PHYSICS 489/1489

LECTURE 13: PARITY VIOLATION AND THE WEAK INTERACTION

GRADING

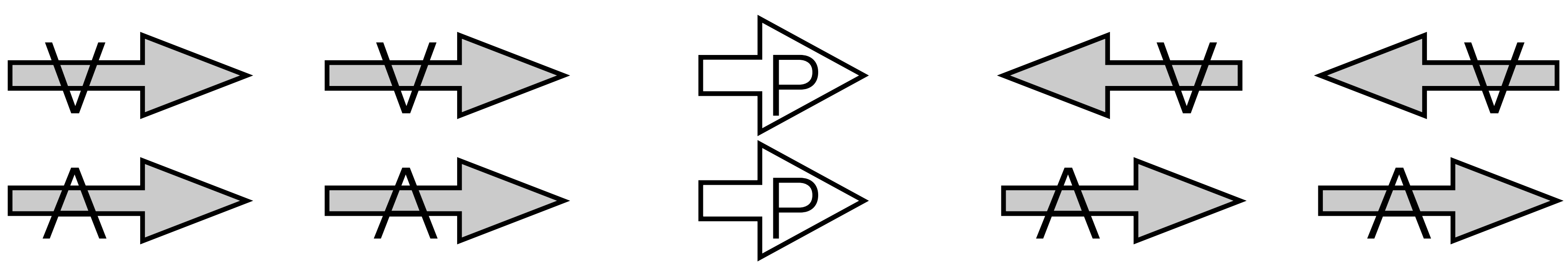
- Propose to replace midterm grade with final grade if final grade > midterm grade
  - i.e. in this case, final becomes 60% of your grade
  - if final < midterm, original 20%/40% split.
- Is that okay?
- Final Exam:
  - 1900-2200 on 18 December (Monday) in UC273

THE WEAK INTERACTION:

- Gauge theory:
  - the electromagnetic, weak, and strong interactions can be formulated as gauge theories
  - the weak interaction (and electromagnetism) have three very peculiar twists
- Parity violation
  - Weak interactions violate parity symmetry
  - (talk about today)
- Quark (and lepton)mixing
  - quarks can transition between "generations" (flavors are mixtures of mass states)
  - next week
- Electroweak mixing
  - weak, electromagnetic interactions are actually (orthogonal) mixtures of two gauge theories
  - (maybe next week)
- Spontaneous symmetry breaking
  - the weak gauge bosons (W, Z) are massive . .. .
  - we need a back door to giving these particles mass (a few weeks from now)

PARITY

- The operation by which we reverse spatial coordinates: **x** → -**x**
- Consider a vector **V**: parity reverses it to -**V**
  - P(**V**) = -**V**
- The "axial" or "pseudo"vector:
  - consider **c**= **a** x **b**, where **a**, **b** are vectors
  - P(**c**) = P(**a** x **b**) = -**a** x -**b** = **a** x **b** = **c**
- Parity symmetry can be preserved if quantities are constructed entirely as vectors or as axial vectors



- consider:

$$\vec{F} = m\vec{a} \qquad \vec{L} = \vec{r} \times \vec{p}$$

PARITY EIGENSTATES

- If a state is an eigenvector of the parity operator:

$$P|A\rangle = p|A\rangle$$

  - where p is the eigenvalue. If we apply P again, we have:

$$P(P|A\rangle) = P(p|A\rangle) = pP|A\rangle = p^2|A\rangle$$

    - applying P twice brings us back to the initial state, so

$$PP = P^2 = I \qquad p = \pm 1$$

- The parity eigenvalue is conserved if parity is a symmetry of the system (e.g. . [H, P]= 0)

PARITY OF A BOUND STATE

- A bound state (e.g. meson = quark + antiquark) has two components that determine its parity
  - "intrinsic" parity of the constituent particle
    - quarks/leptons have intrinsic parity 1, antiquarks/antileptons -1
  - parity due to the wave function of the bound state
    - $(-1)^l$ where l is the orbital momentum

$$Y_0^0(\theta,\varphi) = \frac{1}{2}\sqrt{\frac{1}{\pi}}$$

$$Y_1^0(\theta,\varphi) = \frac{1}{2}\sqrt{\frac{3}{\pi}}\cos\theta$$

$$Y_1^1(\theta,\varphi) = \frac{-1}{2}\sqrt{\frac{3}{2\pi}}\sin\theta\, e^{i\varphi}$$

$$Y_2^{-2}(\theta,\varphi) = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\sin^2\theta\, e^{-2i\varphi}$$

$$Y_2^{-1}(\theta,\varphi) = \frac{1}{2}\sqrt{\frac{15}{2\pi}}\sin\theta\,\cos\theta\, e^{-i\varphi}$$

$$Y_2^{1}(\theta,\varphi) = \frac{-1}{2}\sqrt{\frac{15}{2\pi}}\sin\theta\,\cos\theta\, e^{i\varphi}$$

$$Y_2^{0}(\theta,\varphi) = \frac{1}{4}\sqrt{\frac{5}{\pi}}(3\cos^2\theta - 1)$$

$$Y_2^{2}(\theta,\varphi) = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\sin^2\theta\, e^{2i\varphi}$$

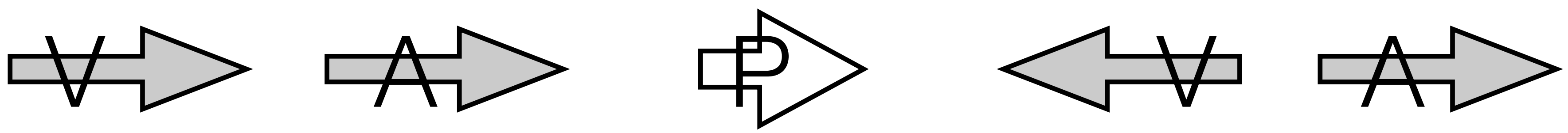
  - Total parity is the product of the two
    - parity eigenvalue is unchanged by an interaction if it conserves parity

