CHIRAL STRUCTURE OF WEAK INTERACTION

WHEN WE DISCUSSED CHIRALITY, INTRODUCED

$$P_R = \frac{1}{2}(1+\gamma^5) \qquad P_L = \frac{1}{2}(1-\gamma^5)$$

ANY SPINOR CAN BE DECOMPOSED INTO LEFT- AND RIGHT-HANDED CHIRAL COMPONENTS

$$u = \frac{1}{2}(1+\gamma^5)u + \frac{1}{2}(1-\gamma^5)u = P_R u + P_L u = a_R u_R + a_L u_L$$

IN QED ONLY 2 COMBINATIONS OF CHIRAL SPINORS GAVE NON-ZERO CONTRIBUTIONS TO THE QED VECTOR CURRENT $\bar{u}(p')\gamma^\mu u(p)$. THESE ARE RR AND LL.

FOR THE WEAK INTERACTION, V−A VERTEX FACTOR

$$\gamma^\mu \longrightarrow \gamma^\mu \underbrace{\tfrac{1}{2}(1-\gamma^5)}$$

LEFT-HANDED PROJECTION OPERATOR

SO THE CURRENT WHERE BOTH SPINORS ARE RIGHT-HANDED ⟶ ZERO

$$j^\mu_{RR} = \frac{g_W}{\sqrt{2}}\, \bar{u}_R(p')\, \gamma^\mu \tfrac{1}{2}(1-\gamma^5)\, u_R(p)$$

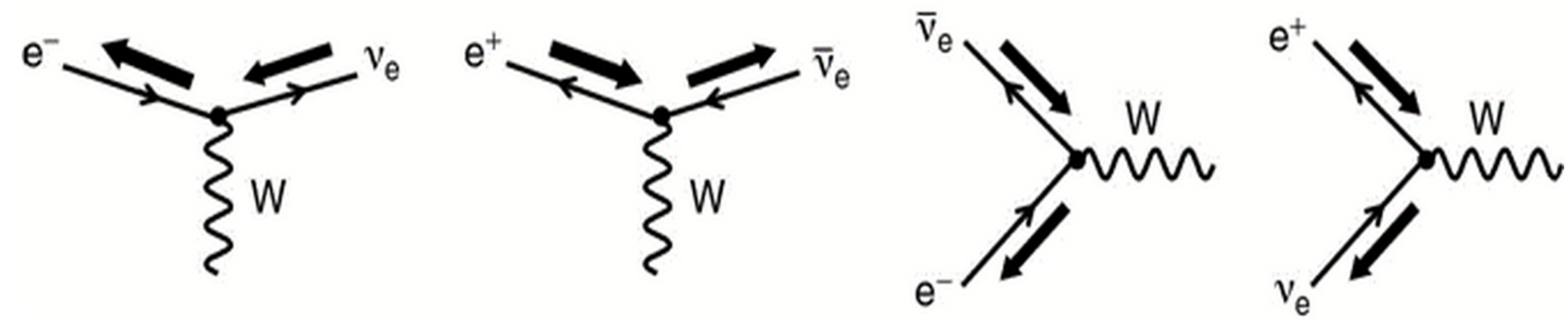
$$= \frac{g_W}{\sqrt{2}}\, \bar{u}_R(p')\, \gamma^\mu\, P_L u_R(p) = 0$$

ONLY LEFT-HANDED PARTICLE CHIRAL STATES SEE THE WEAK INTERACTION.

ANTIPARTICLES RIGHT HANDED

$$\tfrac{1}{2}(1-\gamma_5)\, v = v_R$$

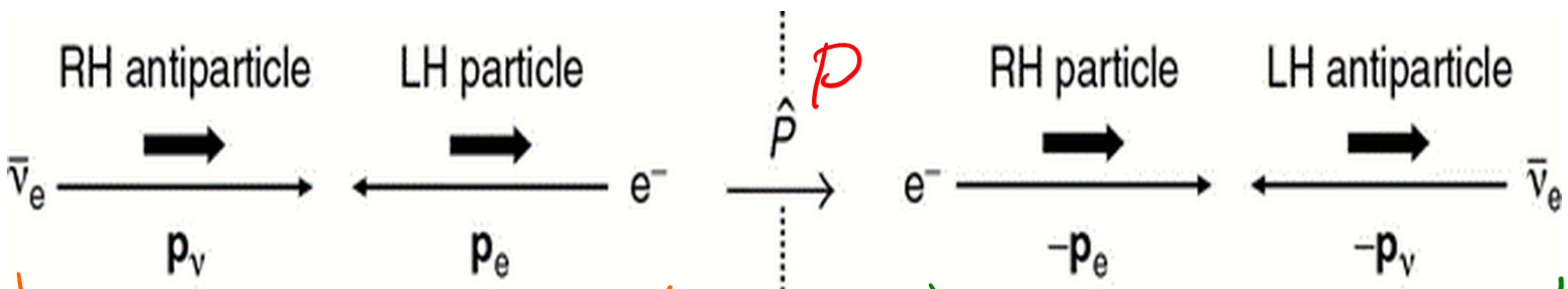
PROJECTS OUT RIGHT HANDED ANTI PARTICLE SPINOR



