Title: Standard Model - Review (PHYS 622) - Lecture 7

Date: Dec 08, 2009 09:00 AM

URL: http://pirsa.org/09120039

Abstract:

$$\mathcal{L} = -\frac{1}{4g^2}\left(\mathbb{F}_{\mu\nu}^{a}\right)^2$$

$$\mathcal{L} = -\frac{1}{4g^2}\left(F^a_{\mu\nu}\right)^2 \quad -\frac{1}{2}\, a^a_\lambda\, \Delta^{\mu}_{1,1}\, a^c_\nu \;-\; \bar{c}\,\Delta_{0,0}\, c \;+\; \overset{\frac{1}{2}n_f}{\overset{\downarrow}{\bar{\Psi}}}\, \Delta_{\frac{1}{2},\frac{1}{2}}\, \Psi$$

$$\mathcal{L} = -\frac{1}{4g^2}\left(\mathbb{F}^a_{\mu\nu}\right)^2 - \frac{1}{2} a^a_\lambda \Delta^{\lambda\nu}_{G,1} a^a_\nu + \bar{c}\,\Delta_{G,0}\, c + \overset{\frac{1}{2} n_f}{\bar{\psi}\,\Delta_{r,\frac{1}{2}}}\,\psi + \phi^* \Delta_{r,0}\,\phi$$

$$\Delta = -\mathbb{D}^2 + 2\,\frac{1}{2}\mathbb{F}^a_{\mu\nu}\,\mathcal{J}^{\mu\nu}\,t^a_r$$

$$\overset{\frac{1}{2}n_f}{\swarrow}$$

$$\mathcal{L} = -\frac{1}{4g^2}(F^a_{\mu\nu})^2 - \frac{1}{2} a^a_\lambda \Delta^{\lambda\nu}_{G,1} a^a_\nu + \bar{c}\,\Delta_{G,0}\, c + \bar{\psi}\,\Delta_{r,\frac{1}{2}}\,\psi + \phi^*\Delta_{r,0}\,\phi$$

$$\Delta = -D^2 + 2\,\frac{1}{2}F^a_{\mu\nu}\,\mathcal{J}^{\mu\nu}\,t^a_r$$

$\mathcal{J}^{\mu\nu} = \frac{i}{4}[\gamma^\mu, \gamma^\nu]$ Dirac

$= i(\delta^\mu_\alpha \delta^\nu_\beta - \delta^\nu_\alpha \delta^\mu_\beta)$ 4-vectr

$$\overset{\frac{1}{2}n_f \downarrow}{}$$

$$\mathcal{L} = -\frac{1}{4g^2}(F^a_{\mu\nu})^2 - \frac{1}{2}A^a_\lambda \Delta^{\lambda\nu}_{G,1} A^a_\nu + \bar{c}\,\Delta_{G,0}\,c + \bar{\Psi}\,\Delta_{r,\frac{1}{2}}\,\Psi + \phi^*\Delta_{r,0}\,\phi$$

$$\Delta = -D^2 + 2\,\tfrac{1}{2}F^a_{\mu\nu}\,\mathcal{J}^{\mu\nu}\,t^a_r$$

$\mathcal{J}^{\mu\nu} = \frac{i}{4}[\gamma^\mu, \gamma^\nu]$ Drac

$= i(\delta^\mu_\alpha \delta^\nu_\beta - \delta^\nu_\alpha \delta^\mu_\beta)$ 4-vectr

$\Psi + \phi^* \Delta_{ro} \phi$

$\gamma^\nu]$ Dria

$\delta^\nu_\beta - \delta^\nu_\alpha \delta^\mu_\rho)$ 4-vectr

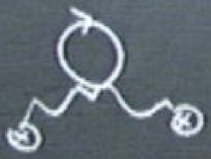
$$\vec{\mu} = g \frac{Qe\hbar}{m} \vec{S}$$

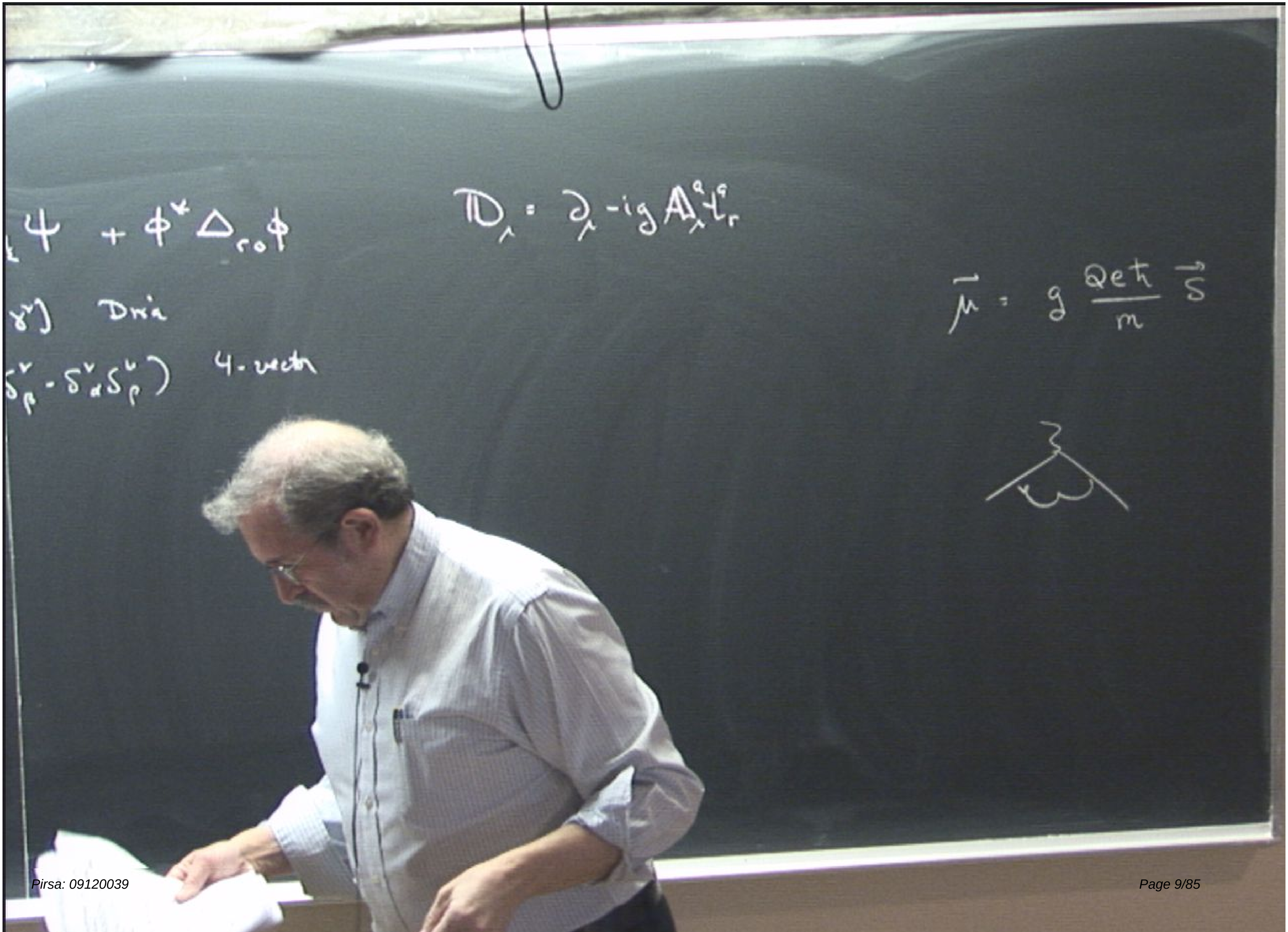
$$\mathcal{L} = -\frac{1}{4g^2}\left(\mathbb{F}^a_{\mu\nu}\right)^2 - \frac{1}{2} a^a_\lambda \Delta^{\mu\nu}_{g,1} a^c_\nu + \bar{c}\,\Delta_{g,0}\, c + \overset{\overset{\frac{1}{2}n_f}{\downarrow}}{\bar{\Psi}}\, \Delta_{r,\frac{1}{2}}$$

$$\Delta = -\mathbb{D}^2 + 2\,\frac{1}{2}\mathbb{F}^a_{\mu\nu}\,\mathcal{J}^{\mu\nu} t^a_r$$

$$\mathcal{J}^{\mu\nu} = \frac{i}{4}(\gamma^\mu$$

$$= i(\delta^\mu_\alpha\,\delta$$





$\psi + \phi^* \Delta_{ro}\phi$

$\mathbb{D}_\lambda = \partial_\lambda - ig\,\mathbb{A}^a_\lambda t^a_r$

$\gamma^\nu]$ Dirac

$\delta^\nu_\beta - \delta^\nu_\alpha \delta^\mu_\rho)$ 4-vector

$\vec{\mu} = g\,\frac{Qe\hbar}{m}\,\vec{S}$

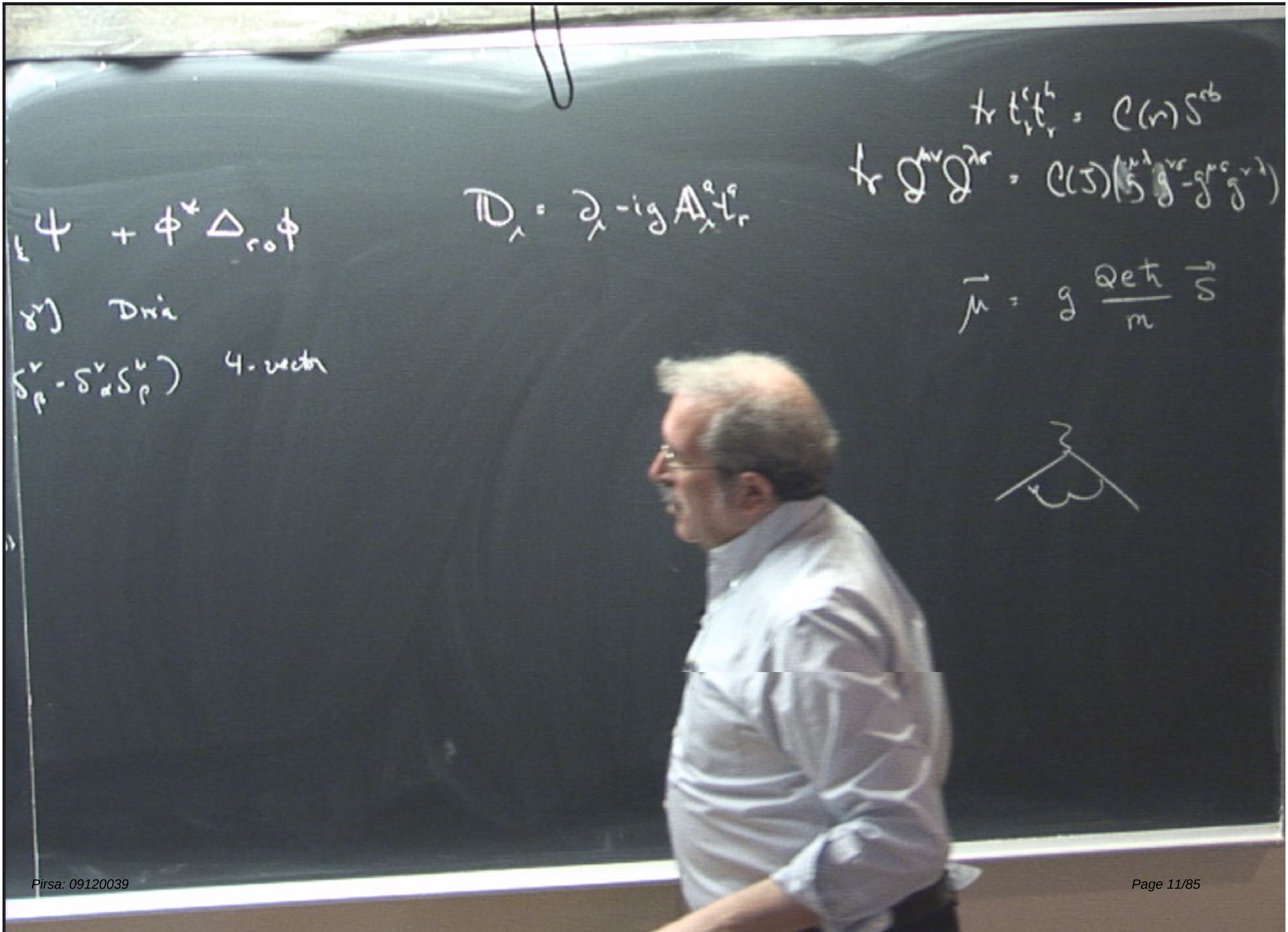
$$\mathcal{L} = -\frac{1}{4g^2}(\mathbb{F}^a_{\mu\nu})^2 - \frac{1}{2} a^a_\lambda \Delta^{\lambda\nu}_{G,1} a^c_\nu + \bar{c}\,\Delta_{G,0}\,c + \overset{\frac{1}{2}n_f \atop \swarrow}{\bar{\Psi}}\,\Delta_{r,\frac{1}{2}}$$

$$\Delta = -\mathbb{D}^2 + 2\,\frac{1}{2}\mathbb{F}^a_{\mu\nu}\,\mathcal{J}^{\mu\nu}\,t^a_r$$

$$\mathcal{J}^{\mu\nu} = \frac{i}{4}(\gamma^\mu\,\gamma$$

$$= i(\delta^\mu_\alpha\,\delta$$

$$\frac{1}{2}\int\frac{d^4q}{(2\pi)^4}\,\mathbb{A}^a_\mu(-q)\,\mathbb{A}^b_\nu(q) \quad i(q^2 g^{\mu\nu} - q^\mu q^\nu)\,\frac{1}{48\pi^2}\log(-q^2)\,\mathrm{tr}\,t^a_r t^b_r$$



$\Psi + \phi^* \Delta_{r_0} \phi$

$\gamma^\nu]$ Dirac

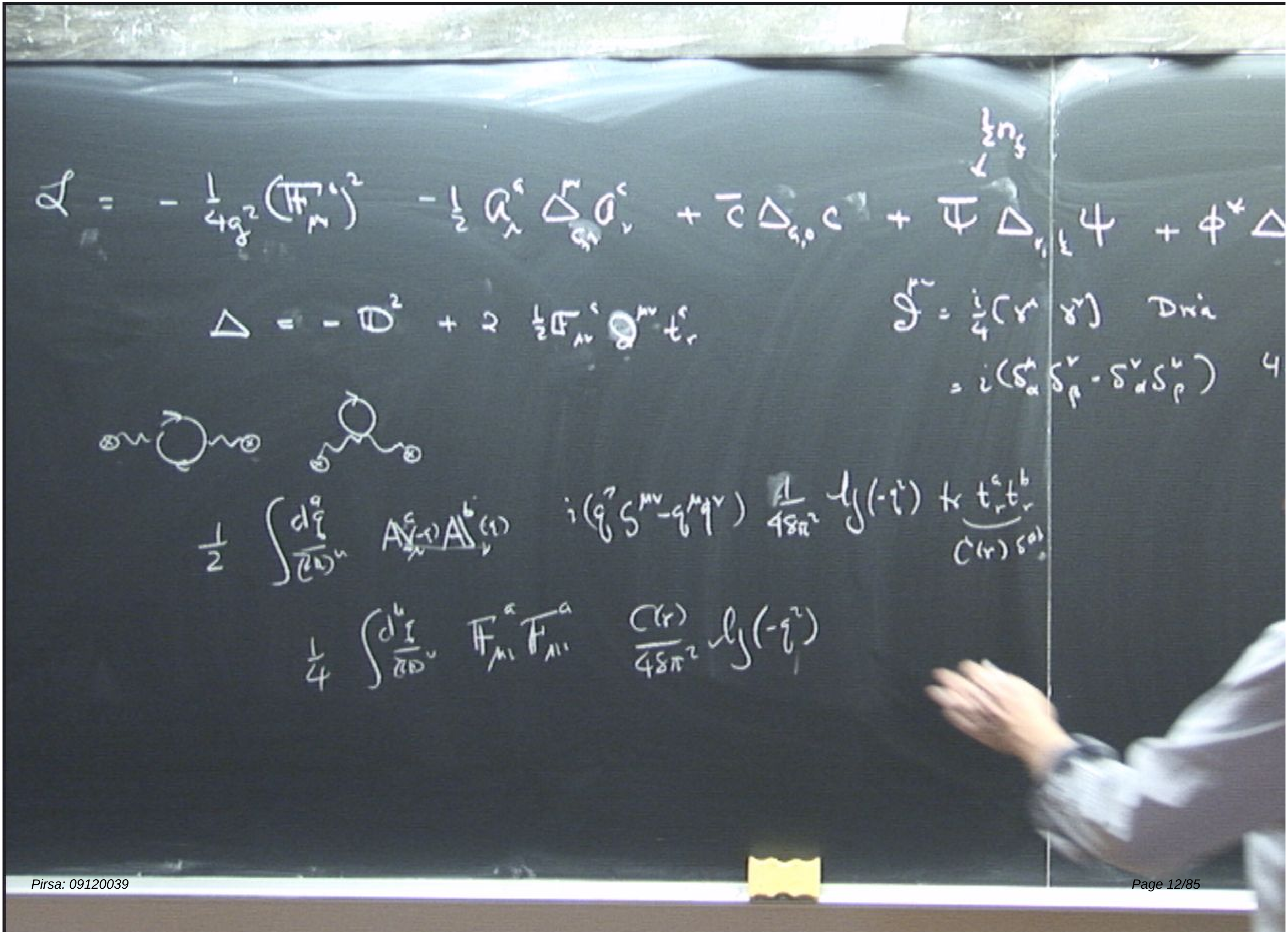
$\delta^\nu_\beta - \delta^\nu_\alpha \delta^\mu_\rho)$ 4-vectr

$\mathbb{D}_\lambda = \partial_\lambda - ig\mathbb{A}^a_\lambda t^a_r$

$\mathrm{tr}\, t^a_r t^b_r = C(r)\delta^{ab}$

$\mathrm{tr}\, \mathcal{J}^{\mu\nu}\mathcal{J}^{\lambda\sigma} = C(J)(g^{\mu\lambda}g^{\nu\sigma} - g^{\mu\sigma}g^{\nu\lambda})$

$\vec{\mu} = g\frac{Qe\hbar}{m}\vec{S}$



$$\mathcal{L} = -\frac{1}{4g^2}(F^a_{\mu\nu})^2 \quad -\frac{1}{2} a^a_\lambda \, \Delta^{\mu\nu}_{G,1} \, a^c_\nu \quad + \bar{c}\,\Delta_{G,0}\,c \quad + \bar{\Psi}\, \overset{\frac{1}{2}n_f}{\downarrow} \Delta_{r,\frac{1}{2}} \Psi \quad + \phi^* \Delta$$

$$\Delta = -D^2 + 2\,\tfrac{1}{2}F^c_{\mu\nu}\,\mathcal{J}^{\mu\nu}\,t^c_r$$

$$\mathcal{J}^{\mu\nu} = \frac{i}{4}[\gamma^\mu, \gamma^\nu] \quad \text{Dira}$$

$$= i(\delta^\mu_\alpha \delta^\nu_\beta - \delta^\nu_\alpha \delta^\mu_\beta) \quad 4$$

$$\frac{1}{2}\int \frac{d^4q}{(2\pi)^4} \, A^a_\mu(-q) A^b_\nu(q) \quad i(q^2 g^{\mu\nu} - q^\mu q^\nu) \, \frac{1}{48\pi^2} \log(-q^2) \; \underbrace{\mathrm{tr}\, t^a_r t^b_r}_{C(r)\,\delta^{ab}}$$

$$\frac{1}{4}\int \frac{d^4q}{(2\pi)^4} \, F^a_{\mu\nu} F^a_{\mu\nu} \quad \frac{C(r)}{48\pi^2} \log(-q^2)$$

$$\mathcal{L} = -\frac{1}{4g^2}\left(F^a_{\mu\nu}\right)^2 - \frac{1}{2} A^a_\lambda \Delta^{\lambda\nu}_{G,1} A^c_\nu + \bar{c}\,\Delta_{G,0}\,c + \overset{\frac{1}{2}n_f}{\bar{\Psi}}\,\Delta_{r,\frac{1}{2}}\Psi + \phi^* \Delta$$

