

Title: Standard Model - Review (PHYS 622) - Lecture 11

Date: Dec 14, 2009 09:00 AM

URL: <http://pirsa.org/09120045>

Abstract:

$$n \rightarrow p e^- \bar{\nu}$$

$$\pi^+ \rightarrow \mu^+ \nu$$

$$n \rightarrow p e^- \bar{\nu}$$

$$\pi^+ \rightarrow \mu^+ \nu$$

$$K^0 \rightarrow \pi^+ \pi^-$$

$$K^0 \rightarrow \pi^+ \pi^- \pi^0$$

$$n \rightarrow p e^- \bar{\nu}$$

$$\pi^+ \rightarrow \mu^+ \nu$$

$$K^0 \rightarrow \pi^+ \pi^-$$

$$P = +$$

$$K^0 \rightarrow \pi^+ \pi^- \pi^0$$

$$P = -$$

Feynman - Gell-Mann Marshak Sudanshan.

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(V-A)

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(V-A)

$$S_{\mathcal{L}} = -\frac{4G_F}{\sqrt{2}} J_{\mu}^{+} J^{\mu -}$$

Feynman - Gell-Mann Marshak Sudarshan.
(V-A)

$$S_{\mathcal{L}} = -\frac{4G_F}{\sqrt{2}} J_{\mu}^{+} J^{\mu -}$$

$$J_{\mu}^{+} = (J^{\mu 1} - J^{\mu 5}) \pm i(J^{\mu 2} - J^{\mu 5})$$

Feynman - Gell-Mann Marshak Sudanshan.
(V-A)

$$S_{\mathcal{L}} = -\frac{4G_F}{\sqrt{2}} J_{\mu}^{+} J^{\mu -}$$

$$J_{\mu}^{+} = \left[(\bar{J}^{\mu 1} - J^{\mu 51}) \pm i(\bar{J}^{\mu 2} - J^{\mu 52}) \right]$$

Feynman - Gell-Mann Marshak Sudanshan.
(V-A)

$$S_{\mathcal{L}} = -\frac{4G_F}{\sqrt{2}} J_{\mu}^{+} J^{\mu -}$$

$$J_{\mu}^{+} = \left[(\bar{u} \gamma^{\mu} - \bar{u} \gamma^{\mu} \gamma_5) + i(\bar{d} \gamma^{\mu} - \bar{d} \gamma^{\mu} \gamma_5) \right]$$

$$= (\bar{u}_L \gamma^{\mu} d_L + \bar{\nu}_{eL} \gamma^{\mu} e_L) +$$

Feynman - Gell-Mann Marshak Sudanshan.
(V-A)

$$S_{\mathcal{L}} = -\frac{4G_F}{\sqrt{2}} J_{\mu}^{+} J^{\mu -}$$

$$J_{\mu}^{+} = \left[(\bar{J}^{\mu 1} - J^{\mu 51}) \pm i(\bar{J}^{\mu 2} - J^{\mu 52}) \right]$$

$$= (\bar{u}_L \gamma^{\mu} d_L + \bar{\nu}_{eL} \gamma^{\mu} e_L) + \begin{pmatrix} c s & t L \\ \nu_{\mu} & \nu e \end{pmatrix}$$

Feynman - Gell-Mann Marshak Sudanshan.
(V-A)

$$S_{\mathcal{L}} = -\frac{4G_F}{\sqrt{2}} J_{\mu}^{+} J^{\mu -}$$

$$J_{\mu}^{+} = \left[(\bar{u}^{\mu 1} - \bar{d}^{\mu 1}) + i(\bar{u}^{\mu 2} - \bar{d}^{\mu 2}) \right]$$

$$= (\bar{u}_L \gamma^{\mu} d_L + \bar{\nu}_{eL} \gamma^{\mu} e_L) + \begin{pmatrix} c s & t_L \\ \nu_{\mu} & \nu_C \end{pmatrix}$$

$$n \rightarrow p e^- \bar{\nu}$$

$$\pi^+ \rightarrow \mu^+ \nu$$

$$K^0 \rightarrow \pi^+ \pi^-$$

$$P = +$$

$$K^0 \rightarrow \pi^+ \pi^- \pi^0$$

$$P = -$$

$$F_1^S(q^2=0) = g_A$$

$$n \rightarrow p e^- \bar{\nu}$$

$$\pi^+ \rightarrow \mu^+ \nu$$

$$K^0 \rightarrow \pi^+ \pi^-$$

$$P = +$$

$$K^0 \rightarrow \pi^+ \pi^- \pi^0$$

$$P = -$$

$$F_1^S(\vec{q}^2=0) = g_A$$

$$F_1(\vec{q}^2=0) = 1$$

Feynman - Gell-Mann Marshak Sudanshan.
(V-A)

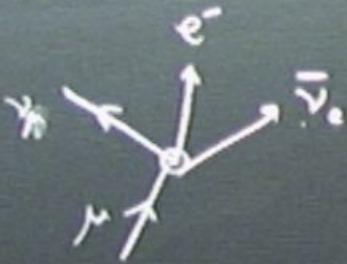
$$S_{\mathcal{L}} = -\frac{4G_F}{\sqrt{2}} J_{\mu}^{+} J^{\mu -}$$

$$J_{\mu}^{+} = \left[(\bar{u}^{\mu 1} - \bar{d}^{\mu 1}) + i(\bar{u}^{\mu 2} - \bar{d}^{\mu 2}) \right]$$

$$= (\bar{u}_L \gamma^{\mu} d_L + \bar{\nu}_{eL} \gamma^{\mu} e_L) + \begin{pmatrix} c s & tL \\ \nu_{\mu} & \nu c \end{pmatrix}$$

מלאי $\bar{e} \rightarrow \bar{\mu}$

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



$$n \rightarrow p e^- \bar{\nu}$$

$$\pi^+ \rightarrow \mu^+ \nu$$

$$K^0 \rightarrow \pi^+ \pi^-$$

$$P = +$$

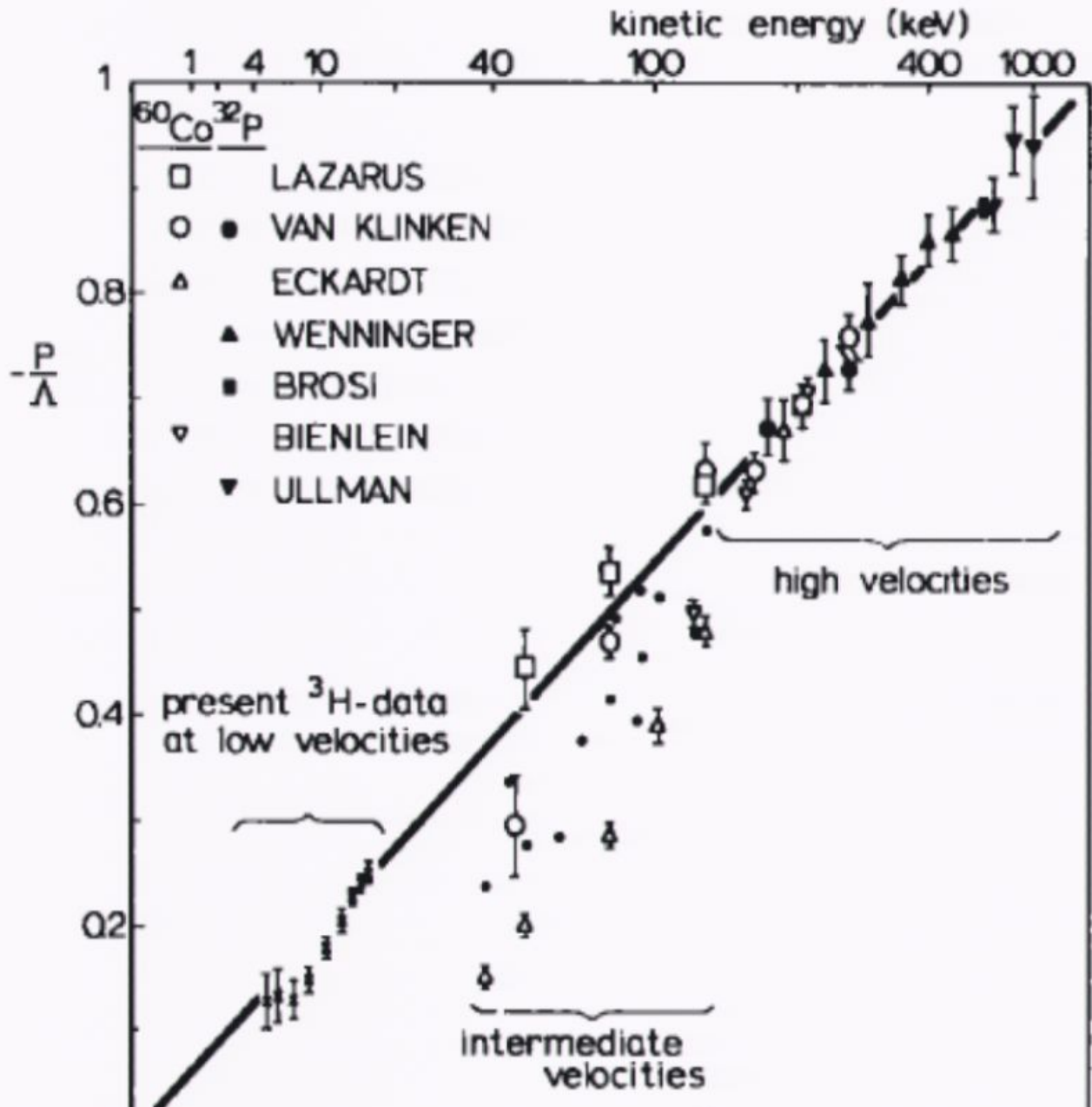
$$K^0 \rightarrow \pi^+ \pi^- \pi^0$$

$$P = -$$

$$F_1^S(q^2=0) = g_A$$

$$F_1(q^2=0) = 1$$

$$h_e = -\frac{1}{2} \cdot \frac{v_e}{c}$$



Feynman - Gell-Mann Marshak Sudanshan.
(V-A)

$$S_{\mathcal{L}} = -\frac{4G_F}{\sqrt{2}} J_{\mu}^{+} J^{\mu -}$$

$$J_{\mu}^{+} = \left[(\bar{u}^{\mu 1} - \bar{d}^{\mu 1}) + i(\bar{s}^{\mu 2} - \bar{c}^{\mu 2}) \right]$$

$$= (\bar{u}^{\mu} \gamma^{\mu} P_L + \bar{\nu}_{eL} \gamma^{\mu} P_L) + \begin{pmatrix} c s & t l \\ \nu_{\mu} & \nu_{\tau} \end{pmatrix}$$