$E \gg m \rightarrow$ CHIRAL STATES = HELICITY STATES

ONLY LEFT-HANDED PARTICLES
RIGHT-HANDED ANTIPARTICLES } CONTRIBUTE

ORIGIN OF PARITY VIOLATION



EXIST IN NATURE $\xrightarrow[P]{}$ DO NOT EXIST

MAXIMAL PARITY VIOLATION

THE W-BOSON PROPAGATOR

PROPAGATOR OF MASSLESS SPIN-1 $\frac{-i g_{\mu\nu}}{q^2}$

$m_W \sim 80\,\mathrm{GeV} \rightarrow \frac{1}{q^2 - m_W^2}$

IN QED $\sum_\lambda \varepsilon_\mu^{\lambda *} \varepsilon_\nu^\lambda = -g_{\mu\nu}$ ← MASSLESS γ

TWO POLARIZATION STATES → TRANSVERSE

WEAK INTERACTION $\sum_\lambda \varepsilon_\mu^{\lambda *} \varepsilon_\nu^\lambda = -g_{\mu\nu} + \frac{q_\mu q_\nu}{m_W^2}$ ← MASSIVE W

3 POLARIZATION STATES.

TRANS + LONGITUD

W PROPAGATOR $\frac{-i}{q^2 - m_W^2}\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{m_W^2} \right)$

$q^2 \ll m_W^2 \rightarrow \frac{-i g_{\mu\nu}}{q^2 - m_W^2}$

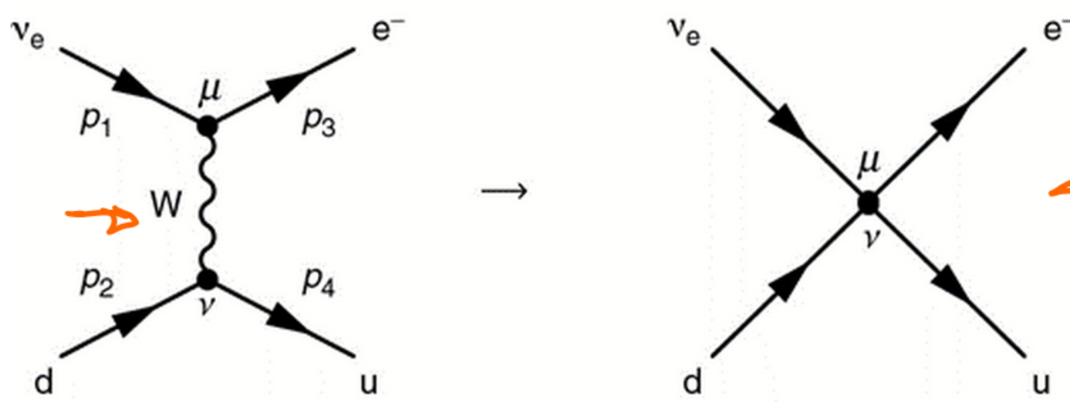
FERMI CONTACT INTERACTION

IF WE DO EXPERIMENTS WHERE $q^2 \ll m_{GB}$

WHERE m_{GB} IS SOME NEW MASSIVE GAUGE BOSON

→ WE EFFECTIVELY HAVE CONTACT INTERACTIONS

GB →



← $q^2 \ll m_{GB}$

WHEN FERMI FIRST FORMULATED WEAK INTERACTION THIS WAS THE SITUATION

LHC LOOKS FOR NEW CONTACT INTERACTION

→ BEYOND STANDARD MODEL INTERACTIONS

FERMI $\mathcal{M}_{fi} = G_F\, g_{\mu\nu} [\psi_3 \gamma^\mu \psi_1][\bar{\psi}_4 \gamma^\nu \psi_2]$ ANALOGY WITH QED

$\uparrow$ FERMI COUPLING "CONSTANT"

PARITY VIOLATION $\mathcal{M}_{fi} = \frac{1}{\sqrt{2}} G_F\, g_{\mu\nu} [\bar{\psi}_3 \gamma^\mu (1-\gamma^5) \psi_1][\bar{\psi}_4 \gamma^\mu (1-\gamma^5) \psi_2]$

$\leftarrow$ KEEPS VALUE OF G_F SAME

$$\mathcal{M}_{fi} = -\left[\frac{g_w}{\sqrt{2}} \bar{\psi}_3 \frac{1}{2} \gamma^\mu (1-\gamma^5) \psi_1\right]\left[\frac{g_{\mu\nu} - q_\mu q_\nu / m_W^2}{q^2 - m_W^2}\right]\left[\frac{g_w}{\sqrt{2}} \bar{\psi}_4 \frac{1}{2} \gamma^\mu (1-\gamma^5) \psi_2\right]$$

