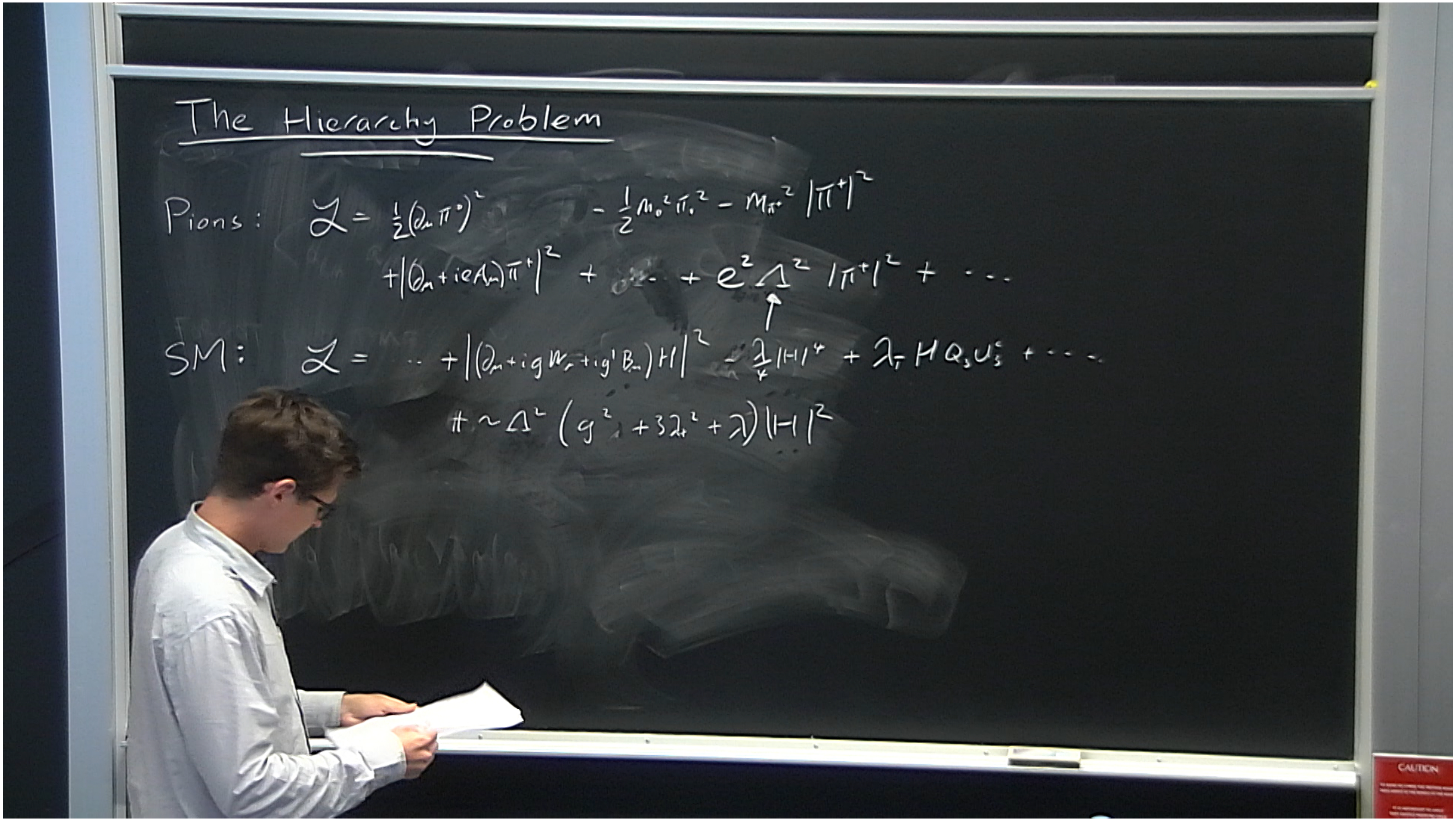
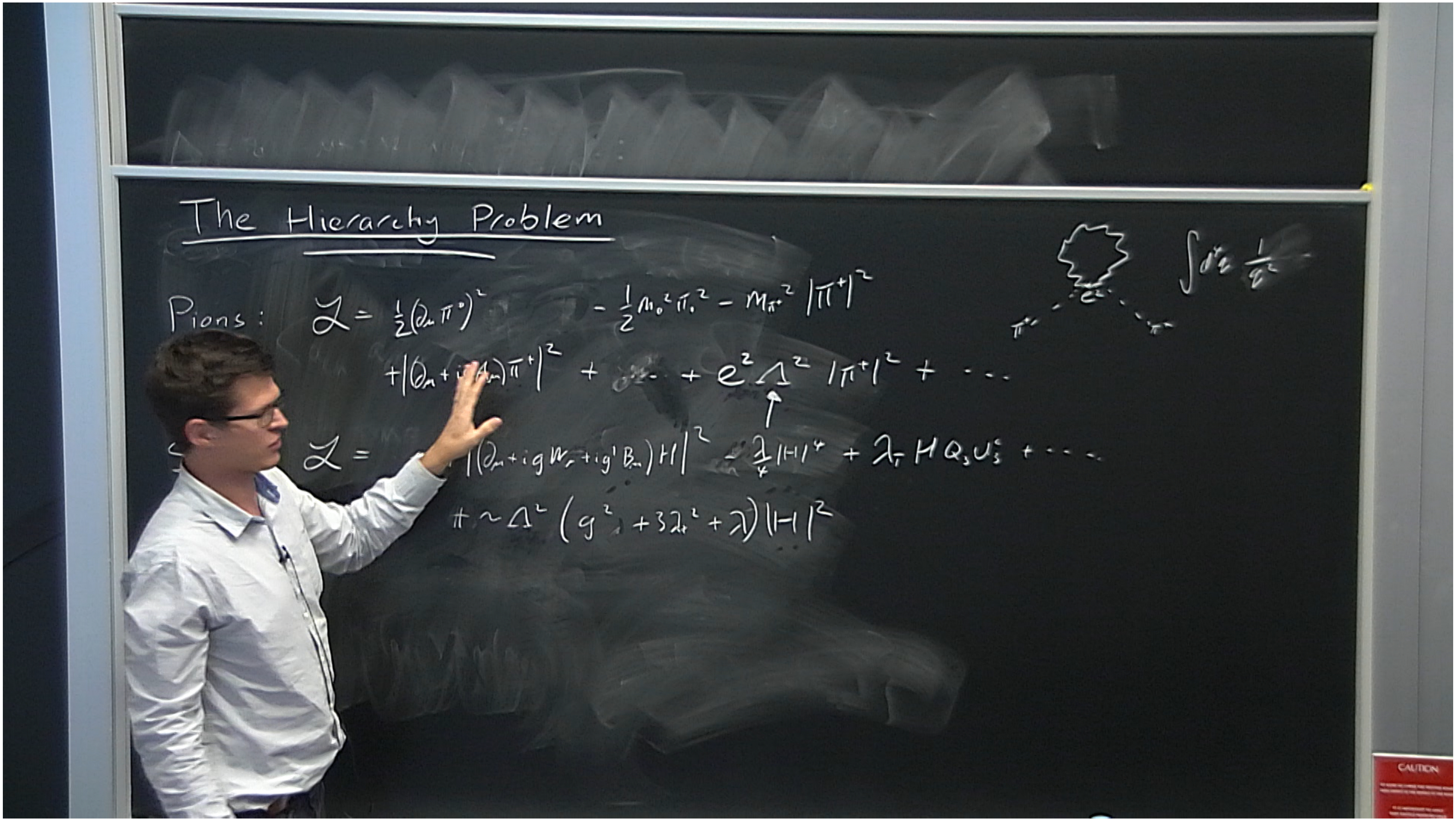
Title: BSM Theory 2

