

Title: PSI 2015/2016 More/Beyond Standard Model - Lecture 8

Date: Mar 02, 2016 09:00 AM

URL: <http://pirsa.org/16030037>

Abstract:

Chiral Supermultiplet :  $\Phi = (\phi, \psi, F)$   
Vector Supermultiplet :  $V = (\lambda, A_\mu, D)$



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 Vector Supermultiplet:  $V = (\lambda, A_m, D)$

non-Abelian  $(\lambda^a, A_m^a, D^a)$

$$S = \int d^4x \left[ \bar{\lambda}^a i \bar{\sigma} \cdot D \lambda^a - \frac{1}{4} G_{\mu\nu}^a G^{\mu\nu a} + \frac{1}{2} D^a D^a \right]$$

$$\begin{cases} G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g f^{abc} A_\mu^b A_\nu^c \\ D_\mu \lambda^a = \partial_\mu \lambda^a - g f^{abc} A_\mu^b \lambda^c \end{cases}$$



Chiral Supermultiplet:  $\Phi = (\phi, \Psi, F)$  ( $N=1, d=4$ )

Vector Supermultiplet:  $V = (\lambda, A_m, D)$

Non-Abelian:  $(\lambda^a, A_m^a, D^a)$

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$$\begin{cases} G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g f^{abc} A_\mu^b A_\nu^c \\ D_\mu \lambda^a = \partial_\mu \lambda^a - g f^{abc} A_\mu^b \lambda^c \end{cases}$$



$$\Phi_i \rightarrow [e^{-i\alpha t_r^a}]_{ij} \Phi_j$$

$$[D_\mu \Phi]_i = \partial_\mu \Phi_i + ig t_{ij}^a G_\mu^a \Phi_j$$

$$[D_\mu \Psi]_i =$$

[derived from W]

$$S_{\text{matter}} = \int d^4x \left[ \bar{\Psi} i \not{\partial} \Psi + |\mathcal{D}\Phi|^2 + \frac{1}{2} F_i^a F_i^a + V_{\text{int}}(\dots) \right]$$

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[derived from W]

$$S_{\text{matter}} = \int d^4x \left[ \bar{\Psi} i \not{D} \Psi + |\mathcal{D}\Phi|^2 + \frac{1}{2} F_i^a F_i^a + V_{\text{int}}(\dots) \right. \\ \left. - \sqrt{2} g (\Phi^\dagger t^a \Psi) \lambda^a + \text{h.c.} - g (\Phi^\dagger t^a \Phi) D^a \right]$$

