

Title: PSI 2019/2020 - Standard Model and Beyond - Part 1 - Lecture 4

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Collection/Series: PSI 2019/2020 - Standard Model and Beyond - Part 1

Subject: Cosmology, Particle Physics

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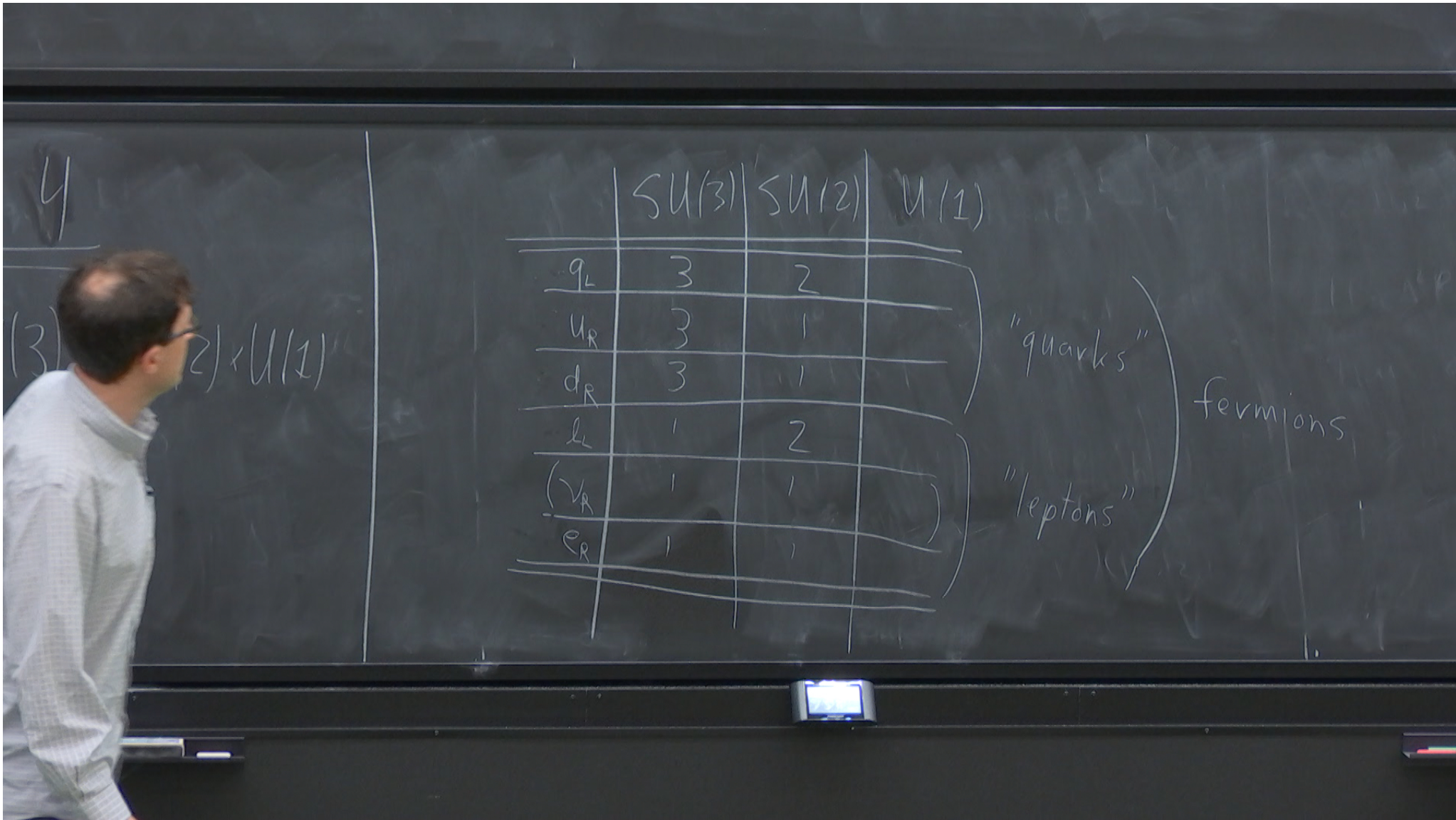
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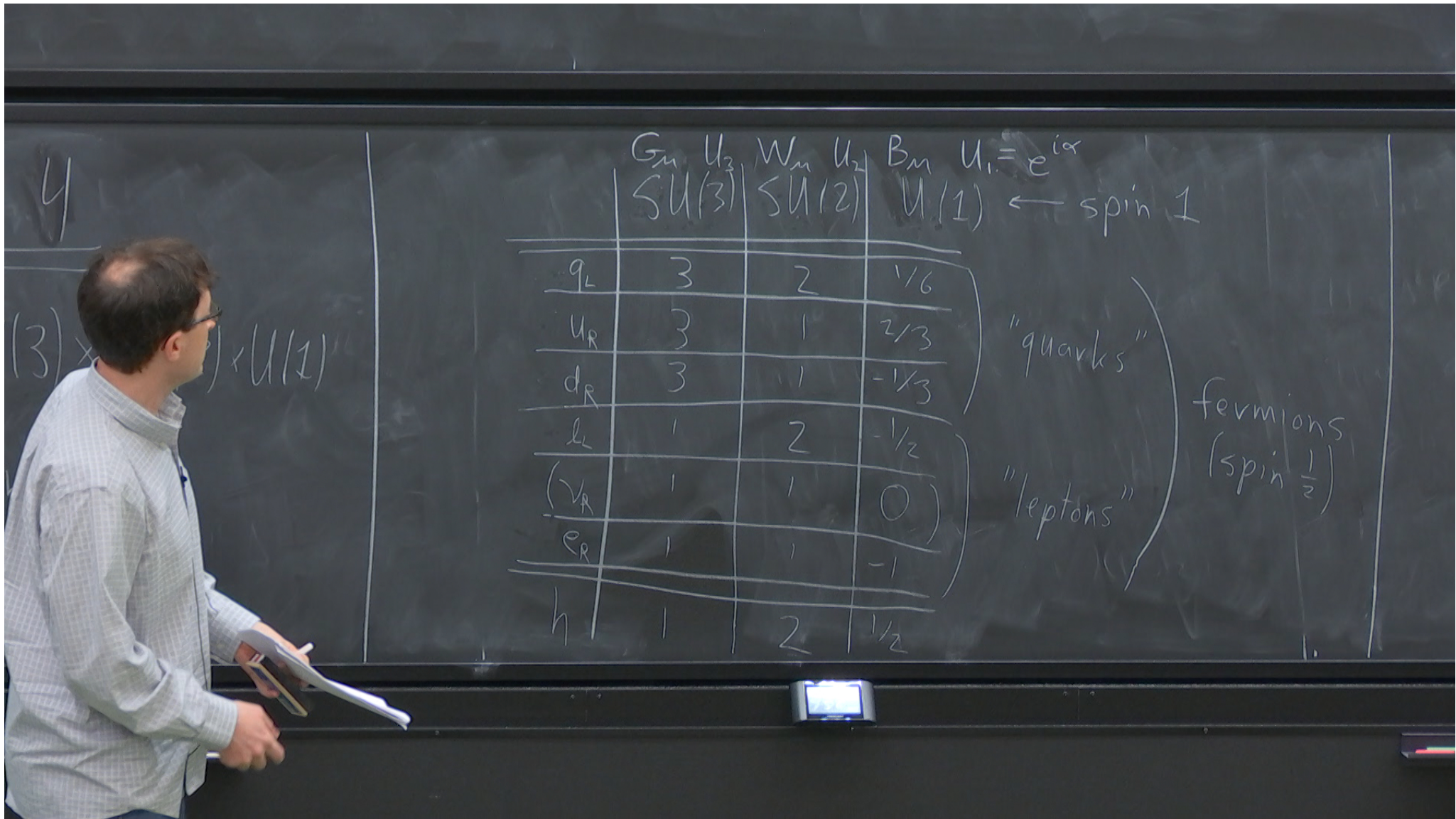
Lecture 4