EXAMPLES

- Pion: quark + antiquark in s = 0, l = 0 state:
  - $P = 1 \times -1 \times (-1)^0 = -1$
- ρ: quark, anti-quark in s=1, l = 0 state
  - $P = 1 \times -1 \times (-1)^0 = -1$
- Two pions in l = 0 state
  - $P = -1 \times -1 \times (-1)^0 = 1$
- Two pions in l =1 state
  - $P = -1 \times -1 \times (-1)^1 = -1$
- Decay of ρ: since s (and J=l+s) = 1, we must have l =1 in final state
  - two pions is OK: $P = -1 \times -1 \times (-1)^1 = -1$
  - three pions violates parity: $-1 \times -1 \times -1 \times (-1)^1 = +1$

MXING VECTORS + PSEUDOVECTORS

- geometrically obvious that something has changed



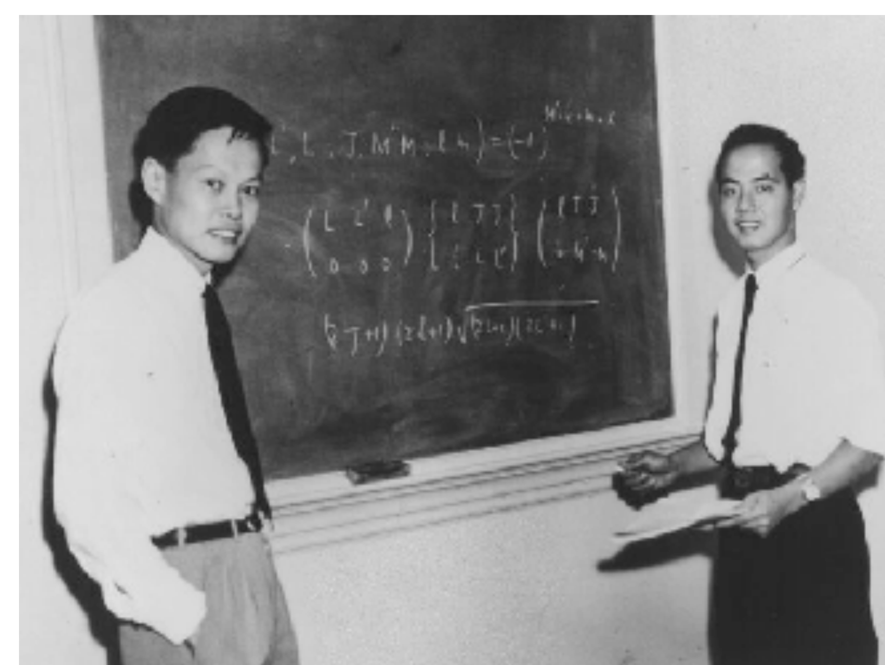
  - two things that were pointing in the same direction are now pointing in opposite directions
- One can formalize this by considering a dot vector:
  - $P(\mathbf{V} \cdot \mathbf{A}) = -\mathbf{V} \cdot \mathbf{A} \neq \mathbf{V} \cdot \mathbf{A}$
- or add a vector and pseudovector (axial-vector)
  - $P(|\mathbf{V}+\mathbf{A}|) = |-\mathbf{V}+\mathbf{A}| \neq |\mathbf{V}+\mathbf{A}|$
- Parity is violated by an observable/interaction that:
  - correlates a vector and a pseudovector
  - is the sum of a vector and a pseudovector

"θ/τ" PUZZLE

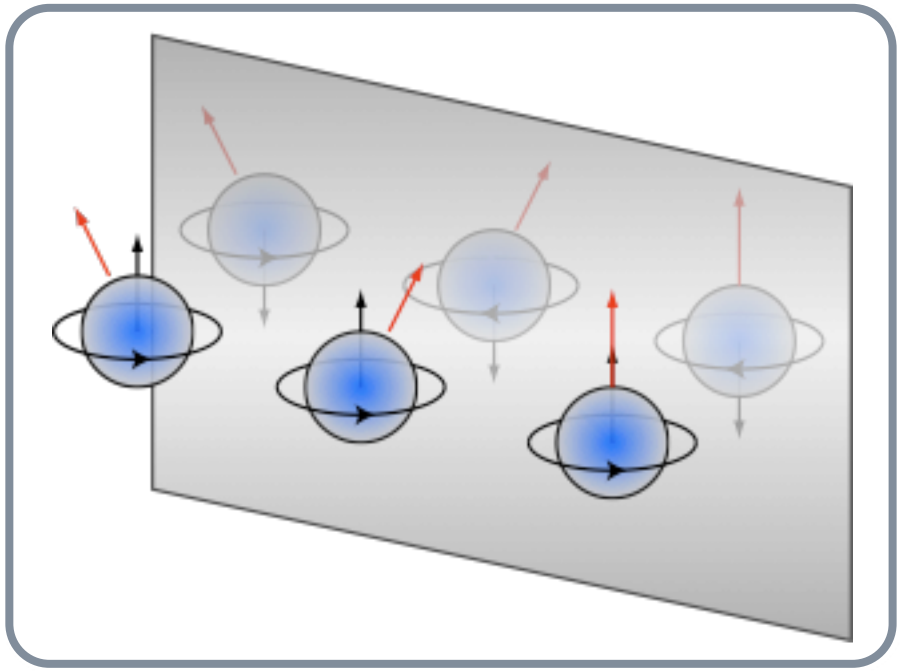
- Imagine two particles identical in every way, but decay to different parity eigenstates:

$$
\begin{aligned}
\theta^+ &\rightarrow \pi^+ + \pi^0 && (P = (-1)^2 = 1) \\
\tau^+ &\rightarrow \pi^+ + \pi^0 + \pi^0 && (P = (-1)^3 = -1) \\
&\rightarrow \pi^+ + \pi^+ + \pi^- && (P = (-1)^3 = -1)
\end{aligned}
$$

