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

Date: Dec 14, 2009 09:00 AM

URL: http://pirsa.org/09120045

Abstract:

$n \to p e^- \nu \qquad \pi^+ \to \mu^+ \nu$

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$K^0 \longrightarrow \pi^+ \pi^- \qquad K^0 \to \pi^+ \pi^- \pi^0$

$n \to p e^- \nu \qquad \pi^+ \to \mu^+ \nu$

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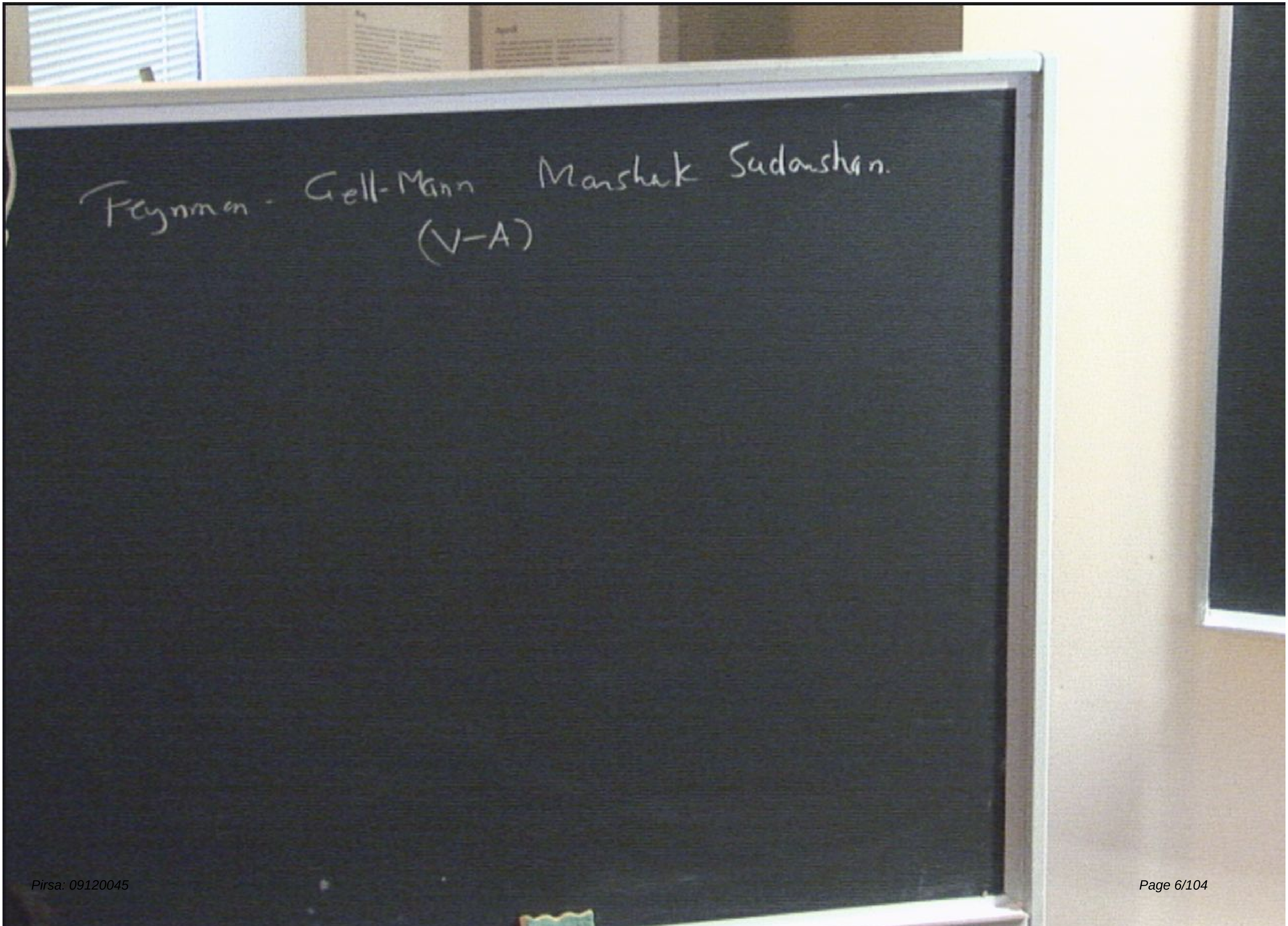
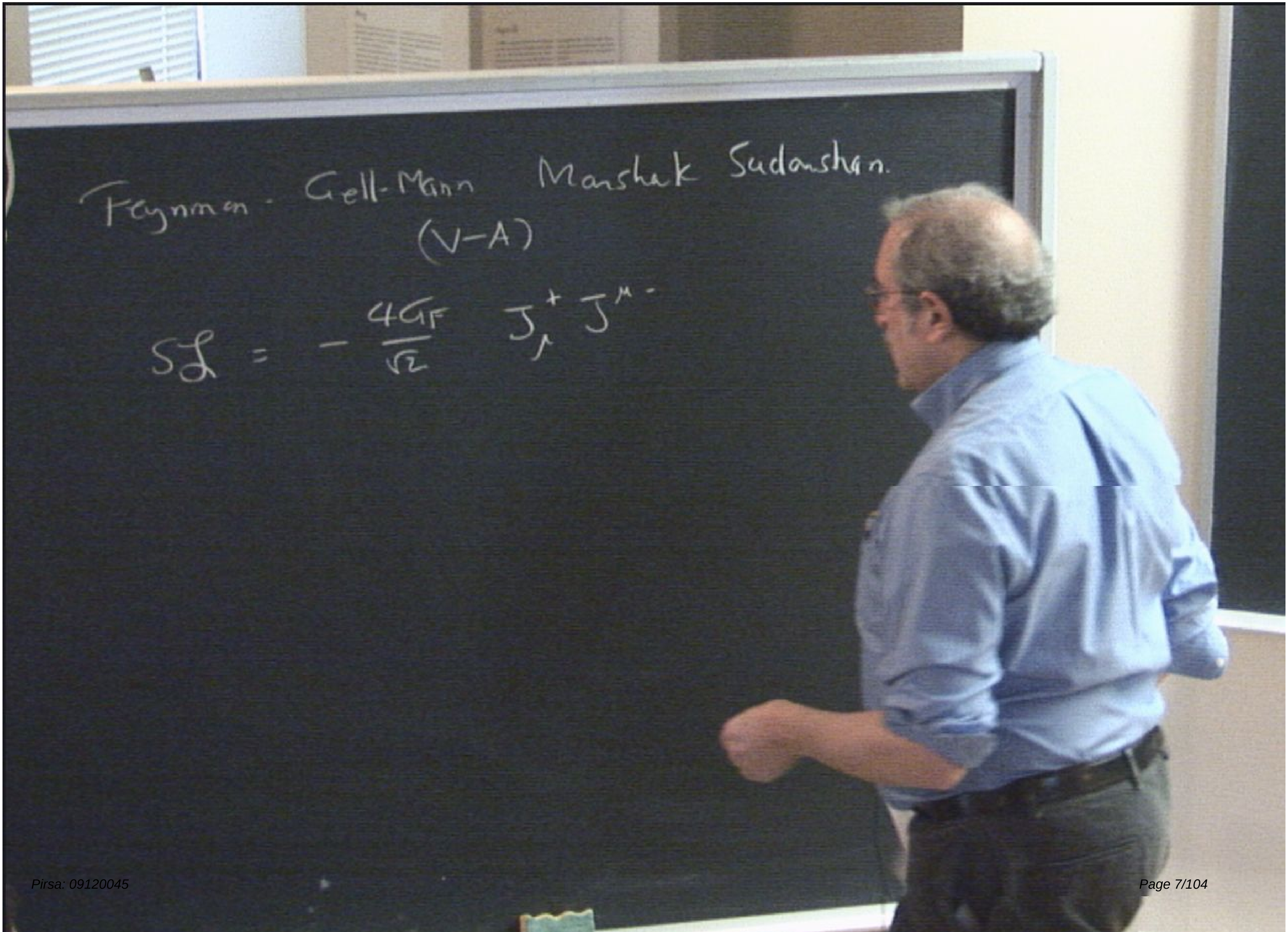
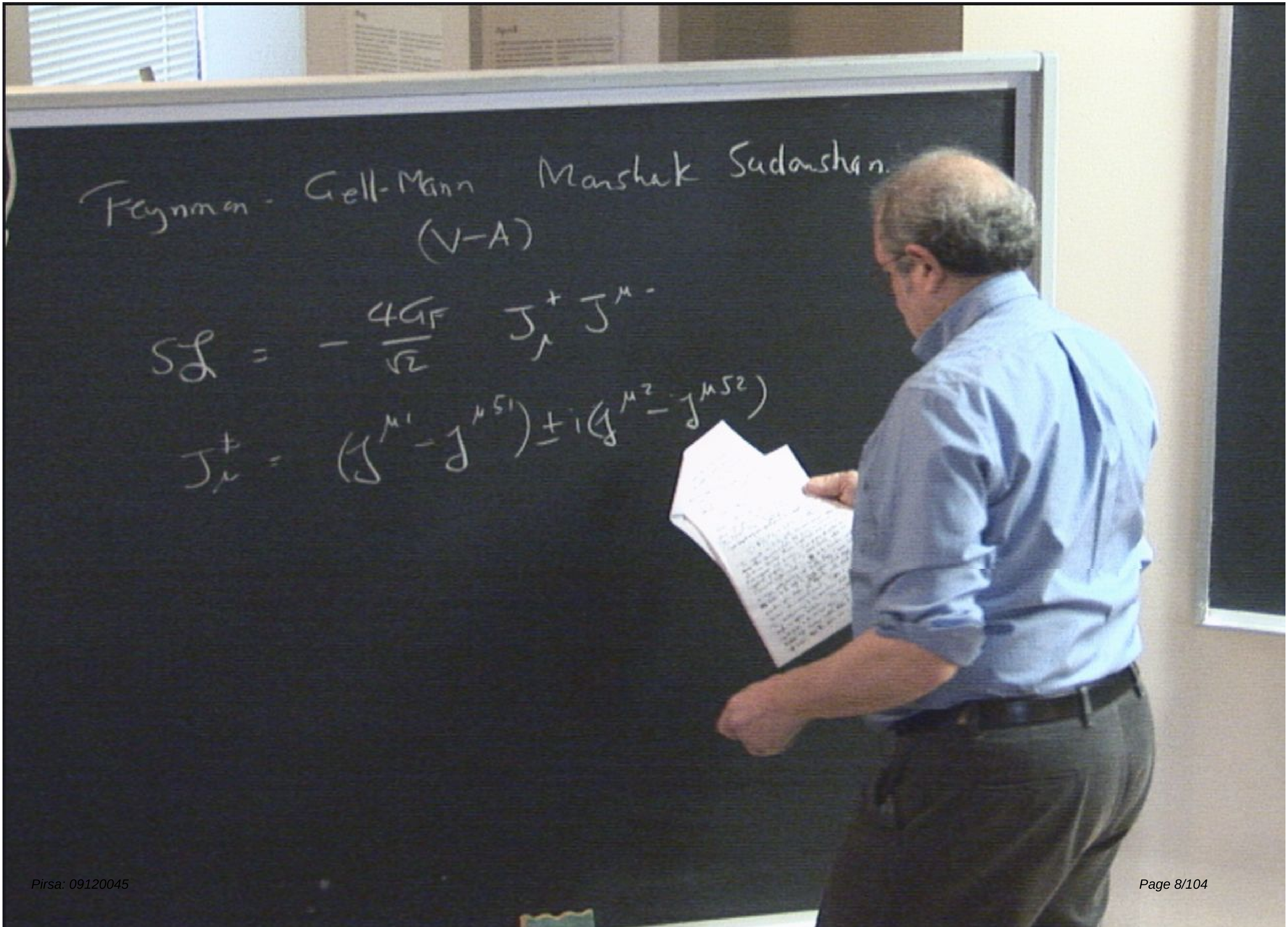
$P = + \qquad P = -$

Feynman - Gell-Mann Marshak Sudarshan.


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


Feynman - Gell-Mann Marshak Sudarshan.
(V−A)
$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}} J_\lambda^+ J^{\mu -}$


Feynman - Gell-Mann Marshak Sudarshan.
(V–A)
$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}} J_\mu^{+} J^{\mu -}$
$J_\mu^{\pm} = (J^{\mu 1} - J^{\mu 5 1}) \pm i (J^{\mu 2} - J^{\mu 5 2})$

Feynman - Gell-Mann Marshak Sudarshan.

(V−A)

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

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

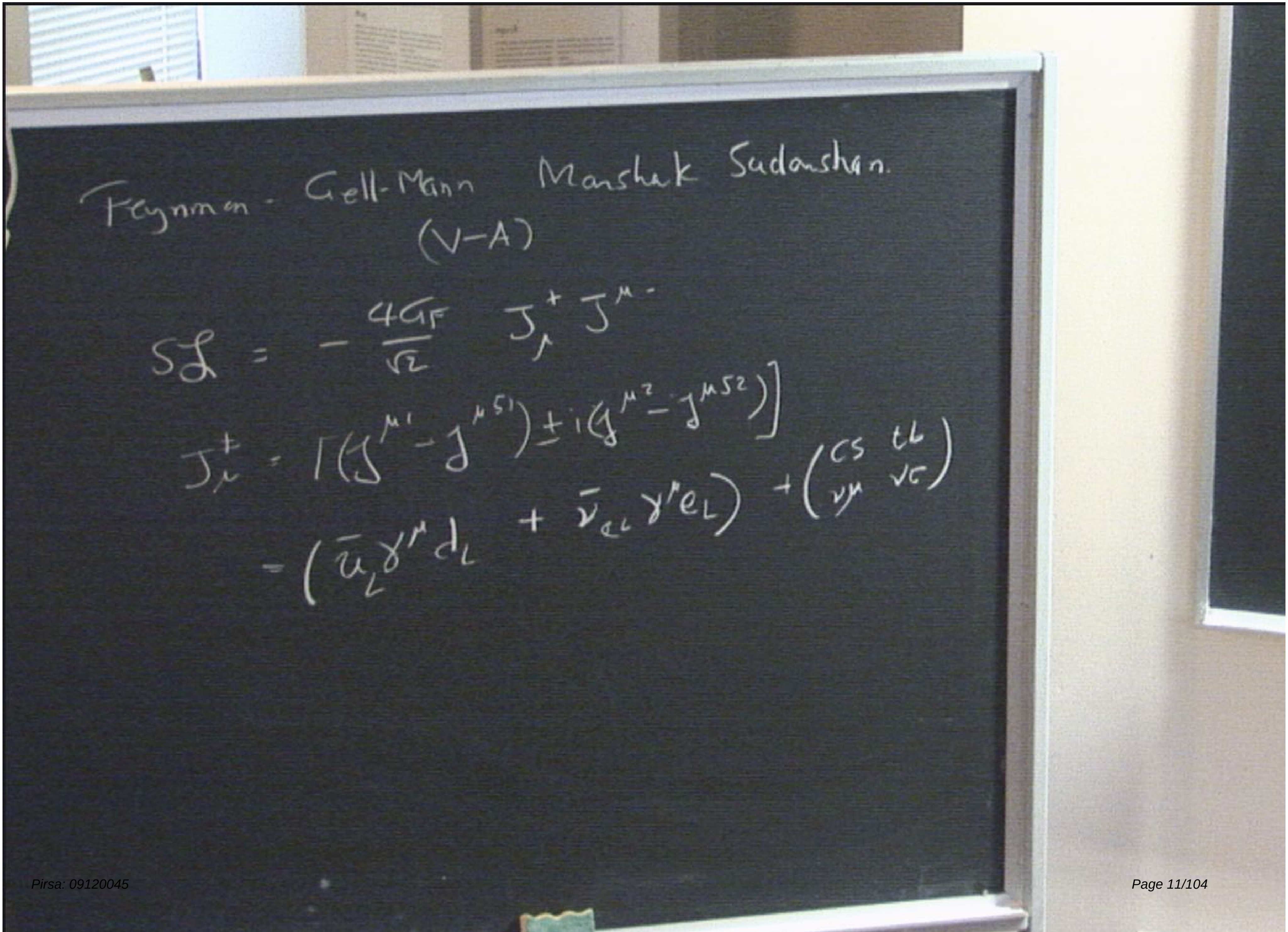
Feynman - Gell-Mann Marshak Sudarshan.