FULL FEYMAN RULES

$q^2 <<< m_W^2$

$$M_{fi} = \frac{g_w^2}{8 m_W^2} g_{\mu\nu} [\bar{\psi}_3 \gamma^\mu (1-\gamma^5) \psi_1][\bar{\psi}_4 \gamma^\nu (1-\gamma^5) \psi_2]$$

$$\rightarrow \quad \frac{G_F}{\sqrt{2}} = \frac{g_w^2}{8 m_W^2}$$

STRENGTH OF WEAK INTERACTION

CAN DETERMINE ACCURATELY FROM PRECISE LOW ENERGY DECAYS ← JUST AN EXPERIMENTAL ISSUE

EXAMPLE IS $\mu^- \to e^- \nu_\mu \bar{\nu}_e$ SEE HALZEN–MARTIN P. 261

$$\Gamma_\mu(\mu^- \to e^- \nu_\mu \bar{\nu}_e) = \frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}$$

PRECISION MEUSUREMENTS

$m_\mu = 0.1056583715(53)$ GeV, $\tau_\mu = 2.1969811(22) \times 10^{-6}$ s

$$G_F = 1.16638 \times 10^{-5}\ \text{GeV}^{-2}$$

A "COUPLING CONSTANT" DOES NOT HAVE DIMENSIONS

EG $\alpha = \dfrac{e^2}{4\pi\varepsilon_0 \hbar c}$ → DIMENSIONLESS

EQUIVALENT IN WEAK INTERACTION $\sim g_W$

AS, I HOPE, WE WILL SEE, THE W MASS CAN AT TEVATRON, THEN LHC

$$m_W = 80.385 \pm 0.015 \text{ GeV}$$

$$\alpha_W = \frac{g_W^2}{4\pi} = \frac{8 m_W^2 G_F}{4\sqrt{2}\,\pi} \sim \frac{1}{30}$$

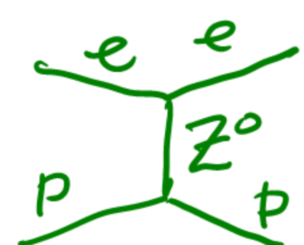
STILL DEPENDS ON q^2

WEAK INTERACTION ONLY LOOKS WEAK AT $q^2 \sim 0$, m_W LARGE

CC

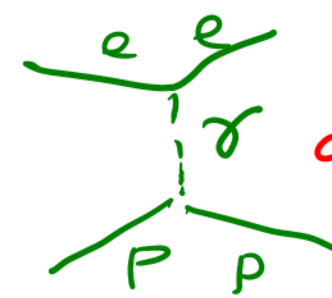
α_W

NC

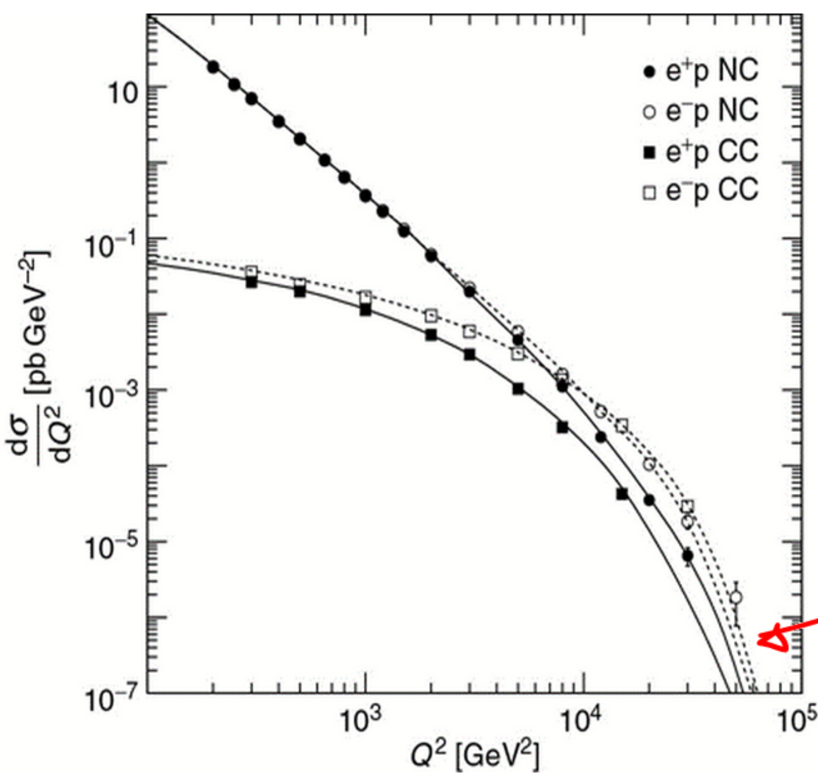


α_W

+



α_{QED}



FOR $q^2 \gg m_W^2$

BOTH $\sim \frac{1}{q^2}$ $\alpha_W \approx \alpha_{QED}$

HELICITY IN PION DECAY

INTERESTING DEMONSTRATION OF HELICITY

$\pi^{\pm}$ $J^P = 0^-$ $u\bar{d}$, $d\bar{u}$ $m_{\pi^\pm} \sim 140\,\mathrm{MeV}$