Feynman - Gell-Mann Marshak Sudanshan.
(V-A)

$$S\mathcal{L} = -\frac{4G_F}{\sqrt{2}} J^+ J^-$$

$$J_\mu^+ = \left[(\bar{u}^{\mu 1} - \bar{d}^{\mu 1}) \pm i(\bar{u}^{\mu 2} - \bar{d}^{\mu 2}) \right]$$

$$J^+ = (\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L) + \begin{pmatrix} c s & t_L \\ \nu_\mu & \nu_C \end{pmatrix}$$

$$J^- = (J^+)^*$$

$$\mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu$$



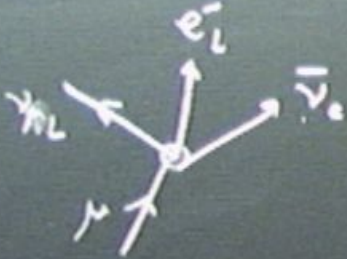
$$= \frac{4i G_F}{\sqrt{2}} \bar{u}_e \gamma^\mu \nu_e \bar{\nu}_\mu \gamma_\mu \nu_\mu$$

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



$$= -\frac{4 G_F}{\sqrt{2}} \bar{u}_l(\nu_\mu) \sigma^\mu u_l(\mu) \bar{u}_l(e) \sigma_\mu v_l(\bar{\nu}_e)$$

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

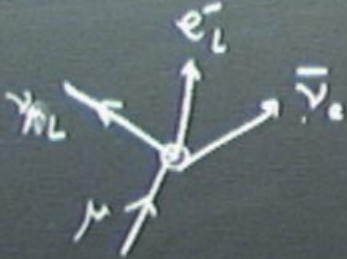


$$= -\frac{4 G_F}{\sqrt{2}}$$

$$\overbrace{+}^{J^+} \bar{u}_L(\nu_\mu) \sigma^\mu u_L(\mu)$$

$$\overbrace{+}^{J^-} u_L(e) \sigma^\mu v_L(\bar{\nu}_e)$$

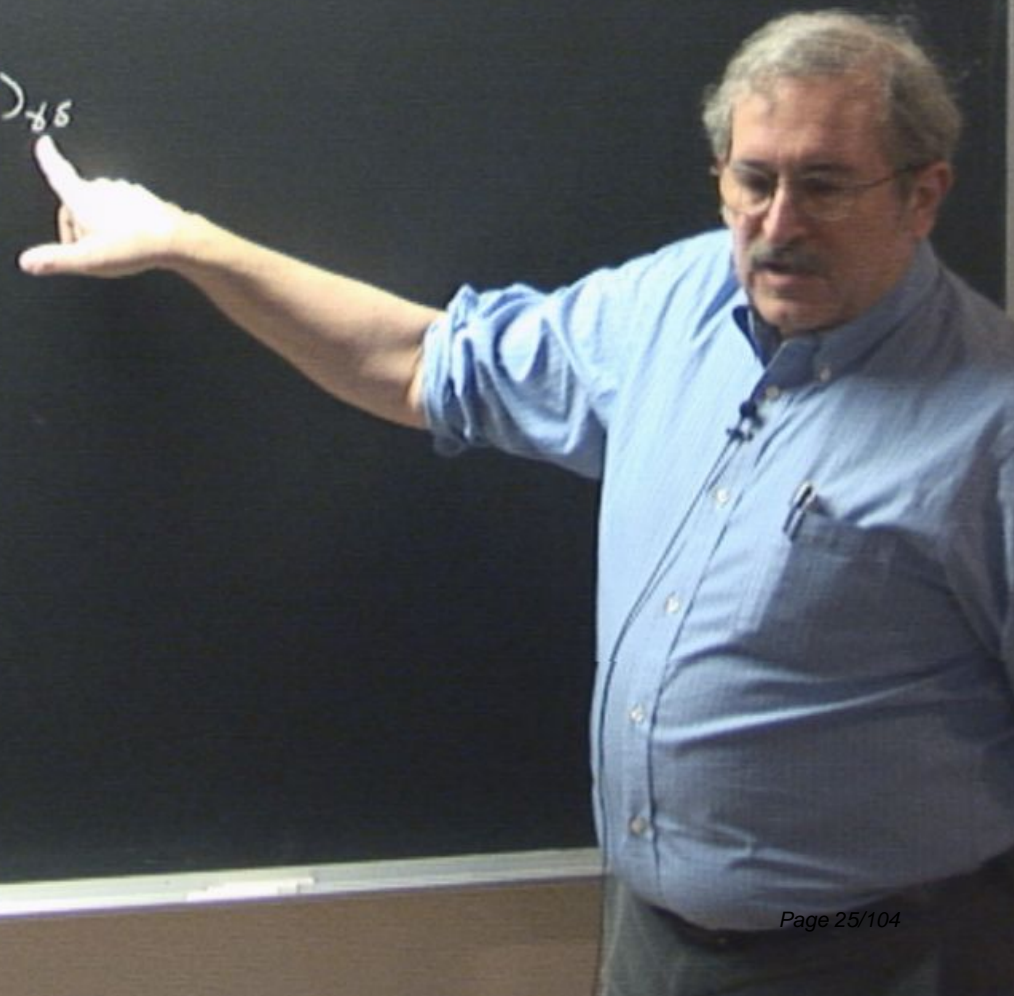
$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$$



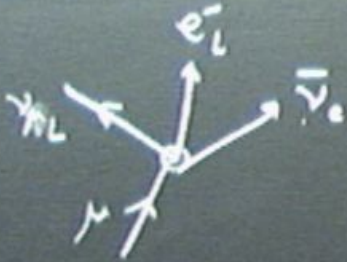
$$= -\frac{4i G_F}{\sqrt{2}}$$

$$\underbrace{+}_{J^+} \bar{u}_l(\nu_\mu) \bar{\sigma}^\mu u_l(\mu) \quad \underbrace{+}_{J^-} \bar{u}_l(e) \bar{\sigma}^\mu u_l(\bar{\nu}_e)$$

$$(\bar{\sigma}^\mu)_{\nu\mu} \quad (\bar{\sigma})_{\delta\delta}$$



$$\mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu$$

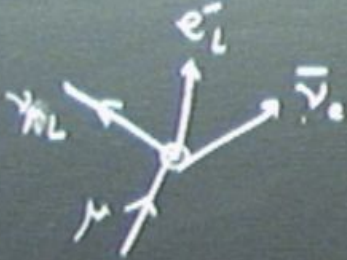


$$= -\frac{4i G_F}{\sqrt{2}}$$

$$\overbrace{+}^{J^+} \frac{1}{\sqrt{2}} \bar{u}_l(\nu_\mu) \sigma^\mu u_l(\mu) \quad \overbrace{+}^{J^-} \frac{1}{\sqrt{2}} \bar{u}_l(e) \sigma_\mu u_l(\bar{\nu}_e)$$

$$(\bar{\sigma}^\mu)_{\nu\mu} (\bar{\sigma})_{\delta\delta} = 2 \epsilon_{\alpha\gamma} \epsilon_{\beta\delta}$$

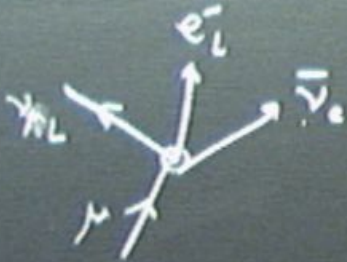
$$\mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu$$



$$= -\frac{4 G_F}{\sqrt{2}} \overbrace{u_\ell(\nu_\mu) \bar{\sigma}^\mu u_\ell(\mu)}^{J^+} \overbrace{u_\ell(e) \bar{\sigma}_\mu u_\ell(\bar{\nu}_e)}^{J^-}$$

$$(\bar{\sigma}^\mu)_{\nu\mu} (\bar{\sigma}_\mu)_{\delta\delta} = 2 \epsilon_{\alpha\gamma} \epsilon_{\beta\delta}$$

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



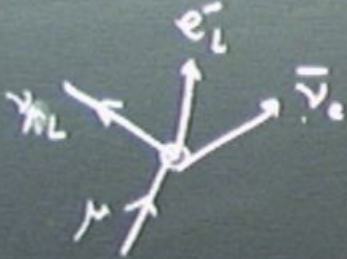
$$= -\frac{4iG_F}{\sqrt{2}} \overbrace{u_L(\nu_\mu) \bar{\sigma}^\mu u_L(\mu)}^{J^+} \overbrace{u_L(e) \bar{\sigma}_\mu u_L(\bar{\nu}_e)}^{J^-}$$

Fierz identity

$$(\bar{\sigma}^\mu)_{\nu\rho} (\bar{\sigma}^\mu)_{\delta\sigma} = 2 \epsilon_{\alpha\gamma} \epsilon_{\beta\delta}$$

$$= -\frac{4iG_F}{\sqrt{2}} \cdot 2 \cdot u_L^\dagger(\nu_\mu) \epsilon_{\alpha\gamma} u_L^\dagger(e) u_L(\mu) \epsilon_{\beta\delta} u_L(\bar{\nu}_e)$$

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



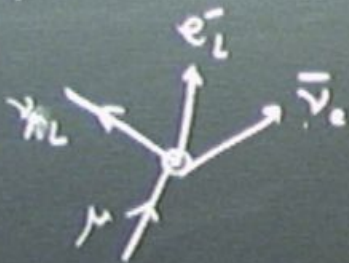
$$= -\frac{4iG_F}{\sqrt{2}} \underbrace{u_\mu^\dagger \bar{\sigma}^\mu u_\mu}_{J^+} \underbrace{u_e \bar{\sigma}_\mu \nu_e}_{J^-}$$

Fierz identity

$$(\bar{\sigma}^\mu)_{\nu\rho} (\bar{\sigma}^\mu)_{\delta\sigma} = 2 \epsilon_{\alpha\gamma} \epsilon_{\beta\delta}$$

$$= -\frac{4iG_F}{\sqrt{2}} \cdot 2 u_{L\alpha}^\dagger \epsilon_{\alpha\gamma} u_{L\beta}^\dagger \epsilon_{\beta\delta} \nu(\bar{\nu}_e)_\delta$$

$$\mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu$$



$$= -\frac{4iG_F}{\sqrt{2}} \underbrace{+}_{J^+} u_L(\nu_\mu) \bar{\sigma}^\mu u_L(\mu) \underbrace{+}_{J^-} u_L(e) \bar{\sigma}_\mu u_L(\bar{\nu}_e)$$

