

Title: 12/13 PSI - Beyond the Standard Model Lecture 1

Date: Feb 19, 2013 09:00 AM

URL: <http://www.pirsa.org/13020089>

Abstract:

Comp scalar

$$\phi(x)$$

Comp scalar

$$\phi(x)$$

Weyl fermion

$$\psi^\alpha(x)$$

Comp scalar

$\phi(x)$

Weyl fermion

?

(Majorana)

$$\int D\phi D\psi D\phi^* D\bar{\psi}$$

Comp scalar

$$\phi(x)$$

Weyl fermion

$$\psi^\alpha(x)$$

(Majorana)

$$\bar{\psi}_\alpha(x)$$

$$\int D\phi D\psi^\alpha D\phi^* D\bar{\psi}_\alpha$$

$$\Psi = \begin{pmatrix} \vdots \\ \vdots \end{pmatrix}$$

$$\bar{\Psi} = \Psi^\dagger \gamma_0$$

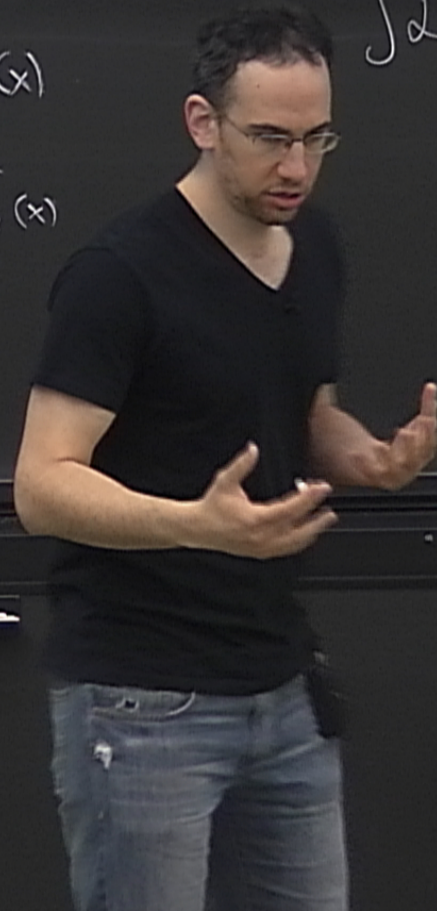
Comp scalar  
Weyl fermion  
(Majorana)

$$\phi(x)$$

$$\psi(x)$$

$$\psi_{\alpha}^{\dagger}(x)$$

$$\int \mathcal{D}\phi \mathcal{D}\psi \mathcal{D}\phi^* \mathcal{D}\bar{\psi} e^{iS(\phi, \psi)}$$



Comp scalar

$$\phi(x)$$

Weyl fermion

$$\psi(x)$$

(Majorana)

$$\psi_{\alpha}^{\dagger}(x)$$

$$\int \mathcal{D}\phi \mathcal{D}\psi \mathcal{D}\psi^{\dagger} \mathcal{D}\bar{\psi} e^{iS(\phi, \psi, \bar{\psi})}$$



$$\Psi = \begin{pmatrix} \cdot \\ \cdot \\ \cdot \end{pmatrix}$$

$$\bar{\Psi} = \bar{\Psi}^+ \gamma_0$$

 $\Lambda$ high-energy  
cut-off

Comp scalar

$$\phi(x)$$

Weyl fermion

$$\psi(x)$$

(Majorana)

$$\psi_{\dot{\alpha}}^{\dagger}(x)$$

$$\int \mathcal{D}\phi \mathcal{D}\psi \mathcal{D}\phi^* \mathcal{D}\bar{\psi} e^{iS(\phi, \psi, \bar{\psi})}$$

$$S = \int d^D x$$

Comp scalar

$$\phi(x)$$

Weyl fermion

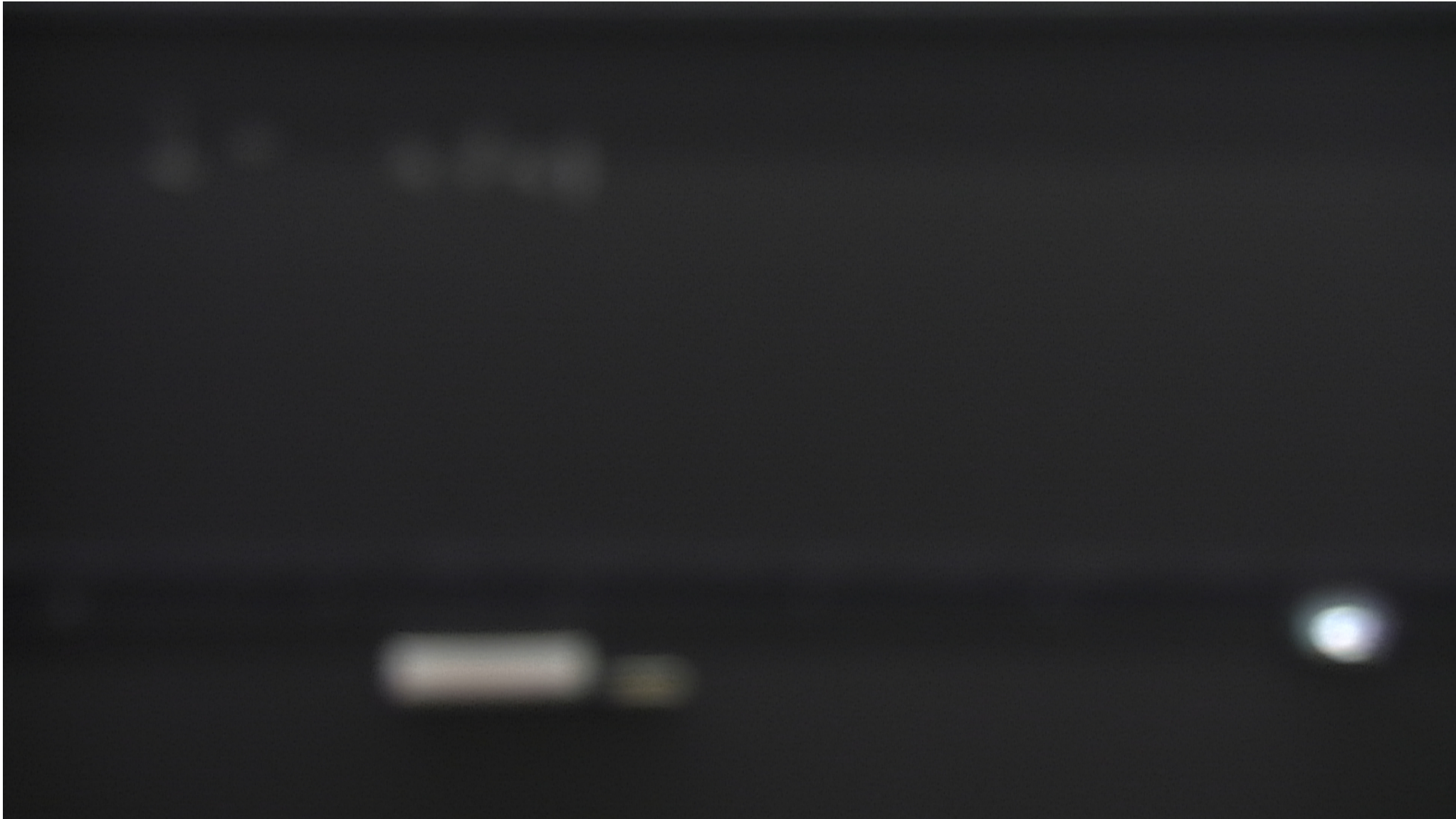
$$\psi(x)$$

(Majorana)

