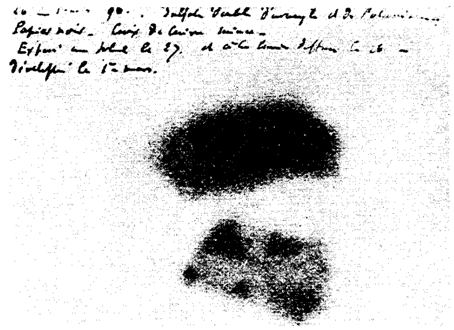
Antecedents of EW Theory

Commins & Bucksbaum, *Weak Int^{ns} of Leptons & Quarks*

1896: Becquerel radioactivity



Several varieties, including β decay

$$^{A}\mathrm{Z} \rightarrow \ ^{A}(\mathrm{Z}+1) + \beta^{-}$$

Examples:

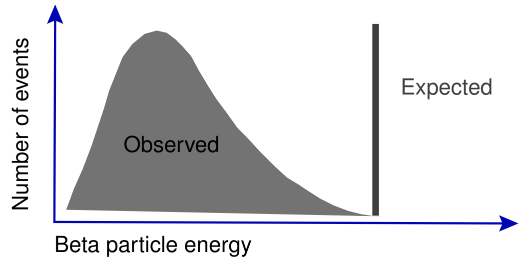
$$^{3}\mathrm{H}_{1} \rightarrow \ ^{3}\mathrm{He}_{2} + \beta^{-} \ ,$$

$$n \rightarrow p + \beta^{-} \ ,$$

$$^{214}\mathrm{Pb}_{82} \rightarrow \ ^{214}\mathrm{Bi}_{83} + \beta^{-} \ .$$

β^{+}-emitters, $^{A}\mathrm{Z} \rightarrow \ ^{A}(\mathrm{Z}-1) + \beta^{+}$, are rare among naturally occurring isotopes. Radio-phosphorus produced 1934 by the Joliot-Curie, *after* positron discovery in cosmic rays. $^{19}\mathrm{Ne} \rightarrow \ ^{19}\mathrm{F} + \beta^{+}$ studied for right-handed charged currents and time reversal invariance; *positron-emission tomography*

1914: Chadwick β spectrum



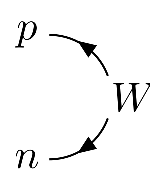
Energy conservation in question

1930: Pauli $\approx$ massless, neutral, penetrating particle

nuclear spin & statistics

$\hookrightarrow$ neutrino ν

β decay first hint for flavor



charged-current, flavor-changing interactions

1932: Chadwick neutron

$\hookrightarrow$ isospin symmetry

1956: Cowan, Reines, . . . neutrino observation

Science **124,** 103 (1956)

Aside on β beams . . .

Possibility to create interesting few-GeV neutrino beams by storing radioactive ions.

P. Zucchelli, hep-ex/0107006

$\bar{\nu}_e$: ${}^{6}\mathrm{He}^{++} \rightarrow {}^{6}\mathrm{Li}^{+++}\ e^{-}\bar{\nu}_e$

ν_e: ${}^{18}\mathrm{Ne}^{10+} \rightarrow {}^{18}\mathrm{F}^{9+}\ e^{+}\nu_e$

Electron capture for monochromatic neutrino beams: hep-ph/0505054

ν_e: ${}^{148}\mathrm{Dy}\ \mathrm{EC} \rightarrow {}^{148}\mathrm{Tb}\ \nu_e$

Neutron & flavor symmetry

$$M(n) = 939.565\,63 \pm 0.000\,28 \text{ MeV}/c^2$$
$$M(p) = 938.272\,31 \pm 0.000\,28 \text{ MeV}/c^2$$
$$\Delta M = 1.293318 \pm 0.000\,009 \text{ MeV}/c^2$$

$$\boxed{\Delta M/M \approx 1.4 \times 10^{-3}}$$

Charge-independent nuclear forces?

$$^3\mathrm{H}(pnn) = 8.481\,855 \pm 0.000\,013 \text{ MeV}$$
$$^3\mathrm{He}(ppn) = 7.718\,109 \pm 0.000\,013 \text{ MeV}$$
$$\Delta(\mathrm{B.E.}) = 0.763\,46 \text{ MeV}$$

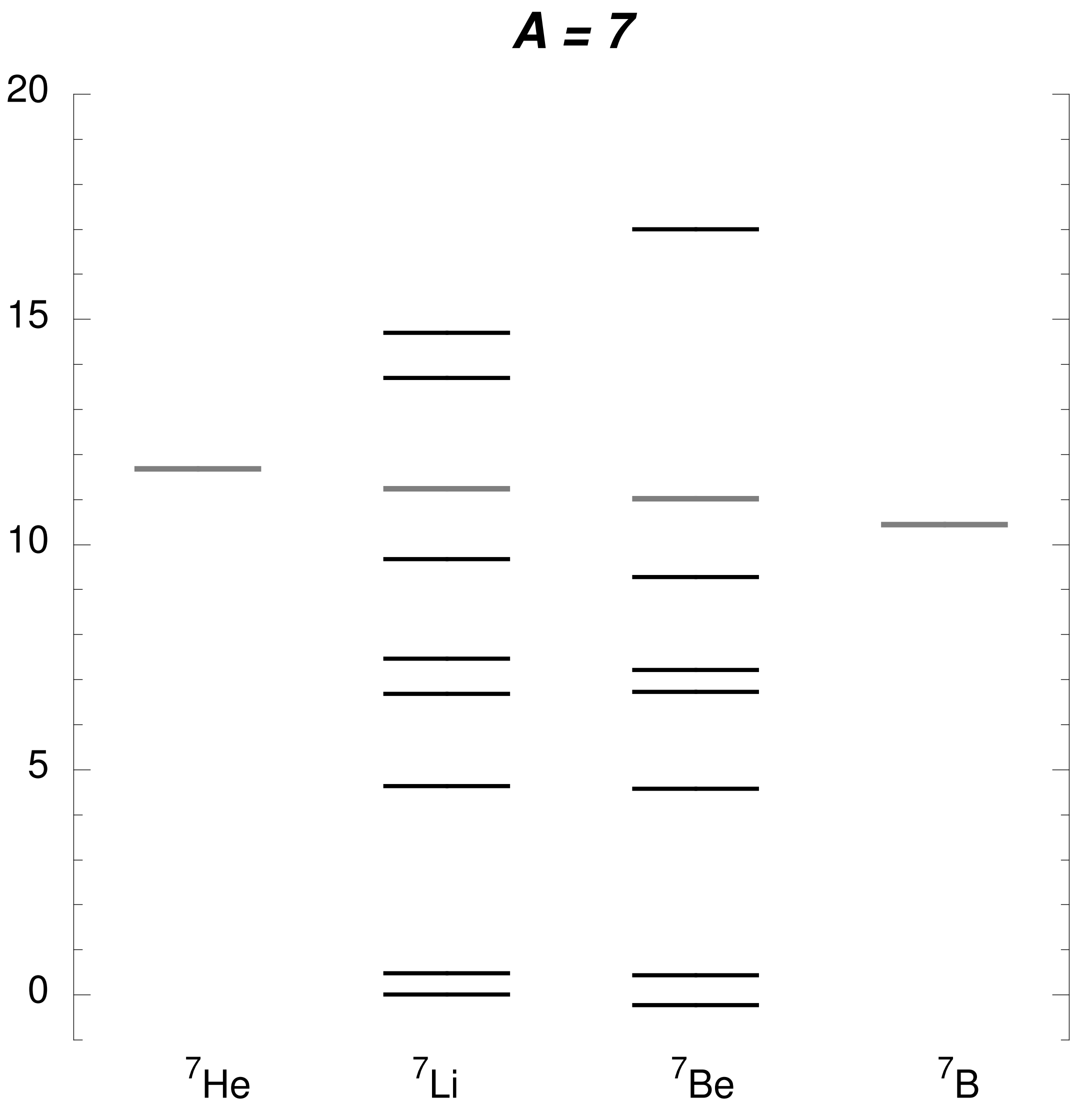
^{3}He charge radius $r = 1.97 \pm 0.015$ fm