(V−A)

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

$$J_\mu^{\pm} = [(j^{\mu 1} - j^{\mu 5 1}) \pm i(j^{\mu 2} - j^{\mu 5 2})]$$

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


Feynman - Gell-Mann Marshak Sudarshan.
(V−A)
$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}} J_\mu^+ J^{\mu -}$
$J_\mu^\pm = [(J^{\mu 1} - J^{\mu 51}) \pm i(J^{\mu 2} - J^{\mu 52})]$
$= (\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L) + \begin{pmatrix} cs & tb \\ \nu\mu & \nu\tau \end{pmatrix}$

Feynman - Gell-Mann Marshak Sudarshan.

(V−A)

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

$$J^{\pm}_{\mu} = [(J^{\mu 1} - J^{\mu 5 1}) \pm i(J^{\mu 2} - J^{\mu 5 2})]$$

$$= (\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L) + \begin{pmatrix} cs & tb \\ \nu\mu & \nu\tau \end{pmatrix}$$

$n \to p e^- \nu \qquad \pi^+ \to \mu^+ \nu$

$K^0 \longrightarrow \pi^+ \pi^- \qquad K^0 \to \pi^+ \pi^- \pi^0$

$P = + \qquad P = -$

$F_1^5(q^2 = 0) = g_A$

$n \to p e^- \nu$ $\pi^+ \to \mu^+ \nu$

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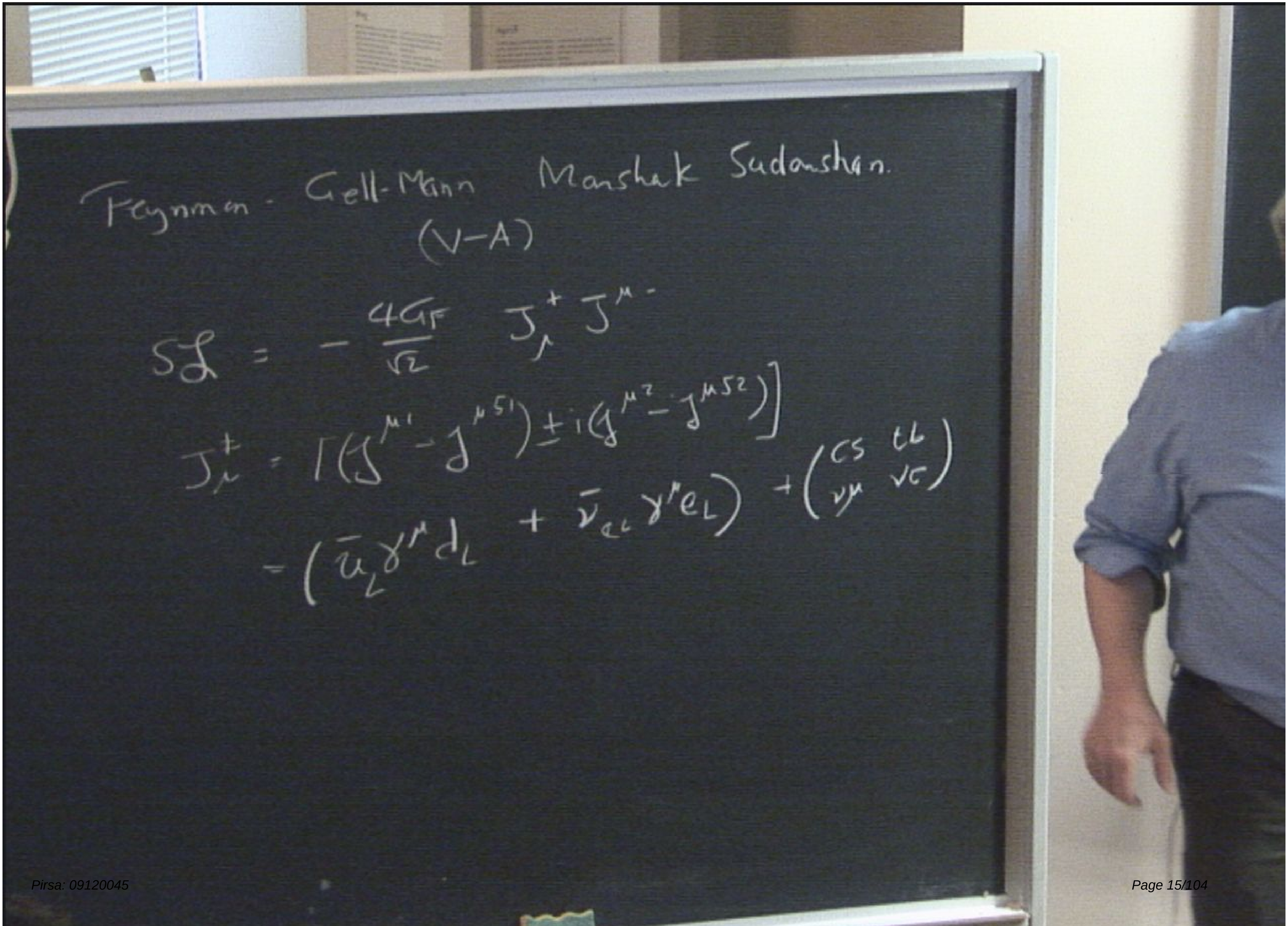
$P = +$ $P = -$

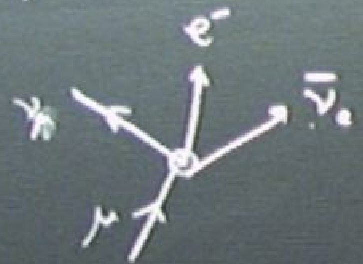
$F_1^5 (q^2 = 0) = g_A$

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


Feynman - Gell-Mann Marshak Sudarshan.
(V−A)
$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}} J^+_\mu J^{\mu -}$
$J^\pm_\mu = [(J^{\mu 1} - J^{\mu 51}) \pm i(J^{\mu 2} - J^{\mu 52})]$
$= (\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L) + \begin{pmatrix} cs & tb \\ \nu\mu & \nu\tau \end{pmatrix}$

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

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



$n \to p e^- \nu$ $\pi^+ \to \mu^+ \nu$

$K^0 \longrightarrow \pi^+\pi^-$ $K^0 \to \pi^+\pi^-\pi^0$

$P = +$ $P = -$

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

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

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

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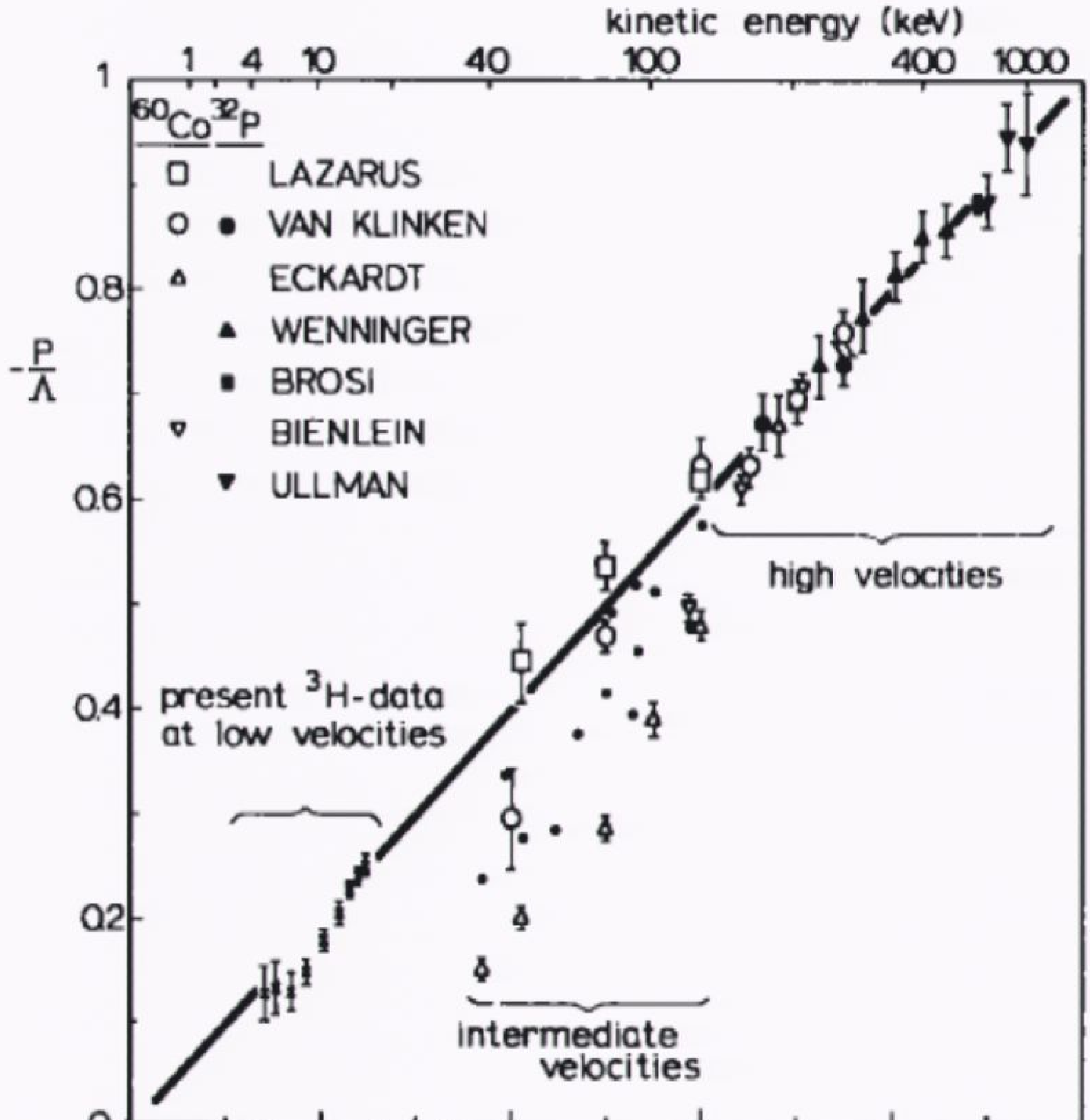

kinetic energy (keV)
1 4 10 40 100 400 1000
1
0.8
0.6
0.4
0.2
0
$-\frac{P}{\Lambda}$
60Co 32P
LAZARUS
VAN KLINKEN
ECKARDT
WENNINGER
BROSI
BIENLEIN
ULLMAN
high velocities
present 3H-data
at low velocities
intermediate
velocities

Feynman - Gell-Mann Marshak Sudarshan.

(V−A)

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

$$J^{\pm}_{\mu} = [(j^{\mu 1} - j^{\mu 5 1}) \pm i(j^{\mu 2} - j^{\mu 5 2})]$$

$$= (\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L) + \begin{pmatrix} cs & tb \\ \nu\mu & \nu\tau \end{pmatrix}$$

Feynman - Gell-Mann Marshak Sudarshan.

