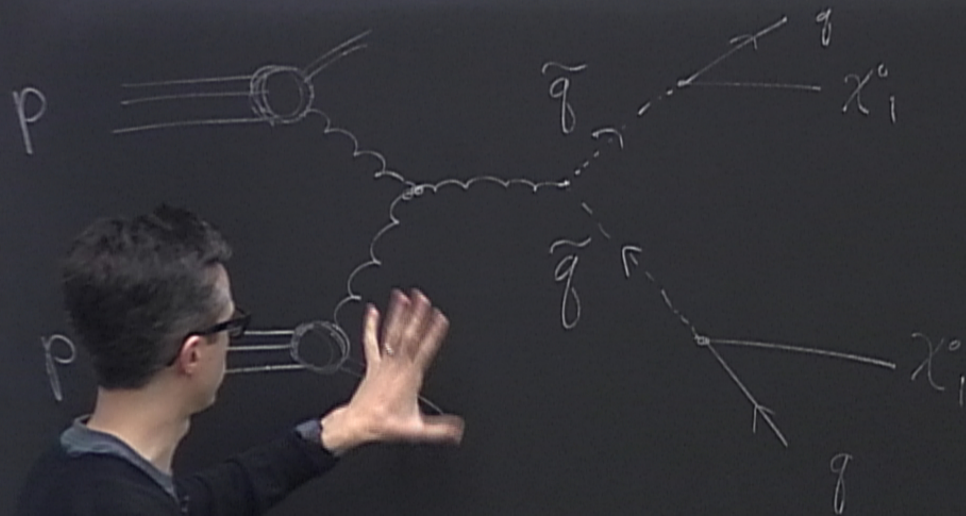


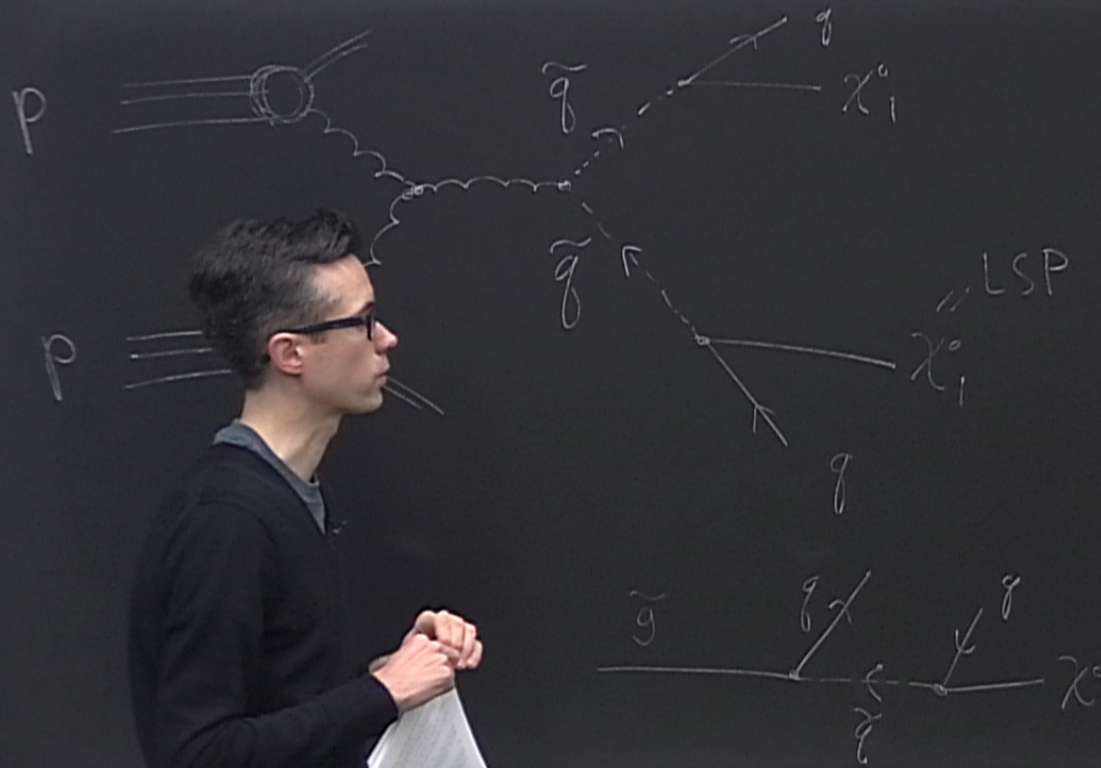
Title: PSI 2015/2016 More/Beyond Standard Model - Lecture 10

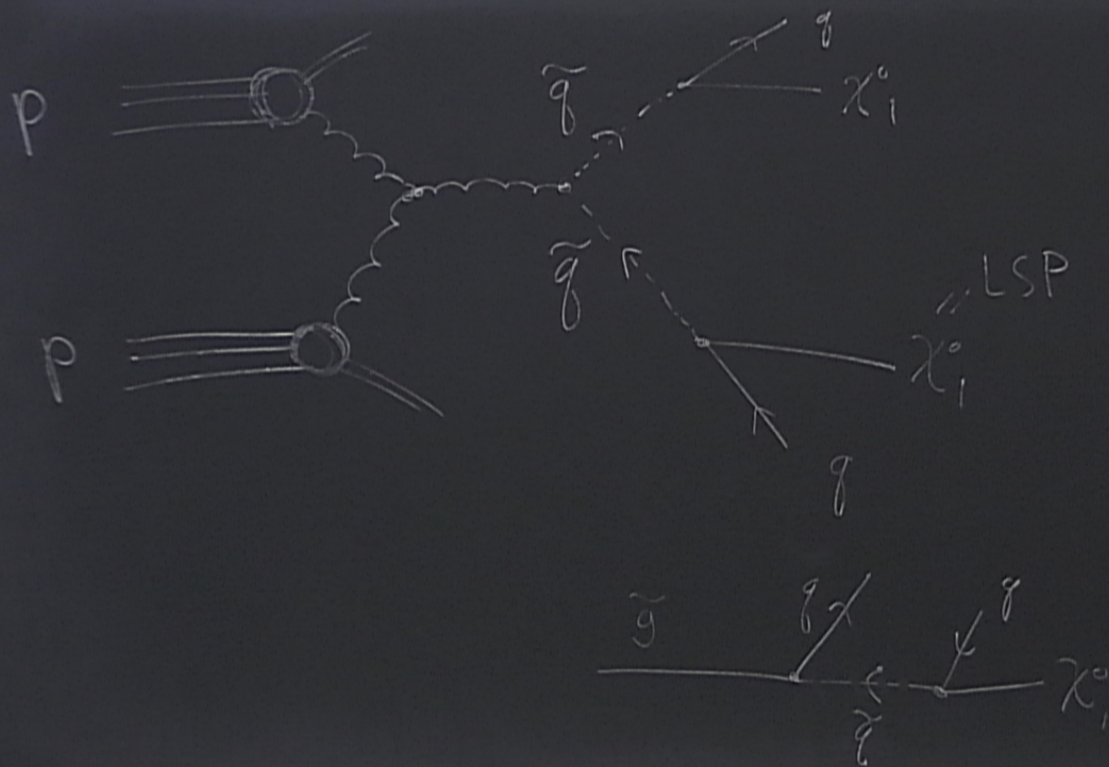
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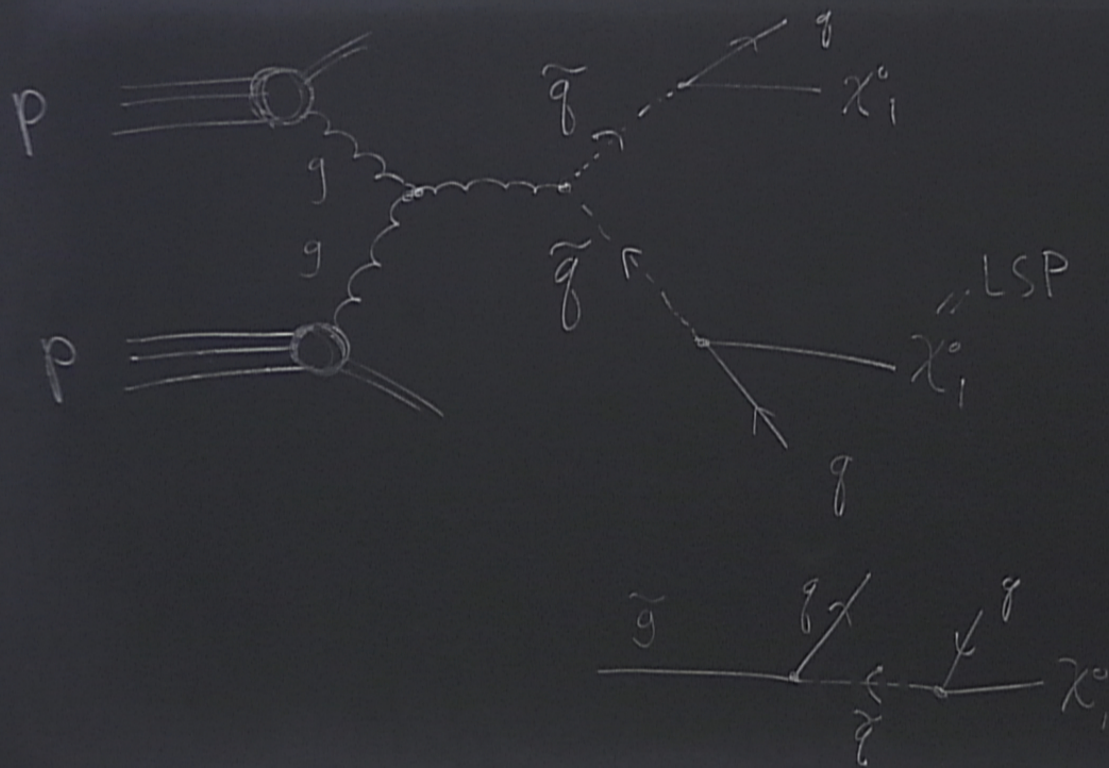
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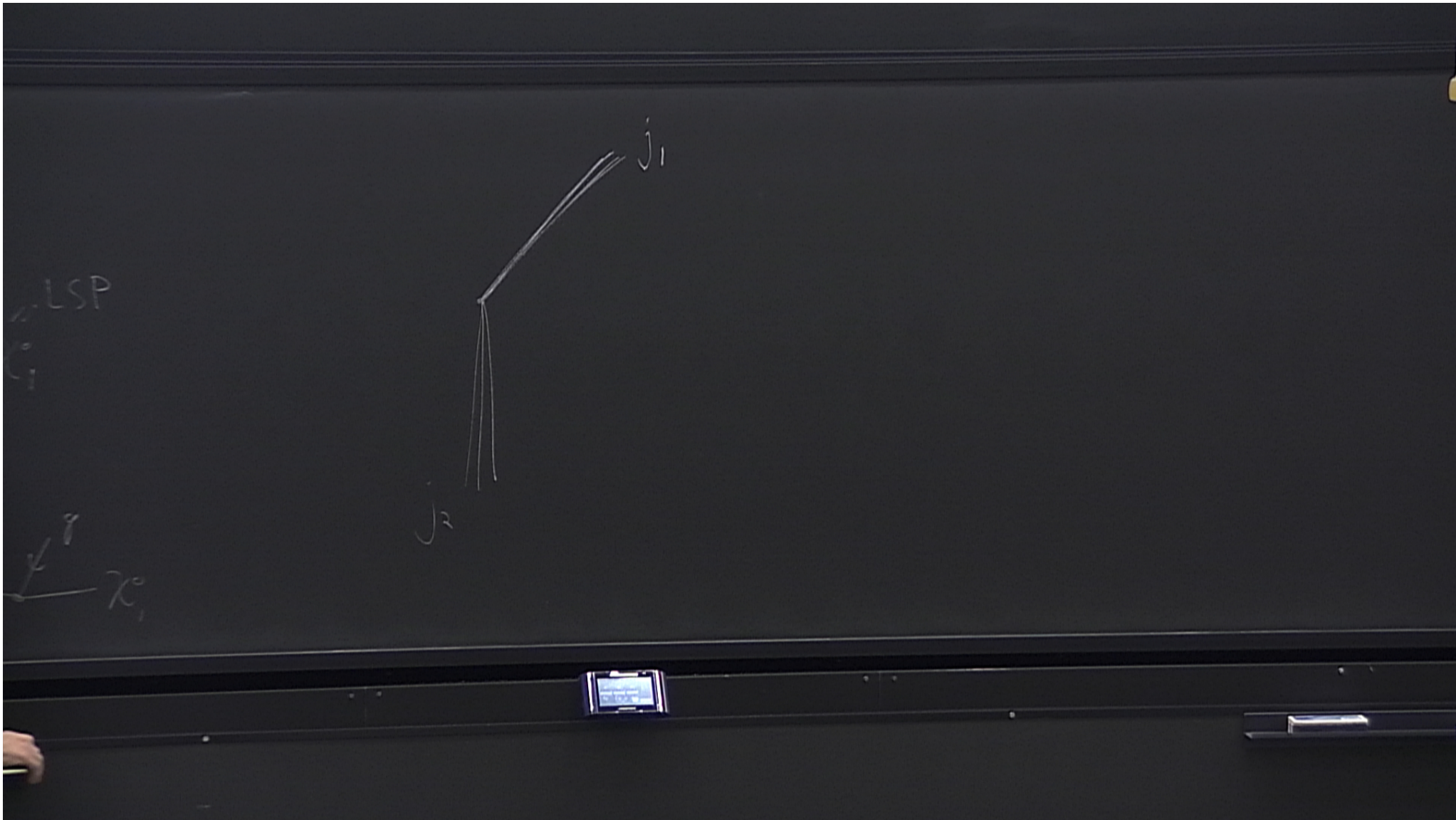
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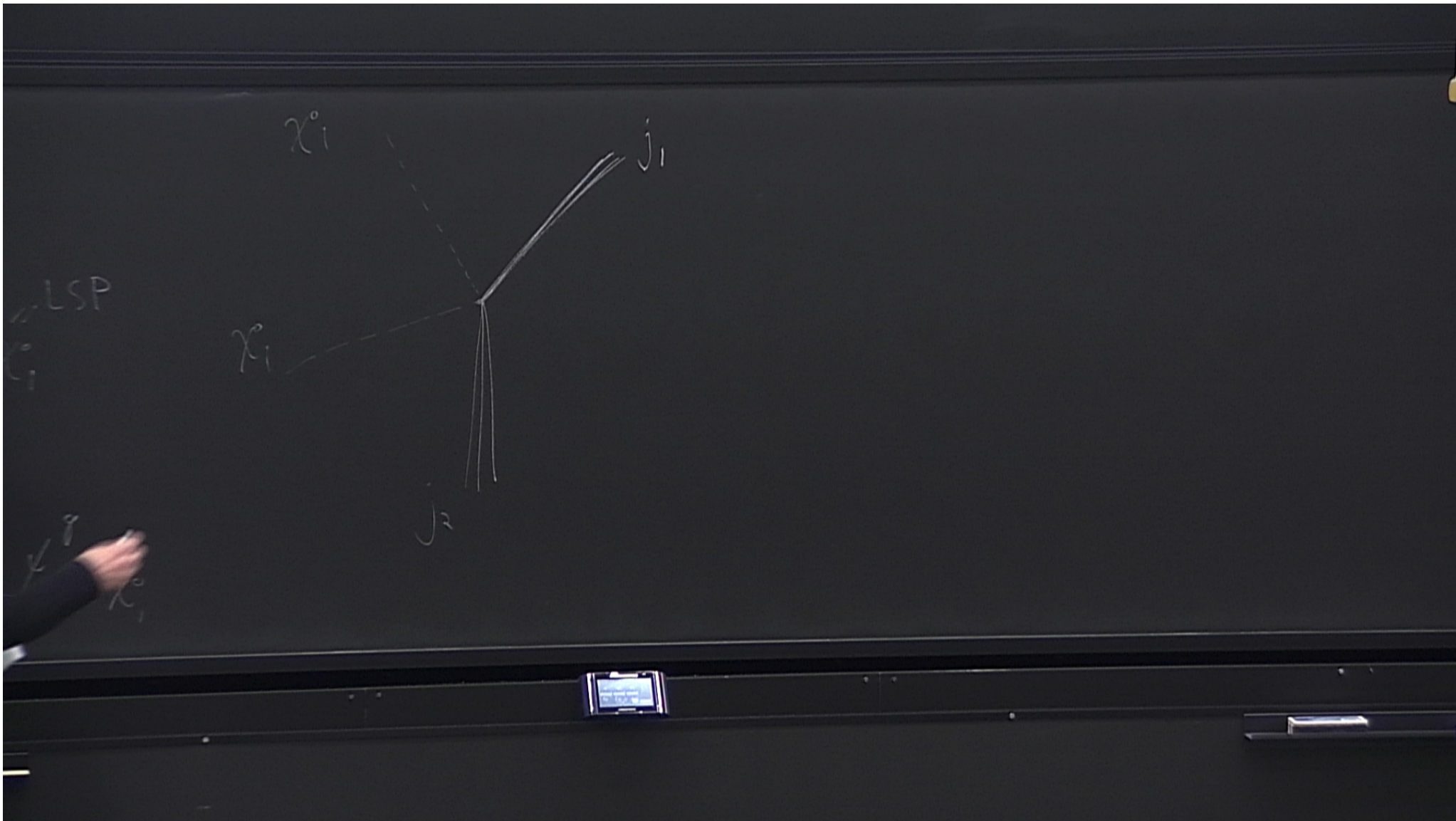