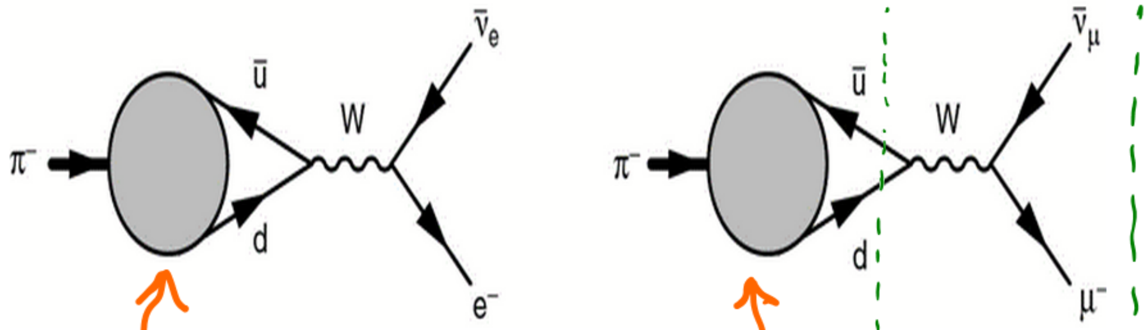
$\pi^- \to e^- \bar{\nu}_e$ $\pi^- \to \mu^- \bar{\nu}_\mu$ $\pi^- \to \mu^- \bar{\nu}_\mu \gamma$

2 BODY DECAYS DOMINANT → WHY?

SAME COUPLING CONSTANT – RATES EQUAL

$m_\mu \simeq m_\pi$ → PHASE SPACE IS MUCH GREATER IN $\pi^- \to e^- \bar{\nu}_e$

→ SO, IT SHOULD BE DOMINANT.



UNKOWN
SAME IN
BOTH

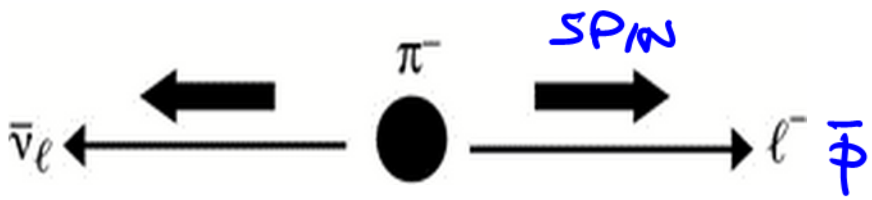
CALCULABLE

$$\frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} = 1.230(4) \times 10^{-4} \; !$$

REFLECTION OF DIFFERENCE BETWEEN

HELICITY $\frac{\vec{\sigma} \cdot \vec{p}}{|\vec{p}|}$

CHIRALITY $\rightarrow$ $P_L = \frac{1}{2}(1 - \gamma^5)$



PION REST FRAME

WEAK INTERACTION PARTICLE LH, ANTIPARTICLE RH

$m_\nu \sim 0 \rightarrow \psi^{\text{NEUTRINO}}_{\text{CHIRAL}} = \psi^{\text{NEUTRINO}}_{\text{HELICITY}}$

↳ $\bar{\nu}$ ALWAYS RH HELICITY

$\pi \rightarrow$ SPIN 0 $\rightarrow$ LOOK AT DIAGRAM

CONSERVATION OF ANGULAR MOMENTUM $\rightarrow$ e, μ ALSO RH

WEAK INTERACTION ONLY LH $\bar{\nu}$!

DECAY ONLY OCCURS BECAUSE e, μ MASSIVE

↳ RH + LH

IF $m_e = m_\mu = 0$ DOESN'T OCCUR

$0 < m_e < m_\mu$

LOOK AT THIS IN OUR FORMALISM

RH HELICITY SPINOR $u_\uparrow \rightarrow \underbrace{\text{RH} + \text{LH}}_{\text{CHIRAL}}$

$$u_\uparrow \equiv \frac{1}{2}\left(1 + \frac{p}{E+m}\right) u_R + \underbrace{\frac{1}{2}\left(1 - \frac{p}{E+m}\right) u_L}_{\text{ONLY THIS CONTRIBUTES WEAK INTERACTION}}$$

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$$\mathcal{M}_{WK} \sim \frac{1}{2}\left(1 - \frac{p_\ell}{E_\ell + m_\ell}\right) \qquad \ell = e \text{ OR } \mu$$

IF $\ell \rightarrow$ RELATIVISTIC LH CHIRAL ~ 0

$m_\nu = 0 \qquad E_e = \dfrac{m_\pi^2 + m_\ell}{2m_\pi} \ , \quad p_\ell = \dfrac{m_\pi^2 - m_\ell^2}{2 m_\pi}$

So. . . . . .

