Title: Standard Model - Review (PHYS 622) - Lecture 3

Date: Dec 02, 2009 09:00 AM

URL: http://pirsa.org/09120033

Abstract:

perimeter scholars
international

$e^+e^- \longrightarrow \mu^+\mu^-$

$e^+ e^- \longrightarrow \mu^+ \mu^-$

<u>helicity</u>

$e^+ e^- \longrightarrow \mu^+ \mu^-$

<u>helicity</u>

$$i\bar{\sigma}\cdot\partial\,\psi_L = 0$$

$$e^+e^- \longrightarrow \mu^+\mu^-$$

<u>helicity</u>

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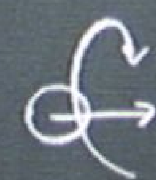
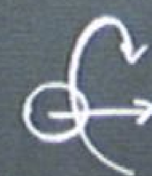


$$e^+e^- \longrightarrow \mu^+\mu^-$$

<u>helicity</u>

$$i\bar{\sigma}\cdot\partial\,\psi_L = 0$$



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helicity

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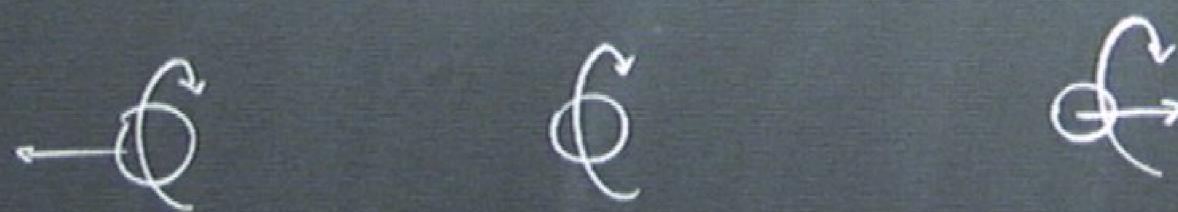
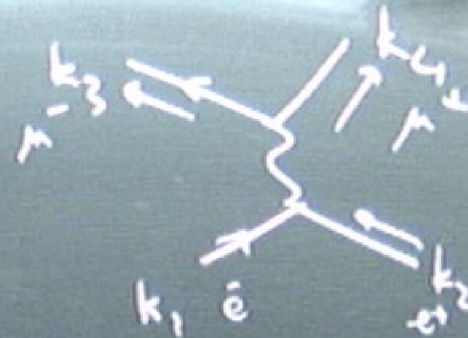
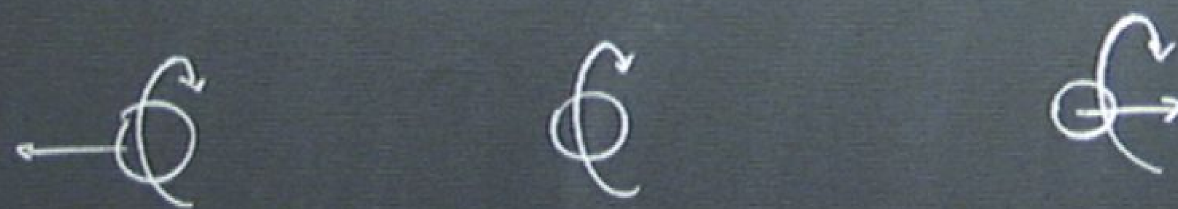


$$e^+e^- \longrightarrow \mu^+\mu^-$$

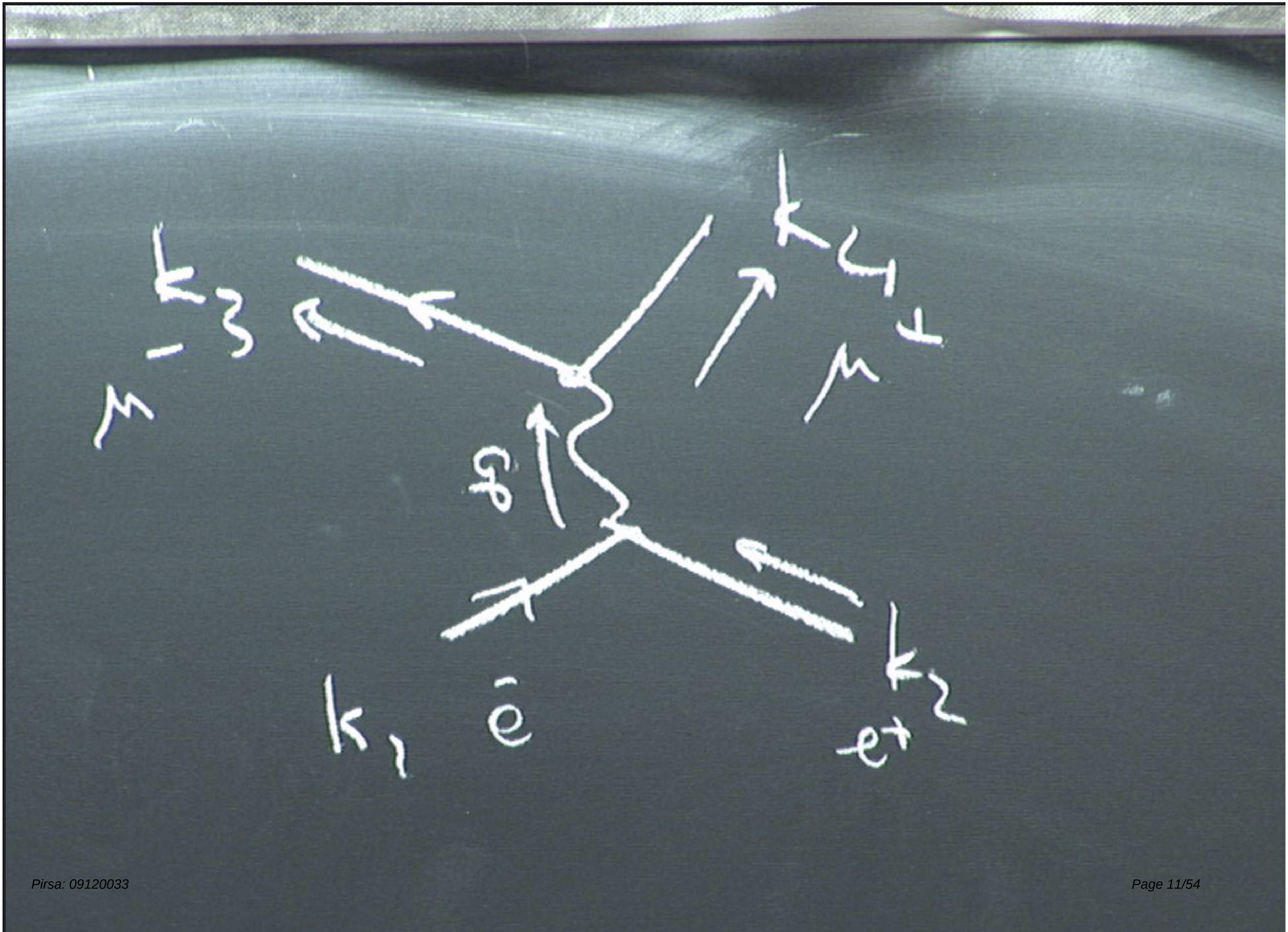


helicity

$$i\bar{\sigma}\cdot\partial\,\psi_L = 0$$



$$i\mathcal{M} = (-ie)^2 \quad \bar{u}(k_3)\gamma^\mu u(k_4) \frac{-i}{q^2} \bar{v}(k_2)\gamma^\mu u(k_1)$$


k_3
μ^-
k_4
μ^+
q
k_1 $\bar{e}$
k_2
e^+

$$i\mathcal{M} = (-ie)^2 \; \bar{u}(k_3)\gamma^\mu u(k_4) \; \frac{-i}{q^2} \; \bar{v}(k_2)\gamma^\mu u(k_1)$$

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \bar{\sigma}^\mu & 0 \end{pmatrix} \qquad \sigma^\mu = (1, \vec{\sigma}) \qquad \bar{\sigma}^\mu = (1, -\vec{\sigma})$$