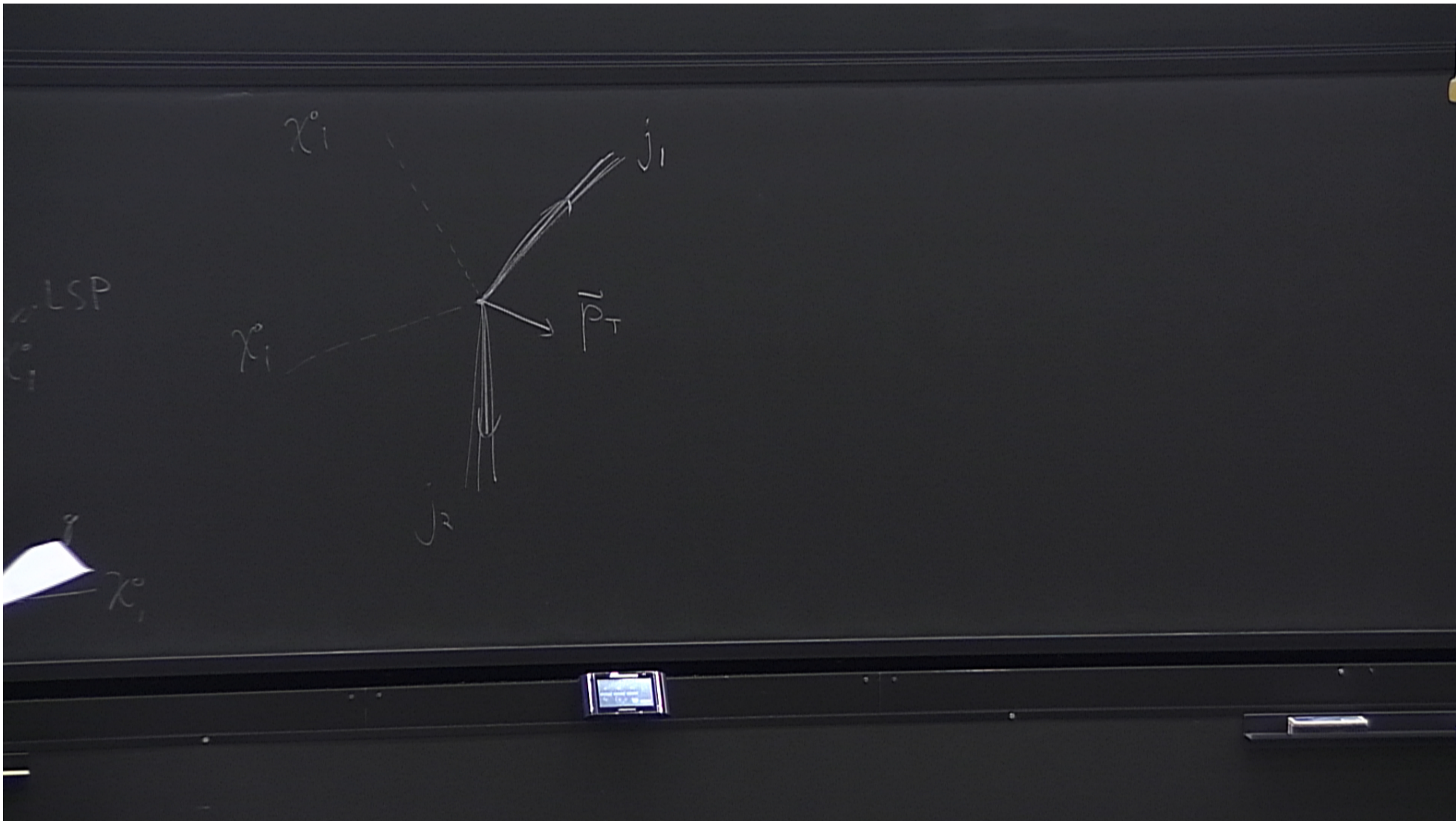


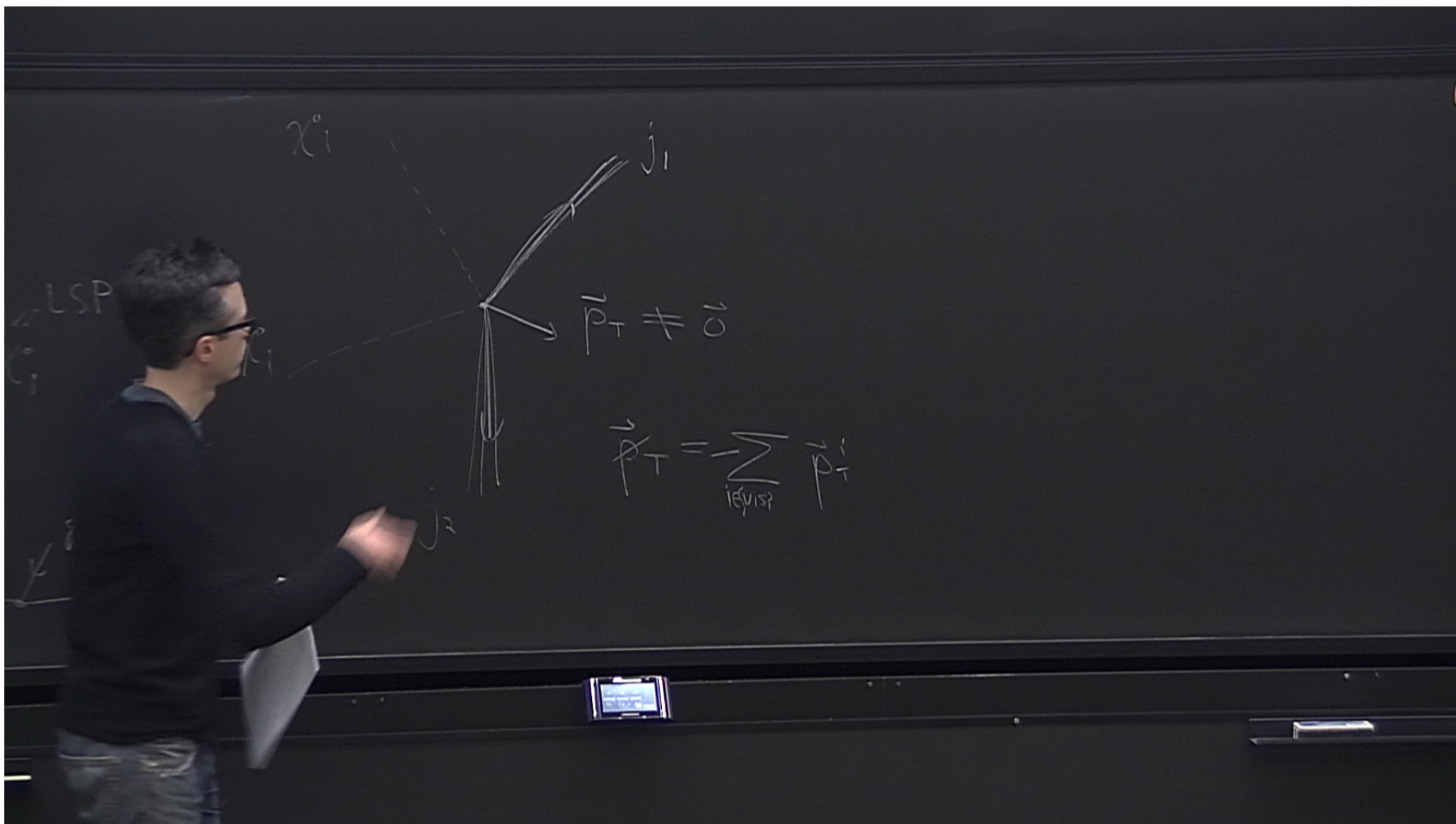


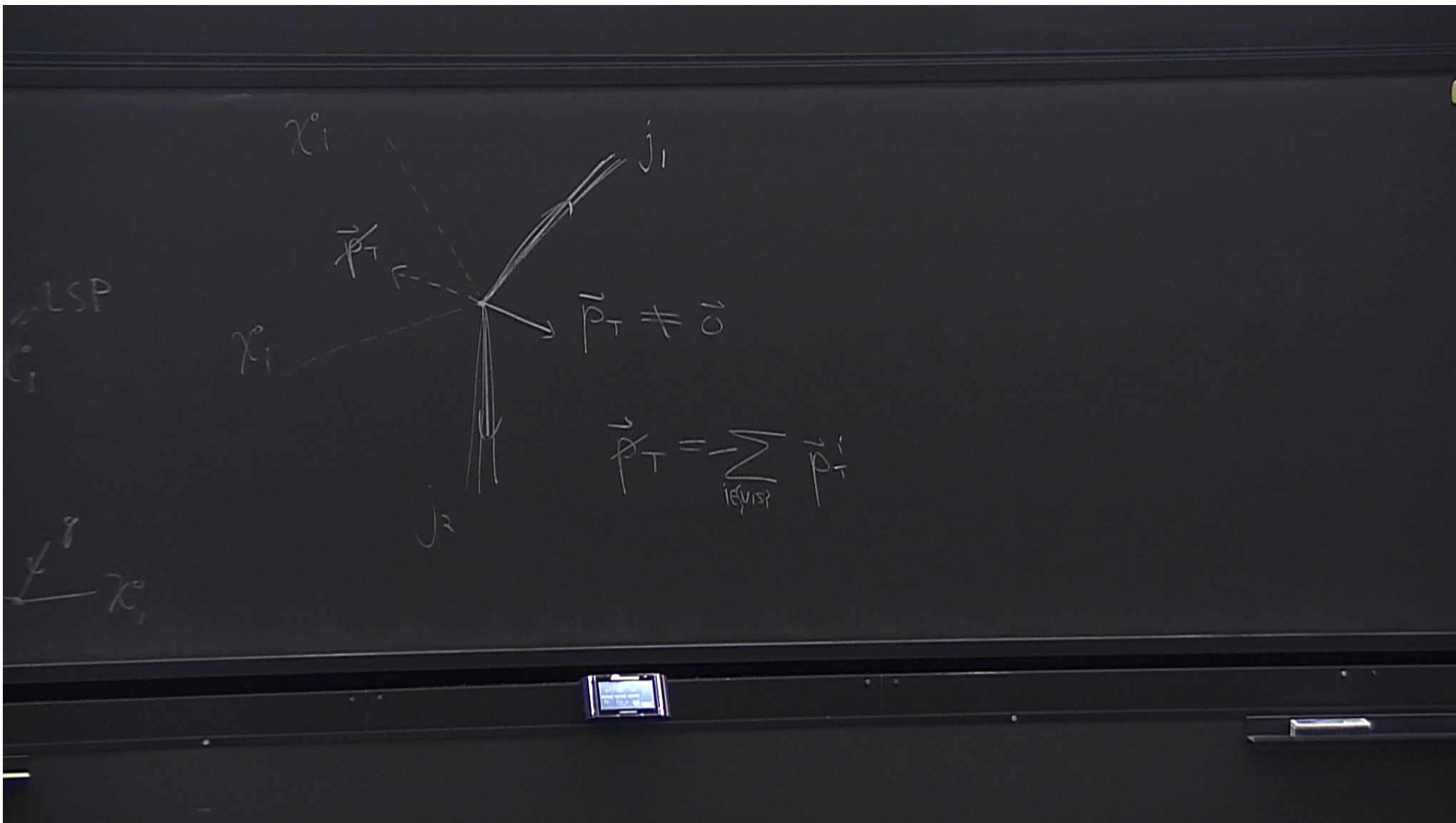