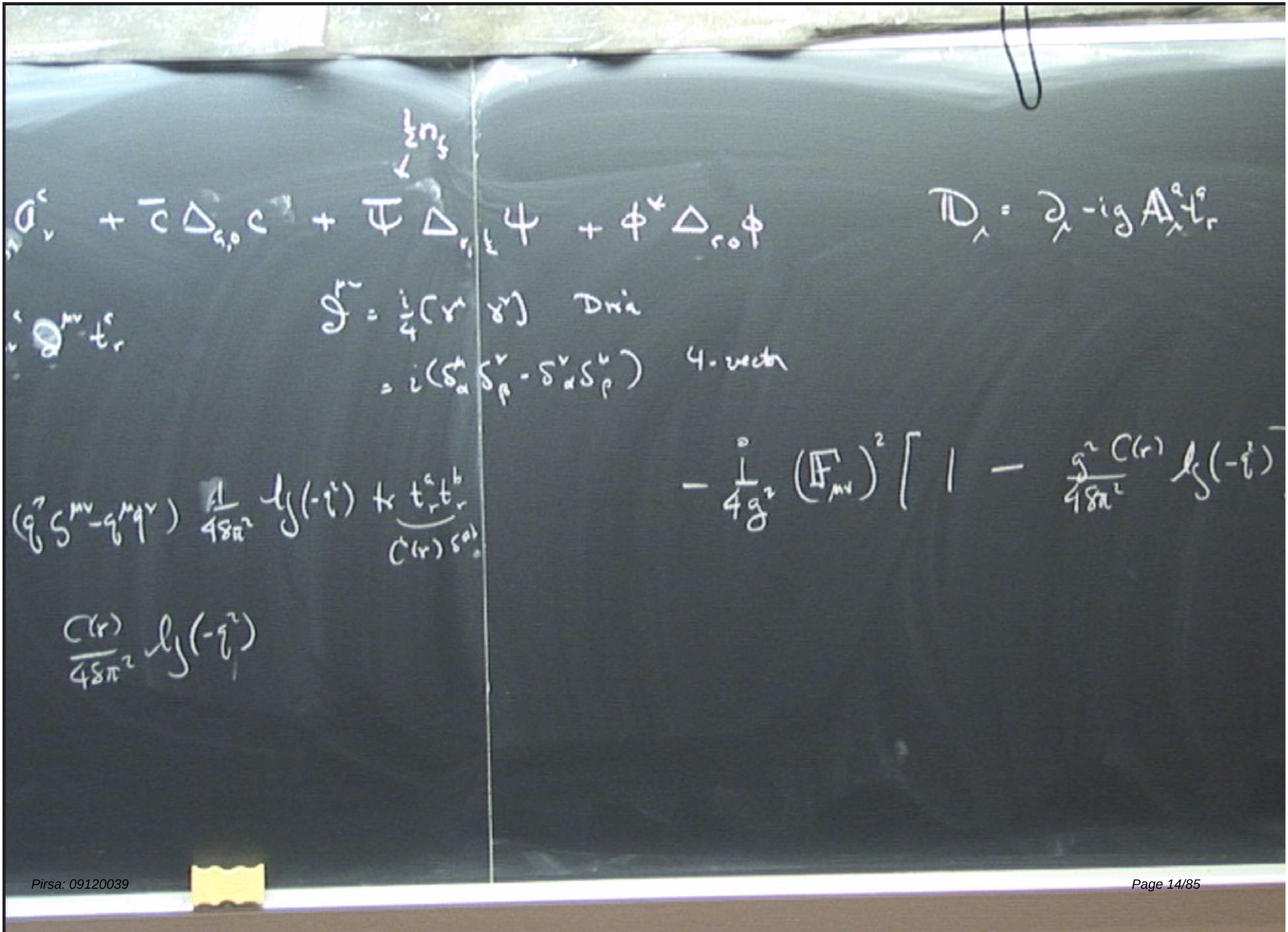
$$\Delta = -D^2 + 2\,\frac{1}{2}F^c_{\mu\nu}\mathcal{J}^{\mu\nu} t^c_r$$

$$\mathcal{J}^{\mu\nu} = \frac{i}{4}[\gamma^\mu, \gamma^\nu] \quad \text{Dira}$$

$$= i\left(\delta^\mu_\alpha \delta^\nu_\beta - \delta^\nu_\alpha \delta^\mu_\beta\right) \quad 4$$

$$1 + \frac{1}{2}\int\frac{d^4q}{(2\pi)^4} A^a_\mu(-q) A^b_\nu(q) \quad i\left(q^2 g^{\mu\nu} - q^\mu q^\nu\right)\frac{1}{48\pi^2}\log(-q^2)\,\underbrace{\mathrm{tr}\, t^a_r t^b_r}_{C(r)\,\delta^{ab}}$$

$$1 + \frac{i}{4}\int\frac{d^4q}{(2\pi)^4} F^a_{\mu\nu}F^a_{\mu\nu} \quad \frac{C(r)}{48\pi^2}\log(-q^2)$$



$\frac{1}{2}n_f$

$$A^c_\nu + \bar{c}\,\Delta_{G,0}\,c + \bar{\Psi}\,\Delta_{r,\frac{1}{2}}\,\Psi + \phi^*\Delta_{r,0}\,\phi$$

$$\mathbb{D}_\lambda = \partial_\lambda - ig\,\mathbb{A}^a_\lambda t^a_r$$

$\mathcal{S}^{\mu\nu} t^c_r$

$\mathcal{S}^{\mu\nu} = \frac{i}{4}[\gamma^\mu, \gamma^\nu]$ Dirac

$= i(\delta^\mu_\alpha \delta^\nu_\beta - \delta^\nu_\alpha \delta^\mu_\beta)$ 4-vector

$$(q^2 g^{\mu\nu} - q^\mu q^\nu)\,\frac{1}{48\pi^2}\log(-q^2)\,\mathrm{tr}\,\underbrace{t^a_r t^b_r}_{C(r)\,\delta^{ab}}$$

$$-\frac{1}{4g^2}(\mathbb{F}_{\mu\nu})^2\left[1 - \frac{g^2 C(r)}{48\pi^2}\log(-q^2)\right.$$

$$\frac{C(r)}{48\pi^2}\log(-q^2)$$

$$\bar{c}\,\Delta_{G,0}\,c + \bar{\Psi}\,\Delta_{r,\overset{\frac{1}{2}n_f}{\downarrow}\!\frac{1}{2}}\,\Psi + \phi^*\,\Delta_{r,0}\,\phi$$

$$\mathbb{D}_\lambda = \partial_\lambda - ig\,\mathbb{A}^a_\lambda t^a_r$$

tr $\mathcal{J}$

$$\mathcal{J}^{\mu\nu} = \frac{i}{4}[\gamma^\mu, \gamma^\nu] \quad \text{Dirac}$$

$$= i(\delta^\mu_\alpha \delta^\nu_\beta - \delta^\nu_\alpha \delta^\mu_\beta) \quad \text{4-vector}$$

$$q^\nu)\ \frac{1}{48\pi^2} \log(-q^2)\ \mathrm{tr}\ \underbrace{t^a_r t^b_r}_{C(r)\,\delta^{ab}}$$

$$-\frac{1}{4g^2}(\mathbb{F}_{\mu\nu})^2\left[1 - \frac{g^2 C(r)}{48\pi^2}\log(-q^2)\right]$$

$$\log(-q^2)$$

$\frac{1}{2}n_f$

$$\bar{c}\,\Delta_{G,0}\,c + \bar{\Psi}\,\Delta_{r,\frac{1}{2}}\,\Psi + \phi^*\,\Delta_{r,0}\,\phi$$

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$$\mathbb{D}_\lambda = \partial_\lambda - ig\,\mathbb{A}^a_\lambda t^a_r$$

$\mathrm{tr}\ g$

$$q^\nu)\ \frac{1}{48\pi^2}\log(-q^2)\ \mathrm{tr}\,\underbrace{t^a_r t^b_r}_{C(r)\,\delta^{ab}}$$

$$-\frac{1}{4g^2}(\mathbb{F}_{\mu\nu})^2\left[1 - \frac{g^2 C(r)}{48\pi^2}\log(-q^2)\right]$$

$${}_2\log(-q^2)$$

$$g^2(-q^2) = \frac{g^2}{1 - \frac{g^2 C(r)}{48\pi^2}\log(-q^2)}$$

$$\bar{c}\,\Delta_{G,0}\,c + \bar{\Psi}\,\overset{\frac{1}{2}n_f}{\downarrow}\!\Delta_{r,\frac{1}{2}}\Psi + \phi^*\Delta_{r,0}\phi$$

$$\mathbb{D}_\lambda = \partial_\lambda - ig\mathbb{A}^a_\lambda t^a_r$$

tr g

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$$= i(\delta^\mu_\alpha\delta^\nu_\beta - \delta^\nu_\alpha\delta^\mu_\beta) \quad \text{4-vector}$$

$$q^\nu)\ \frac{1}{48\pi^2}\lg(-q^2)\ \mathrm{tr}\,\underbrace{t^a_r t^b_r}_{C(r)\,\delta^{ab}}$$

$$-\frac{1}{4g^2}(\mathbb{F}_{\mu\nu})^2\left[1 - \frac{g^2 C(r)}{48\pi^2}\lg(-q^2)\right]$$

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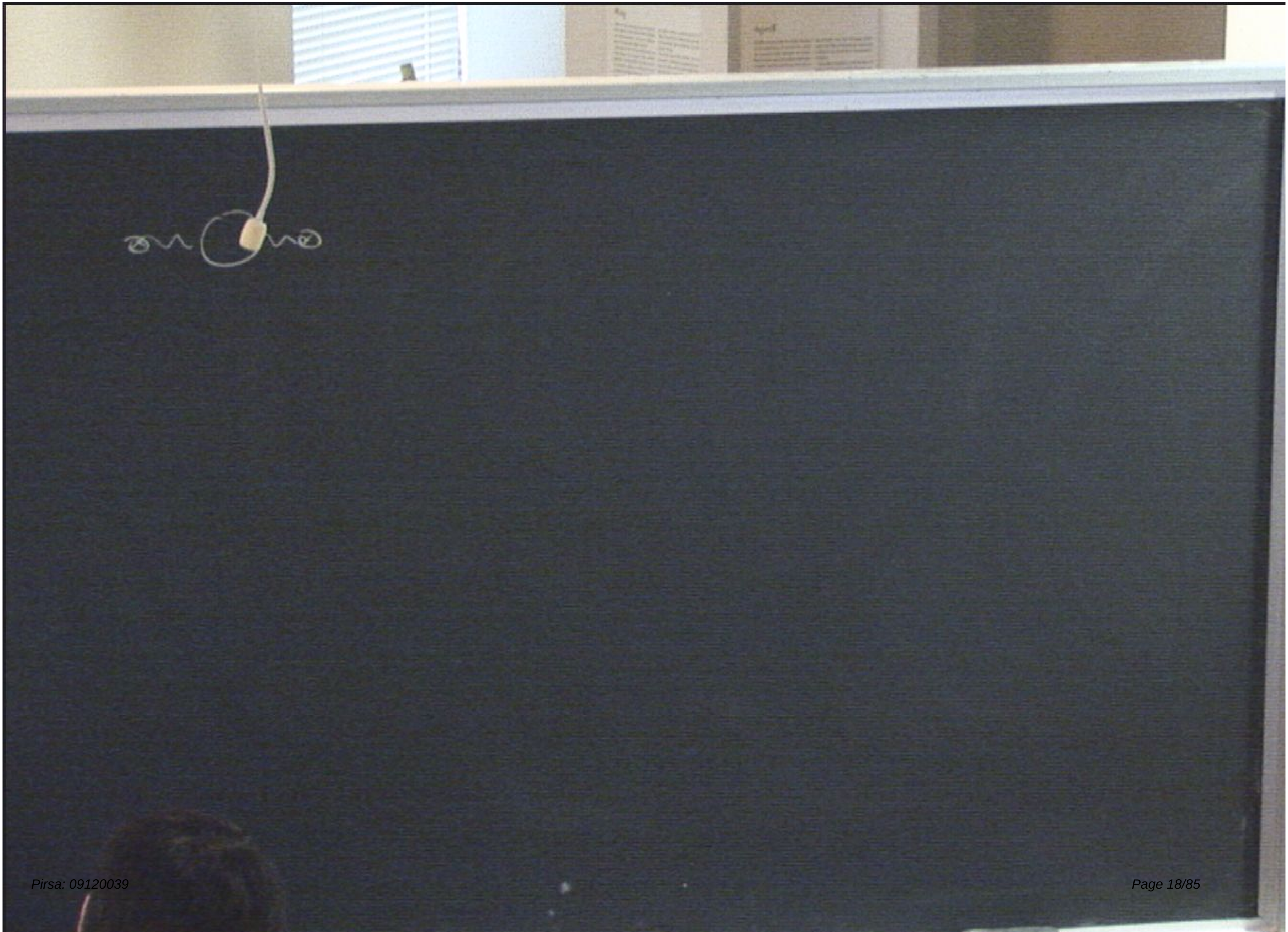
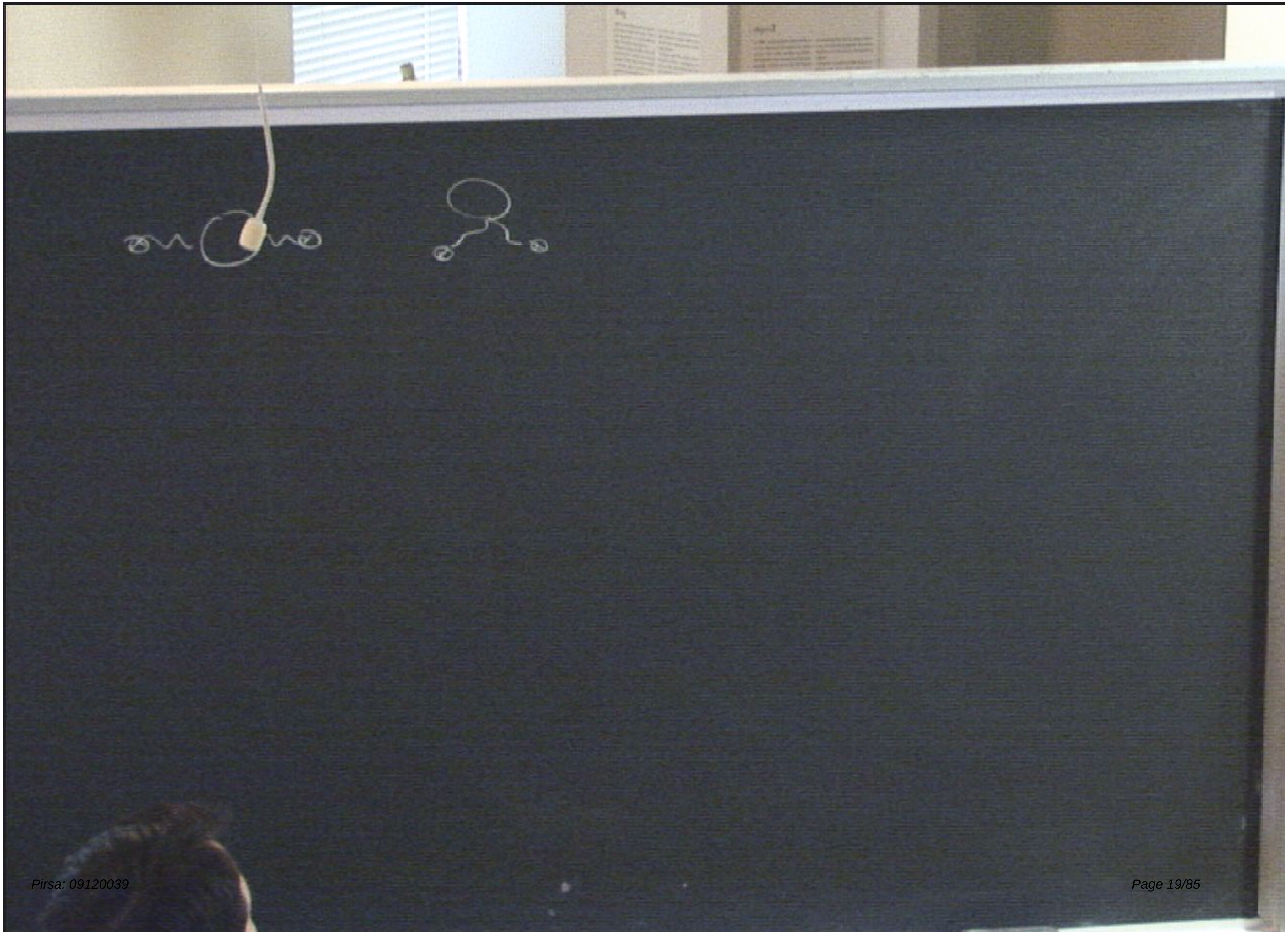
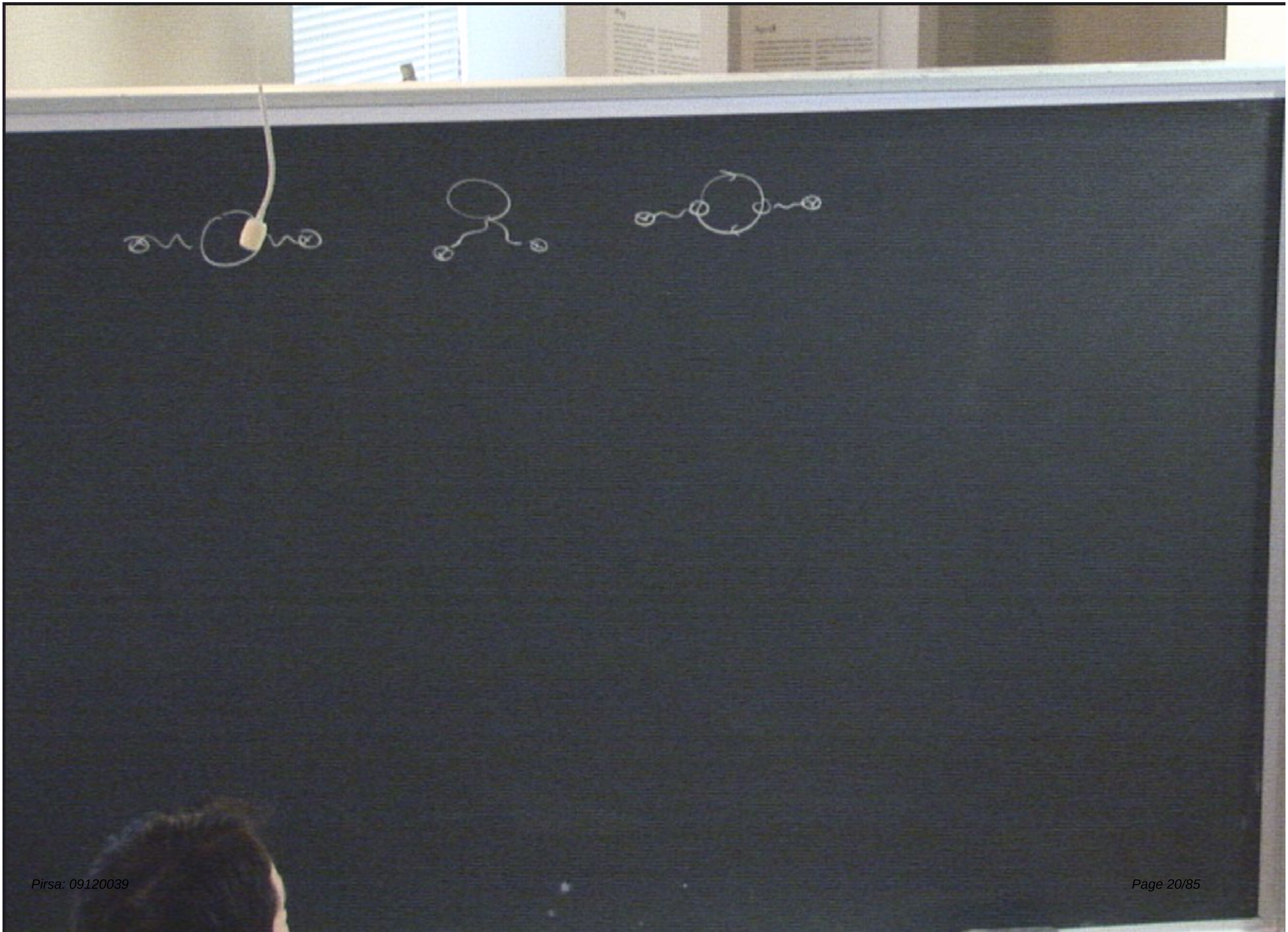
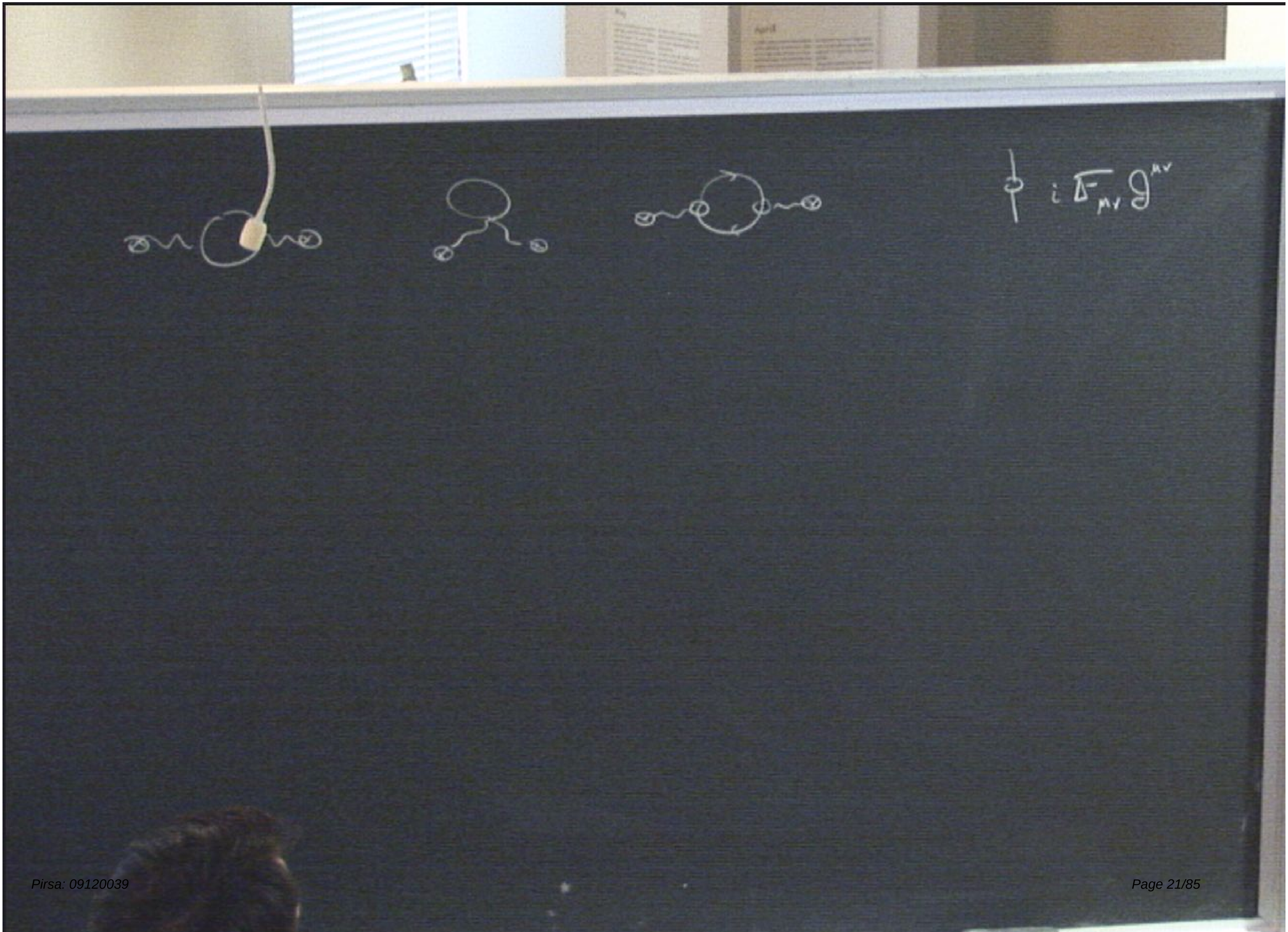