Fierz identity

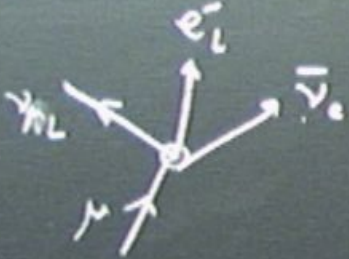
$$(\bar{\sigma}^\mu)_{\nu\rho} (\bar{\sigma}^\rho)_{\delta\sigma} = 2 \epsilon_{\alpha\delta} \epsilon_{\beta\sigma}$$

$$= -\frac{4iG_F}{\sqrt{2}} \cdot 2 u_L^\dagger(\nu_\mu) \epsilon_{\alpha\delta} u_L^\dagger(e) u_L(\mu) \epsilon_{\beta\sigma} u_L(\bar{\nu}_e) \epsilon$$

$$u(\mu) = \sqrt{m} \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

$$u_L(\mu) = \sqrt{m} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$\mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu$$



$$= -\frac{4i G_F}{\sqrt{2}}$$

$$\underbrace{+}_{J^+} u_L(\nu_\mu) \sigma_1 u_L(\mu) \quad \underbrace{+}_{J^-} u_L(e) \sigma_1 u_L(\bar{\nu}_e)$$

Fierz identity

$$(\sigma^\mu)_{\alpha\beta} (\sigma^\mu)_{\gamma\delta} = 2 \epsilon_{\alpha\gamma} \epsilon_{\beta\delta}$$

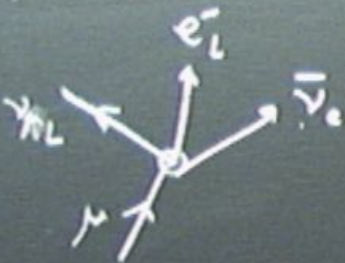
$$= -\frac{4i G_F \cdot 2}{\sqrt{2}} u_L^\dagger(\nu_\mu) \epsilon_{\alpha\gamma} u_L^\dagger(e) \epsilon_{\beta\delta} u_L(\mu) u_L(\bar{\nu}_e)$$

$$u(\mu) = \sqrt{m} \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

$$u_L = \sqrt{2E} \begin{pmatrix} -\sin\theta_L \\ \cos\theta_L \end{pmatrix}$$

$$u_L(\mu) = \sqrt{m} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

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



$$= -\frac{4iG_F}{\sqrt{2}} \underbrace{u_L^+(\nu_\mu) \bar{\sigma}^\mu u_L(\mu)}_{J^+} \underbrace{u_L^-(e) \bar{\sigma}_\mu u_L(\bar{\nu}_e)}_{J^-}$$

Fierz identity

$$(\bar{\sigma}^\mu)_{\nu\rho} (\bar{\sigma}^\mu)_{\delta\sigma} = 2 \epsilon_{\alpha\gamma} \epsilon_{\beta\delta}$$

$$= -\frac{4iG_F \cdot 2}{\sqrt{2}} u_L^+(\nu_\mu) \epsilon_{\alpha\gamma} u_L^+(e) \left[u_L^+(\nu_\mu) \epsilon_{\beta\delta} u_L^-(\bar{\nu}_e) \right]$$

$$u(\mu) = \sqrt{m} \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}$$

$$u_L(\mu) = \sqrt{m} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$u_L = \sqrt{2E} \begin{pmatrix} -\sin \theta_L \\ \cos \theta_L \end{pmatrix}$$

$$\sqrt{2E} m \cos \theta_L$$



Diagram showing a semi-circular arc with an angle θ and a radius r . The arc is divided into several segments. A handwritten equation is written below the diagram:

$$\left| \int_{-\theta/2}^{\theta/2} \epsilon_{ps} \nu_s \right| = \epsilon_{ps} m_r (1 + \cos \theta)$$

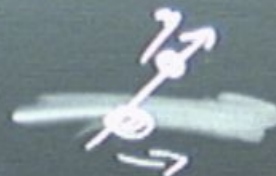


$$|u_L \epsilon_{\beta\gamma} v_L| = E v m (1 + \cos \theta)$$

$$|u_L \epsilon_{\beta\gamma} v_s| = \epsilon_{\beta\gamma} m_\mu (1 + \cos \theta)$$



$$|u_L \epsilon_{\beta\gamma} v_s| = 2 E_{\nu} m_{\nu} (1 + \cos \theta)$$





$$|u_L \epsilon_{\beta\gamma} v_L| = E_\nu m_\nu (1 + \cos \theta)$$

$$u_L^{(\nu)} \epsilon_{\alpha\gamma} v_L^{(\nu)}$$



$$|u_L(\nu) \epsilon_{\beta\gamma} u_L(\nu)|^2 = 2 E_\nu m_\nu (1 + \cos\theta)$$

$$u_L(\nu) \epsilon_{\alpha\gamma} u_L(\nu)$$

$$u_L(\nu) = \sqrt{2E_\nu} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$= \sqrt{4E_\nu E_e} \begin{pmatrix} -1 \end{pmatrix}$$

$$u_L(e) = \sqrt{2E_e} \begin{pmatrix} -1 \\ 0 \end{pmatrix}$$

$$|u_L(\nu) \epsilon_{\alpha\gamma} u_L(e)|^2 = 4E_\nu E_e =$$





$$|u_L(v_f) \epsilon_{\beta\gamma} u_L(v_i)|^2 = 2 E_v m_f (1 + \cos \theta)$$

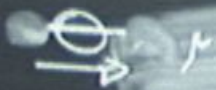
$$u_L(v_f) \epsilon_{\alpha\gamma} u_L(v_i)$$

$$u_L(v_f) = \sqrt{2E_v} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$u_L(v_i) = \sqrt{2E_e} \begin{pmatrix} -1 \\ 0 \end{pmatrix}$$

$$= \sqrt{4E_v E_e} (-1)$$

$$|u_L(v_f) \epsilon_{\alpha\gamma} u_L(v_i)|^2 = 4E_v E_e = (p_v + p_e)^2$$



$$|u_L(v) \epsilon_{\beta\gamma} u_L(v)|^2 = 2 E_v m_p (1 + \cos \theta)$$

$$u_L(v) \epsilon_{\alpha\gamma} u_L(v)$$

$$u_L(v) = \sqrt{2E_v} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

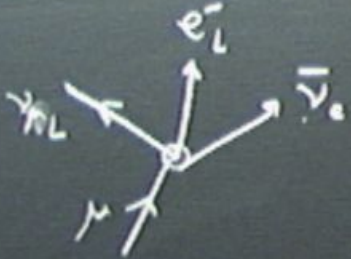
$$= \sqrt{4E_v E_e} \begin{pmatrix} -1 \\ 0 \end{pmatrix}$$

$$u_L(e) = \sqrt{2E_e} \begin{pmatrix} -1 \\ 0 \end{pmatrix}$$

$$|u_L(v) \epsilon_{\alpha\gamma} u_L(e)|^2 = 4E_v E_e = (p_v + p_e)^2 = (p_v - p_v)^2$$



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



$$= -\frac{4 G_F}{\sqrt{2}}$$

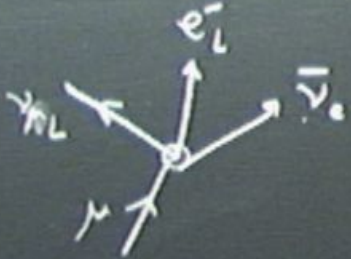
$$\underbrace{J^+}_{+\bar{u}_l(\nu_l) \gamma^\mu u_l(\mu)}$$

$$\underbrace{J^-}_{+\bar{u}_l(e) \gamma^\mu u_l(\bar{\nu}_e)}$$

Fierz identit

$$|M|^2 = \frac{64}{2} G_F^2$$

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



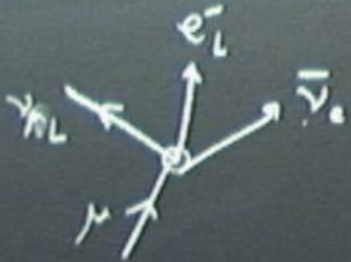
$$= -\frac{4 G_F^2}{\sqrt{2}}$$

$$\underbrace{+}_{J^+} u_\ell(\nu_\mu) \bar{\sigma}_\mu u_\ell(\mu) \quad \underbrace{+}_{J^-} u_\ell(e) \bar{\sigma}_\mu u_\ell(\bar{\nu}_e)$$

Fierz identity

$$|M|^2 = \frac{64}{2} G_F^2 \frac{m_\mu^2}{128\pi^3} \int E_{\nu_\mu} (P_\mu - P_e)^2$$

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



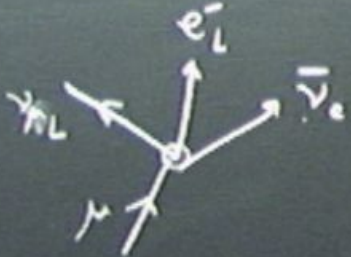
$$= -\frac{4 G_F^2}{\sqrt{2}}$$

$$\underbrace{+}_{J^+} \bar{u}_l(\nu_\mu) \sigma^\mu u_l(\mu) \quad \underbrace{+}_{J^-} \bar{u}_l(e) \sigma^\mu u_l(\bar{\nu}_e)$$

Freiz identity

$$|M|^2 = \frac{64}{2} G_F^2 \frac{m_\mu^2}{128\pi^3} \int dx_0 dx_\nu \frac{\frac{1}{2} m_\mu x_\nu}{E_\nu m_\mu} (P_\mu - P_\nu)^2$$

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



$$= -\frac{4i G_F}{\sqrt{2}}$$

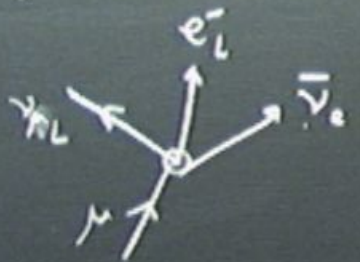
$$\underbrace{J^+}_{+} \bar{u}_l(\nu_\mu) \sigma^\mu u_l(\mu)$$

$$\underbrace{J^-}_{+} \bar{u}_l(e) \sigma_\mu u_l(\bar{\nu}_e)$$

Fierz identity

$$|M|^2 = \frac{64}{2} G_F^2 \frac{m_\mu^2}{128\pi^3} \int dx_0 dx_\nu \frac{\frac{1}{2} m_\mu x_\nu}{E_\nu m_\mu} \frac{(p_\mu - p_\nu)^2}{m_\mu^2 (1 - x_\nu)}$$