$$\psi_{\alpha}^{\dagger}(x)$$

$$\int \mathcal{D}\phi \mathcal{D}\psi \mathcal{D}\phi^* \mathcal{D}\bar{\psi} \quad e^{iS(\phi, \psi, \bar{\psi})}$$

$$S = \int d^D x \quad \mathcal{L}(\phi, \psi, \bar{\psi})$$



$$\mathcal{L} = \partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi$$

$$\mathcal{L} = \partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi$$

$$\begin{aligned}
 \mathcal{L} = & \frac{\partial_\mu \phi^* \partial^\mu \phi}{\partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi} \\
 & + i \psi_\alpha^\dagger \partial_\mu \psi^\alpha
 \end{aligned}$$

$$c = 1$$

$$\hbar = 1$$

$$\eta_{\mu\nu} = \begin{pmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{pmatrix}$$

$$\Psi = \begin{pmatrix} \psi \\ \chi \end{pmatrix}$$

$$\bar{\Psi} = \bar{\Psi}^+ \gamma_0$$

$$\Lambda$$

high-energy  
cut-off

$$D = 4$$



$$\begin{aligned}
 \mathcal{L} = & \frac{\partial_\mu \phi^* \partial^\mu \phi}{\partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi} \\
 & + i \psi_\alpha^\dagger \partial_\mu \psi^\alpha
 \end{aligned}$$

$$\begin{aligned}
 \mathcal{L} = & \frac{\partial_\mu \phi^* \partial^\mu \phi}{\partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi} \\
 & + i \psi^\dagger \not{\partial} \psi
 \end{aligned}$$

$$\mathcal{L} = \frac{\partial_\mu \phi^* \partial^\mu \phi}{\partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi}$$

$$+ i \psi^\dagger \overleftrightarrow{\partial}_\mu \psi$$

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$C = 1$$

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \quad \sigma_{\mu} = (\sigma_0, \vec{\sigma})$$

$$1$$

$$\begin{pmatrix} 1 \\ \vdots \end{pmatrix}$$

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$c = 1$$

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

$$\hbar = 1$$

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$\sigma_{\mu} = (\sigma_0, \vec{\sigma})$$

$$\bar{\sigma}_{\mu} = (\sigma_0, -\vec{\sigma})$$



$$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\gamma_\mu = \begin{pmatrix} 0 & p_\mu \\ p_\mu & 0 \end{pmatrix}$$

Weyl rep.

$$\{\gamma_\mu, \gamma_\nu\} = 2\eta_{\mu\nu}$$

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$\sigma_\mu = (\sigma_0, \vec{\sigma})$$

$$\bar{\sigma}_\mu = (\sigma_0, -\vec{\sigma})$$

$$\gamma_\mu = \begin{pmatrix} 0 & \beta_\mu \\ \beta_\mu & 0 \end{pmatrix}$$

Weyl rep.



$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \sigma_{M \times M} = (\sigma_0, \vec{\sigma})$$

$$\mathbb{D}_M^{\text{Dirac}} = \begin{pmatrix} \sigma_0 & \\ & -\sigma_0 \end{pmatrix}$$

$$\gamma_\mu = \begin{pmatrix} 0 & \mathbb{D}_M \\ \mathbb{D}_M & 0 \end{pmatrix}$$

Weyl rep.

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

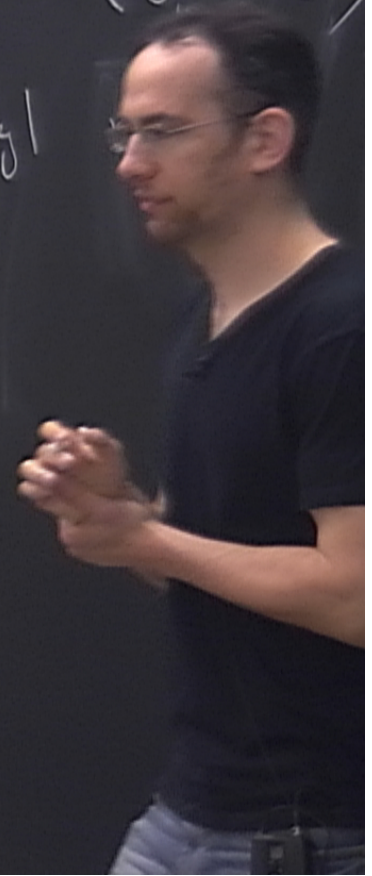
$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \sigma_{\mu\alpha\beta} = (\sigma_0, \vec{\sigma})$$

$$\sigma_{\mu\alpha\beta} = (\sigma_0, -\vec{\sigma})$$

$$\sigma_{\mu\alpha\beta}$$

$$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \sigma_\mu & 0 \end{pmatrix}$$

Weyl



$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \sigma_{\mu\alpha\dot{\alpha}} = (\sigma_0, \vec{\sigma})$$

$$\sigma_{\mu\dot{\alpha}\alpha} = (\sigma_0, -\vec{\sigma})$$

$$\sigma_{\mu\alpha\dot{\alpha}}$$

$$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \sigma_\mu & 0 \end{pmatrix}$$

Weyl rep.

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \sigma_{\mu\alpha i} = (\sigma_0, \vec{\sigma})$$

$$\sigma_{\mu\alpha i} = (\sigma_0, -\vec{\sigma})$$

$$\sigma_{\mu\alpha i} \quad \sigma_{\mu\alpha i}$$

$$\gamma_{\mu} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

Weyl rep.

$$= \frac{\partial_\mu \phi^* \partial^\mu \phi}{\partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi}$$

$$+ i \psi^\dagger \overleftrightarrow{\partial}_\mu \psi$$

$$\mathcal{L} = \frac{\partial_\mu \phi^* \partial^\mu \phi}{\partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi}$$

$$+ i \psi^\dagger \overleftrightarrow{\partial}_\mu \psi$$

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \sigma_{\mu\alpha\beta} = (\sigma_0, \vec{\sigma})$$

$$\sigma_{\mu\alpha\beta} = (\sigma_0, -\vec{\sigma})$$

$$\sigma_{\mu\alpha\beta} \sigma_{\nu\gamma\delta} = \eta_{\mu\nu} \text{Weyl rep.}$$

$$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \sigma_\mu & 0 \end{pmatrix}$$

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \nabla_{\mu \alpha \dot{\alpha}} = (\sigma_0, \vec{\sigma})$$

$$\overline{\nabla}_{\mu \dot{\alpha} \alpha} = (\sigma_0, -\vec{\sigma})$$

$$\nabla_{\mu \alpha \dot{\alpha}} \quad \overline{\nabla}_{\dot{\alpha} \mu \alpha} = \eta_{\mu\nu} \quad \gamma_{\mu} = \begin{pmatrix} 0 & \sigma_{\mu} \\ \sigma_{\mu} & 0 \end{pmatrix}$$

Weyl rep.