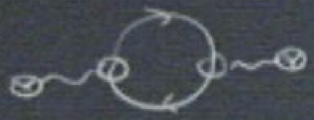




$i\bar{\Delta}_{F\mu\nu}\, g^{\mu\nu}$

$$\mathrm{tr}\ \vartheta^{\mu\nu}\,\vartheta^{\lambda\sigma}\ \mathbb{F}_{\mu\nu}\,\mathbb{F}_{\lambda\sigma}$$

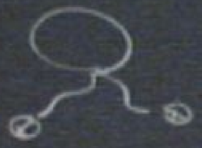
$$i\,\mathbb{F}_{\mu\nu}\,\vartheta^{\mu\nu}$$



$i\,\mathbb{F}_{\mu\nu}\mathcal{J}^{\mu\nu}$

$\mathrm{tr}\,\mathcal{J}^{\mu\nu}\mathcal{J}^{\lambda\sigma}\;\mathbb{F}_{\mu\nu}\mathbb{F}_{\lambda\sigma}$

$$\frac{1}{4}\int\frac{d^4q}{(2\pi)^4}\;\mathbb{F}^c_{\mu\nu}\mathbb{F}^{c\mu\nu}\Big\{\;C(r)$$



$i\,\mathbb{F}_{\mu\nu}\,\theta^{\mu\nu}$

$\mathrm{tr}\;\theta^{\mu\nu}\,\theta^{\lambda\sigma}\;\mathbb{F}_{\mu\nu}\mathbb{F}_{\lambda\sigma}$

$$\frac{1}{4}\int\frac{d^4q}{(2\pi)^4}\;\mathbb{F}^c_{\mu\nu}\mathbb{F}^{c\mu\nu}\left\{\,C(r)\quad\left[\;\frac{4}{4\,16\pi^2}\;-\;\frac{4\,C(J)}{16\pi^2}\right]\lg(-q^2)\right.$$

$\otimes \quad i\,\mathbb{F}_{\mu\nu}\, g^{\mu\nu}$

$\mathrm{tr}\; g^{\mu\nu} g^{\lambda\sigma}\; \mathbb{F}_{\mu\nu} \mathbb{F}_{\lambda\sigma}$

$$\frac{1}{4}\int \frac{d^4 q}{(2\pi)^4}\; \mathbb{F}^c_{\mu\nu}\mathbb{F}^{c\,\mu\nu} \left\{ C(r)\,\frac{(-1)}{2}\left[\; \frac{4}{48\pi^2} \;-\; \frac{4\,C(J)}{16\pi^2}\right] \lg(-q^2) \right\}$$

$$\operatorname{tr} t_r^a t_r^b = C(r)\,\delta^{ab}$$

$$\operatorname{tr} \mathcal{J}^{\mu\nu}\mathcal{J}^{\lambda\sigma} = C(J)\left(g^{\mu\lambda}g^{\nu\sigma} - g^{\mu\sigma}g^{\nu\lambda}\right)$$

$$\Psi + \phi^{*}\Delta_{r0}\phi$$

$$\mathbb{D}_\lambda = \partial_\lambda - ig\,\mathbb{A}_\lambda^a t_r^a$$

$\gamma^\nu]$ Dirac

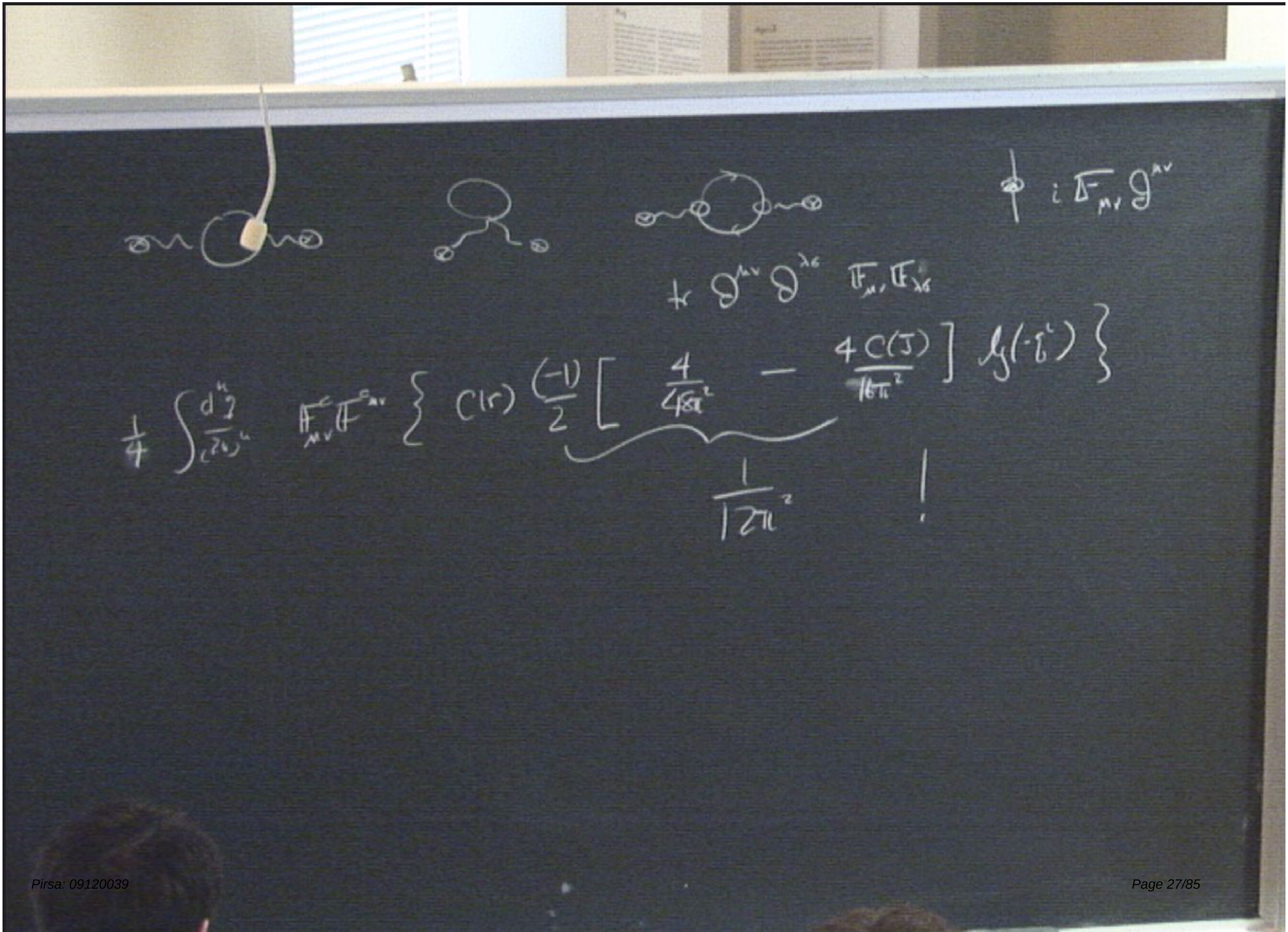
$\delta^\nu_\beta - \delta^\nu_\alpha\delta^\mu_\beta)$ 4-vector

$$C(J) = \begin{cases} 0 & \text{scal} \\ 1 & \text{Dirac} \\ 2 & \text{vector} \end{cases}$$

$$\vec{\mu} = g\,\frac{Qe\hbar}{m}\,\vec{S}$$

$$-\frac{1}{4g^2}\left(\mathbb{F}_{\mu\nu}\right)^2\left[1 - \frac{g^2 C(r)}{48\pi^2}\lg(-q^2)\right]$$

$$g^2(-q^2) = \frac{g^2}{1 - \frac{g^2 C(r)}{48\pi^2}\lg(-q^2)}$$



$$i\,\mathbb{F}_{\mu\nu}\,\mathcal{J}^{\mu\nu}$$

$$\mathrm{tr}\ \mathcal{J}^{\mu\nu}\mathcal{J}^{\lambda\sigma}\ \mathbb{F}_{\mu\nu}\mathbb{F}_{\lambda\sigma}$$

$$\frac{1}{4}\int\frac{d^4q}{(2\pi)^4}\ \mathbb{F}^c_{\mu\nu}\mathbb{F}^{c\mu\nu}\left\{ C(r)\,\frac{(-1)}{2}\underbrace{\left[\ \frac{4}{48\pi^2}\ -\ \frac{4\,C(J)}{16\pi^2}\right]}_{\frac{1}{12\pi^2}}\log(-q^2)\right\}$$

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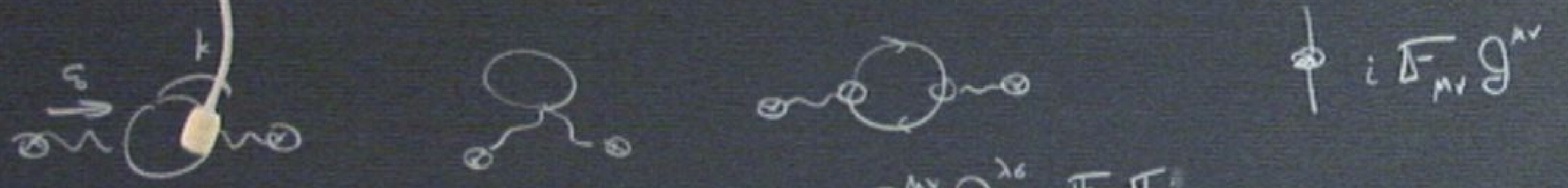


$i\,\mathbb{F}_{\mu\nu}\,\vartheta^{\mu\nu}$

$\mathrm{tr}\,\vartheta^{\mu\nu}\vartheta^{\lambda\sigma}\;\mathbb{F}_{\mu\nu}\mathbb{F}^{i}_{\lambda\sigma}$

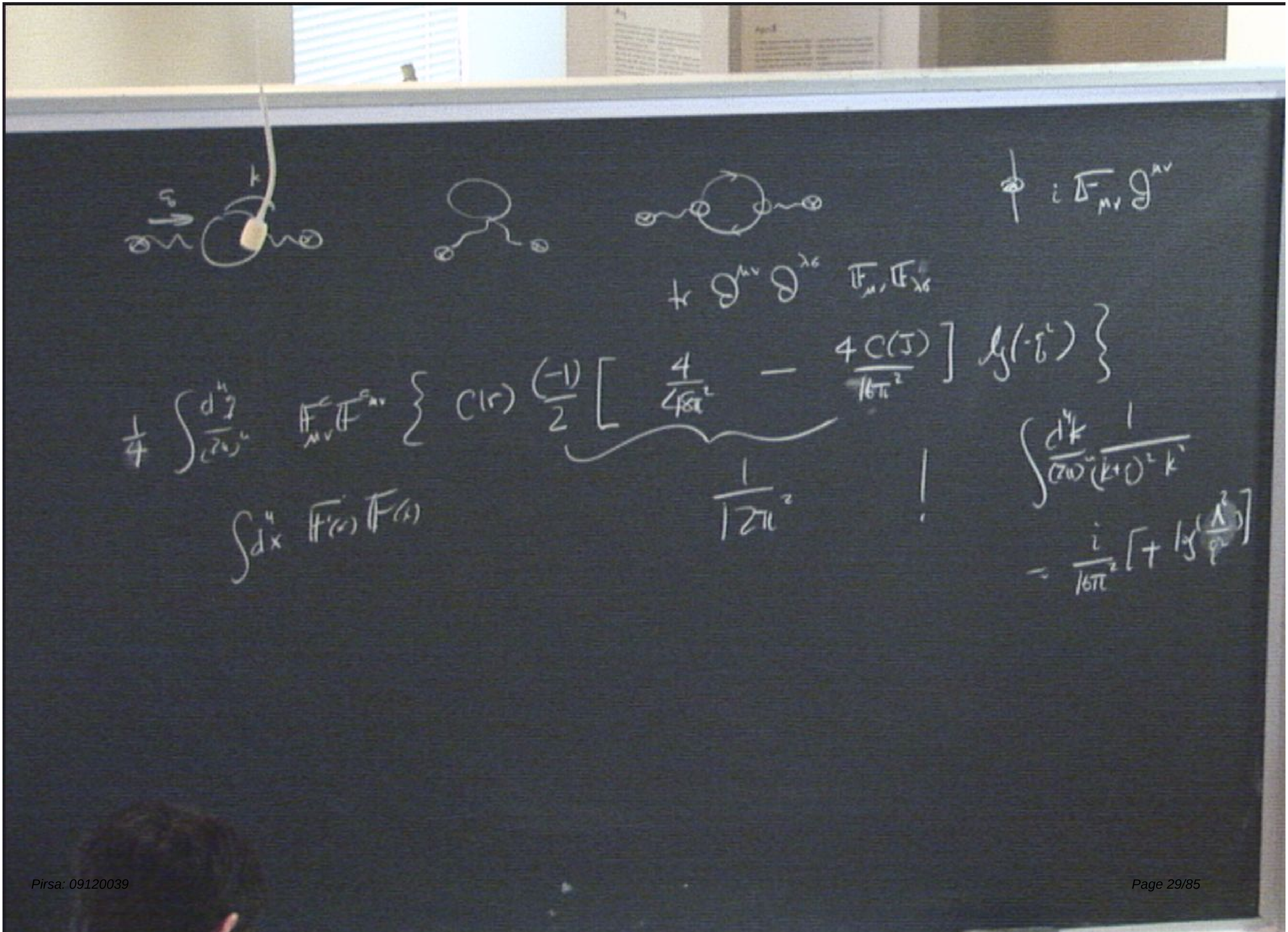
$$\frac{1}{4}\int\frac{d^4q}{(2\pi)^4}\,\mathbb{F}^c_{\mu\nu}\mathbb{F}^{c\mu\nu}\Big\{C(r)\,\frac{(-1)}{2}\underbrace{\Big[\;\frac{4}{48\pi^2}\;-}_{\frac{1}{12\pi^2}}\;\frac{4\,C(J)}{16\pi^2}\Big]\,\lg(-q^2)\Big\}$$

$$\int d^4x\;\mathbb{F}^i(x)\,\mathbb{F}(x)$$

!

$$\int\frac{d^4k}{(2\pi)^4}\frac{1}{(k+q)^2k^2}$$

$$=\frac{i}{16\pi^2}\Big[+\lg\Big(\frac{\Lambda^2}{q^2}\Big)\Big]$$



$$i\,\mathbb{F}_{\mu\nu}\,\vartheta^{\mu\nu}$$

$$\mathrm{tr}\,\vartheta^{\mu\nu}\vartheta^{\lambda\sigma}\;\mathbb{F}_{\mu\nu}\mathbb{F}_{\lambda\sigma}$$

$$\frac{1}{4}\int\frac{d^4q}{(2\pi)^4}\;\mathbb{F}^c_{\mu\nu}\mathbb{F}^{c\mu\nu}\left\{C(r)\,\frac{(-1)}{2}\left[\underbrace{\frac{4}{48\pi^2}}_{\frac{1}{12\pi^2}}-\frac{4\,C(J)}{16\pi^2}\right]\lg(-q^2)\right\}$$

$$\int d^4x\;\mathbb{F}'(x)\,\mathbb{F}(x)$$

!

$$\int\frac{d^4k}{(2\pi)^4}\frac{1}{(k+q)^2\,k^2}$$

$$=\frac{i}{16\pi^2}\left[+\lg\left(\frac{\Lambda^2}{q^2}\right)\right]$$

$$\Psi + \phi^* \Delta_{r0} \phi$$

$\gamma^\nu]$ Dira

$\delta^\nu_\beta - \delta^\nu_\alpha \delta^\mu_\rho)$ 4-vecto

$$\mathbb{D}_\lambda = \partial_\lambda - ig \mathbb{A}^a_\lambda t^a_r$$

$$\operatorname{tr} t^a_r t^b_r = C(r)\,\delta^{ab}$$

$$\operatorname{tr} \mathcal{J}^{\mu\nu}\mathcal{J}^{\lambda\sigma} = C(J)\left(g^{\mu\lambda} g^{\nu\sigma} - g^{\mu\sigma} g^{\nu\lambda}\right)$$

$$C(J) = \begin{cases} 0 & \text{scal} \\ 1 & \text{Dira} \\ 2 & \text{vecto} \end{cases}$$

$$\vec{\mu} = g\,\frac{Qe\hbar}{m}\,\vec{S}$$

$$-\frac{1}{4g^2}\left(\mathbb{F}_{\mu\nu}\right)^2\left[1 - \frac{g^2 C(r)}{48\pi^2}\lg(-q^2) - \frac{g^2 C(r)}{12\pi^2}\lg(-q^2)\right]$$

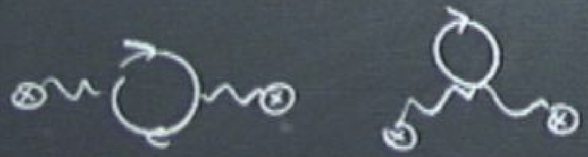
$$g^2(-q^2) = \frac{g^2}{1 - \frac{g^2 C(r)}{48\pi^2}\lg(-q^2)}$$

$$\mathcal{L} = -\frac{1}{4g^2}\left(\mathbb{F}^a_{\mu\nu}\right)^2 - \frac{1}{2} a^a_\lambda \Delta^{\mu\nu}_{g,1} a^c_\nu + \bar{c}\,\Delta_{g,0}\, c + \overset{\overset{\frac{1}{2}n_f}{\swarrow}}{\bar{\Psi}}\, \Delta_{r,\frac{1}{2}}$$

$$\Delta = -\mathbb{D}^2 + 2\,\frac{1}{2}\mathbb{F}^a_{\mu\nu}\,\mathcal{J}^{\mu\nu}\, t^a_r$$

$$\mathcal{J}^{\mu\nu} = \frac{i}{4}(\gamma^\mu$$

$$= i(\delta^\mu_\alpha \delta$$



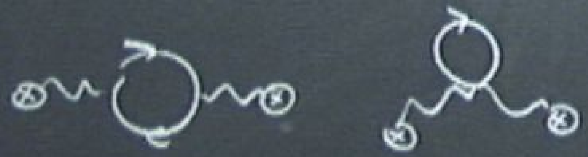
$$1 + \frac{1}{2}\int\frac{d^4\xi}{(2\pi)^4}\left(\mathbb{F}^a_{\mu\nu}\mathbb{F}^{\mu\nu a}\right)$$

$$\mathcal{L} = -\frac{1}{4g^2}\left(\mathbb{F}^a_{\mu\nu}\right)^2 - \frac{1}{2} a^a_\lambda \Delta^{\mu\nu}_{G,1} a^c_\nu + \bar{c}\,\Delta_{G,0}\, c + \overset{\frac{1}{2}n_f}{\overset{\downarrow}{\bar{\Psi}}}\,\Delta_{r,\frac{1}{2}}$$

$$\Delta = -\mathbb{D}^2 + 2\,\frac{1}{2}\mathbb{F}^a_{\mu\nu}\,\mathcal{S}^{\mu\nu}\, t^a_r$$

$$\mathcal{S}^{\mu\nu} = \frac{i}{4}[\gamma^\mu\ \gamma$$

$$= i(\delta^\mu_\alpha\,\delta$$



$$1 + \frac{1}{2}\int\frac{d^4\xi}{(2\pi)^4}\left(\mathbb{F}^a_{\mu\nu}\mathbb{F}^{\mu\nu a}\right) \qquad \overline{48\pi^2}$$

$$\mathcal{L} = -\frac{1}{4g^2}\left(\mathbb{F}^a_{\mu\nu}\right)^2 - \frac{1}{2} a^a_\lambda \Delta^{\mu\nu}_{G,1} a^c_\nu + \bar{c}\,\Delta_{G,0}\,c + \overset{\frac{1}{2}n_f \downarrow}{\bar{\Psi}}\,\Delta_{r,}$$

$$\Delta = -\mathbb{D}^2 + 2\,\frac{1}{2}\mathbb{F}^a_{\mu\nu}\mathcal{J}^{\mu\nu} t^a_r \qquad \mathcal{J}^{\mu\nu} = \frac{i}{4}(\gamma^\mu$$

$$= i(\delta^\mu_\alpha \delta$$

$$1 + \frac{1}{2}\int \frac{d^4\xi}{(2\pi)^4}\left(\mathbb{F}^a_{\mu\nu}\mathbb{F}^{\mu\nu a}\right) \frac{L}{2}\left(\frac{4}{48\pi^2} - \frac{4\cdot 2}{16\pi^2}\right)$$

$$\overset{\frac{1}{2}n_f}{\downarrow}$$

$$\mathcal{L} = -\frac{1}{4g^2}\left(\mathbb{F}^a_{\mu\nu}\right)^2 - \frac{1}{2} a^a_\lambda \Delta^{\mu\nu}_{a,1} a^c_\nu + \bar{c}\, \Delta_{a,0}\, c + \bar{\Psi}\, \Delta_{r,}$$

$$\Delta = -\mathbb{D}^2 + 2\, \frac{1}{2}\mathbb{F}^a_{\mu\nu}\, \mathcal{J}^{\mu\nu}\, t^a_r$$

$$\mathcal{J}^{\mu\nu} = \frac{i}{4}[\gamma^\mu$$

$$= i(\delta^\mu_\alpha \delta$$

$$1 + \frac{1}{2}\int \frac{d^4 q}{(2\pi)^4}\left(\mathbb{F}^a_{\mu\nu}\mathbb{F}^{\mu\nu a}\right)\left\{\frac{1}{2}\left(\frac{4}{48\pi^2} - \frac{4\cdot 2}{16\pi^2}\right)\lg(-q^2)\right.$$