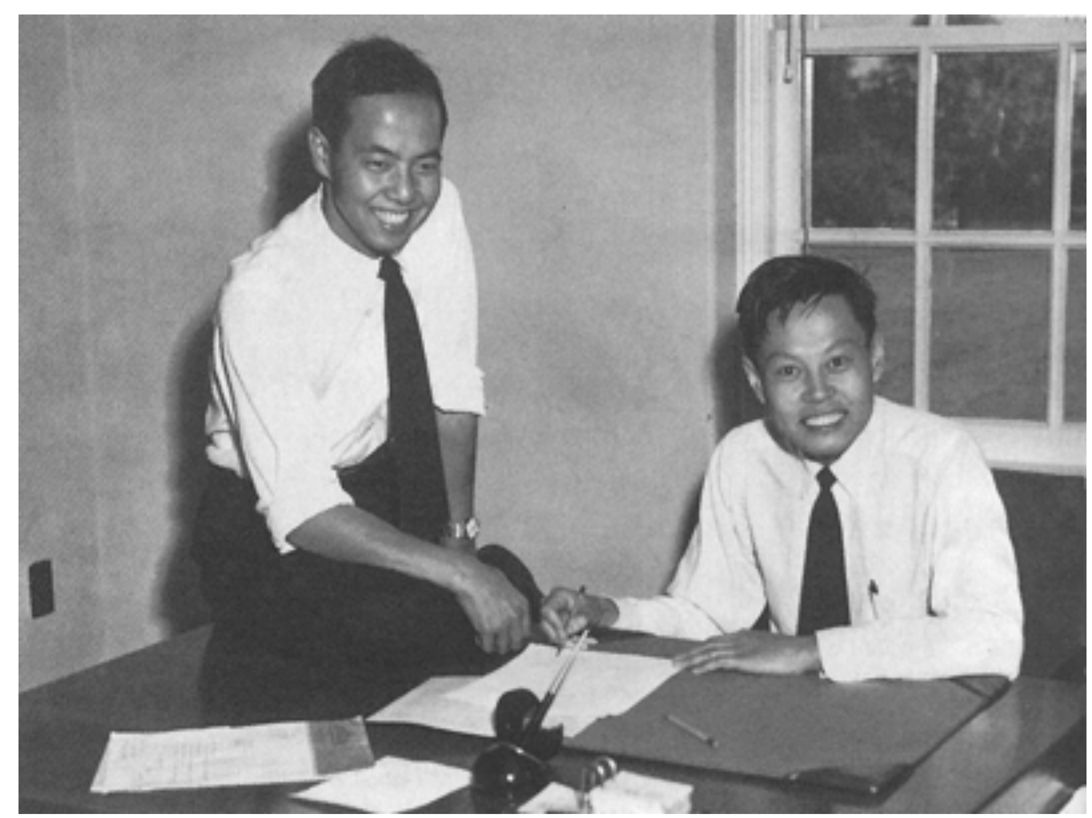
- Coincidence that two such particles exist?
- T. D. Lee, C. N. Yang:
  - θ/τ are the same particle
  - parity not conserved in weak decays



DEMONSTRATION OF PARITY VIOLATION

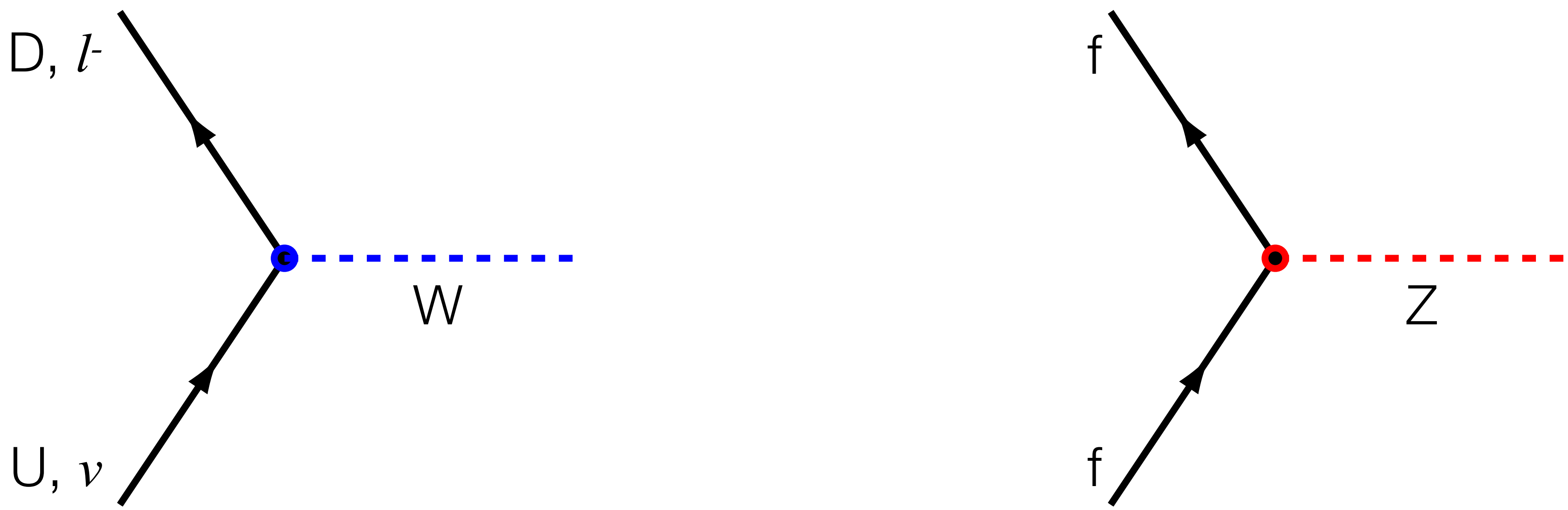


- β decay in polarized ^{60}Co
  - cool ^{60}Co atoms to polarize them
    - magnetic moment/spin become aligned
    - angular momentum is a pseudo vector
    - momentum of positron is a vector
  - Correlation would demonstrate parity violation
  - N.B. left shows “mirror” transformation
    - parity transformation + rotation by 180 degrees