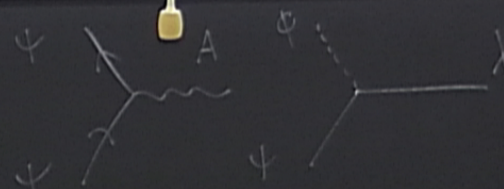


$$\Phi_i \rightarrow [e^{-i\alpha t_r^a}]_{ij} \Phi_j$$

$$[D_\mu \Phi]_i = \partial_\mu \Phi_i + ig t_{ij}^a G_\mu^a \Phi_j$$

$$[D_\mu \Psi]_i =$$

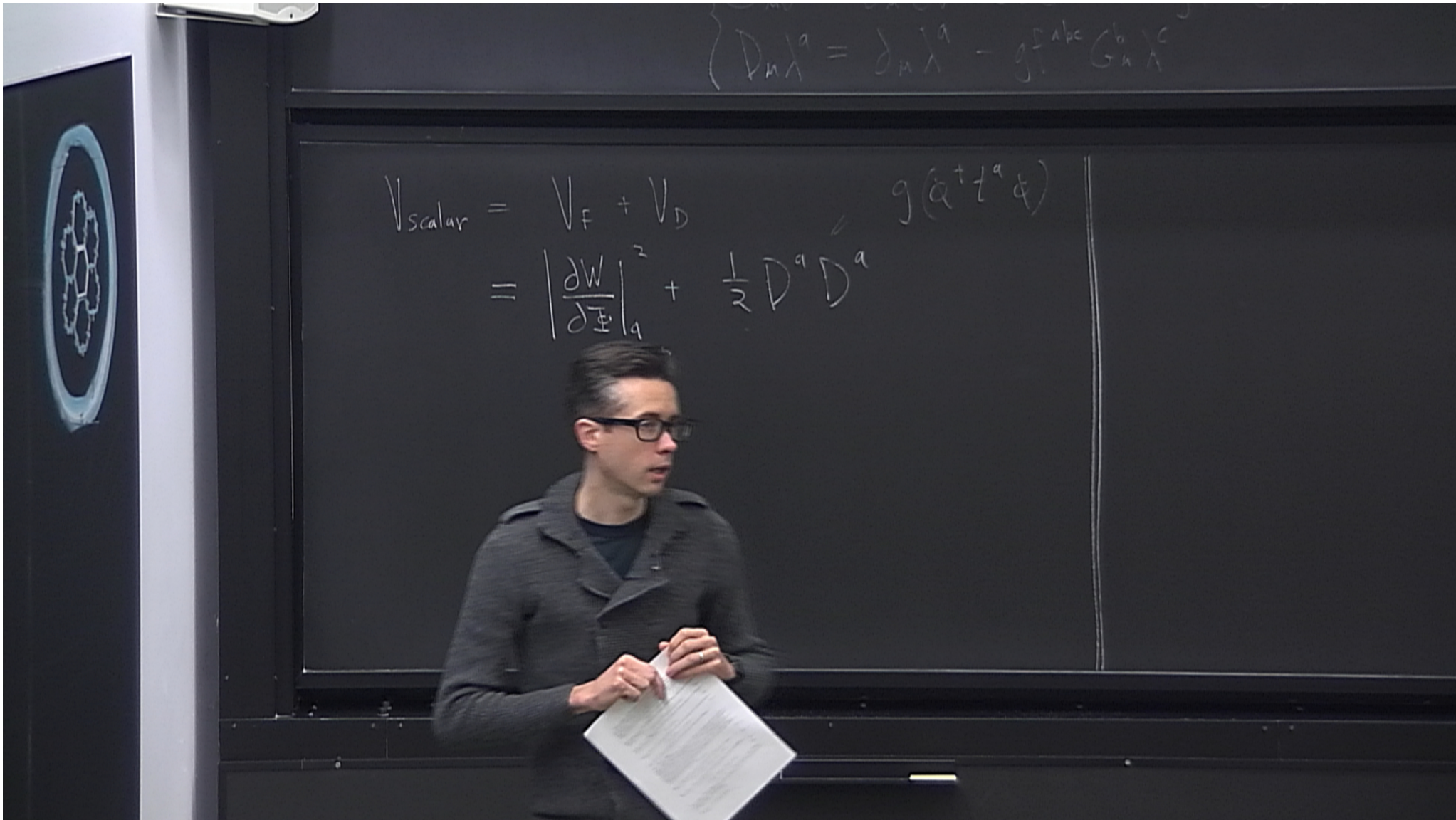
$\downarrow$   
Q



[derived from  $W$

$$\mathcal{L}_{\text{matter}} = \int d^4x \left[ \bar{\Psi} i \not{\partial} D \Psi + |\mathcal{D}\Phi|^2 + \frac{1}{2} F_i^a F_i^a + V_{\text{int}}(\dots) \right. \\ \left. - \sqrt{2} g (\Phi^\dagger t^a \Psi) \lambda^a + \text{h.c.} - g (\Phi^\dagger t^a \Phi) D^a \right] \rightarrow F^a \frac{\partial W}{\partial \Phi^a} + \text{h.c.}$$







$$D_\mu \lambda^a = \partial_\mu \lambda^a - g f^{abc} A_\mu^b \lambda^c$$

$$V_{\text{scalar}} = V_F + V_D$$

$$= \left| \frac{\partial W}{\partial \Phi} \right|^2 + \frac{1}{2} D^a D^a$$

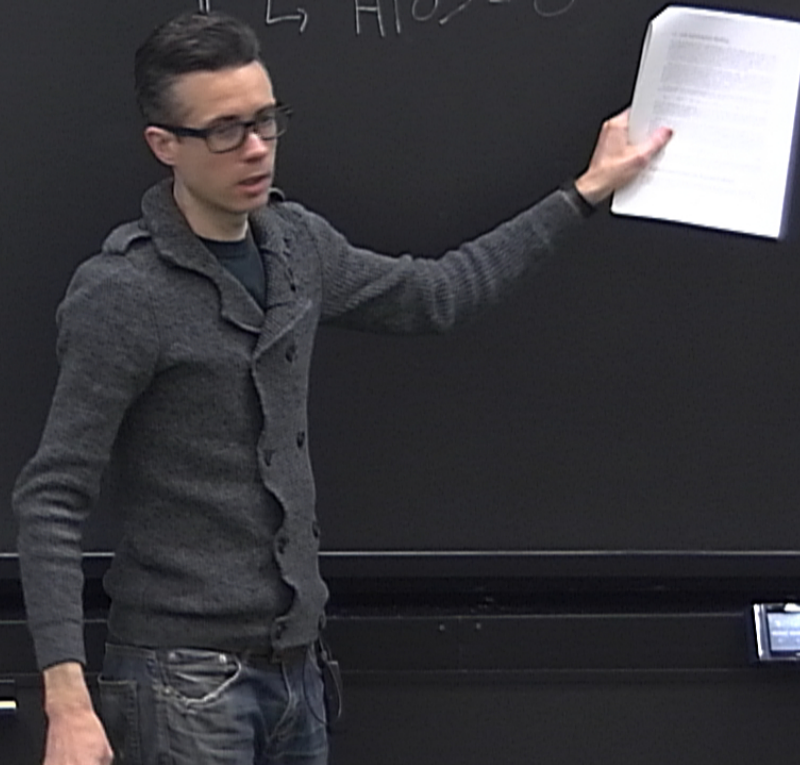
$\equiv F^{\dagger}$

$$g(\tilde{q}^{\dagger} t^a \tilde{q})$$

$$Q|0\rangle = 0$$

$$\hookrightarrow H|0\rangle = 0$$

$$e^{-i(\tilde{3}Q + \tilde{3}\bar{Q})} |0\rangle$$





$$\begin{cases} G_m = \partial_m G_\nu - \partial_\nu G_m + g f^{abc} G_\mu G_\nu \\ D_m \lambda^a = \partial_m \lambda^a - g f^{abc} G_m^b \lambda^c \end{cases}$$