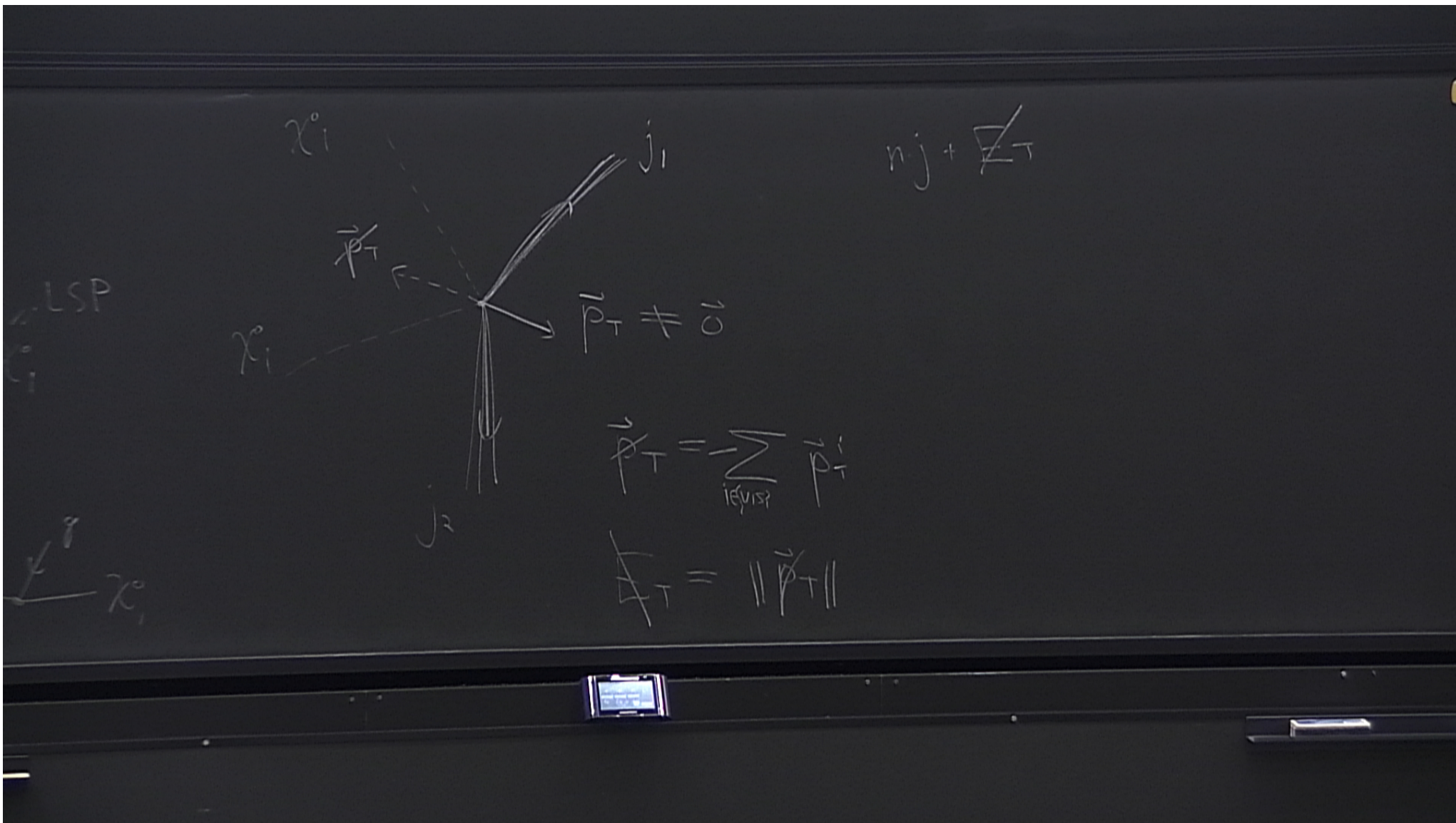












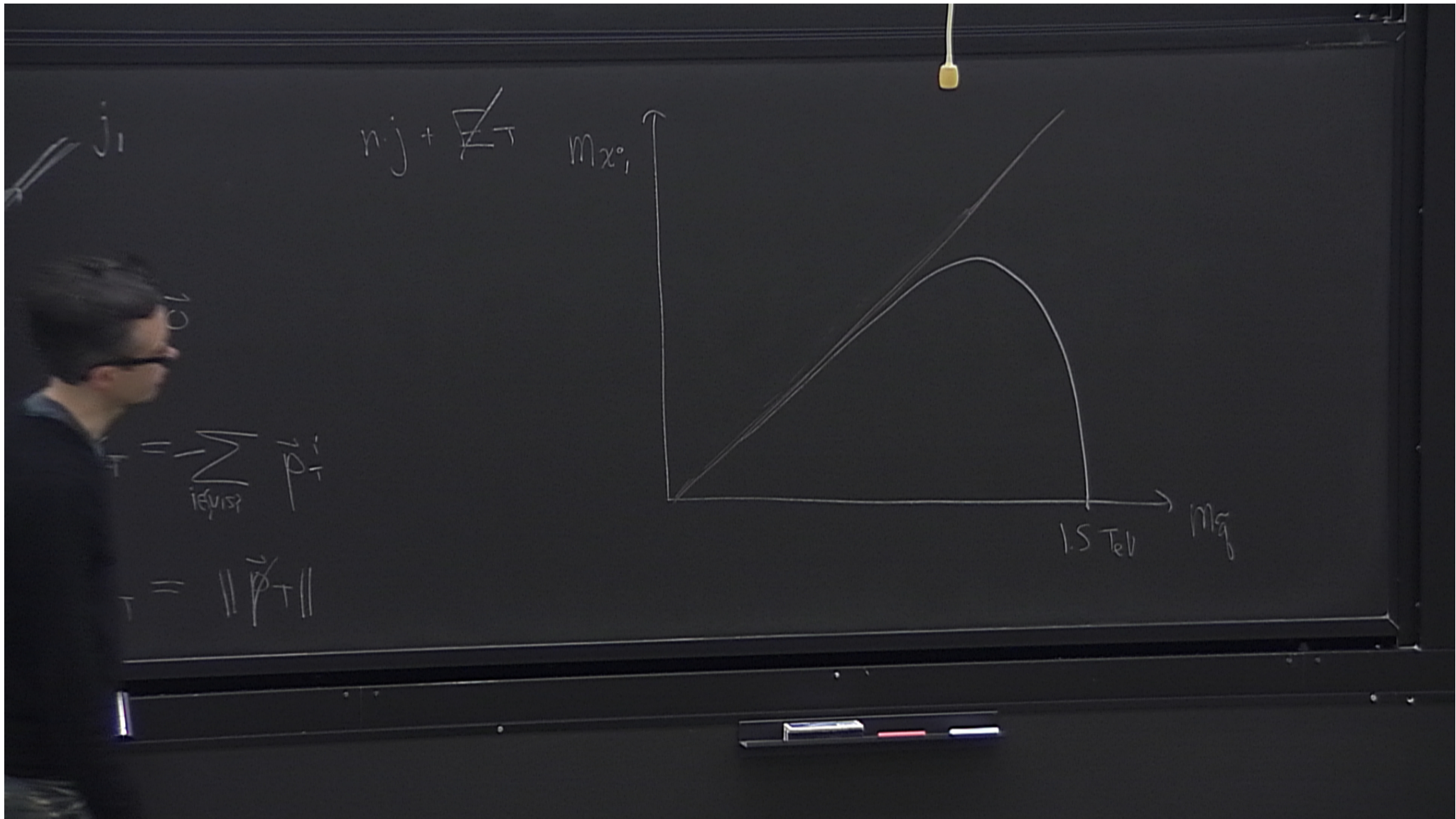
$$j_1 \quad n_j + \cancel{\Sigma}_T \quad m_{x_1}$$