WEAK INTERACTIONS

- Fundamental vertices

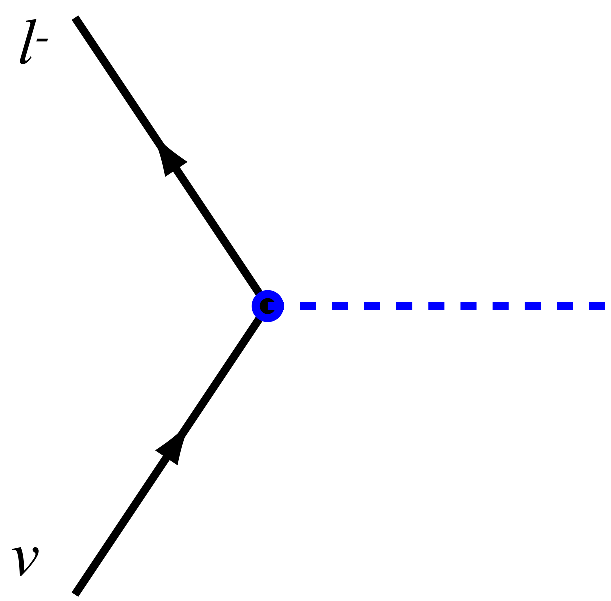


- Weak charged current:
  - couples charged lepton (e, μ, τ) into its corresponding neutrino (ν_e, ν_μ, ν_τ)
  - change a "down"-type quake (d, s, b) into an up-type quark (u,c,t)
- Weak neutral current:
  - particle identity does not change
  - same particle in and out

THE WEAK CHARGED CURRENT

- Feynman rules:

Vertex Factor for Leptons:



$$\frac{-ig_w}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)$$

W propagator

$$\frac{-i(g_{\mu\nu}-q_\mu q_\nu/M_W^2c^2)}{q^2-M_W^2c^2}$$

WEAK VS. QED

$\bar{\psi}\psi$	scalar
$\bar{\psi}\gamma^5\psi$	pseudoscalar
$\bar{\psi}\gamma^\mu\psi$	vector
$\bar{\psi}\gamma^\mu\gamma^5\psi$	pseudovector
$\bar{\psi}\sigma^{\mu\nu}\psi$	antisymmetric tensor

QED vertex

$$-ig_e\gamma^\mu$$

photon propagator

$$\frac{-ig_{\mu\nu}}{q^2}$$

Weak CC vertex

$$\frac{-ig_w}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)$$

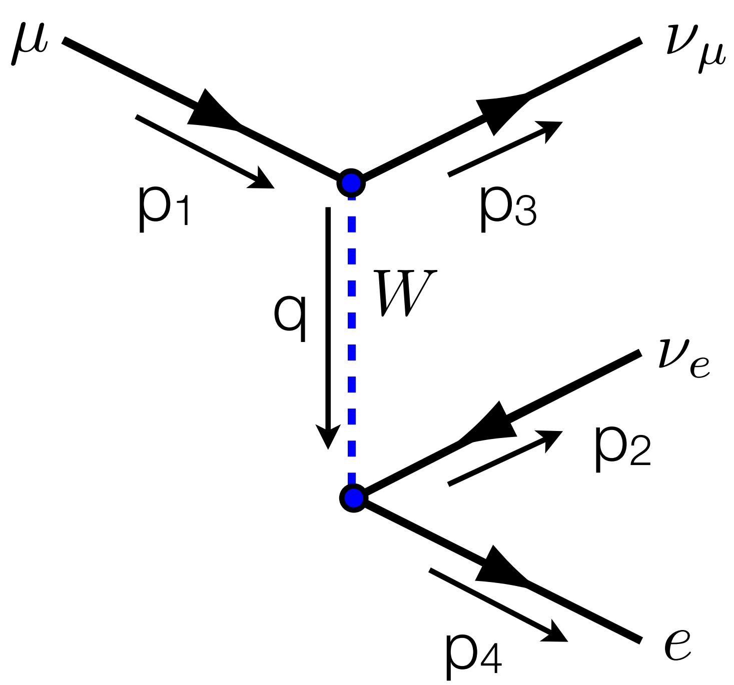
W propagator

$$\frac{-i(g_{\mu\nu}-q_\mu q_\nu/M_W^2c^2)}{q^2-M_W^2c^2}$$

- Vertex:
  - coupling constant
  - γ^μ vs. γ^μ-$\gamma^\mu\gamma^5$
  - charge: W carries one unit
- Propagator
  - massive particle (3 polarizations)
  - at low energies: q << M_Wc^2

$$\frac{-i(g_{\mu\nu}-q_\mu q_\nu/M_W^2c^2)}{q^2-M_W^2c^2} \Rightarrow \frac{ig_{\mu\nu}}{M_W^2c^2}$$

EXAMPLE: MUON DECAY:



- upper fermion leg

$$[\bar{u}_3 \frac{-ig_w}{2\sqrt{2}} \gamma^\mu (1-\gamma^5) u_1] \quad (2\pi)^4 \delta(p_1 - q - p_3)$$

- lower fermion leg

$$[\bar{u}_4 \frac{-ig_w}{2\sqrt{2}} \gamma^\mu (1-\gamma^5) v_2] \quad (2\pi)^4 \delta(q - p_2 - p_4)$$

- Propagator

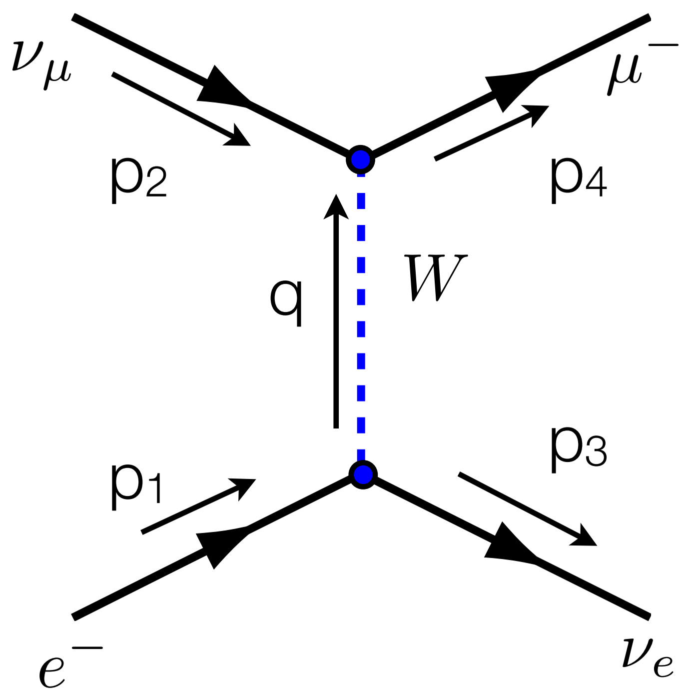
$$\int \frac{1}{(2\pi)^4} d^4 q \quad \frac{ig_{\mu\nu}}{M_W^2 c^2}$$