$$-\sqrt{2} g (\psi^\dagger t^a \psi) \lambda^a$$

$$\begin{aligned} V_F + V_D \\ = \left| \frac{\partial W}{\partial \Phi} \right|_a^2 + \frac{1}{2} D^a D^a \\ = F^\dagger \end{aligned} \quad g(\psi^\dagger t^a \psi)$$

$$\begin{aligned} Q_\alpha |0\rangle &= 0 \\ \hookrightarrow H|0\rangle &= 0 \end{aligned}$$

$$e^{-i(\frac{3}{2}Q + \frac{3}{2}\bar{Q})} |0\rangle = |0\rangle$$



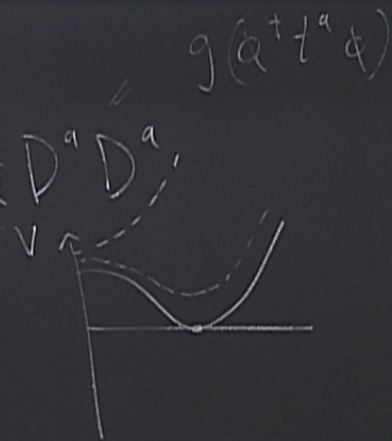
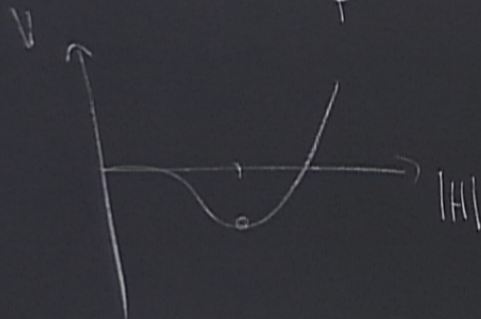
$$\begin{cases} G_{\mu\nu} = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g f^{abc} G_\mu^b G_\nu^c \\ D_\mu \lambda^a = \partial_\mu \lambda^a - g f^{abc} G_\mu^b \lambda^c \end{cases}$$