1)

$$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \sigma_\mu & 0 \end{pmatrix}$$

$\sigma_\mu \alpha_i$   $\sigma_\mu^{\dot{\alpha}i}$   $\gamma_\nu = \eta_{\mu\nu}$  Weyl rep.

$$\{\gamma_\mu, \gamma_\nu\} = 2\eta_{\mu\nu}$$

$$\{\sigma_{\mu\nu}, \sigma_{\alpha\beta}^{\dot{\alpha}\beta}\} = 2\eta_{\mu\nu} \delta_{\alpha\beta}$$

1)

$$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \sigma_\mu & 0 \end{pmatrix}$$

$\sigma_{\mu\alpha\dot{\alpha}} \sigma_{\nu\dot{\alpha}\alpha} = \eta_{\mu\nu}$   
Weyl rep.

$$\{\gamma_\mu, \gamma_\nu\} = 2\eta_{\mu\nu}$$

$$\{\sigma_{\mu\alpha\dot{\alpha}}, \sigma_{\nu\dot{\beta}\beta}\} = 2\eta_{\mu\nu} \delta_{\alpha\beta}$$

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \mathcal{D}_{\mathbb{R}^2} = (\sigma_0, \vec{\sigma})$$

$$\mathbb{P}^2 = (\sigma_0, \vec{\sigma})$$

$$\mathcal{D}_{\mathbb{R}^2}$$

$$\mathcal{D}_{\mathbb{C}^2}$$

$$= \mathbb{Z}_2$$

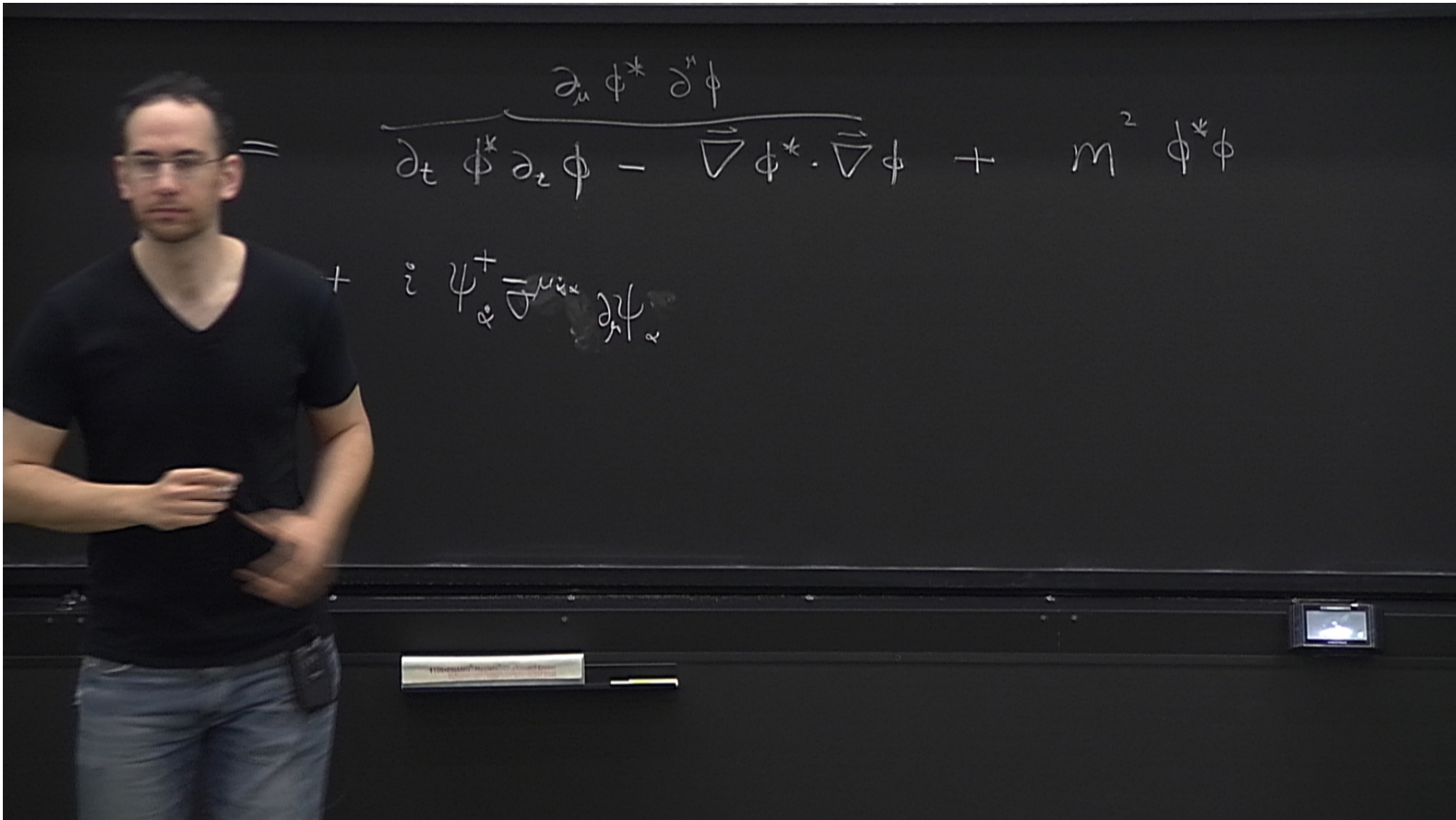
Weyl

rep.

$$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \sigma_\mu & 0 \end{pmatrix}$$

$$\mathcal{F}_{\mathbb{R}^2} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

$$\mathcal{F}_{\mathbb{C}^2} = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$



$$\mathcal{L} = \frac{\partial_\mu \phi^* \partial^\mu \phi}{\partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi} + m^2 \phi^* \phi$$

$$+ i \psi^\dagger \overleftrightarrow{\not{D}} \psi$$

$$\phi^* \phi \mapsto \phi^* \phi$$

$$\phi \rightarrow e^{i\theta} \phi$$

$$\phi^* \rightarrow e^{-i\theta} \phi^*$$

$$\phi \phi \mapsto e^{2i\theta} \phi \phi$$

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \mathcal{D}_{\mathbb{R}^2} = (\sigma_0, \vec{\sigma})$$

$$\mathcal{D}_{\mathbb{C}^2} = (\sigma_0, -\vec{\sigma})$$

$$\mathcal{D}_{\mu \alpha \dot{\alpha}}$$

$$\mathcal{D}^{\dot{\alpha} \alpha}$$

$$= \eta_{\mu\nu}$$

Weyl

rep.