$$\frac{-ig_W^2}{8M_W^2 c^2} \left[\bar{u}_3 \gamma^\mu (1-\gamma^5) u_1\right] \left[\bar{u}_4 \gamma_\mu (1-\gamma^5) v_2\right] \times (2\pi)^4 \delta(p_1 - p_2 - p_3 - p_4)$$

$$\frac{g_W^2}{8M_W^2 c^2} \left[\bar{u}_3 \gamma^\mu (1-\gamma^5) u_1\right] \left[\bar{u}_4 \gamma_\mu (1-\gamma^5) v_2\right]$$

INVERSE MUON DECAY:

$$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$$



- upper fermion leg

$$\left[\bar{u}_4 \frac{-ig_W}{2\sqrt{2}} \gamma^\nu (1-\gamma^5) u_2\right] (2\pi)^4 \delta^4(p_2 + q - p_4)$$

- lower fermion leg

$$\left[\bar{u}_3 \frac{-ig_W}{2\sqrt{2}} \gamma^\mu (1-\gamma^5) u_1\right] (2\pi)^4 \delta^4(p_1 - q - p_3)$$

- Propagator

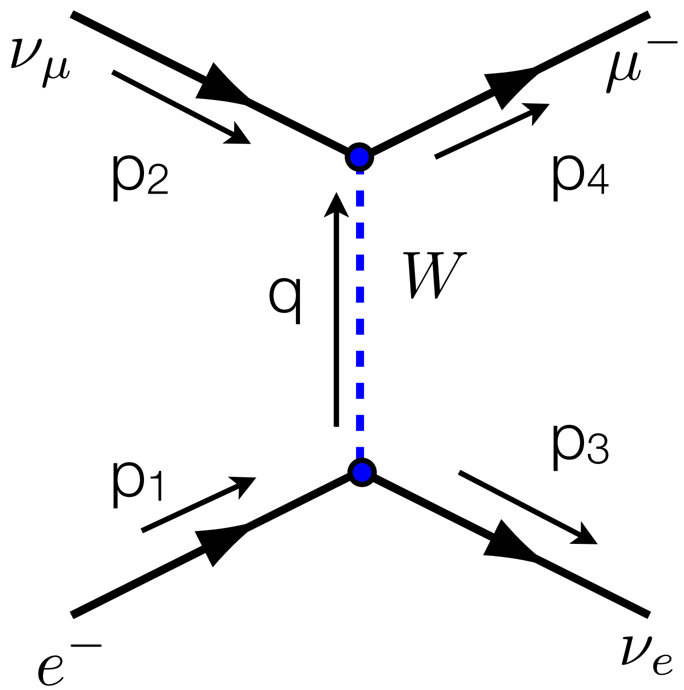
$$\int \frac{1}{(2\pi)^4} d^4q \quad \frac{ig_{\mu\nu}}{M_W^2 c^2}$$

$$\frac{-ig_W^2}{8M_W^2 c^2} \left[\bar{u}_3 \gamma^\mu (1-\gamma^5) u_1\right] \left[\bar{u}_4 \gamma_\mu (1-\gamma^5) u_2\right] \times (2\pi)^4 \delta(p_1 + p_2 - p_3 - p_4)$$

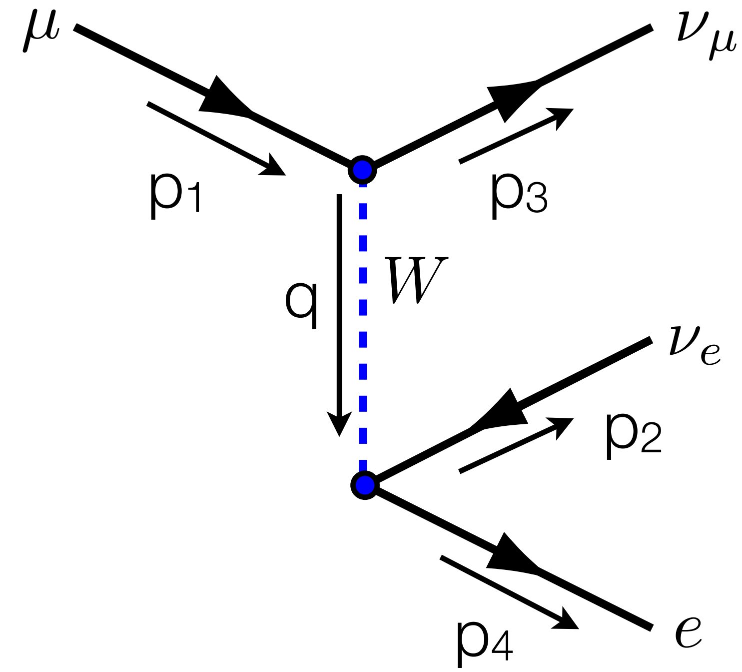
$$\mathcal{M} = \frac{g_W^2}{8M_W^2 c^2} \left[\bar{u}_3 \gamma^\mu (1-\gamma^5) u_1\right] \left[\bar{u}_4 \gamma_\mu (1-\gamma^5) u_2\right]$$