$$\boxed{\text{Coulomb energy: } \alpha/r \approx 0.731 \text{ MeV}}$$

Level structures in mirror nuclei. 1

$I_3 = -\frac{1}{2}$: $^7\mathrm{Li}(3p + 4n)$ $\quad$ $^7\mathrm{Be}(4p + 3n)$: $I_3 = \frac{1}{2}$

$I_3 = -\frac{3}{2}$: $^7\mathrm{He}(2p + 3n)$ $\quad$ $^7\mathrm{B}(5p + 2n)$: $I_3 = \frac{3}{2}$



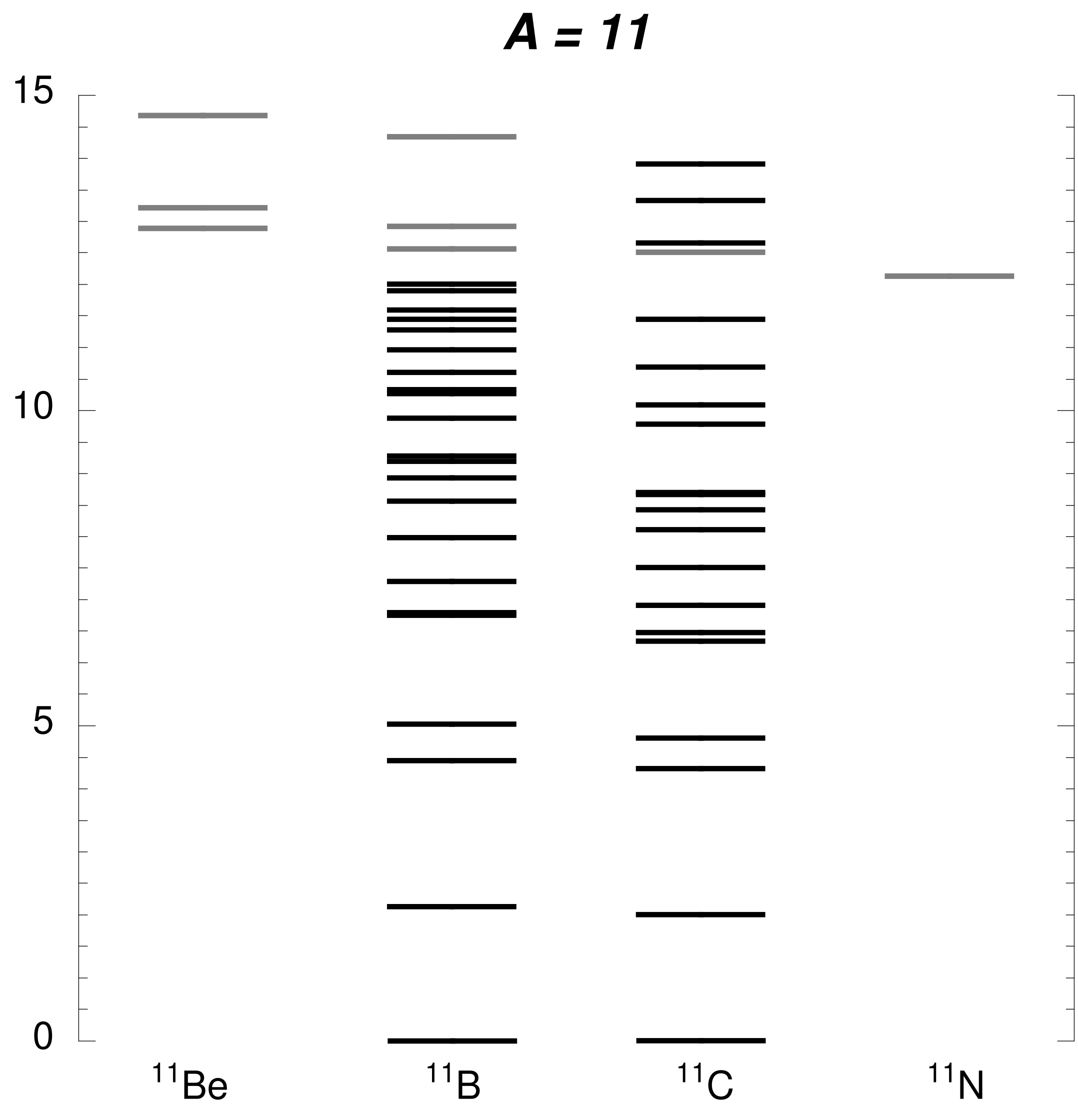
n - p mass difference, Coulomb energy removed

(isobaric analogue states)

Level structures in mirror nuclei. 2

$I_3 = -\frac{1}{2}$: $^{11}\mathrm{B}(5p + 6n)$ $^{11}\mathrm{C}(6p + 5n)$: $I_3 = \frac{1}{2}$

$I_3 = -\frac{3}{2}$: $^{11}\mathrm{Be}(4p + 7n)$ $^{11}\mathrm{N}(7p + 4n)$: $I_3 = \frac{3}{2}$