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



$$= -\frac{4 G_F^2}{\sqrt{2}}$$

$$\overbrace{+}^{J^+}$$

$$u_l(\nu_e) \sigma_\mu u_l(\mu)$$

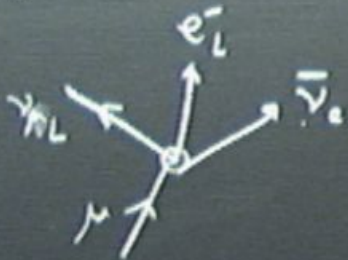
$$\overbrace{+}^{J^-}$$

$$u_l(e) \sigma_\mu v_l(\bar{\nu}_e)$$

$$\Gamma = \frac{1}{2m} \int d\pi_3 |M|^2 = \frac{1}{2m} \frac{G_F^2}{2} G_F^2 \frac{m_\mu^2}{128\pi^3} \int dx_e dx_{\bar{\nu}} \frac{1}{E_\nu m_\mu} \frac{(p_\mu - p_\nu)^2}{m_\mu^2 (1-x_{\bar{\nu}})}$$

$$= \frac{G_F^2 m_\mu^5}{16\pi^3}$$

$$\mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu$$



$$= -\frac{4 G_F^2}{\sqrt{2}}$$

$$\underbrace{J^+}$$

$$+ \frac{1}{\sqrt{2}} \bar{u}_l(\nu_\mu) \sigma^\mu u_l(\mu)$$

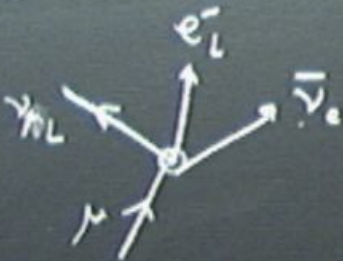
$$\underbrace{J^-}$$

$$+ \frac{1}{\sqrt{2}} \bar{u}_l(e) \sigma^\mu u_l(\bar{\nu}_e)$$

$$\Gamma = \frac{1}{2m} \int d\pi_3 |M|^2 = \frac{1}{2m} \frac{G_F^2}{2} G_F^2 \frac{m_\mu^2}{128\pi^3} \int dx_\mu dx_\nu \frac{\frac{1}{2} m_\mu x_\nu}{E_\nu m_\mu} \frac{(p_\mu - p_\nu)^2}{m_\mu^2 (1-x_\nu)}$$

$$= \frac{G_F^2 m_\mu^5}{16\pi^3} \int dx_\mu \int dx_\nu x_\nu (1-x_\nu)$$

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



$$= \frac{4 G_F^2}{\sqrt{2}}$$

$$\underbrace{+}_{J^+} \frac{1}{2} m_\mu \not{x}_\nu \underbrace{+}_{J^-} \frac{1}{2} m_e \not{x}_\nu$$

Freizid

$$= \frac{1}{2} \int d\Omega_3 |M|^2 = \frac{1}{2m_\mu} \frac{64}{2} G_F^2 \frac{m_\mu^2}{128\pi^3} \int dx_e dx_{\bar{\nu}} \frac{1}{E_\nu m_\mu} \frac{(P_\mu - P_e)^2}{m_\mu^2 (1-x_{\bar{\nu}})}$$

$$= \frac{G_F^2 m_\mu^5}{16\pi^3} \int_0^1 dx_e \int_{1-x_e}^1 dx_{\bar{\nu}} x_{\bar{\nu}} (1-x_{\bar{\nu}})$$

$$\int_0^{x_e} d\omega (1-\omega) \omega = \left(\frac{x_e^2}{2} - \frac{x_e^3}{3} \right)$$

$$= \frac{G_F^2 m_\mu^5}{16\pi^3} \int_0^1 dx_e x_e^2 \left(1 - \frac{2}{3} x_e \right)$$

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



$$= -\frac{4i G_F}{\sqrt{2}}$$

$$\underbrace{+}_{J^+} \frac{1}{2} m_\mu \gamma_5 u_\ell(\mu) \bar{\sigma}_\mu \nu_\ell(\bar{\nu}_e) \underbrace{+}_{J^-} u_\ell(e) \bar{\sigma}_\mu \nu_\ell(\bar{\nu}_e)$$

Fierz identity

$$\frac{1}{m} \int d^3x |M|^2 = \frac{1}{2m_\mu} \frac{G_F^2}{2} G_F^2 \frac{m_\mu^2}{128\pi^3} \int dx_e dx_{\bar{\nu}} \frac{1}{E_{\bar{\nu}} m_\mu} \frac{(p_\mu - p_{\bar{\nu}})^2}{m_\mu^2 (1-x_{\bar{\nu}})}$$

$$= \frac{G_F^2 m_\mu^5}{16\pi^3} \int_0^1 dx_e \int_{1-x_e}^1 dx_{\bar{\nu}} x_{\bar{\nu}} (1-x_{\bar{\nu}})$$

$$\int_0^{x_e} d\omega (1-\omega) \omega = \left(\frac{x_e^2}{2} - \frac{x_e^3}{3} \right)$$

$$= \frac{G_F^2 m_\mu^5}{16\pi^3} \int_0^1 dx_e x_e^2 \left(1 - \frac{2}{3} x_e \right)$$



$$|\mathcal{U}_L \epsilon_{\beta\gamma} v_{L\gamma}| = F m r (1 + \cos \theta)$$

$$I = \frac{G_F^2 m^5}{192 \pi^3}$$



$$= \frac{1}{2} m \int d\theta$$



$$|\mathcal{U}_{L\beta} \Sigma_{\beta\delta} \mathcal{U}_{L\delta}| = E_{\nu} m_{\nu} (1 + \cos \Theta)$$

$$I = \frac{G_F^2 m_{\nu}^5}{192 \pi^3}$$



$$= \frac{1}{2} \int d\Omega$$



$$|u_{L, \beta} \epsilon_{\beta \delta} v_{L, \delta}| = E \cdot m_p (1 + \cos \theta)$$

$$I = \frac{G_F^2 m_p^5}{192 \pi^3}$$

$$G_F = 1.166$$

$$= \frac{1}{2} \int d\Omega$$

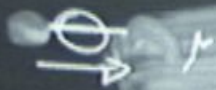


$$|\mathcal{M}_{\beta\beta} \epsilon_{\beta\delta} v_{\delta}| = E_{\nu} m_{\nu} (1 + \cos\theta)$$

$$I = \frac{G_F^2 m_{\nu}^5}{192\pi^3}$$

$$G_F = 1.16637(1) \times 10^{-5} \text{ GeV}^{-2}$$

$$= \frac{1}{2m} \int d\Omega$$



$$|\mathcal{M}_{\beta\beta}^{\nu, s}| = E_{\nu} m_{\nu} (1 + \cos\theta)$$

$$I = \frac{G_F^2 m_{\nu}^5}{192\pi^3}$$

$$G_F = 1.16637(1) \times 10^{-5} \text{ GeV}^{-2}$$

#



$\times e$

$$= \frac{1}{2m} \int d^3p$$



$$|\mathcal{M}_{\beta\beta}^2| = E_\nu m_\mu (1 + \cos\theta)$$

$$I = \frac{G_F^2 m_\mu^5}{192 \pi^3}$$

$$G_F = 1.16637(1) \times 10^{-5} \text{ GeV}^{-2}$$

#



$\times e$

$$= \frac{1}{2m} \int d\Omega$$



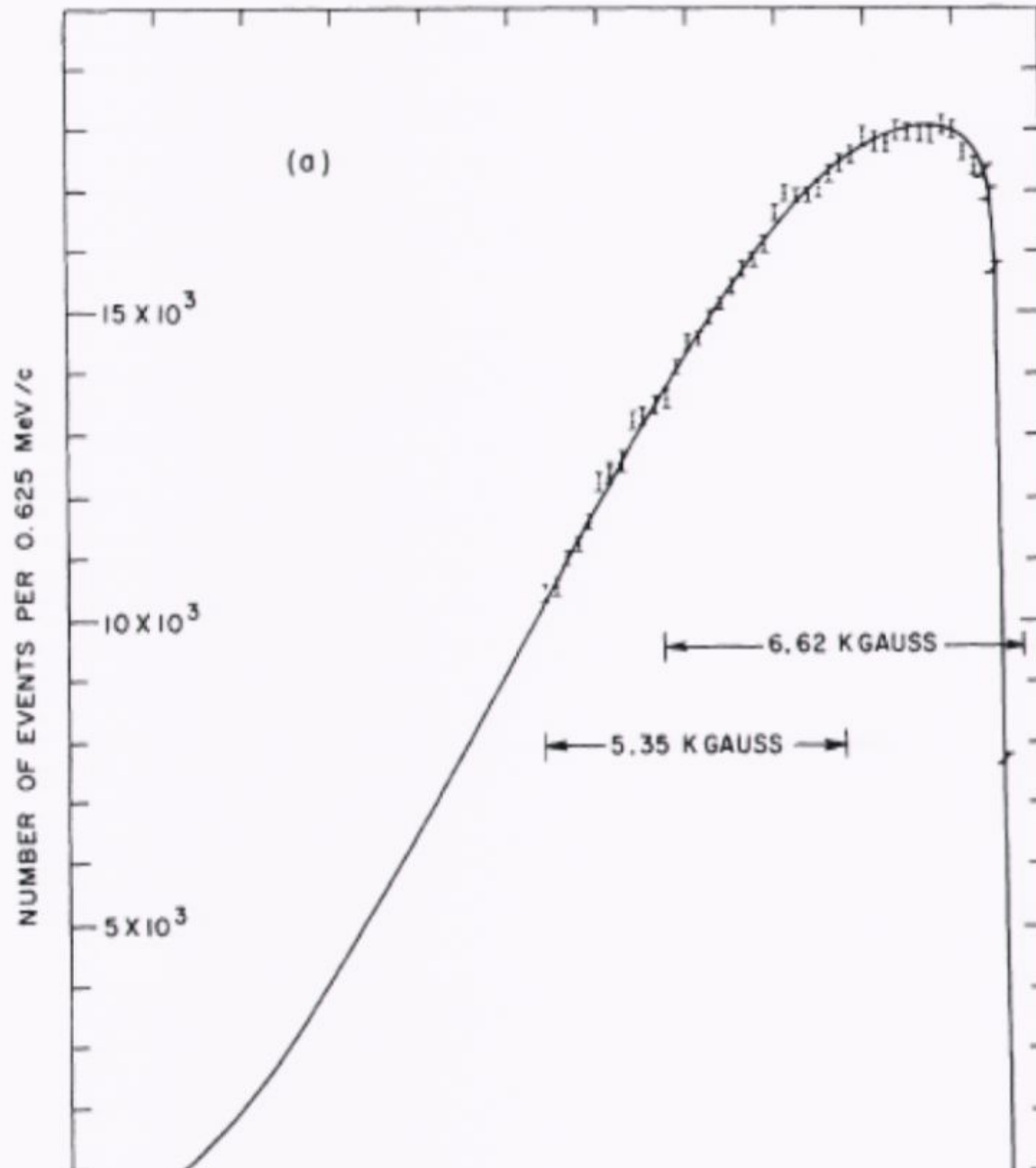
$$|\mathcal{M}_{\beta\beta}^2| = E_\nu m_\nu (1 + \cos\theta)$$