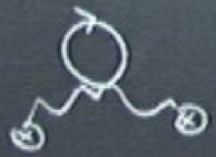
$$\overset{\frac{1}{2}n_f}{\downarrow}$$

$$\mathcal{L} = -\frac{1}{4g^2}\left(\mathbb{F}^a_{\mu\nu}\right)^2 - \frac{1}{2} a^a_\lambda \Delta^{\mu\nu}_{G,1} a^c_\nu + \bar{c}\,\Delta_{G,0}\, c + \bar{\Psi}\,\Delta_{r,}$$

$$\Delta = -\mathbb{D}^2 + 2\,\tfrac{1}{2}\mathbb{F}^a_{\mu\nu}\,\mathcal{J}^{\mu\nu}\,t^a_r$$

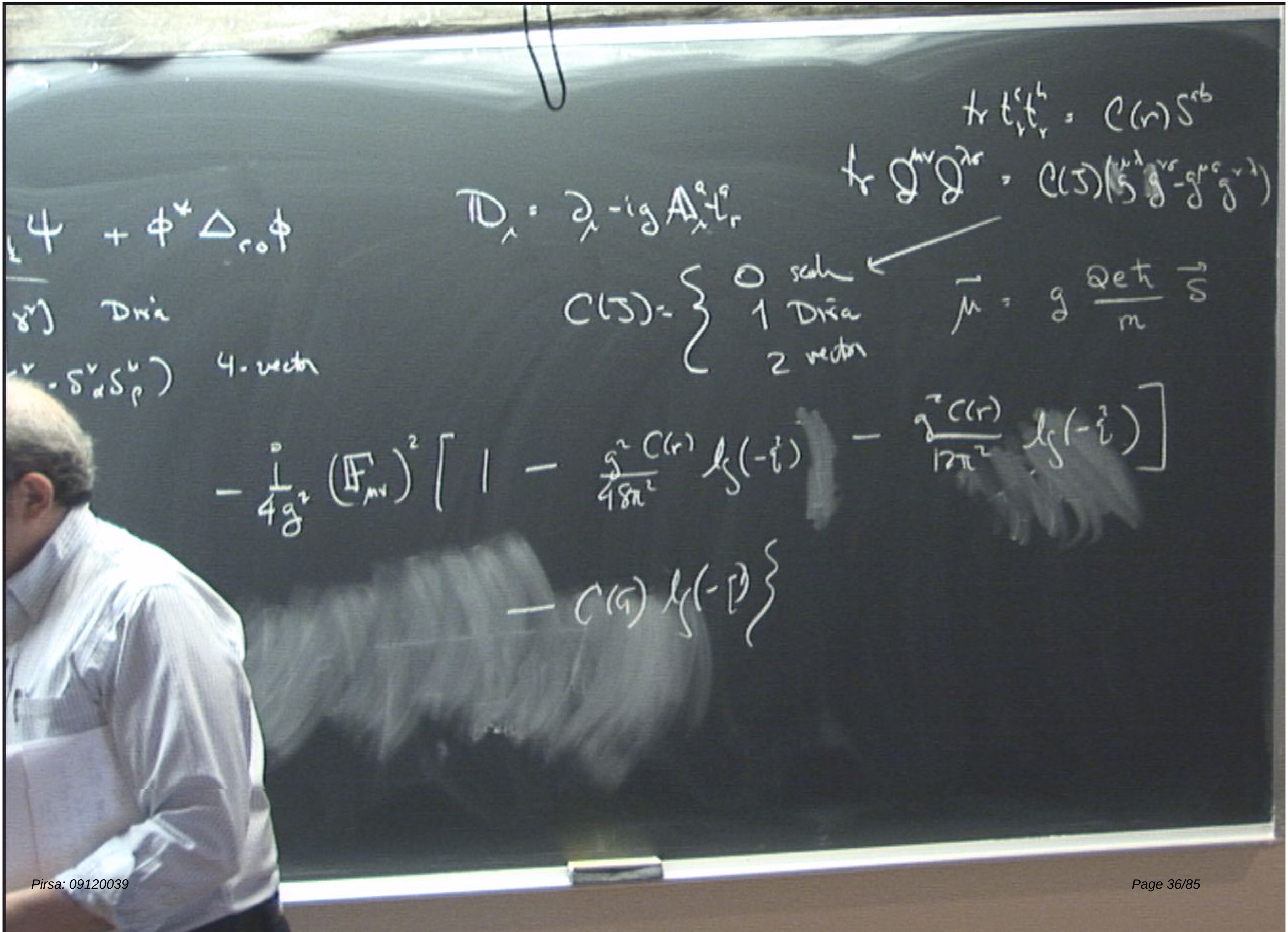
$$\mathcal{J}^{\mu\nu} = \frac{i}{4}(\gamma^\mu$$

$$= i(\delta^\mu_\alpha\,\delta$$



$$1 + \frac{1}{2}\int\frac{d^4q}{(2\pi)^4}\left(\mathbb{F}^a_{\mu\nu}\mathbb{F}^{\mu\nu a}\right)\left\{\frac{1}{2}\left(\frac{4}{48\pi^2} - \frac{4\cdot 2}{16\pi^2}\right)\lg(-q^2)\right.$$

$$- \frac{1}{48\pi^2}\,C(a)\,\lg(-q^2)$$



$$\operatorname{tr} t^a_r t^b_r = C(r)\,\delta^{ab}$$

$$\operatorname{tr} \mathcal{J}^{\mu\nu}\mathcal{J}^{\lambda\sigma} = C(J)\left(g^{\mu\lambda}g^{\nu\sigma} - g^{\mu\sigma}g^{\nu\lambda}\right)$$

$$\psi + \phi^* \Delta_{r0}\,\phi$$

$$\mathbb{D}_\lambda = \partial_\lambda - ig\,\mathbb{A}^a_\lambda t^a_r$$

$\gamma^\nu]$ Dirac

$- \delta^\nu_\alpha \delta^\mu_\rho)$ 4-vector

$$C(J) = \begin{cases} 0 & \text{scalar} \\ 1 & \text{Dirac} \\ 2 & \text{vector} \end{cases}$$

$$\vec{\mu} = g\,\frac{Qe\hbar}{m}\,\vec{S}$$

$$-\frac{1}{4g^2}\left(\mathbb{F}_{\mu\nu}\right)^2\left[1 - \frac{g^2 C(r)}{48\pi^2}\lg(-\partial^2) - \frac{g^2 C(r)}{12\pi^2}\lg(-\partial^2)\right]$$

$$- C(G)\lg(-\partial^2)\Big\}$$

$\frac{1}{2} n_f$

$$\frac{1}{4g^2}(\mathbb{F}^a_{\mu\nu})^2 - \frac{1}{2} a^a_\lambda \Delta^{\mu\nu}_{g,1} a^c_\nu + \bar{c}\,\Delta_{g,0}\,c + \bar{\Psi}\,\Delta_{r,\frac{1}{2}}\,\Psi + \phi^*\Delta_{r,0}$$

$$\Delta = -\mathbb{D}^2 + 2\,\frac{1}{2}\mathbb{F}^a_{\mu\nu}\,\mathcal{J}^{\mu\nu}\,t^a_r$$

$\mathcal{J}^{\mu\nu} = \frac{i}{4}[\gamma^\mu, \gamma^\nu]$ Dirac

$= i(\delta^\mu_\alpha \delta^\nu_\beta - \delta^\nu_\alpha \delta^\mu_\beta)$ 4-v

$$\frac{1}{2}\int \frac{d^4q}{(2\pi)^4}\left(\mathbb{F}^a_{\mu\nu}\mathbb{F}^{\mu\nu a}\right)\left\{\frac{1}{2}\overbrace{\left(\frac{4}{48\pi^2} - \frac{4\cdot 2}{16\pi^2}\right)}^{\frac{5}{12}}\log(-q^2)\,C(G)\right. \quad - \frac{1}{4}$$

$$- \frac{1}{48\pi^2}\,C(r)\log(-q^2)$$

$\mathrm{tr}\, t_r^a t_r^b = C(r)\delta^{ab}$

$\mathrm{tr}\, \mathcal{J}^{\mu\nu}\mathcal{J}^{\lambda\sigma} = C(J)(g^{\mu\lambda}g^{\nu\sigma} - g^{\mu\sigma}g^{\nu\lambda})$

$\psi + \phi^* \Delta_{r0}\phi$

$\mathbb{D}_\lambda = \partial_\lambda - ig\mathbb{A}_\lambda^a t_r^a$

$\gamma^\nu]$ Dirac

$\delta^\nu_\beta - \delta^\nu_\alpha\delta^\mu_\beta)$ 4-vectr

$$C(J) = \left\{\begin{array}{ll} 0 & \text{scal} \\ 1 & \text{Dirac} \\ 2 & \text{vectr} \end{array}\right.$$

$$\vec{\mu} = g\,\frac{Qe\hbar}{m}\,\vec{S}$$

$C(G)$

$$-\frac{i}{4g^2}(\mathbb{F}_{\mu\nu})^2\left[1 - \frac{g^2 C(r)}{48\pi^2}\lg(-q^2) - \frac{g^2 C(r)}{12\pi^2}\lg(-q^2)\right]$$

$$- C(G)\lg(-q^2)\left\{\frac{10}{24} + \frac{1}{24}\right\}$$

$$\beta(g) = \quad + \frac{g^3}{12\pi^2} C(r) n_f + \frac{g^3}{48\pi^2} C(r) n_b +$$

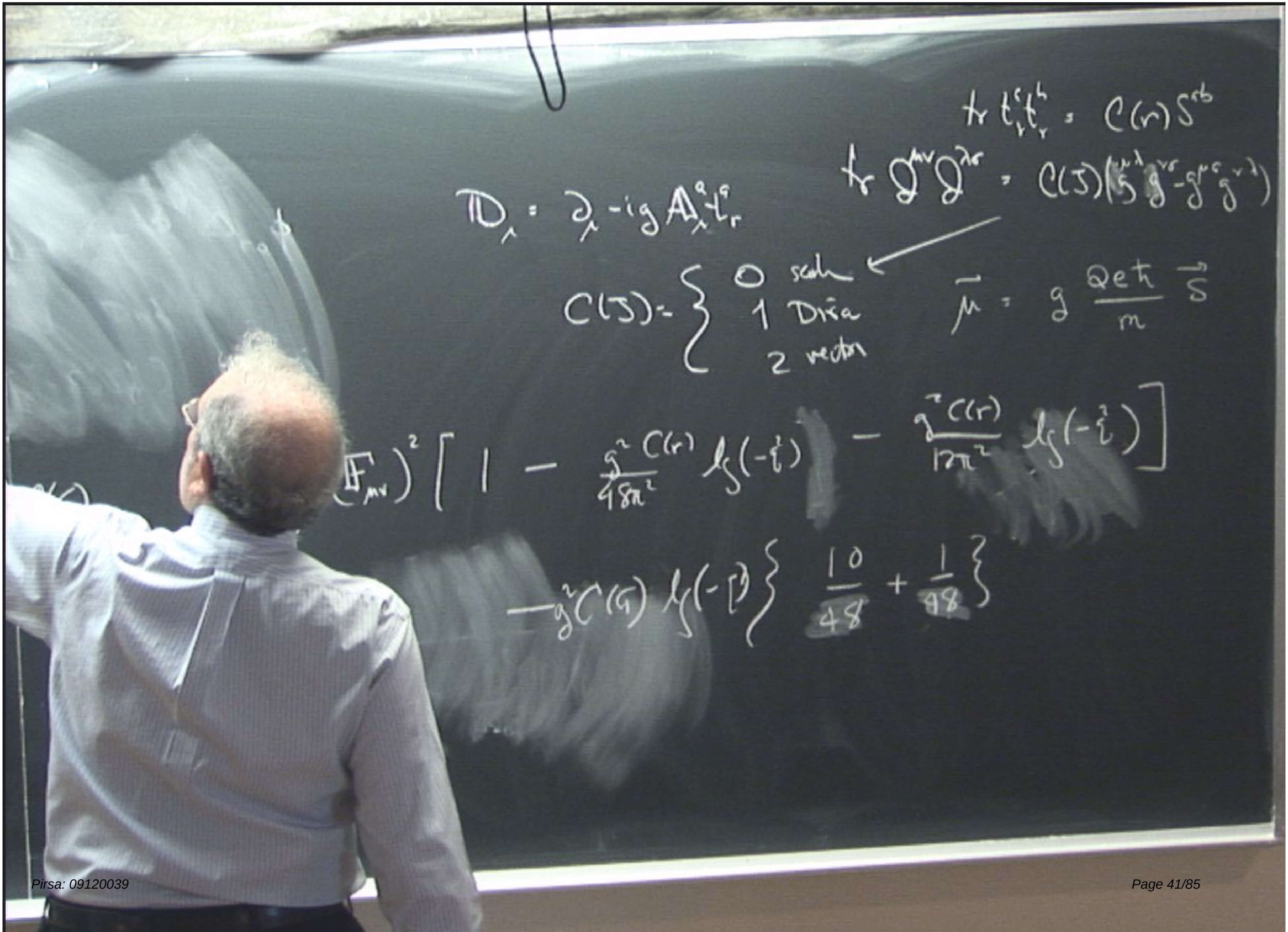
$$1 + \frac{1}{2} \int \frac{d^4 q}{(2\pi)^4} \left(\mathbb{F}^a_{\mu\nu} \mathbb{F}^{\mu\nu a} \right) \Big\{ \frac{1}{2} \left(\frac{4}{48\pi^2} - \frac{4 \cdot 2}{16\pi^2} \right) \lg(-q^2)$$

$$- \frac{1}{48\pi^2} C(A) \lg(-q^2)$$

$$\beta(g) = + \frac{g^3}{12\pi^2} C(r) n_f + \frac{g^3}{48\pi^2} C(r) n_b - \frac{11}{24\pi^2}$$

$$1 + \frac{1}{2} \int \frac{d^4 q}{(2\pi)^4} \left(\mathbb{F}^a_{\mu\nu} \mathbb{F}^{\mu\nu a} \right) \Big\{ \frac{1}{2} \left(\frac{4}{48\pi^2} - \frac{4 \cdot 2}{16\pi^2} \right) \lg(-q^2)\, C(G)$$

$$- \frac{1}{48\pi^2} C(G) \lg(-q^2)$$



$$\mathrm{tr}\, t^a_r t^b_r = C(r)\delta^{ab}$$

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$$\vec{\mu} = g\,\frac{Qe\hbar}{m}\vec{S}$$

$$(\mathbb{F}_{\mu\nu})^2\left[1 - \frac{g^2C(r)}{48\pi^2}\lg(-q^2) - \frac{g^2C(r)}{12\pi^2}\lg(-q^2)\right]$$

$$-g^2C(G)\lg(-q^2)\left\{\frac{10}{48} + \frac{1}{48}\right\}$$

$$\beta(g) = + \frac{g^3}{12\pi^2} C(r) n_f + \frac{g^3}{48\pi^2} C(r) n_b - \frac{11}{48\pi^2} C(G)$$

$$1 + \frac{1}{2} \int \frac{d^4 q}{(2\pi)^4} \left(\mathbb{F}^a_{\mu\nu} \mathbb{F}^{\mu\nu a} \right) \left\{ \frac{1}{2} \left(\frac{4}{48\pi^2} - \frac{4 \cdot 2}{16\pi^2} \right) \lg(-q^2) \, C(G) \right.$$

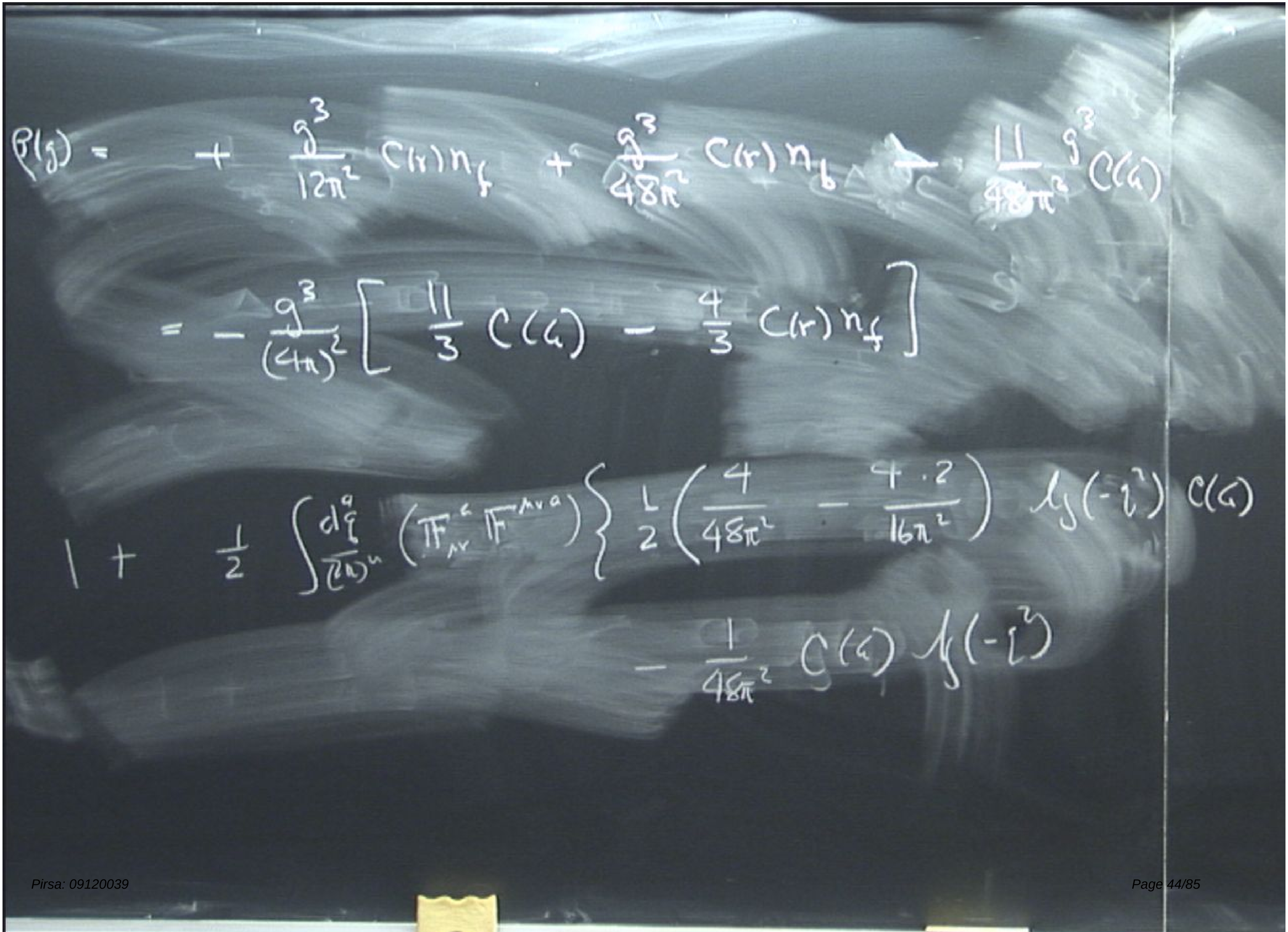
$$- \frac{1}{48\pi^2} C(G) \lg(-q^2)$$

$$\beta(g) = + \frac{g^3}{12\pi^2} C(r) n_f + \frac{g^3}{48\pi^2} C(r) n_b - \frac{11}{48\pi^2} g^3 C(G)$$

$$= - \frac{g^3}{(4\pi)^2} \left[\frac{11}{3} C(G) - \frac{4}{3} C(r) n_f \right]$$

$$1 + \frac{1}{2} \int \frac{d^4 q}{(2\pi)^4} \left(\mathbb{F}^a_{\mu\nu} \mathbb{F}^{\mu\nu a} \right) \left\{ \frac{1}{2} \left(\frac{4}{48\pi^2} - \frac{4 \cdot 2}{16\pi^2} \right) \lg(-q^2) \, C(G) \right.$$

$$\left. - \frac{1}{48\pi^2} C(G) \lg(-q^2) \right.$$



$$\beta(g) = + \frac{g^3}{12\pi^2} C(r) n_f + \frac{g^3}{48\pi^2} C(r) n_b - \frac{11}{48\pi^2} g^3 C(G)$$