$-\sqrt{2}g$

$$V_{\text{scalar}} = V_F + V_D$$

$$= \left| \frac{\partial W}{\partial \Phi} \right|_a^2 + \frac{1}{2} D^a D^a$$

$= F^\dagger$



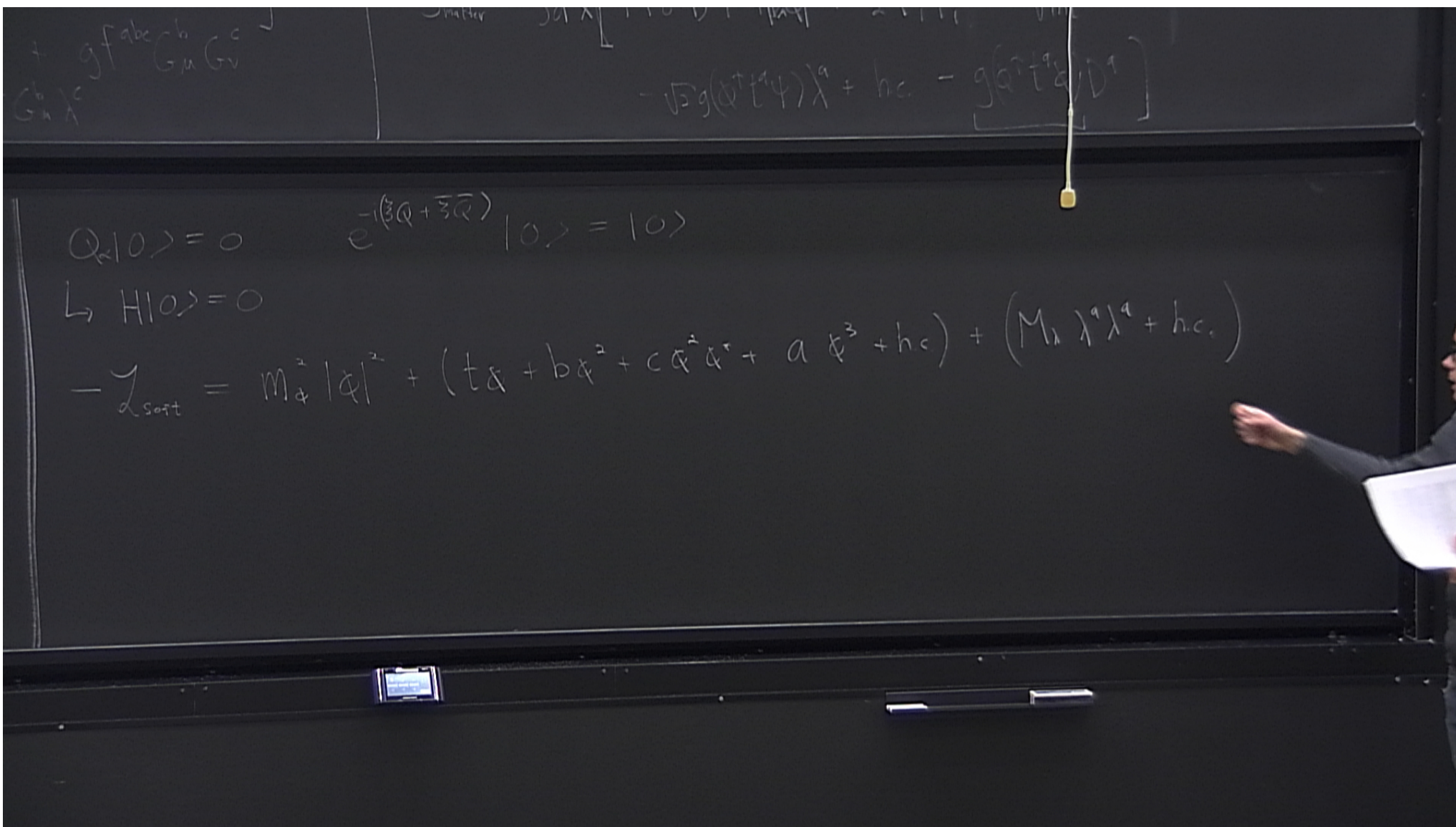
$$Q_\alpha |0\rangle = 0$$

$$\hookrightarrow H|0\rangle = 0$$

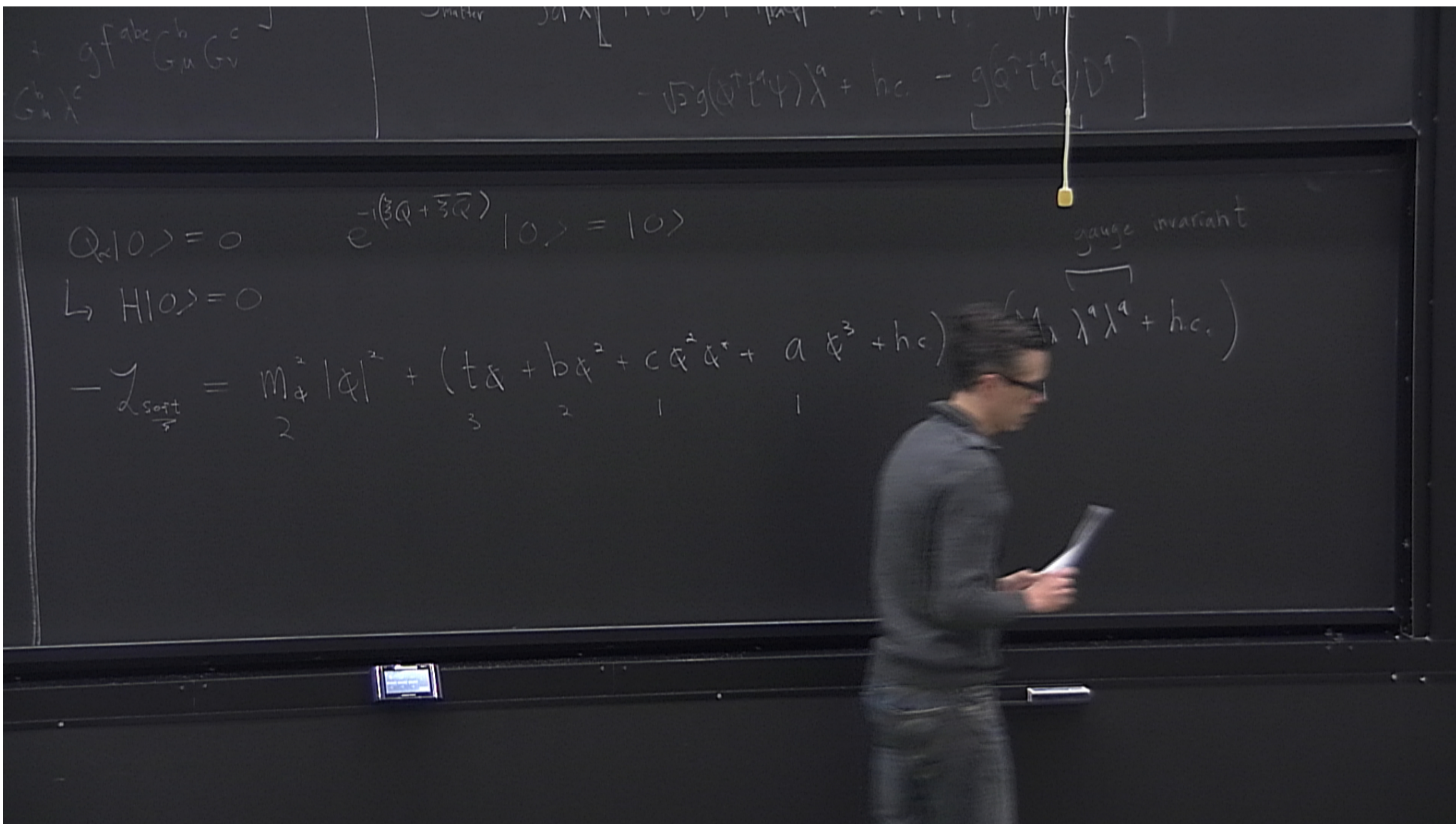
$$e^{-i(\frac{2}{3}Q + \frac{2}{3}\bar{Q})} |0\rangle = |0\rangle$$

$$-\mathcal{L}_{\text{soft}} = m_\phi^2 |\phi|^2 +$$









$$\begin{aligned}
 & + g f^{abc} G_{\mu}^b G_{\nu}^c \\
 & - \sqrt{2} g (\bar{\psi} \gamma^{\mu} T^a \psi) \lambda^a + \text{h.c.} - g (\bar{\psi} \gamma^{\mu} T^a \psi) D^{\mu} \lambda^a
 \end{aligned}$$