$$\frac{p_e}{E_e + m_e} = \frac{m_\pi - m_e}{m_\pi + m_e}$$

$$\mathcal{M} \sim \frac{1}{2}\left(1 - \frac{p_e}{E_e + m_e}\right) \rightarrow \mathcal{M} \sim \frac{m_e}{m_\pi + m_e}$$

$$\frac{m_\mu}{m_\pi} \sim 200$$

HELICITY SUPPRESION OF e-DECAY

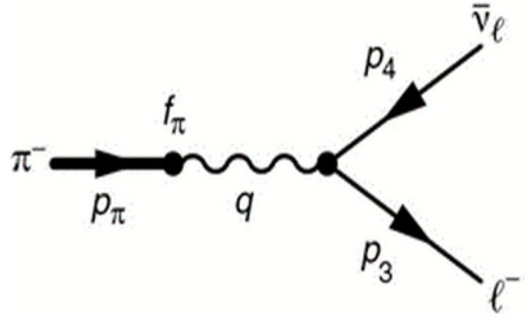
$e \rightarrow \beta = 0.9997$

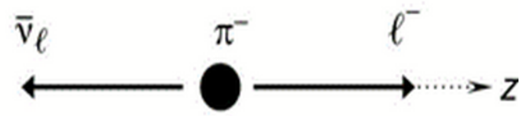
$\hookrightarrow$ CHIRAL = HELICITY

$\mu \rightarrow \beta = 0.27$

$\frac{1}{2}\left(1 - \frac{p}{E+m}\right) u_L \rightarrow$ SIGNIFICANT

LET'S CALCULATE IN DETAIL





PION
REST FRAME

$$p_\pi = (m_\pi, 0, 0, 0) \qquad p_\ell = p_3 = (E_\ell, 0, 0, p) \qquad p_{\bar\nu} = p_4 = (p, 0, 0, -p)$$

WEAK LEPTONIC CURRENT $\ell^- \bar{\nu}_e$ VERTEX

$$j_\ell^\nu = \frac{g_W}{\sqrt{2}} \bar{u}(p_3) \frac{1}{2} \gamma^\nu (1-\gamma^5)\, v(p_4)$$

ANTIPARTICLE

HADRONIC CURRENT → COMPLEXITY OF π
NOT POINT

→ IS A 4-VECTOR → ONLY AVAILABLE IS p_π

REPLACE $\bar{v} \gamma^\mu (1-\gamma^5) u \longrightarrow f_\pi\, p_\pi^\mu$

PION DECAY CONSTANT
EXPERIMENT, MAYBE QCD

$$\mathcal{M}_{fi} = \left[\frac{g_W}{\sqrt{2}}\frac{1}{2} f_\pi p_\pi^\mu\right] \left[\frac{g_{\mu\nu}}{m_W^2}\right] \left[\frac{g_W}{\sqrt{2}} \bar{u}(p_3)\gamma^\nu \frac{1}{2}(1-\gamma^5) v(p_4)\right]$$

HADRONIC VERTEX

LEPTONIC VERTEX

$$= \frac{g_W^2}{4m_W^2} g_{\mu\nu} f_\pi p_\pi^\mu \, u(p_3)\gamma^\nu \frac{1}{2}(1-\gamma^5) v(p_4)$$

USED FERMI FOR PROPAGATOR $q^2 = m_\pi^2 \ll m_W^2$

IN REST FRAME $p_\pi^\mu = (m_\pi, 0, 0, 0)$

$$\mathcal{M}_{fi} = \frac{g_W^2}{4m_W^2} \cdot f_\pi m_\pi \bar{u}(p_3) \gamma^0 \frac{1}{2}(1-\gamma^5) v(p_4)$$

$\bar{u}\gamma^0 = u^\dagger\gamma^0\gamma^0 = u^\dagger$ SO...

$$\mathcal{M}_{fi} = \frac{g_W^2}{4m_W^2} f_\pi m_\pi u^\dagger(p_3)\frac{1}{2}(1-\gamma^5) v(p_4)$$

$$\mathcal{M}_{fi} = \frac{g_W^2}{4m_W^2} f_\pi m_\pi u^+(p_3)\tfrac{1}{2}(1-\gamma^5)v(p_4)$$

FOR THE NEUTRINO $(m \ll E)$ HELICITY EIGENSTATES SAME AS CHIRAL STATES $\tfrac{1}{2}(1-\gamma^5)v(p_4) = v_\downarrow(p_4)$

SO ABOVE $\longrightarrow$

$$\mathcal{M}_{fi} = \frac{g_W^2}{4m_W^2} f_\pi m_\pi u^+(p_3) v_\downarrow(p_4)$$

SHOWED

$$u_\uparrow = \sqrt{E+m}\begin{pmatrix} c \\ se^{i\phi} \\ \frac{p}{E+p}c \\ \frac{p}{E+m}se^{i\phi} \end{pmatrix} \qquad u_\downarrow = \sqrt{E+m}\begin{pmatrix} -s \\ ce^{i\phi} \\ \frac{p}{E+p}s \\ -\frac{p}{E+m}ce^{i\phi} \end{pmatrix}$$

FOR CHARGED LEPTON

IN THESE PUT $\theta = 0,\ \phi = 0$

THEN FOR CHARGED LEPTON

$$u_\uparrow(p_3) = \sqrt{E_e+m_e}\begin{pmatrix} 1 \\ 0 \\ \frac{p}{E_e+m_e} \\ 0 \end{pmatrix} \qquad u_\downarrow(p_3) = \begin{pmatrix} 0 \\ 1 \\ 0 \\ \frac{-p}{E_e+m_e} \end{pmatrix}$$