COMPARISON

$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$



$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$

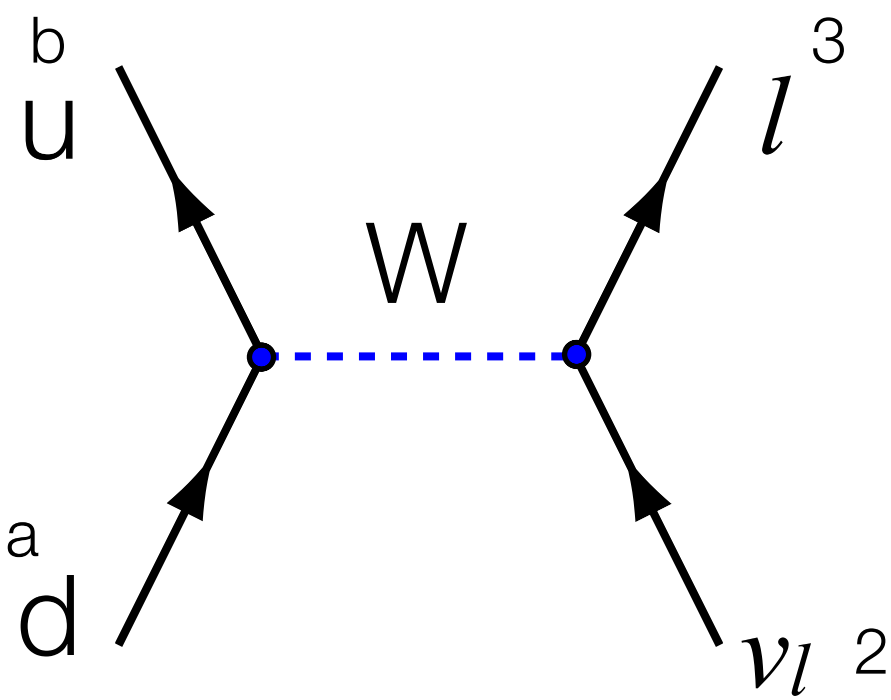


$$\mathcal{M} = \frac{g_W^2}{8M_W^2c^2}\left[\bar{u}_3\gamma^\mu(1-\gamma^5)u_1\right]\left[\bar{u}_4\gamma_\mu(1-\gamma^5)u_2\right]$$

$$\frac{g_W^2}{8M_W^2c^2}\left[\bar{u}_3\gamma^\mu(1-\gamma^5)u_1\right]\left[\bar{u}_4\gamma_\mu(1-\gamma^5)v_2\right]$$

- The similarity is not a coincidence

EXAMPLE: PION DECAY



- Lepton fermion leg

$$[\bar{u}_3 \frac{-ig_w}{2\sqrt{2}} \gamma^\mu (1-\gamma^5) v_2]$$

- Quark Fermion leg

$$[\bar{v}_b \frac{-ig_w}{2\sqrt{2}} \gamma^\nu (1-\gamma^5) u_a]$$

$$[\bar{v}_b \frac{-ig_w}{2\sqrt{2}} \gamma^\nu (1-\gamma^5) u_a] \Rightarrow F^\nu = f_\pi p^\nu$$

- Propagator

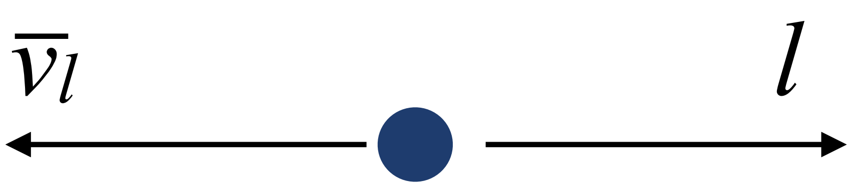
$$\int \frac{1}{(2\pi)^4} d^4 q \qquad \frac{ig_{\mu\nu}}{M_W^2 c^2}$$

$$\mathcal{M} = \frac{g_W^2}{8 M_W^2 c^2} \left[\bar{u}_3 \gamma^\mu (1-\gamma^5) v_2\right] f_\pi p_\mu$$

CARRYING OUT THE CALCULATION

$$\mathcal{M} = \frac{g_W^2}{8M_W^2c^2}\left[\bar{u}_3\gamma^\mu(1-\gamma^5)v_2\right] f_\pi p_\mu$$

$$\bar{u}_3\gamma^\mu(1-\gamma^5)v_2$$



- As before, we consider the various helicity combinations . . .
  - assume decay occurs along the z-axis
- but some interesting things happen

$$1-\gamma^5 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} - \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ -1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 \end{pmatrix}$$

$$v_{\uparrow 2} = \sqrt{E}\begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix} \qquad v_{\downarrow 2} = \sqrt{E}\begin{pmatrix} 0 \\ -1 \\ 0 \\ -1 \end{pmatrix}$$

THE LEPTON (ASIDE)

$$u_{\uparrow 3} = \sqrt{E+m}\begin{pmatrix} 1 \\ 0 \\ \frac{p}{E+m} \\ 0 \end{pmatrix} \qquad \bar{u}_{\uparrow 3} = \sqrt{E+m}\begin{pmatrix} 1, & 0, & \frac{p}{E+m}, & 0 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} = \sqrt{E+m}\begin{pmatrix} 1, & 0, & -\frac{p}{E+m}, & 0 \end{pmatrix}$$

$$u_{\downarrow 3} = \sqrt{E+m}\begin{pmatrix} 0 \\ 1 \\ 0 \\ -\frac{p}{E+m} \end{pmatrix} \qquad \bar{u}_{\downarrow 3} = \sqrt{E+m}\begin{pmatrix} 0, & 1, & 0 & -\frac{p}{E+m} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} = \sqrt{E+m}\begin{pmatrix} 0, & 1, & 0 & \frac{p}{E+m} \end{pmatrix}$$

$$\bar{u}_3\gamma^\mu(1-\gamma^5)v_2 \longrightarrow \bar{u}_3(1+\gamma^5)\gamma^\mu v_2$$

$$1+\gamma^5 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{pmatrix}$$

$$\bar{u}_{\uparrow 3}(1+\gamma^5) = \sqrt{E+m}\begin{pmatrix} 1-\frac{p}{E+M}, & 0, & 1-\frac{p}{E+M}, & 0 \end{pmatrix}$$

$$\bar{u}_{\downarrow 3}(1+\gamma^5) = \sqrt{E+m}\begin{pmatrix} 0, & 1+\frac{p}{E+M} & 0, & 1+\frac{p}{E+M} \end{pmatrix}$$

BACK TO MATRIX ELEMENT

$$\mathcal{M} = \frac{g_W^2}{8M_W^2c^2}\left[\bar{u}_3\gamma^\mu(1-\gamma^5)v_2\right] f_\pi p_\mu$$

$$u_{\uparrow 3} = \sqrt{E+m}\begin{pmatrix} 1 \\ 0 \\ \frac{p}{E+m} \\ 0 \end{pmatrix}$$