Date: Jul 12, 2018 02:30 PM

URL: http://pirsa.org/18070012

Abstract:


The Hierarchy Problem
Pions: $\mathcal{L} = \frac{1}{2}(\partial_\mu \pi^0)^2 - \frac{1}{2} m_0^2 \pi_0^2 - m_{\pi^+}^2 |\pi^+|^2$
$+ |(\partial_\mu + ieA_\mu)\pi^+|^2 + \ldots + e^2 \Lambda^2 |\pi^+|^2 + \ldots$
SM: $\mathcal{L} = \ldots + |(\partial_\mu + igW_\mu + ig' B_\mu) H|^2 - \frac{\lambda}{4}|H|^4 + \lambda_T H Q_3 U_3^c + \ldots$
$+ \sim \Lambda^2 (g^2 + 3\lambda_T^2 + \lambda)|H|^2$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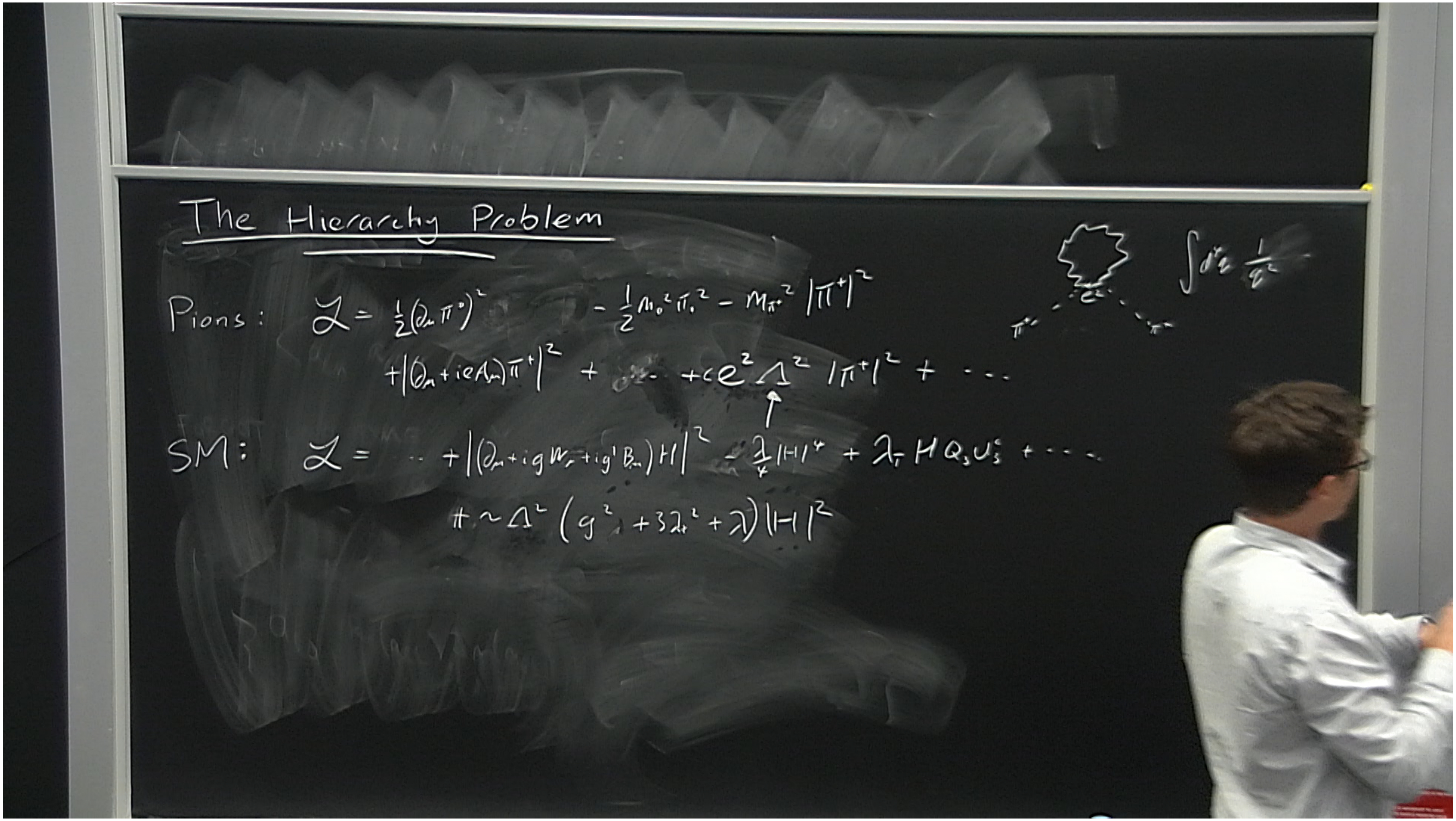