RIGHT HANDED ν SPINOR:

$$v_\uparrow(p_4) = \sqrt{E+m}\begin{pmatrix} \frac{p}{E+m}\cdot c \\ \frac{p}{E+m}\cdot s e^{i\phi} \\ c \\ s e^{i\phi} \end{pmatrix} \xrightarrow[\phi=\pi]{\theta=\pi} \sqrt{p}\begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix}$$

CLEARLY $u_\downarrow^\dagger(p_3)\, v_\uparrow(p_4) = 0$ AS EXPECTED FROM PREVIOUS DISCUSSION BOTH ν AND ℓ HAVE TO BE IN RIGHT-HANDED STATES.

$$u_\uparrow(p_3)\cdot v_\uparrow(p_4') = \left(1,\ 0,\ \frac{p_e}{E_e+m_e},\ 0\right)\begin{pmatrix}1\\0\\-1\\0\end{pmatrix}\cdot\sqrt{E_e+m_e}\cdot\sqrt{p}$$

RH RH

$$= \sqrt{E_e+m_e}\,\sqrt{p}\left(1-\frac{p}{E_e+m_e}\right)$$

$$\mathcal{M}_{fi} = \frac{g_w^2}{4m_W^2} f_\pi m_\pi \sqrt{E_e+m_e}\,\sqrt{p}\left(1-\frac{p}{E_e+m_e}\right)$$

$E_e = (m_\pi^2+m_e^2)/2m_\pi \quad , \quad p_\nu = -p_e = -(m_\pi^2-m_e^2)/2m_\pi$

$$\mathcal{M}_{fi} = \frac{g_w^2}{m_W^2} f_\pi m_\pi \frac{m_\pi+m_e}{\sqrt{2m_\pi}}\cdot\left(\frac{m_\pi^2-m_e^2}{2m_\pi}\right)^{1/2}\cdot\frac{2m_e}{m_\pi+m_e}$$

$$\mathcal{M}_{fi} = \left(\frac{g_w}{2m_W}\right)^2 f_\pi m_e \left(m_\pi^2-m_e^2\right)^{\frac{1}{2}}$$

$$\mathcal{M}_{fi} = \left(\frac{g_W}{2m_W}\right)^2 f_\pi m_e \left(m_\pi^2 - m_e^2\right)^{\frac{1}{2}}$$

PION IS SPIN-0 $\rightarrow$ NO NEED TO AVERAGE OVER INITIAL STATE SPIN

$$\langle |\mathcal{M}_{fi}|^2 \rangle = 2G_F^2 f_\pi^2 m_e^2 (m_\pi^2 - m_e^2)$$

USE $\Gamma = \dfrac{p^*}{32\pi^2 m^2} \underbrace{\int |\mathcal{M}_{fi}|^2 d\Omega}_{4\pi}$

$4\pi \rightarrow$ NO ANGULAR DEP SPIN 0

$$\Gamma = \frac{4\pi}{32\pi^2 m_\pi^2} \, p \, \langle |\mathcal{M}_{fi}|^2 \rangle$$

$$p = \frac{m_\pi^2 - m_e^2}{2m_\pi}$$

$$\Gamma = \frac{G_F^2}{8\pi m_\pi^3} f_\pi^2 \left[m_e (m_\pi^2 - m_e^2)\right]^2$$

$$\Gamma = \frac{G_F^2}{8\pi m_\pi^3} f_\pi^2 \left[m_e \left(m_\pi^2 - m_e^2 \right) \right]^2$$

TO CALCULATE Γ FOR EACH OF $\pi^- \to e^- \bar{\nu}_e$ AND $\pi^- \to \mu^- \bar{\nu}_\mu$ NEED G_F & f_π

THESE HAVE BEEN MEASURED, BUT MASSES ARE ACCURATELY KNOWN :-

$$\frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} = \left[\frac{m_e \left(m_\pi^2 - m_e^2 \right)}{m_\mu \left(m_\pi^2 - m_\mu^2 \right)} \right]^2 = 1.26 \times 10^{-4}$$

EXPERIMENT $\to$ $1.23(0) \times 10^{-4}$

EXPERIMENTAL EVIDENCE FOR V−A

THERE IS AN ENORMOUS BODY OF EXPERIMENTAL EVIDENCE FOR V−A

ν EXPERIMENTS

WEAK DECAYS OF MESONS, BARYONS

$e^+e^- \xrightarrow[Z^0]{} f\bar{f}$ AT HIGH ENERGY

FROM OUR EXAMPLE, SAY $\pi \to \ell\nu$ WAS ACTUALLY SCALAR $(\bar{\psi}\phi)$ OR PSEUDOSCALAR $(\bar{\psi}\gamma^5\phi)$

$$\frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} = 5.5$$

BUT THERE IS A CATCH →

ANY DECAY COULD BE DESCRIBED BY LINEAR COMB.