- if pion is at rest, only p_0 matters$(= m_\pi)$
  - ignore $\mu \neq 0$
  - $\bar{u}\,\gamma^\mu = u^\dagger\gamma^0\gamma^\mu \rightarrow u^\dagger$

$$u_{\downarrow 3} = \sqrt{E+m}\begin{pmatrix} 0 \\ 1 \\ 0 \\ -\frac{p}{E+m} \end{pmatrix}$$

- we only need to consider $v_{\uparrow 2}$

$$u^\dagger_{\uparrow 3} = \sqrt{E_3+m_3}\begin{pmatrix} 1, & 0, & \frac{p}{E_3+m_3}, & 0 \end{pmatrix}$$

$$u^\dagger_{\downarrow 3} = \sqrt{E_3+m_3}\begin{pmatrix} 0, & 1, & 0, & -\frac{p}{E_3+m_3} \end{pmatrix}$$

$$(1-\gamma^5)v_{\uparrow 2} = 2\sqrt{E_2}\begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix}$$

$$\bar{u}_3\gamma^\mu(1-\gamma^5)f_\pi p_0 \rightarrow 2\sqrt{E_2}\sqrt{E_3+m_3}\left(1-\frac{p}{E_3+m_3}\right)f_\pi m_\pi$$

$$\mathcal{M} = \frac{g_W^2}{4M_W^2}f_\pi m_\pi\sqrt{E_2(E_3+m_3)}\left(1-\frac{p}{E_3+m_3}\right)$$

SOME KINEMATICS

$$\mathcal{M} = \frac{g_W^2}{4M_W^2} f_\pi m_\pi \sqrt{E_2(E_3 + m_3)} \left(1 - \frac{p}{E_3 + m_3}\right)$$

$$E_3 = \frac{m_\pi^2 + m_\ell^2}{2m_\pi}$$

$$p_2 = E_2 = \frac{m_\pi^2 - m_\ell^2}{2m_\pi} = p_3$$

$$\mathcal{M} = \frac{g_W^2}{4M_W^2} f_\pi m_\pi \sqrt{\frac{m_\pi^2 - m_\ell^2}{2m_\pi} \frac{m_\pi^2 + m_\ell^2 + 2m_\pi m_\ell}{2m_\pi}} \left(\frac{2m_\pi}{m_\pi^2 + m_\ell^2 + 2m_\pi m_\ell}\right) \left(\frac{m_\pi^2 + m_\ell^2 + 2m_\pi m_\ell - m_\pi^2 + m_\ell^2}{2m_\pi}\right)$$

$$\frac{1}{2m_\pi}(m_\pi + m_\ell)\sqrt{m_\pi^2 - m_\ell^2}$$

$$2 \times \frac{m_\ell^2 + m_\pi m_\ell}{(m_\pi + m_\ell)^2}$$

$$\frac{m_\ell}{m_\pi}\sqrt{m_\pi^2 - m_\ell^2}$$

$$\mathcal{M} = \frac{g_W^2}{4M_W^2} f_\pi m_\ell \sqrt{m_\pi^2 - m_\ell^2}$$

DECAY RATE

$$\mathcal{M} = \frac{g_W^2}{4M_W^2} f_\pi m_\ell \sqrt{m_\pi^2 - m_\ell^2}$$

$$p_2 = E_2 = \frac{m_\pi^2 - m_\ell^2}{2m_\pi} = p_3$$

$$\Gamma = \frac{|\mathbf{p}^*|}{32\pi^2 M^2} \int |\mathcal{M}|^2 \, d\Omega = \frac{|\mathbf{p}^*|}{8\pi m_\pi^2} |\mathcal{M}|^2$$

$$= \frac{g_W^4}{8\pi m_\pi^2 \times 16 m_W^4} f_\pi^2 m_\ell^2 (m_\pi^2 - m_\ell^2) \frac{m_\pi^2 - m_\ell^2}{2m_\pi}$$

$$= \frac{g_W^4}{256\pi m_\pi^3 m_W^4} f_\pi^2 m_\ell^2 (m_\pi^2 - m_\ell^2)^2$$

RATIOS:

- Consider the two decays:
  - $\pi^- \rightarrow e^- + \bar{\nu}_e$
  - $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

$$\Gamma = \frac{g_W^4}{256 M_W^4 m_\pi^3} f_\pi^2 m_3^2 (m_\pi^2 - m_3^2)^2$$

$$\frac{\Gamma_e}{\Gamma_\mu} = \frac{m_e^2 (m_\pi^2 - m_e^2)^2}{m_\mu^2 (m_\pi^2 - m_\mu^2)^2}$$

- Using the masses
  - m_π = 139.57 MeV
  - m_μ = 105.65 MeV
  - m_e = 0.511 MeV

$$\frac{\Gamma_e}{\Gamma_\mu} = 1.28 \times 10^{-4}$$

PIENU

$$\frac{\Gamma_e}{\Gamma_\mu} = 1.2344 \pm 0.0023(\mathrm{stat}) \pm 0.0019(\mathrm{syst.}) \times 10^{-4}$$