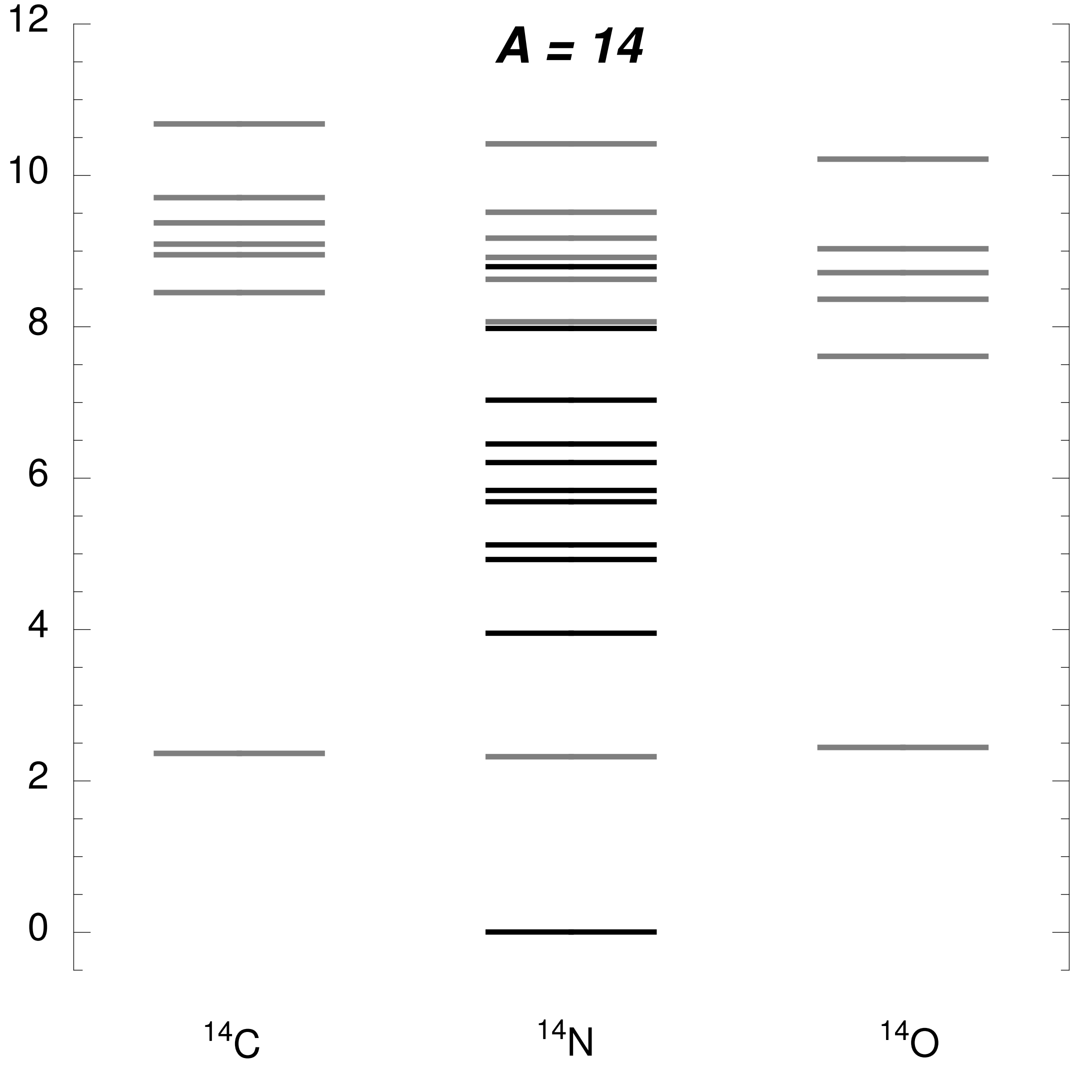


$^{11}\mathrm{Li}(3p + 8n)$ ground state $(34.4$ MeV$)$ $I = \frac{5}{2}$ isobaric analogue

Level structures in mirror nuclei. 3

$A = 14$: NN outside closed core

$$
\begin{array}{lll}
{}^{14}\mathrm{O}: & {}^{12}\mathrm{C} + (pp) & I_3 = +1 \\
{}^{14}\mathrm{N}: & {}^{12}\mathrm{C} + (pn) & I_3 = 0 \\
{}^{14}\mathrm{C}: & {}^{12}\mathrm{C} + (nn) & I_3 = -1
\end{array}
$$



The first flavor symmetry

isospin invariance $\begin{pmatrix} p \\ n \end{pmatrix}$ isospin rotations

In the absence of EM, *convention* determines which (combination) is up

Aside: *Without EM,* how would we know there are two species of nucleons?

Parity violation in weak decays

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

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

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

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

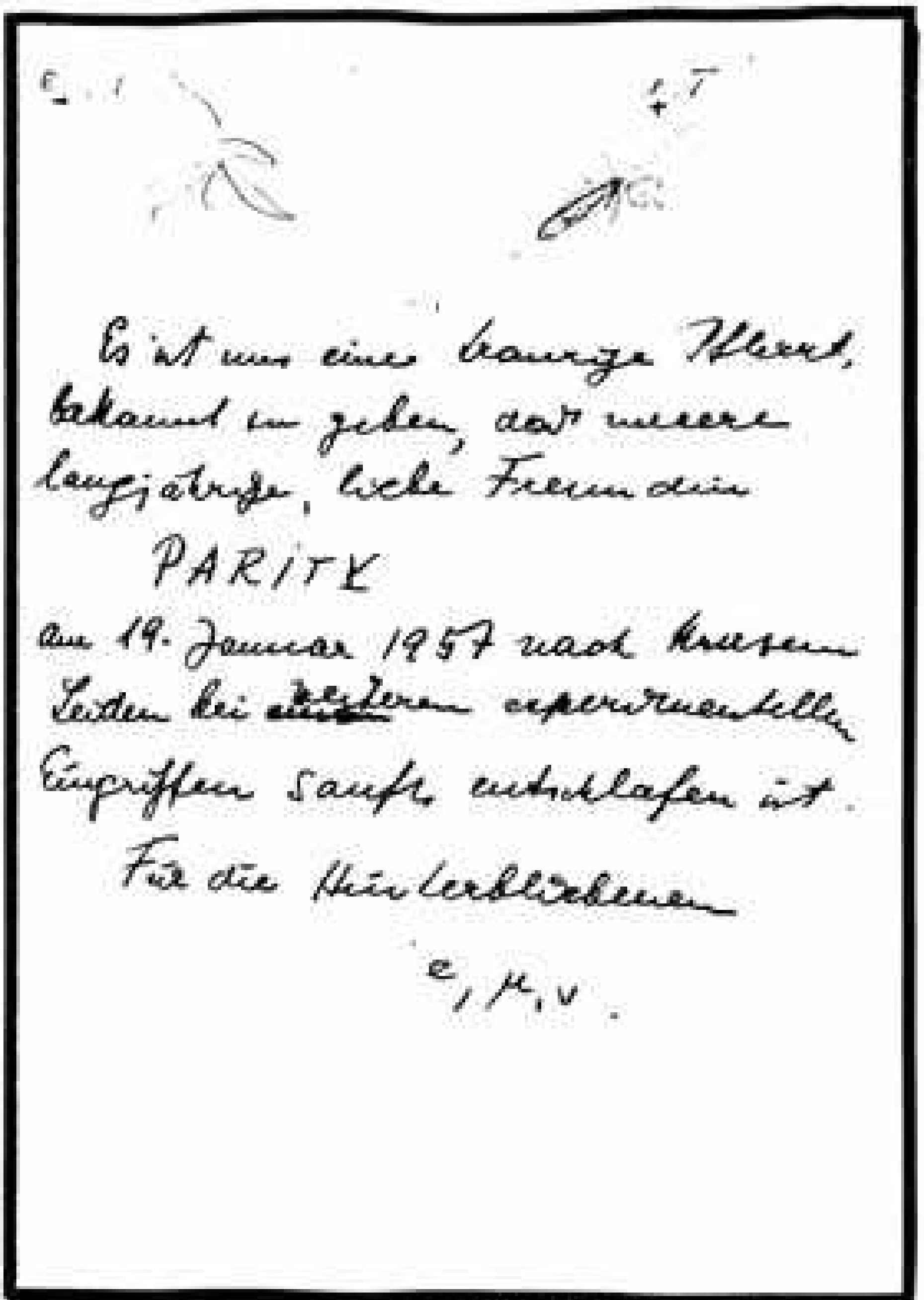
Experiments in late 1950s established that
(charged-current) weak interactions are left-handed