(V−A)

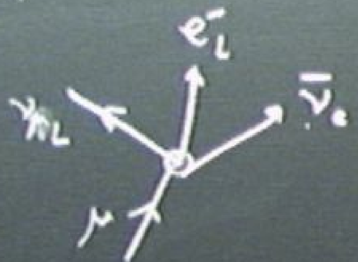
$$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}} J^{+}_{\mu} J^{\mu -}$$

$$J^{\pm}_{\mu} = [(j^{\mu 1} - j^{\mu 5 1}) \pm i(j^{\mu 2} - j^{\mu 5 2})]$$

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

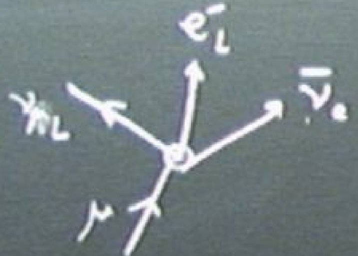
$$J^{-} = (J^{+})^{\dagger}$$

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



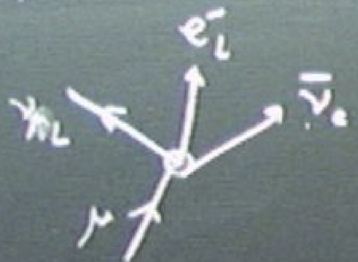
$$= -\frac{4 i G_F}{\sqrt{2}} \quad \bar{u}_L(\nu_\mu)\, \gamma^\mu\, u_L(\mu)$$

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

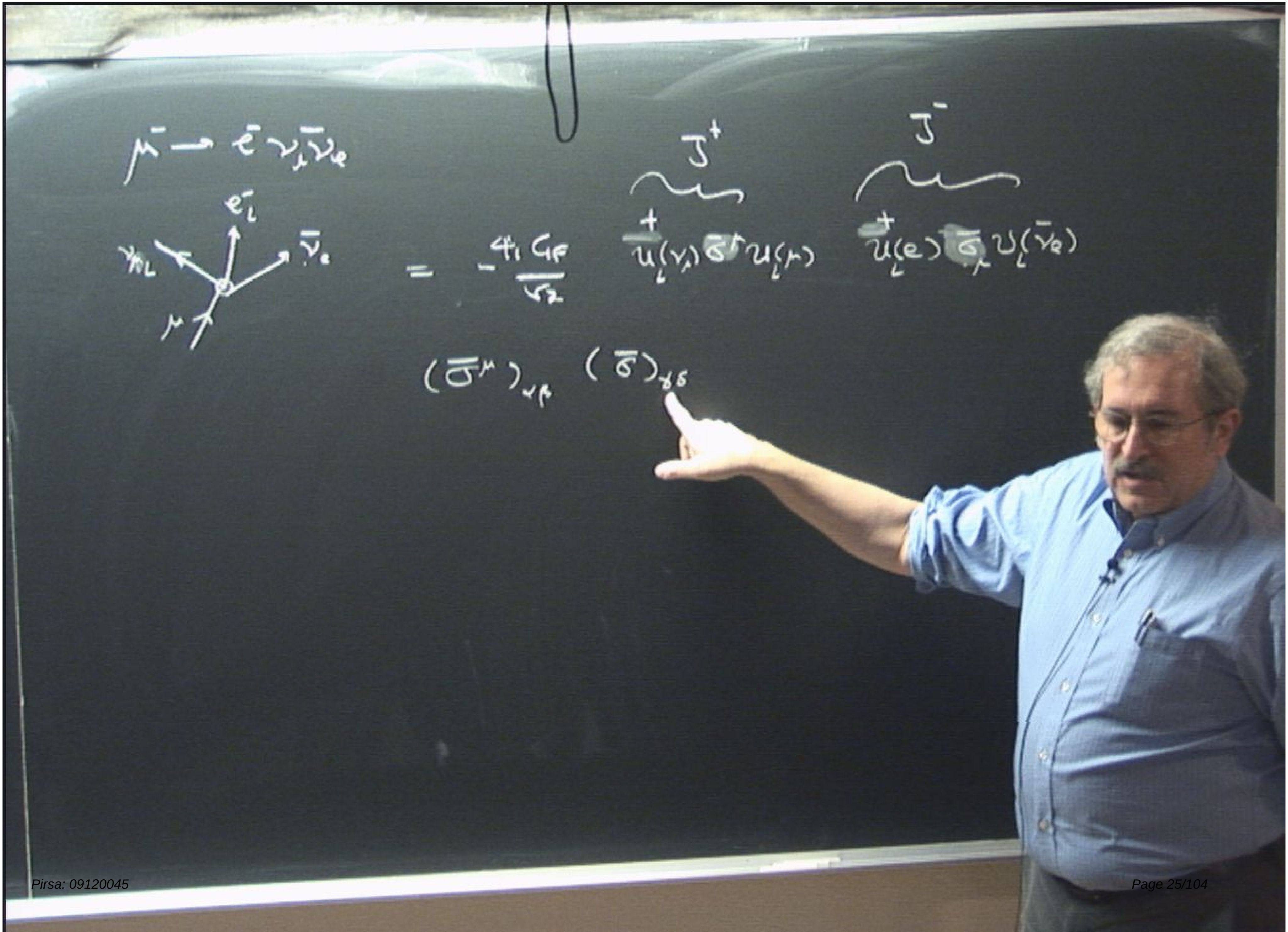


$$= -\frac{4 G_F}{\sqrt{2}} \, u_L^\dagger(\nu_\mu)\,\bar{\sigma}^\mu u_L(\mu) \;\; u_L^\dagger(e)\,\bar{\sigma}_\mu v_L(\bar{\nu}_e)$$

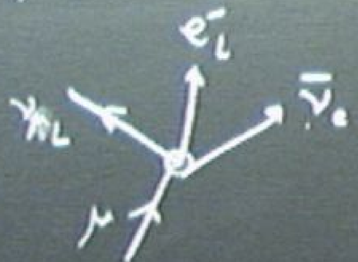
$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$



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


$\mu^- \to e^- \nu_\mu \bar{\nu}_e$
e^-_L
$\nu_{\mu L}$
$\bar{\nu}_e$
μ
J^+
J^-
$= -\frac{4 i G_F}{\sqrt{2}} \; u_L^\dagger(\nu_\mu)\, \bar{\sigma}^\mu\, u_L(\mu) \;\; u_L^\dagger(e)\, \bar{\sigma}_\mu\, v_L(\bar{\nu}_e)$
$(\bar{\sigma}^\mu)_{\alpha\beta} \quad (\bar{\sigma})_{\gamma\delta}$

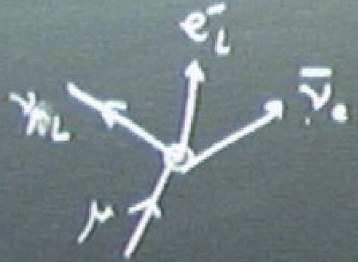
$\mu^- \to e^- \nu_\mu \bar{\nu}_e$



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

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

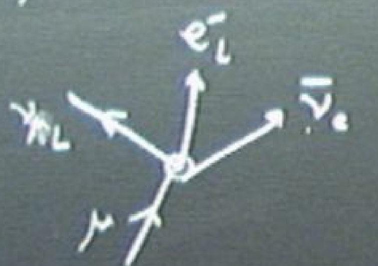
$\mu^- \to e^- \nu_\mu \bar{\nu}_e$



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

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

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



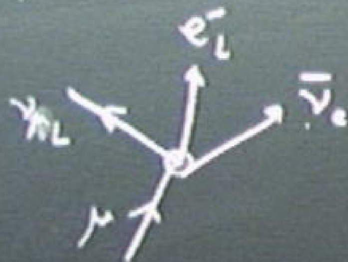
$$= -\frac{4iG_F}{\sqrt{2}} \overbrace{u_L^\dagger(\nu_\mu)\,\bar{\sigma}^\mu\, u_L(\mu)}^{J^+} \; \overbrace{u_L^\dagger(e)\,\bar{\sigma}_\mu\, v_L(\bar{\nu}_e)}^{J^-}$$

Fierz identity

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

$$= -\frac{4iG_F}{\sqrt{2}}\cdot 2\; u^\dagger_{L\alpha}(\nu_\mu)\,\varepsilon_{\alpha\gamma}\, u^\dagger_L(e) \quad u_L(\mu)_\beta\; \varepsilon_{\beta\delta}\; v(\bar{\nu}_e)$$

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



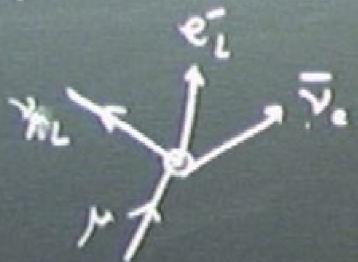
$$= -\frac{4 i G_F}{\sqrt{2}} \; \overbrace{u_L^\dagger(\nu_\mu)\, \bar{\sigma}^\mu\, u_L(\mu)}^{J^+} \; \overbrace{u_L^\dagger(e)\, \bar{\sigma}_\mu\, v_L(\bar{\nu}_e)}^{J^-}$$

Fierz identity

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

$$= -\frac{4 i G_F \cdot 2}{\sqrt{2}} \; u^\dagger_{L\alpha}(\nu_\mu)\, \varepsilon_{\alpha\gamma}\, u_L^\dagger(e)_\gamma \;\; u_L(\mu)_\beta\, \varepsilon_{\beta\delta}\, v(\bar{\nu}_e)_\delta$$

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



$$= -\frac{4 i G_F}{\sqrt{2}} \; \overbrace{u_L^\dagger(\nu_\mu)\, \bar{\sigma}^\mu u_L(\mu)}^{J^+} \; \overbrace{u_L^\dagger(e)\, \bar{\sigma}_\mu v_L(\bar{\nu}_e)}^{J^-}$$

Fierz identity

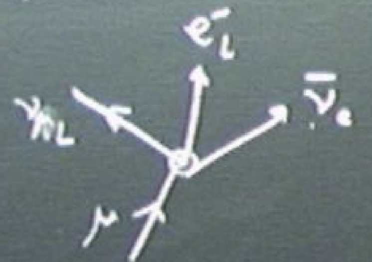
$$(\bar{\sigma}^\mu)_{\alpha\beta} \, (\bar{\sigma}_\mu)_{\gamma\delta} = 2\, \varepsilon_{\alpha\gamma}\, \varepsilon_{\beta\delta}$$

$$= -\frac{4 i G_F \cdot 2}{\sqrt{2}} \; u^\dagger_{L\alpha}(\nu_\mu)\, \varepsilon_{\alpha\gamma}\, u_L^\dagger(e)_\gamma \quad u_L(\mu)_\beta \, \varepsilon_{\beta\delta}\, v_L(\bar{\nu}_e)_\delta$$

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

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

$\mu^- \to e^- \nu_\mu \bar\nu_e$



$$\begin{array}{ccc} & J^+ & J^- \\ = -\frac{4 i G_F}{\sqrt{2}} & u_L^\dagger(\nu_\mu)\,\bar\sigma^\mu\, u_L(\mu) & u_L^\dagger(e)\,\bar\sigma_\mu\, v_L(\bar\nu_e) \end{array}$$

Fierz identity

$$(\bar\sigma^\mu)_{\alpha\beta}\,(\bar\sigma_\mu)_{\gamma\delta} = 2\,\varepsilon_{\alpha\gamma}\,\varepsilon_{\beta\delta}$$

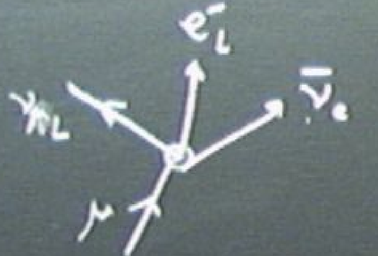
$$= -\frac{4 i G_F \cdot 2}{\sqrt{2}}\; u_L^\dagger(\nu_\mu)_\alpha\, \varepsilon_{\alpha\gamma}\, u_L^\dagger(e)_\gamma \;\; u_L(\mu)_\beta\, \varepsilon_{\beta\delta}\, v_L(\bar\nu_e)_\delta$$

$$v_L = \sqrt{2E_{\bar\nu}} \begin{pmatrix} -\sin\theta/2 \\ \cos\theta/2 \end{pmatrix}$$

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

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

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



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

Fierz identity

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

$$= -\frac{4iG_F \cdot 2}{\sqrt{2}}\, u^\dagger_{L\alpha}(\nu_\mu)\,\varepsilon_{\alpha\gamma}\, u_L^\dagger(e)_\gamma \;\boxed{u_L(\mu)_\beta\,\varepsilon_{\beta\delta}\, v_L(\bar{\nu}_e)_\delta}$$

$$v_L = \sqrt{2E_{\bar{\nu}}}\begin{pmatrix} -\sin\theta/2 \\ \cos\theta/2 \end{pmatrix}$$

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

$$\sqrt{2E_{\bar{\nu}}\, m}\;\cos\theta/2$$

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

θ_μ

$$|U_{L\beta}\Sigma_{\beta\delta}V_{i\delta}|^2 = E_\nu m_\mu\,(1+\cos\theta)$$

μ

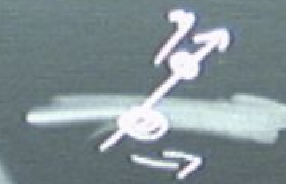
$$\left| u_{L\beta} \Sigma_{\beta\delta} v_{i\delta} \right|^2 = E_\nu m_\mu \, (1 + \cos\theta)$$

e

$\ominus_\mu$

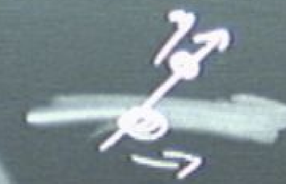
$$\left| u_{L\beta} \Sigma_{\beta\delta} v_{L\delta} \right|^2 = E_\nu m_\mu (1 + \cos\theta)$$

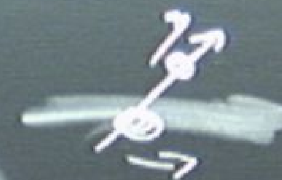
$$|u_{L\beta}\Sigma_{\beta\delta} v_{i\delta}|^2 = E_\nu m_\mu (1+\cos\theta)$$



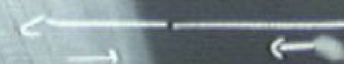
$$\left| u_{L\beta}\, \varepsilon_{\beta\delta}\, v_{L\delta} \right|^2 = E_\nu m_\mu \,(1+\cos\theta)$$

$$u_{L\alpha}^{(\nu_\mu)}\, \varepsilon_{\alpha\gamma}\, u_{L\gamma}^{(e^-)}$$





$$\left| u_{L\beta}\,\varepsilon_{\beta\delta}\, v_{L\delta} \right|^2 = \; E_\nu m_\mu \,(1+\cos\theta)$$



$$u_{L\alpha}^{(\nu_\mu)}\, \varepsilon_{\alpha\gamma}\, u_{L\gamma}^{(e^-)}$$

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

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

$$= \sqrt{4E_\nu E_e}\,(-1)$$

$$\left| u_L(\nu_\mu)_\alpha\, \varepsilon_{\alpha\gamma}\, u_{L\gamma} \right|^2 = 4E_\nu E_e =$$

$$\left| u_{L\beta}\,\epsilon_{\beta\delta}\, v_{L\delta} \right|^2 = E_\nu m_\mu \,(1+\cos\theta)$$

$$u_{L\,\alpha}^{(\nu_\mu)}\,\epsilon_{\alpha\gamma}\, u_{L\gamma}^{(e^-)}$$

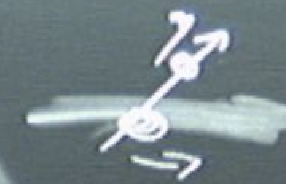
$$v_L(e) = \sqrt{2E_e}\begin{pmatrix}-1\\0\end{pmatrix}$$

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

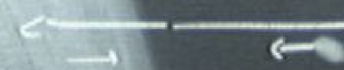
$$= \sqrt{4E_\nu E_e}\,(-1)$$

$$\left| u_L(\nu_\mu)_\alpha\, \epsilon_{\alpha\gamma}\, u_{L\gamma} \right|^2 = 4E_\nu E_e = (p_\nu + p_e)^2$$

μ



$$\left| u_{L\beta}\,\varepsilon_{\beta\delta}\, v_{L\delta} \right|^2 = E_\nu m_\mu \,(1+\cos\theta)$$