$\mathcal{L} = |(\partial_\mu + i g W_\mu + i g' B_\mu) H|^2 - \frac{\lambda}{4}|H|^4 + \lambda_t H Q_3 U_3^c + \ldots$
$+ \sim \Lambda^2 (g^2 + 3\lambda_t^2 + \lambda)|H|^2$
$\int d^4 q \frac{1}{q^2}$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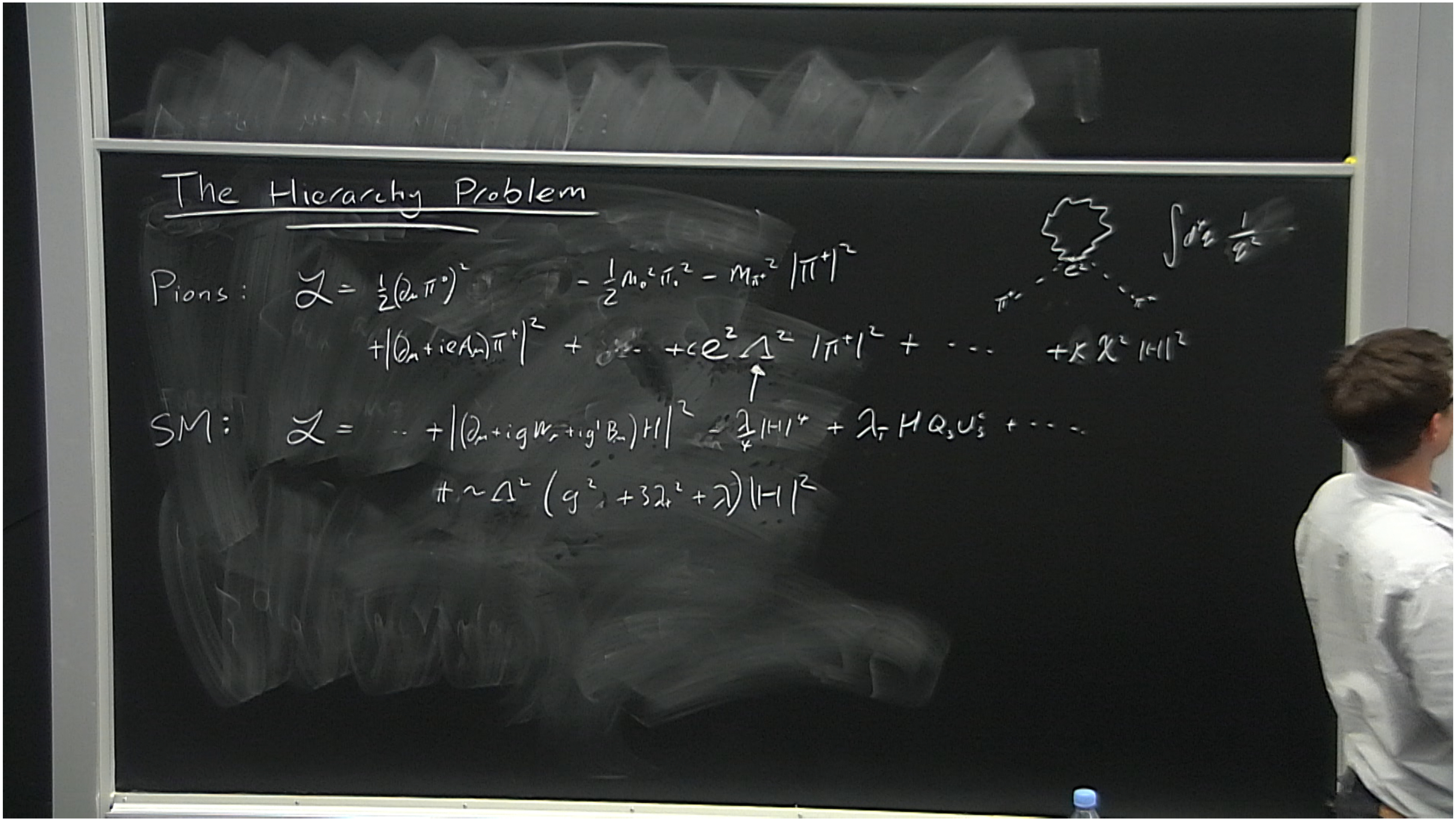
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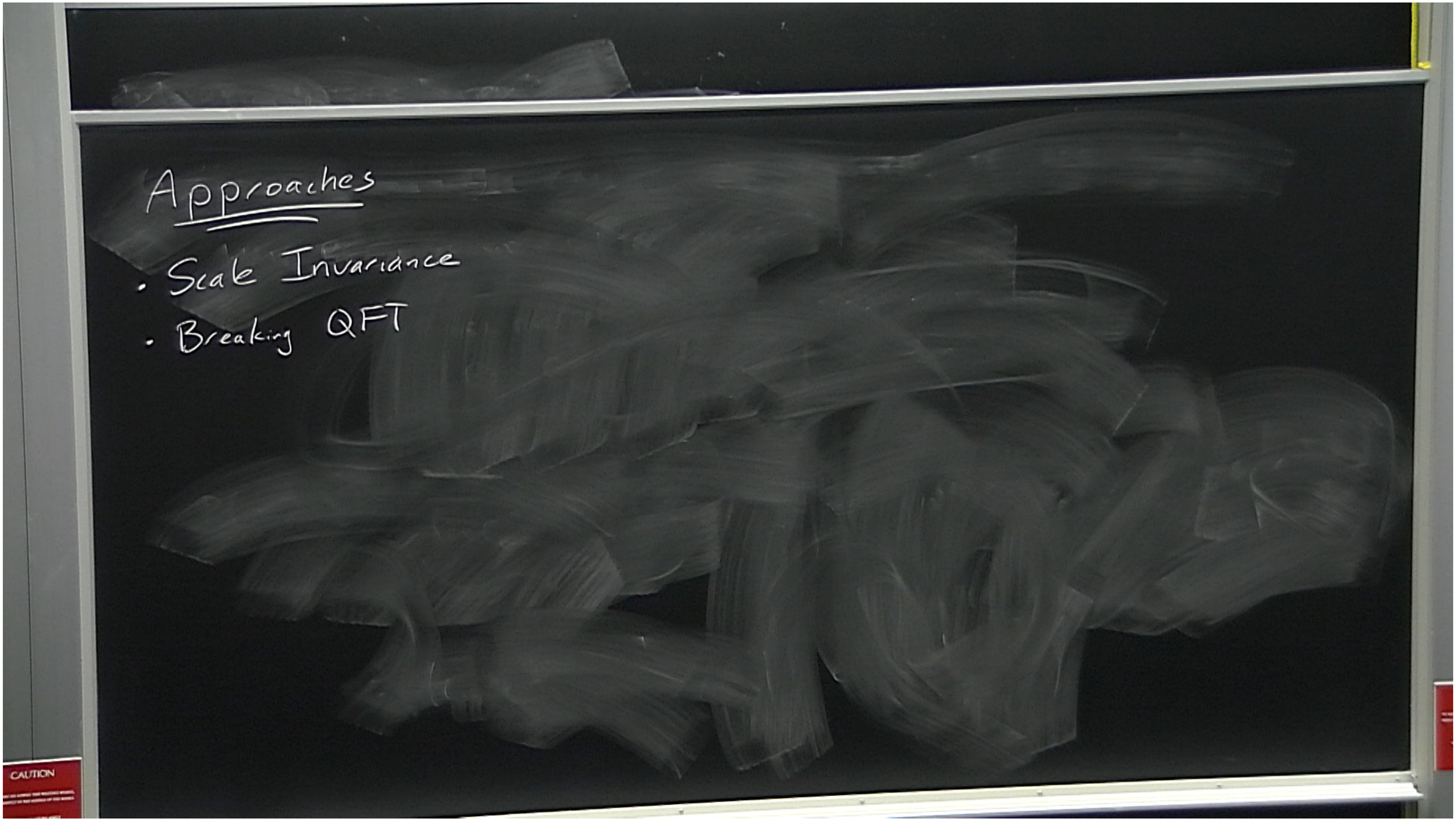
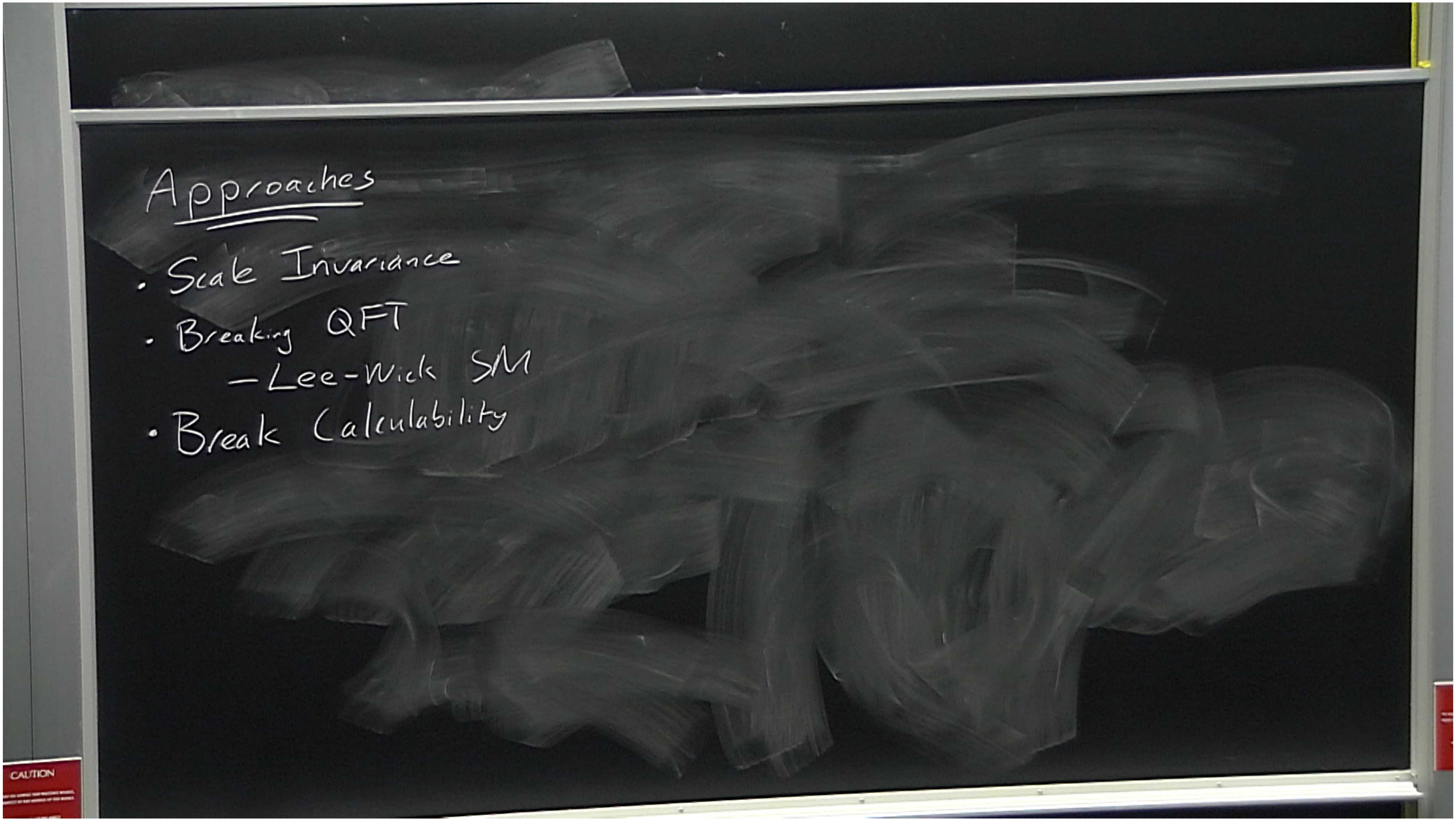
$\int d^4q \frac{1}{q^2}$
e^2
π^+
π^+