Parity links left-handed, right-handed neutrinos,

$$\nu_L \xrightarrow{\Lleftarrow} \mathcal{P} \xleftarrow{\Lleftarrow} \not\!\nu_R$$

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

Pauli's Reaction to the Downfall of Parity



Es ist uns eine traurige Pflicht, bekannt zu geben, daß unsere langjährige, liebe Freundin

PARITY

am 19. Januar 1957 nach kurzem Leiden bei weiteren experimentellen Eingriffen sanft entschlafen ist.

Für die Hinterbliebenen

e, μ, ν.

Pauli's Reaction to the Downfall of Parity

Es ist uns eine traurige Pflicht, bekannt zu geben, daß unsere langjährige ewige Freundin

PARITY

den 19. Januar 1957 nach kurzen Leiden bei weiteren experimentellen Eingriffen sanfte entschlafen ist.

Für die hinterbliebenen

$e \quad \mu \quad \nu$

It is our sad duty to announce that our loyal friend of many years

PARITY

went peacefully to her eternal rest on the nineteenth of January 1957, after a short period of suffering in the face of further experimental interventions.

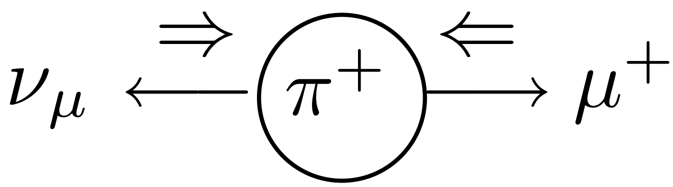
For those who survive her,

$e \quad \mu \quad \nu$

Pauli's assertiveness training . . .

How do we know ν is LH?

▷ Measure μ^+ helicity in (spin-zero) $\pi^+ \to \mu^+\nu_\mu$



$$h(\nu_\mu) = h(\mu^+)$$

Bardon, *Phys. Rev. Lett.* **7**, 23 (1961)

Possoz, *Phys. Lett.* **70B**, 265 (1977)

μ^+ forced to have "wrong" helicity

...inhibits decay, and inhibits $\pi^+ \to e^+\nu_e$ more

$$\Gamma(\pi^+ \to e^+\nu_e)/\Gamma(\pi^+ \to \mu^+\nu_\mu) = 1.23 \times 10^{-4}$$

▷ Measure longitudinal polarization of recoil nucleus in $\mu^{-12}\mathrm{C}(J=0) \to {}^{12}\mathrm{B}(J=1)\nu_\mu$

Infer $h(\nu_\mu)$ by angular momentum conservation

Roesch, *Am. J. Phys.* **50**, 931 (1981)

▷ Measure longitundinal polarization of recoil nucleus in

$$e^- \ {}^{152}\mathrm{Eu}^m(J=0) \quad \rightarrow \quad {}^{152}\mathrm{Sm}^*(J=1)\,\nu_e$$
$$\hookrightarrow \gamma\ {}^{152}\mathrm{Sm}$$

Infer $h(\nu_e)$ from γ polarization

Goldhaber, *Phys. Rev.* **109**, 1015 (1958)

Charge conjugation is also violated . . .

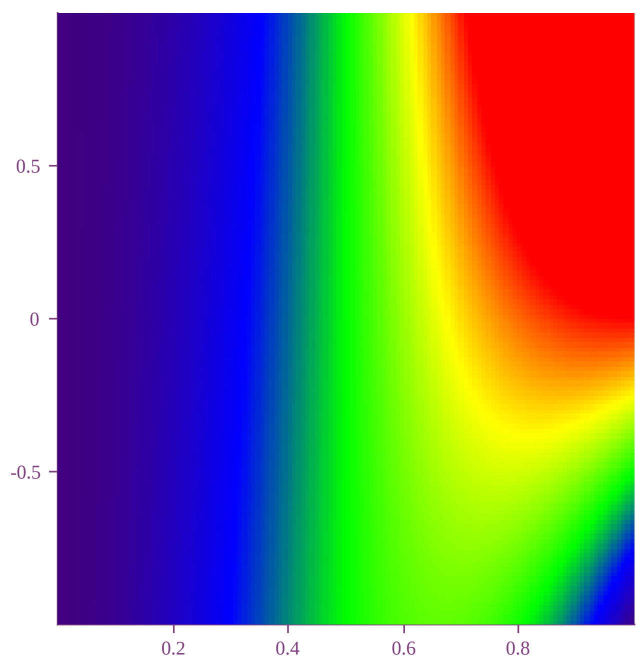
$$\nu_L \overset{\Leftarrow}{\longrightarrow} \mathcal{C} \overset{\Leftarrow}{\longrightarrow} \not{\bar{\nu}}_L$$