$$\mathcal{F}_{\dot{\alpha} \alpha} = \begin{pmatrix} 0 & - \\ - & 0 \end{pmatrix}$$

$$\mathcal{F}^{\dot{\alpha} \alpha} = \begin{pmatrix} 0 & - \\ - & 0 \end{pmatrix}$$

$$\gamma_{\mu} = \begin{pmatrix} 0 & \beta_{\mu} \\ \beta_{\mu} & 0 \end{pmatrix}$$

$$\mathcal{L} = \frac{\partial_\mu \phi^* \partial^\mu \phi}{\partial^2 \phi} - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi + m^2 \phi^* \phi$$

$$i \bar{\psi} \gamma^\mu \partial_\mu \psi + \frac{1}{2} M \psi^\alpha \psi^\beta + \frac{1}{2} M \psi_\alpha^\dagger \psi_\beta^\dagger$$



$$\begin{aligned}
 \mathcal{L} = & \frac{\partial_\mu \phi^* \partial^\mu \phi}{\partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi} + m^2 \phi^* \phi \\
 & + i \psi^\dagger \not{\partial} \psi + \frac{1}{2} M \psi^\alpha \psi_\alpha + \frac{1}{2} M \psi^\dagger \psi^\dagger
 \end{aligned}$$

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \mathcal{D}_{\mathbb{R}^2} = (\sigma_0, \vec{\sigma})$$

$$\mathcal{D}_{\mathbb{R}^2}^{\text{cl}} = (\sigma_0, -\vec{\sigma})$$

$$\mathcal{D}_{\mu \alpha \dot{\alpha}}$$

$$\mathcal{D}^{\dot{\alpha} \alpha}$$

$$\gamma = \eta_{\mu\nu}$$

$$\gamma_\mu = \begin{pmatrix} 0 & \beta_\mu \\ \beta_\mu & 0 \end{pmatrix}$$

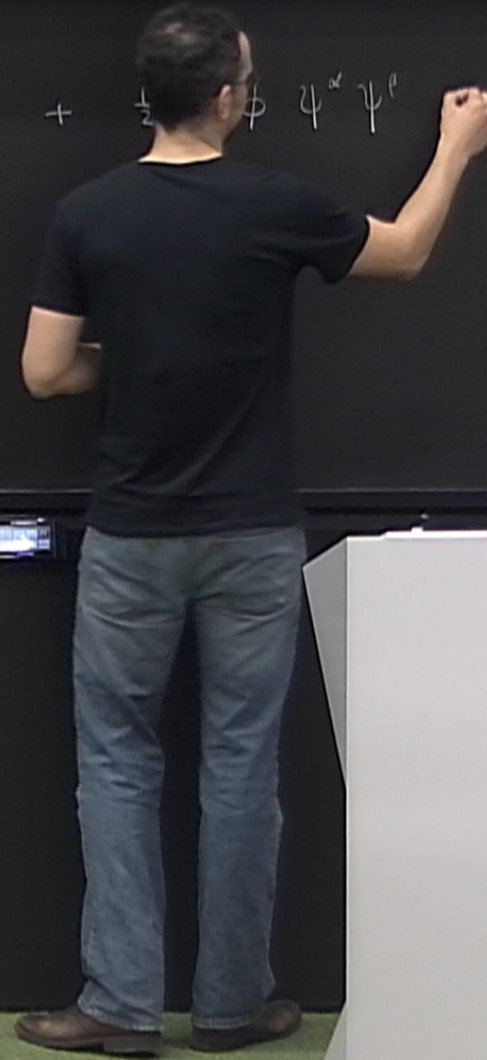
Weyl rep.

$$\mathcal{F}_{\mathbb{R}^2} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$\mathcal{F}^{\dot{\alpha} \beta} = \begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix}$$

$$\begin{aligned}
 & \delta\phi \\
 & \vec{\nabla}\phi^* \cdot \vec{\nabla}\phi + m^2 \phi^* \phi + \frac{1}{2} g \phi \psi^\alpha \psi^\beta \\
 & + \frac{1}{2} M \psi^\alpha \psi^\beta + \frac{1}{2} M \psi_\alpha^\dagger \psi_\beta^\dagger
 \end{aligned}$$

$$\begin{aligned}
 \mathcal{L} = & \frac{\partial_\mu \phi^* \partial^\mu \phi}{\partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi} + m^2 \phi^* \phi + \frac{1}{2} \phi \psi^\alpha \psi^\rho \\
 & + i \psi_\alpha^\dagger \bar{\sigma}^{\mu\nu} \partial_\mu \psi_\nu + \frac{1}{2} M \psi^\alpha \psi^\rho + \frac{1}{2} M \psi_\alpha^\dagger \psi^\dagger_\rho
 \end{aligned}$$



$$\begin{aligned}
 \mathcal{L} = & \frac{\partial_\mu \phi^* \partial^\mu \phi}{\partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi} + m^2 \phi^* \phi + \frac{1}{2} g \phi \psi^\alpha \psi^\beta \epsilon_{\alpha\beta} \\
 & + i \psi_\alpha^\dagger \overleftrightarrow{\partial}^{\mu\alpha} \psi_\mu + \frac{1}{2} M \psi^\alpha \psi^\beta \epsilon_{\alpha\beta} + \frac{1}{2} M \psi_\alpha^\dagger \psi_\beta^\dagger
 \end{aligned}$$

$$\begin{aligned}
 \mathcal{L} = & \frac{\partial_\mu \phi^* \partial^\mu \phi}{\partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi} + m^2 \phi^* \phi + \frac{1}{2} g \phi \psi^\alpha \psi^\beta \epsilon_{\alpha\beta} + \frac{1}{2} y \phi^* \psi_\alpha^+ \psi_\beta^+ \epsilon^{-\alpha\beta} \\
 & + i \psi_\alpha^+ \overleftrightarrow{\partial}^{\mu\alpha} \psi_\mu + \frac{1}{2} M \psi^\alpha \psi_\beta \epsilon_{\alpha\beta} + \frac{1}{2} M \psi_\alpha^+ \psi_\beta^+
 \end{aligned}$$