Approaches
• Scale Invariance
• Breaking QFT
CAUTION


Approaches
• Scale Invariance
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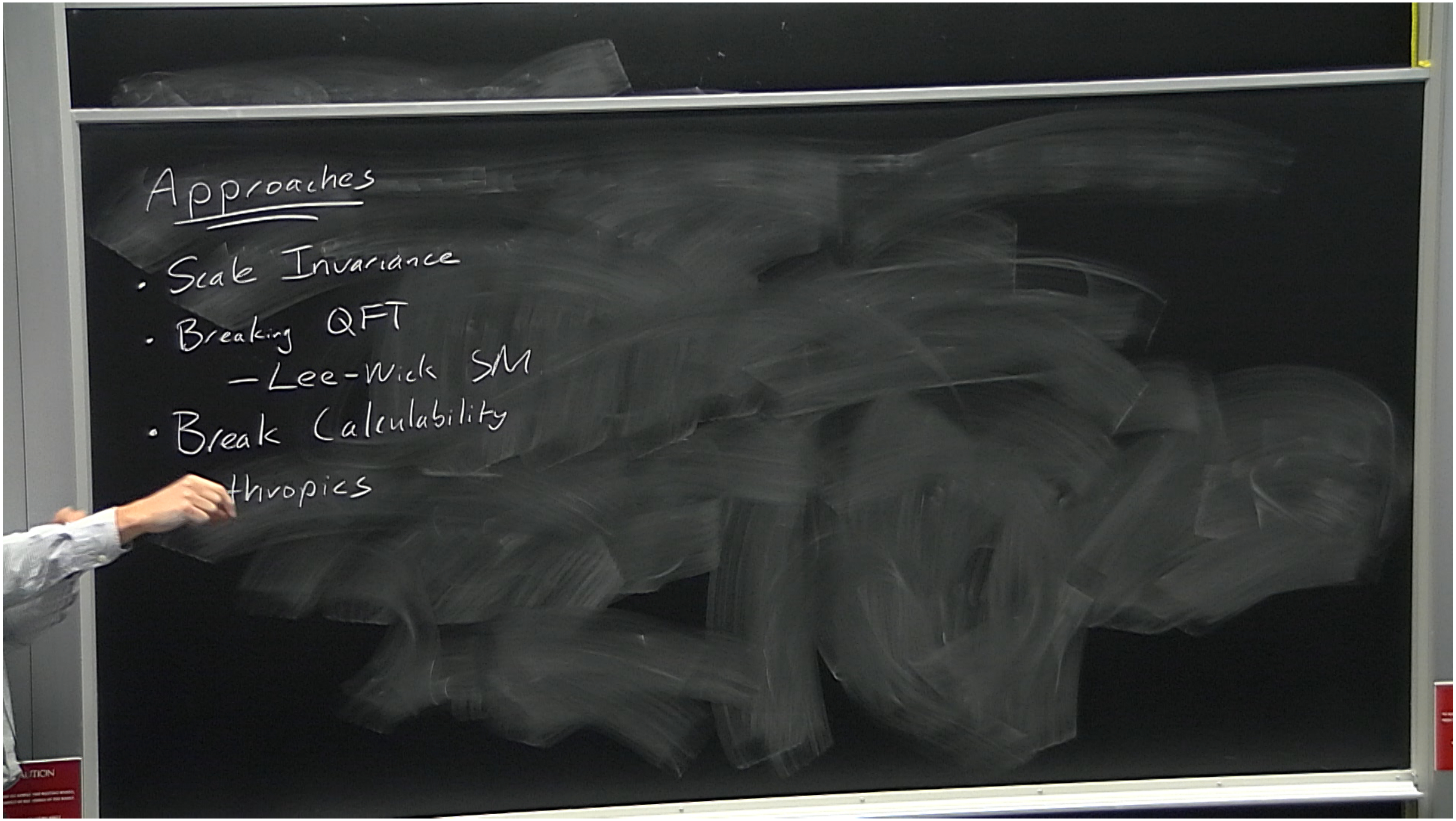
— Lee-Wick SM
• Break Calculability
CAUTION