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$$\left. - \frac{1}{48\pi^2} C(G) \lg(-q^2) \right.$$

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$SU(N)$ $\quad C(G) = N$ $\quad C(r)$

$$\beta(g) = + \frac{g^3}{12\pi^2} C(r) n_f + \frac{g^3}{48\pi^2} C(r) n_b - \frac{11}{48\pi^2} g^3 C(G)$$

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$SU(N)$ $\quad C(G) = N \quad C(r) - \frac{1}{2}$

$$\beta(g) = - \frac{g^3}{(4\pi)^2} \left[\frac{11}{3} N - \frac{2}{3} n_f \right]$$

$$\beta(g) = + \frac{g^3}{12\pi^2} C(r) n_f + \frac{g^3}{48\pi^2} C(r) n_b - \frac{11}{48\pi^2} g^3 C(G)$$

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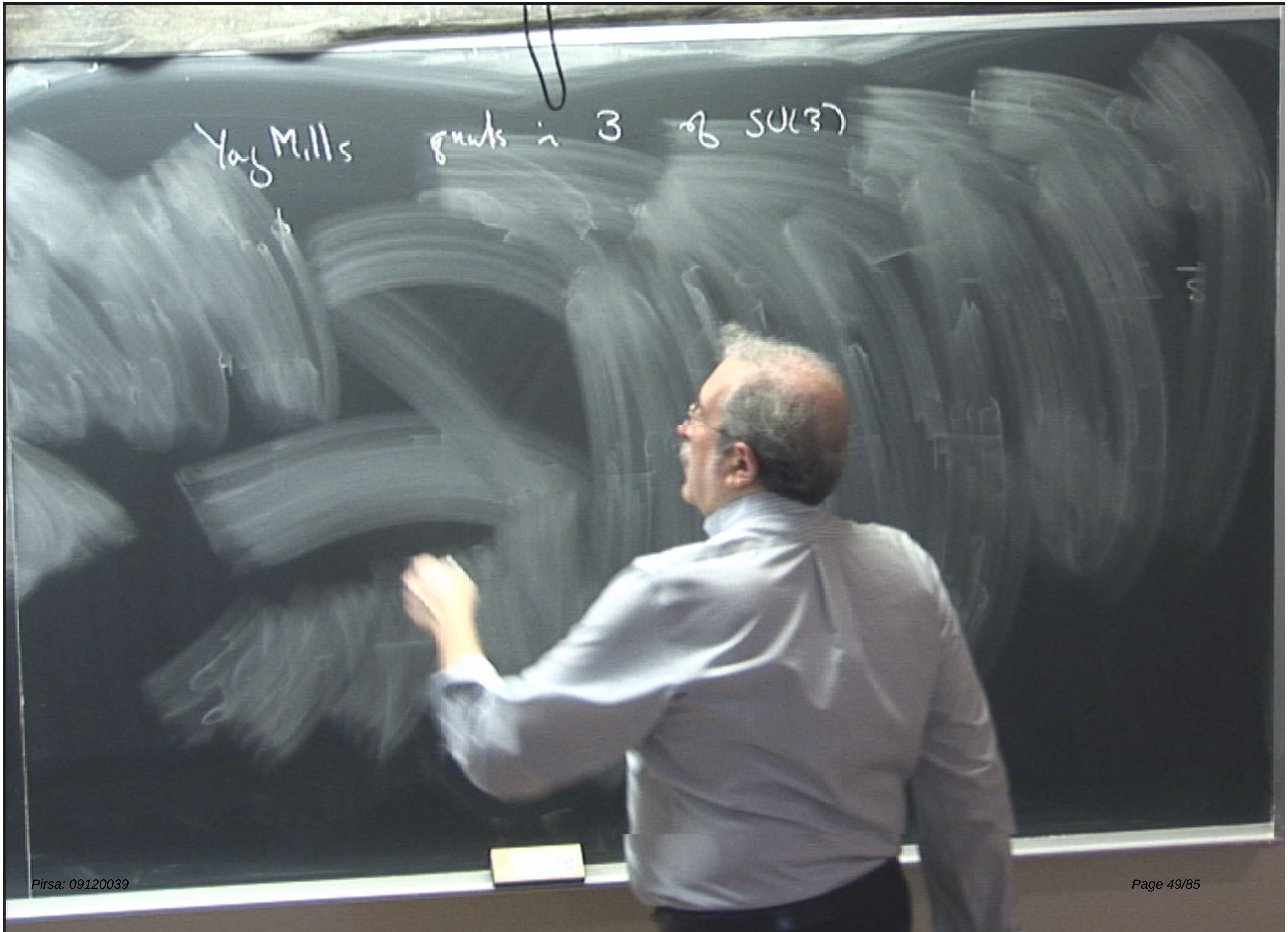
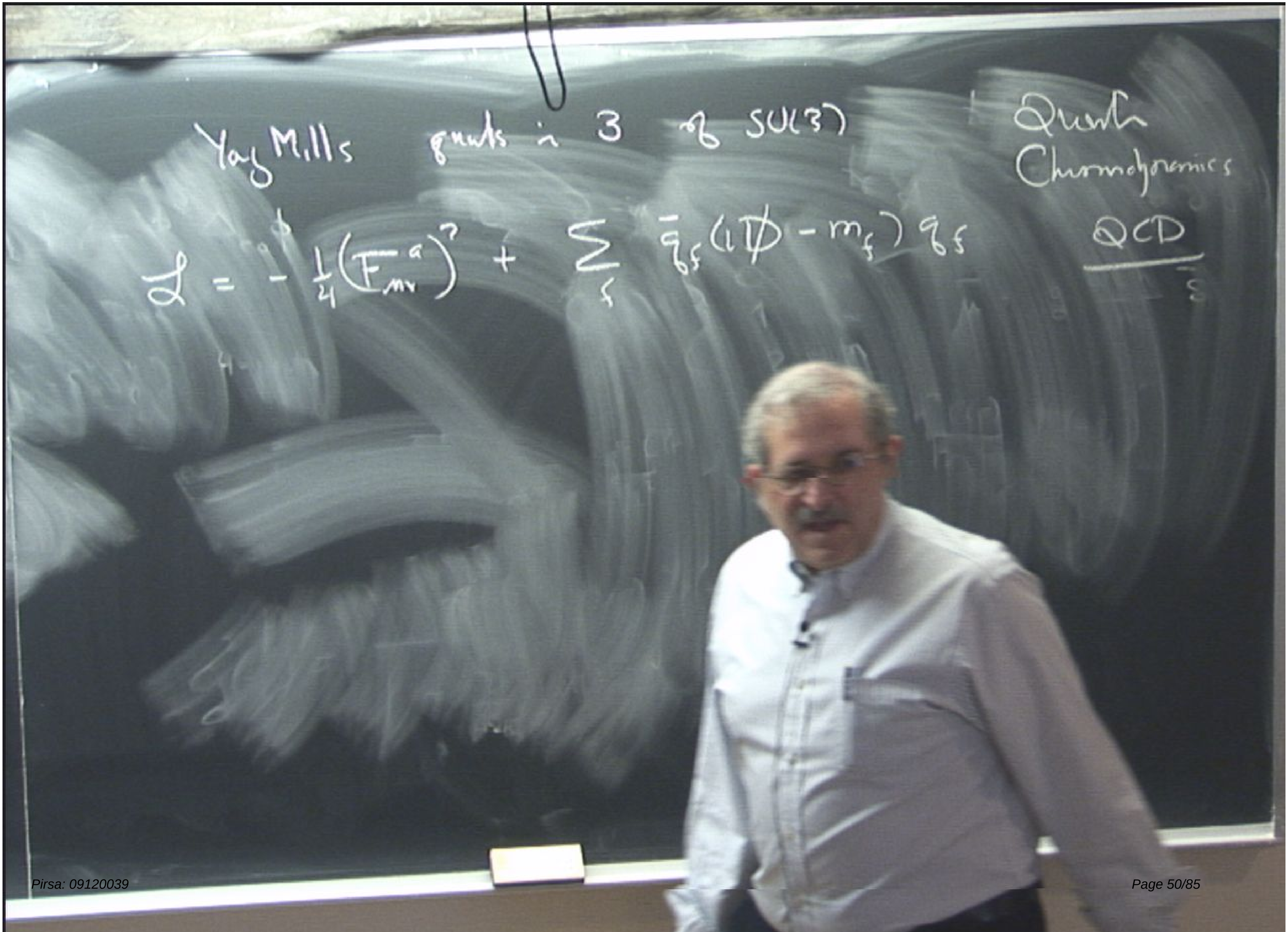
$SU(N)$ $\quad C(G) = N$ $\quad C(r) - \frac{1}{2}$

$$\beta(g) = - \frac{g^3}{(4\pi)^2} \left[\frac{11}{3} N - \frac{2}{3} n_f \right]$$

"asymptotic freedom"



Yang Mills quarks in 3 of SU(3)

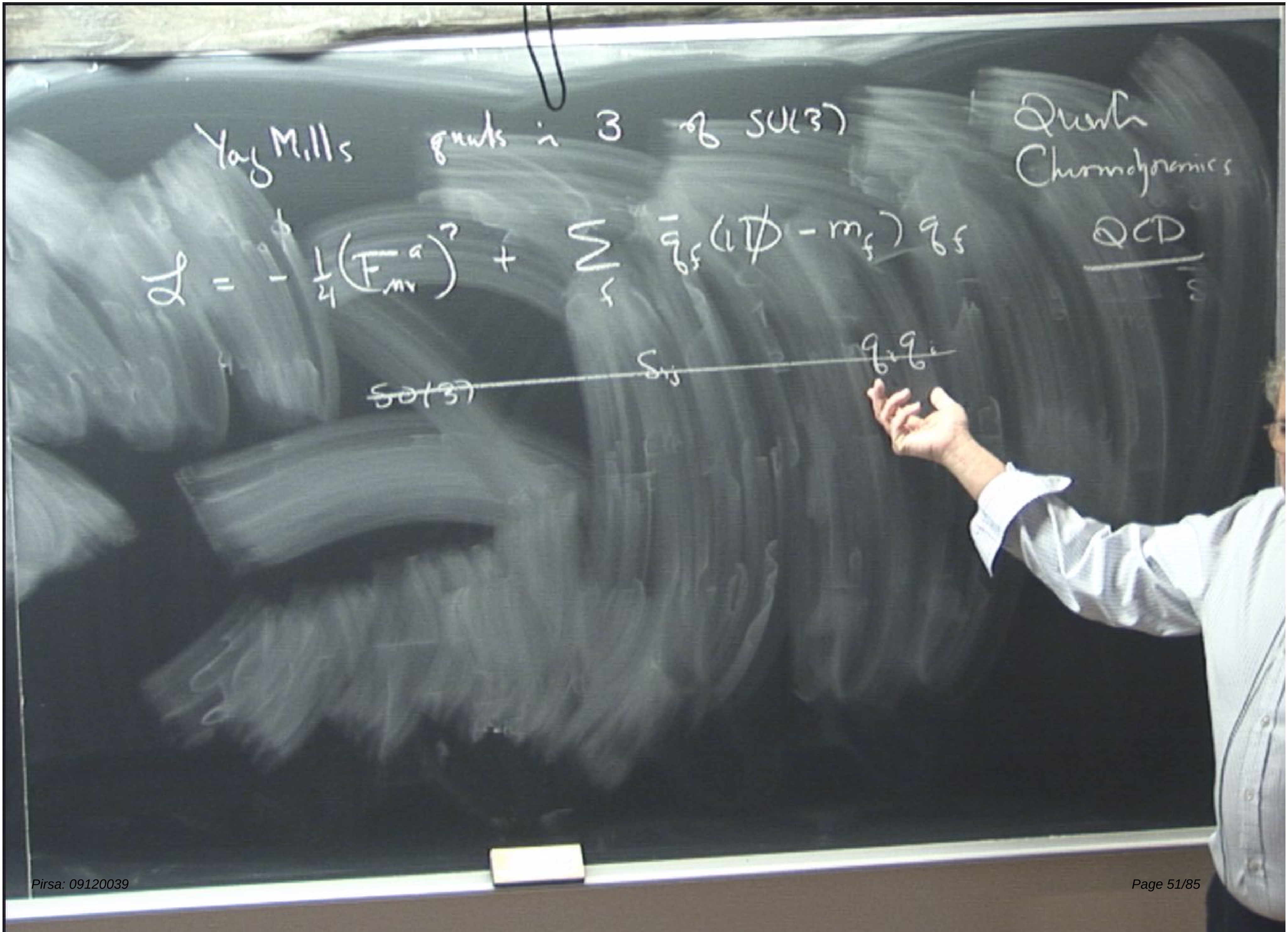


Yang Mills quarks in 3 of SU(3)

Quantum Chromodynamics

QCD

$$\mathcal{L} = -\frac{1}{4}\left(F_{\mu\nu}^{a}\right)^2 + \sum_f \bar{q}_f \left(i\not{D} - m_f\right) q_f$$



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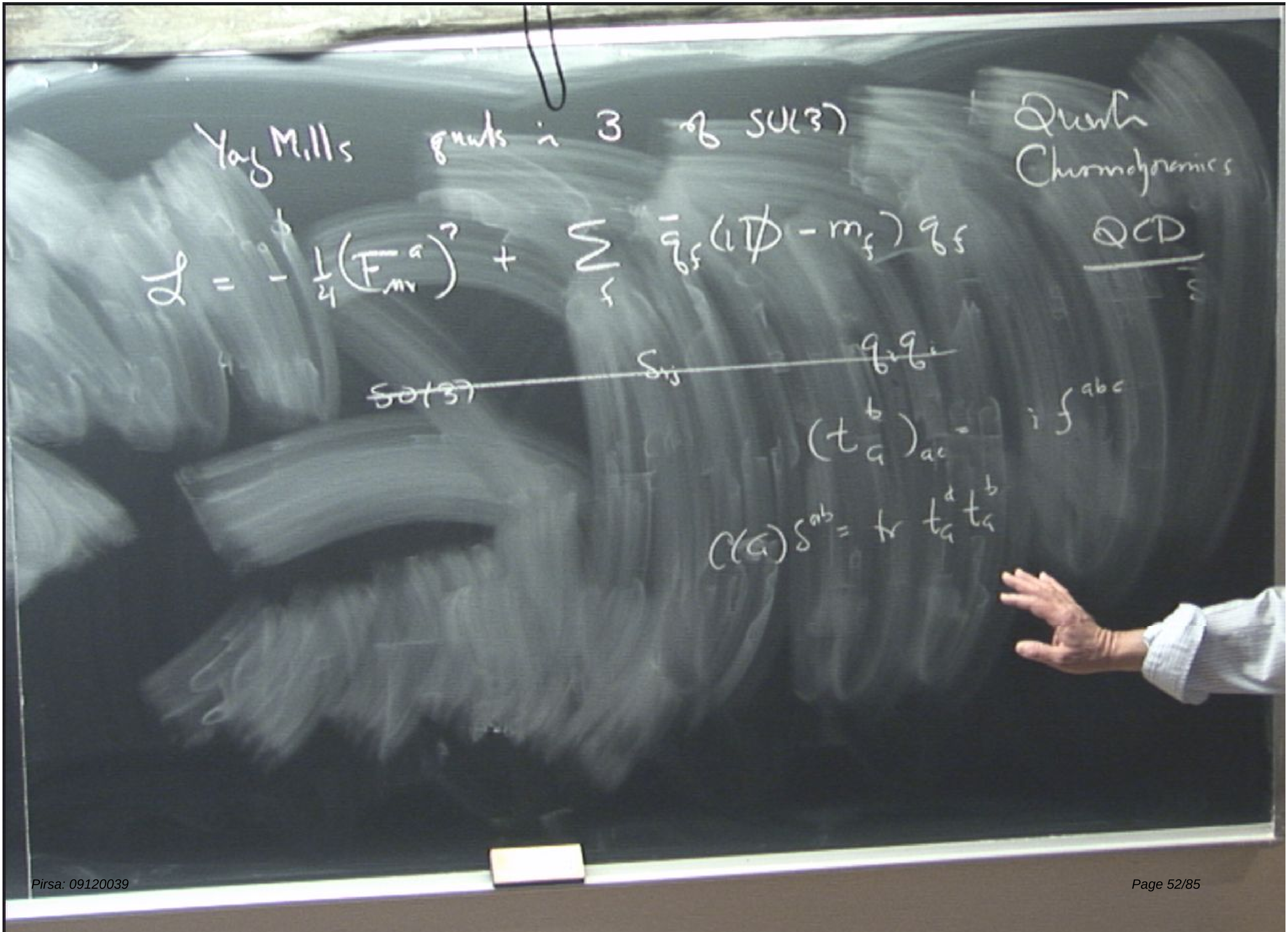
~~SU(3)~~ S_{ij} $q_i q_j$



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Quantum Chromodynamics

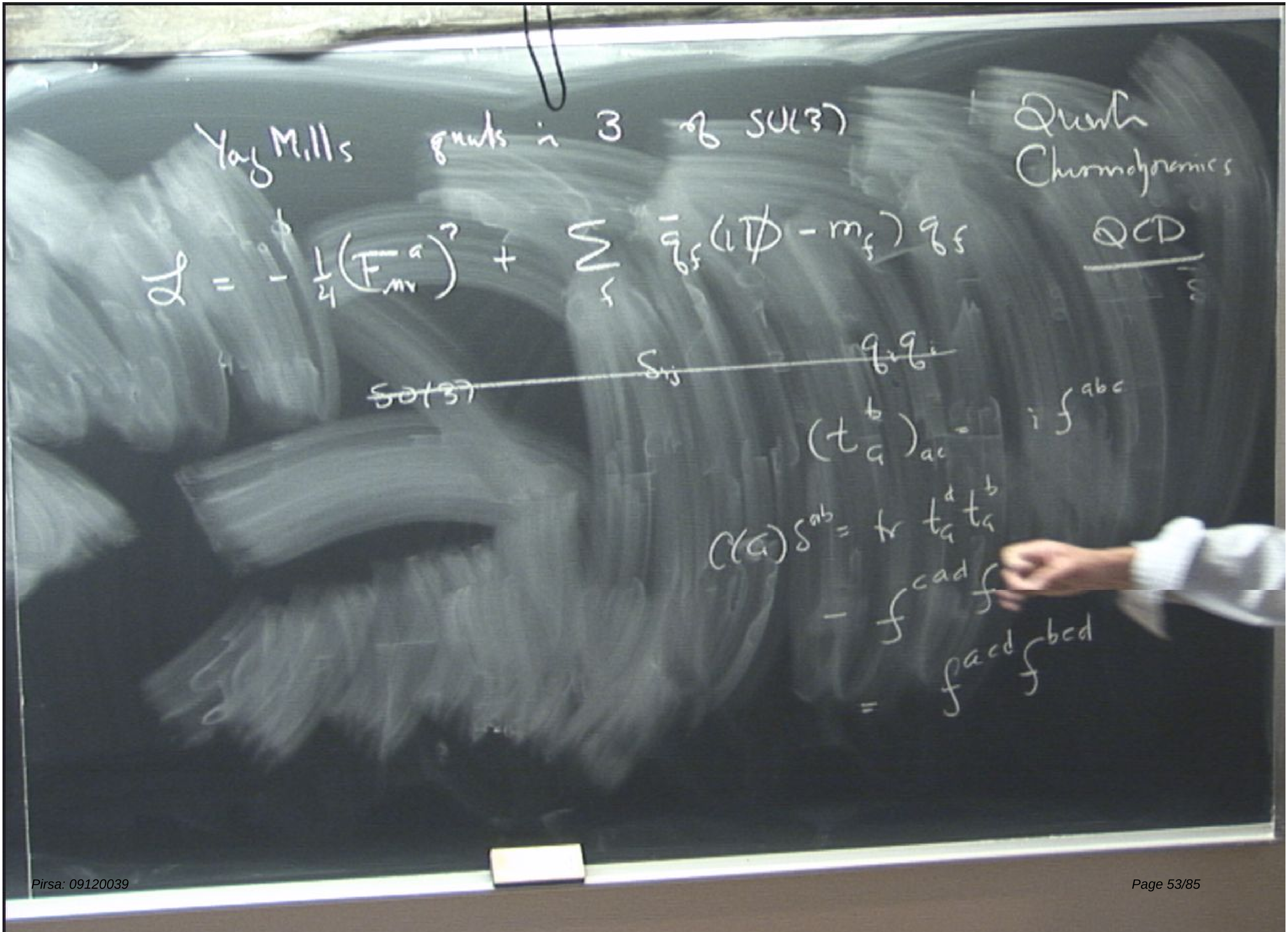
QCD

$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu}^a)^2 + \sum_f \bar{q}_f (i\not{D} - m_f) q_f$$