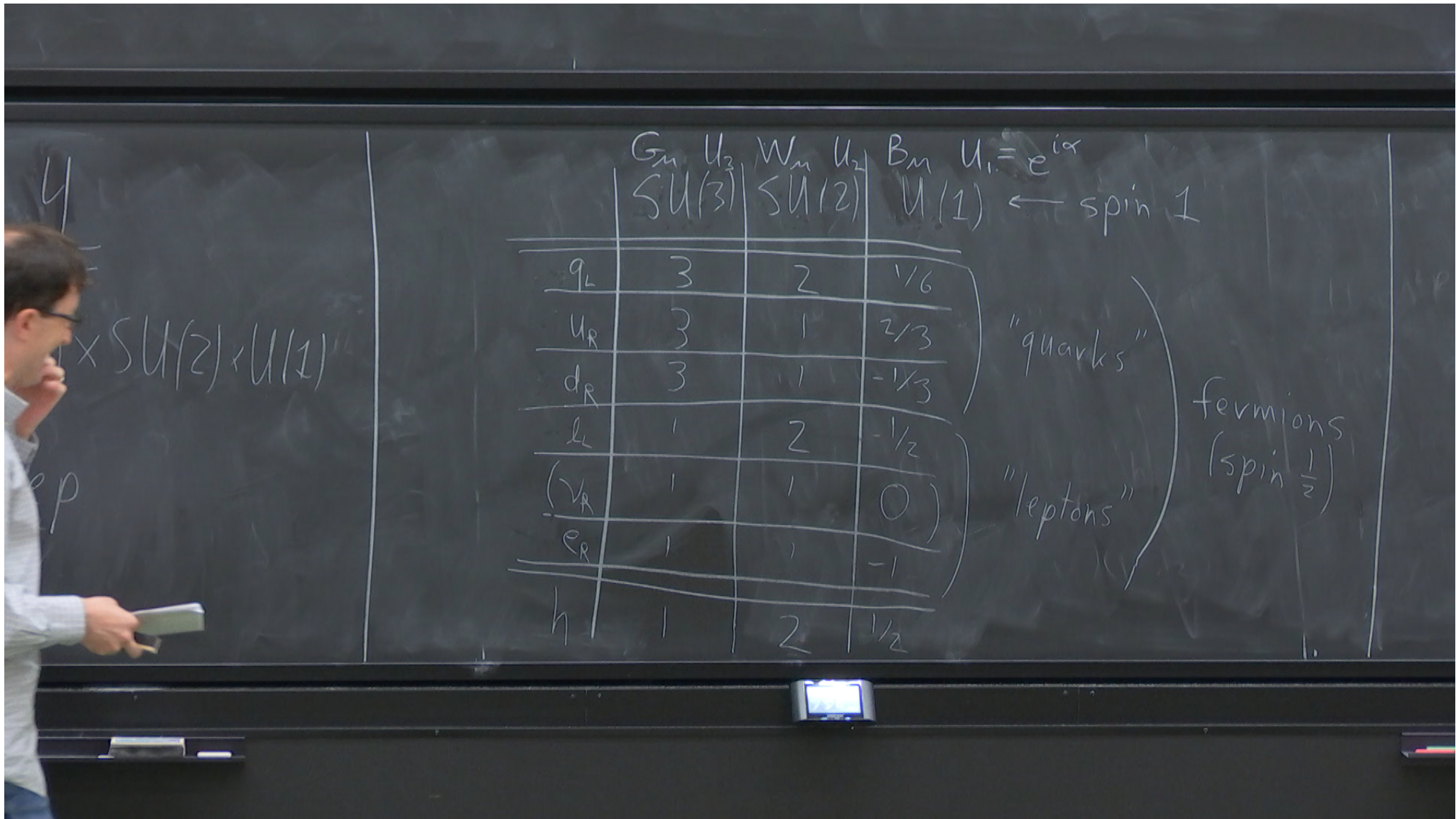
1) $G = SU(3) \times SU(2) \times U(1)$

2) Pick rep

	$SU(3)$	$SU(2)$	$U(1)$
q_L	3		
u_R	3		
d_R	3		
l_L	1		
$(\bar{\nu}_R)$	1		
e_R	1		







$e^{i\alpha}$
spin 1

"quarks"
"leptons"