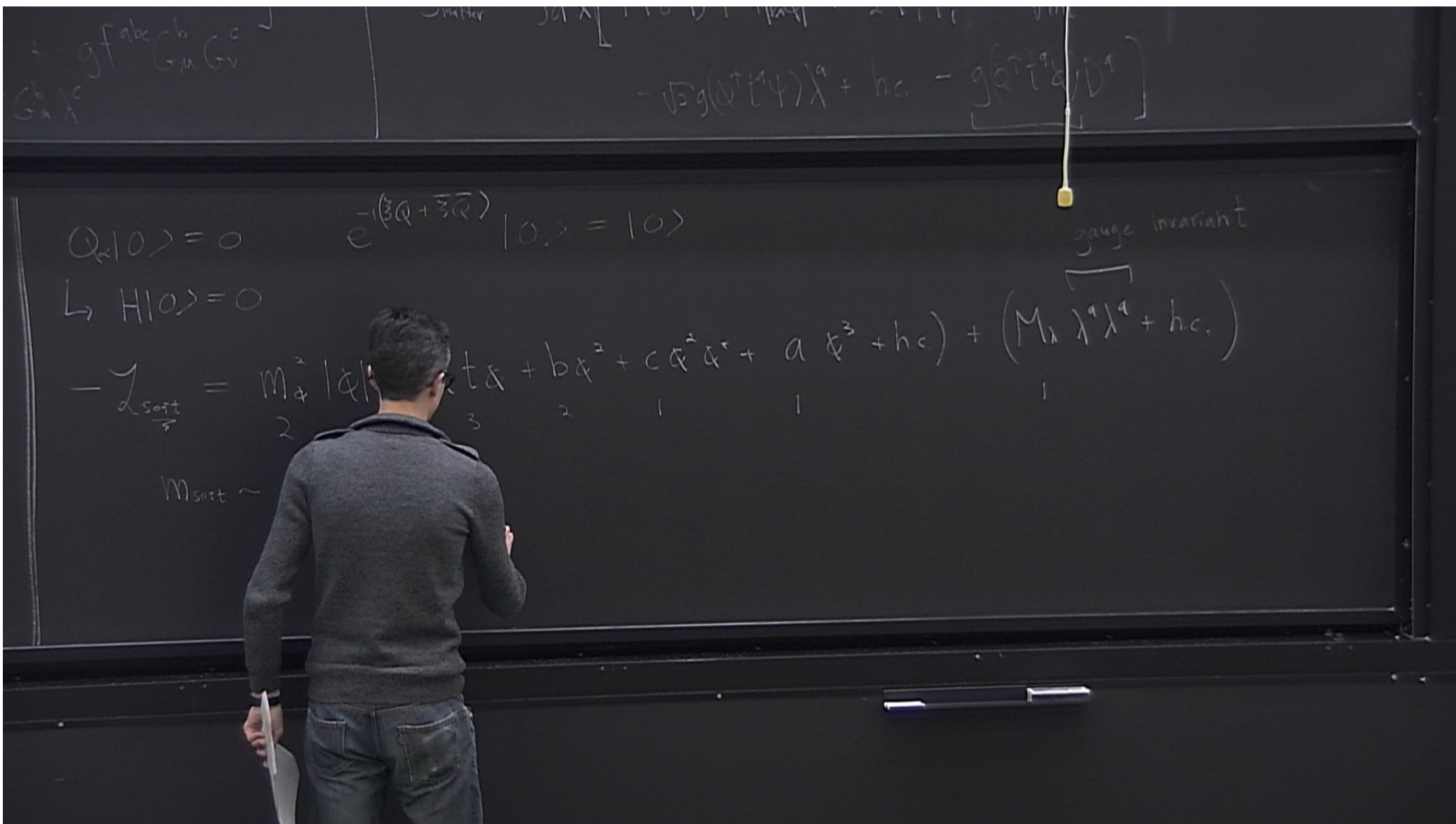
$$\begin{aligned}
 Q_{\mu} |0\rangle &= 0 & e^{-i(\frac{1}{2}Q + \frac{1}{2}\bar{Q})} |0\rangle &= |0\rangle \\
 \hookrightarrow H |0\rangle &= 0
 \end{aligned}$$

$$-\mathcal{L}_{\text{soft}} = \underbrace{\frac{m_{\phi}^2}{2} |\phi|^2}_{\substack{3 \\ 2}} + \underbrace{(t\phi + b\phi^2 + c\phi^2\phi^{\dagger} + a\phi^3 + \text{h.c.})}_{\substack{1 \\ 1}} + \underbrace{(M_{\lambda} \lambda^a \lambda^a + \text{h.c.})}_{\substack{1 \\ \text{gauge invariant}}}$$