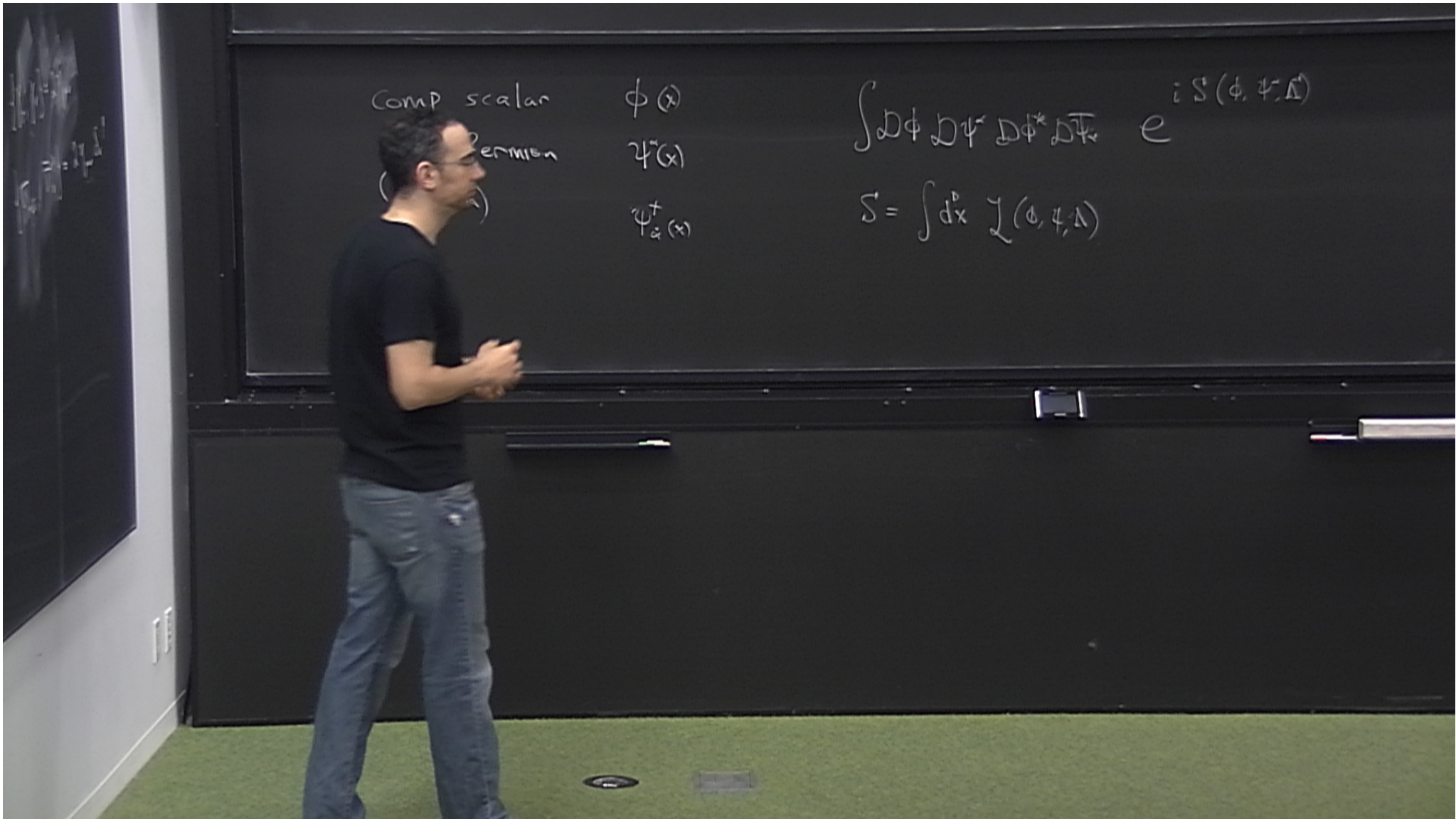
$$\phi^* \phi \mapsto \phi^* \phi$$

$$\phi \rightarrow e^{i\theta} \phi$$

$$\phi^* \rightarrow e^{-i\theta} \phi^*$$

$$\phi \phi \mapsto e^{2i\theta} \phi \phi$$

$$M^2 \phi^2 + \text{h.c.}$$





$$\phi^* \phi \mapsto \phi^* \phi$$

$$\phi \rightarrow e^{i\theta} \phi$$

$$\phi^* \rightarrow e^{-i\theta} \phi^*$$

$$\phi \phi \mapsto e^{2i\theta} \phi \phi$$

$$m^2 \phi^2 + \text{h.c.}$$

$$\phi \psi^\alpha \psi^\dagger$$

$$\phi^* \phi \mapsto \phi^* \phi \quad \phi \rightarrow e^{i\theta} \phi$$

$$\phi^* \rightarrow e^{-i\theta} \phi^*$$

$$\phi \phi \mapsto e^{2i\theta} \phi \phi$$

$$M^2 \phi^2 + \text{h.c.}$$

$$\phi \psi^\alpha \psi^\beta \in \alpha\beta$$

$$\begin{aligned} \phi^* \phi &\mapsto \phi^* \phi & \phi &\rightarrow e^{i\theta} \phi \\ & & \phi^* &\rightarrow e^{-i\theta} \phi^* \\ \phi \phi &\mapsto e^{2i\theta} \phi \phi \\ m^2 \phi^2 &+ \text{h.c.} \end{aligned}$$

$$\phi \psi^\alpha \partial_\mu \psi^{\dagger\beta} \nabla_{\alpha\beta}^M$$

$$\phi^* \phi \mapsto \phi^* \phi \quad \phi \rightarrow e^{i\theta} \phi$$

$$\phi^* \rightarrow e^{-i\theta} \phi^*$$

$$\phi \phi \mapsto e^{2i\theta} \phi \phi$$

$$m^2 \phi^2 + \text{h.c.}$$

$$\phi \psi^\alpha \partial_\mu \psi^{\dagger\beta} \quad \nabla_{\alpha\beta}^M$$

$$\phi^* \phi \mapsto \phi^* \phi$$

$$\begin{aligned} \phi &\rightarrow e^{i\theta} \phi \\ \phi^* &\rightarrow e^{-i\theta} \phi^* \end{aligned}$$

$$\phi \phi \mapsto e^{2i\theta} \phi \phi$$

$$M^2 \phi^2 + \text{h.c.}$$

$$\phi \psi^\alpha \partial_\mu \psi^{\dagger\beta} \sigma_{\alpha\beta}^\mu$$

$$\begin{aligned} \epsilon_{\alpha\beta} \\ \sigma_{\alpha\beta}^\mu \end{aligned}$$

$$\phi^* \phi \mapsto \phi^* \phi$$

$$\phi \rightarrow e^{i\theta} \phi$$

$$\phi^* \rightarrow e^{-i\theta} \phi^*$$

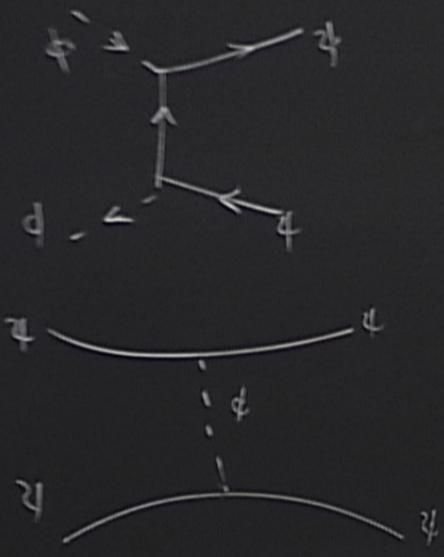
$$\phi \phi \mapsto e^{2i\theta} \phi \phi$$