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$$k = (E, 0, 0, k)$$

$$(\not{k} - m)\, u = 0$$

$$\begin{pmatrix} -m & E - k\sigma^3 \\ E + k\sigma^3 & -m \end{pmatrix} \begin{pmatrix} u \end{pmatrix} = 0$$

$$i\mathcal{M} = (-ie)^2 \; \bar{u}(k_3)\gamma^\mu v(k_4) \; \frac{-i}{q^2} \; \bar{v}(k_2)\gamma^\mu u(k_1)$$

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \bar{\sigma}^\mu & 0 \end{pmatrix} \qquad \sigma^\mu = (1, \vec{\sigma}) \qquad \bar{\sigma}^\mu = (1, -\vec{\sigma})$$

$$k = (E, 0, 0, k) \qquad \odot \longrightarrow \qquad \longrightarrow \hat{3}$$

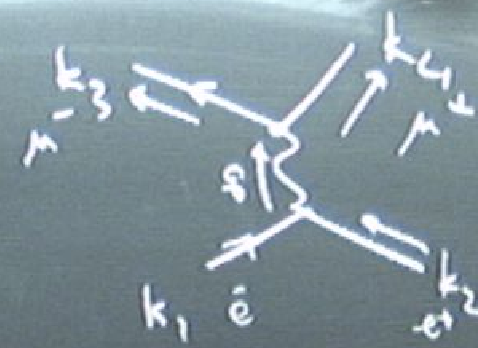
$$(\not{k} - m)\, u = 0 \qquad\qquad h = +\tfrac{1}{2} \quad u = \begin{pmatrix} \sqrt{E-k} \\ \sqrt{E+k} \end{pmatrix} \otimes \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$\begin{pmatrix} -m & E - k\sigma^3 \\ E + k\sigma^3 & -m \end{pmatrix} \begin{pmatrix} u \end{pmatrix} = 0 \qquad h = -\tfrac{1}{2} \quad u = \begin{pmatrix} \sqrt{E+k} \\ \sqrt{E-k} \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$(\not{k}+m)\,v = 0$$

$$k = (E, 0, 0, -k)$$

$$\begin{pmatrix} m & E+k\sigma^3 \\ E-k\sigma^3 & m \end{pmatrix} v = 0$$

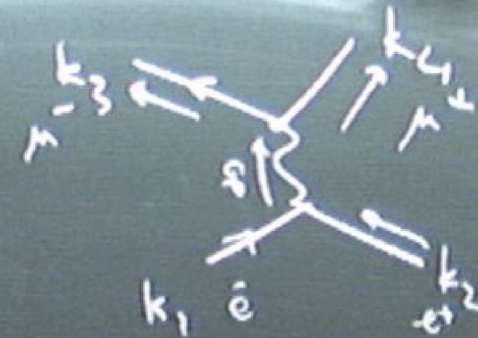


$$(\not{k}+m)\, v = 0$$

$$k = (E, 0, 0, -k)$$

$$\begin{pmatrix} m & E+k\sigma^3 \\ E-k\sigma^3 & m \end{pmatrix} v = 0$$

$$v(k) = \begin{pmatrix} \sqrt{E-k} \\ -\sqrt{E+k} \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \qquad \begin{pmatrix} \sqrt{E+k} \\ -\sqrt{E-k} \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$



$$(\not{k}+m)\, v = 0$$

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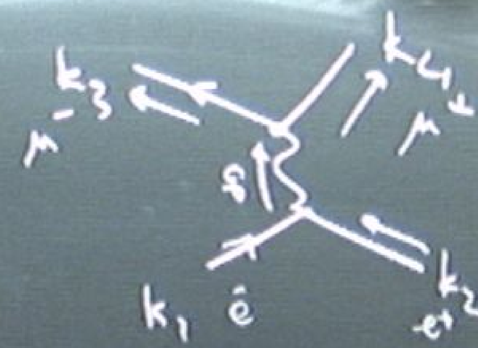
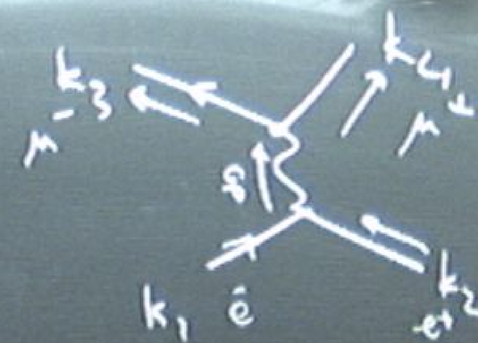


$$-\hat{3} \longleftarrow \qquad \longrightarrow \hat{3}$$

$$v(k) = \begin{pmatrix} \sqrt{E-k} \\ -\sqrt{E+k} \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \qquad \begin{pmatrix} \sqrt{E+k} \\ -\sqrt{E-k} \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$(\not{k}+m)\,v = 0$$



$$k = (E, 0, 0, -k)$$

$$-\hat{3} \longleftarrow \qquad \longrightarrow \hat{3}$$

$$\begin{pmatrix} m & E + k\sigma^3 \\ E - k\sigma^3 & m \end{pmatrix} v = 0$$

$$v(k) = \begin{pmatrix} \sqrt{E-k} \\ -\sqrt{E+k} \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \qquad \begin{pmatrix} \sqrt{E+k} \\ -\sqrt{E-k} \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$h = -\tfrac{1}{2} \qquad\qquad h = +\tfrac{1}{2}$$

electron $+\hat{z}$ $\quad h = -\frac{1}{2} \quad \begin{pmatrix}\sqrt{E+k}\\ \sqrt{E-k}\end{pmatrix}\begin{pmatrix}0\\ 1\end{pmatrix} \qquad h = +\frac{1}{2} \quad \begin{pmatrix}\sqrt{E-k}\\ \sqrt{E+k}\end{pmatrix}\begin{pmatrix}1\\ 0\end{pmatrix}$

positron $-\hat{z}$ $\quad h = -\frac{1}{2} \quad \begin{pmatrix}\sqrt{E-k}\\ \sqrt{E+k}\end{pmatrix}\begin{pmatrix}0\\ 1\end{pmatrix}$

electron $+\hat{z}$ $\quad h=-\frac{1}{2} \quad \begin{pmatrix}\sqrt{E+k}\\ \sqrt{E-k}\end{pmatrix}\begin{pmatrix}0\\ 1\end{pmatrix} \quad h=+\frac{1}{2} \quad \begin{pmatrix}\sqrt{E-k}\\ \sqrt{E+k}\end{pmatrix}\begin{pmatrix}1\\ 0\end{pmatrix}$

positr $-\hat{z}$ $\quad h=-\frac{1}{2} \quad \begin{pmatrix}\sqrt{E-k}\\ -\sqrt{E+k}\end{pmatrix}\begin{pmatrix}0\\ 1\end{pmatrix} \quad h=+\frac{1}{2} \quad \begin{pmatrix}\sqrt{E+k}\\ -\sqrt{E-k}\end{pmatrix}\begin{pmatrix}-1\\ 0\end{pmatrix}$

$$i\mathcal{M} = (-ie)^2 \; \bar{u}(k_3)\gamma^\mu u(k_4) \; \frac{-i}{q^2} \; \bar{v}(k_2)\gamma^\mu u(k_1)$$

$m = 0$

$$\bar{v}\gamma^\mu u = v^\dagger \gamma^0 \gamma^\mu u = v^\dagger \begin{pmatrix} \bar{\sigma}^\mu & 0 \\ 0 & \sigma^\mu \end{pmatrix} u$$

$$i\mathcal{M} = (-ie)^2 \; \bar{u}(k_3)\gamma^\mu u(k_4) \; \frac{-i}{q^2} \; \bar{v}(k_2)\gamma^\mu u(k_1)$$