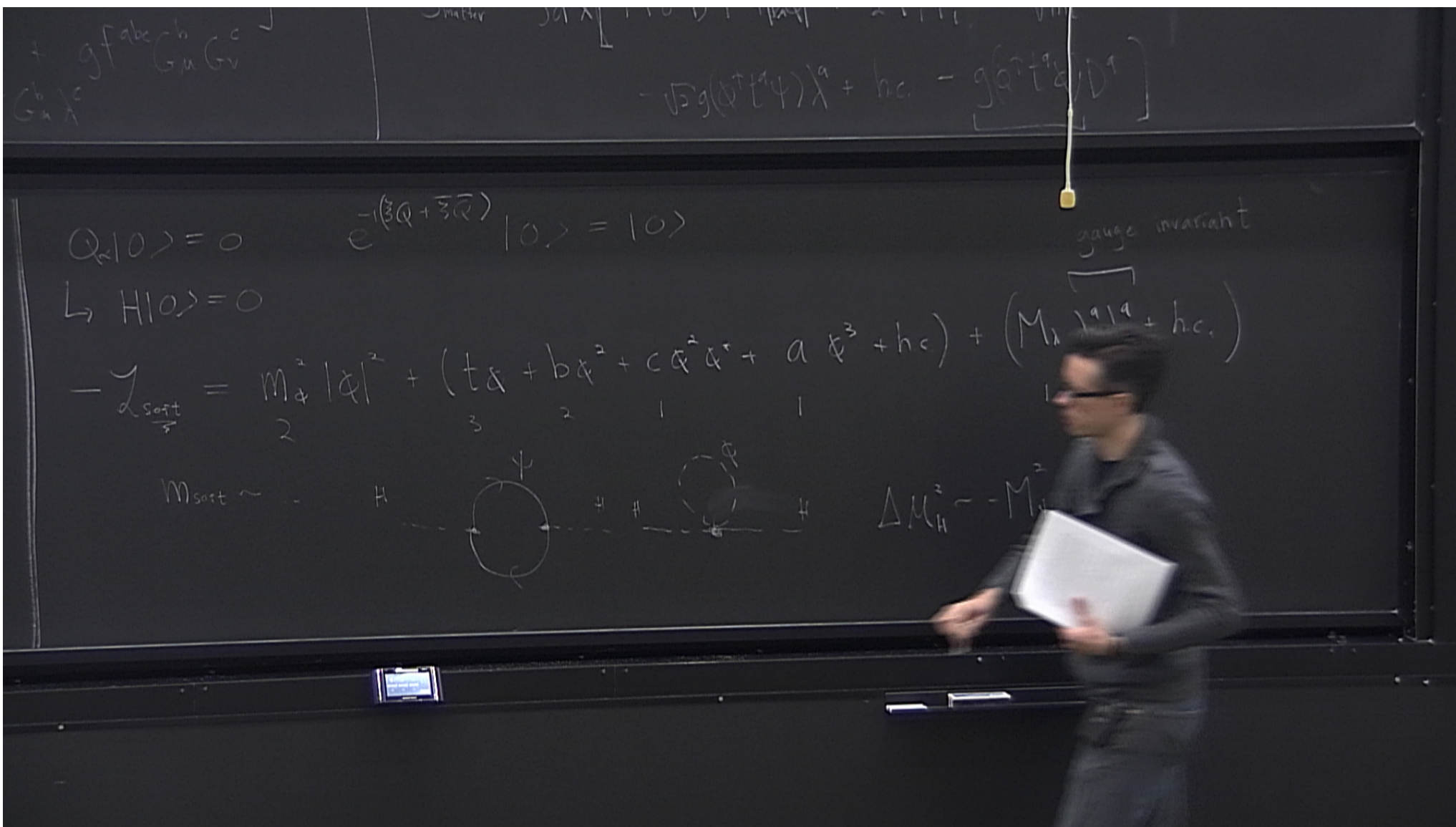


$$\begin{aligned}
 & + g f^{abc} G_{\mu\nu}^b G_{\nu\lambda}^c \\
 & G_{\mu\lambda}^a \\
 & - \sqrt{2} g (\bar{\psi} \gamma^\mu t^a \psi) \lambda^a + \text{h.c.} - g (\bar{\psi} \gamma^\mu t^a \psi) D^\mu \lambda^a \\
 & Q_\mu |0\rangle = 0 \quad e^{-i(\vec{3}Q + \vec{3}\bar{Q})} |0\rangle = |0\rangle \\
 & \hookrightarrow H|0\rangle = 0 \\
 & -\mathcal{L}_{\text{soft}} = \underbrace{m_\phi^2}_{2} |\phi|^2 + \underbrace{(t\phi + b\phi^2 + c\phi^2\phi^\dagger + a\phi^3 + \text{h.c.})}_{3 \quad 2 \quad 1 \quad 1} + \underbrace{(M_\lambda \lambda^a \lambda^a + \text{h.c.})}_{1} \quad \text{gauge invariant} \\
 & m_{\text{soft}} \sim \dots
 \end{aligned}$$











$$+ g f^{abc} G_\mu^b G_\nu^c$$

$$- \sqrt{2} g (\psi^\dagger t^a \psi) \lambda^a + \text{h.c.} - g (\psi^\dagger t^a \psi / D^1)$$

$$Q_\mu |0\rangle = 0$$

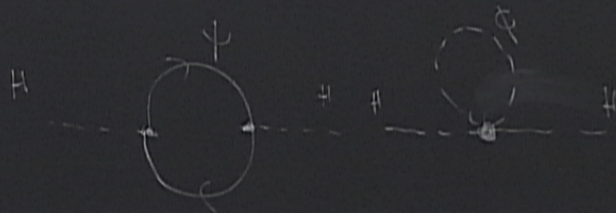
$$e^{-i(\vec{Q} + \vec{P})} |0\rangle = |0\rangle$$