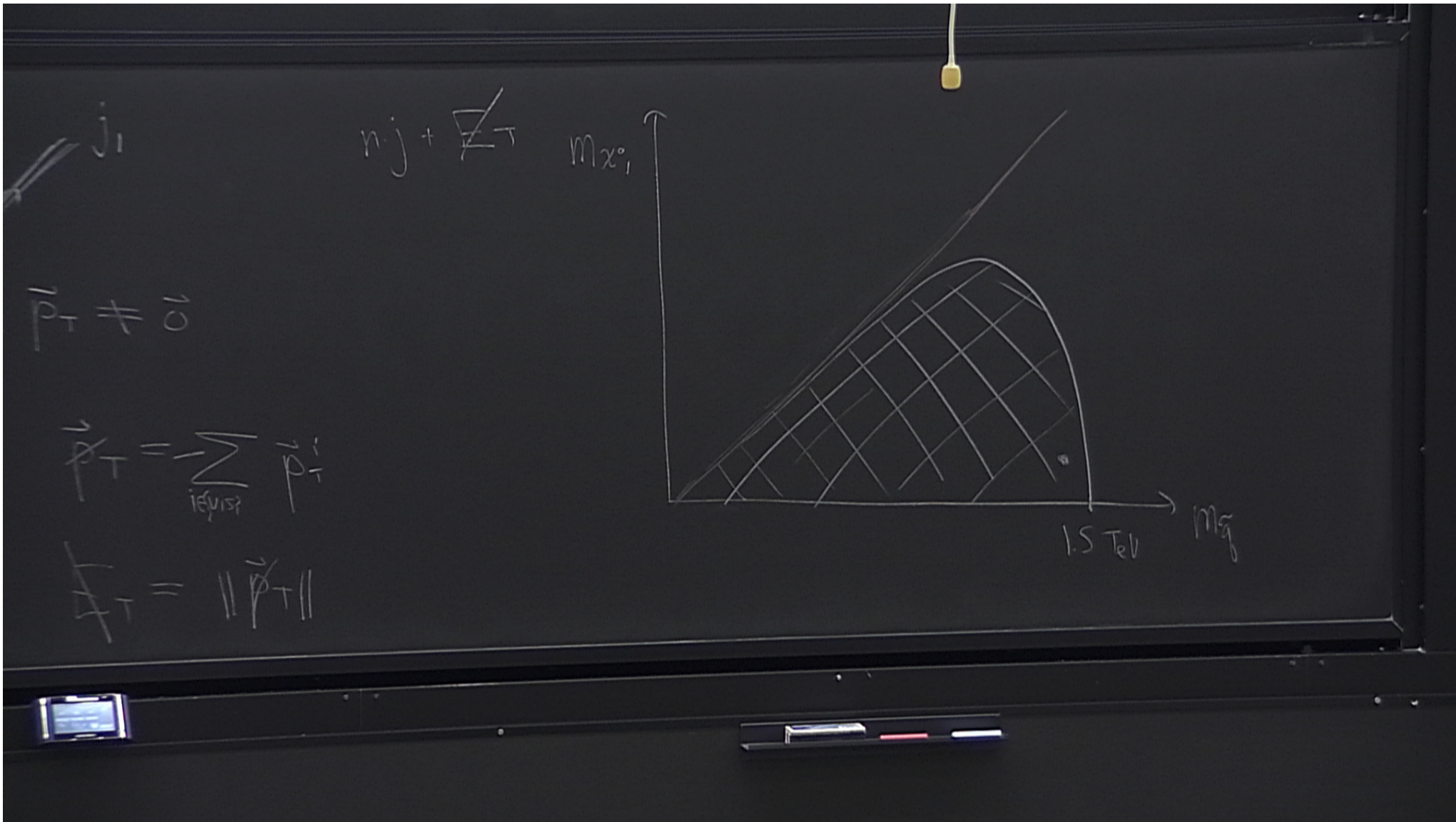
$$\vec{p}_T \neq \vec{0}$$

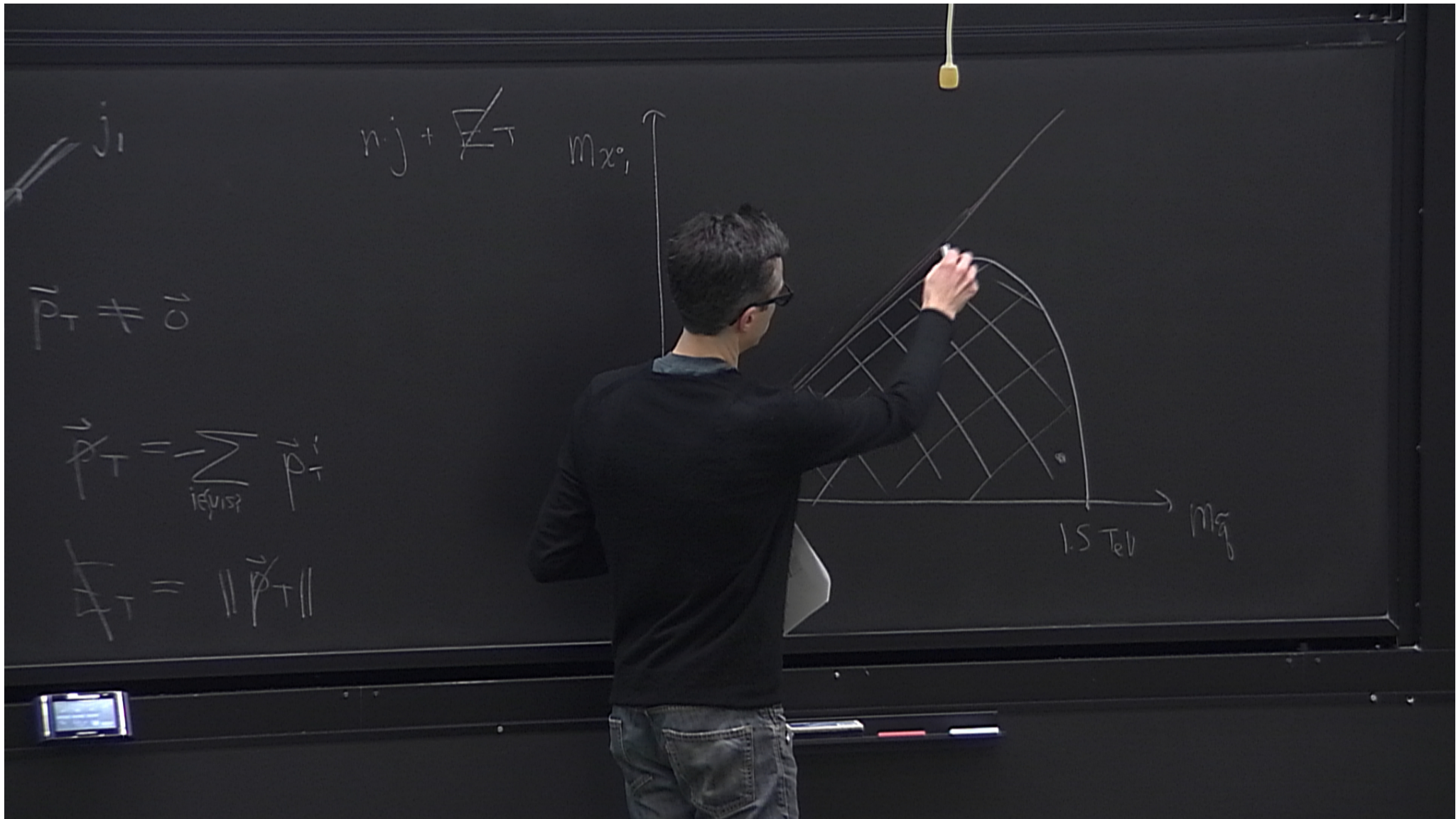
$$\vec{p}_T = - \sum_{i \in \text{vis}} \vec{p}_T^i$$