~~SO(3)~~ ~~δ_{ij}~~ ~~$q_i q_i$~~

$$(t_G^b)_{ac} = i f^{abc}$$

$$C(G)\delta^{ab} = \mathrm{tr}\, t_G^a t_G^b$$



Yang Mills quarks in 3 of SU(3)

Quantum Chromodynamics

$\underline{QCD}$

$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu}^a)^2 + \sum_f \bar{q}_f (i\not{D} - m_f) q_f$$

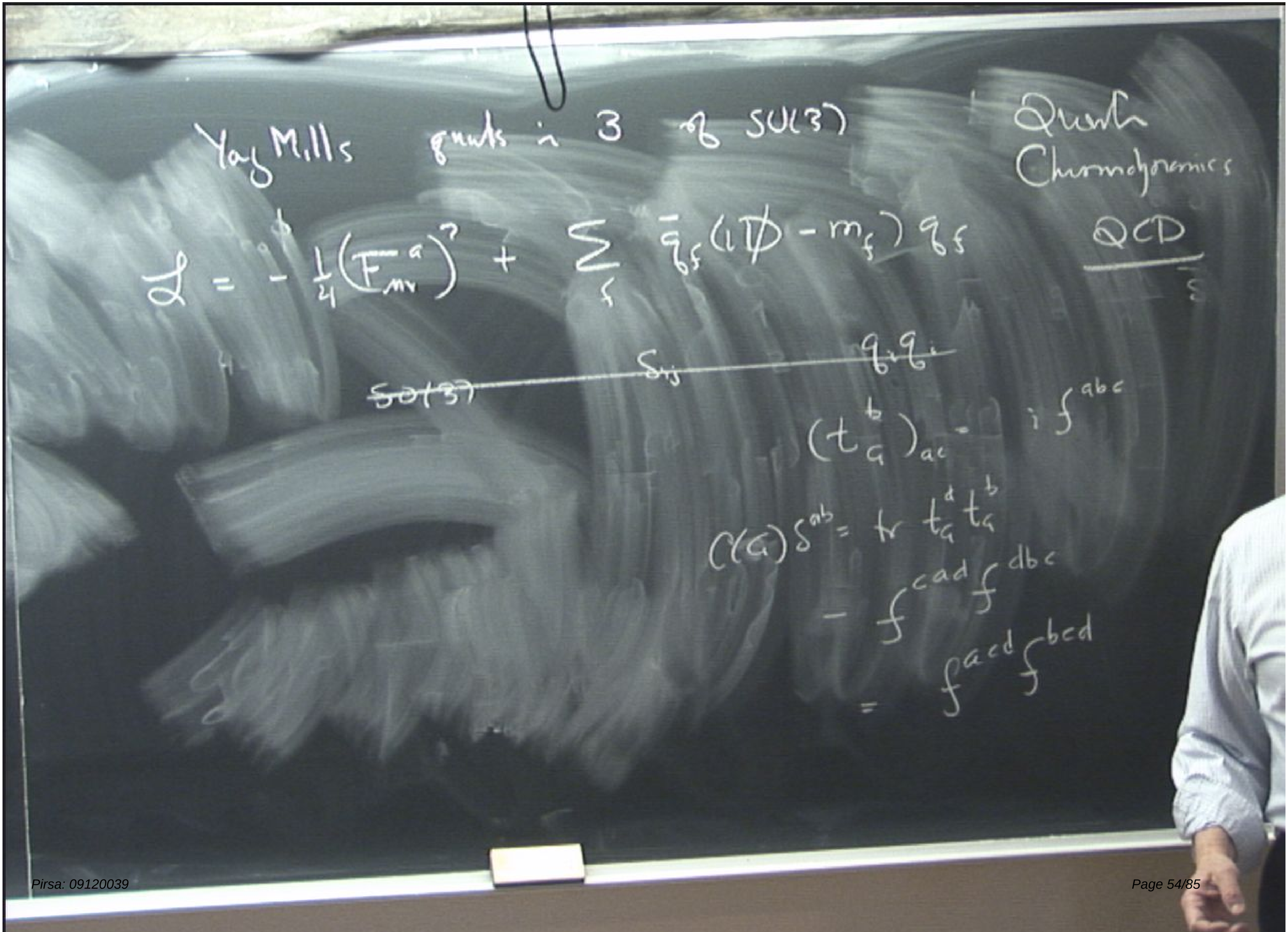
~~SO(3)~~ δ_{ij} $q_i q_i$

$$(t_G^b)_{ac} = i f^{abc}$$

$$C(G)\delta^{ab} = \operatorname{tr} t_G^d t_G^b$$

$$- f^{cad} f$$

$$= f^{acd} f^{bcd}$$



Yang Mills quarks in 3 of SU(3)

Quantum Chromodynamics

QCD

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~~SO(3)~~ δ_{ij} $q_i q_i$

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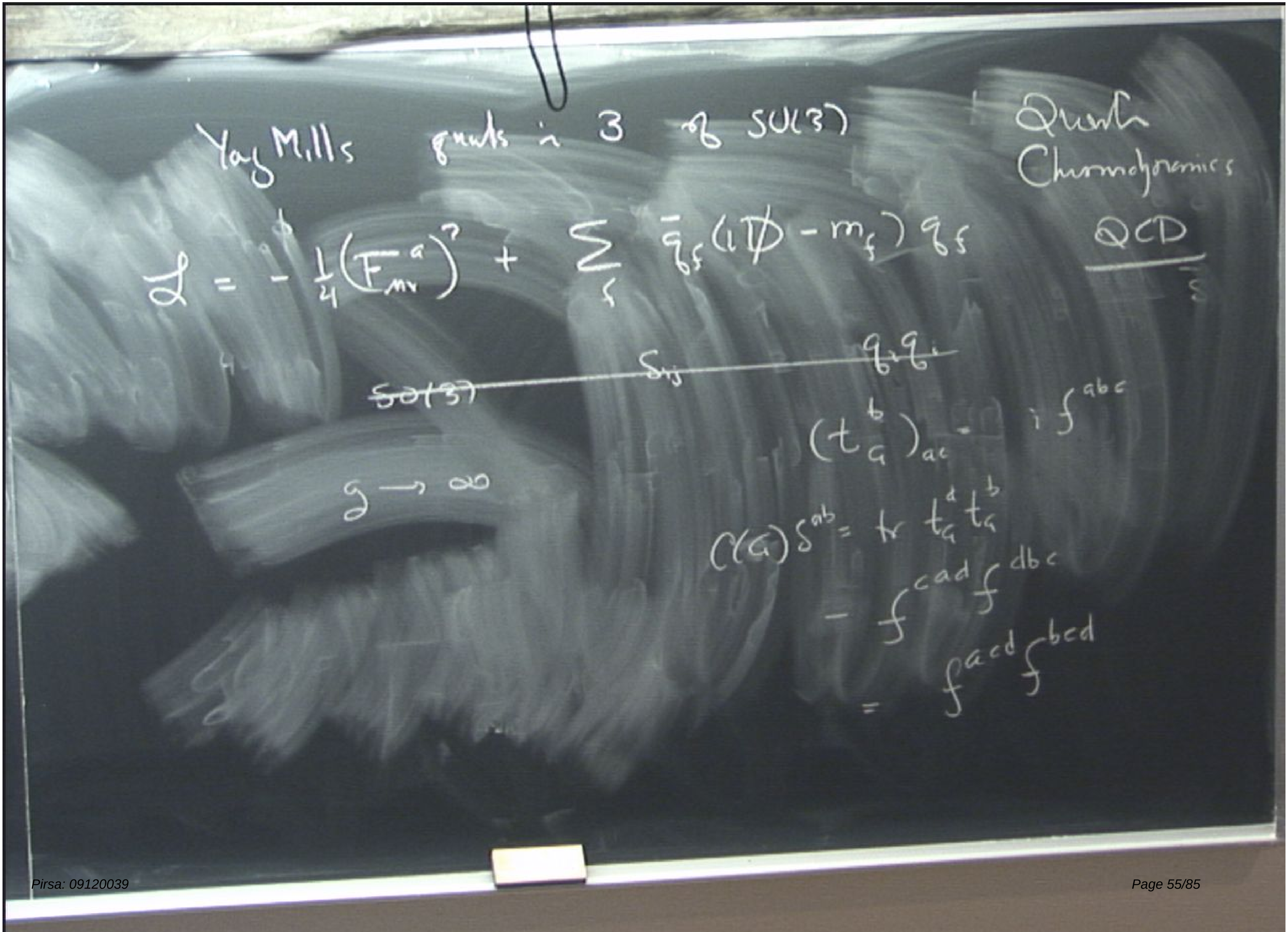
$$C(G)\delta^{ab} = \mathrm{tr}\, t^a_G t^b_G$$

$$- f^{cad} f^{dbc}$$

$$= f^{acd} f^{bcd}$$



Yang Mills quarks in 3 of SU(3)

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QCD

$$\mathcal{L} = -\frac{1}{4}\left(F^{a}_{\mu\nu}\right)^2 + \sum_f \bar{q}_f\left(i\not{D} - m_f\right)q_f$$

~~$SU(3)$ δ_{ij} $q_i q_i$~~

$g \to \infty$

$(t^{b}_{G})_{ac} = i f^{abc}$

$C(G)\,\delta^{ab} = \mathrm{tr}\; t^{d}_{G}\, t^{b}_{G}$

$- f^{cad} f^{dbc}$

$= f^{acd} f^{bcd}$

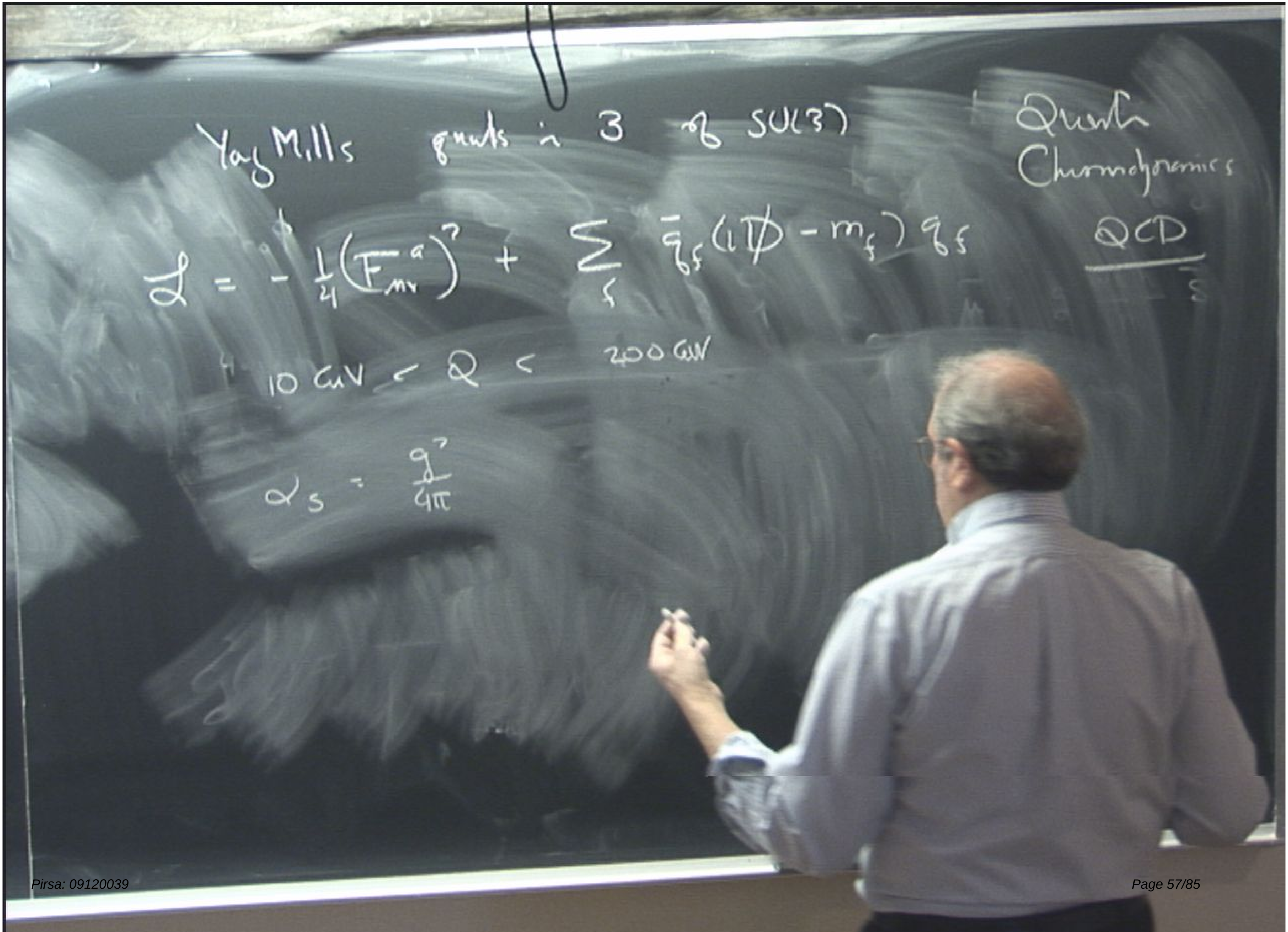
Yang Mills   quarks in 3 of SU(3)

Quantum
Chromodynamics

QCD

$$\mathcal{L} = -\frac{1}{4}\left(F_{\mu\nu}^{a}\right)^2 + \sum_f \bar{q}_f \left(i\not{D} - m_f\right) q_f$$

10 GeV < Q < 200 GeV



Yang Mills quarks in 3 of SU(3)

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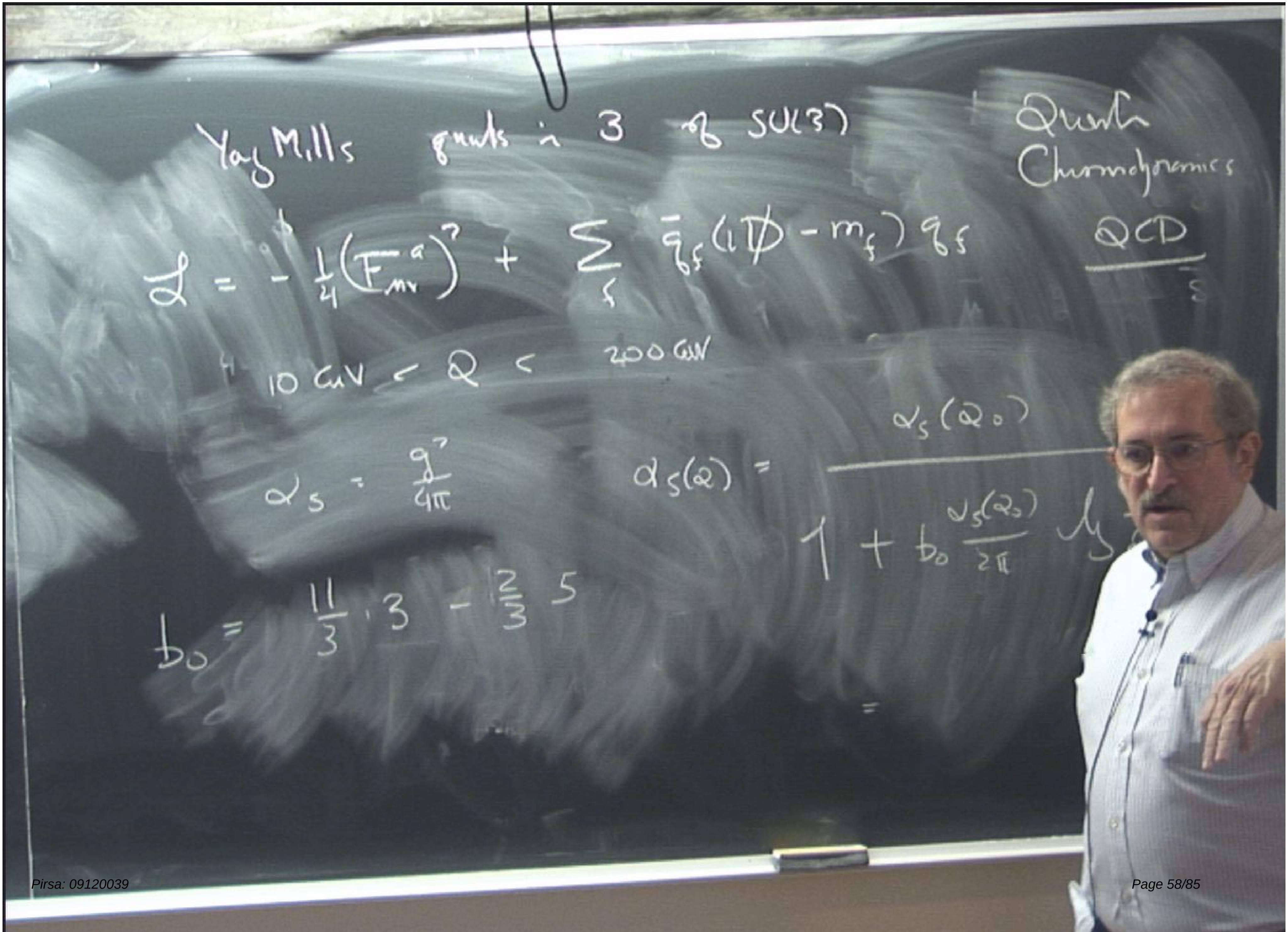
10 GeV < Q < 200 GeV

$$\alpha_s = \frac{g^2}{4\pi}$$



Yang Mills quarks in 3 of SU(3)

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10 GeV < Q < 200 GeV

$$\alpha_s = \frac{g^2}{4\pi}$$

$$\alpha_s(Q) = \frac{\alpha_s(Q_0)}{1 + b_0 \frac{\alpha_s(Q_0)}{2\pi} \log}$$

$$b_0 = \frac{11}{3}\cdot 3 - \frac{2}{3}\, 5$$

=

Yang Mills quarks in 3 of SU(3)

Quantum Chromodynamics

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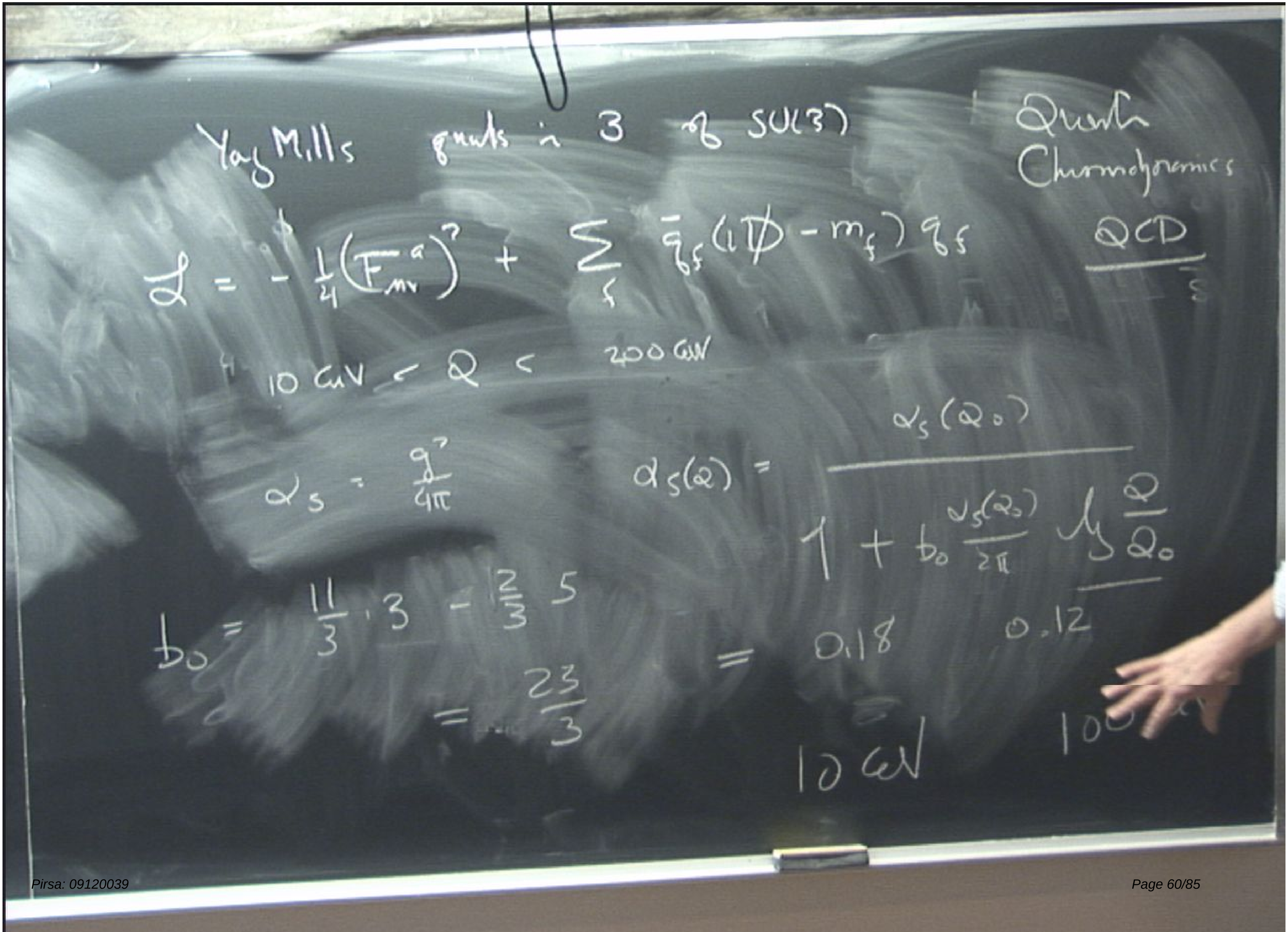
$$b_0 = \frac{11}{3} \cdot 3 - \frac{2}{3}\, 5$$

$$= \frac{23}{3}$$

=



Yang Mills quarks in 3 of SU(3)