$\underline{m = 0}$ $\quad \bar{v}\gamma^\mu u = v^\dagger \gamma^0 \gamma^\mu u = v^\dagger \begin{pmatrix} \bar{\sigma}^\mu & 0 \\ 0 & \sigma^\mu \end{pmatrix} u$

$$e^-_L e^+_R \quad (\sqrt{2E})^2 (-1\ 0)(1\ -\vec{\sigma})\begin{pmatrix} 0 \\ 1 \end{pmatrix} = +2E(0\ 1, -i, 0)$$

$$e^-_R e^+_L \quad (\sqrt{2E})^2 (0\ 1)(1\ -\vec{\sigma})\begin{pmatrix} 1 \\ 0 \end{pmatrix} = -2E(0, 1, i, 0)$$

$$i\mathcal{M} = (-ie)^2 \; \bar{u}(k_3)\gamma^\mu v(k_4) \; \frac{-i}{q^2} \; \bar{v}(k_2)\gamma^\mu u(k_1)$$

$\underline{m = 0}$ $$\bar{v}\gamma^\mu u = v^\dagger \gamma^0 \gamma^\mu u = v^\dagger \begin{pmatrix} \bar{\sigma}^\mu & 0 \\ 0 & \sigma^\mu \end{pmatrix} u$$

"helicity conservation"

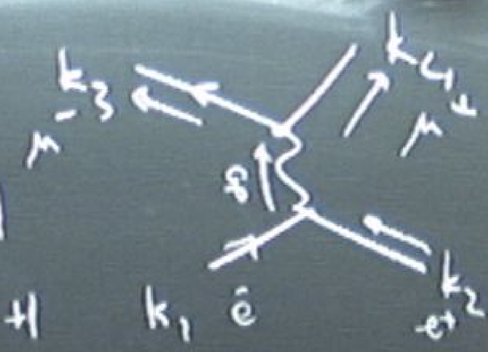
$e^-_L e^+_R$ $$(\sqrt{2E})^2 \, (-1 \;\; 0)(1 \;\; -\vec{\sigma})\begin{pmatrix} 0 \\ 1 \end{pmatrix} = +2E(0, 1, -i, 0)$$

$e^-_R e^+_L$ $$(\sqrt{2E})^2 \, (0 \;\; 1)(1 \;\; -\vec{\sigma})\begin{pmatrix} 1 \\ 0 \end{pmatrix} = -2E(0, 1, i, 0)$$

$$\varepsilon_L = \frac{1}{\sqrt{2}}(0\ 1\ -i\ 0)^\mu \qquad J^3 = -1$$

$$\varepsilon_R = \frac{1}{\sqrt{2}}(0\ 1\ i\ 0)^\mu \qquad J^3 = +1$$

$$\varepsilon_0 = (0\ 0\ 0\ 1) \qquad J^3 = 0 \qquad \hat{3}$$



"helicity
conservation

$$\varepsilon_L = \frac{1}{\sqrt{2}}(0\ 1\ -i\ 0)^\mu \qquad J^3 = -1$$

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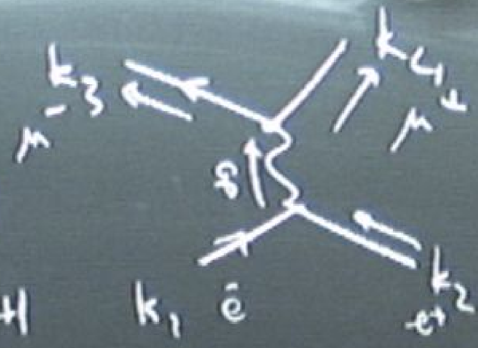
$$\varepsilon_0 = (0\ 0\ 0\ 1) \qquad J^3 = 0 \quad \hat{3} \longleftarrow$$

$$\varepsilon_i^* \cdot \varepsilon_j = \delta_{ij}(-1)$$



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$$i\mathcal{M} = (-ie)^2 \; \bar{u}(k_3)\gamma^\mu v(k_4) \, \frac{-i}{q^2} \, \bar{v}(k_2)\gamma^\mu u(k_1)$$

$\underline{m = 0}$

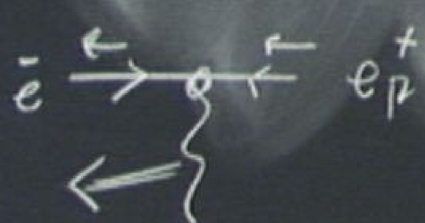
$$\bar{v}\gamma^\mu u = v^\dagger \gamma^0 \gamma^\mu u = v^\dagger \begin{pmatrix} \bar{\sigma}^\mu & 0 \\ 0 & \sigma^\mu \end{pmatrix} u$$

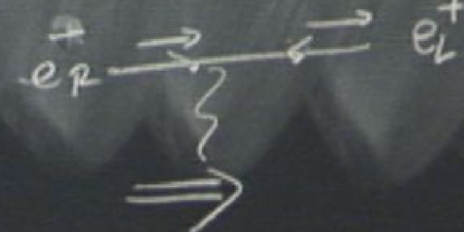
$e_L^- e_R^+$ $\quad (\sqrt{2E})^2 \, (-1 \;\; 0)(1 \; -\vec{\sigma}) \begin{pmatrix} 0 \\ 1 \end{pmatrix} = +2E(0, 1, -i, 0)$

$e_R^- e_L^+$ $\quad (\sqrt{2E})^2 \, (0 \;\; 1)(1 \; -\vec{\sigma}) \begin{pmatrix} 1 \\ 0 \end{pmatrix} = -2E(0, 1, i, 0)$

$e_L^- e_R^+$ $\quad 2E\sqrt{2}\, \varepsilon_L^\mu$

$e_R^- e_L^+$ $\quad -2E\sqrt{2}\, \varepsilon_R^\mu$





electron $+\hat{z}$ $\quad h = -\frac{1}{2} \begin{pmatrix} \sqrt{E+k} \\ \sqrt{E-k} \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ $\quad h = +\frac{1}{2} \begin{pmatrix} \sqrt{E-k} \\ \sqrt{E+k} \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$

positron $-\hat{z}$ $\quad h = -\frac{1}{2} \begin{pmatrix} \sqrt{E-k} \\ -\sqrt{E+k} \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ $\quad h = +\frac{1}{2} \begin{pmatrix} \sqrt{E+k} \\ -\sqrt{E-k} \end{pmatrix} \begin{pmatrix} -1 \\ 0 \end{pmatrix}$

$$\sqrt{E+k}\,\sqrt{E-k} = \sqrt{E^2-k^2} = m$$

$$i\mathcal{M} = (-ie)^2 \; \bar{u}(k_3)\gamma^\mu u(k_4) \; \frac{-i}{q^2} \; \bar{v}(k_2)\gamma_\mu u(k_1)$$

$\underline{m = 0}$

$$\bar{v}\gamma^\mu u = v^\dagger \gamma^0 \gamma^\mu u = v^\dagger \begin{pmatrix} \bar\sigma^\mu & 0 \\ 0 & \sigma^\mu \end{pmatrix} u$$

$e_L^- e_R^+$ $\quad (\sqrt{2E})^2 \, (-1 \; 0)(1 \; -\vec\sigma)\begin{pmatrix} 0 \\ 1 \end{pmatrix} = +2E(0, 1, -i, 0)$

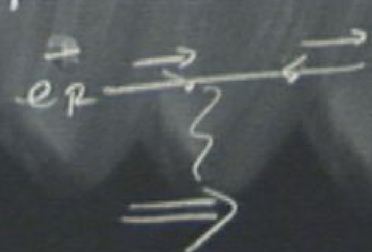
$e_R^- e_L^+$ $\quad (\sqrt{2E})^2 \, (0 \; 1)(1 \; -\vec\sigma)\begin{pmatrix} 1 \\ 0 \end{pmatrix} = -2E(0, 1, i, 0)$