$$I = \frac{G_F^2 m_\nu^5}{192\pi^3}$$

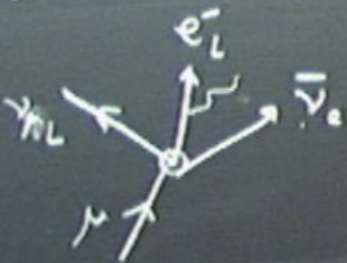
$$G_F = 1.16637(1) \times 10^{-5} \text{ GeV}^{-2}$$



$$= \frac{1}{2m} \int d\Omega$$



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



$$= \frac{4 G_F^2}{s^2}$$

$$\overbrace{+}^{J^+}$$

$$u_\mu(\nu_\mu) \gamma^\mu u_\mu(\mu)$$

$$\overbrace{+}^{J^-}$$

$$u_e(e) \gamma^\mu u_e(\bar{\nu}_e)$$

Fierz identity

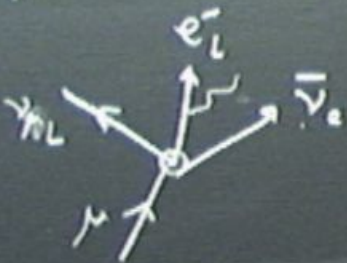


electrons at $x_e = 1$

$$\frac{d\Gamma}{d\cos\theta} \sim (1 + \cos\theta)$$

$$\frac{d\Gamma}{d\cos\theta_e} \sim (1 - \cos\theta_e)$$

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



$$= \frac{4 G_F^2}{s^2}$$

$$\underbrace{J^+}_{\psi_l(\nu_\mu) \gamma^\mu \psi_l(\mu)} \quad \underbrace{J^-}_{\psi_l(e) \gamma^\mu \psi_l(\bar{\nu}_e)}$$

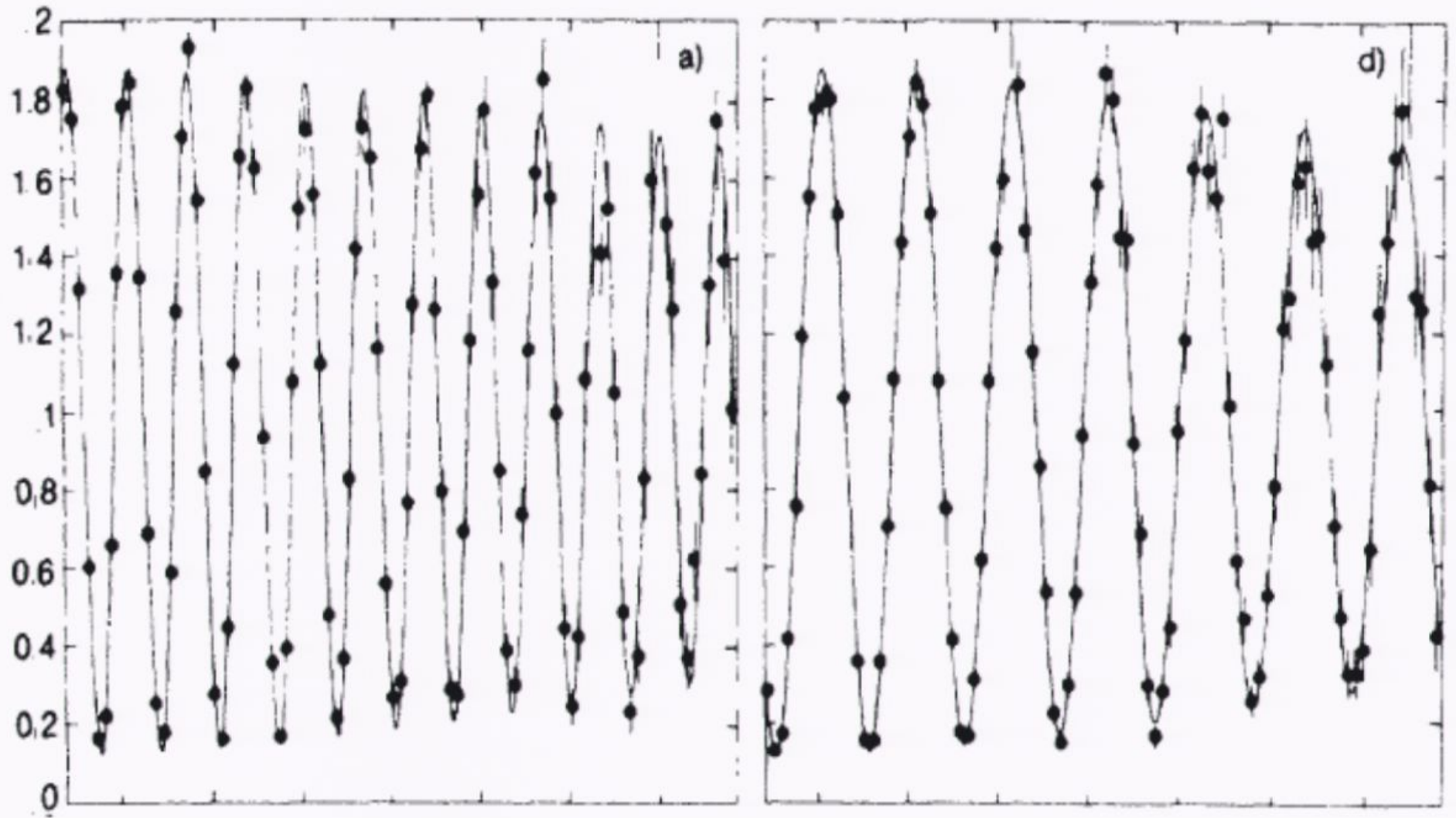
Fierz identity



electrons at $x_e = 1$

$$\frac{d\Gamma}{d\cos\theta} \sim (1 + \cos\theta)$$

$$\frac{d\Gamma}{d\cos\theta_e} \sim (1 - \cos\theta_e)$$



$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$



$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

$$\bar{u}_1 \gamma^\mu d_2 = \frac{1}{\sqrt{2}} \bar{u} \gamma^\mu (1 - \gamma_5) u$$

$$\frac{1}{\sqrt{2}} \bar{u} \gamma^\mu (1 - \gamma_5) u = \sqrt{2} \langle 1 | \bar{u} \gamma^\mu (1 - \gamma_5) u | 0 \rangle$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

$$\bar{u}_i \gamma^\mu d_i = \frac{1}{2} \bar{u} \gamma^\mu (1 - \gamma^5) d$$

$$\langle 0 | (\bar{u} \gamma^\mu d) | \pi^-(k) \rangle = \sqrt{2} i k^\mu f_\pi$$

$$\mathcal{M} = -\frac{4iG_F}{\sqrt{2}} \sqrt{2} i k^\mu f_\pi$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

$$\bar{u}_i \gamma^\mu d_i = \frac{1}{2} \bar{u}_i \gamma^\mu (1 - \gamma_5) d_i$$

$$\langle 0 | (\bar{u}_i \gamma^\mu d_i) | \pi^- \rangle = \sqrt{2} f_\pi k^\mu$$

$$\mathcal{M} = -\frac{4iG_F}{\sqrt{2}} \sqrt{2} f_\pi k^\mu \bar{u}_i \gamma_\mu (1 - \gamma_5) \nu_i(\bar{\nu}_\mu)$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

$$\bar{u}_1 \gamma^\mu d_2 = \bar{u} \gamma^\mu (1 - \gamma^5) d$$

$$\langle 0 | (\bar{u} \gamma^\mu d) | \pi^- \rangle = \sqrt{2} f_\pi k^\mu$$

$$\mathcal{M} = -\frac{4iG_F}{\sqrt{2}} \sqrt{2} f_\pi k^\mu \bar{u}_1 \gamma_\mu (1 - \gamma^5) v_2$$

$$u = \begin{pmatrix} \dots \\ \dots \end{pmatrix} \quad v = \sqrt{2E} \begin{pmatrix} \dots \\ \dots \end{pmatrix}$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$



$$\bar{u}_1 \gamma^\mu d_2 = \bar{u} \gamma^\mu (1 - \gamma_5) d$$

$$\langle 0 | \bar{u} \gamma^\mu d | \pi^- \rangle = \sqrt{2} f_\pi k^\mu$$

$$\mathcal{M} = -\frac{4iG_F}{\sqrt{2}} \sqrt{2} f_\pi k^\mu \bar{u}_1 \gamma_\mu (1 - \gamma_5) v_2$$

$$u = \begin{pmatrix} \dots \\ \dots \end{pmatrix} \quad v = \sqrt{2E} \begin{pmatrix} -1 \\ 0 \end{pmatrix}$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$



$$\bar{u}_1 \gamma^\mu d_2 = \bar{u} \gamma^\mu (1 - \gamma_5) d$$

$$\langle 0 | \bar{u} \gamma^\mu (1 - \gamma_5) d | \pi^- \rangle = \sqrt{2} f_\pi k^\mu$$

$$\mathcal{M} = -\frac{4iG_F}{\sqrt{2}} \sqrt{2} f_\pi k^\mu \bar{u}_1 \gamma_\mu (1 - \gamma_5) v_2$$

$$u = \begin{pmatrix} \sqrt{E+k} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \\ \sqrt{E+k} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \end{pmatrix} \quad | \quad v = \sqrt{2E} \begin{pmatrix} -1 \\ 0 \end{pmatrix}$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$



$$\bar{u}_i \gamma^\mu d_i = \frac{1}{\sqrt{2}} \bar{u} \gamma^\mu (1 - \gamma_5) d$$

$$\langle 0 | (\bar{u} \gamma^\mu d) | \pi^-(k) \rangle = \sqrt{2} i k^\mu f_\pi$$

$$\mathcal{M} = -\frac{4iG_F}{\sqrt{2}} \sqrt{2} i k^\mu f_\pi \bar{u}_i \gamma_\mu d_i$$

$$u = \begin{pmatrix} \sqrt{E+k} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \\ \sqrt{E-k} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \end{pmatrix} \quad \nu = \sqrt{2E} \begin{pmatrix} -1 \\ 0 \end{pmatrix}$$

$$k_1 \bar{u} \gamma_1 = \bar{u} k_1 = m_1 \bar{u}$$

$$k_1 \bar{u} \gamma_1 \left(\frac{1-\delta}{2} \right) v_L = m_1 \bar{u} \left(\frac{1-\delta}{2} \right) v = m_1 \bar{u} \gamma_1^+ v_L$$