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10 GeV < Q < 200 GeV

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$$b_0 = \frac{11}{3} \cdot 3 - \frac{2}{3} 5$$

$$= \frac{23}{3}$$

= 0.18 0.12

10 GeV 100

Yang Mills quarks in 3 of SU(3)

Quantum Chromodynamics

QCD

$$\mathcal{L} = -\frac{1}{4}\left(F_{\mu\nu}^{a}\right)^2 + \sum_f \bar{q}_f (i\not{D} - m_f) q_f$$

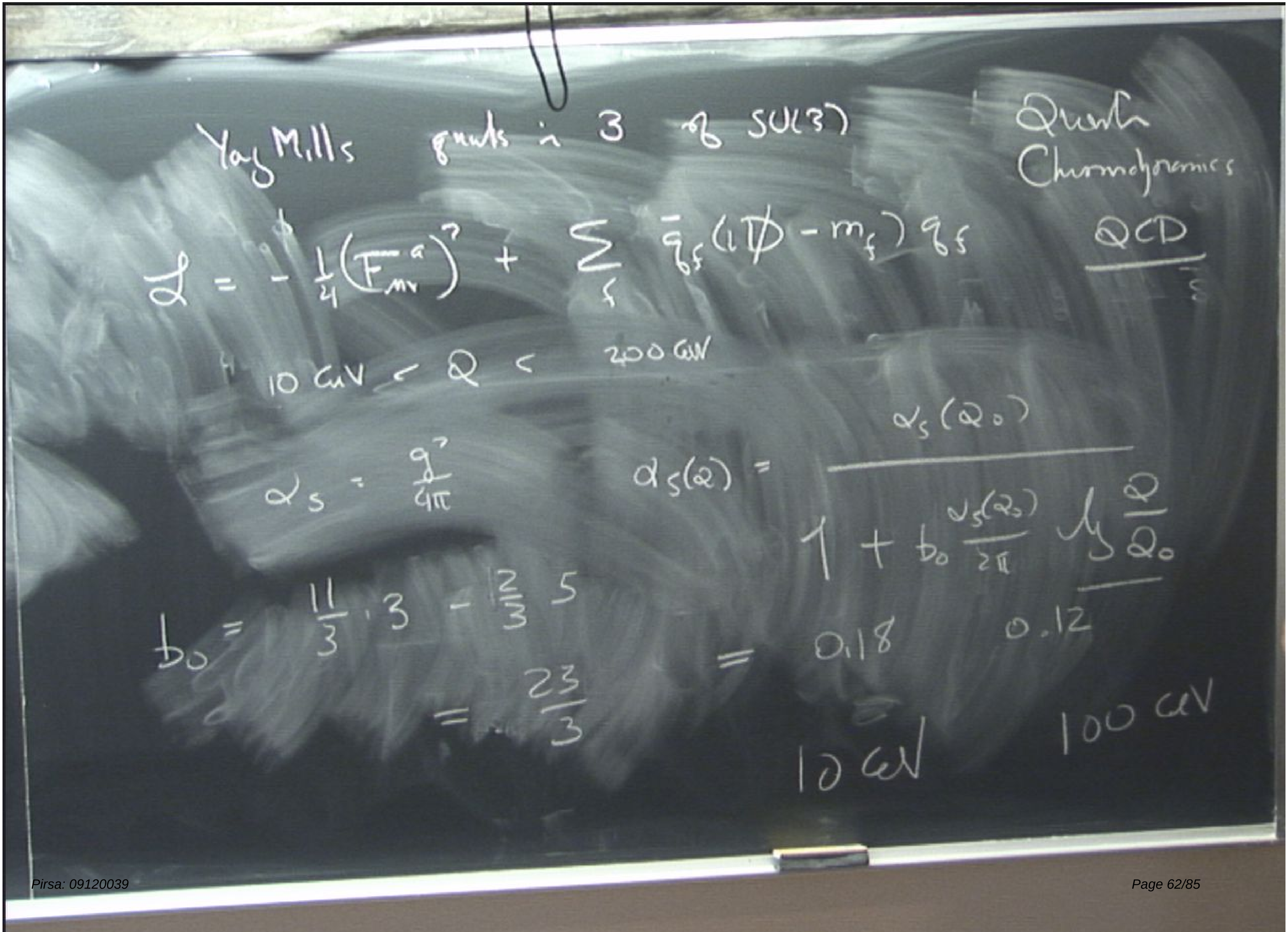
10 GeV < Q < 200 GeV

$$\alpha_s = \frac{g^2}{4\pi} \qquad \alpha_s(Q) = \frac{\alpha_s(Q_0)}{1 + b_0 \frac{\alpha_s(Q_0)}{2\pi} \log\frac{Q}{Q_0}}$$

$$b_0 = \frac{11}{3} \cdot 3 - \frac{2}{3}\, 5 = \frac{23}{3}$$

= 0.18   0.12

10 GeV   100 GeV



Yang Mills quarks in 3 of SU(3)

Quantum Chromodynamics

QCD

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10 GeV < Q < 200 GeV

$$\alpha_s = \frac{g^2}{4\pi}$$

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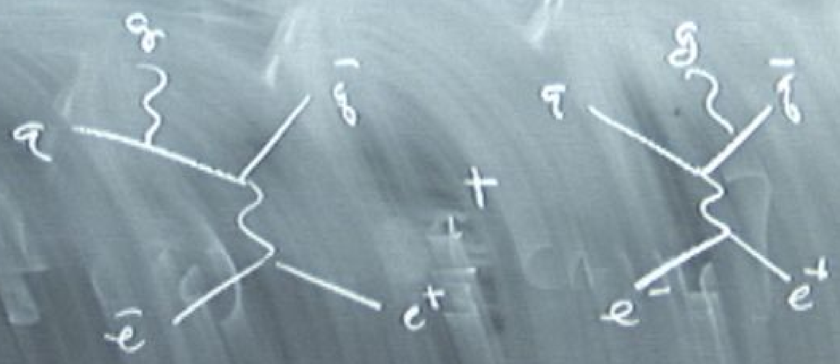
$$b_0 = \frac{11}{3} \cdot 3 - \frac{2}{3}\, 5 = \frac{23}{3}$$

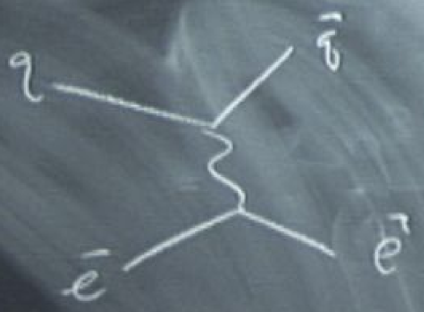
= 0.18 0.12

10 GeV 100 GeV

$e^- e^+ \to$ hadn.

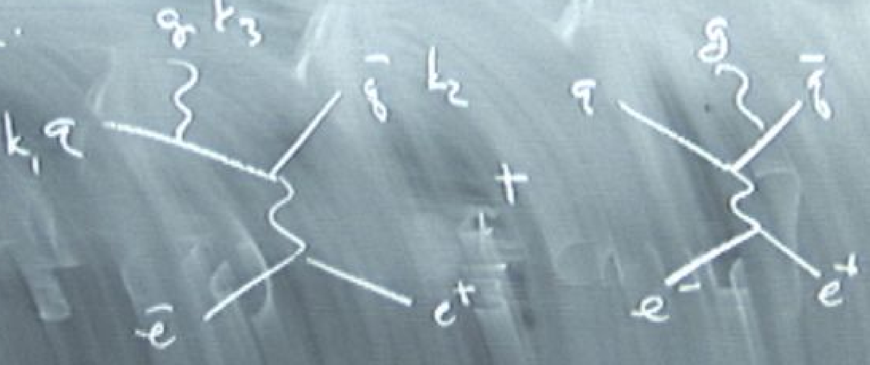


$e^- e^+ \to$ hadr.



$$Q = k_1 + k_2 + k_3 \qquad x_i = \frac{2 Q k_i}{Q^2}$$

$e^- e^+ \to$ hadr.

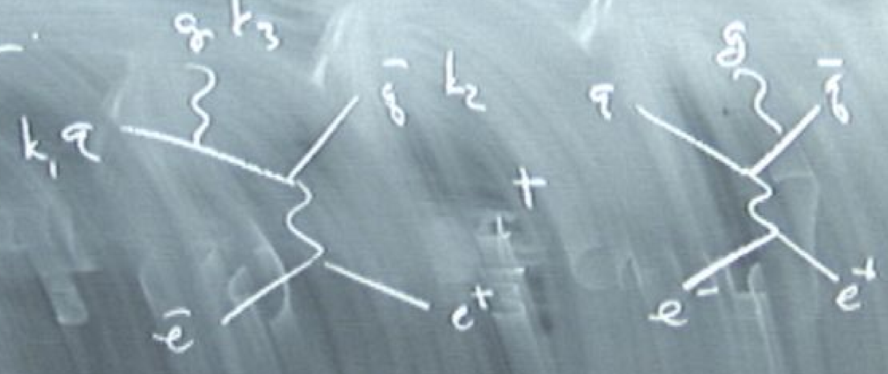


$Q = k_1 + k_2 + k_3$ $\quad x_i = \frac{2Q\cdot k_i}{Q^2} =$

$\sigma_0 = \frac{4\pi}{3}\frac{\alpha^2}{S}\sum_f 3Q_f^2$

$x_1 + x_2 + x_3 = 1$

$e^- e^+ \to$ hadn.



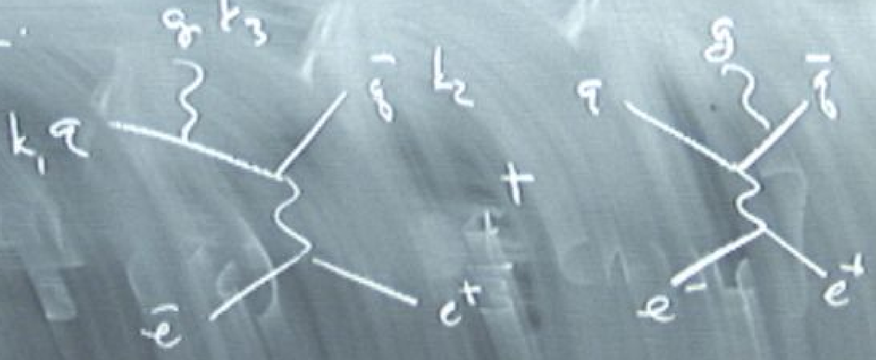
$$Q = k_1 + k_2 + k_3 \qquad x_i = \frac{2Q k_i}{Q^2} =$$

$$x_1 + x_2 + x_3 = 1$$

$$\sigma_0 = \frac{4\pi}{3}\frac{\alpha^2}{S}\sum_f 3Q_f^2$$

$$\frac{d\sigma}{dx_1 dx_2} = \sigma_0 \cdot \frac{2\alpha_s}{3\pi}\frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}$$

$e^- e^+ \to$ hadr.



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$$\sigma_0 = \frac{4\pi}{3} \frac{\alpha^2}{S} \sum_f 3 Q_f^2$$

$$x_1 + x_2 + x_3 = 1$$

$$\frac{d\sigma}{dx_1 dx_2} = \sigma_0 \cdot \frac{2\alpha_s}{3\pi} \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}$$


Farhi
T =

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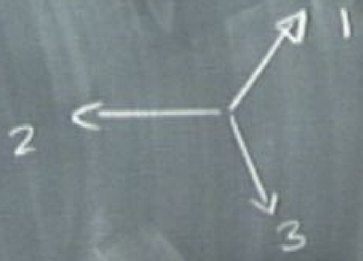

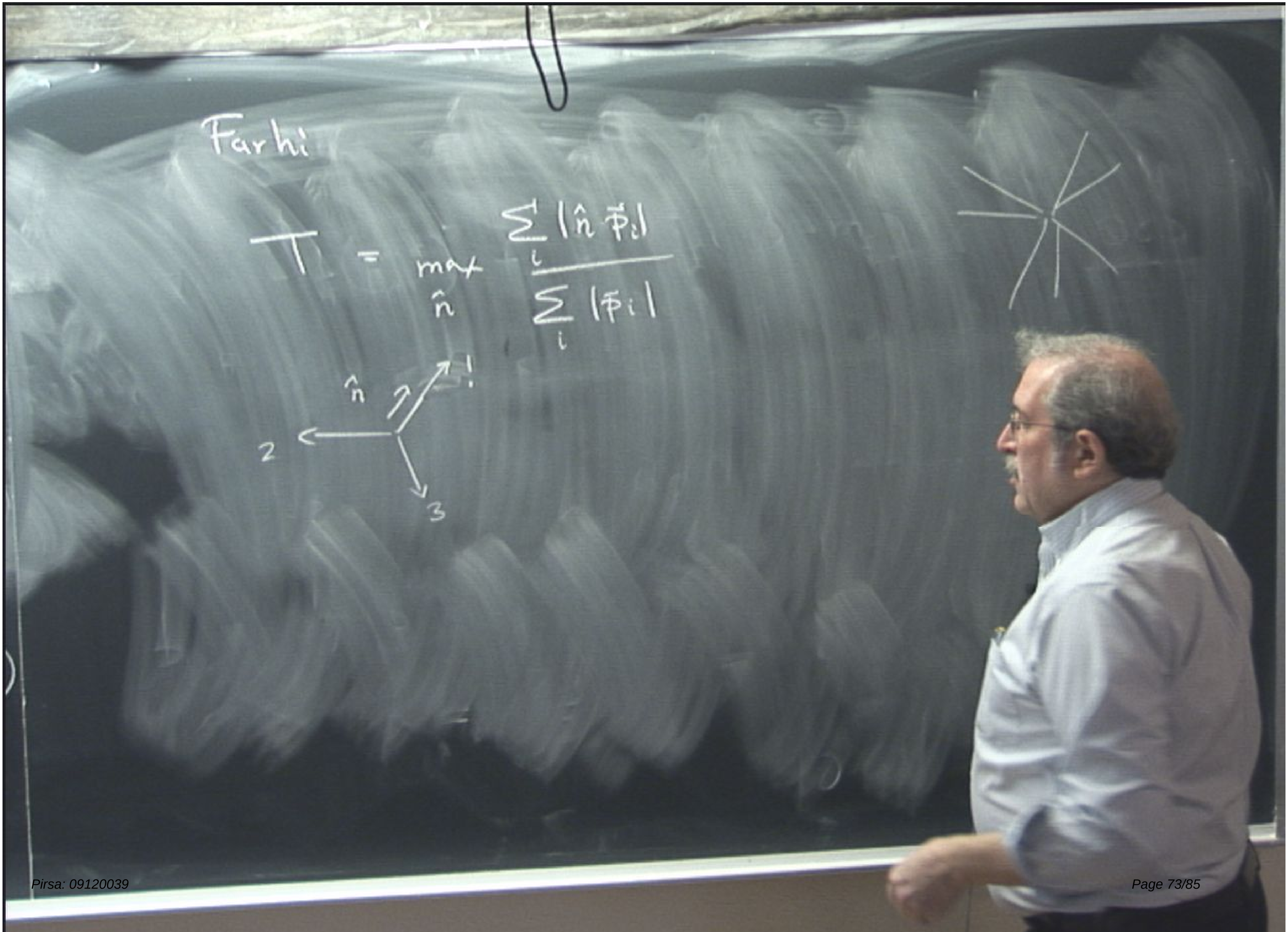

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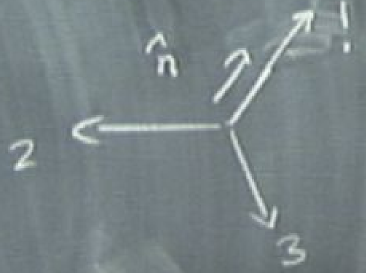
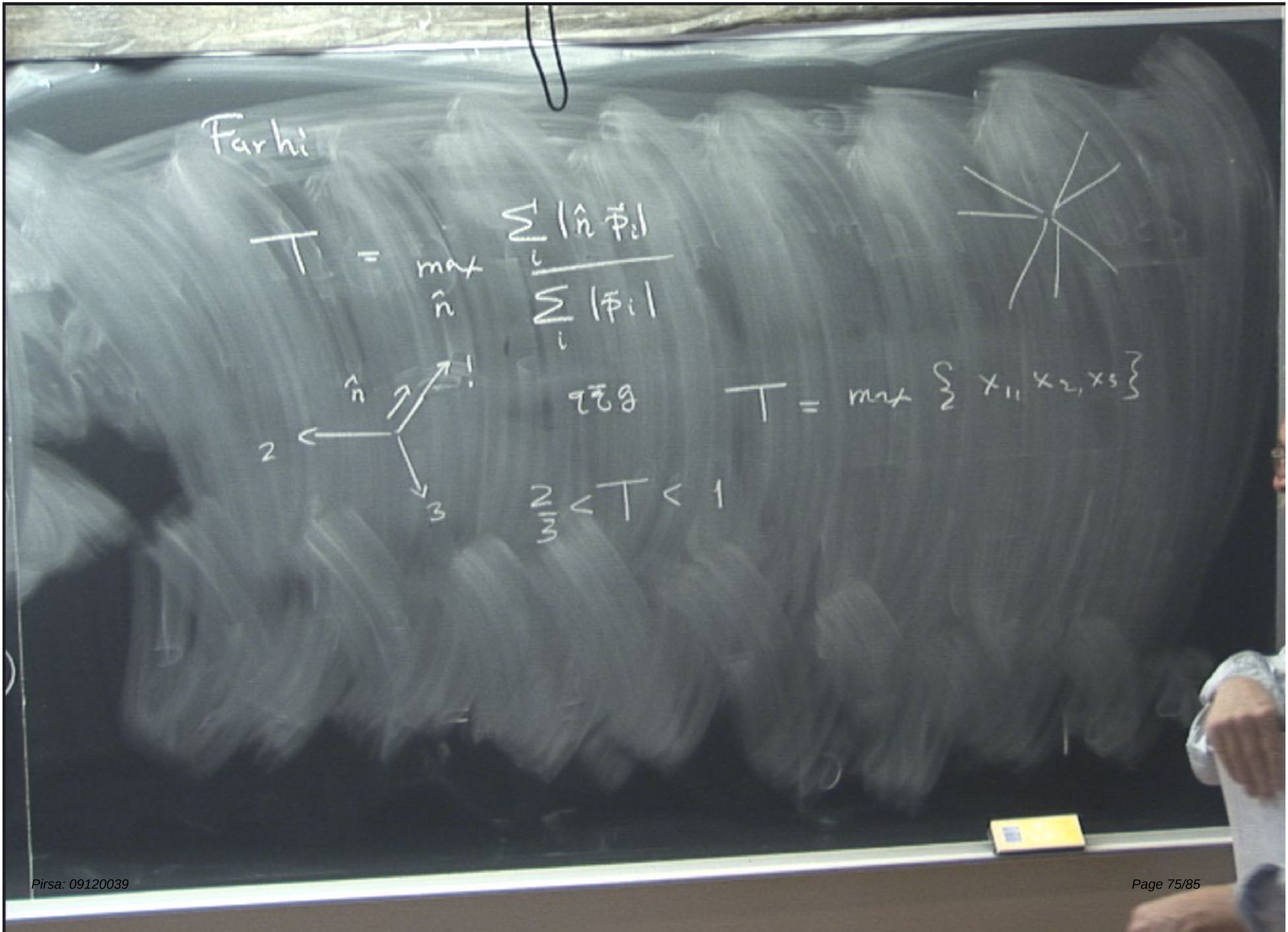


$q\bar{q}g$

$T = \max \{ x_1, x_2, x_3 \}$



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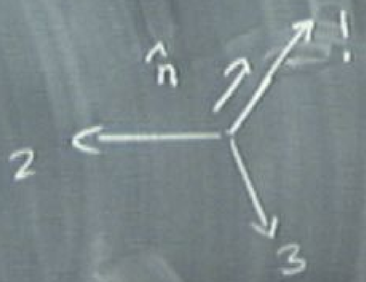