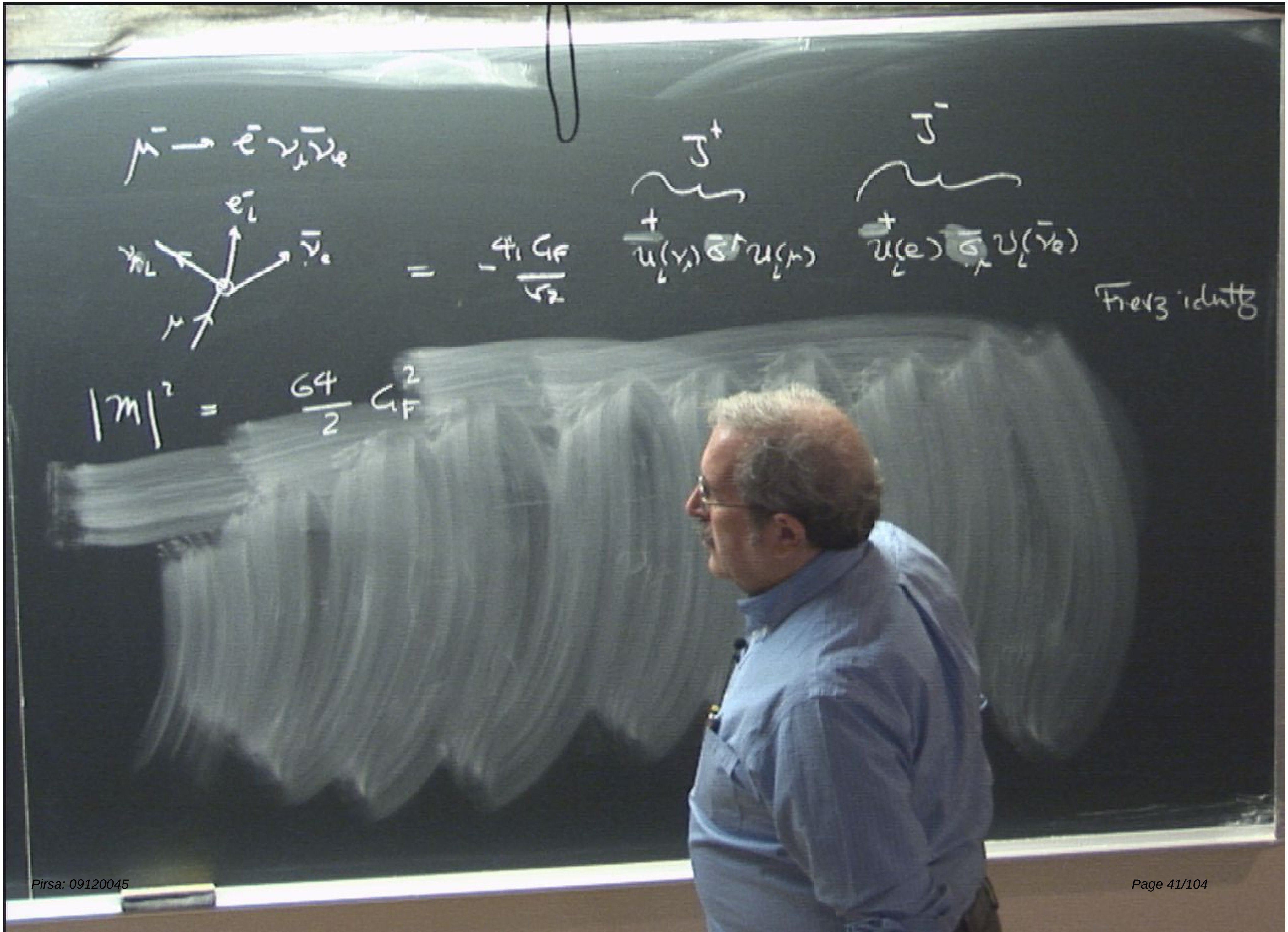
$$u_{L\alpha}^{(\nu_\mu)}\,\varepsilon_{\alpha\gamma}\; u_{L\gamma}^{(e^-)}$$

$$u_L(\nu_\mu) = \sqrt{2E_\nu}\begin{pmatrix}0\\1\end{pmatrix} \qquad v_L(e) = \sqrt{2E_e}\begin{pmatrix}-1\\0\end{pmatrix}$$

$$= \sqrt{4E_\nu E_e}\,(-1)$$

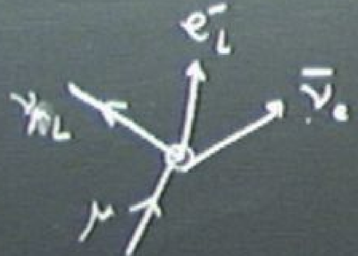
$$\left| u_L(\nu_\mu)_\alpha\, \varepsilon_{\alpha\gamma}\, u_{L\gamma} \right|^2 = 4E_\nu E_e = (p_\nu + p_e)^2$$

$$= (p_\mu - p_{\bar\nu})^2$$



$\mu^- \to e^- \nu_\mu \bar{\nu}_e$
J^+
J^-
$= -\frac{4 G_F}{\sqrt{2}}$
Fierz identity
$|m|^2 = \frac{64}{2} G_F^2$

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

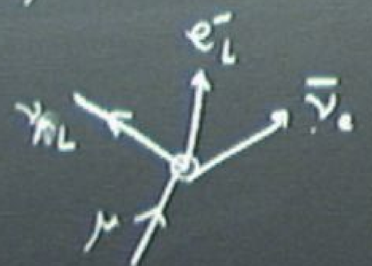


$$= -\frac{4 i G_F}{\sqrt{2}} \overbrace{u_L^\dagger(\nu_\mu)\, \bar{\sigma}^\lambda u_L(\mu)}^{J^+} \overbrace{u_L^\dagger(e)\, \bar{\sigma}_\lambda v_L(\bar{\nu}_e)}^{J^-}$$

Fierz identity

$$|\mathcal{M}|^2 = \frac{64}{2} G_F^2 \frac{m_\mu^2}{128\pi^3} \int \quad E_{\bar{\nu}} m_\mu \, (p_\mu - p_{\bar{\nu}})^2$$

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

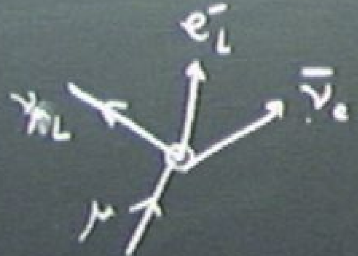


$$= -\frac{4 G_F}{\sqrt{2}} \; \overbrace{u_L^\dagger(\nu_\mu)\,\bar{\sigma}^\lambda\, u_L(\mu)}^{J^+} \; \overbrace{u_L^\dagger(e)\,\bar{\sigma}_\lambda\, u_L(\bar{\nu}_e)}^{J^-}$$

Fierz identity

$$|\mathcal{M}|^2 = \frac{64}{2} G_F^2 \frac{m_\mu^2}{128\pi^3} \int dx_e \, dx_{\bar{\nu}} \; \overbrace{E_{\bar{\nu}}}^{\frac{1}{2} m_\mu x_{\bar{\nu}}} m_\mu \, (p_\mu - p_{\bar{\nu}})^2$$

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

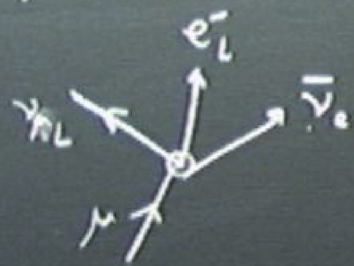


$$= -\frac{4 G_F}{\sqrt{2}} \overbrace{u_L^\dagger(\nu_\mu)\,\bar{\sigma}^\lambda\, u_L(\mu)}^{J^+} \; \overbrace{u_L^\dagger(e)\,\bar{\sigma}_\lambda\, u_L(\bar{\nu}_e)}^{J^-}$$

Fierz identity

$$|\mathcal{M}|^2 = \frac{64}{2} G_F^2 \frac{m_\mu^7}{128\pi^3} \int dx_e\, dx_{\bar{\nu}} \; \overbrace{E_{\bar{\nu}} m_\mu}^{\frac{1}{2} m_\mu x_{\bar{\nu}}} \; \frac{(p_\mu - p_{\bar{\nu}})^2}{m_\mu^2 (1 - x_{\bar{\nu}})}$$

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



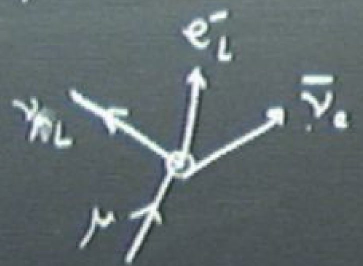
$$= -\frac{4 G_F}{\sqrt{2}} \; \overbrace{\bar{u}_L(\nu_\mu)\,\bar{\sigma}^\mu\, u_L(\mu)}^{J^+} \; \overbrace{\bar{u}_L(e)\,\bar{\sigma}_\mu\, v_L(\bar{\nu}_e)}^{J^-}$$

Fier

$$\Gamma = \frac{1}{2m}\int d\Pi_3 |\mathcal{M}|^2 = \frac{1}{2m_\mu}\,\frac{64}{2}\, G_F^2\, \frac{m_\mu^2}{128\pi^3}\int dx_e\, dx_{\bar{\nu}}\; \overbrace{E_{\bar{\nu}}}^{\frac{1}{2} m_\mu x_{\bar{\nu}}}\, m_\mu\, \underbrace{(p_\mu - p_{\bar{\nu}})^2}_{m_\mu^2 (1 - x_{\bar{\nu}})}$$

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

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



J^+ J^-

$$= -\frac{4 G_F}{\sqrt{2}} \; \bar{u}_L(\nu_\mu)\, \bar{\sigma}^\mu u_L(\mu) \; \bar{u}_L(e)\, \bar{\sigma}_\mu v_L(\bar{\nu}_e)$$

Fier

$$\Gamma = \frac{1}{2m}\int d\Pi_3 |\mathcal{M}|^2 = \frac{1}{2m_\mu}\frac{64}{2} G_F^2 \frac{m_\mu^2}{128\pi^3}\int dx_e\, dx_{\bar{\nu}} \; \overbrace{E_{\bar{\nu}} m_\mu}^{\frac{1}{2} m_\mu x_{\bar{\nu}}} \; \frac{(p_\mu - p_{\bar{\nu}})^2}{m_\mu^2 (1 - x_{\bar{\nu}})}$$

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

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

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

Fierz id

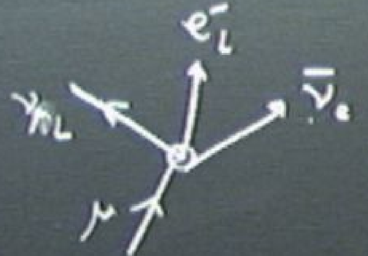
$$\Gamma = \frac{1}{2m_\mu}\int d\Pi_3 |\mathcal{M}|^2 = \frac{1}{2m_\mu}\,\frac{64}{2}\, G_F^2\, \frac{m_\mu^2}{128\pi^3}\int dx_e\, dx_{\bar{\nu}}\; \overbrace{E_{\bar{\nu}}}^{\frac{1}{2} m_\mu x_{\bar{\nu}}}\, m_\mu\, \underbrace{(p_\mu - p_{\bar{\nu}})^2}_{m_\mu^2 (1 - x_{\bar{\nu}})}$$

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

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

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

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



$$= -\frac{4 G_F}{\sqrt{2}} \; \overbrace{\bar{u}_L(\nu_\mu)\, \bar{\sigma}^\lambda u_L(\mu)}^{J^+} \; \overbrace{\bar{u}_L(e)\, \bar{\sigma}_\lambda v_L(\bar{\nu}_e)}^{J^-}$$

Fierz identity

$$\frac{1}{2m_\mu}\int d\Pi_3 |\mathcal{M}|^2 = \frac{1}{2m_\mu}\,\frac{64}{2}\, G_F^2\, \frac{m_\mu^2}{128\pi^3} \int dx_e\, dx_{\bar{\nu}}\, \overbrace{E_{\bar{\nu}}}^{\frac{1}{2} m_\mu x_{\bar{\nu}}} m_\mu \underbrace{(p_\mu - p_{\bar{\nu}})^2}_{m_\mu^2 (1 - x_{\bar{\nu}})}$$

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

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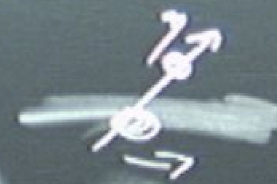
$$\left| u_{L\beta} \varepsilon_{\beta\delta} v_{L\delta} \right|^2 = E_\nu m_\mu (1 + \cos\theta)$$

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

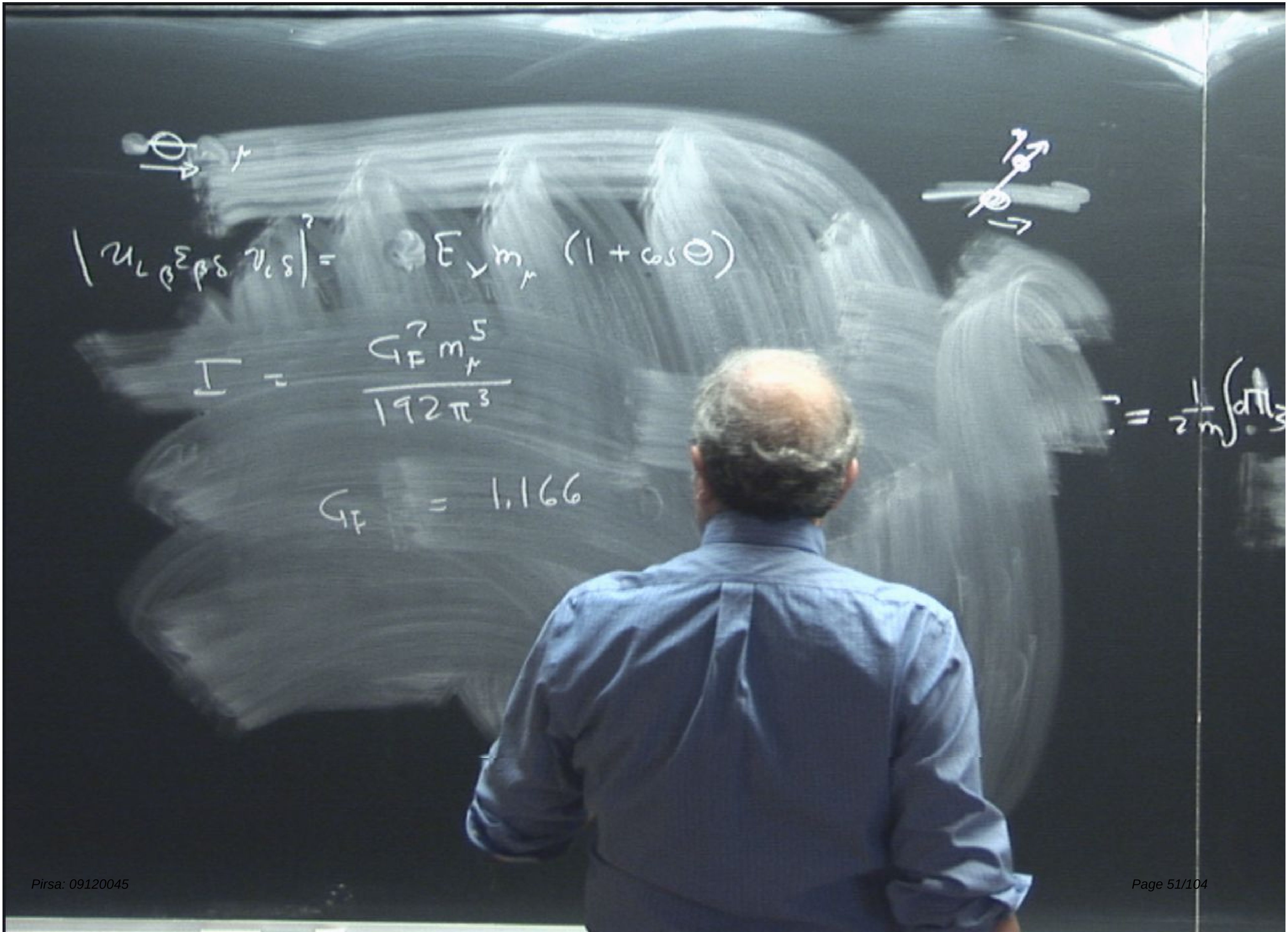
$$\Gamma = \frac{1}{2m} \int d\Pi_3$$

$$|u_{L\beta}\,\epsilon_{\beta\delta}\,v_{L\delta}|^2 = E_\nu m_\mu \,(1+\cos\theta)$$