$$k_1 \bar{u} \gamma_1 = \bar{u} k_1 = m_1 \bar{u}$$

$$k_1 \bar{u} \gamma_1 \left(\frac{1-\beta}{2} \right) v_L = m_1 \bar{u} \left(\frac{1-\beta}{2} \right) v = m_1 u_R^+ v_L$$

$$= m_1 \sqrt{E_1 + k_1} \sqrt{2E_2} (-1)$$

$$k_x \bar{u} \gamma_x = \bar{u} k_x = m_\mu \bar{u}$$

$$k_x \bar{u} \gamma_x \left(\frac{1-\delta}{2}\right) v_L = m_\mu \bar{u} \left(\frac{1-\delta}{2}\right) v = m_\mu \bar{u}_R^+ v_L$$

$$= m_\mu \sqrt{E_p + k_x} \sqrt{2E_\nu} (-1)$$

$$|m|^2$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$



$$\bar{u}_l \gamma^\mu d_l = \frac{1}{\sqrt{2}} \bar{u}_l \gamma^\mu (1 - \gamma^5) d_l$$

$$\langle 0 | (\bar{u}_l \gamma^\mu d_l) | \pi^-(k) \rangle = \sqrt{2} i k^\mu f_\pi$$

$$\mathcal{M} = -\frac{4iG_F}{\sqrt{2}} \sqrt{2} i k^\mu f_\pi \bar{u}_l \gamma_\mu (1 - \gamma^5) v_l(\bar{\nu}_\mu)$$

$$u = \begin{pmatrix} \sqrt{E-k} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \\ \sqrt{E+k} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \end{pmatrix} \quad \nu = \sqrt{2E} \begin{pmatrix} -1 \\ 0 \end{pmatrix}$$

$$k_x \bar{u} \gamma_x = \bar{u} k_x = m_\lambda \bar{u}$$

$$k_x \bar{u} \gamma_x \left(\frac{1-\delta}{2}\right) v_L = m_\lambda \bar{u} \left(\frac{1-\delta}{2}\right) v = m_\lambda u_R^+ v_L$$

$$= m_\lambda \sqrt{E_p + k_x} \sqrt{2E_p} (-1)$$

$$|m|^2 = 4 c_F^2 v_F^2 m_\lambda^2$$

$$k_x \bar{u} \gamma_x = \bar{u} k_x = m_\lambda \bar{u}$$

$$k_x \bar{u} \gamma_x \left(\frac{1-\delta}{2} \right) v_L = m_\lambda \bar{u} \left(\frac{1-\delta}{2} \right) v = m_\lambda u_R^+ v_L$$

$$= m_\lambda \sqrt{E_+ + k_x} \sqrt{2E_-} (-1)$$

$$|m|^2 = 4 c_F^2 v_F^2 m_\lambda^2 (E_+ + k_x) E_- \cdot 2$$

$$k_{\lambda} \bar{u} \gamma_{\lambda} = \bar{u} k = m_{\lambda} \bar{u}$$

$$k_{\lambda} \bar{u} \gamma_{\lambda} \left(\frac{1-\delta}{2}\right) u_{\pm} = m_{\lambda} \bar{u} \left(\frac{1-\delta}{2}\right) u = m_{\lambda} u_{\mp}^{\pm} u_{\pm}$$

$$= m_{\lambda} \sqrt{E_{\lambda} + k_{\lambda}} \sqrt{2E_{\pm}} (-1)$$

$$|m|^{-2} = 4 \left(\frac{1}{4\pi}\right)^2 \delta_{\pi}^2 m_{\lambda}^2 (E_{\lambda} + k_{\lambda}) E_{\pm} \cdot 2$$

$$k_{\mu} = k_{\pm} = E_{\pm} = \frac{m_{\pi}^2 - m_{\lambda}^2}{2m_{\pi}} \quad E_{\lambda} = \frac{m_{\pi}^2 + m_{\lambda}^2}{2m_{\pi}}$$

$$I = \frac{1}{2m_{\pi}} \frac{1}{\delta_{\pi}} \left(\frac{2k}{m_{\pi}}\right)$$

$$k_{\lambda} \bar{u} \gamma_{\lambda} = \bar{u} k = m_{\lambda} \bar{u}$$

$$k_{\lambda} \bar{u} \gamma_{\lambda} \left(\frac{1-\delta}{2}\right) u_{\pm} = m_{\lambda} \bar{u} \left(\frac{1-\delta}{2}\right) u = m_{\lambda} u_{\mp}^{\pm} u_{\pm}$$

$$= m_{\lambda} \sqrt{E_{\lambda} + k_{\lambda}} \sqrt{2E_{\pm}} (-1)$$

$$|m|^2 = 4 \left(\frac{1}{4\pi}\right)^2 \left(\frac{2}{5\pi}\right)^2 m_{\lambda}^2 (E_{\lambda} + k_{\lambda}) E_{\pm} \cdot 2$$

$$k_{\lambda} = k_{\pm} = E_{\pm} = \frac{m_{\pi}^2 - m_{\lambda}^2}{2m_{\pi}} \quad E_{\lambda} = \frac{m_{\pi}^2 + m_{\lambda}^2}{2m_{\pi}}$$

$$I = \frac{1}{2m_{\pi}} \frac{1}{8\pi} \left(\frac{2k}{m_{\pi}}\right) |m|^2$$

$$I = \frac{\left(\frac{1}{4\pi}\right)^2 \left(\frac{2}{5\pi}\right)^2 m_{\pi}^3}{4\pi} m_{\lambda}^2 \left(\frac{m_{\pi}^2 - m_{\lambda}^2}{m_{\pi}^2}\right)^2$$

$$k_\mu \bar{u} \gamma_\mu = \bar{u} k = m_\mu \bar{u}$$

$$k_\mu \bar{u} \gamma_\mu \left(\frac{1-\gamma_5}{2}\right) v = m_\mu \bar{u} \left(\frac{1-\gamma_5}{2}\right) v = m_\mu \bar{u}_R^+ v_L$$

$$= m_\mu \sqrt{E_\mu + k_\mu} \sqrt{2E_\nu} (-1)$$

$$|M|^2 = 4 \left(\frac{g_F}{4\pi}\right)^2 f_\pi^2 m_\mu^2 (E_\mu + k_\mu) E_\nu \cdot 2$$

$$k_\mu = k_\nu = E_\nu = \frac{m_\pi^2 - m_\mu^2}{2m_\pi}$$

$$E_\mu = \frac{m_\pi^2 + m_\mu^2}{2m_\pi}$$

$$f_\pi = 92 \text{ MeV}$$

$$I = \frac{1}{2m_\pi} \frac{1}{8\pi} \left(\frac{2k}{m_\pi}\right) |M|^2$$

$$\frac{g_F^2}{4\pi} \frac{f_\pi^2}{8\pi} \frac{m_\pi^3}{m_\mu^2} \left(\frac{m_\pi^2 - m_\mu^2}{m_\pi^2}\right)^2$$

$$I = \frac{\dots}{4\pi}$$

$$\frac{\text{BR}(\pi \rightarrow e\nu)}{\text{BR}(\pi \rightarrow \mu\nu)} = \frac{m_e^2}{m_\mu^2} \left(\frac{1 - m_e^2/m_\pi^2}{1 - m_\mu^2/m_\pi^2} \right)^2 = 1.28 \times 10^{-4}$$

up 1.23×10^{-4}

$$\frac{\text{BR}(\pi \rightarrow e \nu)}{\text{BR}(\pi \rightarrow \mu \nu)} = \frac{m_e^2}{m_\mu^2} \left(\frac{1 - m_e^2/m_\pi^2}{1 - m_\mu^2/m_\pi^2} \right)^2 = 1.28 \times 10^{-4}$$

upto 1.23×10^{-4}


$$\frac{\text{BR}(\pi \rightarrow e\nu)}{\text{BR}(\pi \rightarrow \mu\nu)} = \frac{m_e^2}{m_\mu^2} \left(\frac{1 - m_e^2/m_\pi^2}{1 - m_\mu^2/m_\pi^2} \right)^2 = 1.28 \times 10^{-4}$$

up 1.23×10^{-4}

$$\frac{ds}{dx dy} (\nu A \rightarrow)$$


$$\frac{d\sigma}{dx dy} (\nu A \rightarrow \mu^- X)$$





A Feynman diagram showing a neutrino (ν) and an electron (e) interacting via a W boson. The neutrino line is on the left, and the electron line is on the right. A wavy line representing the W boson connects them. The neutrino line ends in an arrow pointing right, and the electron line ends in an arrow pointing right. There are some scribbles below the electron line.

$$\frac{d\sigma}{dx dy} (\nu A \rightarrow \mu^- X)$$



A Feynman diagram showing a neutrino (ν) and an antineutrino (ν̄) interacting via a Z boson with a quark (q) and an antiquark (q̄). The neutrino and antineutrino lines are solid, and the quark and antiquark lines are also solid. A wavy line represents the Z boson exchange between the neutrino and quark vertices.

$$\frac{d\sigma}{dx dy} (\nu A \rightarrow \mu^- X) = \frac{G_F^2 s}{4} \left[x f_q(x) + x f_{\bar{q}}(1-y)^2 \right]$$





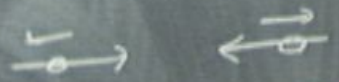
$$\frac{d\sigma}{dx dy} (\nu A \rightarrow \mu^- \bar{\nu}) = \frac{G_F^2 s}{\pi} [x f_q(x) + x f_{\bar{q}}(1-y)^2]$$

$$\frac{d\sigma}{dx dy} (\bar{\nu} A \rightarrow \mu^+ \bar{\nu}) = \frac{G_F^2 s}{\pi} [x f_q(x)(1-y)^2 + x f_{\bar{q}}(x) \cdot 1]$$



$$\frac{d\sigma}{dx dy} (\nu A \rightarrow \mu^- X) = \frac{G_F^2 s}{\pi} \left[x f_q(x) + x f_{\bar{q}}(1-y)^2 \right]$$

$$\frac{d\sigma}{dx dy} (\bar{\nu} A \rightarrow \mu^+ X) = \frac{G_F^2 s}{\pi} \left[x f_q(x)(1-y)^2 + x f_{\bar{q}}(x) \cdot 1 \right]$$