$$\cancel{A}_T = \|\vec{p}_T\|$$









j_1

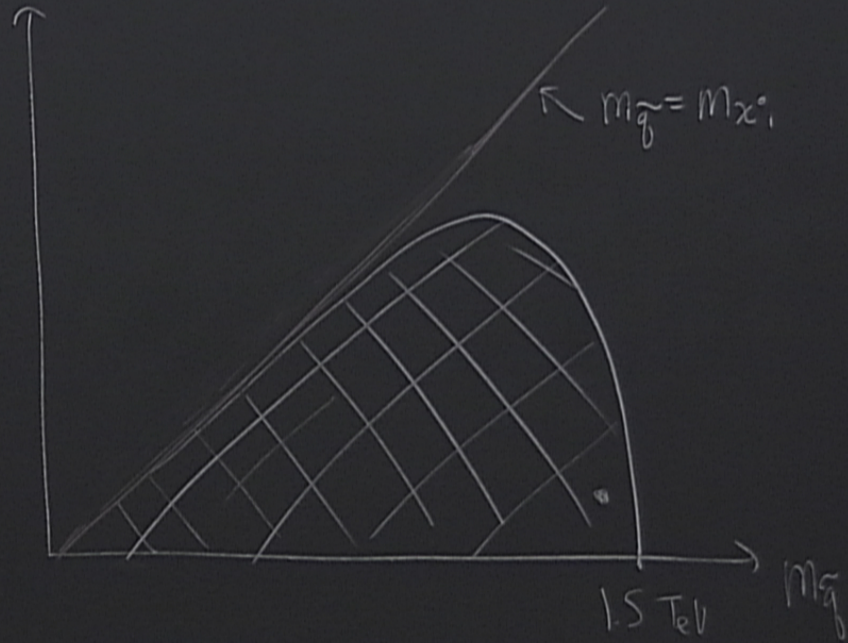
$$n_j + \cancel{\Sigma}_T$$

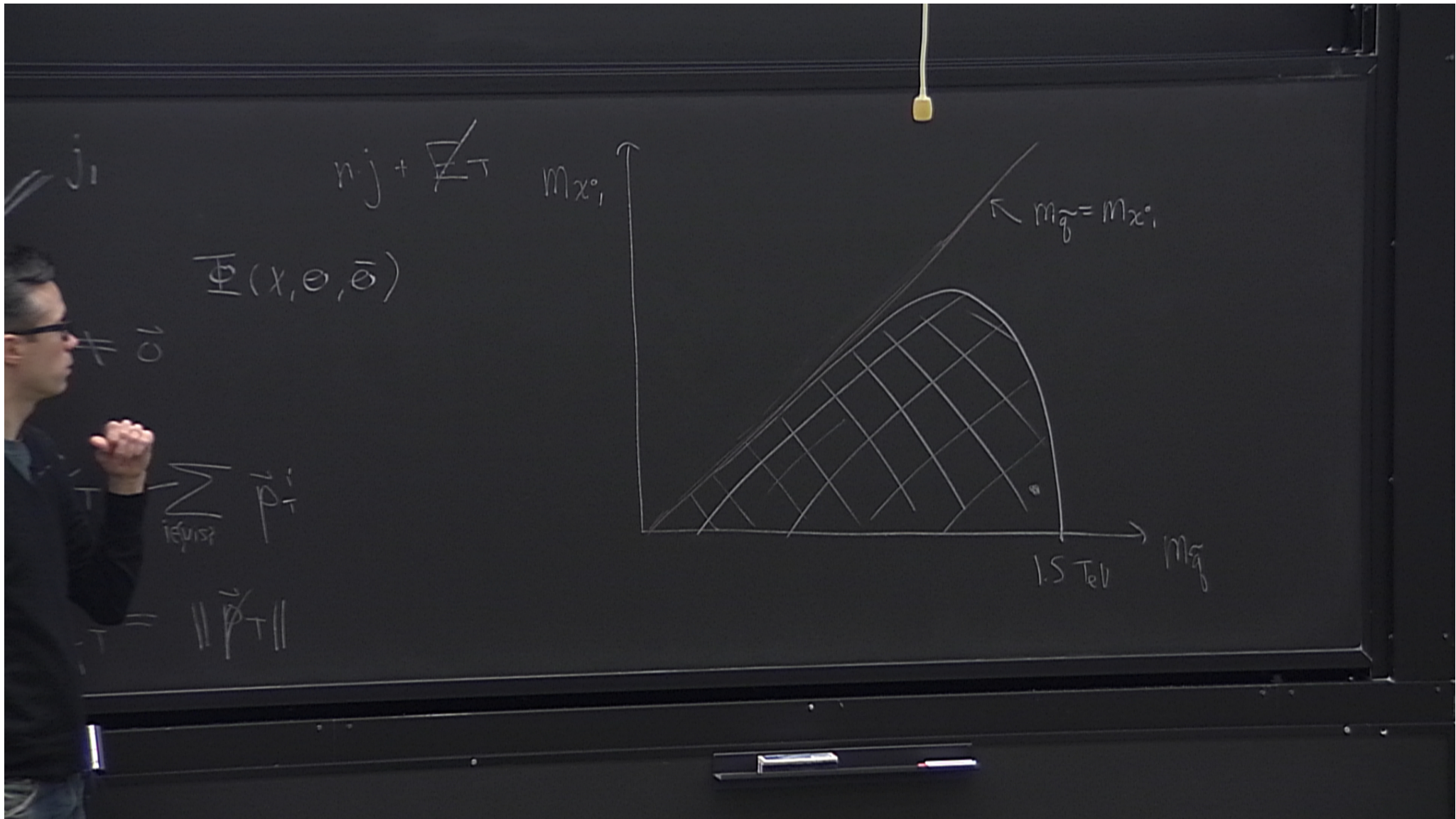
$m_{\chi^0_1}$

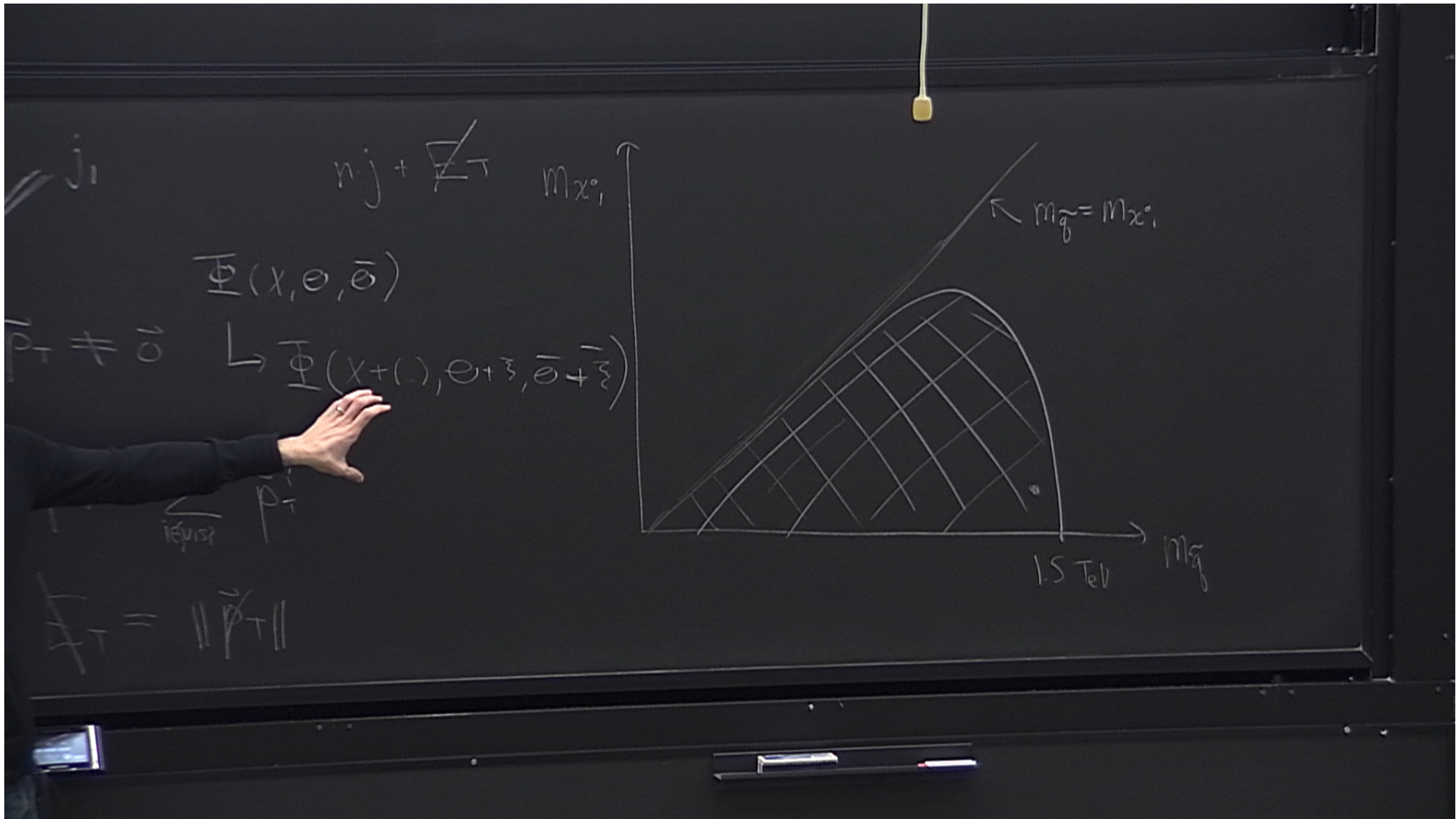
$$\vec{p}_T \neq \vec{0}$$

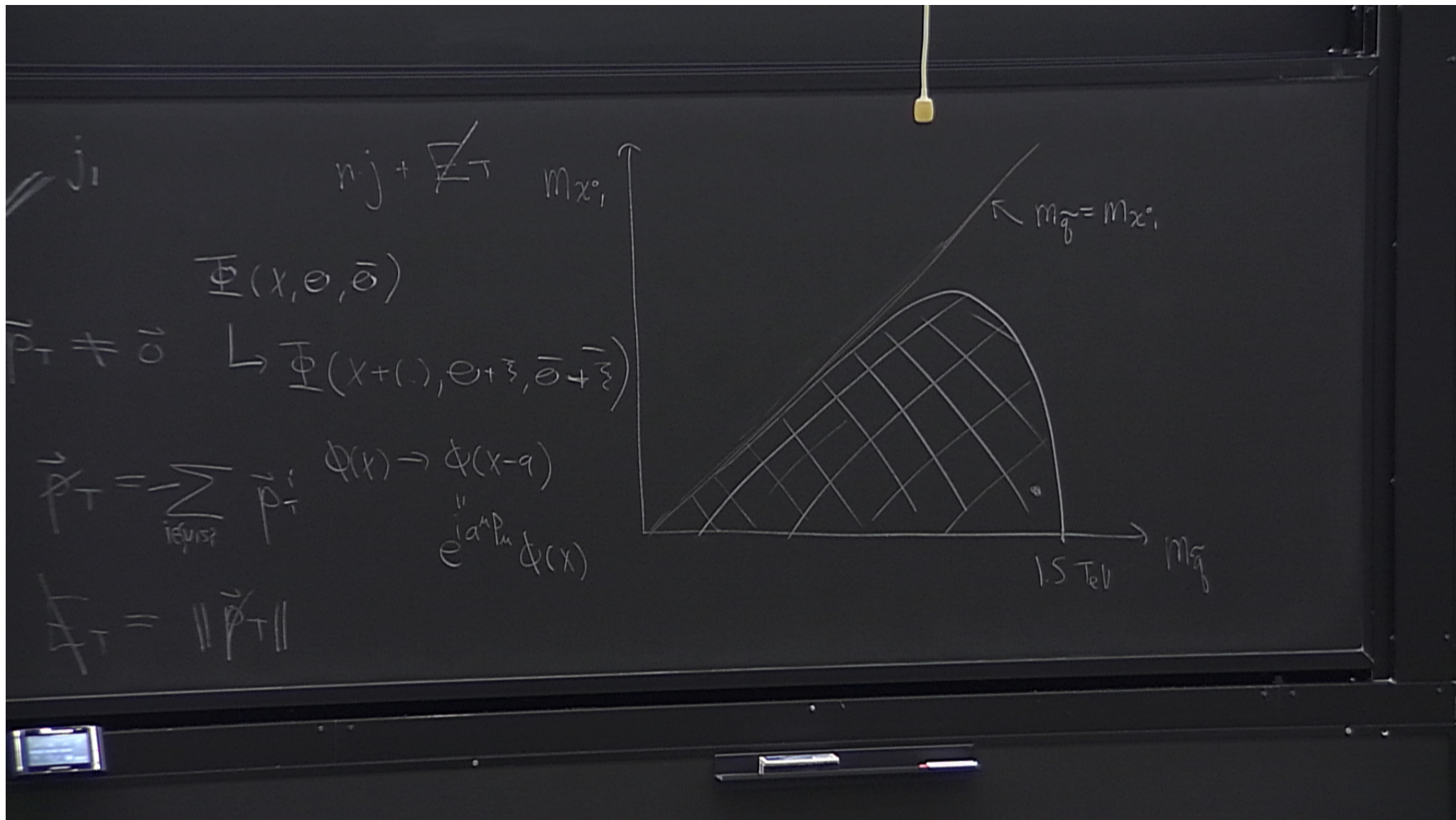
$$\vec{p}_T = -\sum_{i \in \text{vis}} \vec{p}_T^i$$

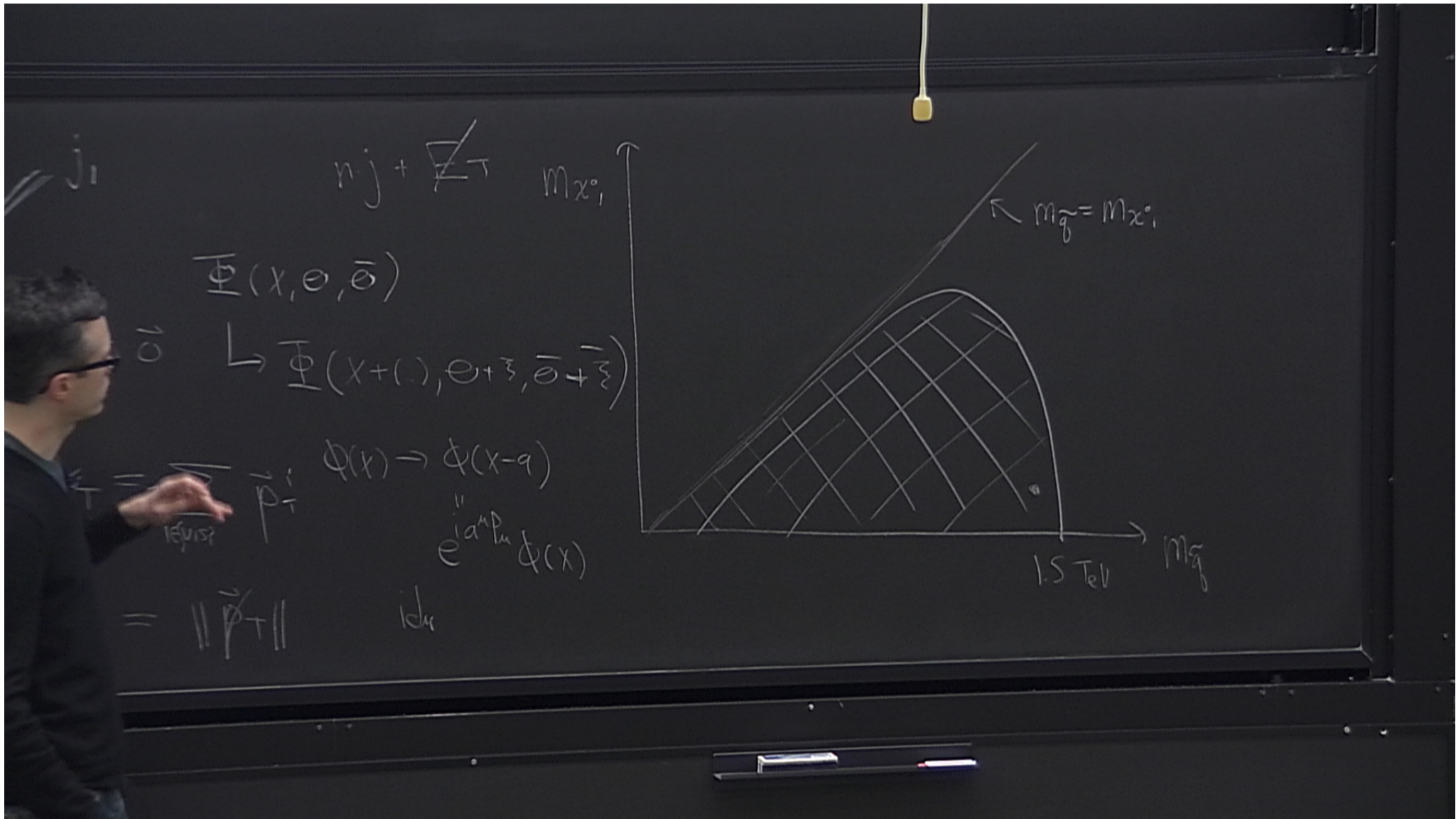
$$\cancel{E}_T = \|\vec{p}_T\|$$











Strong Dynamics

$$\mathcal{L} = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \sum_{\mathbf{I}} \bar{q}_{\mathbf{I}} (i\gamma^\mu D_\mu - m_{\mathbf{I}}) q_{\mathbf{I}}$$