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

$$\Gamma = \frac{1}{2}\frac{1}{m}\int d\Pi_3$$


μ
|u_{Lβ} ε_{βδ} v_{Lδ}|² = E_ν m_μ (1 + cos θ)
Γ = G_F² m_μ⁵ / 192π³
G_F = 1.166
Γ = 1/2 1/m ∫dΠ₃

$$\left| u_{L\beta} \varepsilon_{\beta\delta} v_{L\delta} \right|^2 = E_\nu m_\mu (1 + \cos\theta)$$

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

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

$$\Gamma = \frac{1}{2}\frac{1}{m}\int d\Pi_3$$

$$|u_{L\beta}\,\varepsilon_{\beta\delta}\,v_{L\delta}|^2 = \; E_\nu m_\mu \,(1+\cos\theta)$$

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μ

$$\left|\bar{u}_{L\beta}\,\epsilon_{\beta\delta}\,v_{L\delta}\right|^2 = \; E_\nu m_\mu\,(1+\cos\theta)$$

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

$$\Gamma = \frac{1}{2}\frac{1}{m}\int d\Pi_3$$

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

μ

$$\left| u_{L\beta}\, \varepsilon_{\beta\delta}\, v_{L\delta} \right|^2 = E_\nu m_\mu \,(1+\cos\theta)$$

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

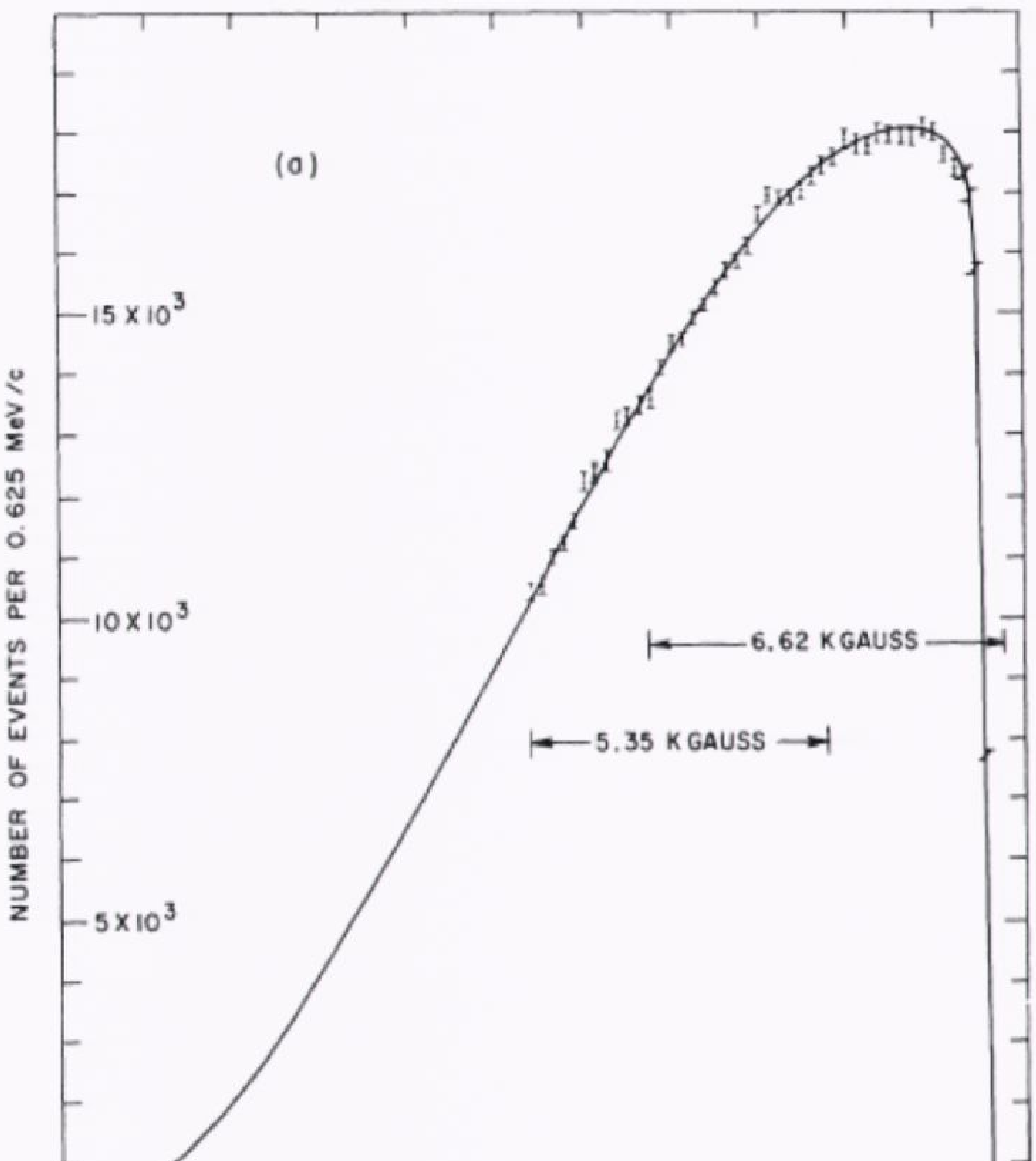
$$G_F = 1.16637(1)\times 10^{-5}\ \mathrm{GeV}^{-2}$$

$$\Gamma = \frac{1}{2}\frac{1}{m}\int d\Pi_3$$

\#

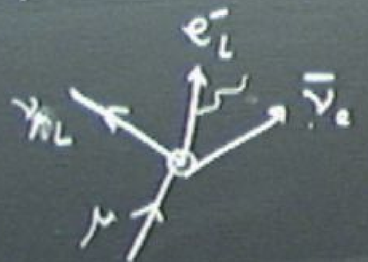
x_e

der
dow Help



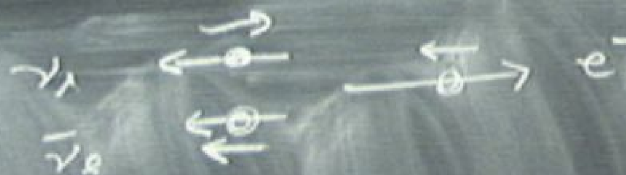
(a)
15 X 10^3
10 X 10^3
5 X 10^3
NUMBER OF EVENTS PER 0.625 MeV/c
6.62 KGAUSS
5.35 KGAUSS

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



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

Fierz identity

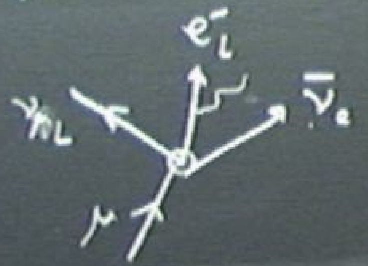


electron at $x_e = 1$

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

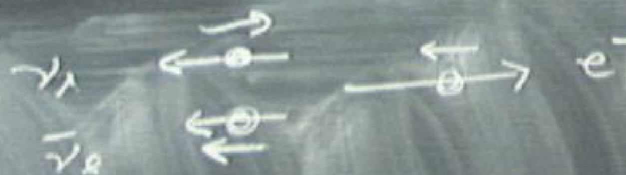
$$\frac{d\Gamma}{d\cos\theta_e} \sim (1-\cos\theta_e)$$

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



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

Fierz identity

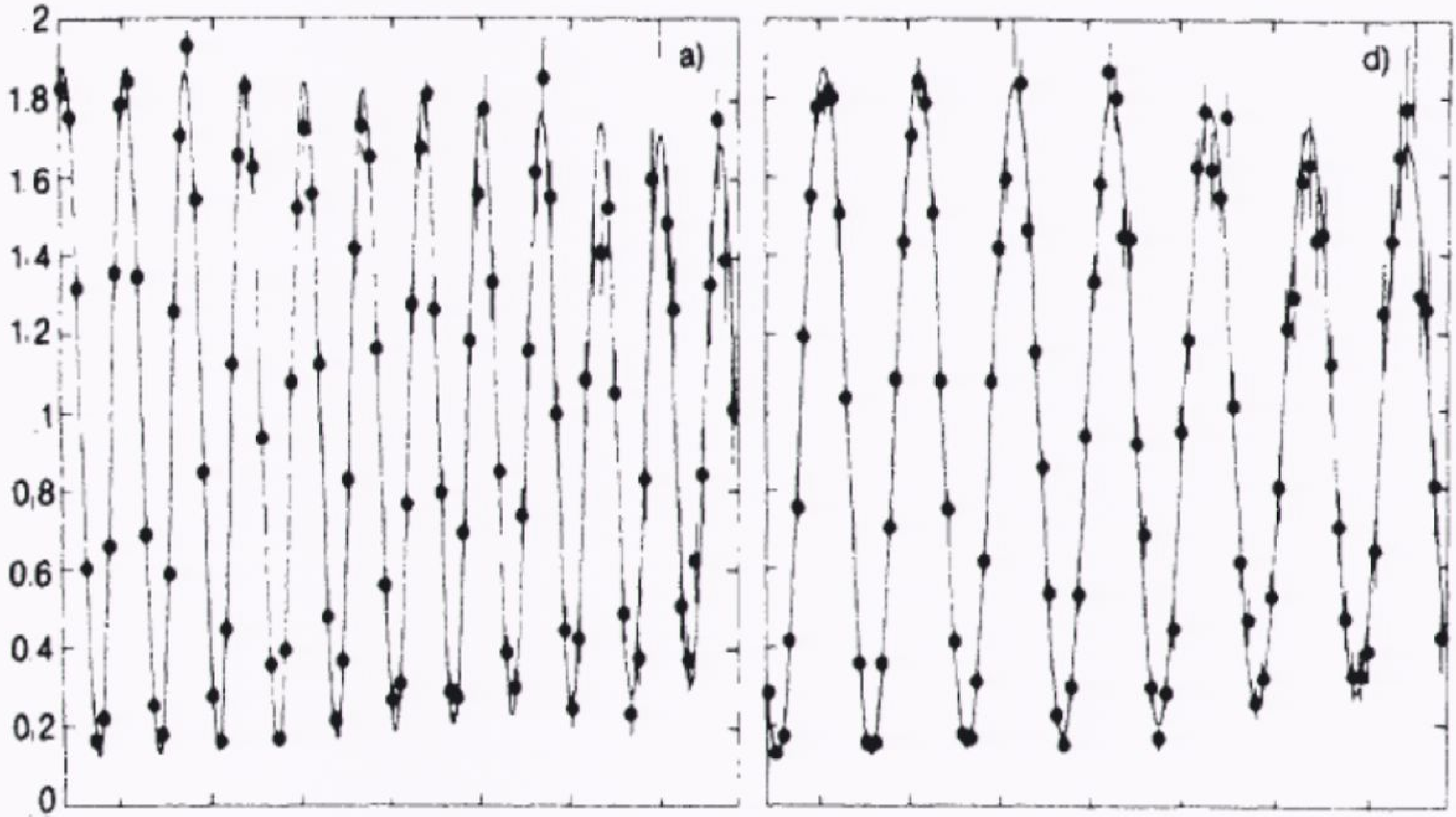


electrons at $x_e = 1$

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

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

der
dow Help



B. Balke et al, Berkeley-TRIUMF

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

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

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

$$\langle 0 | (\bar{u} \gamma^\mu \gamma^5 d) | \pi^-(k) \rangle = \sqrt{2}\, i\, k^\mu f_\pi$$

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

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

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

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$$\mathcal{M} = -\frac{4 i G_F}{\sqrt{2}} \sqrt{2}\, i\, k^\mu f_\pi \quad \bar{u}_L(\mu) \gamma_\mu v_L(\bar{\nu}_\mu)$$

$\pi^- \longrightarrow \mu^- \bar{\nu}_\mu$ $\qquad$ $\nu_\mu \longleftarrow \otimes \longrightarrow \mu$ $\qquad$ $\hat{3} \longrightarrow$

$$\bar{u}_L \gamma^\mu d_L = \tfrac{1}{2} \bar{u} \gamma^\mu (1-\gamma^5) d$$

$$\langle 0 | (\bar{u} \gamma^\mu \gamma^5 d) | \pi^-(k) \rangle = \sqrt{2}\, i k^\mu f_\pi$$