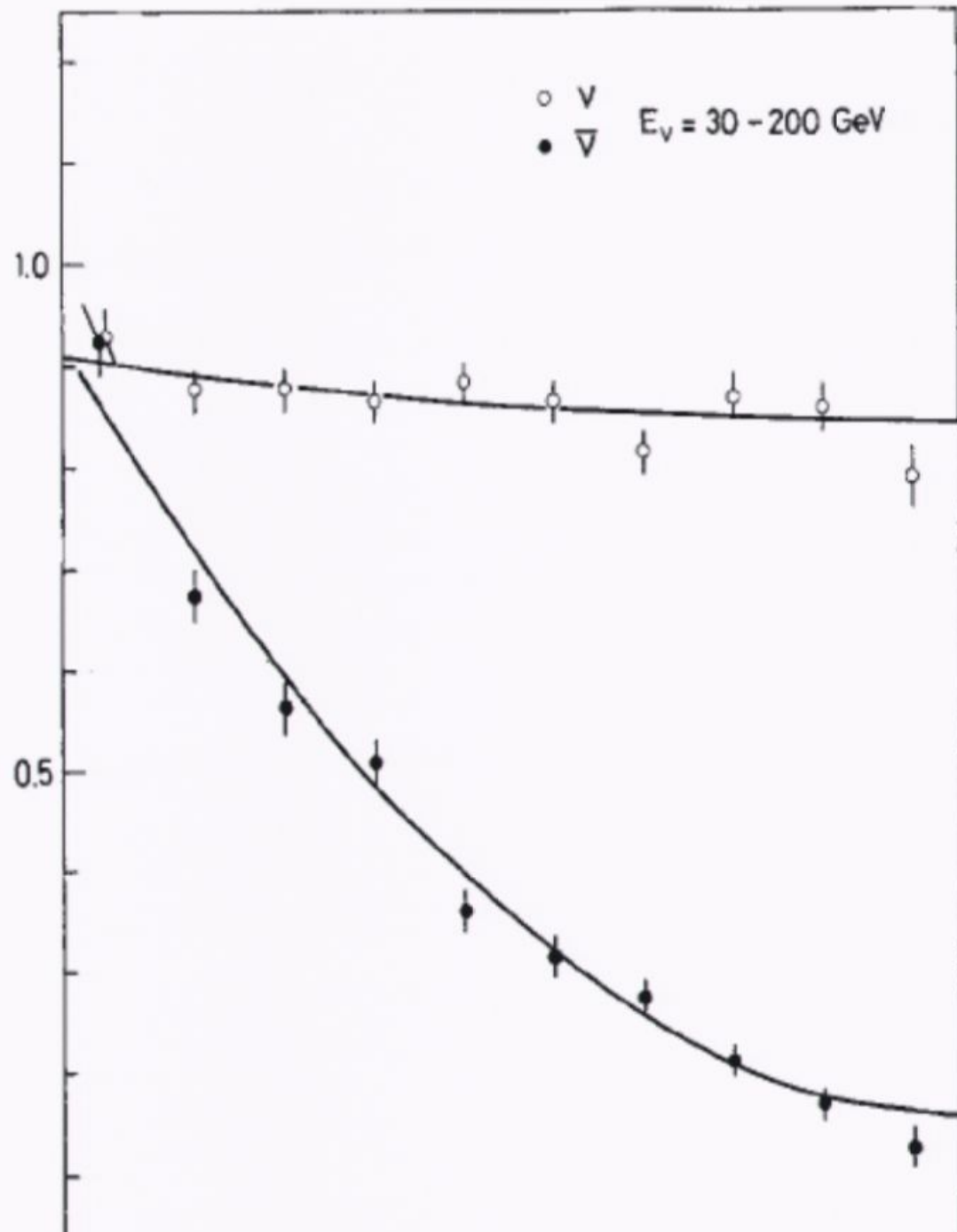


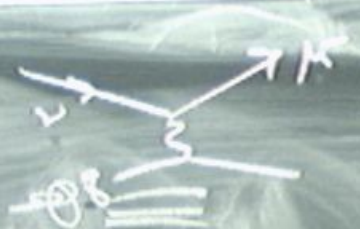


$$\frac{d\sigma}{dx dy} (\nu A \rightarrow \mu^- X) = \frac{G_F^2 s}{4} \left[x f_q(x) + x f_{\bar{q}}(1-y)^2 \right]$$

$$\frac{d\sigma}{dx dy} (\bar{\nu} A \rightarrow \mu^+ X) = \frac{G_F^2 s}{4} \left[x f_{\bar{q}}(x)(1-y)^2 + x f_q(x) \cdot 1 \right]$$







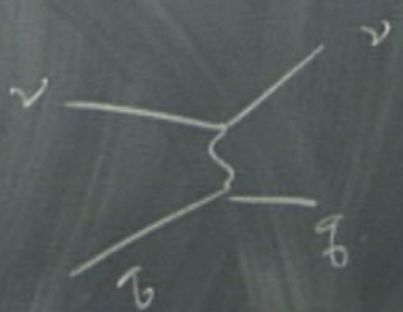
charged-current

$$\frac{d\sigma}{dx dy} (\nu A \rightarrow \mu^- X) = \frac{G_F^2 S}{\pi} [x f_q(x) + x f_{\bar{q}}(1-y)^2]$$

$$\frac{d\sigma}{dx dy} (\bar{\nu} A \rightarrow \mu^+ X) = \frac{G_F^2 S}{\pi} [x f_q(x)(1-y)^2 + x f_{\bar{q}}(x) \cdot 1]$$



neutral-current

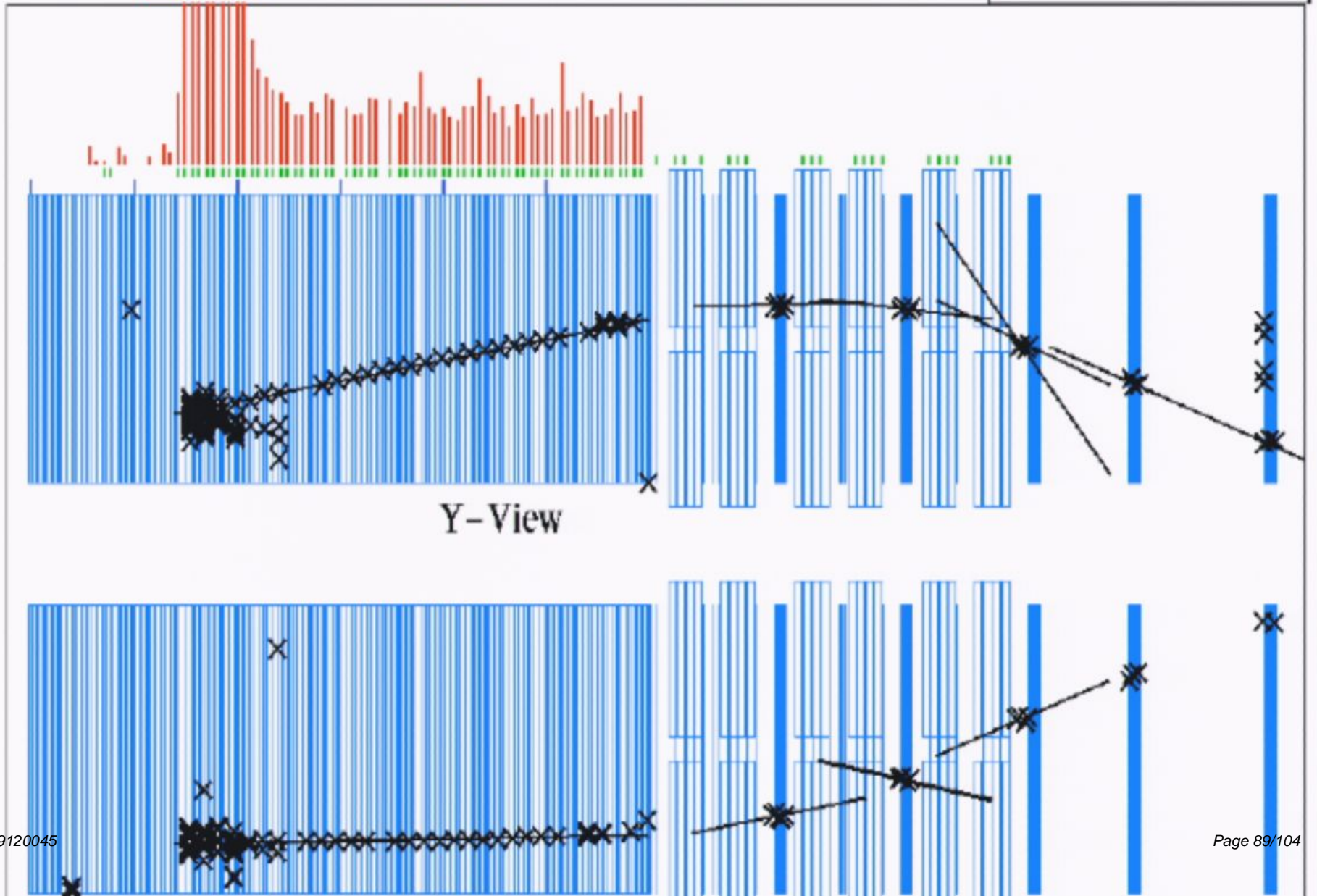


Run: 5153 Event: 1105 Date: Sat Jun 22 22:55:32 1996

EHAD0: 117.06 GeV

Triggers: 1 2 3 4 5 6 7 8 9 10 11 12 13

EMU1: 26.40 GeV



Feynman - Gell-Mann Marshak Sudanshan.
(V-A)

$$S_{\mathcal{L}} = -\frac{4G_F}{\sqrt{2}} \left[(J_{\mu}^+) + (J_{\mu}^{\prime}) \right]^2 + J_{\mu}^3 - S_w^2$$

$$J_{\mu}^{\pm} = \left[(J_{\mu}^{\mu 1} - J_{\mu}^{\mu 51}) \pm i(J_{\mu}^{\mu 2} - J_{\mu}^{\mu 52}) \right]$$

$$J_{\mu}^+ = (\bar{u}_L \gamma^{\mu} d_L + \bar{\nu}_{eL} \gamma^{\mu} e_L) + \begin{pmatrix} c_s & t_l \\ \nu_{\mu} & \nu_e \end{pmatrix}$$

$$J_{\mu}^{-} = (J_{\mu}^+)^{\dagger}$$

Feynman - Gell-Mann Marshak Sudanshan.
(V-A)

$$S_{\mathcal{L}} = -\frac{4G_F}{\sqrt{2}} \left[(J_{\mu}^+) + (J_{\mu}^0) \right]^2 + (J_{\mu}^3 - s_w^2 J_{\mu}^{EM})^2$$

$$J_{\mu}^{\pm} = \left[(\bar{\psi}^{\mu 1} - \bar{\psi}^{\mu 51}) \pm i(\bar{\psi}^{\mu 2} - \bar{\psi}^{\mu 52}) \right]$$

$$J^+ = (\bar{u}_L \gamma^{\mu} d_L + \bar{\nu}_{eL} \gamma^{\mu} e_L) + \begin{pmatrix} c_s & t_L \\ s_w & c_s \end{pmatrix}$$