$e_R^- e_L^+ \quad -2E\sqrt{2}\; \varepsilon_R^\mu$

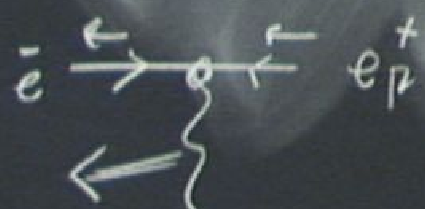
$\underline{\text{massive}}$

$e_L^- e_R^+ \quad 2E\sqrt{2}\; \varepsilon_L^\mu$

$e_L^- e_L^+ = e_R^- e_R^+$



$= 2m\; \varepsilon_0^\mu$



$$i\mathcal{M} = (-ie)^2 \; \bar{u}(k_3)\gamma^\mu u(k_4) \; \frac{-i}{q^2} \; \bar{v}(k_2)\gamma^\mu u(k_1)$$

$\underline{m = 0}$

$$\bar{v}\gamma^\mu u = v^+ \gamma^0 \gamma^\mu u = v^+ \begin{pmatrix} \bar{\sigma}^\mu & 0 \\ 0 & \sigma^\mu \end{pmatrix} u$$

$e_L^- e_R^+ \quad (\sqrt{2E})^2 \, (-1 \; 0)(1 \; -\vec{\sigma})\binom{0}{1} = +2E(0 \; 1, -i, 0)$

" $\quad e_R^- e_L^+ \quad (\sqrt{2E})^2 \, (0 \; 1)(1 \; -\vec{\sigma})\binom{1}{0} = -2E(0, 1, i, 0)$

$e_L^- e_R^+ \quad 2E\sqrt{2}\, \varepsilon_L^\mu$

$e_R^- e_L^+ \quad -2E\sqrt{2} \; \varepsilon_R^\mu$

massive

$e_L^- e_L^+ = e_R^- e_R^+$

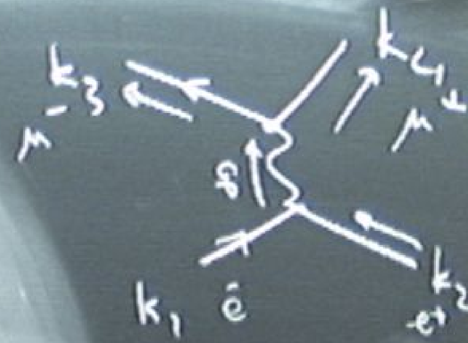
$= 2m \; \varepsilon_0^\mu$

$e^- \; e_R^+$

$e_R^- \; e_L^+$

$m_e = 0 \qquad m_\mu = 0$

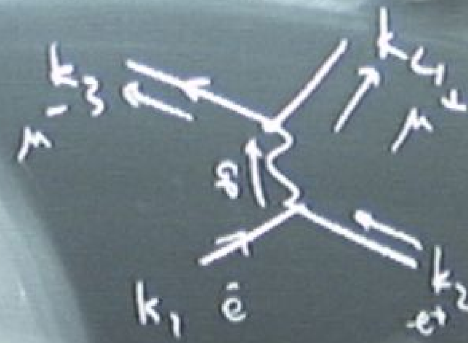
$$\mathcal{M} = \frac{ie^2}{s}$$



$E_{cm}^2 = s$

"helicity conservation"

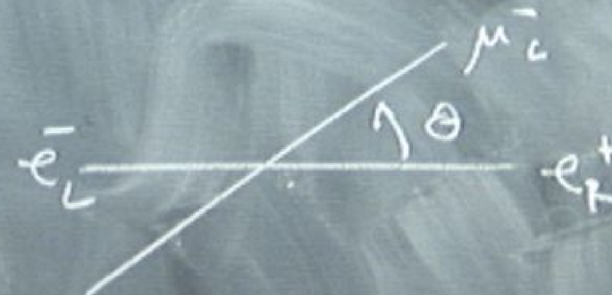
$m_e = 0 \qquad m_\mu = 0$



$E_{cm}^2 = s$

$$\mathcal{M} = \frac{ie^2}{s}\, 2s\, \varepsilon^{*}_{L\mu}(\theta)\, \varepsilon_L^{\mu}$$

$e^+_R \to \mu^-_L \mu^+_R$



"helicity conservation

electron $+\hat{z}$ $\quad h = -\tfrac{1}{2} \quad \begin{pmatrix} \sqrt{E+k} \\ \sqrt{E-k} \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \qquad h = +\tfrac{1}{2} \quad \begin{pmatrix} \sqrt{E-k} \\ \sqrt{E+k} \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$

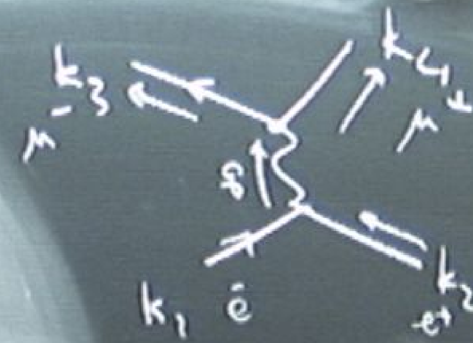
positron $-\hat{z}$ $\quad h = -\tfrac{1}{2} \quad \begin{pmatrix} \sqrt{E-k} \\ -\sqrt{E+k} \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \qquad h = +\tfrac{1}{2} \quad \begin{pmatrix} \sqrt{E+k} \\ -\sqrt{E-k} \end{pmatrix} \begin{pmatrix} -1 \\ 0 \end{pmatrix}$

$$\varepsilon_L = \frac{1}{\sqrt{2}}(0\ 1\ -i\ 0) \qquad \xrightarrow{\theta} \qquad \frac{1}{\sqrt{2}}(0\ \cos\theta\ -i\ -\sin\theta)$$

$$\varepsilon_0 \quad (0\ 0\ 0\ 1) \qquad\qquad (0\ \sin\theta\ 0\ \cos\theta)$$

$$\varepsilon_R = \frac{1}{\sqrt{2}}(0\ 1\ i\ 0) \qquad\qquad \frac{1}{\sqrt{2}}(0\ \cos\theta\ i\ -\sin\theta)$$

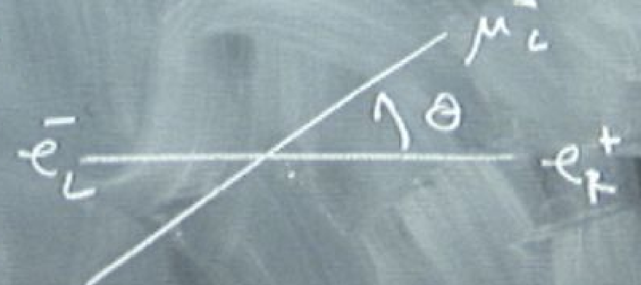
$m_e = 0 \qquad m_\mu = 0$



$E_{cm}^2 = s$

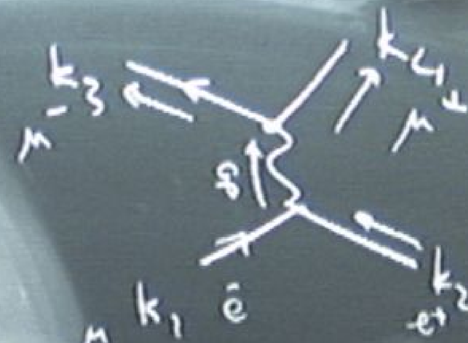
$$\mathcal{M} = \frac{ie^2}{s}\, 2s \underbrace{\varepsilon^*_{L\mu}(\theta)\,\varepsilon_L^\mu}_{-\frac{1}{2}(1+\cos\theta)}$$

$e^-_L e_R^+ \to \mu_L^- \mu_R^+$



"helicity conservation"

$m_e = 0 \qquad m_\mu = 0$



$E_{cm}^2 = s$

$$\mathcal{M} = \frac{ie^2}{\not s}\, 2\not s \;\underbrace{\varepsilon^*_{L\mu}(\theta)\, \varepsilon_L^\mu}_{-\frac{1}{2}(1+\cos\theta)}$$