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$$u = \begin{pmatrix} \\ \hline \\ \end{pmatrix} \qquad v = \sqrt{2E_{\bar{\nu}}}\,\Big($$

$$\pi^- \longrightarrow \mu^- \bar{\nu}_\mu \qquad \bar{\nu}_\mu \longleftarrow \circ \longrightarrow \mu \qquad \hat{3} \longrightarrow$$

$$\bar{u}_L \gamma^\mu d_L = \tfrac{1}{2} \bar{u} \gamma^\mu (1-\gamma^5) d$$

$$\langle 0 | (\bar{u} \gamma^\mu \gamma^5 d) | \pi^-(k) \rangle = \sqrt{2}\, i k^\mu f_\pi$$

$$\mathcal{M} = -\frac{4 i G_F}{\sqrt{2}} \sqrt{2}\, i k^\lambda f_\pi \quad \bar{u}_L(\mu) \gamma_\lambda v_L(\bar{\nu}_\mu)$$

$$u = \begin{pmatrix} \\ \hline \\ \end{pmatrix} \qquad v = \sqrt{2E_{\bar{\nu}}} \begin{pmatrix} -1 \\ 0 \end{pmatrix}$$

$$\pi^- \longrightarrow \mu^- \bar\nu_\mu \qquad \bar\nu_\mu \overset{\Leftarrow}{\longleftarrow} \circ \overset{\Rightarrow}{\longrightarrow} \mu \qquad \hat{3} \longrightarrow$$

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

$$\langle 0 | (\bar u \gamma^\mu \gamma^5 d) | \pi^-(k) \rangle = \sqrt{2}\, i k^\mu f_\pi$$

$$\mathcal{M} = -\frac{4 i G_F}{\sqrt{2}} \sqrt{2}\, i k^\lambda f_\pi \quad \bar u_L(\mu) \gamma_\lambda v_L(\bar\nu_\mu)$$

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

$$\pi^- \longrightarrow \mu^- \bar{\nu}_\mu \qquad \nu_\mu \longleftarrow \odot \longrightarrow \mu \qquad \hat{3} \longrightarrow$$

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$$k_\mu \bar{u} \gamma_\mu = \bar{u} \not{k} = m_\mu \bar{u}$$

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

$$k_\mu \bar{u} \gamma_\mu = \bar{u} \not{k} = m_\mu \bar{u}$$

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

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

$$k_\mu \bar{u}\gamma_\mu = \bar{u}\not{k} = m_\mu \bar{u}$$

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

$$|\mathcal{M}|^2$$

$$\pi^- \longrightarrow \mu^- \bar{\nu}_\mu \qquad \nu_\mu \longleftarrow \circ \longrightarrow \mu \qquad \hat{3} \longrightarrow$$

$$\bar{u}_L \gamma^\mu d_L = \tfrac{1}{2}\, \bar{u} \gamma^\mu (1-\gamma^5)\, d$$

$$\langle 0 |\, (\bar{u} \gamma^\mu \gamma^5 d)\, | \pi^-(k) \rangle = \sqrt{2}\, i\, k^\mu f_\pi$$

$$\mathcal{M} = -\frac{4 i G_F}{\cancel{\sqrt{2}}}\ \cancel{\sqrt{2}}\, i\, \frac{k^\lambda}{2} f_\pi \quad \bar{u}_L(\mu)\, \gamma_\lambda\, v_L(\bar{\nu}_\mu)$$

$$u = \begin{pmatrix} \sqrt{E-k}\, \begin{pmatrix} 1 \\ 0 \end{pmatrix} \\ \sqrt{E+k}\, \begin{pmatrix} 1 \\ 0 \end{pmatrix} \end{pmatrix} \qquad v = \sqrt{2E_{\bar{\nu}}} \begin{pmatrix} -1 \\ 0 \end{pmatrix}$$

$$k_\mu \bar{u} \gamma_\mu = \bar{u} \not{k} = m_\mu \bar{u}$$

$$\bar{u}\left(\frac{1-\gamma^5}{2}\right)v = m_\mu\, u_R^+ v_L$$

$$k_\mu \bar{u} \gamma_\mu \left(\frac{1-\gamma^5}{2}\right) v_L = m_\mu$$

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

$$|m|^2 = 4\, G_F^2 f_\pi^2 m_\mu^2$$

$$k_\mu \bar{u} \gamma_\mu = \bar{u} \not{k} = m_\mu \bar{u}$$

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

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

$$|\mathcal{M}|^2 = 4 G_F^2 f_\pi^2 m_\mu^2 (E_\mu + k_\mu) E_{\bar\nu} \cdot 2$$

$$k_\mu \bar{u}\gamma_\mu = \bar{u}\not{k} = m_\mu \bar{u}$$

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

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

$$|m|^2 = 4 G_F^2 f_\pi^2 m_\mu^2 (E_\mu + k_\mu) E_{\bar{\nu}} \cdot 2$$

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

$$\Gamma = \frac{1}{2m_\pi}\,\frac{1}{8\pi}\left(\frac{2k}{m_\pi}\right)$$

$$k_\mu \bar{u} \gamma_\mu = \bar{u} \not{k} = m_\mu \bar{u}$$

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

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

$$|m|^2 = 4 G_F^2 f_\pi^2 m_\mu^2 (E_\mu + k_\mu) E_{\bar\nu} \cdot 2$$

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

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

$$I = \frac{G_F^2 f_\pi^2 m_\pi^3}{4\pi} m_\mu^2 \left(\frac{m_\pi^2 - m_\mu^2}{m_\pi^2}\right)^2$$

$$k_\mu \bar{u}\gamma_\mu = \bar{u}\not{k} = m_\mu \bar{u}$$

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

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

$$|m|^2 = 4\, G_F^2 f_\pi^2 m_\mu^2 (E_\mu + k_\mu) E_{\bar{\nu}} \cdot 2$$

$$k_\mu = k_{\bar{\nu}} = E_{\bar{\nu}} = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} \qquad E_\mu = \frac{m_\pi^2 + m_\mu^2}{2m_\pi} \qquad f_\pi = 92 \text{ MeV}$$

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

$$\Gamma = \frac{G_F^2 f_\pi^2 m_\pi^3}{4\pi}\, m_\mu^2 \left(\frac{m_\pi^2 - m_\mu^2}{m_\pi^2}\right)^2$$

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

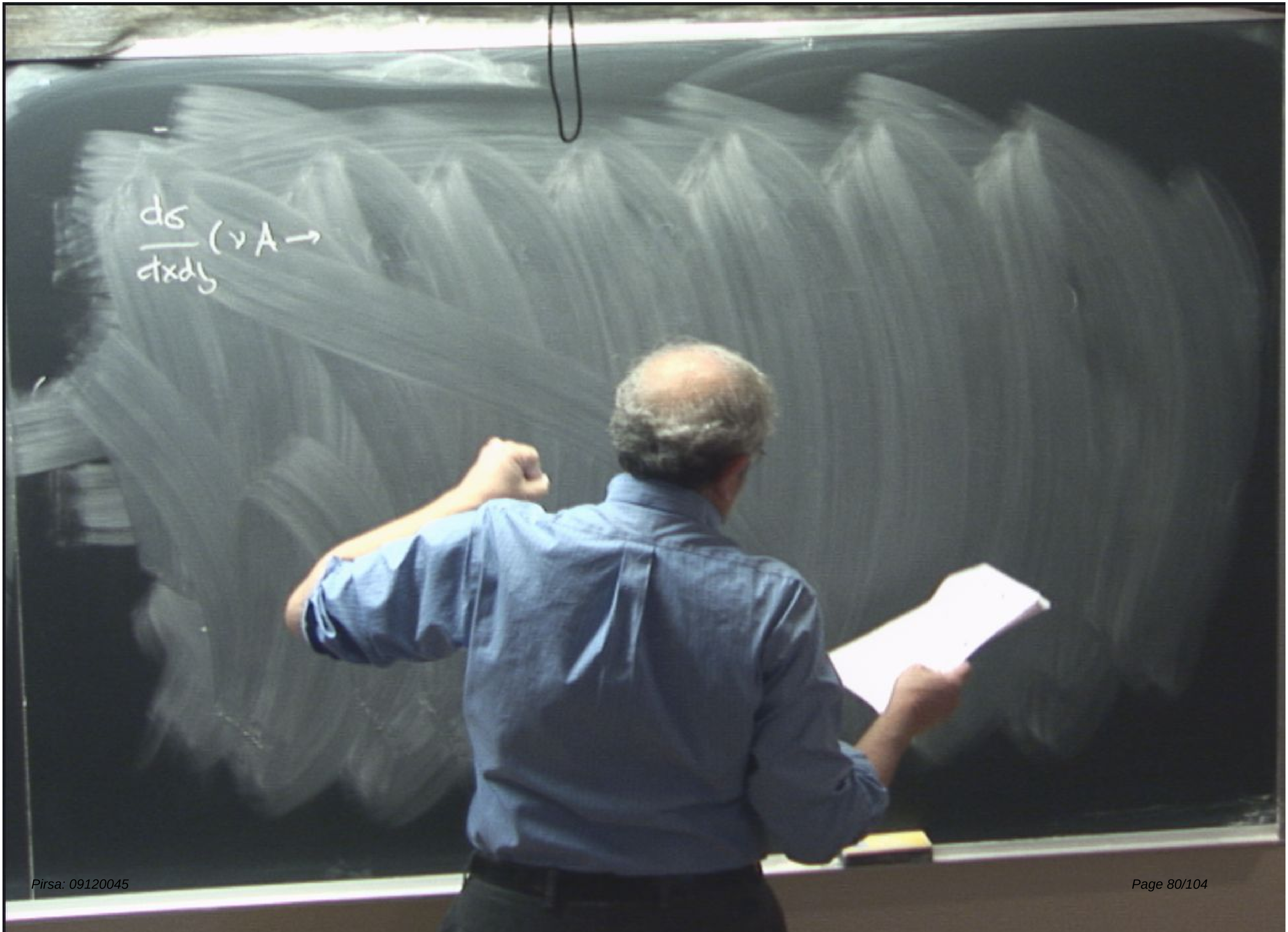
exp $\quad 1.23 \times 10^{-4}$

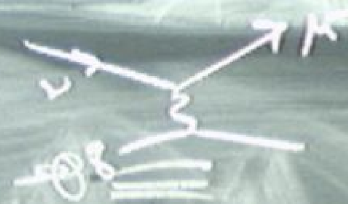
$$\frac{BR(\pi \to e\nu)}{BR(\pi \to \mu\nu)} = \frac{m_e^2}{m_\mu^2} \left(\frac{1 - m_e^2/m_\pi^2}{1 - m_\mu^2/m_\pi^2} \right)^2 = 1.28 \times 10^{-4}$$

exp 1.23×10^{-4}

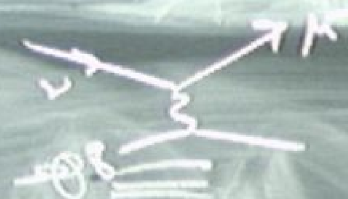
$$\frac{BR(\pi \to e\nu)}{BR(\pi \to \mu\nu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{1 - m_e^2/m_\pi^2}{1 - m_\mu^2/m_\pi^2}\right)^2 = 1.28 \times 10^{-4}$$