Strong Dynamics

$$\mathcal{L} = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \sum_I \bar{q}_I (i\gamma^\mu D_\mu - m_I) q_I$$

$$m_u = 2.5 \text{ MeV}, \quad m_c = 1.25 \text{ GeV}, \quad m_t = 173 \text{ GeV}$$

$$m_d = 5.3 \text{ MeV}, \quad m_s = 110 \text{ MeV}, \quad m_b = 4.5 \text{ GeV}$$

$$\frac{dg}{dt} = -\frac{b}{(4\pi)^2} g^3, \quad t = \ln(\mu/\mu_0)$$

$$b = 11 - \frac{2}{3} N_f$$

" # flavours with $m < \mu$

$$\frac{dg}{dt} = -\frac{b}{(4\pi)^2} g^3, \quad t = \ln(\mu/\mu_0)$$

$$b = 11 - \frac{2}{3} N_f$$

" # flavours with $m < \mu$

$$g(\mu) \rightarrow 0 \quad \text{as } \mu \rightarrow \infty$$

$$\frac{dg}{dt} = -\frac{b}{(4\pi)^2} g^3, \quad t = \ln(\mu/\mu_0)$$

$$b = 11 - \frac{2}{3} N_f$$

" # flavours with $m < \mu$

$$g(\mu) \rightarrow 0 \quad \text{as } \mu \rightarrow \infty$$

$$\alpha_s(M_Z) = 0.118$$

" $\frac{g^2}{4\pi}$

$$\frac{dg}{dt} = -\frac{b}{(4\pi)^2} g^3, \quad t = \ln(\mu/\mu_0)$$

$$b = 11 - \frac{2}{3} N_f$$

" # flavours with $m < \mu$

$$g(\mu) \rightarrow 0 \text{ as } \mu \rightarrow \infty$$

$$\alpha_s(M_Z) \approx 0.118$$

$$\text{" } \frac{g^2}{4\pi}$$

$$\alpha_s^{-1}(\mu) = \alpha_s^{-1}(\mu_0) + \frac{b}{2\pi} \ln\left(\frac{\mu}{\mu_0}\right)$$

$$\frac{dg}{dt} = \frac{-b}{(4\pi)^2} g^3, \quad t = \ln(\mu/\mu_0)$$

$$b = 11 - \frac{2}{3} N_f$$

" # flavours with $m < \mu$

$$g(\mu) \rightarrow 0 \text{ as } \mu \rightarrow \infty$$

$$\alpha_s(M_Z) = 0.118$$

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

$$\alpha_s^{-1}(\mu) = \alpha_s^{-1}(m_Z) + \frac{b}{2\pi} \ln\left(\frac{\mu}{m_Z}\right)$$

$$\frac{dg}{dt} = -\frac{b}{(4\pi)^2} g^3, \quad t = \ln(\mu/\mu_0)$$

$$b = 11 - \frac{2}{3} N_f$$

" # flavours with $m < \mu$

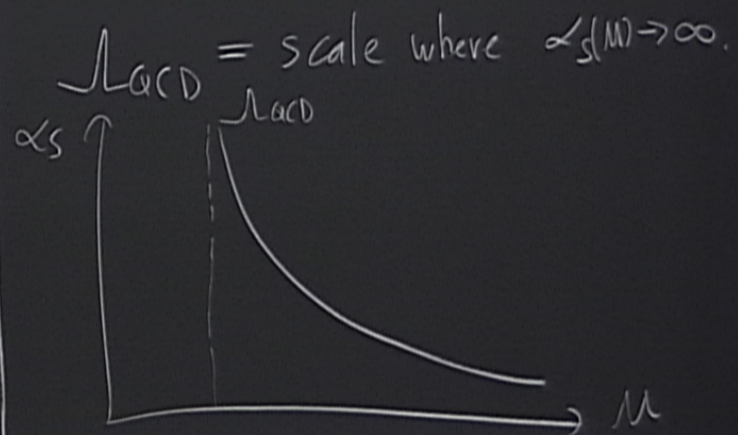
$$g(\mu) \rightarrow 0 \text{ as } \mu \rightarrow \infty$$

$$\alpha_s(M_Z) = 0.118$$

$$\text{" } \frac{g^2}{4\pi}$$

$$\alpha_s^{-1}(\mu) = \alpha_s^{-1}(m_Z) + \frac{b}{2\pi} \ln\left(\frac{\mu}{m_Z}\right)$$

$$\alpha_s(\mu) = \frac{2\pi}{b \ln(\mu/\Lambda_{\text{QCD}})}$$



$$\frac{dg}{dt} = -\frac{b}{(4\pi)^2} g^3, \quad t = \ln(\mu/\mu_0)$$

$$b = 11 - \frac{2}{3} N_f$$

" # flavours with $m < \mu$

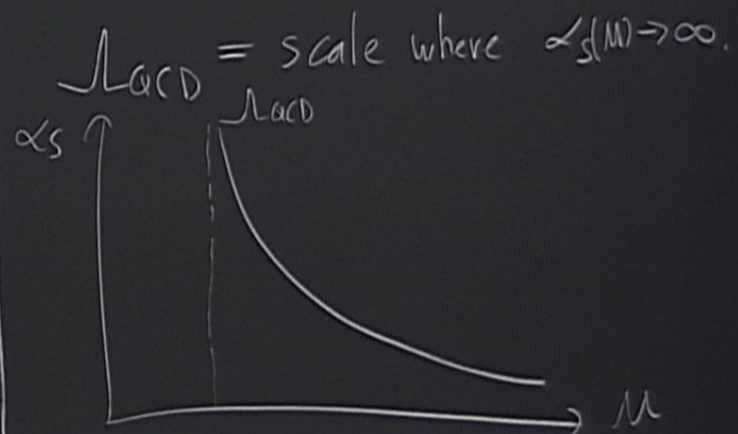
$$g(\mu) \rightarrow 0 \text{ as } \mu \rightarrow \infty$$

$$\alpha_s(\mu_z) = 0.118$$

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

$$\alpha_s^{-1}(\mu) = \alpha_s^{-1}(\mu_z) + \frac{b}{2\pi} \ln\left(\frac{\mu}{\mu_z}\right)$$

$$\alpha_s(\mu) = \frac{2\pi}{b \ln(\mu/\Lambda_{QCD})}$$



$$\frac{dg}{dt} = -\frac{b}{(4\pi)^2} g^3, \quad t = \ln(\mu/\mu_0)$$

$$b = 11 - \frac{2}{3} N_f$$

" # flavours with $m < \mu$

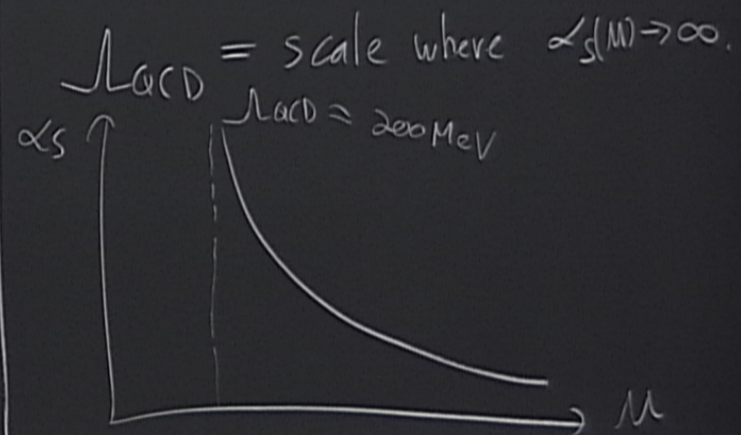
$$g(\mu) \rightarrow 0 \text{ as } \mu \rightarrow \infty$$

$$\alpha_s(\mu_z) = 0.118$$

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

$$\alpha_s^{-1}(\mu) = \alpha_s^{-1}(\mu_z) + \frac{b}{2\pi} \ln\left(\frac{\mu}{\mu_z}\right)$$

$$\alpha_s(\mu) = \frac{2\pi}{b \ln(\mu/\Lambda_{QCD})}$$



$$\frac{dg}{dt} = -\frac{b}{(4\pi)^2} g^3, \quad t = \ln(\mu/\mu_0)$$

$$b = 11 - \frac{2}{3} N_f$$

" # flavours with $m < \mu$

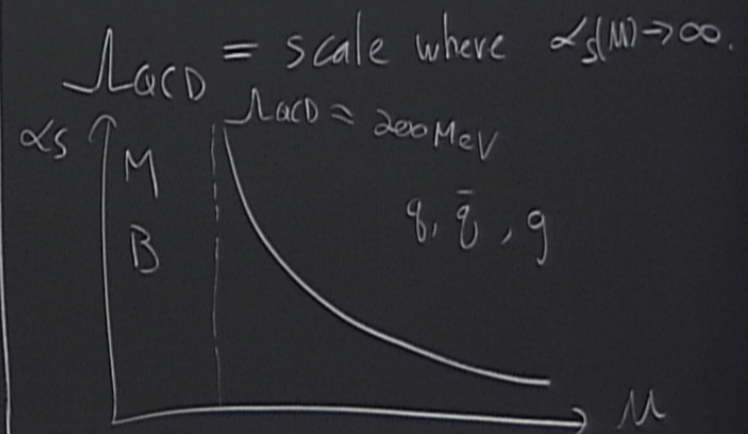
$$g(\mu) \rightarrow 0 \text{ as } \mu \rightarrow \infty$$

$$g^2(\mu_2) = 0.118$$

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

$$\alpha_s^{-1}(\mu) = \alpha_s^{-1}(\mu_2) + \frac{b}{2\pi} \ln\left(\frac{\mu}{\mu_2}\right)$$

$$\alpha_s(\mu) = \frac{2\pi}{b \ln(\mu/\Lambda_{QCD})}$$



$$\frac{dg}{dt} = -\frac{b}{(4\pi)^2} g^3, \quad t = \ln(\mu/\mu_0)$$

$$b = 11 - \frac{2}{3} N_f$$

" # flavours with $m < \mu$

$$g(\mu) \rightarrow 0 \text{ as } \mu \rightarrow \infty$$

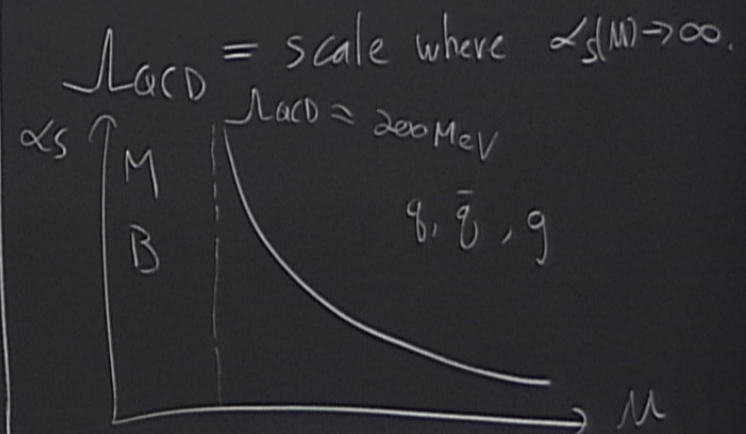
$$\alpha_s(M_Z) = 0.118$$

" $\frac{g^2}{4\pi}$

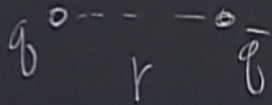
$$\begin{cases} M \sim \bar{q}_i q_j \delta_{ij} \\ B \sim q_i q_j q_k \epsilon_{ijk} \end{cases}$$

$$\alpha_s^{-1}(\mu) = \alpha_s^{-1}(m_Z) + \frac{b}{2\pi} \ln\left(\frac{\mu}{m_Z}\right)$$

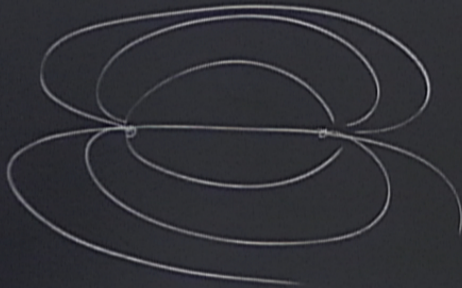
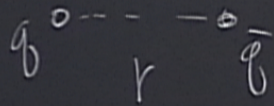
$$\alpha_s(\mu) = \frac{2\pi}{b \ln(\mu/\Lambda_{\text{QCD}})}$$