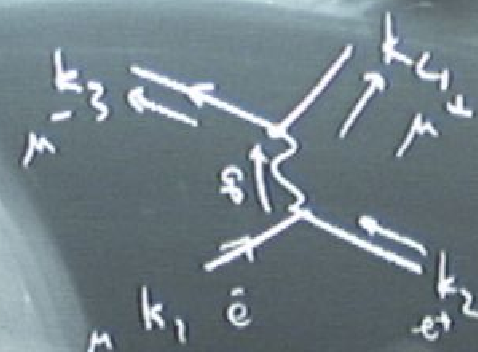
$e_R^+ \to \mu_L^- \mu_R^+$

$e_L^- e_R^+ \to \mu_L^- \mu_R^+ \qquad -ie^2(1+\cos\theta)$

"helicit

conservati

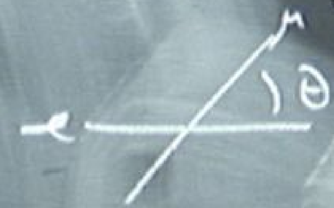
$m_e = 0 \qquad m_\mu = 0$



$E_{cm}^2 = s$

$$\mathcal{M} = \frac{ie^2}{\not s}\, 2\not s \; \underbrace{\varepsilon^*_{L\mu}(\theta)\,\varepsilon_L^\mu}_{-\frac{1}{2}(1+\cos\theta)}$$

$e^+_R \to \mu^-_L \mu^+_R$

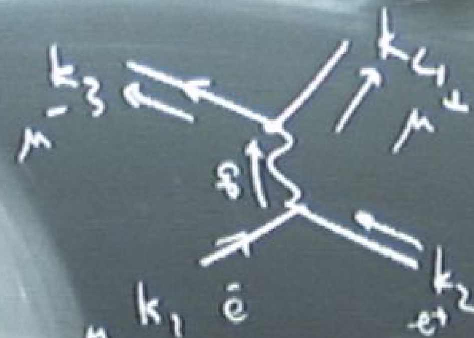


$e^-_L e^+_R \to \mu^-_L \mu^+_R \qquad -ie^2(1+\cos\theta)$

$e^-_L e^+_R \to \mu^-_R \mu^+_L \qquad ie^2(1-\cos\theta)$

"helicit
conservati

$m_e = 0 \qquad \cancel{m_\mu = 0}$



$E_{cm}^2 = s$

$$\mathcal{M} = \frac{ie^2}{\cancel{s}}\, 2\cancel{s}\, \underbrace{\varepsilon^*_{L\mu}(\theta)\,\varepsilon_L^\mu}_{-\frac{1}{2}(1+\cos\theta)}$$

$e^+_R \to \mu^-_L \mu^+_R$

$e^-_L e^+_R \to \mu^-_L \mu^+_R \qquad -ie^2(1+\cos\theta)$

$e^-_L e^+_R \to \mu^-_R \mu^+_L \qquad ie^2(1-\cos\theta)$

$-ie^2 \dfrac{m}{E} \sin\theta$

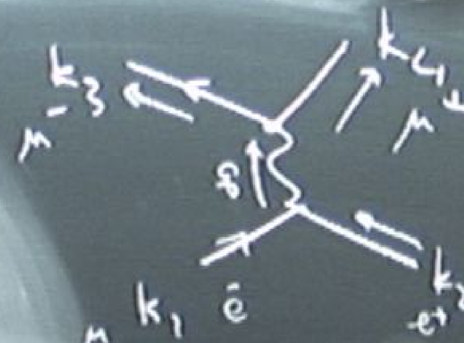
$e^-_L e^+_R \to \mu_L \mu_L$

$\mu_R \mu_R$

"helicit

conservat

$m_e = 0$ $\quad \cancel{m_\mu = 0}$



$E_{cm}^2 = s$

$$\mathcal{M} = \frac{ie^2}{\cancel{s}}\, 2\cancel{s}\, \underbrace{\epsilon^*_{L\mu}(\theta)\, \epsilon_L^\mu}$$

$e^-_L e^+_R \to \mu^-_L \mu^+_R$ $\quad -\frac{1}{2}(1+\cos\theta)$

$s = E_{cm}^2 = (2E)^2$

"helicity conservation"

$e^-_L e^+_R \to \mu^-_L \mu^+_R$ $\quad -ie^2(1+\cos\theta)$

$e^-_L e^+_R \to \mu^-_R \mu^+_L$ $\quad ie^2(1-\cos\theta)$

$e^-_L e^+_R \to \mu_L \mu_L$ $\quad -ie^2 \frac{m}{E} \sin\theta$ $\quad$ helicity flip

$\mu_R \mu_R$

A B

$$\sigma = \frac{1}{2E_A \, 2E_B \, |v_A - v_B|} \int d\Pi \; |\mathcal{M}|^2$$

① mass initial

$$\frac{1}{2s}$$

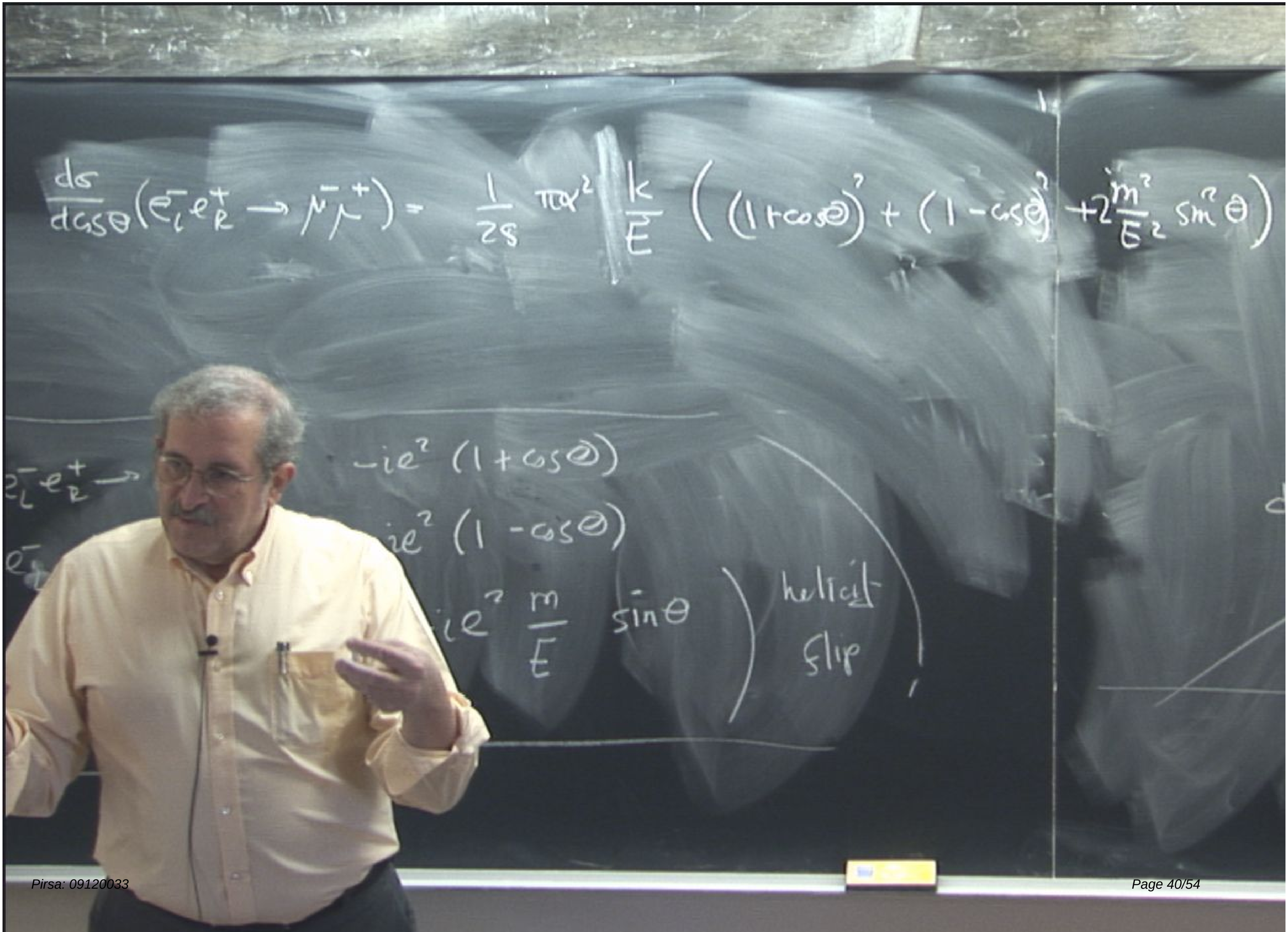
A B

$$\sigma = \frac{1}{2E_A \, 2E_B \, |v_A - v_B|} \int d\Pi \; |\mathcal{M}|^2$$

2-body final

① mass initial

$$d\sigma = \frac{1}{2s} \; \frac{1}{16\pi} \int d\cos\theta \left(\frac{2k}{E_{cm}} \right) |\mathcal{M}|^2$$


