\dagger \phi),$$

where $\mathcal{D}_\mu = \partial_\mu + i\frac{g'}{2}\mathcal{A}_\mu Y + i\frac{g}{2}\vec{\tau} \cdot \vec{b}_\mu$ and

$$\boxed{V(\phi^\dagger \phi) = \mu^2(\phi^\dagger \phi) + |\lambda| (\phi^\dagger \phi)^2}$$

- Add a Yukawa interaction $\mathcal{L}_{\text{Yukawa}} = -\zeta_e \left[\overline{\mathsf{R}}(\phi^\dagger \mathsf{L}) + (\overline{\mathsf{L}}\phi)\mathsf{R}\right]$

Unique and degenerate vacuum states



- Arrange self-interactions so vacuum corresponds to a broken-symmetry solution: $\mu^2 < 0$
  Choose minimum energy (vacuum) state for vacuum expectation value

$$\langle\phi\rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \quad v = \sqrt{-\mu^2/|\lambda|}$$

Hides (breaks) $SU(2)_L$ and $U(1)_Y$

but preserves $U(1)_{\text{em}}$ invariance

Invariance under $\mathcal{G}$ means $e^{i\alpha\mathcal{G}}\langle\phi\rangle_0 = \langle\phi\rangle_0$, so $\mathcal{G}\langle\phi\rangle_0 = 0$

$$\tau_1\langle\phi\rangle_0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$\tau_2\langle\phi\rangle_0 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} -iv/\sqrt{2} \\ 0 \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$\tau_3\langle\phi\rangle_0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} 0 \\ -v/\sqrt{2} \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$Y\langle\phi\rangle_0 = Y_\phi\langle\phi\rangle_0 = +1\langle\phi\rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \neq 0 \quad \text{broken!}$$

Examine electric charge operator Q on the (neutral) vacuum

$$\begin{aligned} Q\langle\phi\rangle_0 &= \tfrac{1}{2}(\tau_3 + Y)\langle\phi\rangle_0 \\ &= \tfrac{1}{2}\begin{pmatrix} Y_\phi + 1 & 0 \\ 0 & Y_\phi - 1 \end{pmatrix}\langle\phi\rangle_0 \\ &= \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \\ &= \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad \textit{unbroken!} \end{aligned}$$

Four original generators are broken, *electric charge is not*

- $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y \to \mathrm{U(1)_{em}}$ (will verify)
- Expect massless photon
- Expect gauge bosons corresponding to

$\tau_1,\ \tau_2,\ \tfrac{1}{2}(\tau_3 - Y) \equiv K$ to acquire masses

Expand about the vacuum state

Let $\phi = \begin{pmatrix} 0 \\ (v+\eta)/\sqrt{2} \end{pmatrix}$; in *unitary gauge*

$$\begin{aligned} \mathcal{L}_{\text{scalar}} &= \tfrac{1}{2}(\partial^\mu \eta)(\partial_\mu \eta) - \mu^2 \eta^2 \\ &+ \frac{v^2}{8}[g^2 \left| b^1_\mu - i b^2_\mu \right|^2 + (g' \mathcal{A}_\mu - g b^3_\mu)^2] \\ &+ \text{interaction terms} \end{aligned}$$

"Higgs boson" η has acquired (mass)^2 $M_H^2 = -2\mu^2 > 0$

$$\text{Define } W^\pm_\mu = \frac{b^1_\mu \mp i b^2_\mu}{\sqrt{2}}$$

$$\frac{g^2 v^2}{8}(\left|W^+_\mu\right|^2 + \left|W^-_\mu\right|^2) \Longleftrightarrow M_{W^\pm} = gv/2$$

$$(v^2/8)(g'\mathcal{A}_\mu - gb^3_\mu)^2 \ldots$$

Now define orthogonal combinations

$$Z_\mu = \frac{-g'\mathcal{A}_\mu + gb^3_\mu}{\sqrt{g^2 + g'^2}} \qquad A_\mu = \frac{g\mathcal{A}_\mu + g'b^3_\mu}{\sqrt{g^2 + g'^2}}$$

$$M_{Z^0} = \sqrt{g^2 + g'^2}\, v/2 = M_W \sqrt{1 + g'^2/g^2}$$

A_μ remains massless

$$
\begin{aligned}
\mathcal{L}_{\mathrm{Yukawa}} &= -\zeta_e \frac{(v+\eta)}{\sqrt{2}} (\bar{e}_{\mathrm{R}} e_{\mathrm{L}} + \bar{e}_{\mathrm{L}} e_{\mathrm{R}}) \\
&= -\frac{\zeta_e v}{\sqrt{2}} \bar{e} e - \frac{\zeta_e \eta}{\sqrt{2}} \bar{e} e
\end{aligned}
$$

electron acquires $m_e = \zeta_e v / \sqrt{2}$

Higgs-boson coupling to electrons: m_e/v ($\propto$ mass)