exp $\quad 1.23 \times 10^{-4}$

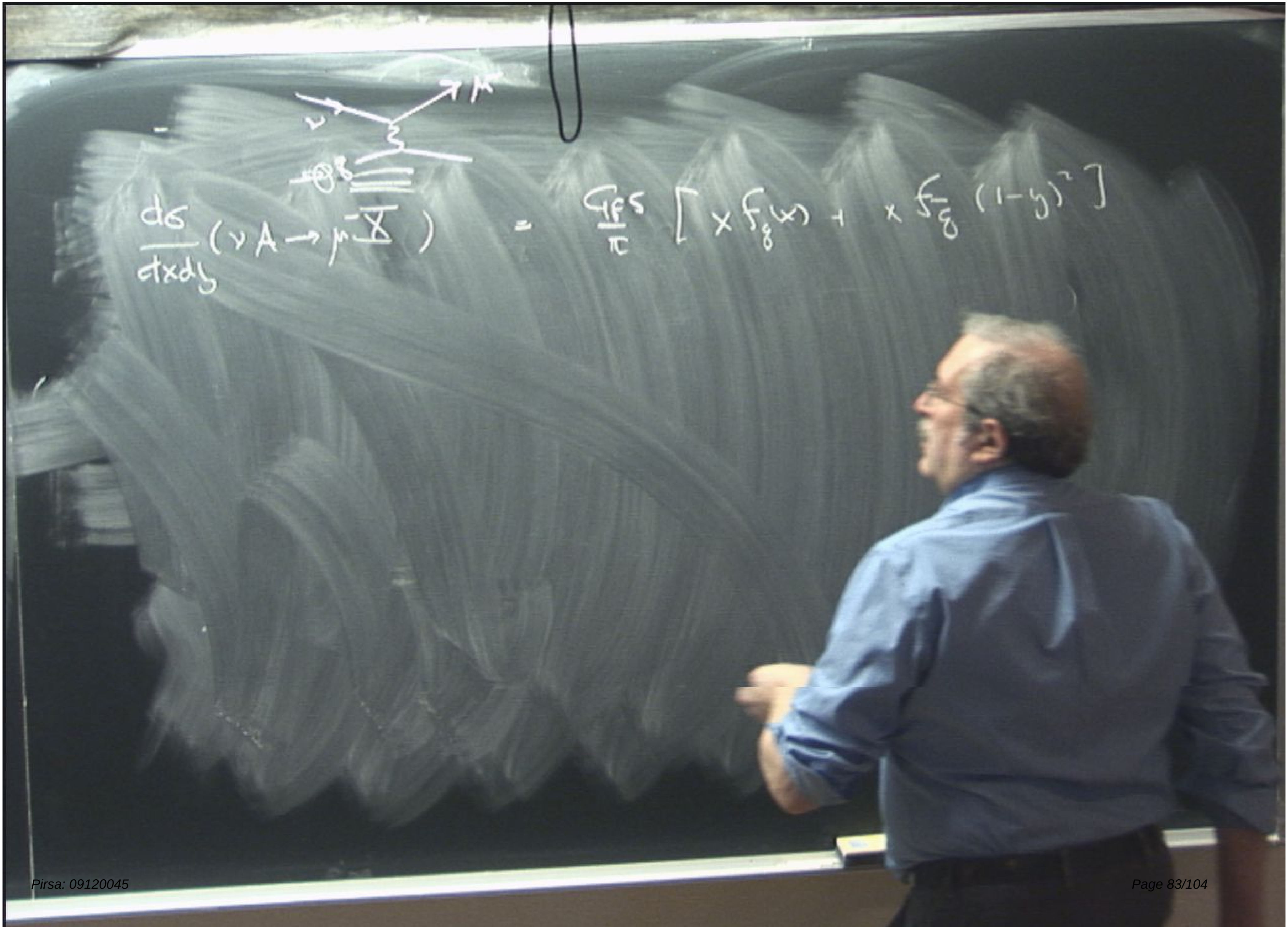

$\frac{d\sigma}{dx\,dy}(\nu A \rightarrow$



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

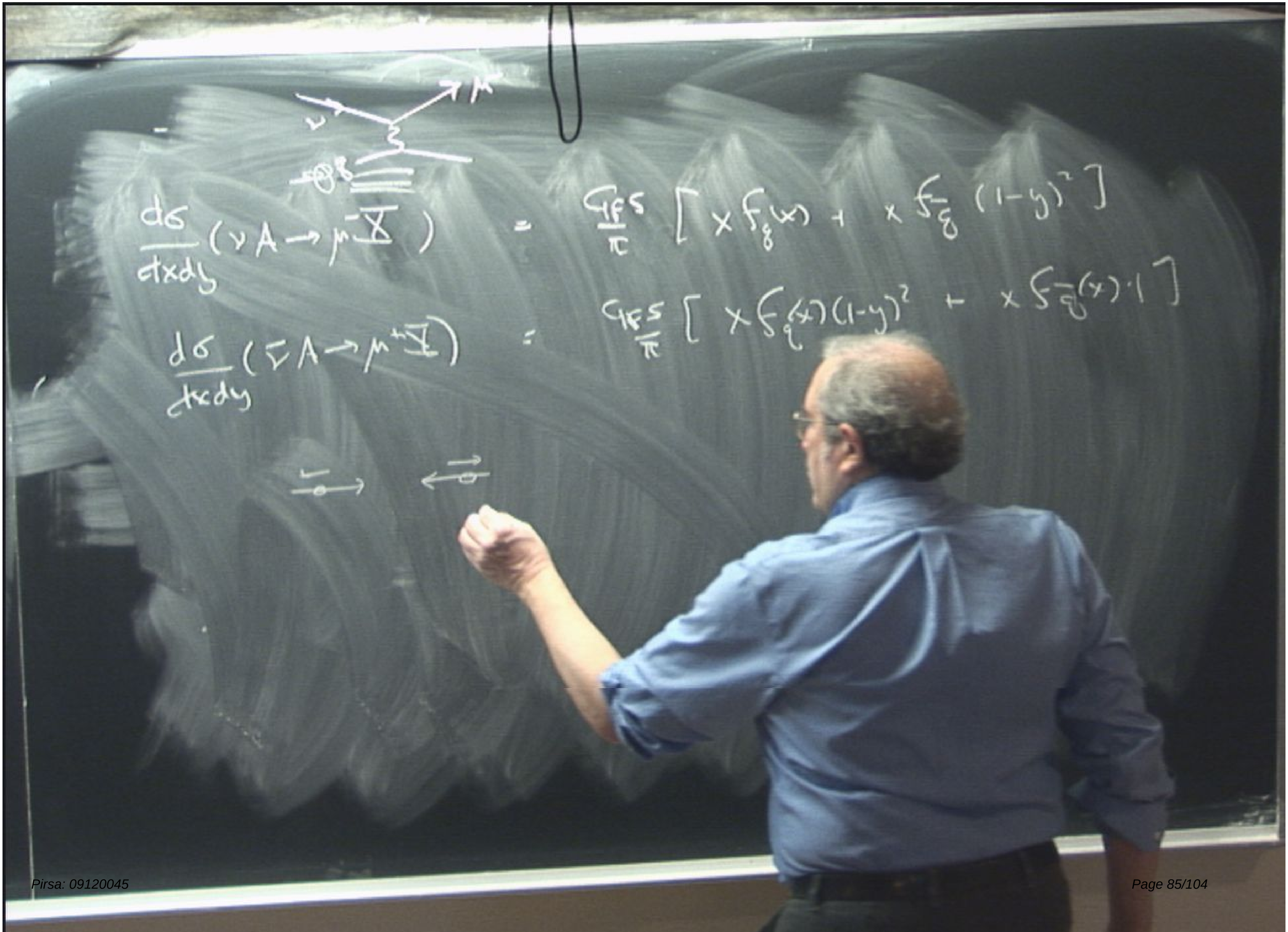


$$\frac{d\sigma}{dx\,dy}(\nu A \to \mu^- X)$$


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

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

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


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

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

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

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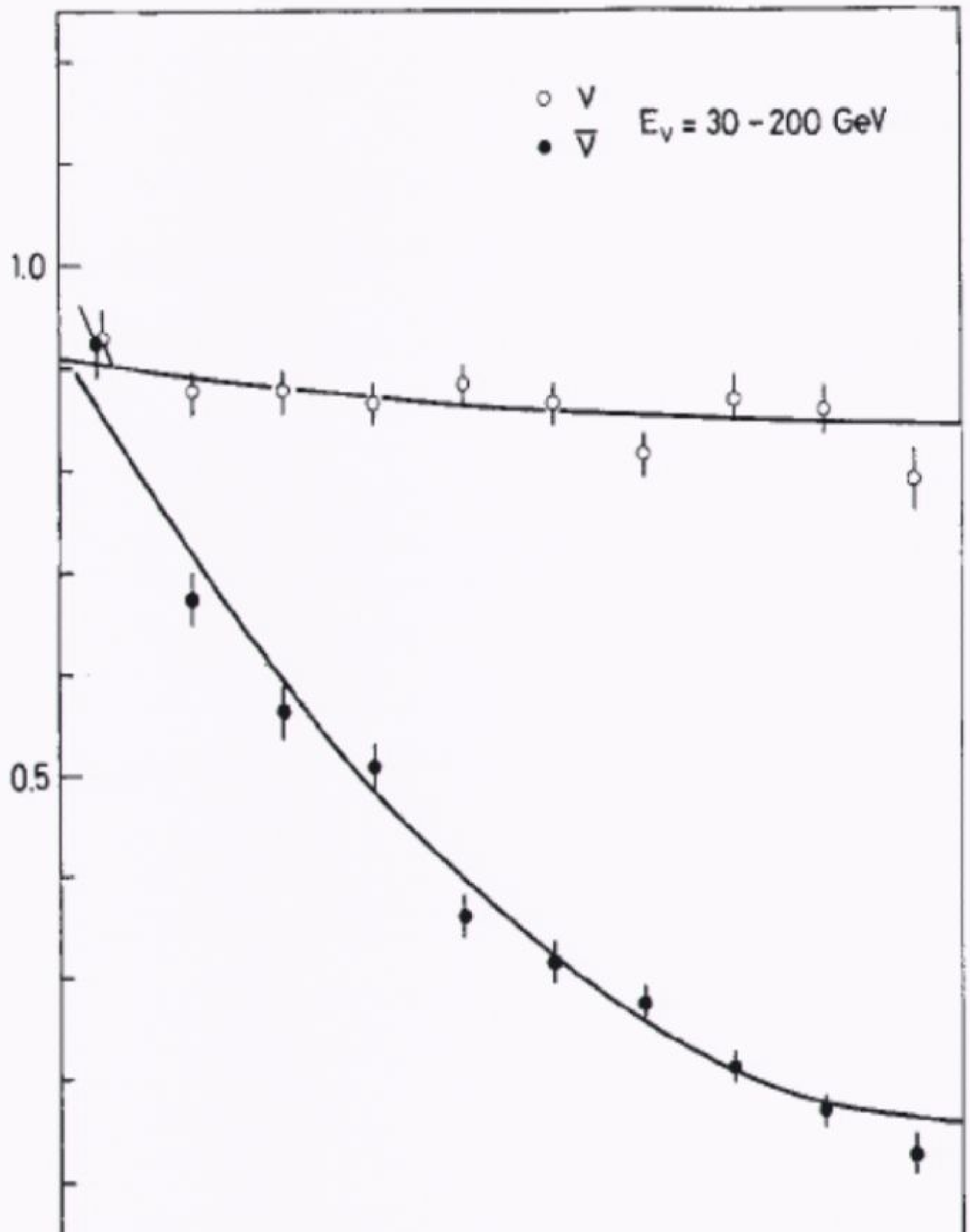
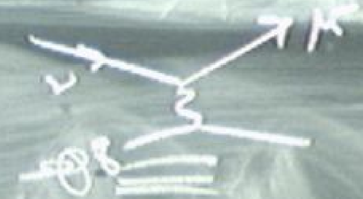


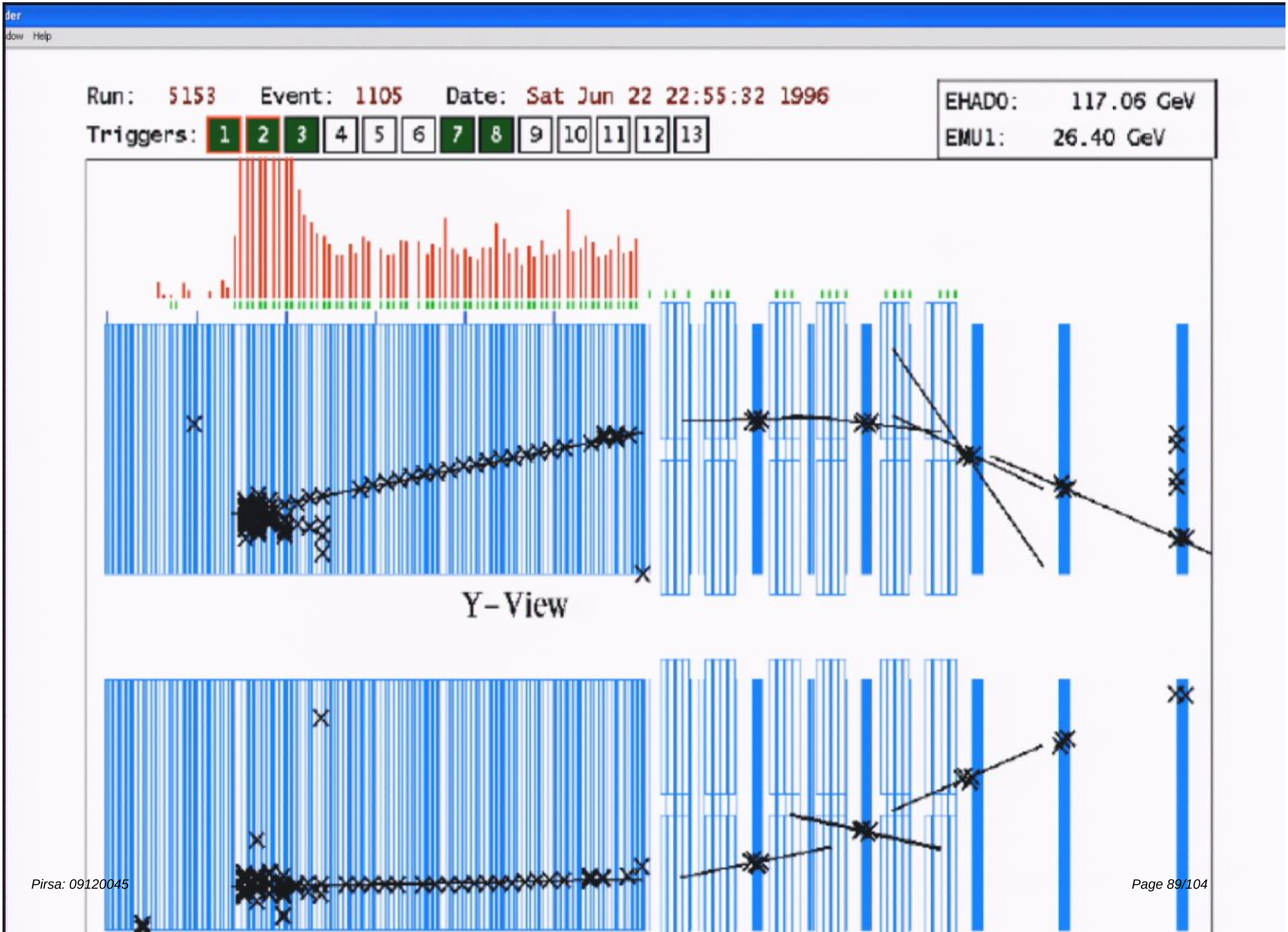


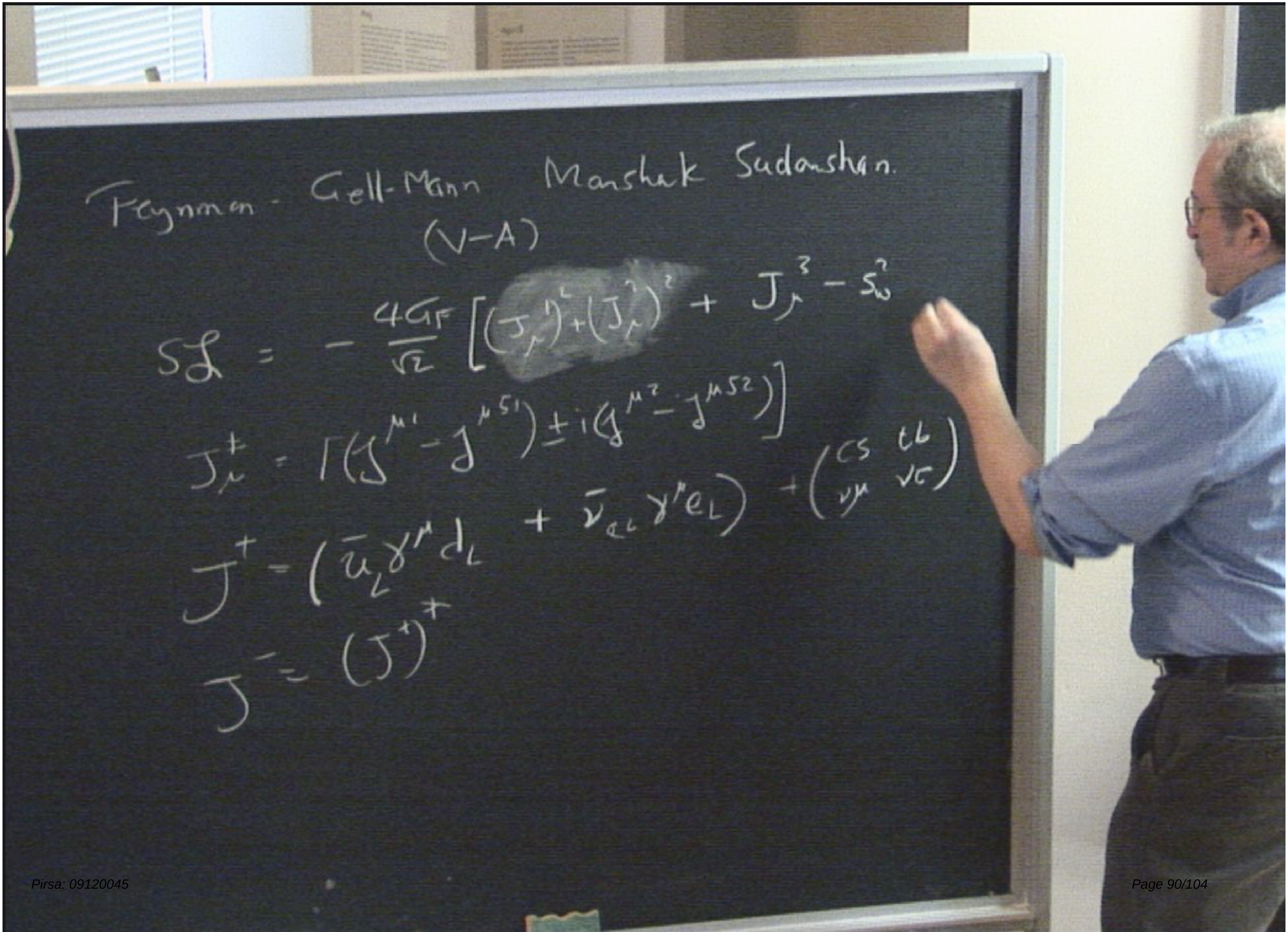
charged-current

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

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

neutral-current


der
dow Help
Run: 5153 Event: 1105 Date: Sat Jun 22 22:55:32 1996
Triggers: 1 2 3 4 5 6 7 8 9 10 11 12 13
EHAD0: 117.06 GeV
EMU1: 26.40 GeV
Y-View


Feynman - Gell-Mann Marshak Sudarshan.
(V−A)
$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[(J_\mu^1)^2 + (J_\mu^2)^2 + J_\mu^3 - s_w^2\right.$
$\left.(g^{\mu 2} - g^{\mu 5 2})\right]$
$J_\mu^\pm = \Gamma(g^{\mu 1} - g^{\mu 5 1}) \pm i(g^{\mu 2} - g^{\mu 5 2})$
$J^+ = (\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L) + \begin{pmatrix} cs & tb \\ \nu\mu & \nu\tau \end{pmatrix}$
$J^- = (J^+)^\dagger$

Feynman - Gell-Mann Marshak Sudarshan.