Improved Measurement of the $\pi \to e\nu$ Branching Ratio

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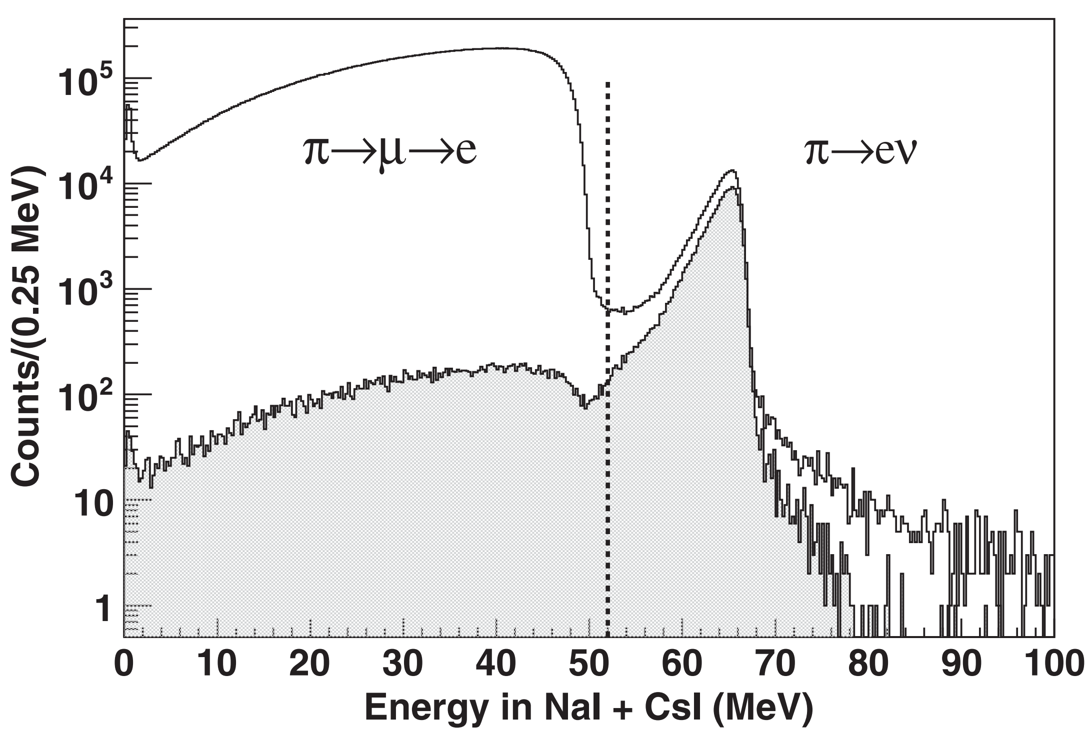
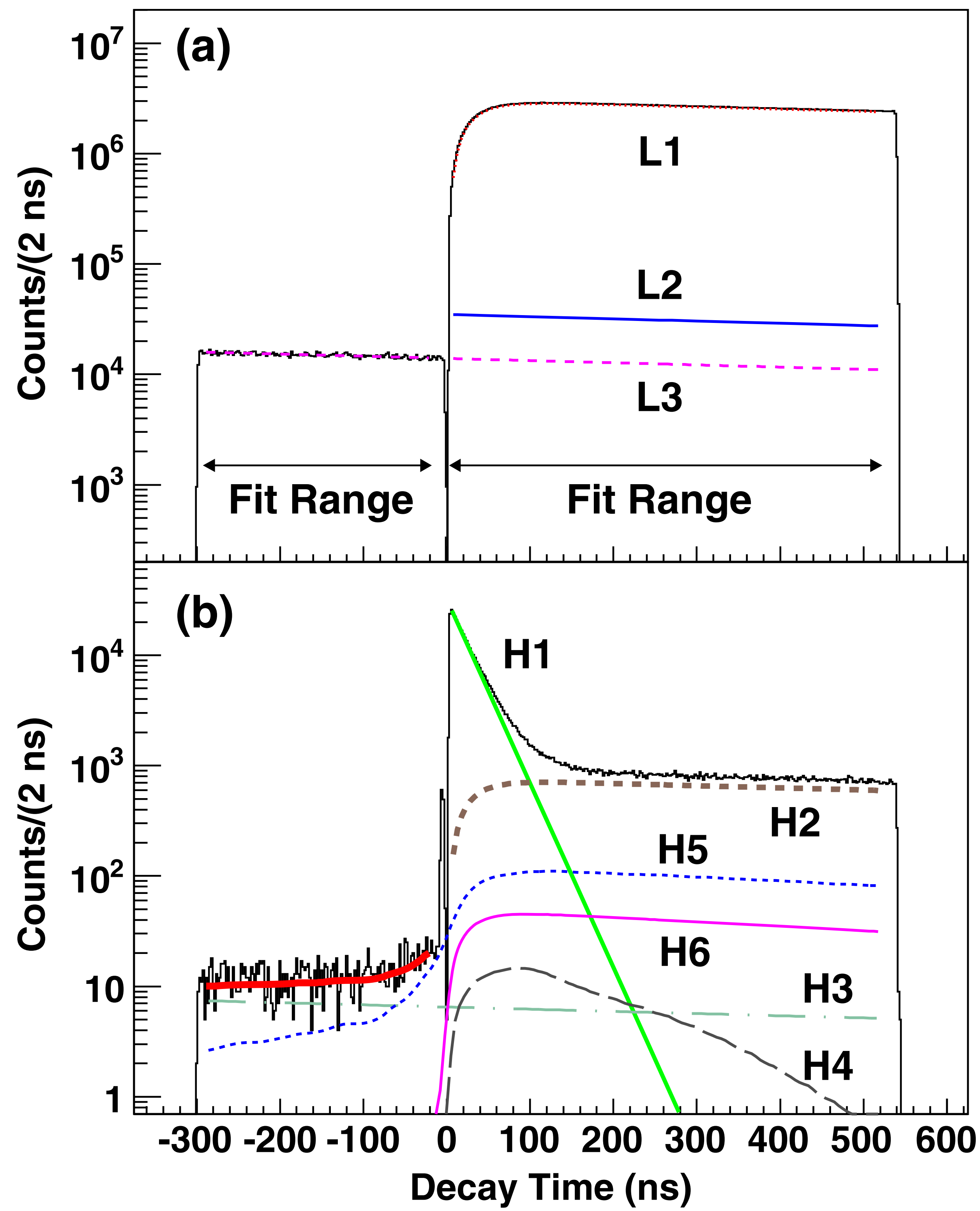
A new measurement of the branching ratio $R_{e/\mu} = \Gamma(\pi^+ \to e^+\nu + \pi^+ \to e^+\nu\gamma)/\Gamma(\pi^+ \to \mu^+\nu + \pi^+ \to \mu^+\nu\gamma)$ resulted in $R^{\mathrm{exp}}_{e/\mu} = [1.2344 \pm 0.0023(\mathrm{stat}) \pm 0.0019(\mathrm{syst})] \times 10^{-4}$. This is in agreement with the standard model prediction and improves the test of electron-muon universality to the level of 0.1%.





NEXT TIME

- Please read chapter 12.1,2