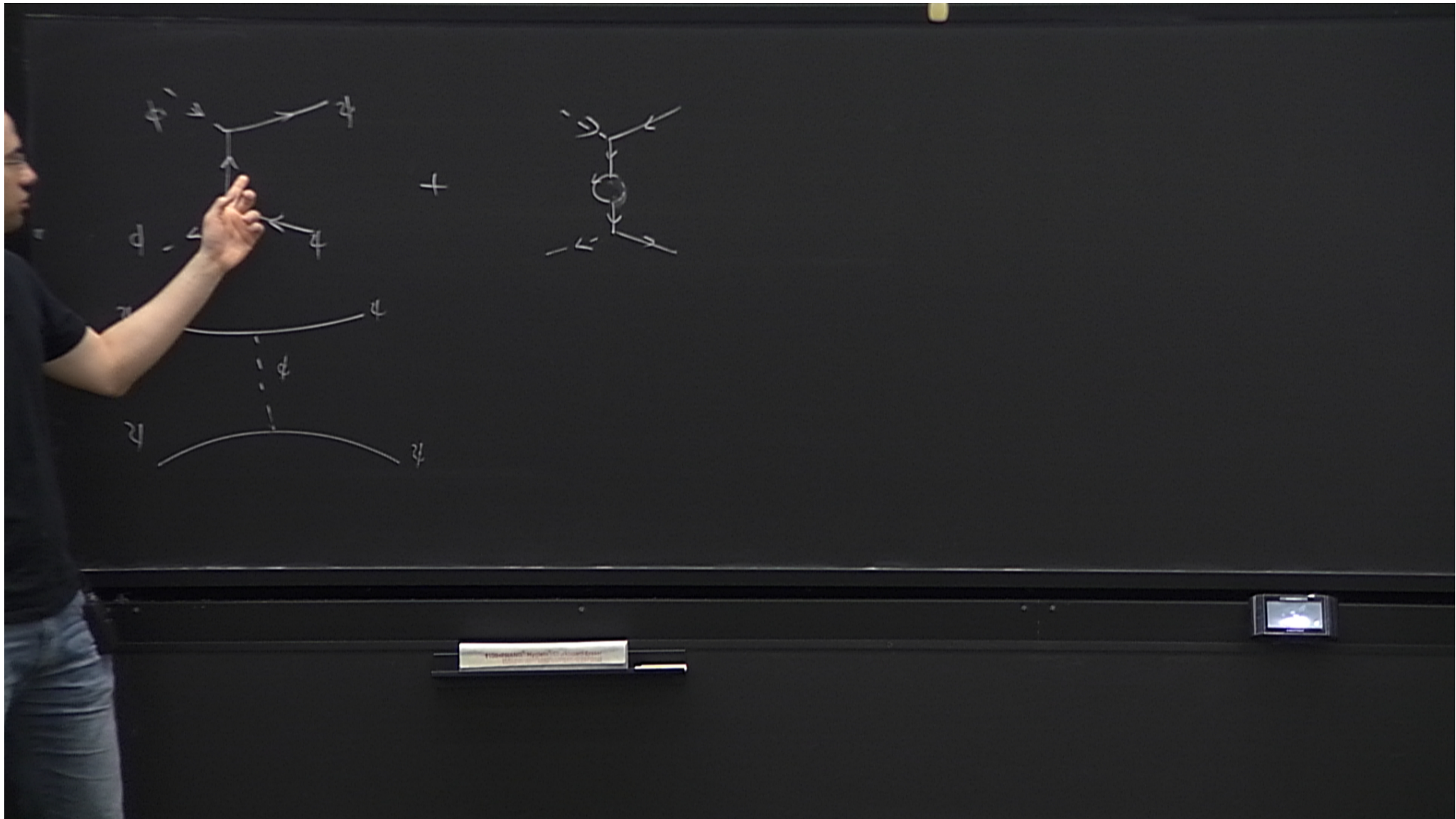
$$M^2 \phi^2 + \text{h.c.}$$

$$\phi \psi^\alpha \partial_\mu \psi^{\dagger\beta} \sigma_{\alpha\beta}^\mu$$

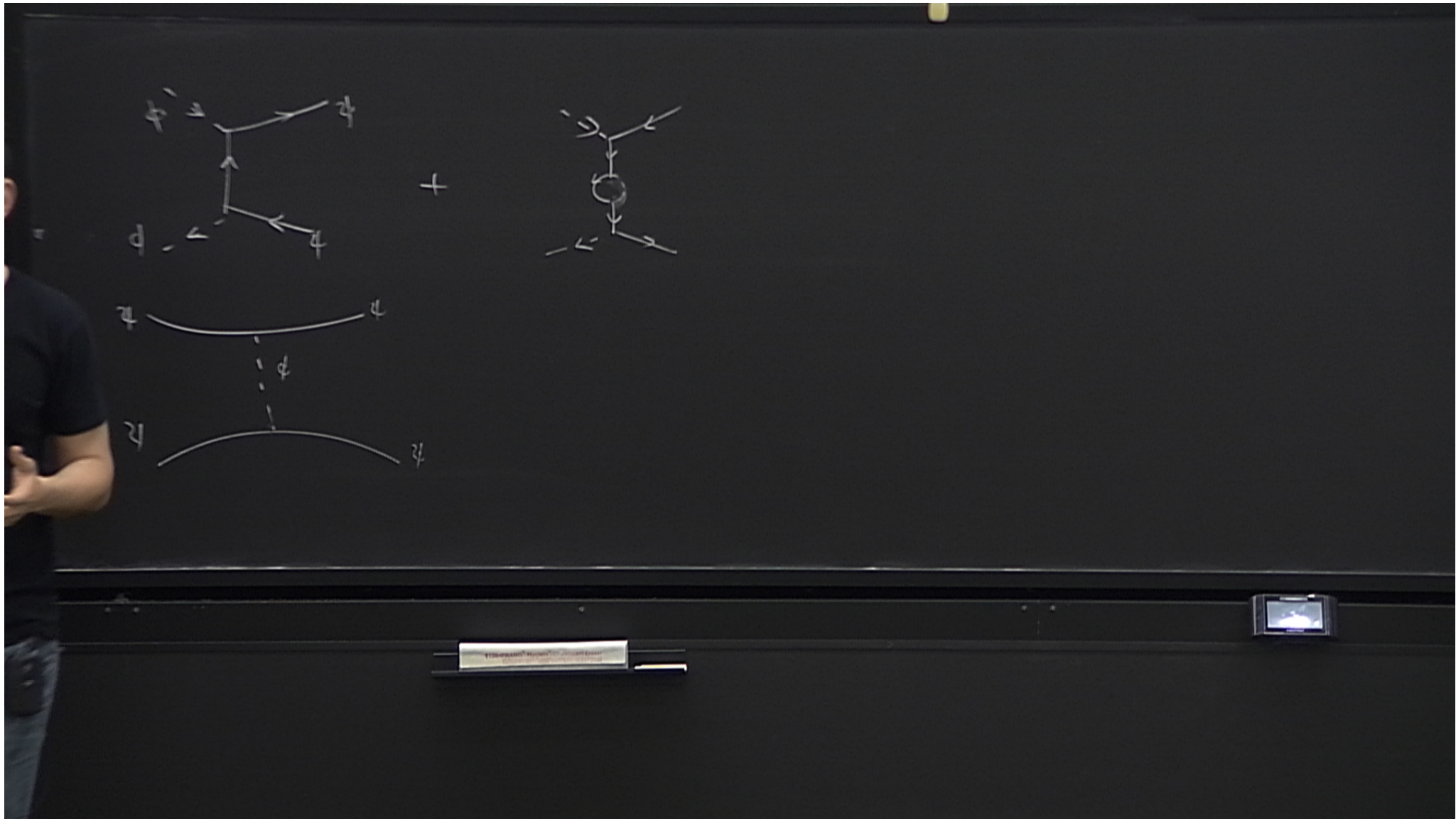
$$\epsilon_{\alpha\beta}$$

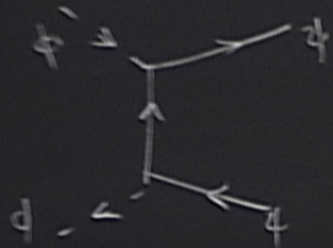
$$\sigma_{\alpha\beta}^\mu$$



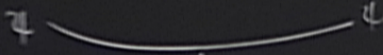
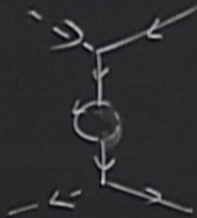


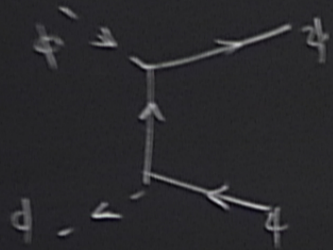




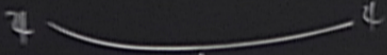
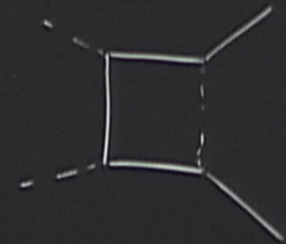