$\mu^{\pm}$ decay: angular distributions of $e^{\pm}$ reversed

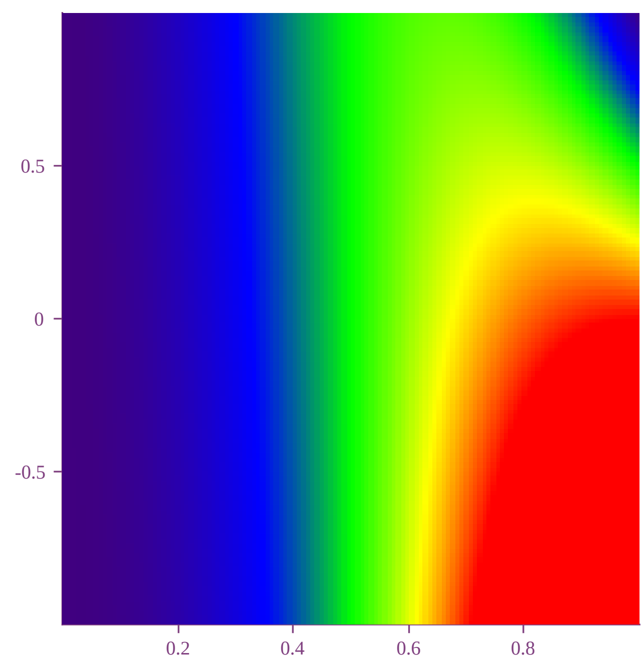
$$\frac{dN(\mu^{\pm} \to e^{\pm} + \ldots)}{dx d\Omega} = \frac{x^2}{2\pi}\left[(3 - 2x) \pm (2x - 1)z\right]$$

$$x \equiv p_e/p_e^{\max},\; z \equiv \hat{s}_\mu \cdot \hat{p}_e$$

e^{+} follows μ^{+} spin



e^{-} avoids μ^{-} spin



Commins & Bucksbaum, pp. 92–98

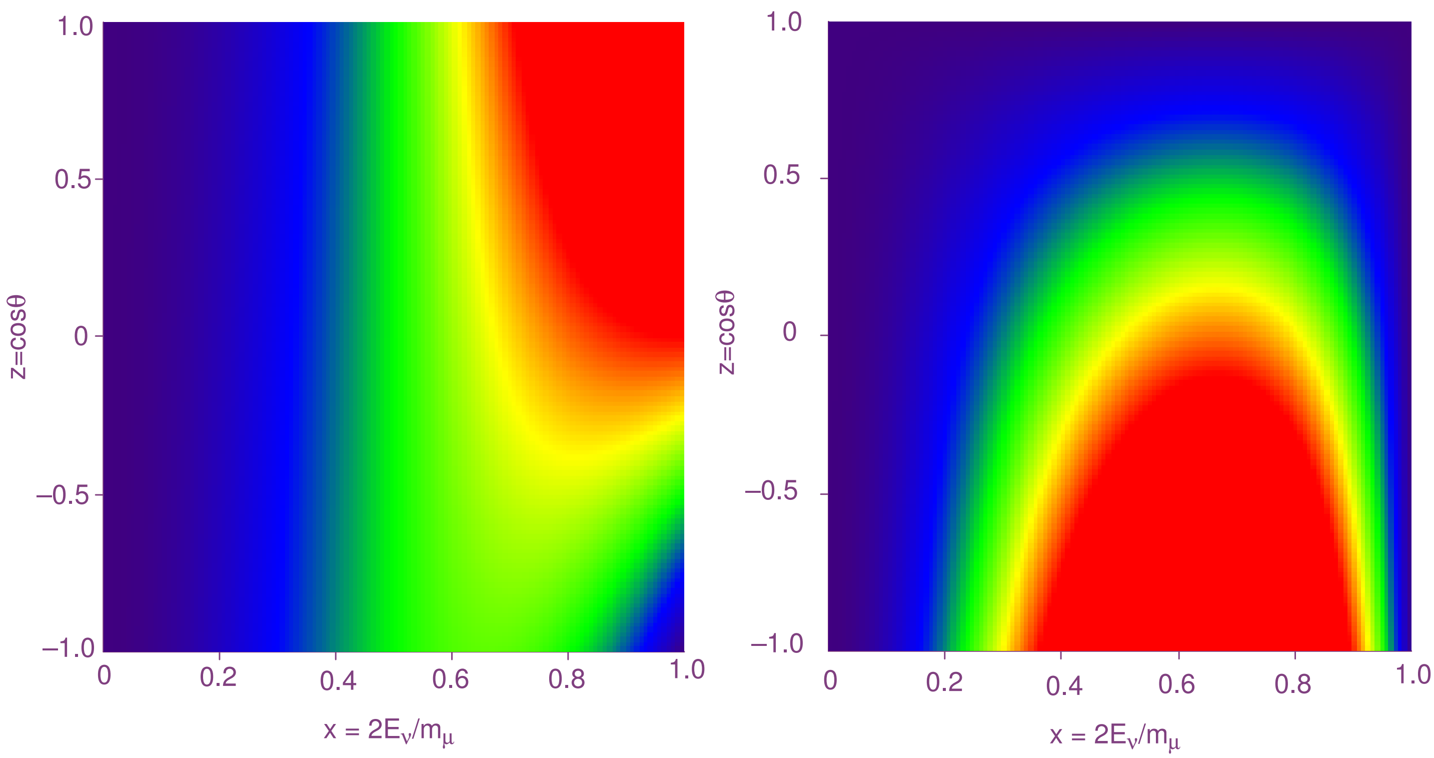
Neutrino factory?

$$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$$

$$\frac{d^2 N_{\bar{\nu}_\mu}}{dx d\Omega} = \frac{x^2}{2\pi}[(3-2x)+(2x-1)z]$$

$$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$$

$$\frac{d^2 N_{\nu_e}}{dx d\Omega} = \frac{3x^2}{\pi}[(1-x)-(1-x)z]$$



$x = 2E_\nu / E_\mu$: neutrino energy

$\hat{s}_\mu$: muon's spin direction $z \equiv \cos\theta = \hat{p}_\nu \cdot \hat{s}_\mu$

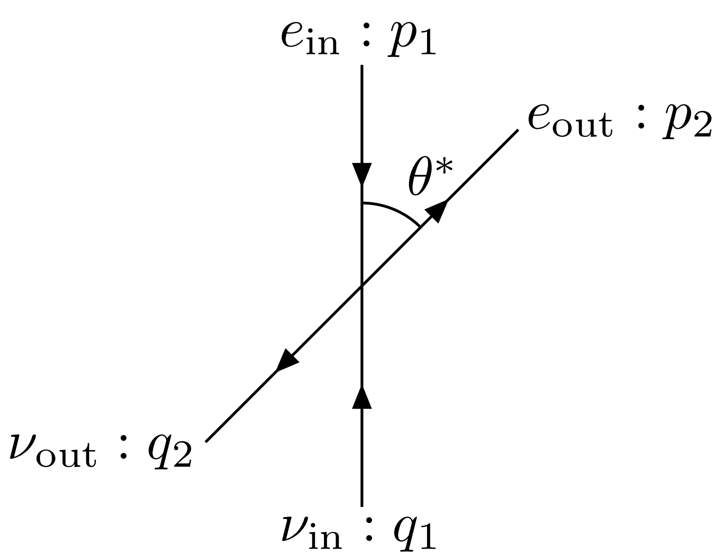
Effective Lagrangian . . .