(V−A)

$$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[(J_\mu^1)^2 + (J_\mu^2)^2 + (J_\mu^3 - s_w^2 J_\mu^{EM})^2\right]$$

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

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

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

$u_L \quad \frac{1}{2} - \frac{2}{3} s_\omega^2 \qquad u_R \qquad -\frac{2}{3} s_\omega^2$

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$u_L \quad \frac{1}{2} - \frac{2}{3} s_w^2 \qquad u_R \quad -\frac{2}{3} s_w^2$

$$\frac{d^2\sigma}{dx\,dy}(\nu) = \frac{G_F s}{\pi} \Big| \; x f_q \Big[\left(\tfrac{1}{2} - \tfrac{2}{3} s_w^2\right)^2 + \left(-\tfrac{1}{2} + \tfrac{1}{3} s_w^2\right)^2 \Big] + \Big[\left(-\tfrac{2}{3} s_w\right)^2 + \left(\tfrac{1}{3} s_w^2\right)^2 \Big] (1-y)^2$$

$u_L \quad \frac{1}{2} - \frac{2}{3}s_w^2 \qquad u_R \qquad -\frac{2}{3}s_w^2$

$$\frac{d^2\sigma}{dx\,dy}(\nu) = \frac{G_F s}{\pi} \Big| \; x f_q \left[\left(\tfrac{1}{2} - \tfrac{2}{3}s_w^2\right)^2 + \left(-\tfrac{1}{2} + \tfrac{1}{3}s_w^2\right)^2 \right]$$
$$+ \left[\left(-\tfrac{2}{3}s_w\right)^2 + \left(+\tfrac{1}{3}s_w^2\right)^2 \right] (1-y)^2$$

$$= \frac{G_F s}{\pi} \Big[\; x f_q \quad \left(\tfrac{1}{2} - s_w^2\right) + \left(\tfrac{5}{9} s_w^4\right)\left(1 + (1-y)^2\right)$$

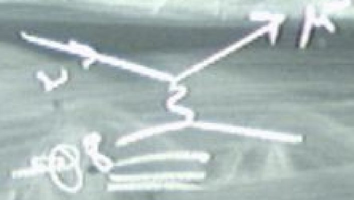
$+$

charged - current

$\to \mu^- X) = \frac{G_F s}{\pi}\left[x f_q(x) + x f_{\bar{q}} (1-y)^2 \right]$

$X) = \frac{G_F s}{\pi}\left[x f_q(x)(1-y)^2 + x f_{\bar{q}}(x)\cdot 1 \right]$

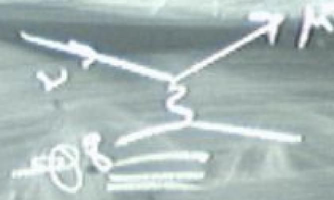
$$r = \frac{\sigma(\bar{\nu}, cc)}{\sigma(\nu\, cc)} = \frac{f_{\bar{q}} + f_q (1-y)^2}{f_q + f_{\bar{q}}(1-y)^2}$$



charged-current

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

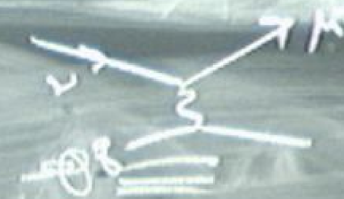
$$r = \frac{\sigma(\bar{\nu}, CC)}{\sigma(\nu\, CC)} = \frac{f_{\bar{q}} + f_q (1-y)^2}{f_q + f_{\bar{q}} (1-y)^2}$$



charged-current

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

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

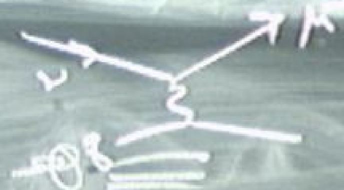


charged-current

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

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

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



charged-current

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

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

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

$$\sim \underline{0.4}$$

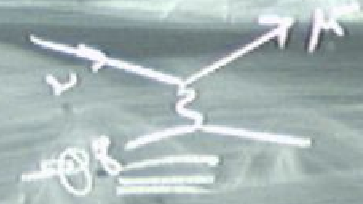
charged-current

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

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

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

$$\sim \underline{0.4}$$



charged-current

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

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

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

$$\sim \underline{0.4}$$

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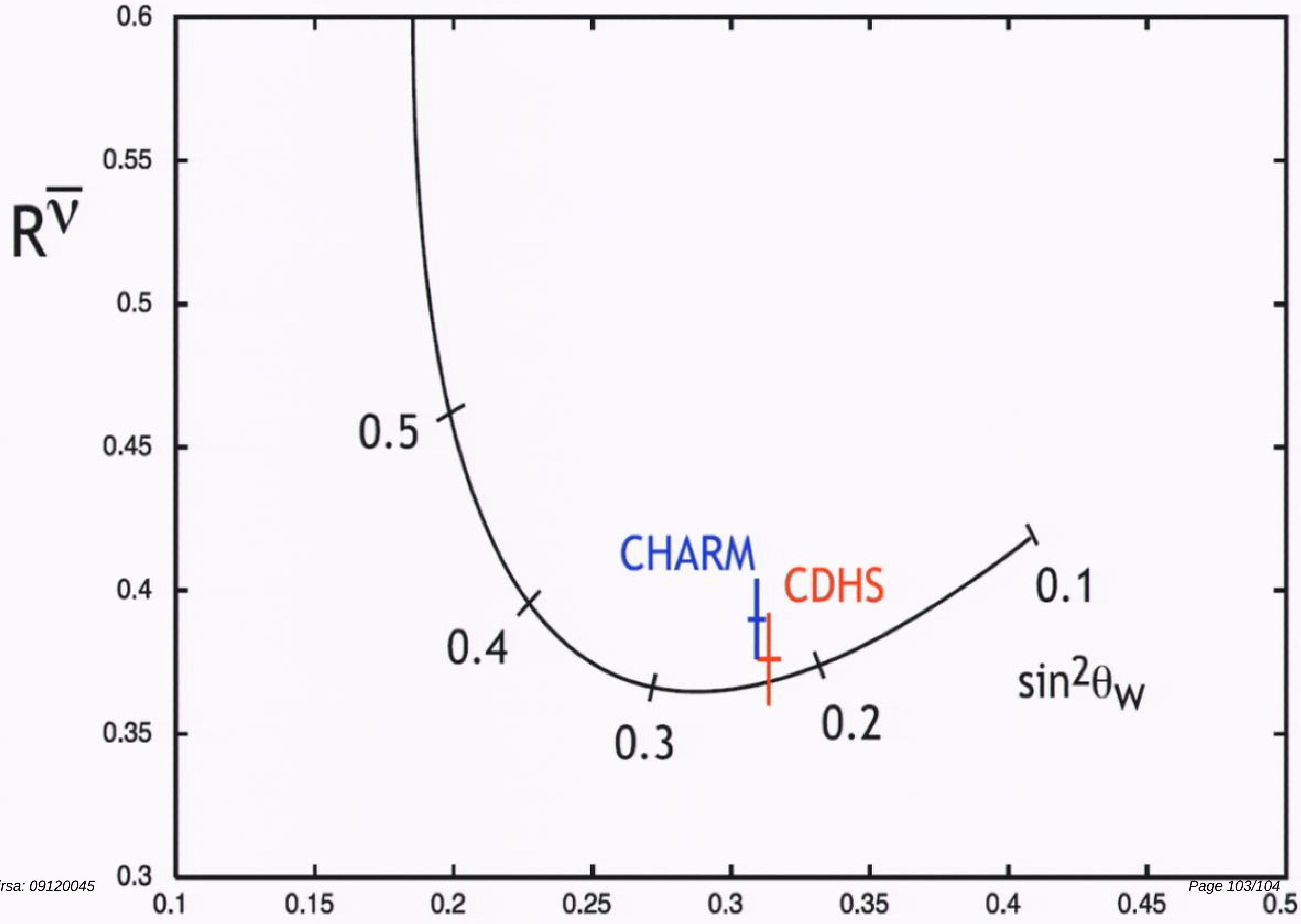
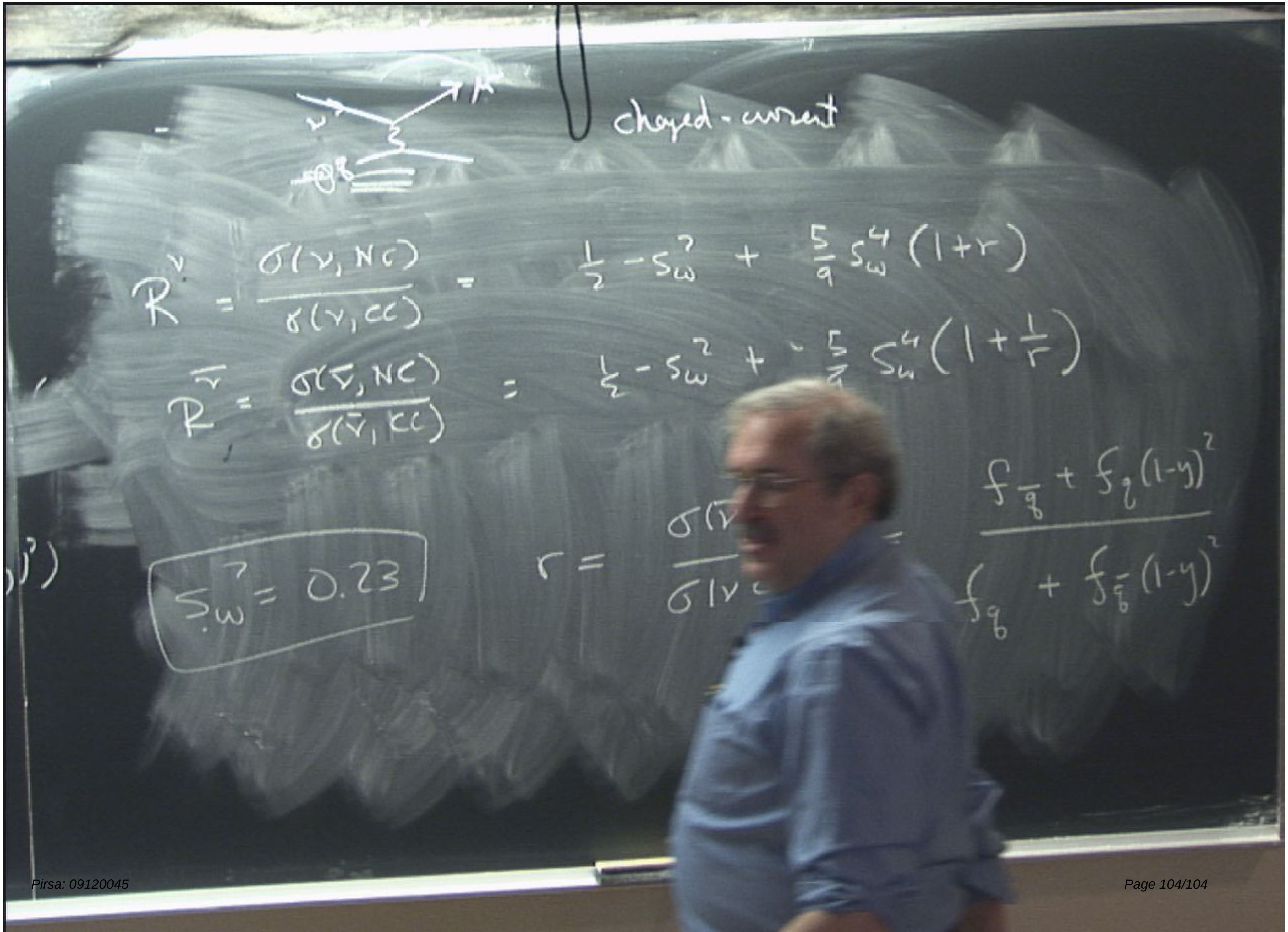


0.6
0.55
0.5
0.45
0.4
0.35
0.3
$R^{\overline{\nu}}$
0.5
0.4
0.3
0.2
0.1
CHARM
CDHS
$\sin^2\theta_W$
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5


charged-current
R^ν = σ(ν, NC) / σ(ν, CC) = 1/2 − s_w^2 + 5/9 s_w^4 (1+r)
R^ν̄ = σ(ν̄, NC) / σ(ν̄, CC) = 1/2 − s_w^2 + 5/9 s_w^4 (1 + 1/r)
s_w^2 = 0.23
r = σ(ν̄ … / σ(ν … = (f_q̄ + f_q (1−y)^2) / (f_q + f_q̄ (1−y)^2)