$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \to \mu^- \mu^+) = \frac{1}{2s} \pi\alpha^2 \frac{k}{E} \left((1+\cos\theta)^2 + (1-\cos\theta)^2 + 2\frac{m^2}{E^2} \sin^2\theta \right)$
$e_L^- e_R^+ \to$
$-ie^2 (1+\cos\theta)$
$ie^2 (1-\cos\theta)$
$ie^2 \frac{m}{E} \sin\theta$
helicity flip

$$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \to \mu^- \mu^+) = \frac{1}{2s}\pi\alpha^2 \frac{k}{E}\left((1+\cos\theta)^2 + (1-\cos\theta)^2 + 2\frac{m^2}{E^2}\sin^2\theta\right)$$

$$\frac{d\sigma}{d\cos\theta}(e^- e^+ \to \mu^- \mu^+) = \frac{\pi\alpha^2}{2s}\left(1-\frac{m_\mu^2}{E^2}\right)^{\frac{1}{2}}\left(1+\cos^2\theta + \frac{m^2}{E^2}\sin^2\theta\right)$$

$e_L^- e_R^+ \to \mu_L^- \mu_R^+$ $\quad -ie^2(1+\cos\theta)$

$e_L^- e_R^+ \to \mu_R^- \mu_L^+$ $\quad ie^2(1-\cos\theta)$

$e_L^- e_R^+ \to \mu_L \mu_L$, $\mu_R \mu_R$ $\quad -ie^2 \frac{m}{E}\sin\theta$ $\quad$ helicity flip

$$+2\frac{m^2}{E^2}\sin^2\theta\Big)$$

$$\sigma = \frac{4\pi}{3}\frac{\alpha^2}{s}\left(1-\frac{m^2}{E^2}\right)^{1/2}\left(1+\frac{1}{2}\frac{m^2}{E^2}\right)$$

2-body final

$$+\frac{m^2}{E^2}\sin^2\theta\Big)$$

① mass initial

$$d\sigma = \frac{1}{2s}\,\frac{1}{16\pi}\int d\cos\theta\left(\frac{2k}{E_{cm}}\right)|\mathcal{M}|^2$$

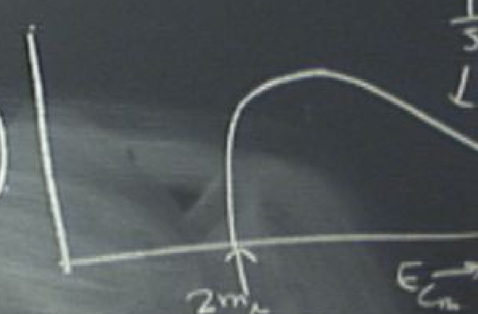
$$\frac{(e^2)^2}{16\pi} = \pi\alpha^2$$

$$+2\frac{m^2}{E^2}\sin^2\theta)$$

$$+\frac{m^2}{E^2}\sin^2\theta)$$

$$\sigma = \frac{4\pi}{3}\frac{\alpha^2}{s}\left(1-\frac{m^2}{E^2}\right)^{1/2}\left(1+\frac{1}{2}\frac{m^2}{E^2}\right)$$

spin 0 $\left(1-\frac{m^2}{E^2}\right)^{3/2}$



2-body final

(1) mass initial

$$d\sigma = \frac{1}{2s}\frac{1}{16\pi}\int d\cos\theta\left(\frac{2k}{E_{cm}}\right)|\mathcal{M}|^2$$

$$\frac{(e^2)^2}{16\pi} = \pi\alpha^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to \mu^- \mu^+) = \frac{1}{2s}\,\pi\alpha^2\,\frac{k}{E}\left((1+\cos\theta)^2 + (1-\cos\theta)^2\right.$$

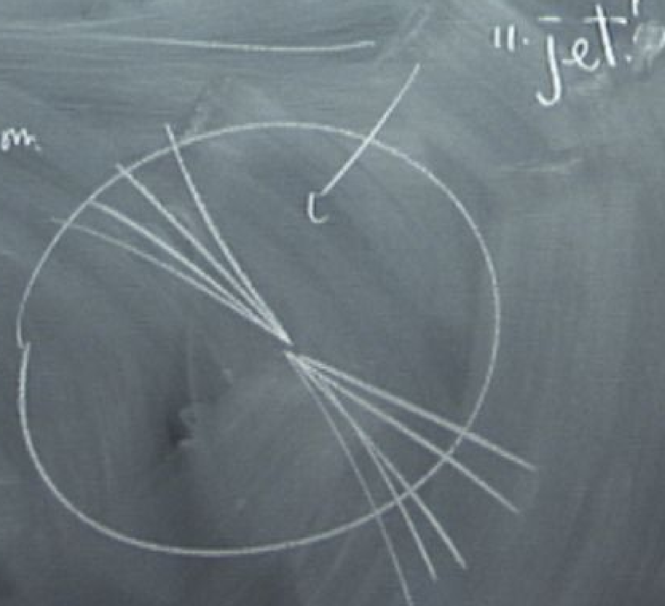
$$\frac{d\sigma}{d\cos\theta}(e^- e^+ \to \mu^- \mu^+) = \frac{\pi\alpha^2}{2s}\left(1-\frac{m_\mu^2}{E^2}\right)^{\frac{1}{2}}\left(1+\cos^2\theta\right.$$

$e^+ e^- \to$ hadrons

$$\frac{d\sigma}{d\cos\theta}\left(e^-_L e^+_R \to \mu^- \mu^+\right) = \frac{1}{2s}\,\pi\alpha^2\,\frac{k}{E}\left((1+\cos\theta)^2 + (1-\cos\theta)^2\right.$$

$$\frac{d\sigma}{d\cos\theta}\left(e^- e^+ \to \mu^- \mu^+\right) = \frac{\pi\alpha^2}{2s}\left(1-\frac{m_\mu^2}{E^2}\right)^{1/2}\left(1+\cos^2\theta\right.$$

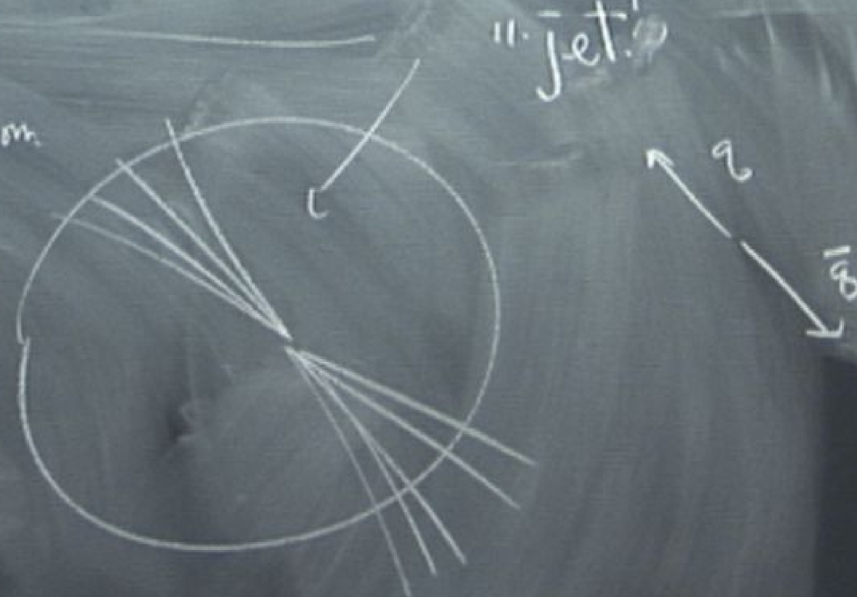
$e^+e^- \to$ hadron



$$\frac{d\sigma}{d\cos\theta}\left(e^-_L e^+_R \to \mu^-\mu^+\right) = \frac{1}{2s}\,\pi\alpha^2\,\frac{k}{E}\left((1+\cos\theta)^2 + (1-\cos\theta)^2\right.$$

$$\frac{d\sigma}{d\cos\theta}\left(e^- e^+ \to \mu^-\mu^+\right) = \frac{\pi\alpha^2}{2s}\left(1-\frac{m_\mu^2}{E^2}\right)^{1/2}\left(1+\cos^2\theta\right.$$