Desired particle content ... plus a Higgs scalar

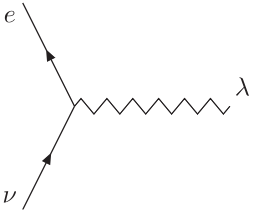
Values of couplings, electroweak scale v?

What about interactions?

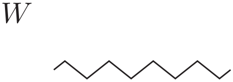
Interactions . . .

$$\mathcal{L}_{W\text{-}\ell} = -\frac{g}{2\sqrt{2}}[\bar{\nu}\gamma^{\mu}(1-\gamma_5)eW_{\mu}^{+} + \bar{e}\gamma^{\mu}(1-\gamma_5)\nu W_{\mu}^{-}]$$

$+$ similar terms for μ and τ



$$\frac{-ig}{2\sqrt{2}}\gamma_{\lambda}(1-\gamma_5)$$



$$= \frac{-i(g_{\mu\nu} - k_{\mu}k_{\nu}/M_W^2)}{k^2 - M_W^2} \; .$$

Compute $\nu_\mu e \to \mu\nu_e$

$$\sigma(\nu_\mu e \to \mu\nu_e) = \frac{g^4 m_e E_\nu}{16\pi M_W^4} \frac{[1 - (m_\mu^2 - m_e^2)/2m_e E_\nu]^2}{(1 + 2m_e E_\nu/M_W^2)}$$

Reproduces 4-fermion result at low energies if

$$\frac{g^4}{16M_W^4} = 2G_F^2 \Rightarrow \frac{g}{2\sqrt{2}} = \left(\frac{G_F M_W^2}{\sqrt{2}}\right)^{\frac{1}{2}}$$

Using $M_W = gv/2$, determine the electroweak scale

$$\boxed{v = (G_F\sqrt{2})^{-\frac{1}{2}} \approx 246 \text{ GeV}}$$

$$\Rightarrow \langle\phi^0\rangle_0 = (G_F\sqrt{8})^{-\frac{1}{2}} \approx 174 \text{ GeV}$$

W-propagator modifies HE behavior

$$\sigma(\nu_\mu e \to \mu\nu_e) = \frac{g^4 m_e E_\nu}{16\pi M_W^4} \frac{[1 - (m_\mu^2 - m_e^2)/2m_e E_\nu]^2}{(1 + 2m_e E_\nu/M_W^2)}$$

$$\lim_{E_\nu \to \infty} \sigma(\nu_\mu e \to \mu\nu_e) = \frac{g^4}{32\pi M_W^2} = \frac{G_F^2 M_W^2}{\sqrt{2}}$$

no asymptotic growth with energy!

Partial-wave unitarity respected for

$$s < M_W^2[\exp(\pi\sqrt{2}/G_F M_W^2) - 1]$$

Problem 8

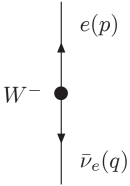
(a) Write the cross section given on the preceding page for $\sigma(\nu_\mu e \to \mu\nu_e)$ in terms of G_F, rather than g.
(b) Now put aside the threshold factor that results from the muon–electron mass difference. Plot the cross section for 1 GeV $\leq E_\nu \leq$ 10 TeV. Also plot the point-coupling expression over the same range.
(c) At what value of E_ν does the W-boson propagator begin to have a perceptible effect on the cross section?
(d) How well would you have to determine the cross section to derive a useful estimate of M_W?

A. Aktas, *et al.* (H1 Collaboration), *Phys. Lett. B* **632**, 35 (2006);
Z. Zhang, *Nucl. Phys. Proc. Suppl.* **191**, 271 (2009).