$$\hookrightarrow H|0\rangle = 0$$

$$-\mathcal{L}_{\text{soft}} = \frac{m_\phi^2}{2} |\phi|^2 + \left( \frac{t}{3} \phi + \frac{b}{2} \phi^2 + \frac{c}{1} \phi^2 \phi^\dagger + \frac{a}{1} \phi^3 + \text{h.c.} \right) + \left( \frac{M_\lambda}{1} \lambda^a \lambda^a + \text{h.c.} \right)$$

gauge invariant

$$m_{\text{soft}} \sim$$



$$\Delta M_H^2 = -M_\psi^2 \frac{Y_\psi^2}{(4\pi)^2} + (M_\psi^2 + m_{\text{soft}}^2) \frac{Y_\psi^2}{(4\pi)^2}$$



$+ g f^{abc} G_{\mu\nu}^b G_{\nu\lambda}^c$   
 $G_{\mu\lambda}^b$

$- \sqrt{2} g (\psi^\dagger t^a \psi) \lambda^a + \text{h.c.} = g (\psi^\dagger t^a \psi / D^a)$

$Q_\psi |0\rangle = 0$   
 $\hookrightarrow H |0\rangle = 0$

$e^{-i(\frac{1}{2}Q + \frac{1}{2}\bar{Q})} |0\rangle = |0\rangle$

$-\mathcal{L}_{\text{soft}} = \frac{m_\phi^2}{2} |\phi|^2 + (t\phi + b\phi^2 + c\phi^2\phi^\dagger + a\phi^3 + \text{h.c.}) + \overbrace{(M_\lambda \lambda^a \lambda^a + \text{h.c.})}^{\text{gauge invariant}}$

$m_{\text{soft}} \sim$

$\Delta M_H^2 = -M_\phi^2 \frac{Y_\phi^2}{(4\pi)^2} + \overbrace{(M_\psi^2 + m_{\text{soft}}^2)}^{\text{cancels}} \frac{Y_\psi^2}{(4\pi)^2}$   
 $\sim \frac{Y_\psi^2}{(4\pi)^2} m_{\text{soft}}^2$



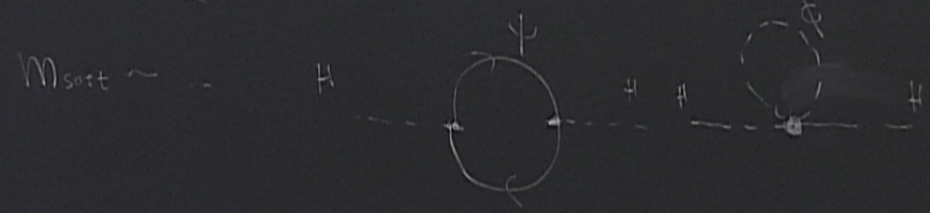
$$+ g f^{abc} G_{\mu\nu}^c G_{\nu\lambda}^a$$

$$- \sqrt{2} g (\bar{\psi} \gamma^\mu \psi) \lambda^a + \text{h.c.} = g (\bar{\psi} \gamma^\mu \psi) D^\mu$$

$$Q_\mu |0\rangle = 0 \quad e^{-i(\vec{Q} + \vec{Q}^\dagger)} |0\rangle = |0\rangle$$

$$\hookrightarrow H |0\rangle = 0$$

$$-\mathcal{L}_{\text{soft}} = \frac{m_\phi^2}{2} |\phi|^2 + \left( \frac{t}{3} \phi + \frac{b}{2} \phi^2 + c \phi^2 \phi^\dagger + a \phi^3 + \text{h.c.} \right) + \left( M_\lambda \lambda^a \lambda^a + \text{h.c.} \right)$$



$$\Delta M_H^2 = -M_\phi^2 \frac{Y_\psi^2}{(4\pi)^2} + \left( M_\psi^2 + m_{\text{soft}}^2 \right) \frac{Y_\psi^2}{(4\pi)^2}$$

cancels

$$\sim \frac{Y_\psi^2}{(4\pi)^2} m_{\text{soft}}^2$$



$$Q = \begin{pmatrix} U_L \\ D_L \end{pmatrix} = (3, 2, \frac{1}{6}) \rightarrow Q = (\tilde{Q}, Q, F_Q)$$

$f_L$

$f_R$

$A_m^a$

$H$



$f_L$   
 $f_R$   
 $A_m^a$   
 $H$

$$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3, 2, \frac{1}{6}) \rightarrow \hat{Q} = (\tilde{Q}, Q, F_Q)$$