Approaches
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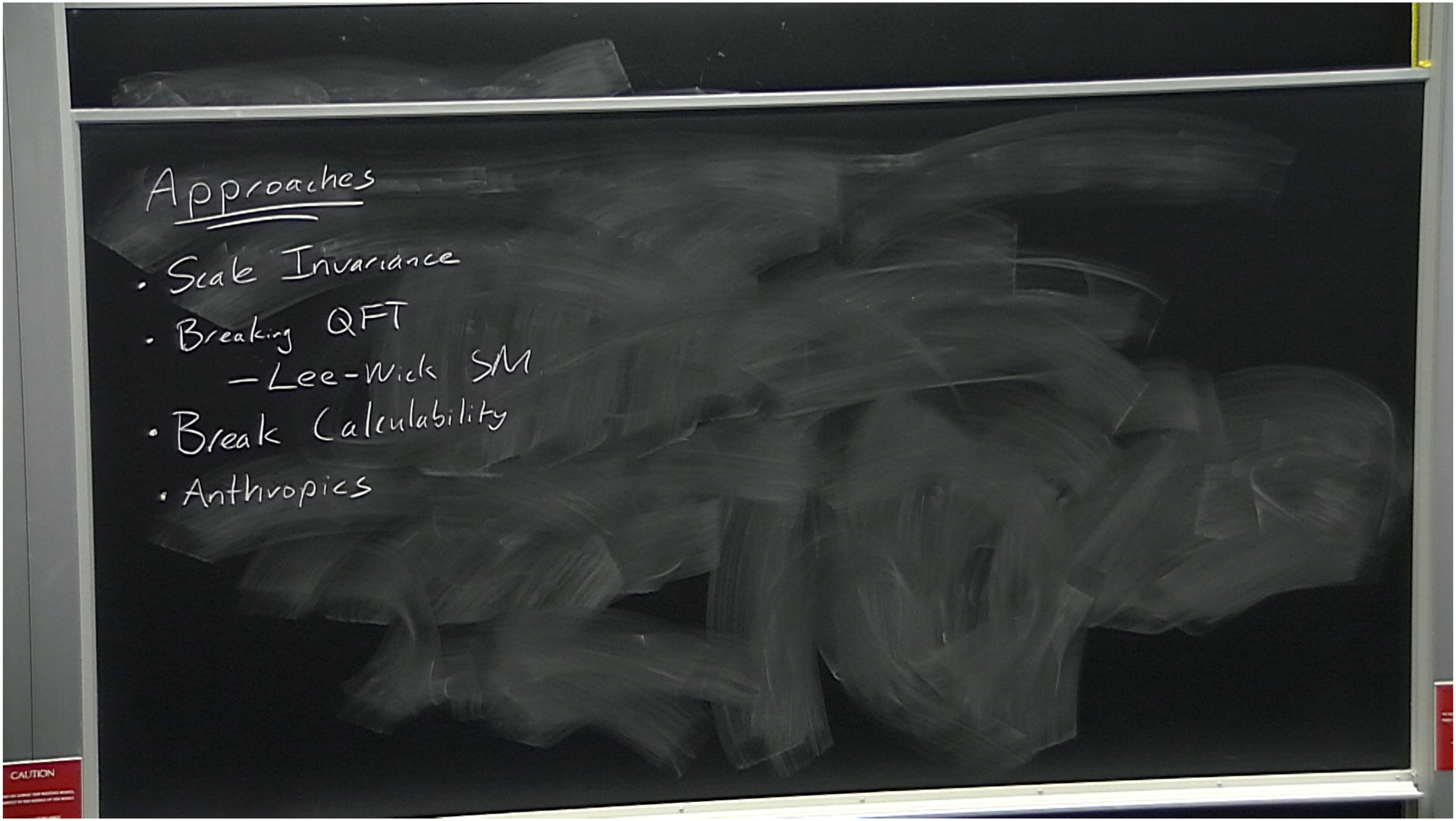
thropics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