W-boson properties

No prediction yet for M_W (haven't determined g)

Leptonic decay $W^- \to e^- \nu_e$



$$p \approx \left(\frac{M_W}{2}; \frac{M_W \sin\theta}{2}, 0, \frac{M_W \cos\theta}{2} \right)$$

$$q \approx \left(\frac{M_W}{2}; -\frac{M_W \sin\theta}{2}, 0, -\frac{M_W \cos\theta}{2} \right)$$

$$\mathcal{M} = -i \left(\frac{G_F M_W^2}{\sqrt{2}} \right)^{\frac{1}{2}} \bar{u}(e,p)\gamma_\mu(1-\gamma_5)v(\nu,q)\,\varepsilon^\mu$$

$\varepsilon^\mu = (0;\hat{\varepsilon})$: W polarization vector in its rest frame

$$\begin{aligned} |\mathcal{M}|^2 &= \frac{G_F M_W^2}{\sqrt{2}} \mathrm{tr}\left[\not{\varepsilon}(1-\gamma_5)\not{q}(1+\gamma_5)\not{\varepsilon}^*\not{p}\right] ; \\ \mathrm{tr}[\cdots] &= \left[\varepsilon \cdot q\, \varepsilon^* \cdot p - \varepsilon \cdot \varepsilon^*\, q \cdot p + \varepsilon \cdot p\, \varepsilon^* \cdot q + i\epsilon_{\mu\nu\rho\sigma}\varepsilon^\mu q^\nu \varepsilon^{*\rho} p^\sigma\right] \end{aligned}$$

$$\mathrm{tr}[\cdots] = [\varepsilon \cdot q\, \varepsilon^* \cdot p - \varepsilon \cdot \varepsilon^*\, q \cdot p + \varepsilon \cdot p\, \varepsilon^* \cdot q + i\epsilon_{\mu\nu\rho\sigma}\varepsilon^\mu q^\nu \varepsilon^{*\rho} p^\sigma]$$

decay rate is independent of W polarization; look first at longitudinal pol. $\varepsilon^\mu = (0; 0, 0, 1) = \varepsilon^{*\mu}$, eliminate $\epsilon_{\mu\nu\rho\sigma}$

$$|\mathcal{M}|^2 = \frac{4G_F M_W^4}{\sqrt{2}} \sin^2\theta$$

$$\frac{d\Gamma_0}{d\Omega} = \frac{|\mathcal{M}|^2}{64\pi^2} \frac{\mathcal{S}_{12}}{M_W^3}$$

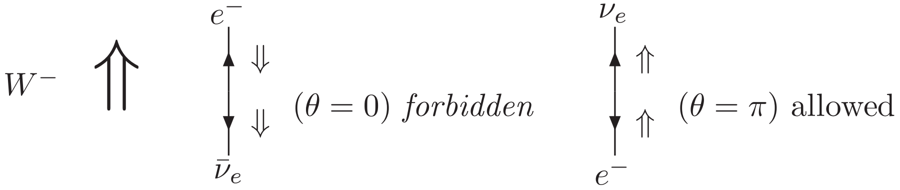
$$\mathcal{S}_{12} = \sqrt{[M_W^2 - (m_e + m_\nu)^2][M_W^2 - (m_e - m_\nu)^2]} = M_W^2$$

$$\frac{d\Gamma_0}{d\Omega} = \frac{G_F M_W^3}{16\pi^2\sqrt{2}} \sin^2\theta \qquad \boxed{\Gamma(W \to e\nu) = \frac{G_F M_W^3}{6\pi\sqrt{2}}}$$

Other helicities: $\varepsilon^{\mu}_{\pm 1} = (0; -1, \mp i, 0)/\sqrt{2}$

$$\frac{d\Gamma_{\pm 1}}{d\Omega} = \frac{G_F M_W^3}{32\pi^2\sqrt{2}}(1 \mp \cos\theta)^2$$

Extinctions at $\cos\theta = \pm 1$ are consequences of angular momentum conservation:



(situation reversed for $W^+ \to e^+\nu_e$)

e^+ follows polarization direction of W^+

e^- avoids polarization direction of W^-

important for discovery of $W^\pm$ in $\bar{p}p$ ($\bar{q}q$) C violation

UA1 $W \to e\nu$ decay angular distribution