Late 1950s: current-current interaction

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

$$G_F = 1.16632 \times 10^{-5} \text{ GeV}^{-2}$$

Compute $\bar{\nu}e$ scattering amplitude:



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

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

$$\begin{aligned}
|\mathcal{M}|^2 &= \frac{G_F^2}{2}\mathrm{tr}[\gamma_\mu(1-\gamma_5)(m+\not{p}_1)(1+\gamma_5)\gamma_\nu\not{q}_1] \\
&\quad \times\mathrm{tr}[\gamma^\mu(1-\gamma_5)\not{q}_2(1+\gamma_5)\gamma^\nu(m+\not{p}_2)] \\
&\equiv \frac{G_F^2}{2}A_{\mu\nu}B^{\mu\nu}
\end{aligned}$$

$$\begin{aligned}
A_{\mu\nu} &= 2\mathrm{tr}[(1+\gamma_5)\gamma_\nu\not{q}_1\gamma_\mu(m+\not{p}_1)] \\
&= 8(q_{1\nu}p_{1\mu} - g_{\mu\nu}q_1 \cdot p_1 + q_{1\mu}p_{1\nu}) - 8i\varepsilon_{\mu\nu\rho\sigma}q_1^\rho p_1^\sigma
\end{aligned}$$

$$B^{\mu\nu} = 8(q_2^\nu p_2^\mu - g^{\mu\nu}q_2 \cdot p_2 + q_2^\mu p_2^\mu) - 8i\varepsilon^{\mu\nu\kappa\lambda}q_{2\kappa}p_{2\lambda}$$

Using $\varepsilon_{\mu\nu\rho\sigma}\varepsilon^{\mu\nu\kappa\lambda} = -2(\delta_\kappa^\rho\delta_\lambda^\sigma - \delta_\lambda^\rho\delta_\kappa^\sigma)\ \ldots$

$$|\mathcal{M}|^2 = 256 q_1 \cdot p_1\ q_2 \cdot p_2$$

$\bar{\nu} e \longrightarrow \quad \bar{\nu} e$

$$\frac{d\sigma_{V-A}(\bar{\nu} e \to \bar{\nu} e)}{d\Omega_{\text{cm}}} = \frac{\overline{|\mathcal{M}|^2}}{64\pi^2 s} = \frac{G_F^2 \cdot 2mE_\nu (1-z)^2}{16\pi^2}$$

$z = \cos\theta^*$

$$\sigma_{V-A}(\bar{\nu} e \to \bar{\nu} e) = \frac{G_F^2 \cdot 2mE_\nu}{3\pi}$$

$$\approx 0.574 \times 10^{-41} \text{ cm}^2 \left(\frac{E_\nu}{1 \text{ GeV}} \right)$$

Small! $\approx 10^{-14}$ $\sigma(pp)$ at 100 GeV

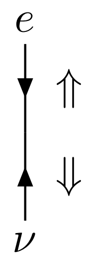
$\nu e \longrightarrow \quad \nu e$

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

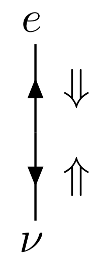
$$\sigma_{V-A}(\nu e \to \nu e) = \frac{G_F^2 \cdot 2mE_\nu}{\pi}$$

$$\approx 1.72 \times 10^{-41} \text{ cm}^2 \left(\frac{E_\nu}{1 \text{ GeV}} \right)$$

Why $3\times$ difference?

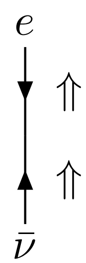
incoming 

$J_z = 0$

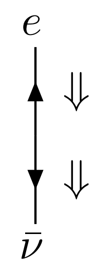
outgoing, $z = +1$ 

$J_z = 0$

allowed at all angles

incoming 

$J_z = +1$

outgoing, $z = +1$ 

$J_z = -1$

forbidden (angular momentum) at $z = +1$

1962: Lederman, Schwartz, Steinberger $\nu_\mu \neq \nu_e$

- ▷ Make HE $\pi \to \mu\nu$ beam
- ▷ Observe $\nu N \to \mu +$ anything
- ▷ Don't observe $\nu N \to e +$ anything

Danby, *et al.*, *Phys. Rev. Lett.* **9**, 36 (1962)

Suggests family structure

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L$$

≈ no interactions known to cross boundaries

Generalize effective (current-current) Lagrangian:

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

Compute muon decay rate

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

accounts for the 2.2-μs muon lifetime

TESTS OF NUMBER CONSERVATION LAWS

LEPTON FAMILY NUMBER

Lepton family number conservation means separate conservation of each of L_e, L_μ, L_τ.

$\Gamma(Z \to e^{\pm}\mu^{\mp})/\Gamma_{total}$	[i]	$<1.7 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to e^{\pm}\tau^{\mp})/\Gamma_{total}$	[i]	$<9.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to \mu^{\pm}\tau^{\mp})/\Gamma_{total}$	[i]	$<1.2 \times 10^{-5}$, CL = 95%
limit on $\mu^- \to e^-$ conversion		
$\sigma(\mu^- \, {}^{32}S \to e^- \, {}^{32}S)$ / $\sigma(\mu^- \, {}^{32}S \to \nu_\mu \, {}^{32}P^*)$		$<7 \times 10^{-11}$, CL = 90%
$\sigma(\mu^- \text{Ti} \to e^- \text{Ti})$ / $\sigma(\mu^- \text{Ti} \to \text{capture})$		$<4.3 \times 10^{-12}$, CL = 90%
$\sigma(\mu^- \text{Pb} \to e^- \text{Pb})$ / $\sigma(\mu^- \text{Pb} \to \text{capture})$		$<4.6 \times 10^{-11}$, CL = 90%
limit on muonium $\to$ antimuonium conversion $R_g = G_C / G_F$		<0.0030, CL = 90%
$\Gamma(\mu^- \to e^- \nu_e \overline{\nu}_\mu)/\Gamma_{total}$	[j]	$<1.2 \times 10^{-2}$, CL = 90%
$\Gamma(\mu^- \to e^- \gamma)/\Gamma_{total}$		$<1.2 \times 10^{-11}$, CL = 90%
$\Gamma(\mu^- \to e^- e^+ e^-)/\Gamma_{total}$		$<1.0 \times 10^{-12}$, CL = 90%
$\Gamma(\mu^- \to e^- 2\gamma)/\Gamma_{total}$		$<7.2 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \to e^- \gamma)/\Gamma_{total}$		$<2.7 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \gamma)/\Gamma_{total}$		$<1.1 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \pi^0)/\Gamma_{total}$		$<3.7 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \pi^0)/\Gamma_{total}$		$<4.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- K^0_S)/\Gamma_{total}$		$<9.1 \times 10^{-7}$, CL = 90%
$\Gamma(\tau^- \to \mu^- K^0_S)/\Gamma_{total}$		$<9.5 \times 10^{-7}$, CL = 90%
$\Gamma(\tau^- \to e^- \eta)/\Gamma_{total}$		$<8.2 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \eta)/\Gamma_{total}$		$<9.6 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \rho^0)/\Gamma_{total}$		$<2.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \rho^0)/\Gamma_{total}$		$<6.3 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- K^*(892)^0)/\Gamma_{total}$		$<5.1 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- K^*(892)^0)/\Gamma_{total}$		$<7.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \overline{K}^*(892)^0)/\Gamma_{total}$		$<7.4 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \overline{K}^*(892)^0)/\Gamma_{total}$		$<7.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \phi)/\Gamma_{total}$		$<6.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \phi)/\Gamma_{total}$		$<7.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- e^+ e^-)/\Gamma_{total}$		$<2.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \mu^+ \mu^-)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 90%

TOTAL LEPTON NUMBER

Violation of total lepton number conservation also implies violation of lepton family number conservation.