fermions
(spin $\frac{1}{2}$)

Standard Model:

- Poincare (Lorentz, translations)
- $SU(3) \times SU(2) \times U(1)$ gauge
- Hermitian
- mass dim ≤ 4

Dim'l Analysis:

$$\hbar = c = 1$$

$$\underline{M} = \frac{1}{L} = \frac{1}{T}$$

$$S = \int d^4x \mathcal{L} \quad \begin{matrix} \downarrow \\ M^4 \end{matrix} \quad \begin{matrix} \downarrow \\ M^4 \end{matrix} \quad e^{iS/\hbar}$$

$$M^4 \sim -(\partial_\mu \phi)(\partial^\mu \phi)$$

$$\begin{matrix} \downarrow & \downarrow & \downarrow & \downarrow \\ M^1 & M^1 & M^1 & M^1 \end{matrix}$$

$$\bar{\psi} i \not{\partial} \psi$$

$$\begin{matrix} \downarrow \\ M^{3/2} & M^1 & M^{3/2} \end{matrix}$$

$$[\phi] = M^1$$

$$[\psi] = M^{3/2}$$

$$-\frac{1}{4} \text{Tr}[F_{\mu\nu} F^{\mu\nu}]$$

$$[A_\mu] = M^1$$

$$\frac{g}{M^2} \frac{\bar{\psi} \psi \bar{\chi} \chi}{M^6}$$

Lecture 4

$$1) G = SU(3) \times SU(2) \times U(1)$$

2) Pick rep

	$G_u U_3$ $SU(3)$	$G_w U_2$ $SU(2)$	$B_u U_1 = e^{i\alpha}$ $U(1) \leftarrow \text{spin } 1$
q_L	3	2	1/6
u_R	3	1	2/3
d_R	3	1	-1/3
ℓ_L	1	2	-1/2
(ν_R, e)	1	1	0

"quarks"

"leptons"

fermions
(spin 1/2)

Standard Model:

- Poincare (Lorentz)
- $SU(3) \times SU(2) \times U(1)$
- Hermitian
- mass dim $\leq$

Min Gauge bosons:

$$D_M = \partial_M + ig A_M$$

$$D_M = \partial_M + ig_3 G_M + ig_2 W_M + ig_1 B_M$$

Kerr Black Hole

Asymptotically flat

Stationary

$\Delta t + a \sin^2 \theta$

Minimal Gauge bosons:

$$D_\mu = \partial_\mu + ig A_\mu : D_\mu \rightarrow U D_\mu U^{-1}$$

$$D_\mu = \partial_\mu + ig_3 G_\mu + ig_2 W_\mu + ig_1 B_\mu$$

$$A_\mu \rightarrow U A_\mu U^{-1} + \frac{i}{g} (\partial_\mu U) U^{-1}$$

Gauge bosons:

$$D_m = \partial_m + ig A_m: D_m \rightarrow U D_m U^{-1}$$

$$D_m = \partial_m + ig_3 G_m + ig_2 W_m + ig_1 B_m$$

$$U = (U_3, U_2, U_1)$$

$$A_m \rightarrow U A_m U^{-1} + \frac{i}{g} (\partial_m U) U^{-1}$$

$$G_m \rightarrow U_3 G_m U_3^{-1} + \frac{i}{g_3} (\partial_m U_3) U_3^{-1}$$

$$W_m \rightarrow U_2 W_m U_2^{-1} + \frac{i}{g_2} (\partial_m U_2) U_2^{-1}$$

$$B_m \rightarrow U_1 B_m U_1^{-1} + \frac{i}{g_1} (\partial_m U_1) U_1^{-1}$$

$$\left\{ \begin{array}{l} \partial_\mu U) U^{-1} \\ (\partial_\mu U_3) U_3^{-1} \\ g_2 (\partial_\mu U_2) U_2^{-1} \\ g_1 (\partial_\mu U_1) U_1^{-1} \end{array} \right.$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + ig[A_\mu, A_\nu]$$

$$G_{\mu\nu} = \partial_\mu G_\nu - \partial_\nu G_\mu + \underline{ig_3}[G_\mu, G_\nu]$$

$$W_{\mu\nu} = \dots$$

$$B_{\mu\nu} = \dots$$

$$F_{\mu\nu} \rightarrow U F_{\mu\nu} U^{-1} \rightarrow -\frac{1}{4} \text{Tr}[F_{\mu\nu} F^{\mu\nu}]$$

$$G_{\mu\nu} \rightarrow U_3 G_{\mu\nu} U_3^{-1} \rightarrow$$

$$W_{\mu\nu} \rightarrow U_2 W_{\mu\nu} U_2^{-1}$$

$$B_{\mu\nu} \rightarrow U_1 B_{\mu\nu} U_1^{-1}$$

e_R	1	1	-1
h	1	2	$\frac{1}{2}$

$$\mathcal{L}_{SM} = -\frac{1}{4} \text{Tr}[G_{\mu\nu} G^{\mu\nu}] - \frac{1}{4} \text{Tr}[W_{\mu\nu} W^{\mu\nu}] - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$$\left. \begin{aligned}
 A_m &\rightarrow U A_m U^{-1} + \frac{i}{g} (\partial_m U) U^{-1} \\
 G_m &\rightarrow U_3 G_m U_3^{-1} + \frac{i}{g_3} (\partial_m U_3) U_3^{-1} \\
 W_m &\rightarrow U_2 W_m U_2^{-1} + \frac{i}{g_2} (\partial_m U_2) U_2^{-1} \\
 B_m &\rightarrow U_1 B_m U_1^{-1} + \frac{i}{g_1} (\partial_m U_1) U_1^{-1} \\
 &\hookrightarrow B_m - \frac{1}{g_1} \partial_m \alpha
 \end{aligned} \right\}$$

$$\begin{aligned}
 F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu + ig [A_\mu, A_\nu] \\
 G_{\mu\nu} &= \partial_\mu G_\nu - \partial_\nu G_\mu + \underline{ig_3} [G_\mu, G_\nu] \\
 W_{\mu\nu} &= \dots \\
 B_{\mu\nu} &= \dots
 \end{aligned}$$