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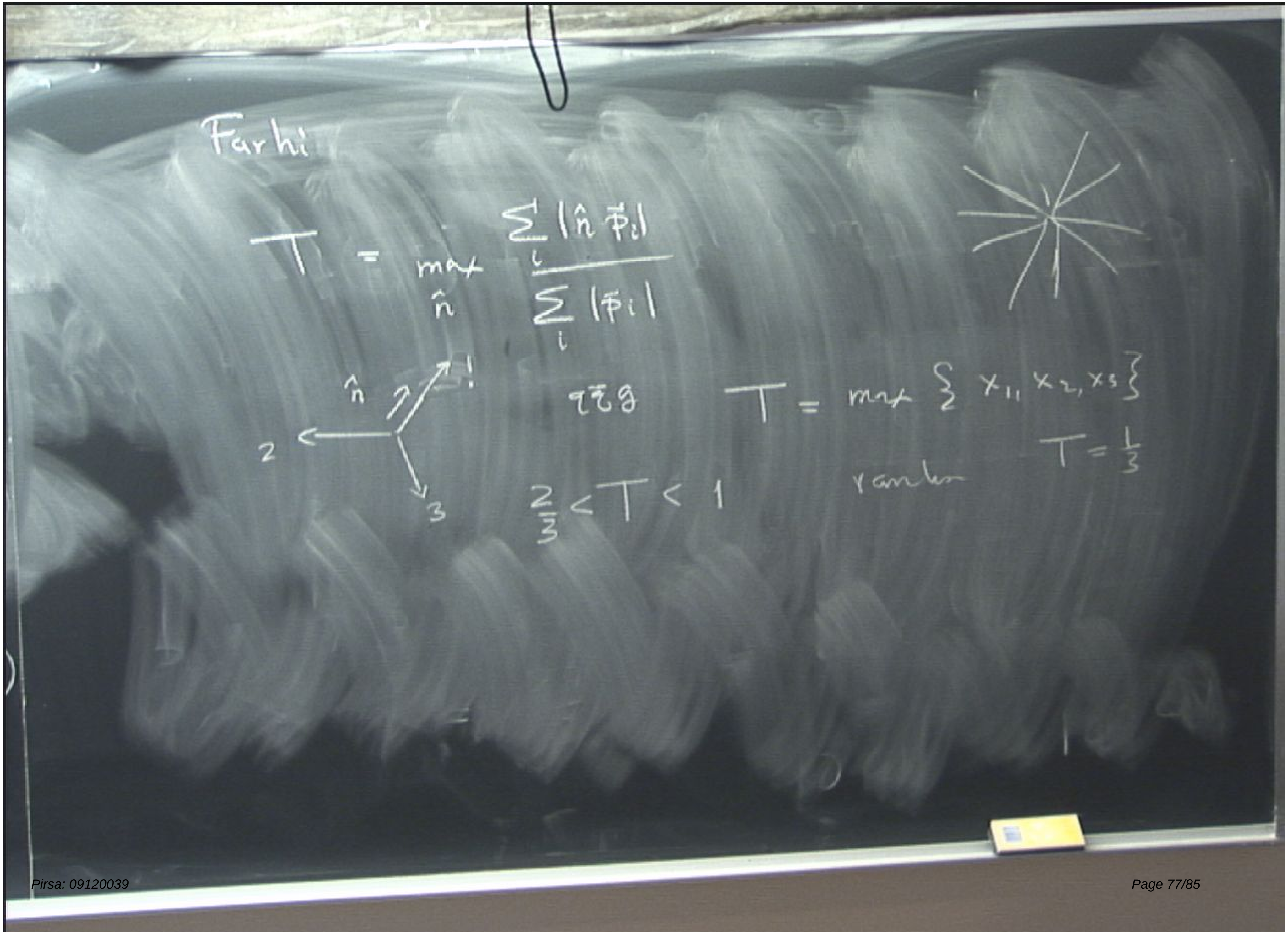

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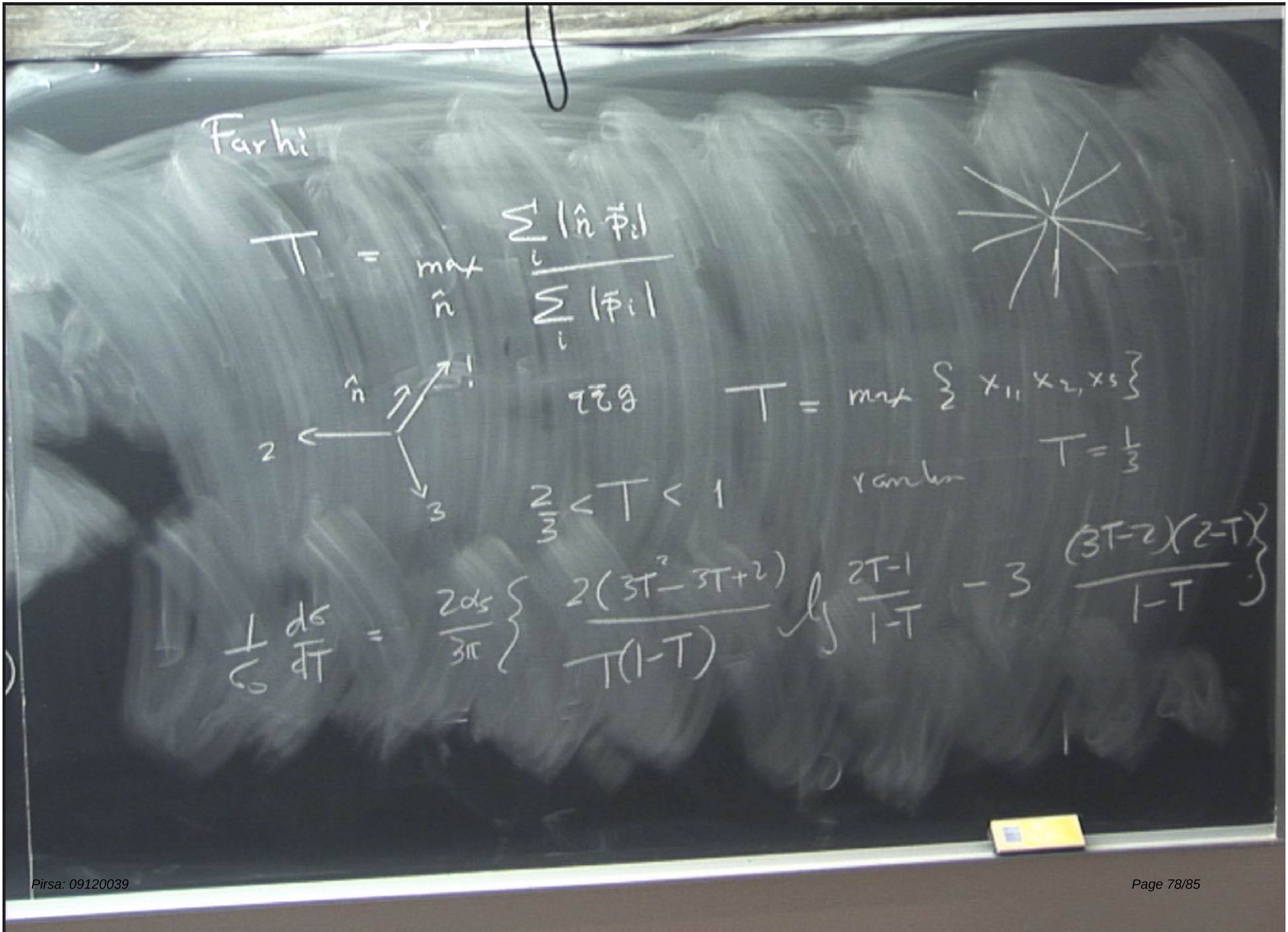

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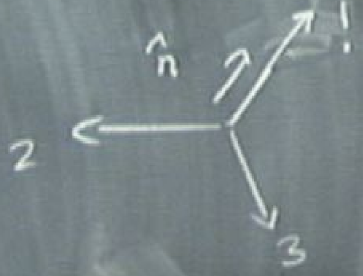

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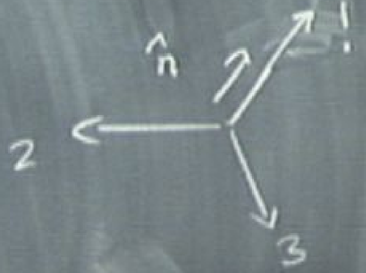

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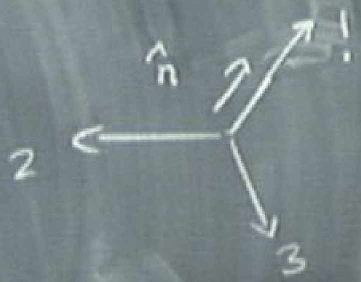

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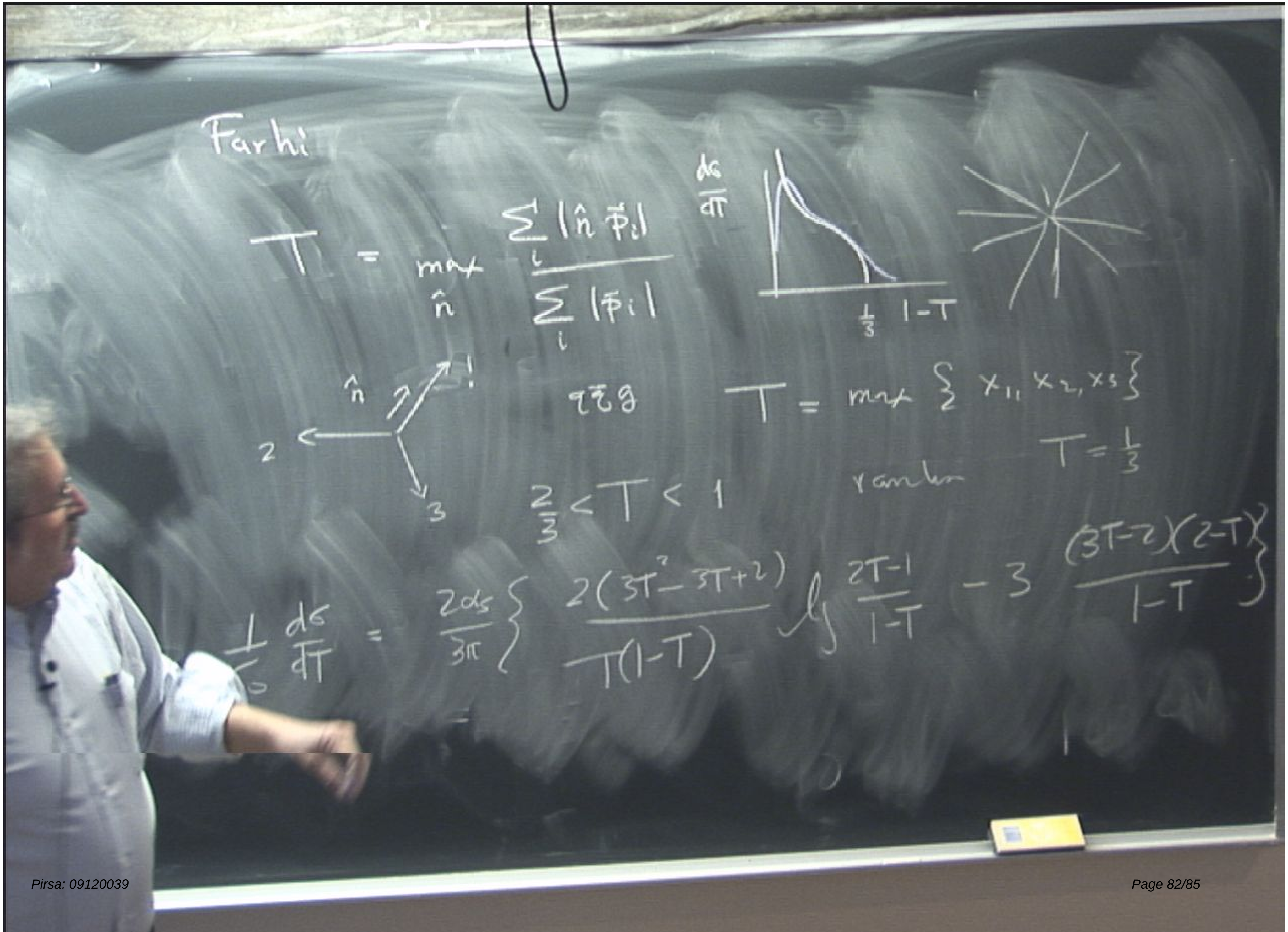

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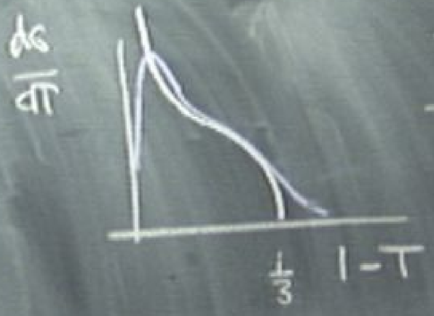

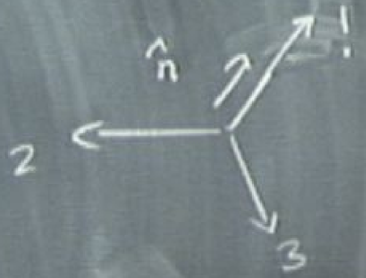

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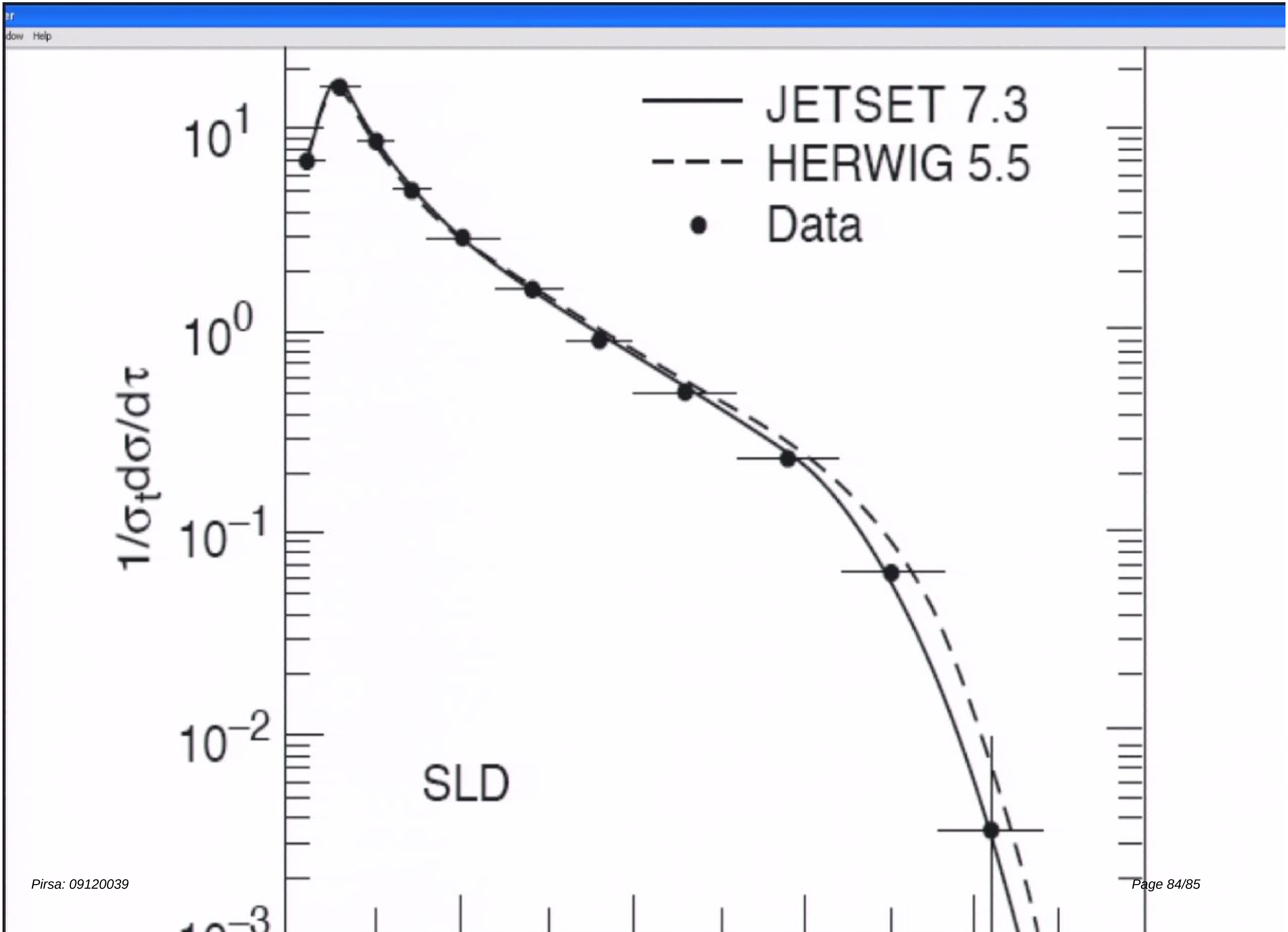
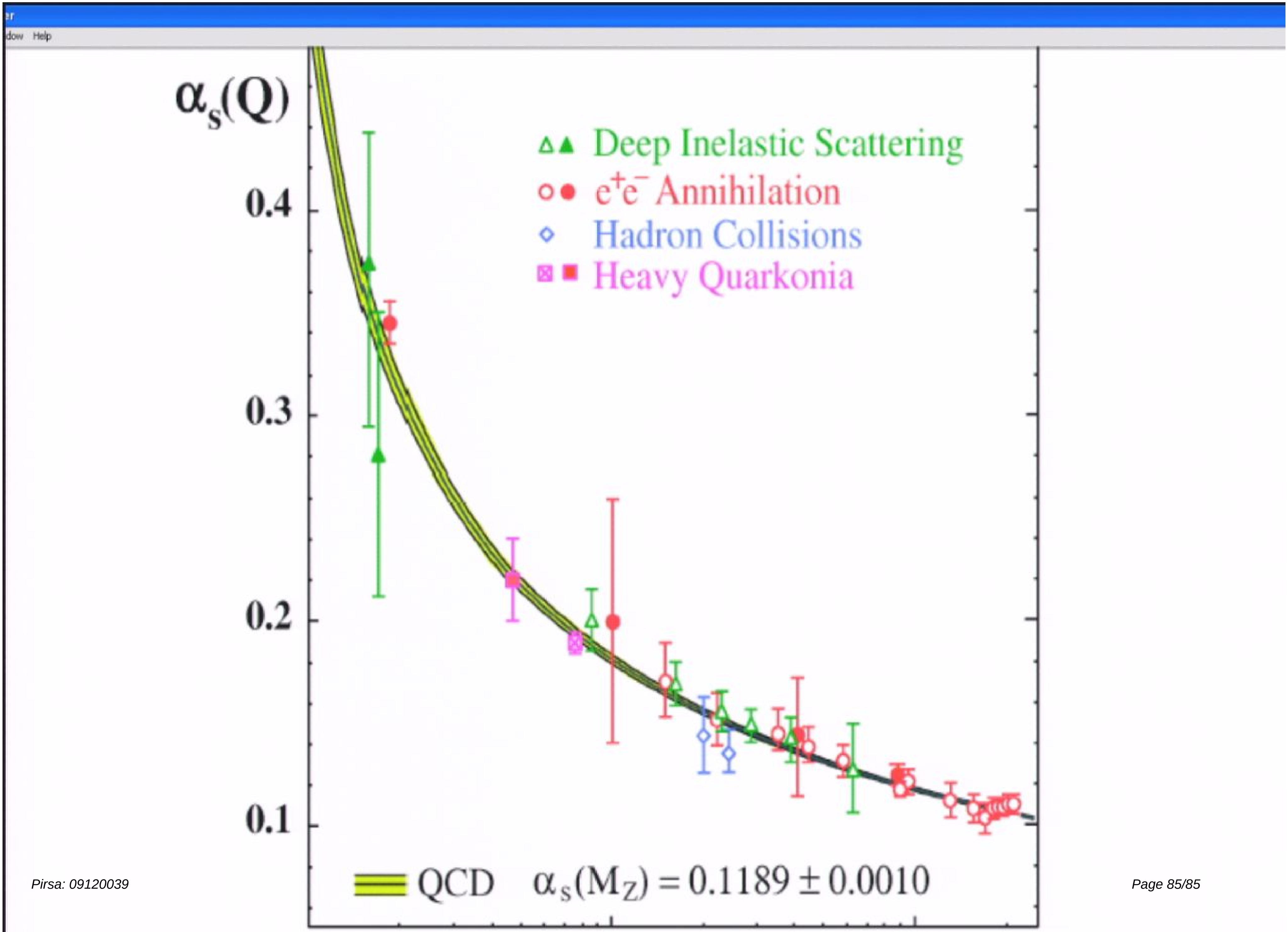

er
dow Help
JETSET 7.3
HERWIG 5.5
Data
$1/\sigma_t d\sigma/d\tau$
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
SLD


dow Help
$\alpha_s(Q)$
0.4
0.3
0.2
0.1
△▲ Deep Inelastic Scattering
○● e^+e^- Annihilation
◇ Hadron Collisions
⊠■ Heavy Quarkonia
QCD $\alpha_s(M_Z) = 0.1189 \pm 0.0010$