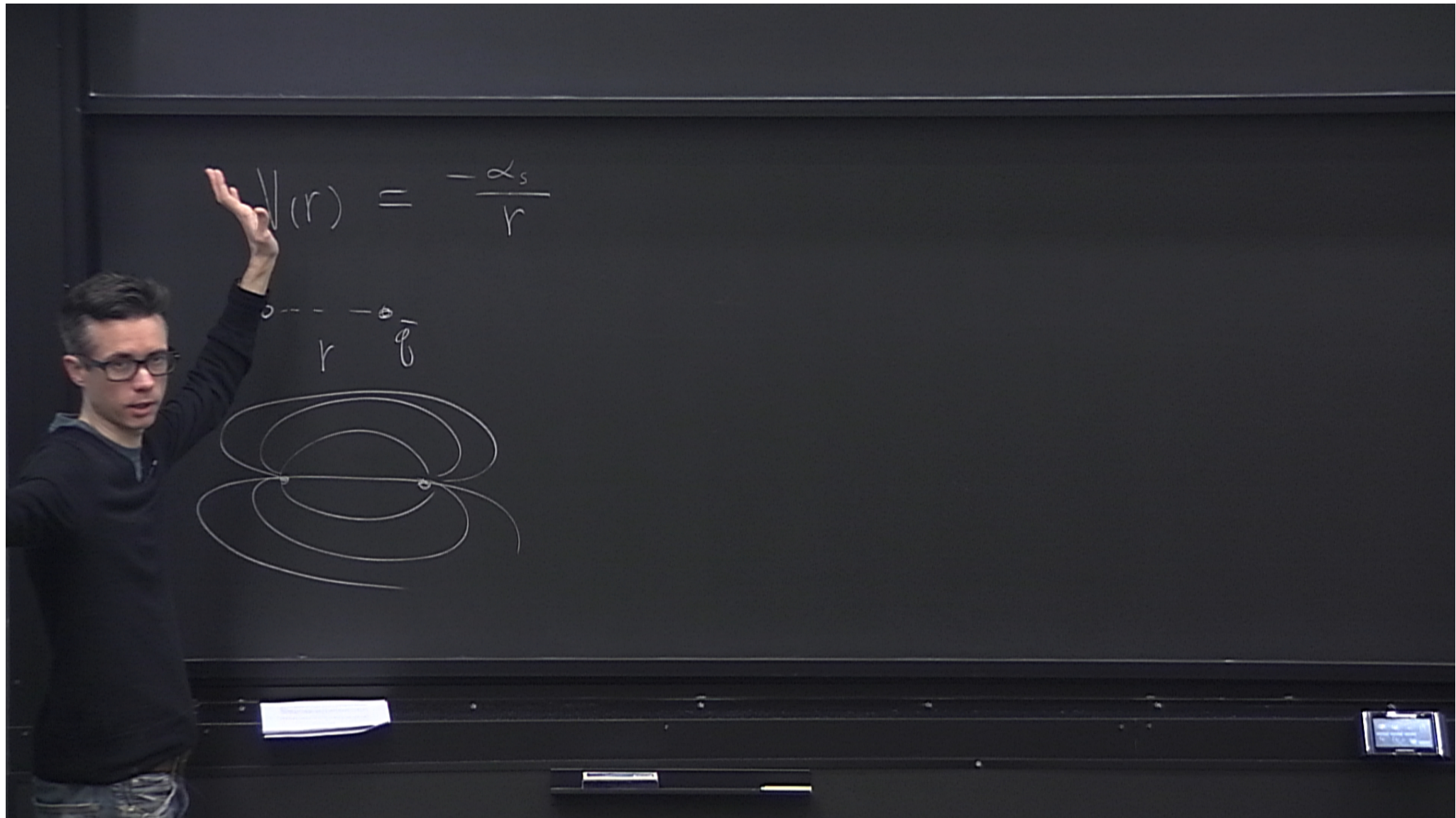


$$V(r) = -\frac{\alpha_s}{r}$$

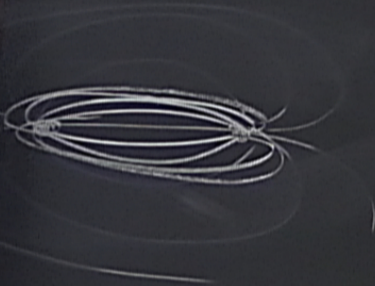
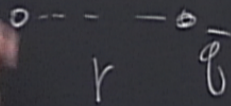


$$V(r) = -\frac{\alpha_s}{r}$$



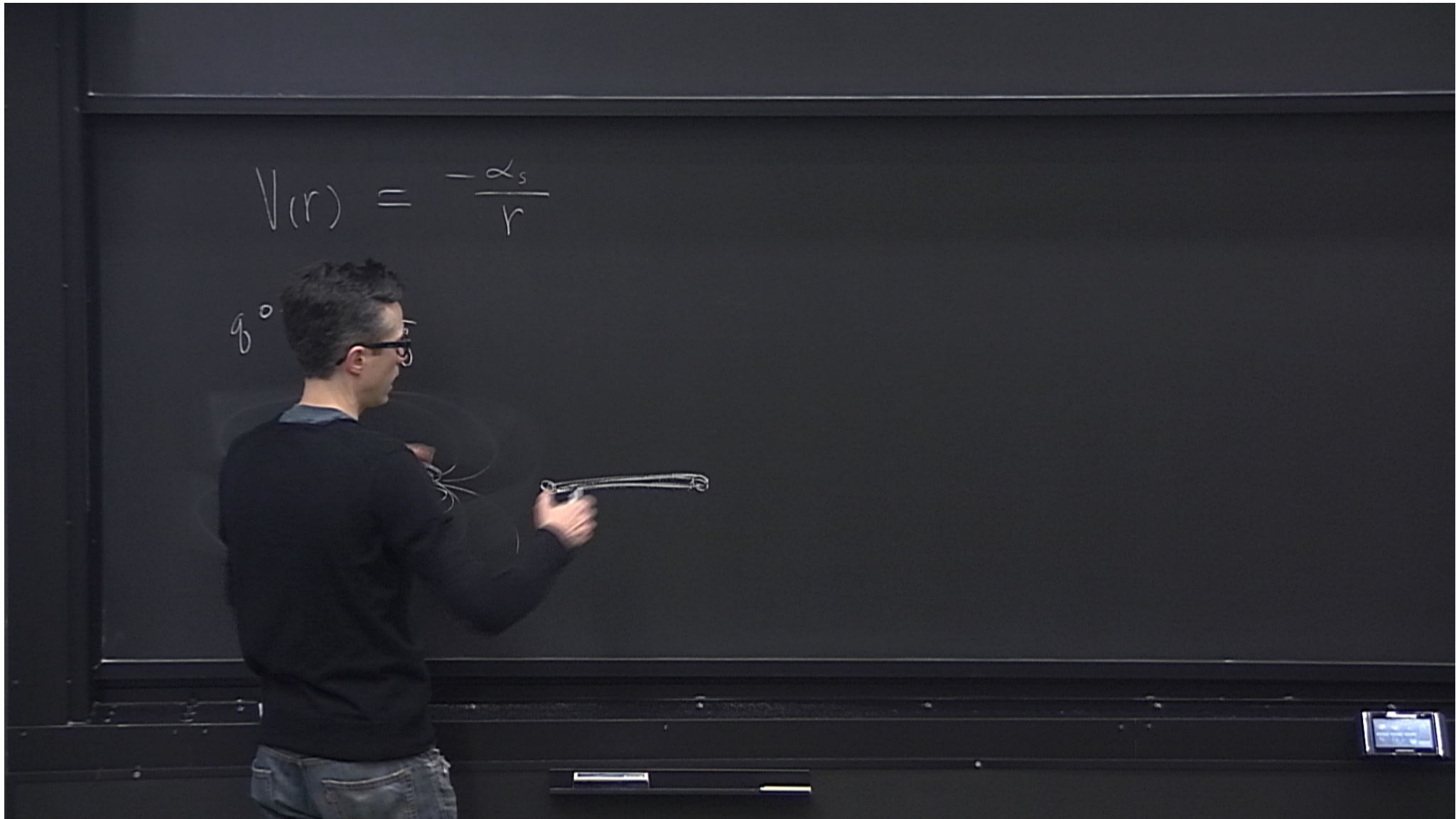


$$V(r) = -\frac{\alpha_s}{r}$$



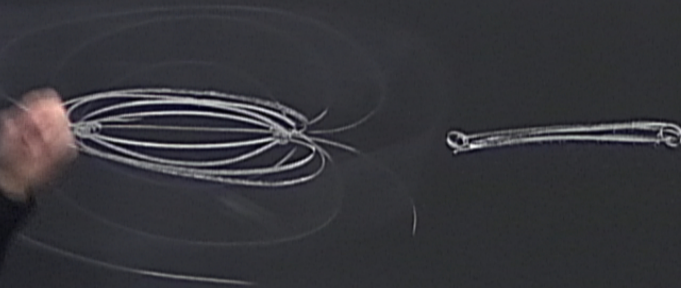
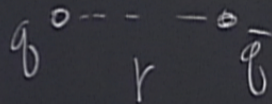
$$V(r) = -\frac{\alpha_s}{r}$$

g^0



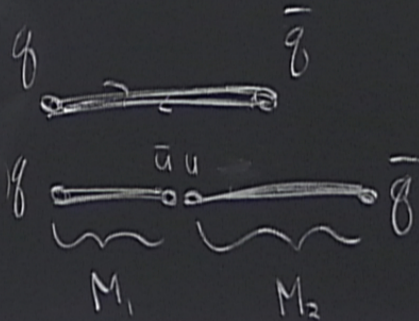
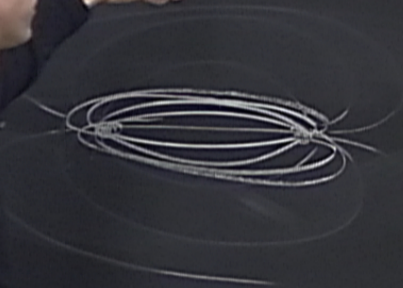
$$V(r) = -\frac{\alpha_s}{r} + \frac{1}{2}kr$$

$\hookrightarrow \frac{1}{2} \sim \Lambda_{QCD}^2$



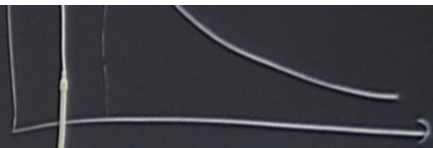
$$V(r) = -\frac{\alpha_s}{r} + \frac{1}{2}kr$$

$\hookrightarrow \frac{1}{2} \sim \Lambda_{QCD}^2$



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

$$B \sim q_i q_j q_k \epsilon^{ijk}$$



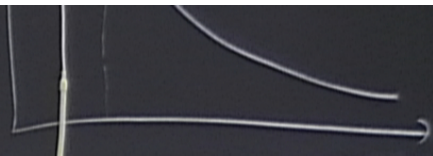
QCD with only u, d .

$$\mathcal{L} = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \bar{Q}_L i \gamma^\mu D_\mu Q_L + \bar{Q}_R i \gamma^\mu D_\mu Q_R - \bar{Q}_L M Q_R - \bar{Q}_R M Q_L$$

$$Q_{L,R} = \begin{pmatrix} u_{L,R} \\ d_{L,R} \end{pmatrix}$$

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

$$B \sim q_i q_j q_k \epsilon^{ijk}$$



QCD with only u, d .