$\Gamma(Z \to pe)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to p\mu)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 95%
limit on $\mu^- \to e^+$ conversion		
$\sigma(\mu^- {}^{32}S \to e^+ {}^{32}Si^*)$ / $\sigma(\mu^- {}^{32}S \to \nu_\mu {}^{32}P^*)$		$<9 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- {}^{127}I \to e^+ {}^{127}Sb^*)$ / $\sigma(\mu^- {}^{127}I \to$ anything)		$<3 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- Ti \to e^+ Ca)$ / $\sigma(\mu^- Ti \to$ capture)		$<3.6 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \to e^+\pi^-\pi^-)/\Gamma_{total}$		$<1.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^+\pi^-\pi^-)/\Gamma_{total}$		$<3.4 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^+\pi^-K^-)/\Gamma_{total}$		$<2.1 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^+K^-K^-)/\Gamma_{total}$		$<3.8 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^+\pi^-K^-)/\Gamma_{total}$		$<7.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^+K^-K^-)/\Gamma_{total}$		$<6.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\gamma)/\Gamma_{total}$		$<3.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\pi^0)/\Gamma_{total}$		$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}2\pi^0)/\Gamma_{total}$		$<3.3 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\eta)/\Gamma_{total}$		$<8.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\pi^0\eta)/\Gamma_{total}$		$<2.7 \times 10^{-5}$, CL = 90%
$t_{1/2}({}^{76}Ge \to {}^{76}Se + 2e^-)$		$>1.9 \times 10^{25}$ yr, CL = 90%
$\Gamma(\pi^+ \to \mu^+\overline{\nu}_e)/\Gamma_{total}$	[k]	$<1.5 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^-\mu^+e^+)/\Gamma_{total}$		$<5.0 \times 10^{-10}$, CL = 90%
$\Gamma(K^+ \to \pi^-e^+e^+)/\Gamma_{total}$		$<6.4 \times 10^{-10}$, CL = 90%
$\Gamma(K^+ \to \pi^-\mu^+\mu^+)/\Gamma_{total}$	[k]	$<3.0 \times 10^{-9}$, CL = 90%
$\Gamma(K^+ \to \mu^+\overline{\nu}_e)/\Gamma_{total}$	[k]	$<3.3 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^0e^+\overline{\nu}_e)/\Gamma_{total}$		$<3 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to \pi^-e^+e^+)/\Gamma_{total}$		$<9.6 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to \pi^-\mu^+\mu^+)/\Gamma_{total}$		$<4.8 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to \pi^-e^+\mu^+)/\Gamma_{total}$		$<5.0 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to \rho^-\mu^+\mu^+)/\Gamma_{total}$		$<5.6 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^-e^+e^+)/\Gamma_{total}$		$<1.2 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^-\mu^+\mu^+)/\Gamma_{total}$		$<1.3 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to K^-e^+\mu^+)/\Gamma_{total}$		$<1.3 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^*(892)^-\mu^+\mu^+)/\Gamma_{total}$		$<8.5 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \pi^-\pi^-e^+e^+ + c.c.)/\Gamma_{total}$		$<1.12 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \pi^-\pi^-\mu^+\mu^+ + c.c.)/\Gamma_{total}$		$<2.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to K^-\pi^-e^+e^+ + c.c.)/\Gamma_{total}$		$<2.06 \times 10^{-4}$, CL = 90%

Cross section for inverse muon decay

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

agrees with CHARM II, CCFR data ($E_\nu \lesssim 600$ GeV)

$$f(\theta) = \left(2\frac{d\sigma}{d\Omega}\right)^{1/2} = \frac{1}{\sqrt{s}}\sum_{J=0}^{\infty}(2J+1)P_J(\cos\theta)\mathcal{M}_J$$

PW unitarity: $|\mathcal{M}_J| < 1$

$V - A$ theory:

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

satisfies pw unitarity for

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

$\Rightarrow V - A$ theory cannot be complete

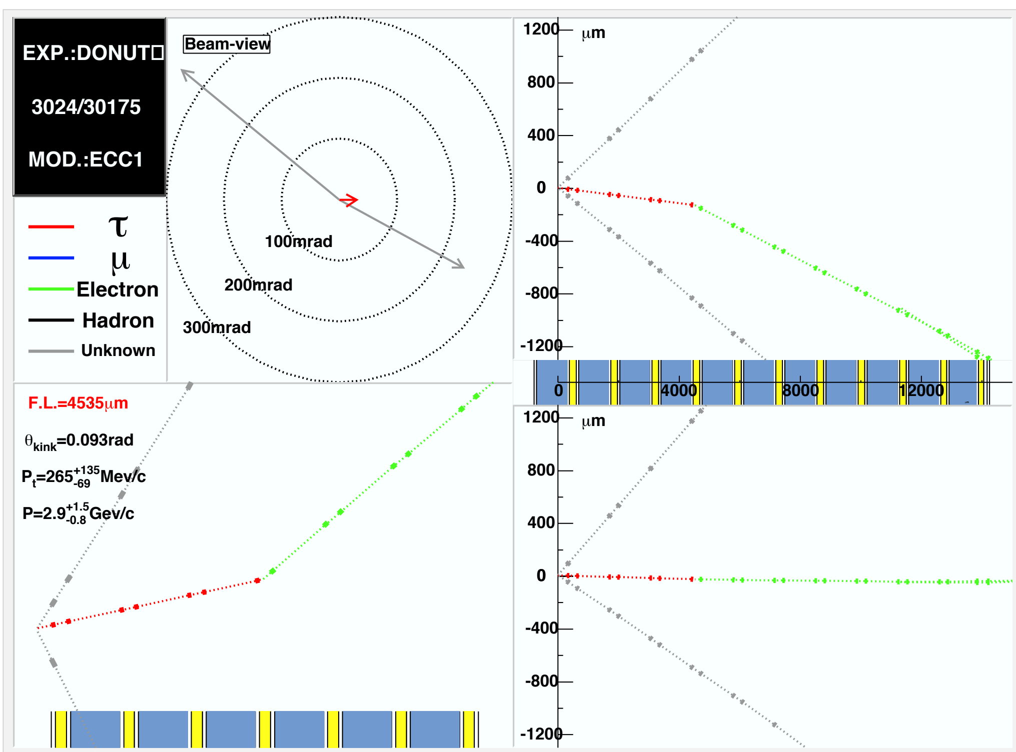
physics must change before $\sqrt{s} \approx 600$ GeV