SCALAR (S)	$g_S \bar{\Psi} \phi$
PSEUDO SCALAR (P)	$g_P \bar{\Psi} \gamma^5 \phi$
VECTOR (V)	$g_V \bar{\Psi} \gamma^\mu \phi$
AXIAL VECTOR (A)	$g_A \bar{\Psi} \gamma^\mu \gamma^5 \phi$
TENSOR (T)	$g_T \bar{\Psi} (\gamma^\mu \gamma^\nu - \gamma^\nu \gamma^\mu) \phi$

YOU CAN ALWAYS FIND A COMBINATION OF S + P + T WHICH MIMICS (V−A)

V−A $\longrightarrow$ PRESERVES HELICITY

S + P + T $\longrightarrow$ FLIPS HELICITY

POLARIZATION OF POSITIVE MUONS PRODUCED IN HIGH-ENERGY ANTINEUTRINO INTERACTIONS

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$\bar{\nu}$ RH

μ^+ MUST BE RH IF V-A

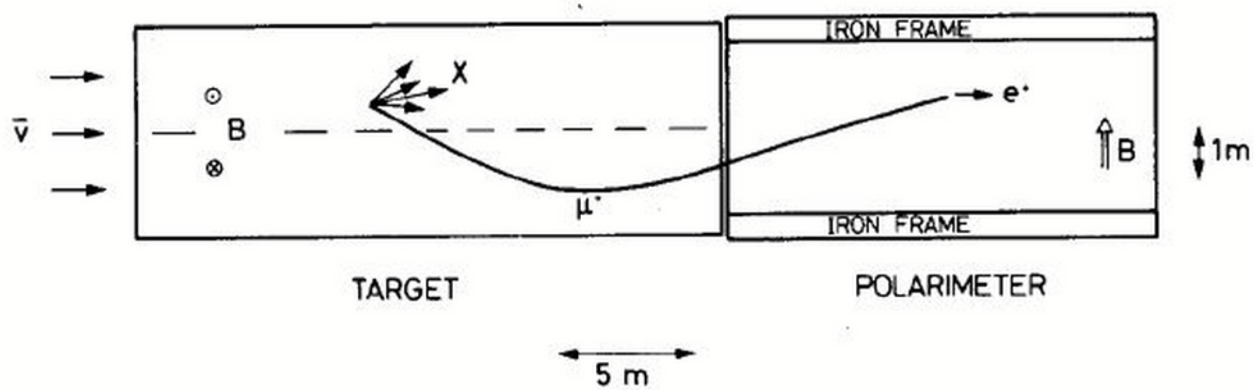


Fig. 1. Layout of the polarization experiment.