$$D_m = \partial_m + ig_3 G_m + ig_2 \underline{W}_m + ig_1 B_m$$

$$D_m h = (\partial_m + ig_2 W_m + \frac{i}{2} g_1 B_m)$$

$$-(\partial_m h)^\dagger (\partial^m h) \rightarrow -(D_m h)^\dagger (D^m h)$$

$$\phi \rightarrow U_{\text{rxr}} \phi$$

$$\phi \rightarrow e^{iq\alpha} \phi$$

$$\partial_m + igq A_m$$

q

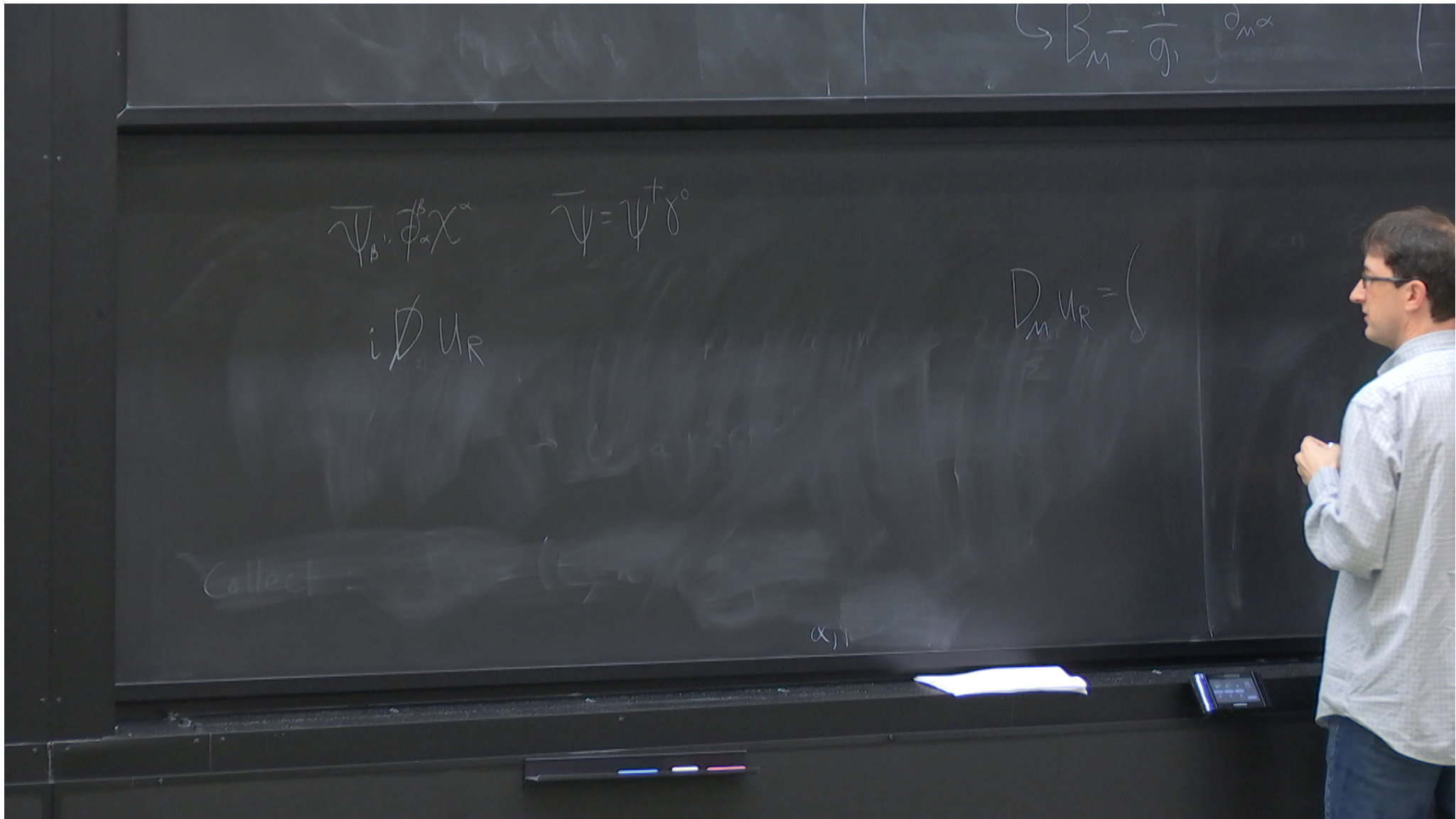
→

$$L_{SM} = -\frac{1}{4} \text{Tr}[G_{\mu\nu} G^{\mu\nu}] - \frac{1}{4} \text{Tr}[W_{\mu\nu} W^{\mu\nu}] - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - (D_\mu h)(D^\mu h)$$

$g \rightarrow 1$

ν_R	1	1	0
e_R	1	1	-1
h	1	2	$\frac{1}{2}$

leptons"



$$\bar{\psi}_\beta \phi^\beta_\alpha \chi^\alpha \quad \bar{\psi} = \psi^\dagger \gamma^0$$

$$i \not{D} U_R$$

$$D_m U_R = \left(\frac{1}{2} \right)$$

Collect:

(α)

$$D_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\bar{\psi}_\beta \phi_\alpha \chi^\alpha \quad \bar{\psi} = \psi^\dagger \gamma^0$$

$$\bar{u}_R i \not{D} u_R$$

$e^{i\frac{1}{3}\alpha}$ $e^{i\frac{2}{3}\alpha}$

$$\not{D} u_R = \gamma^\mu D_\mu u_R = \left(\partial_\mu + i g_3 G_\mu + i g_1 \left(\frac{2}{3} \right) B_\mu \right) u_R$$

$\wedge \quad V^\mu \quad \wedge \quad V_\mu$

$(\alpha, 1)$

			-1
h	1	2	1/2

$$\begin{aligned}
 \mathcal{L}_{SM} = & -\frac{1}{4} \text{Tr}[G_{\mu\nu} G^{\mu\nu}] - \frac{1}{4} \text{Tr}[W_{\mu\nu} W^{\mu\nu}] - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\
 & - (D_\mu h)^\dagger (D^\mu h) \\
 & + i \left[\bar{q}_L \not{D} q_L + \bar{u}_R \not{D} u_R + \bar{d}_R \not{D} d_R + \bar{l}_L \not{D} l_L + (\bar{\nu}_R \not{D} \nu_R) + \bar{e}_R \not{D} e_R \right]
 \end{aligned}$$

$g \rightarrow 1$

e_R^i	1	1	-1
h	1	2	$1/2$

leptons

$$\mathcal{L}_{SM} = -\frac{1}{4} \text{Tr}[G_{\mu\nu} G^{\mu\nu}] - \frac{1}{4} \text{Tr}[W_{\mu\nu} W^{\mu\nu}] - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$g \rightarrow 1$

$$- (D_\mu h)^\dagger (D^\mu h)$$

$$+ i \left[\bar{q}_L^i \not{D} q_L^i + \bar{u}_R \not{D} u_R + \bar{d}_R \not{D} d_R + \bar{l}_L \not{D} l_L + (\bar{\nu}_R \not{D} \nu_R) + \bar{e}_R \not{D} e_R \right]$$

$$K = U \Lambda U^{-1}$$

$$q \rightarrow U^i q \quad q^i \rightarrow \Lambda_{ii}^{1/2} q^i$$

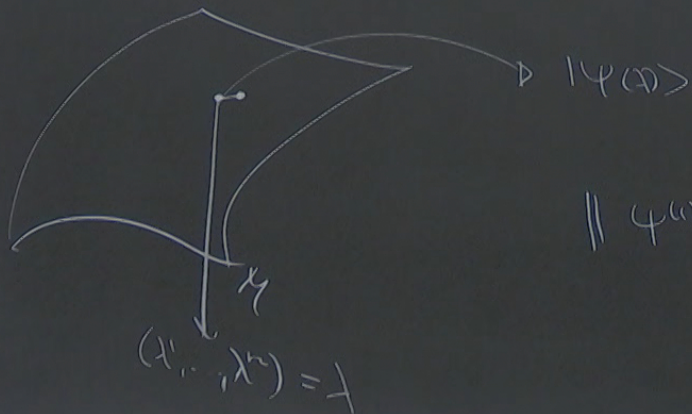
$$F = |\langle \psi^{(1)} | \psi^{(2)} \rangle|$$

$$d(\psi^{(1)}, \psi^{(2)}) = \cos^{-1} F$$

$$F = |\langle \psi^{(1)} | \psi^{(1+\delta\lambda)} \rangle| \simeq 1$$

$$d(\psi^{(1)}, \psi^{(2)}) \simeq \sqrt{1-F^2} \simeq \sqrt{2(1-F)} \equiv d_{FS}$$

Fubini-
Study
Metric



$$d\ell^2 = 2(1-F)$$

$$\|\psi^{(1)} - \psi^{(2)}\|$$