$\begin{matrix} \hookrightarrow u_L, d_L \\ \hookrightarrow \tilde{u}, \tilde{d} \end{matrix}$



$$\hat{L} = (\bar{L}, L, F_L)$$

$$\rightarrow \tilde{\nu}_L, \tilde{e}_L = \text{"sleptons"}$$



$$\begin{array}{l}
 f_L \\
 f_R \\
 A_m \\
 H
 \end{array}
 \quad
 \begin{array}{l}
 Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3, 2, \frac{1}{6}) \rightarrow \hat{Q} = (\tilde{Q}, Q, F_Q) \\
 \quad \quad \quad \downarrow \begin{matrix} \hookrightarrow u_L, d_L \\ \tilde{u}_L, \tilde{d}_L = \text{"squarks"} \end{matrix} \\
 L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1, 2, -\frac{1}{2}) \Rightarrow \hat{L} = (\tilde{L}, L, F_L) \\
 \quad \quad \quad \downarrow \begin{matrix} \text{"}\nu_L, e_L\text{"} \\ \tilde{\nu}_L, \tilde{e}_L = \text{"sleptons"} \end{matrix} \\
 U_R = (3, 1, \frac{2}{3}) \\
 (U_R)^\alpha \quad (\bar{U}_R)_\alpha = \epsilon_{\alpha\beta} (U_R^\beta)^\alpha \\
 \quad \quad \quad \text{"} \quad \quad \quad \text{"} \\
 \quad \quad \quad LH \text{ spinor}
 \end{array}$$



$$\begin{aligned}
 f_L \quad Q &= \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3, 2, \frac{1}{6}) \rightarrow \hat{Q} = (\tilde{Q}, Q, F_Q) \\
 f_R \quad l &= \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1, 2, -\frac{1}{2}) \rightarrow \hat{L} = (\tilde{L}, L, F_L) \\
 A_m^a \quad u_R &= (3, 1, \frac{2}{3}) \\
 H \quad (\bar{u}_R)_\alpha &= \epsilon_{\alpha\beta} (u_R^\beta)^* \\
 &\quad \text{"spinor"} \Rightarrow (u^c)_\alpha \\
 &\quad \tilde{u}_R^* = \\
 &\quad \hat{U}^c = (\tilde{u}^c, u^c, F_{u^c})
 \end{aligned}$$

$\begin{aligned} &\hookrightarrow u_L, d_L \\ &\hookrightarrow \tilde{u}_L, \tilde{d}_L = \text{"squarks"} \\ &\hookrightarrow \tilde{\nu}_L, \tilde{e}_L = \text{"sleptons"} \end{aligned}$



$$\hat{Q} = (\tilde{Q}, Q, F_Q)$$

$$\begin{array}{l} \hookrightarrow u_L, d_L \\ \hookrightarrow \tilde{u}_L, \tilde{d}_L = \text{"squarks"} \end{array}$$

$$\hat{L} = (\tilde{L}, L, F_L)$$

$$\begin{array}{l} \hookrightarrow u_L, e_L \\ \hookrightarrow \tilde{\nu}_L, \tilde{e}_L = \text{"sleptons"} \end{array}$$

$$U^c, F_{U^c} = (\bar{3}, 1, -\frac{2}{3})$$

$$\hat{D}^c = (\tilde{d}^c, d^c, F_{d^c}) = (\bar{3}, 1, +\frac{1}{3})$$

$$\hat{E}^c = (\tilde{e}^c, e^c, F_{e^c}) = (1, 1, +1)$$



$$\begin{aligned}
 & \rightarrow \hat{Q} = (\tilde{Q}, Q, F_Q) \\
 & \quad \downarrow \begin{matrix} \hookrightarrow u_L, d_L \\ \tilde{u}_L, \tilde{d}_L = \text{"squarks"} \end{matrix} \\
 & \rightarrow \hat{L} = (\tilde{L}, L, F_L) \\
 & \quad \downarrow \begin{matrix} \hookrightarrow \tilde{\nu}_L, \tilde{e}_L = \text{"sleptons"} \end{matrix} \\
 & \quad \tilde{u}_R^c = (\tilde{u}^c, u^c, F_{u^c}) = (\bar{3}, 1, -\frac{2}{3}) \\
 & \rightarrow \hat{D}^c = (\tilde{d}^c, d^c, F_{d^c}) = (\bar{3}, 1, +\frac{1}{3}) \\
 & \rightarrow \hat{E}^c = (\tilde{e}^c, e^c, F_{e^c}) = (1, 1, +1) \\
 & \quad \hat{H}_u = (H_u, \tilde{H}_u^{\text{higgsino}}, F_{H_u}) = (1, 2, \frac{1}{2}) \\
 & \quad \hat{H}_d = (H_d, \tilde{H}_d, F_{H_d}) = (1, 2, -\frac{1}{2})
 \end{aligned}$$



$\tilde{u}_R^+$  $\rightarrow \tilde{\nu}_L, \tilde{e}_L = \text{"sleptons"}$ 

$$\hat{U}^c = (\tilde{u}^c, u^c, F_{u^c}) = (\bar{3}, 1, -\frac{2}{3})$$

$$\rightarrow \hat{H}_d = (H_d, \tilde{H}_d, F_{H_d}) = (1, 2, -\frac{1}{2})$$

$$(1, 1, 0)$$

$$W_{\text{MSSM}} = \underbrace{\mu H_u H_d} + \underbrace{\gamma_u Q \cdot H_u U^c} + \underbrace{\gamma_d Q \cdot H_d D^c} + \underbrace{\gamma_e L \cdot H_d E^c}$$

$$\hat{H}_u = \begin{pmatrix} \hat{H}_u^+ \\ \hat{H}_u^0 \end{pmatrix} \quad (H_u), (H_d), \epsilon^{ij} \quad (u_L H_u^0 - d_L H_u^+)$$

$$\hat{H}_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \quad \parallel \quad (H_u^+ H_d^- - H_u^0 H_d^0)$$

$$Q = \frac{1}{3} + Y$$

$$(8, 1, 0)$$