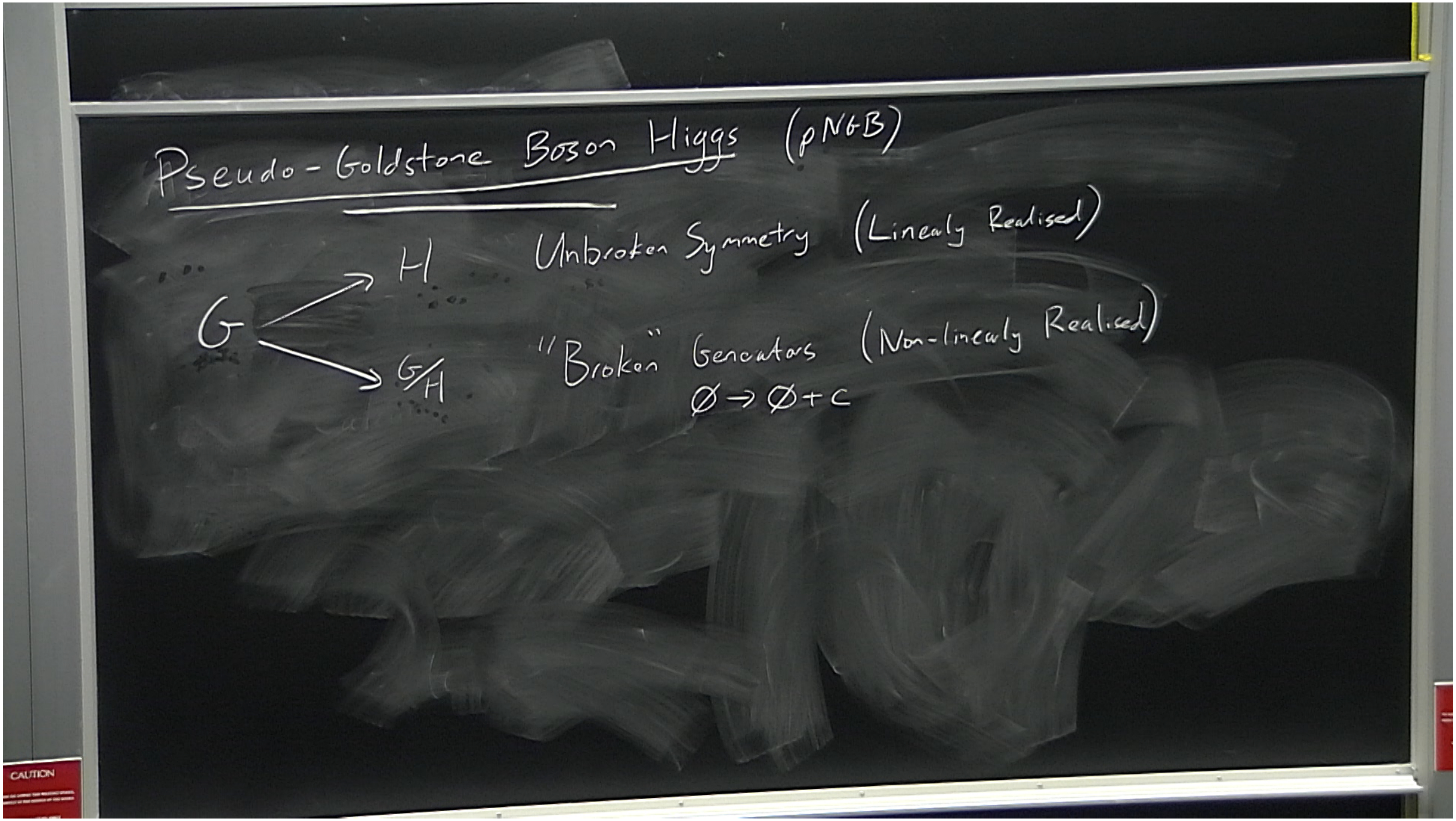
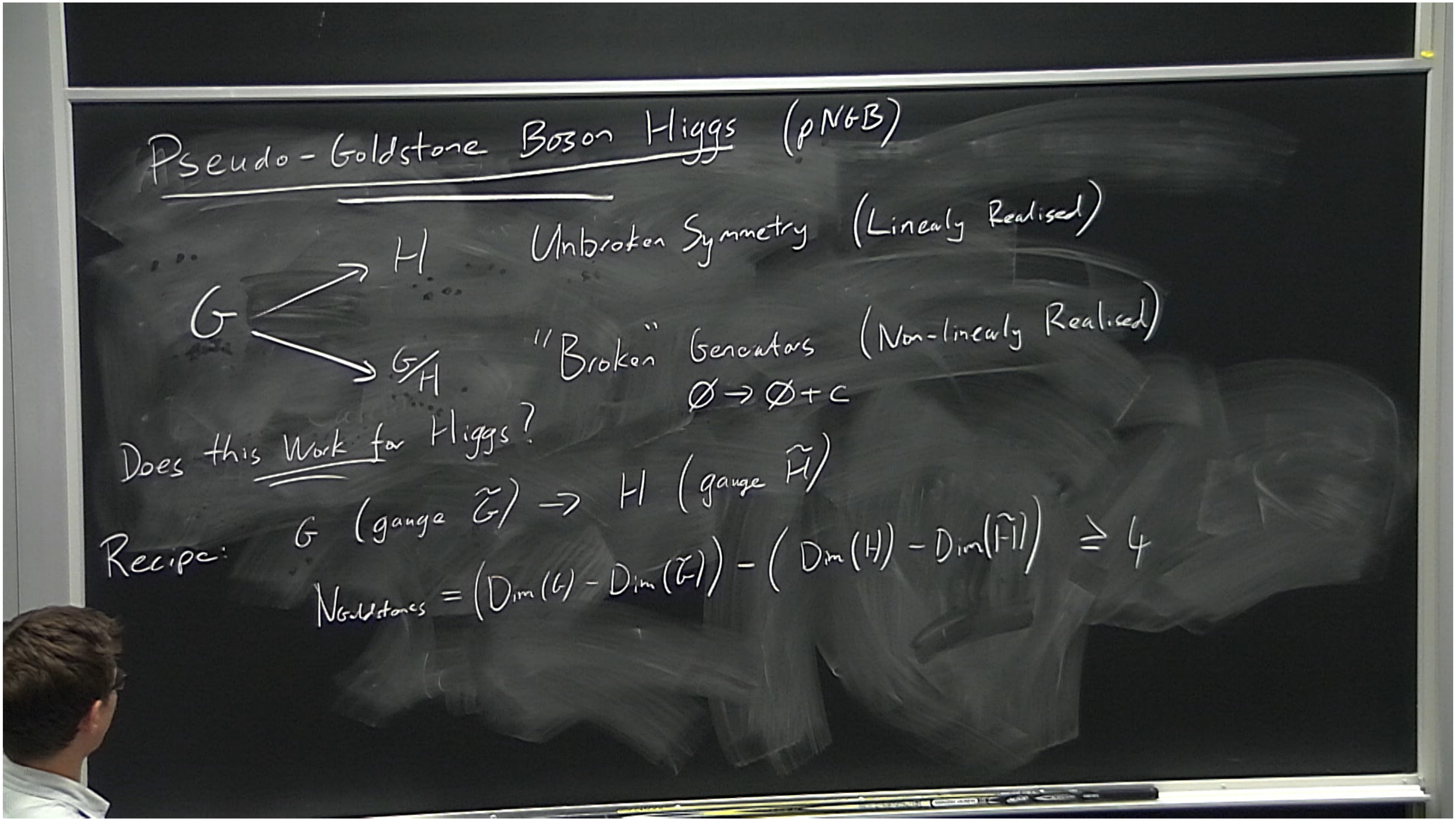
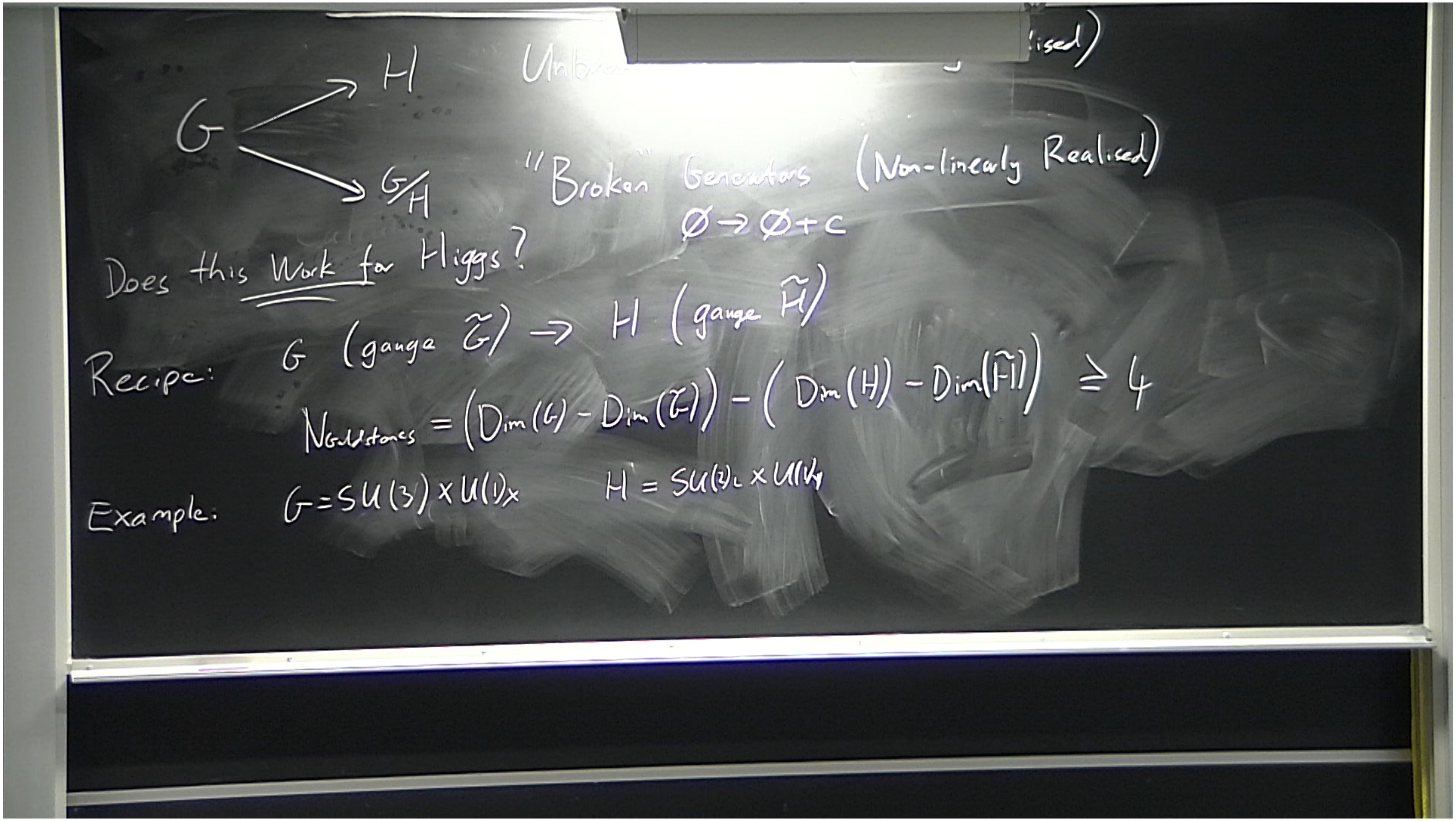