$e^+e^- \to$ hadron



$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to \mu^- \mu^+) = \frac{1}{2s} \pi\alpha^2 \frac{k}{E} \left((1+\cos\theta)^2 + (1-\cos\theta)^2 \right.$$

$$\frac{d\sigma}{d\cos\theta}(e^- e^+ \to \mu^- \mu^+) = \frac{\pi\alpha^2}{2s} \left(1 - \frac{m_\mu^2}{E^2}\right)^{\frac{1}{2}} \left(1 + \cos^2\theta \right.$$

$$\sigma = \frac{4\pi\alpha^2}{s}$$

$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to \mu^- \mu^+) = \frac{1}{2s}\pi\alpha^2 \frac{k}{E}\Big((1+\cos\theta)^2 + (1-\cos\theta)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^- e^+ \to \mu^- \mu^+) = \frac{\pi\alpha^2}{2s}\left(1-\frac{m_\mu^2}{E^2}\right)^{\frac{1}{2}}\Big(1+\cos^2\theta$$

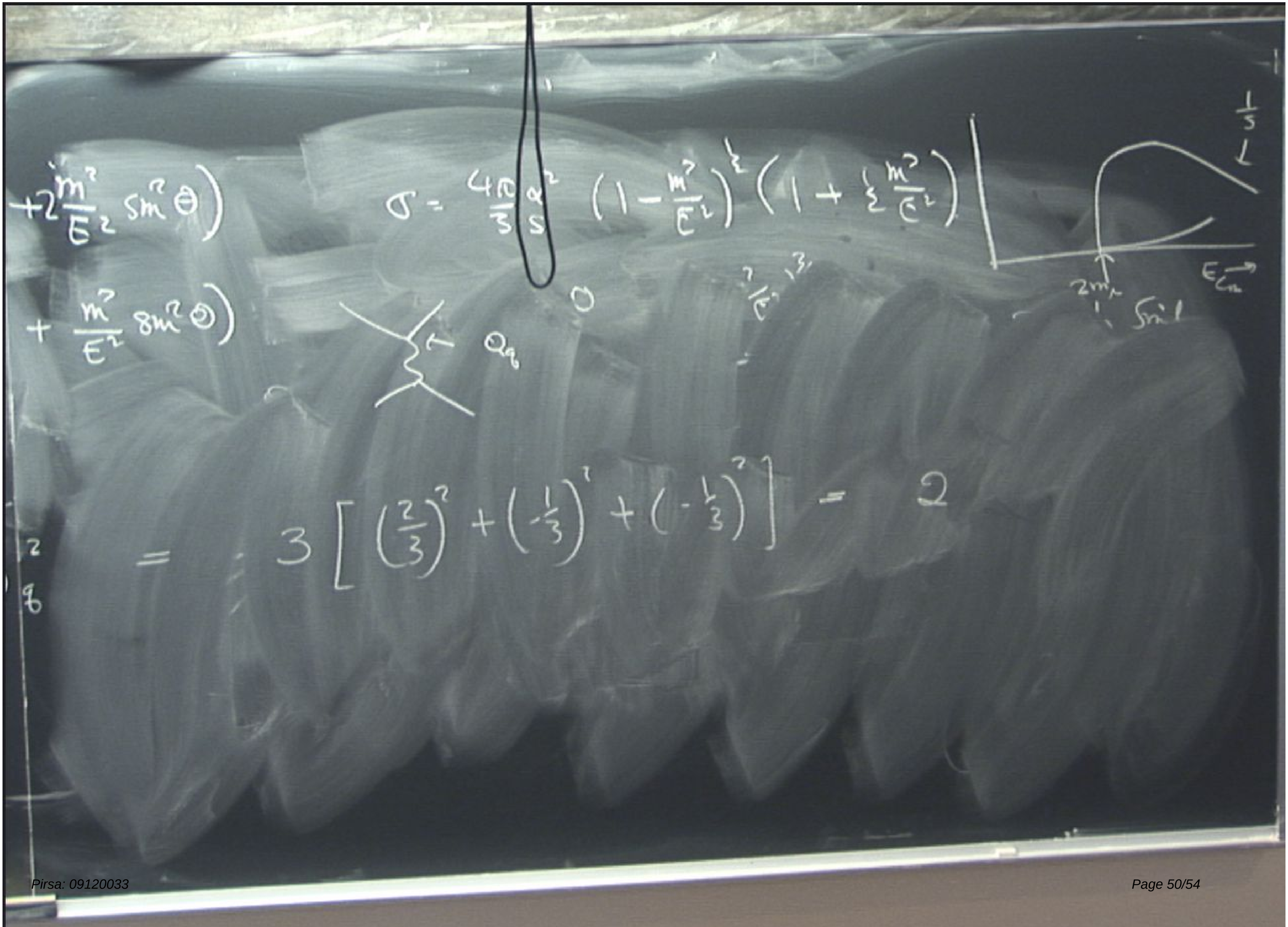
$$\sigma = \frac{4\pi\alpha^2}{s} \qquad e^+e^- \to \mu^+\mu^- \quad "$$

$$R = \frac{\sigma(e^+e^- \to \text{hadr.})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$$+2\frac{m^2}{E^2}\sin^2\theta\Big)$$

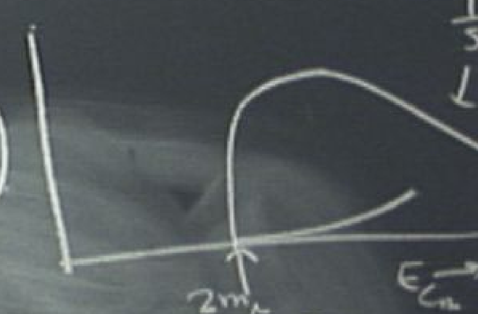
$$+\frac{m^2}{E^2}\sin^2\theta\Big)$$

$$\sigma = \frac{4\pi}{3}\frac{\alpha^2}{s}\left(1-\frac{m^2}{E^2}\right)^{\frac{1}{2}}\left(1+\frac{1}{2}\frac{m^2}{E^2}\right)$$


$+2\frac{m^2}{E^2}\sin^2\theta)$
$\sigma = \frac{4\pi}{3}\frac{\alpha^2}{s}\left(1-\frac{m^2}{E^2}\right)^{\frac{1}{2}}\left(1+\frac{1}{2}\frac{m^2}{E^2}\right)$
$\frac{1}{s}$
E_{cm}
$2m_\mu$
$+\frac{m^2}{E^2}\sin^2\theta)$
Q_q
$= 3\left[\left(\frac{2}{3}\right)^2+\left(-\frac{1}{3}\right)^2+\left(-\frac{1}{3}\right)^2\right] = 2$