$$J^- = (J^+)^{\dagger}$$

$$u_1 \quad \frac{1}{2} - \frac{2}{3} S^2$$

$$u_2$$

$$- \frac{2}{3} S^2$$

$$u_2 \quad \frac{1}{2} - \frac{2}{3} S_w^2$$

$$u_2$$

$$- \frac{2}{3} S_w^2$$

$$u_L = \frac{1}{2} - \frac{2}{3} s \omega^2 \quad u_R = -\frac{2}{3} s \omega^2$$

$$\frac{d\sigma}{d\Omega d\Omega'}(v) = \frac{G_{FS}^2}{\pi} \times f_g \left[\left(\frac{1}{2} - \frac{2}{3} s \omega^2 \right)^2 + \left(-\frac{1}{2} + \frac{1}{3} s \omega^2 \right)^2 \right] + \left[\left(-\frac{2}{3} s \omega^2 \right)^2 + \left(\frac{1}{3} s \omega^2 \right)^2 \right] (1-y)^2$$

$$u_1 = \frac{1}{2} - \frac{2}{3} s_w^2 \quad u_2 = -\frac{2}{3} s_w^2$$

$$\frac{d\sigma}{d\Omega dy}^{(v)} = \frac{G_{FS}}{\pi} \left[x f_q \left[\left(\frac{1}{2} - \frac{2}{3} s_w^2 \right)^2 + \left(-\frac{1}{2} + \frac{1}{3} s_w^2 \right)^2 \right] + \left[\left(-\frac{2}{3} s_w^2 \right)^2 + \left(\frac{1}{3} s_w^2 \right)^2 \right] (1-y)^2 \right]$$

$$= \frac{G_{FS}}{\pi} \left[x f_q \left(\frac{1}{2} - s_w^2 \right) + \left(\frac{5}{9} s_w^4 \right) (1 + (1-y)^2) \right]$$



charged-current

$$\sigma(\nu, \ell) = \frac{G_F^2 s}{\pi} [x f_q(x) + x f_{\bar{q}}(1-y)^2]$$

$$\sigma(\bar{\nu}, \ell) = \frac{G_F^2 s}{\pi} [x f_q(x)(1-y)^2 + x f_{\bar{q}}(x) \cdot 1]$$

$$r = \frac{\sigma(\bar{\nu}, \ell)}{\sigma(\nu, \ell)} = \frac{f_{\bar{q}} + f_q(1-y)^2}{f_q + f_{\bar{q}}(1-y)^2}$$



charged-current

$$R_\nu = \frac{\sigma(\nu, NC)}{\sigma(\nu, CC)} =$$

$$r = \frac{\sigma(\bar{\nu}, CC)}{\sigma(\nu, CC)} = \frac{f_{\bar{q}} + f_q(1-y)^2}{f_q + f_{\bar{q}}(1-y)^2}$$



charged-current

$$R_v = \frac{\sigma(v, NC)}{\sigma(v, CC)} = \frac{1}{2} - s_w^2 + \frac{5}{9} s_w^4 (1+r)$$

$$r = \frac{\sigma(\bar{v}, CC)}{\sigma(v, CC)} = \frac{f_{\bar{g}} + f_g(1-y)^2}{f_g + f_{\bar{g}}(1-y)^2}$$



charged-current

$$R^{\nu} = \frac{\sigma(\nu, NC)}{\sigma(\nu, CC)} = \frac{1}{2} - s_w^2 + \frac{5}{9} s_w^4 (1+r)$$

$$R^{\bar{\nu}} = \frac{\sigma(\bar{\nu}, NC)}{\sigma(\bar{\nu}, CC)} = \frac{1}{2} - s_w^2 + \frac{5}{9} s_w^4 (1 + \frac{1}{r})$$

$$r = \frac{\sigma(\bar{\nu}, CC)}{\sigma(\nu, CC)} = \frac{f_{\frac{2}{3}} + f_{\frac{1}{3}}(1-y)^2}{f_{\frac{1}{3}} + f_{\frac{2}{3}}(1-y)^2}$$



charged-current

$$R^v = \frac{\sigma(v, NC)}{\sigma(v, CC)} = \frac{1}{2} - s_w^2 + \frac{5}{9} s_w^4 (1+r)$$

$$R^{\bar{v}} = \frac{\sigma(\bar{v}, NC)}{\sigma(\bar{v}, CC)} = \frac{1}{2} - s_w^2 + \frac{5}{9} s_w^4 (1 + \frac{1}{r})$$

$$r = \frac{\sigma(\bar{v}, CC)}{\sigma(v, CC)} = \frac{f_{\bar{q}} + f_q (1-y)^2}{f_q + f_{\bar{q}} (1-y)^2}$$

~ 0.4



charged-current

$$R^{\nu} = \frac{\sigma(\nu, NC)}{\sigma(\nu, CC)} = \frac{1}{2} - s_w^2 + \frac{5}{9} s_w^4 (1+r)$$

$$R^{\bar{\nu}} = \frac{\sigma(\bar{\nu}, NC)}{\sigma(\bar{\nu}, CC)} = \frac{1}{2} - s_w^2 + \frac{5}{9} s_w^4 (1 + \frac{1}{r})$$

$$r = \frac{\sigma(\bar{\nu}, CC)}{\sigma(\nu, CC)} = \frac{f_{\bar{q}} + f_q (1-y)^2}{f_q + f_{\bar{q}} (1-y)^2}$$

~ 0.4



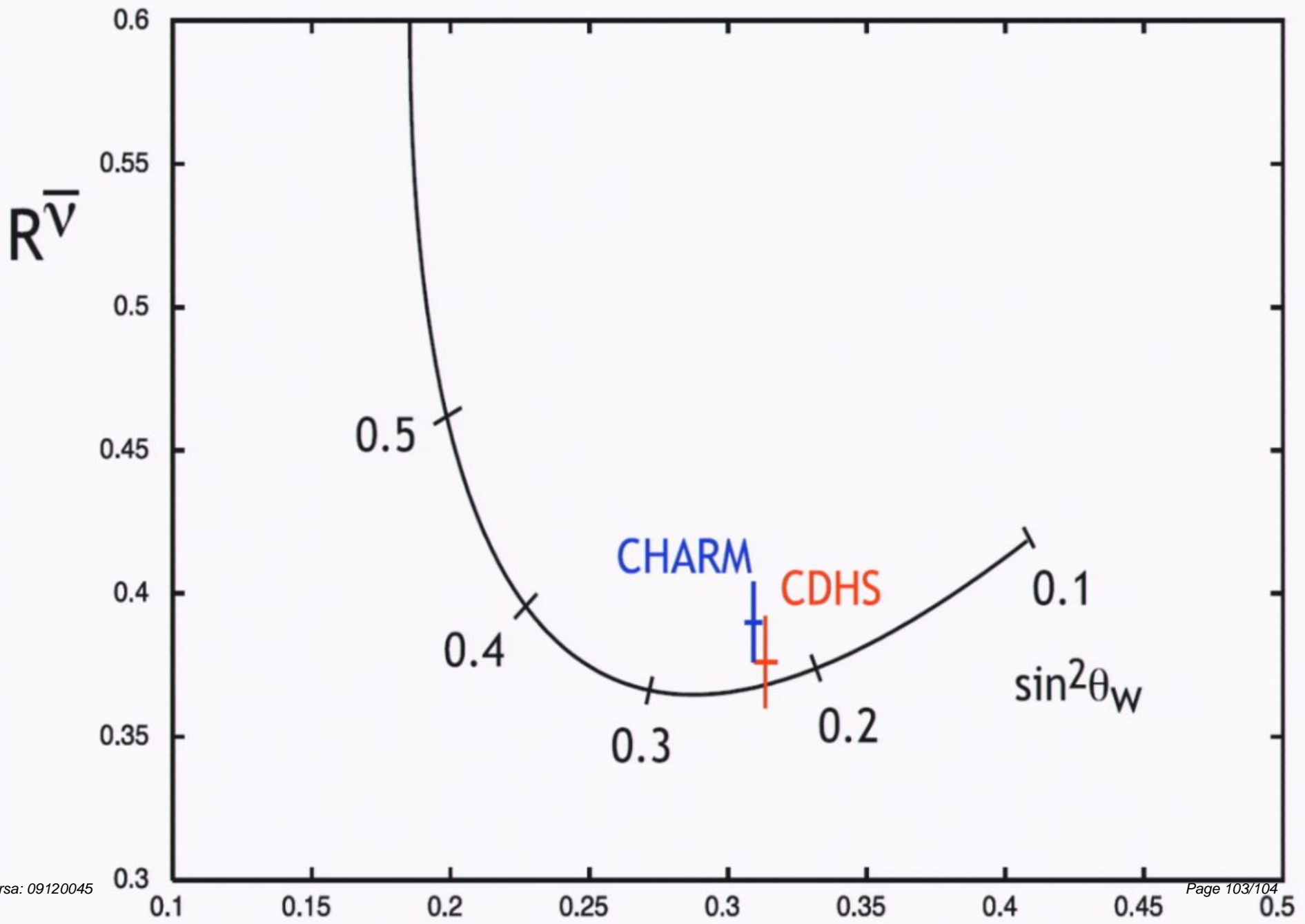
charged-current

$$R^v = \frac{\sigma(v, NC)}{\sigma(v, CC)} = \frac{1}{2} - s_w^2 + \frac{5}{9} s_w^4 (1+r)$$

$$R^{\bar{v}} = \frac{\sigma(\bar{v}, NC)}{\sigma(\bar{v}, CC)} = \frac{1}{2} - s_w^2 + \frac{5}{9} s_w^4 (1 + \frac{1}{r})$$

$$r = \frac{\sigma(\bar{v}, CC)}{\sigma(v, CC)} = \frac{f_{\bar{q}} + f_q (1-y)^2}{f_q + f_{\bar{q}} (1-y)^2}$$

$\sim \underline{0.4}$





charged-current

$$R^{\nu} = \frac{\sigma(\nu, NC)}{\sigma(\nu, CC)} = \frac{1}{2} - s_w^2 + \frac{5}{9} s_w^4 (1+r)$$

$$R^{\bar{\nu}} = \frac{\sigma(\bar{\nu}, NC)}{\sigma(\bar{\nu}, CC)} = \frac{1}{2} - s_w^2 + \frac{5}{9} s_w^4 (1 + \frac{1}{r})$$

$$s_w^2 = 0.23$$

$$r = \frac{\sigma(\bar{\nu})}{\sigma(\nu)} = \frac{f_{\bar{g}} + f_g (1-y)^2}{f_g + f_{\bar{g}} (1-y)^2}$$