Pseudo-Goldstone Boson Higgs (pNGB)
G
H
Unbroken Symmetry (Linearly Realised)
G/H
"Broken" Generators (Non-linearly Realised)
ϕ → ϕ + c
CAUTION


Pseudo-Goldstone Boson Higgs (pNGB)
G
H
G/H
Unbroken Symmetry (Linearly Realised)
"Broken" Generators (Non-linearly Realised)
$\phi \to \phi + c$
Does this Work for Higgs?
Recipe:
G (gauge $\tilde{G}$) → H (gauge $\tilde{H}$)
$N_{Goldstones} = (\mathrm{Dim}(G) - \mathrm{Dim}(\tilde{G})) - (\mathrm{Dim}(H) - \mathrm{Dim}(\tilde{H})) \geq 4$


G → H Unbro... ...ised)
G → G/H "Broken" Generators (Non-linearly Realised)
Ø → Ø + c
Does this Work for Higgs?
Recipe: G (gauge G̃) → H (gauge H̃)
N_Goldstones = (Dim(G) − Dim(G̃)) − (Dim(H) − Dim(H̃)) ≥ 4
Example: G = SU(3) × U(1)_X H = SU(2)_L × U(1)_Y

$N_{Goldstones} = 5$

Nice Prescription: CCWZ

$$\Sigma = \Sigma_0 \, e^{\frac{i \pi^a t^a}{f}}$$

$$\pi = \pi^a t^a = \begin{pmatrix} 0 & 0 & h_1 \\ 0 & 0 & h_2 \\ h_1^+ & h_2^+ & 0 \end{pmatrix}$$

$$\phi = \phi_R + i \phi_I$$

$$\phi = \rho e^{i\theta}$$

$$\Sigma = \begin{pmatrix} i h_1 \frac{\sin\left(\frac{|h|}{f}\right)}{|h|/f} \\ i h_2 \frac{\sin\left(\frac{|h|}{f}\right)}{|h|/f} \\ f \cos\left(\frac{|h|}{f}\right) \end{pmatrix}$$

$N_{Goldstones} = 5$

Nice Prescription: CCWZ

$$\Sigma = \Sigma_0 \, e^{\frac{i \pi^a t^a}{f}}$$

$$\pi = \pi^a t^a = \begin{pmatrix} \frac{\eta}{2} & 0 & h_1 \\ 0 & \frac{\eta}{2} & h_2 \\ h_1^+ & h_2^+ & -\eta \end{pmatrix}$$