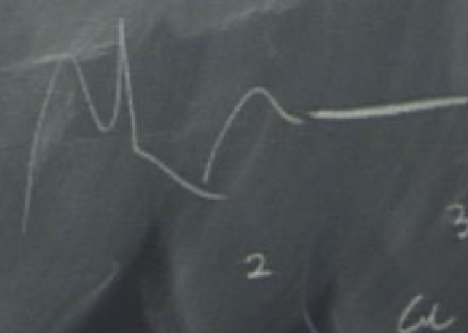
$$+2\frac{m^2}{E^2}\sin^2\theta\Big)$$

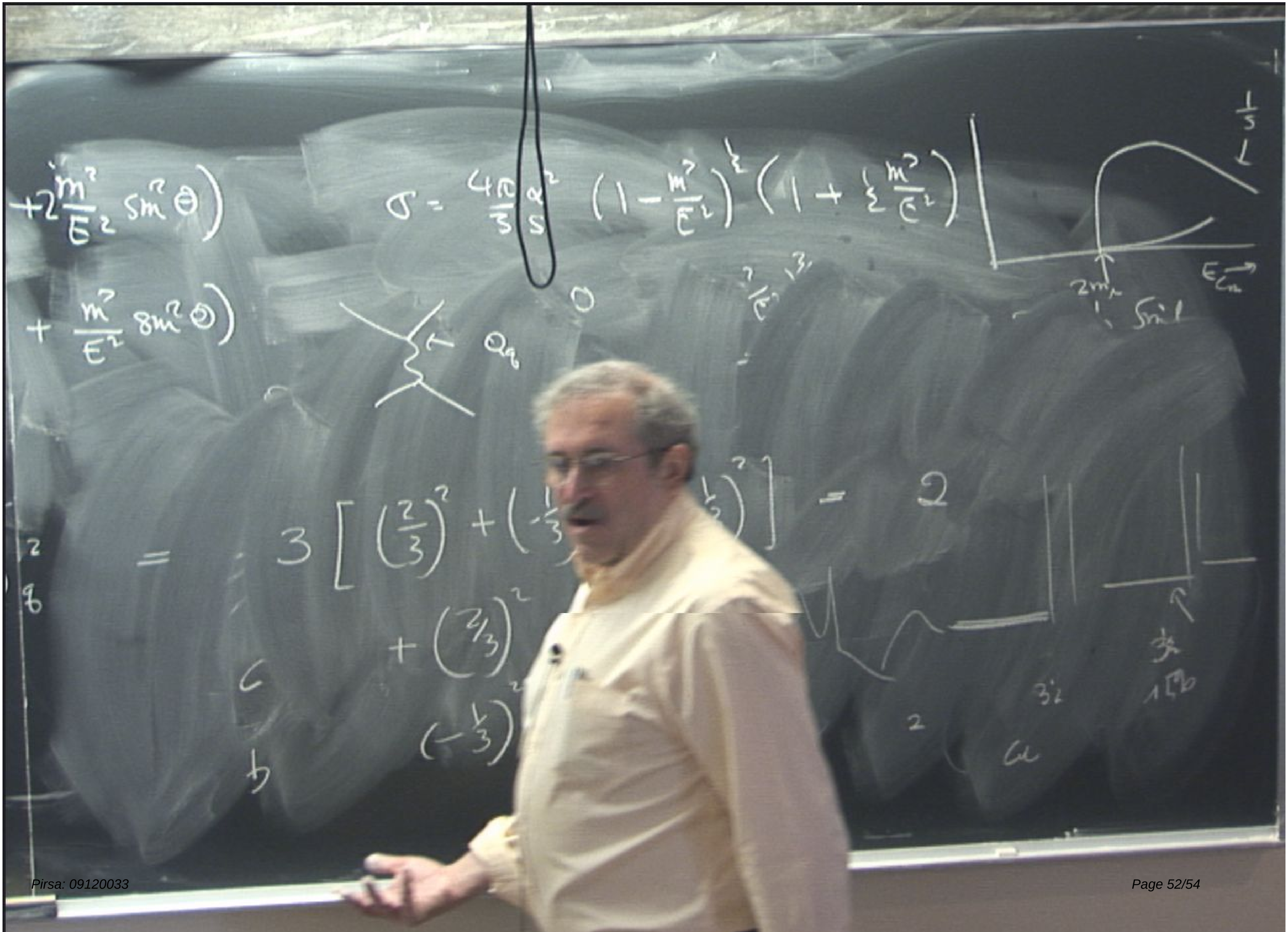
$$\sigma = \frac{4\pi}{3}\frac{\alpha^2}{s}\left(1-\frac{m^2}{E^2}\right)^{1/2}\left(1+\frac{1}{2}\frac{m^2}{E^2}\right)$$



$$+\frac{m^2}{E^2}\sin^2\theta\Big)$$

$$= 3\left[\left(\frac{2}{3}\right)^2+\left(-\frac{1}{3}\right)^2+\left(-\frac{1}{3}\right)^2\right] = 2$$




σ = 4π/3 α²/s (1 − m²/E²)^½ (1 + ½ m²/E²)
3 [(2/3)² + (−1/3)²
= 2
+ (2/3)²
(−1/3)²
E_cm
2m

$$+2\frac{m^2}{E^2}\sin^2\theta\Big)$$

$$+\frac{m^2}{E^2}\sin^2\theta\Big)$$

$$\sigma = \frac{4\pi}{3}\frac{\alpha^2}{s}\left(1-\frac{m^2}{E^2}\right)^{\frac{1}{2}}\left(1+\frac{1}{2}\frac{m^2}{E^2}\right)$$

Q_q

$\frac{1}{s}$

$2m_\mu$

E_{cm}

$$= 3\left[\left(\frac{2}{3}\right)^2+\left(-\frac{1}{3}\right)^2+\left(-\frac{1}{3}\right)^2\right] = 2$$

$$+\left(\frac{2}{3}\right)^2$$

c

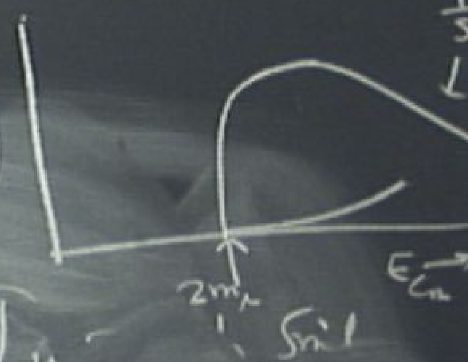
$$\left(-\frac{1}{3}\right)^2$$

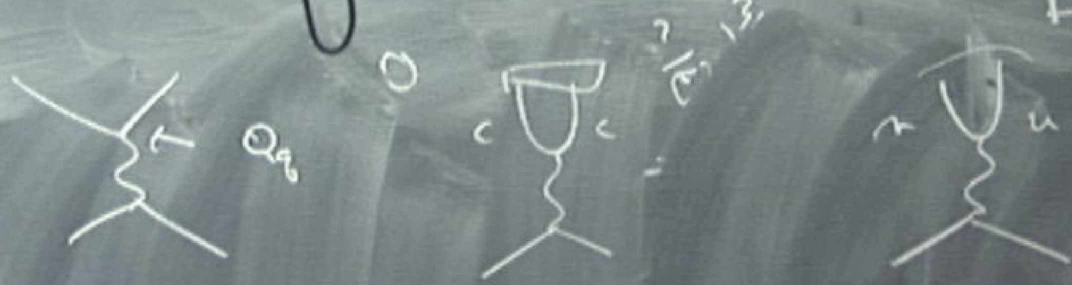
b

$$+2\frac{m^2}{E^2}\sin^2\theta\Big)$$

$$+\frac{m^2}{E^2}\sin^2\theta\Big)$$

$$\sigma = \frac{4\pi}{3}\frac{\alpha^2}{s}\left(1-\frac{m^2}{E^2}\right)^{1/2}\left(1+\frac{1}{2}\frac{m^2}{E^2}\right)$$





$$= 3\left[\left(\frac{2}{3}\right)^2+\left(-\frac{1}{3}\right)^2+\left(-\frac{1}{3}\right)^2\right] = 2$$

$$c \quad +\left(\frac{2}{3}\right)^2$$

$$b \quad \left(-\frac{1}{3}\right)^2$$