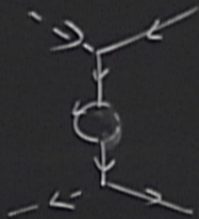


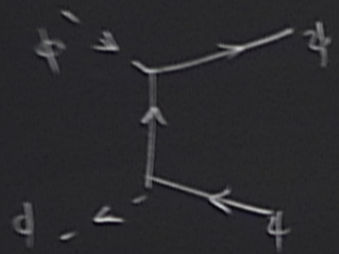
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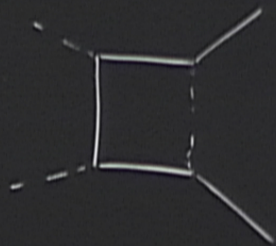
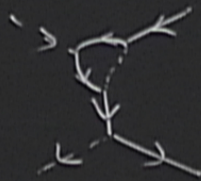


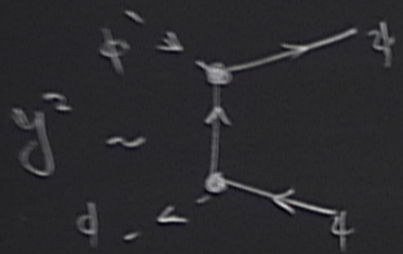
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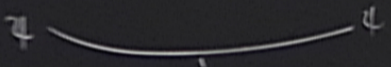
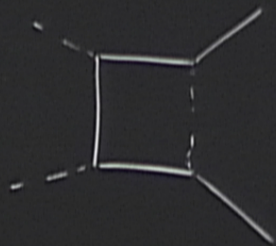
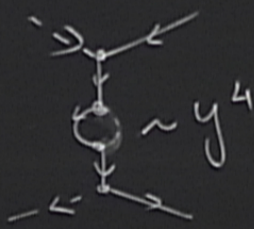


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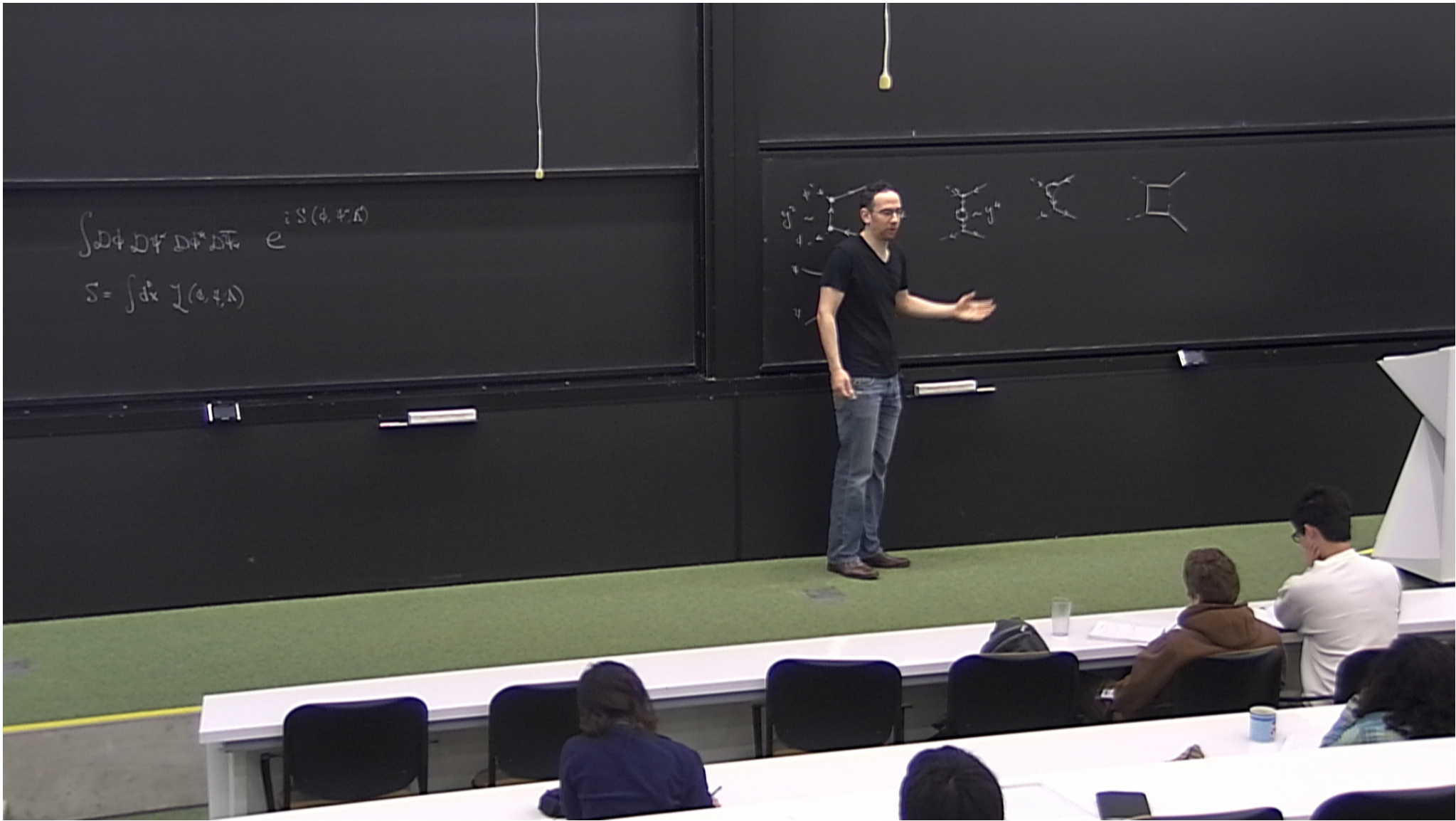