2000: DONuT Three-Neutrino Experiment

▷ Prompt (beam-dump) ν_τ beam produced in

$$D_s^+ \rightarrow \tau^+\nu_\tau$$
$$\hookrightarrow X^+\bar{\nu}_\tau$$

▷ Try to observe $\nu_\tau N \rightarrow \tau +$ anything in emulsion; τ lifetime is 0.3 ps



Kodama, *et al.*, *Phys. Lett.* **B504**, 218 (2001)

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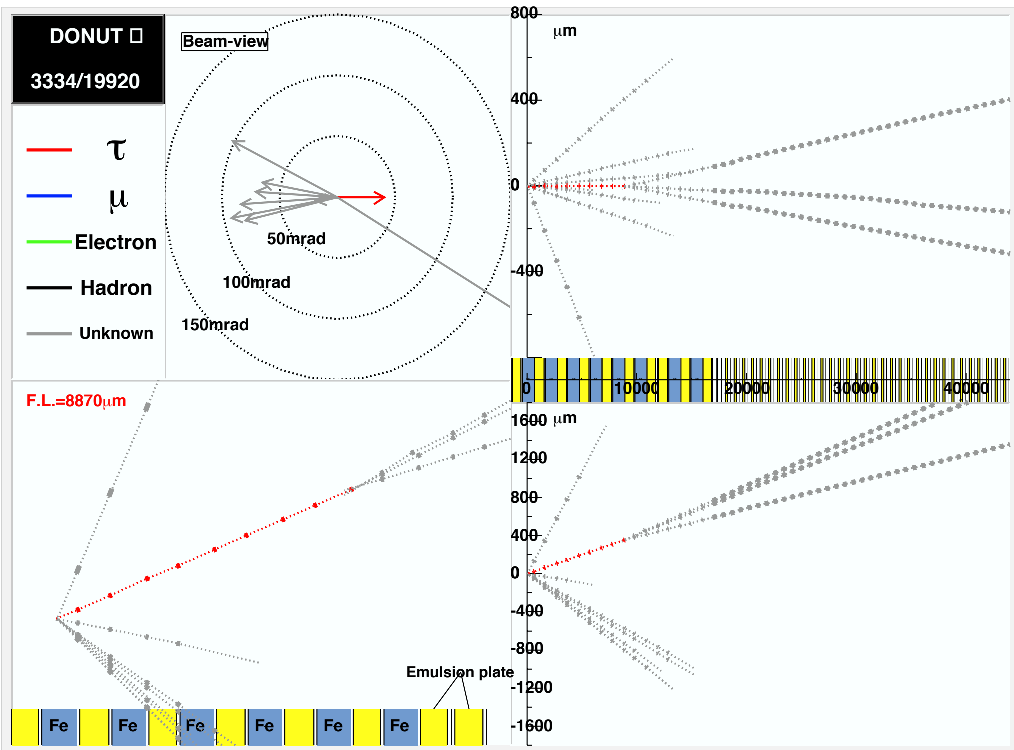

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Leptons are seen as free particles

Table 1: Some properties of the leptons.

Lepton	Mass	Lifetime
e^-	$0.510\,998\,92(4)$ MeV/c^2	$> 4.6 \times 10^{26}$ y $(90\%$ CL$)$
ν_e	< 3 eV/c^2	$\tau/m > 7 \times 10^9$ s/eV
μ^-	$105.658\,369(9)$ MeV/c^2	$2.197\,03(4) \times 10^{-6}$ s
ν_μ	< 0.19 MeV/c^2 $(90\%$ CL$)$	$\tau/m > 15.4$ s/eV
τ^-	$1776.99^{+0.29}_{-0.26}$ MeV/c^2	$290.6 \pm 1.1 \times 10^{-15}$ s
ν_τ	< 18.2 MeV/c^2 $(95\%$ CL$)$	

All spin-$\frac{1}{2}$, pointlike ($\lesssim$ few $\times\, 10^{-17}$ cm)

kinematically determined ν masses consistent with 0

(ν oscillations $\Rightarrow$ nonzero, unequal masses)

Universal weak couplings

Rough and ready test

Fermi constant from muon decay

$$G_\mu = \left[\frac{192\pi^3\hbar}{\tau_\mu m_\mu^5}\right]^{\frac{1}{2}} = 1.1638 \times 10^{-5}\ \text{GeV}^{-2}$$

Meticulous analysis yields $G_\mu = 1.16637(1) \times 10^{-5}$ GeV^{-2}

Fermi constant from tau decay

$$G_\tau = \left[\frac{\Gamma(\tau \to e\bar{\nu}_e\nu_\tau)}{\Gamma(\tau \to \text{all})}\frac{192\pi^3\hbar}{\tau_\tau m_\tau^5}\right]^{\frac{1}{2}} = 1.1642\times 10^{-5}\ \text{GeV}^{-2}$$

Excellent agreement with $G_\beta = 1.16639(2) \times 10^{-5}$ GeV^{-2}

Charged currents acting in leptonic and semileptonic interactions are of universal strength; $\Rightarrow$ *universality of current-current form, or whatever lies behind it*

Nonleptonic enhancement

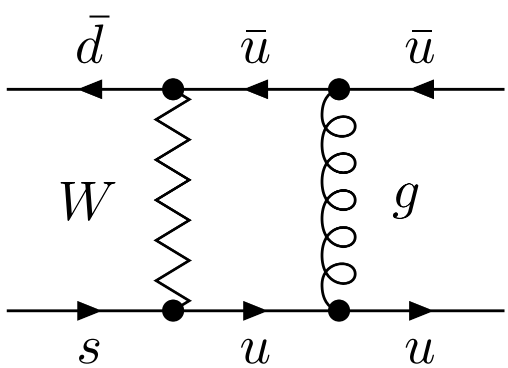
Certain NL transitions are more rapid than universality suggests

$$\underbrace{\Gamma(K_S \to \pi^+\pi^-)}_{I=0,2} \approx 450 \times \underbrace{\Gamma(K^+ \to \pi^+\pi^0)}_{I=2}$$

$$\boxed{A_0 \approx 22 \times A_2}$$

$|\Delta I| = \frac{1}{2}$ rule; "octet dominance" (over **27**)

Origin of this phenomenological rule is only partly understood. Short-distance *(perturbative)* QCD corrections arise from



…explain $\approx \sqrt{\text{enhancement}}$