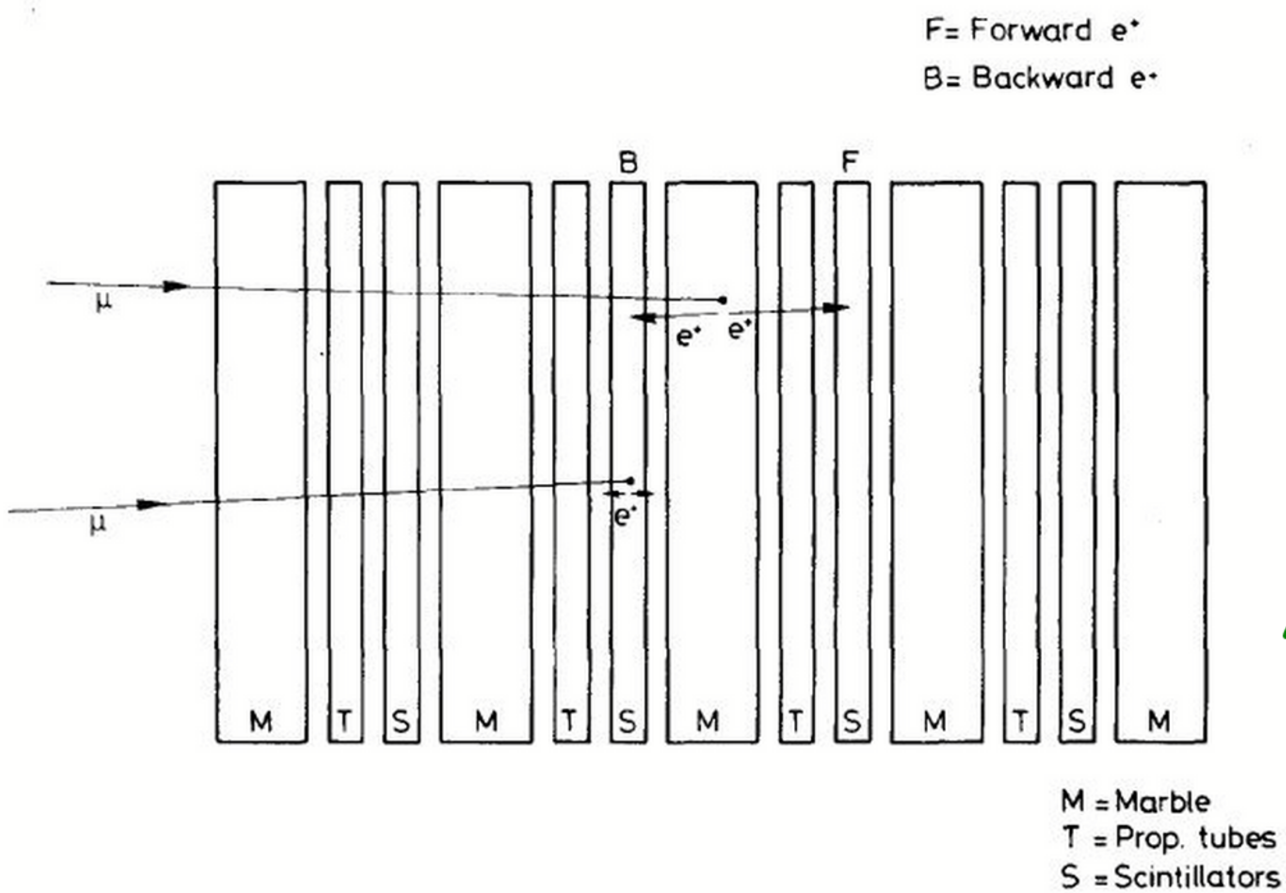
$\bar{\nu}_\mu + p \to \mu^+ X$

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

STOPPED PRECESSES IN MAGNETIC FIELD

MEASURES PRECESSION

TAGS MUON POLARIZATION



w of the polarimeter structure with examples of μ^+ stopping and decaying in marble (M) and in scintillator (S).
is measured using the proportional drift tubes (T).

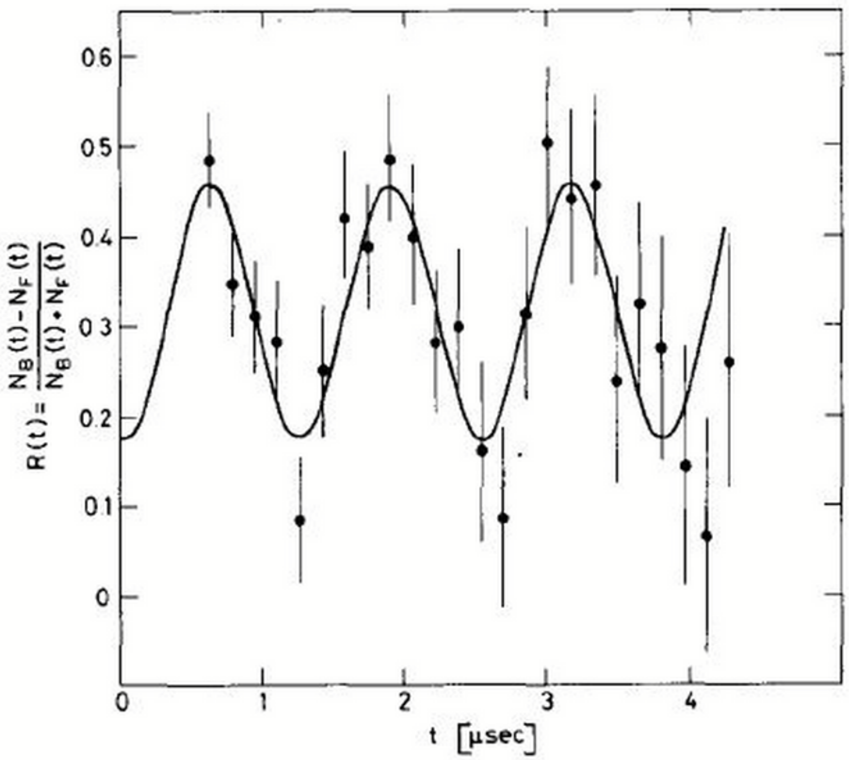


Fig. 3. Observed time dependence of relative backward–forward positron asymmetry. The sinusoidal function is the best fit of eq. (1) to the experimental points corresponding to the results given in table 2.

ELECTRONS FROM PRECESSING μ

Table 2
Comparison of the values of the parameters in eqs. (1) and (2) determined by fitting the data and by the Monte Carlo simulation.

	Data	Monte Carlo $P = +1$
R_0	0.14 ± 0.02	0.14 ± 0.01
ϕ	−3.1 ± 0.2	−3.14
R_1	0.32 ± 0.02	0.36 ± 0.01
ϵ	0.39 ± 0.01	0.38 ± 0.01
R_0^M	0.21 ± 0.03	0.22 ± 0.02
ϵ^M	0.30 ± 0.02	0.28 ± 0.01
β	0.14 ± 0.01	0.16 ± 0.01

MEASURE

V−A PREDICTION

It may be concluded that positive muons produced by interactions of high-energy antineutrinos with nuclei have a longitudinal polarization oriented along their momentum direction. Within the experimental errors the helicity is found to be +1, consistent with a purely V, A form of the interaction. An upper limit $\sigma_{S,P,T}/\sigma_{tot} < 18\%$ at the 95% confidence level can be

BASED ON 250 μ^+

MODERN EXPERIMENT TWISS @ TRIUMF

MEASURES ρ IN DECAY OF μ

MICHEL PARAMETER

V-A $\rightarrow$ 0.75

TWISS $\rightarrow$ 0.74997 ± 0.00026

BASED ON 10^{10} μ $\rightarrow$ STATISTICS IS A WONDERFUL THING