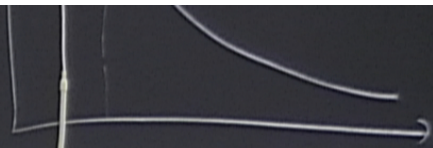
$$\mathcal{L} = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \bar{Q}_L i \gamma^\mu D_\mu Q_L + \bar{Q}_R i \gamma^\mu D_\mu Q_R - \bar{Q}_L M Q_R - \bar{Q}_R M Q_L$$

$\begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix}$

$$Q_{L,R} = \begin{pmatrix} u_{L,R} \\ d_{L,R} \end{pmatrix}$$

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

$$B \sim q_i q_j q_k \epsilon^{ijk}$$



QCD with only u, d .

$$\mathcal{L} = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \bar{Q}_L i \gamma^\mu D_\mu Q_L + \bar{Q}_R i \gamma^\mu D_\mu Q_R$$

$$\left[\begin{array}{c} -\bar{Q}_L M Q_R - \bar{Q}_R M Q_L \\ \text{"} \\ \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix} \end{array} \right]$$

$$Q_{L,R} = \begin{pmatrix} u_{L,R} \\ d_{L,R} \end{pmatrix}$$

QCD with only u, d .

$$\mathcal{L} = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \bar{Q}_L i \gamma^\mu D_\mu Q_L + \bar{Q}_R i \gamma^\mu D_\mu Q_R \left[\begin{array}{c} -\bar{Q}_L M Q_R - \bar{Q}_R M Q_L \\ \text{"} \\ \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix} \end{array} \right]$$

$$Q_{L,R} = \begin{pmatrix} u_{L,R} \\ d_{L,R} \end{pmatrix}$$

$$\begin{cases} Q_L \rightarrow e^{i\alpha_V} e^{i\alpha_A} L Q_L \\ Q_R \rightarrow e^{i\alpha_V} e^{-i\alpha_A} R Q_R \end{cases}, L, R = \text{SU}(2) \text{ matrices}$$

QCD with only u, d .

$$\mathcal{L} = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \bar{Q}_L i \gamma^\mu D_\mu Q_L + \bar{Q}_R i \gamma^\mu D_\mu Q_R \left[\begin{array}{c} -\bar{Q}_L M Q_R - \bar{Q}_R M Q_L \\ \text{"} \\ \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix} \end{array} \right]$$

$$Q_{L,R} = \begin{pmatrix} u_{L,R} \\ d_{L,R} \end{pmatrix}$$

$$\begin{cases} Q_L \rightarrow e^{i\alpha_V} e^{i\alpha_A} L Q_L \\ Q_R \rightarrow e^{i\alpha_V} e^{-i\alpha_A} R Q_R \end{cases}, L, R = \text{SU}(2) \text{ matrices}$$

$$\text{SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1)_V \times \text{U}(1)_A$$

QCD with only u, d .

$$\mathcal{L} = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \bar{Q}_L i \gamma^\mu D_\mu Q_L + \bar{Q}_R i \gamma^\mu D_\mu Q_R \left[\begin{array}{c} -\bar{Q}_L M Q_R - \bar{Q}_R M Q_L \\ \text{"} \\ \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix} \end{array} \right]$$

$$Q_{L,R} = \begin{pmatrix} u_{L,R} \\ d_{L,R} \end{pmatrix}$$

$$\begin{cases} Q_L \rightarrow e^{i\alpha_V} e^{i\alpha_A} L Q_L \\ Q_R \rightarrow e^{i\alpha_V} e^{-i\alpha_A} R Q_R \end{cases}, L, R = \text{SU}(2) \text{ matrices}$$

$$\text{SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1)_V \times \text{U}(1)_A$$

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

$$B \sim q_i q_j q_k \in ij k$$



QCD with only u, d .

$$\mathcal{L} = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \bar{Q}_L i \gamma^\mu D_\mu Q_L + \bar{Q}_R i \gamma^\mu D_\mu Q_R \left[\begin{array}{c} -\bar{Q}_L M Q_R - \bar{Q}_R M Q_L \\ \text{"} \\ \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix} \end{array} \right]$$

$$Q_{L,R} = \begin{pmatrix} u_{L,R} \\ d_{L,R} \end{pmatrix}$$

$$\begin{cases} Q_L \rightarrow e^{i\alpha_V} e^{i\alpha_A} L Q_L \\ Q_R \rightarrow e^{i\alpha_V} e^{-i\alpha_A} R Q_R \end{cases}, L, R = SU(2) \text{ matrices}$$

$$\underbrace{SU(2)_L \times SU(2)_R}_{\text{chiral}} \times U(1)_V \times U(1)_A$$

QCD with only u, d .

$$\mathcal{L} = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \bar{Q}_L i \gamma^\mu D_\mu Q_L + \bar{Q}_R i \gamma^\mu D_\mu Q_R \left[\begin{array}{c} -\bar{Q}_L M Q_R - \bar{Q}_R M Q_L \\ \text{"} \\ \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix} \end{array} \right]$$

$$Q_{L,R} = \begin{pmatrix} u_{L,R} \\ d_{L,R} \end{pmatrix}$$

$$\begin{cases} Q_L \rightarrow e^{i\alpha_V} e^{i\alpha_A} L Q_L \\ Q_R \rightarrow e^{i\alpha_V} e^{-i\alpha_A} R Q_R \end{cases}, L, R = \text{SU}(2) \text{ matrices}$$

$$G_{\text{flav}} = \underbrace{\text{SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1)_V}_{\text{SU}(4)} \times \text{U}(1)_A$$

$$\langle \bar{Q}_{R J} Q_L^I \rangle = \Lambda_{QCD}^3 \cdot \delta^I_J$$

$$\langle \bar{Q}_{Rj} Q_L^I \rangle = \Lambda_{QCD}^3 \cdot \delta^I_j$$

$$\Lambda_{QCD}^3 \mathbb{1} \rightarrow \Lambda_{QCD}^3 R^\dagger \mathbb{1} L = \Lambda_{QCD}^3 R^\dagger L \neq \Lambda_{QCD}^3 \mathbb{1}$$

$$\langle \bar{Q}_{Rj} Q_L^I \rangle = \Lambda_{QCD}^3 \cdot \delta^I_j$$

$$\Lambda_{QCD}^3 \mathbb{1} \rightarrow \Lambda_{QCD}^3 R^\dagger \mathbb{1} L = \Lambda_{QCD}^3 R^\dagger L \neq \Lambda_{QCD}^3 \mathbb{1}$$

$$SU(2)_V = SU(2)_L \times SU(2)_R$$

$$\hookrightarrow L = R$$

$$\langle \bar{Q}_{Rj} Q_L^I \rangle = \Lambda_{QCD}^3 \cdot \delta^I_j$$

$$\Lambda_{QCD}^3 \mathbb{1} \rightarrow \Lambda_{QCD}^3 R^\dagger \mathbb{1} \cdot L = \Lambda_{QCD}^3 R^\dagger L \neq \Lambda_{QCD}^3 \mathbb{1}$$

$$SU(2)_V = SU(2)_L \times SU(2)_R$$

$$\hookrightarrow L = R$$

$$\underbrace{SU(2)_L \times SU(2)_R \times U(1)_V}_{G_{\text{flav}}} \rightarrow \underbrace{SU(2)_V \times U(1)_V}_{H_{\text{flav}}}$$

3 broken generators $\sim G_{\text{flav}} / H_{\text{flav}}$

$$\underbrace{SU(2)_L \times SU(2)_R \times U(1)_V}_{G_{\text{flav}}} \longrightarrow \underbrace{SU(2)_V \times U(1)_V}_{H_{\text{flav}}}$$

1 3 broken generators $\sim G_{\text{flav}}/H_{\text{flav}}$

$\hookrightarrow$ 3 Nambu-Goldstone bosons (NGBs)

$$\Sigma(x) = \exp\left[i\pi^a(x)t^a/f\right], \quad t^a = \sigma^a/2$$

$$\Sigma(x) = \exp[i\pi^a(x)t^a/f] \quad , \quad t^a = \sigma^a/2$$

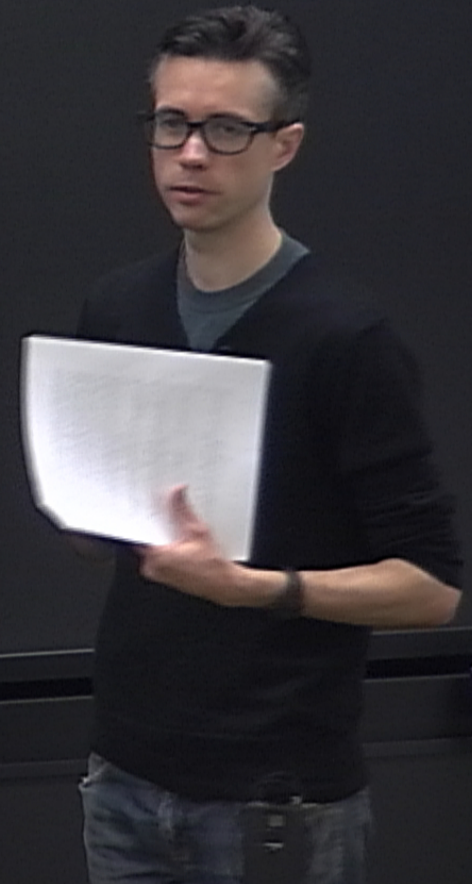
$$\Sigma(x) \rightarrow L\Sigma(x)R^\dagger$$

$$\Sigma(x) = \exp[i\pi^a(x)t^a/f] \quad , \quad t^a = \sigma^a/2$$

$$\Sigma(x) \rightarrow L \Sigma(x) R^\dagger$$

$$L = e^{ic_A^a t^a} e^{ic_V^b t^b}$$

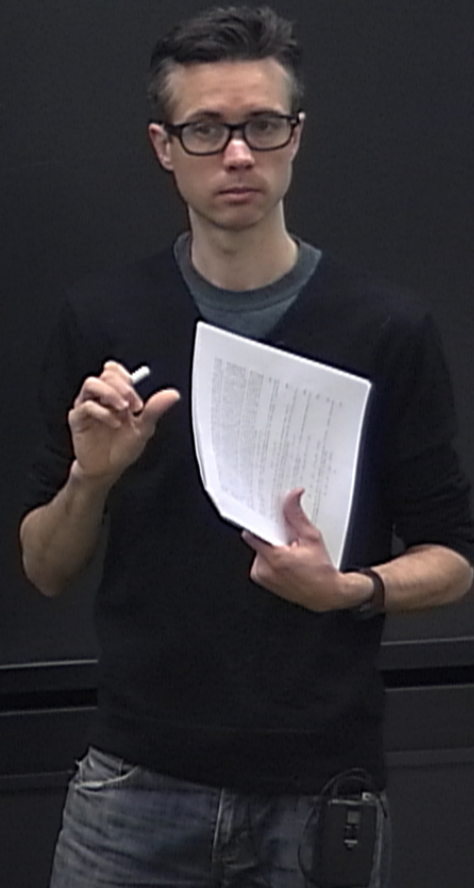
$$R = e^{-ic_A^a t^a} e^{ic_V^b t^b}$$



$$\Sigma(x) = \exp[i\pi^a(x)t^a/f] \quad , \quad t^a = \sigma^a/2$$

$$\Sigma(x) \rightarrow L \Sigma(x) R^\dagger$$

$$\begin{cases} L = e^{ic_A^a t^a} e^{ic_V^b t^b} \\ R = e^{-ic_A^a t^a} e^{ic_V^b t^b} \end{cases}$$



$$\Sigma(x) = \exp[i\pi^a(x)t^a/f] \quad , \quad t^a = \sigma^a/2$$

$$\Sigma(x) \rightarrow L \Sigma(x) R^\dagger$$

$$\begin{cases} L = e^{i c_A^a t^a} e^{i c_V^b t^b} \\ R = e^{\underbrace{-i c_A^a t^a}_{\text{broken}}} e^{\underbrace{i c_V^b t^b}_{V \text{ part}}} \end{cases}$$

$$\Sigma(x) = \exp[i\pi^a(x)t^a/f] \quad , \quad t^a = \sigma^a/2$$

$$\Sigma(x) \rightarrow L \Sigma(x) R^\dagger$$

$$\begin{cases} L = e^{ic_A^a t^a} e^{ic_v^b t^b} \\ R = e^{-ic_A^a t^a} e^{ic_v^b t^b} \end{cases}$$

broken
v part

$$SU(2)_V: C_A^a = 0$$

$$\Sigma \rightarrow V \Sigma V^\dagger$$

$$= \exp(2i\pi^a(Vt^aV^\dagger)/f)$$

$$\Sigma(x) = \exp\left[2i\pi^a(x)t^a/f\right], \quad t^a = \sigma^a/2$$

$$\Sigma(x) \rightarrow L \Sigma(x) R^\dagger$$

$$\begin{cases} L = e^{ic_A^a t^a} e^{ic_v^b t^b} \\ R = e^{-ic_A^a t^a} e^{ic_v^b t^b} \end{cases}$$

broken
v part

$$SU(2)_V: C_A^a = 0$$

$$\Sigma \rightarrow V \Sigma V^\dagger$$

$$= \exp\left[2i\pi^a(V t^a V^\dagger)/f\right]$$

$$V = 1 + i c_v^b t^b + \dots$$

$$\pi^a \rightarrow \pi'^a = \left(\delta^{ac} - f^{abc} c_v^b \right) \pi^c + \mathcal{O}(c_v^2)$$

$\pi(F)$