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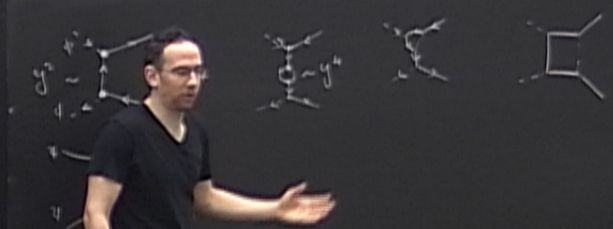


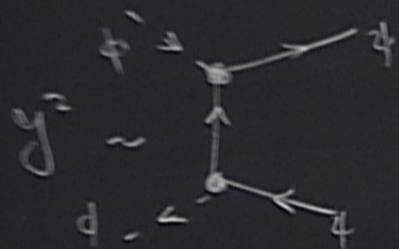
$\phi$



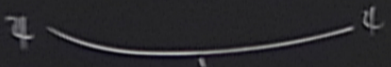
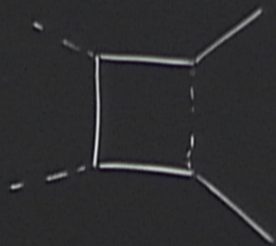
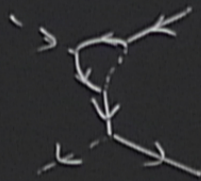
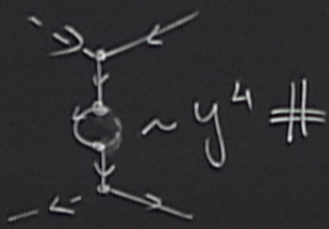


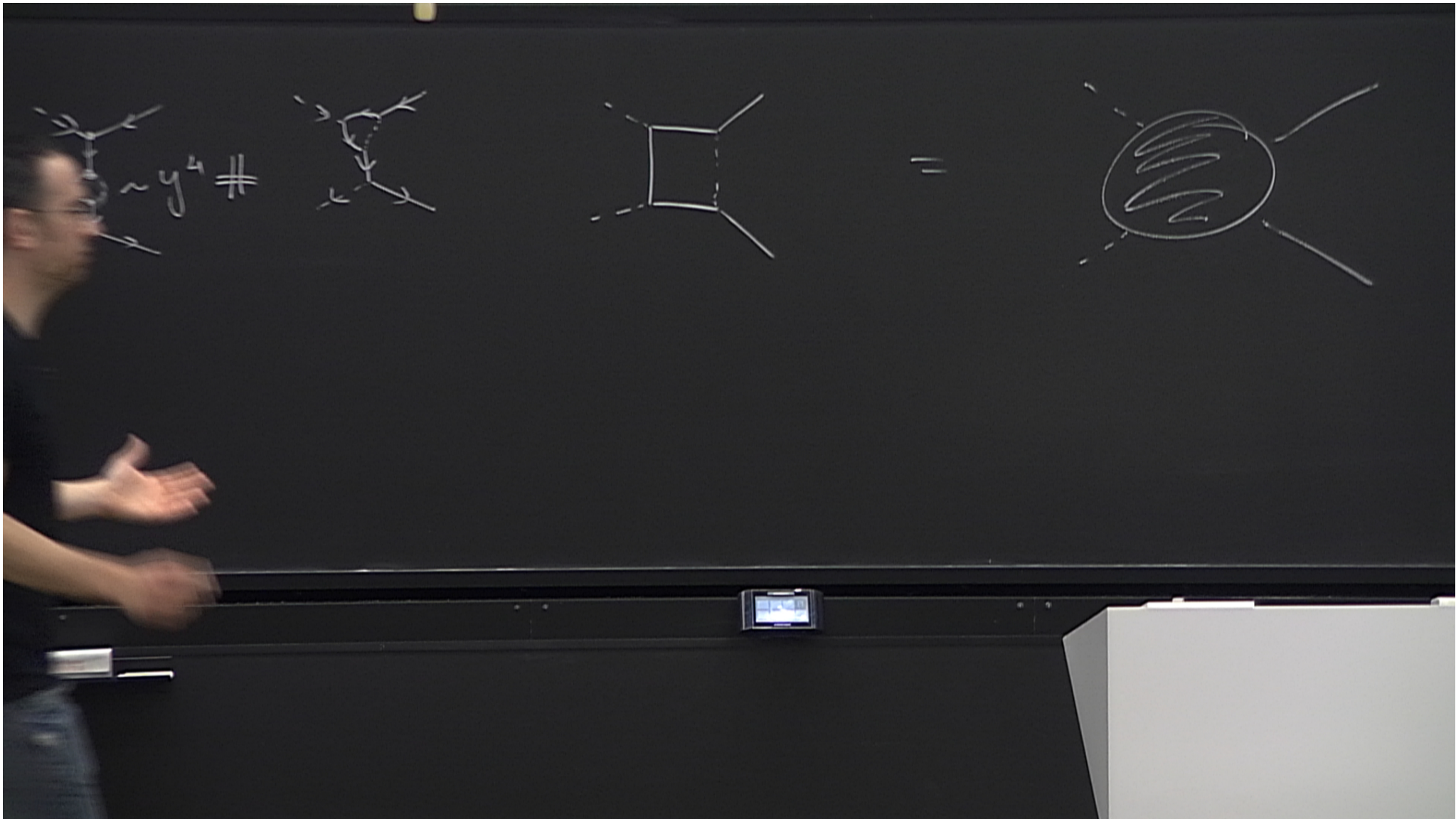
$$\int D\phi D\psi D\bar{\psi} D\bar{\phi} e^{iS(\phi, \psi, \bar{\phi})}$$
$$S = \int dx \mathcal{L}(\phi, \psi, \bar{\phi})$$





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$$\phi \xrightarrow{\quad} \phi = \frac{i}{p^2 - m^2 + i\epsilon}$$

$$\psi \xrightarrow{\quad} \psi = \frac{i \not{\Delta}_p}{p^2 + i\epsilon}$$