$$\phi = \phi_R + i \phi_I$$

$$\phi = \rho e^{i\theta}$$

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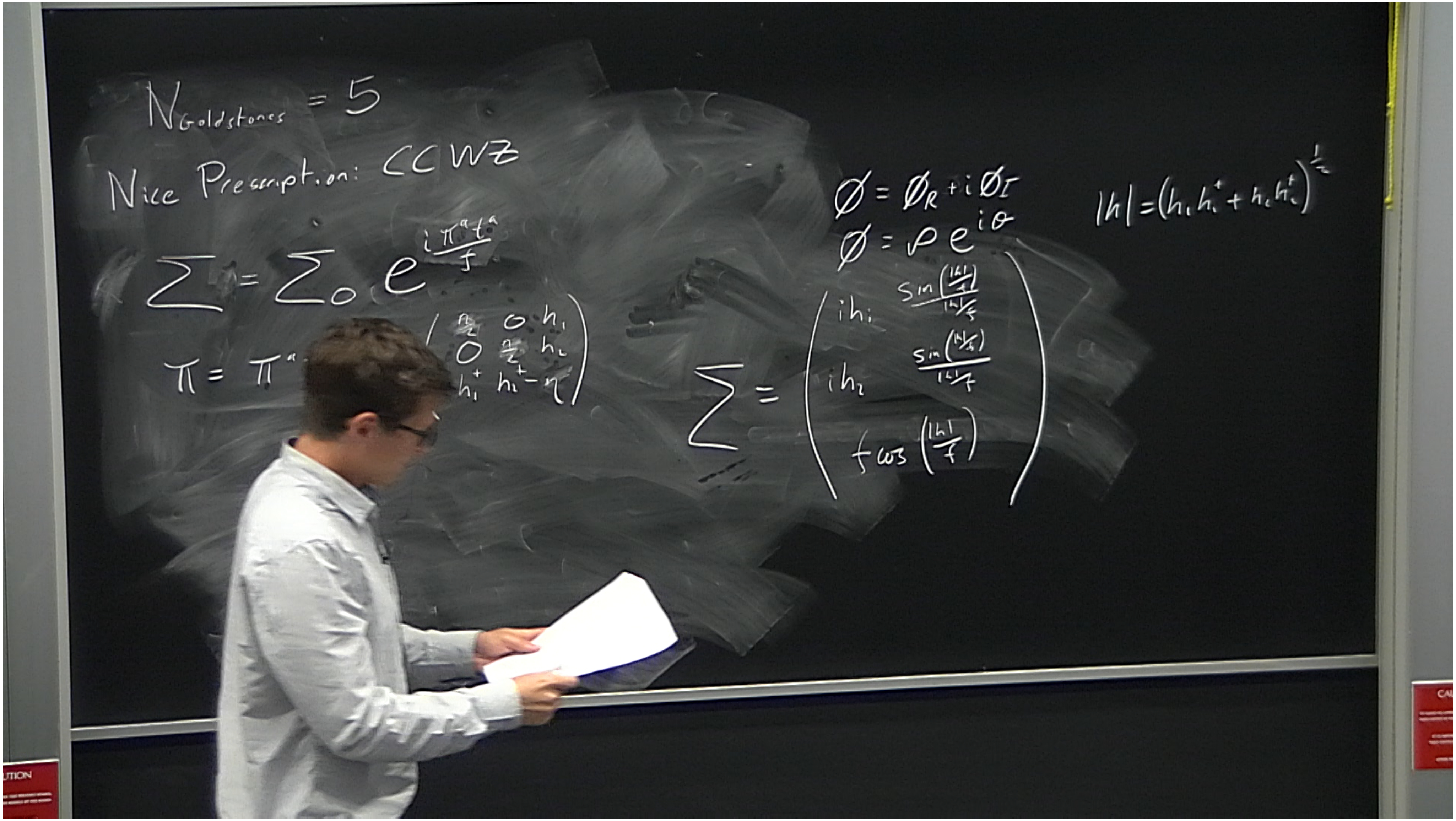
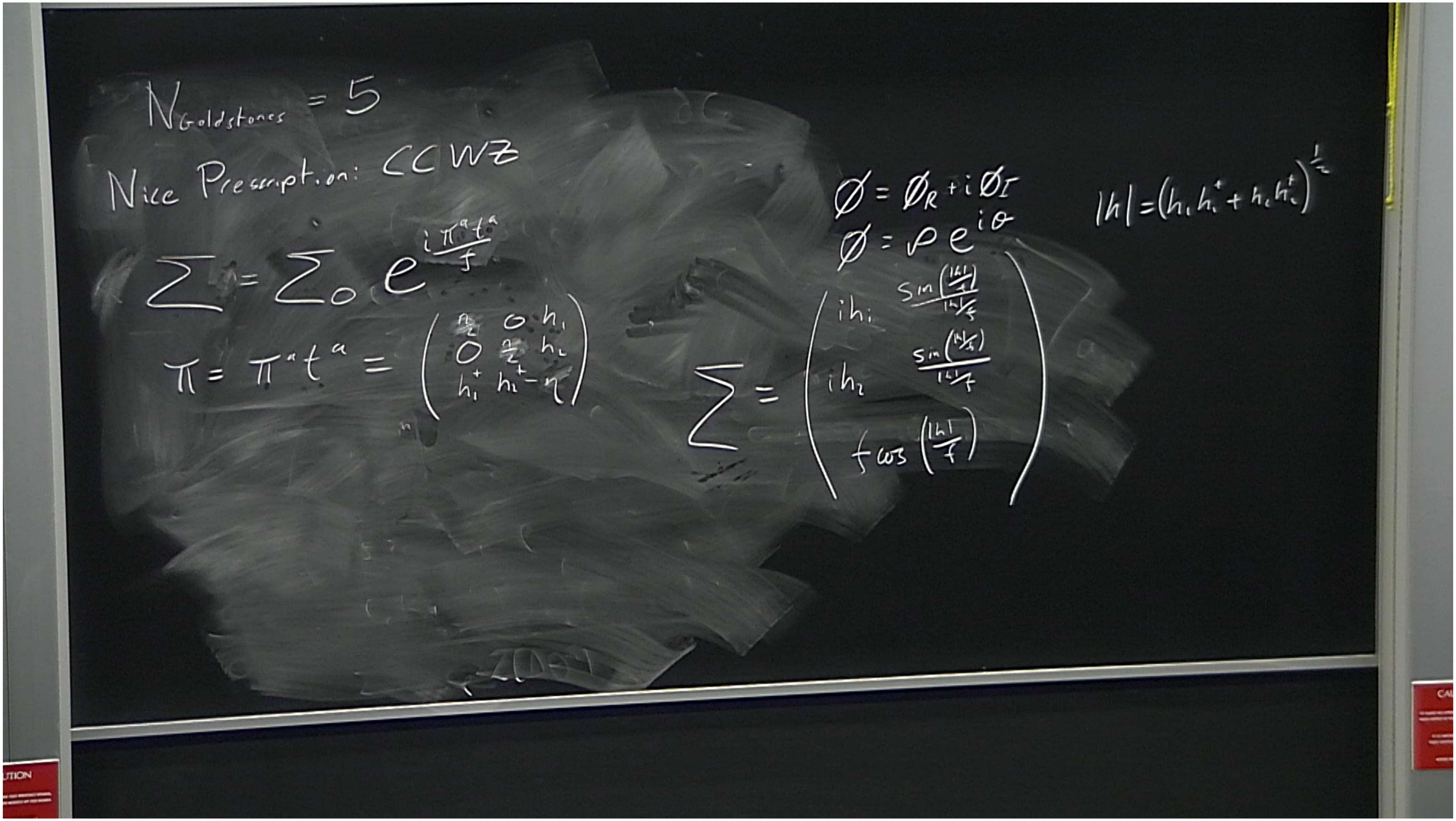

N Goldstones = 5
Nice Prescription: CCWZ
Σ = Σ0 e^(iπ^a t^a / f)
π = π^a
Σ =
ih1
ih2
f cos(|h|/f)
Ø = ØR + i ØI
Ø = ρ e^iθ
|h| = (h1 h1† + h2 h2†)^1/2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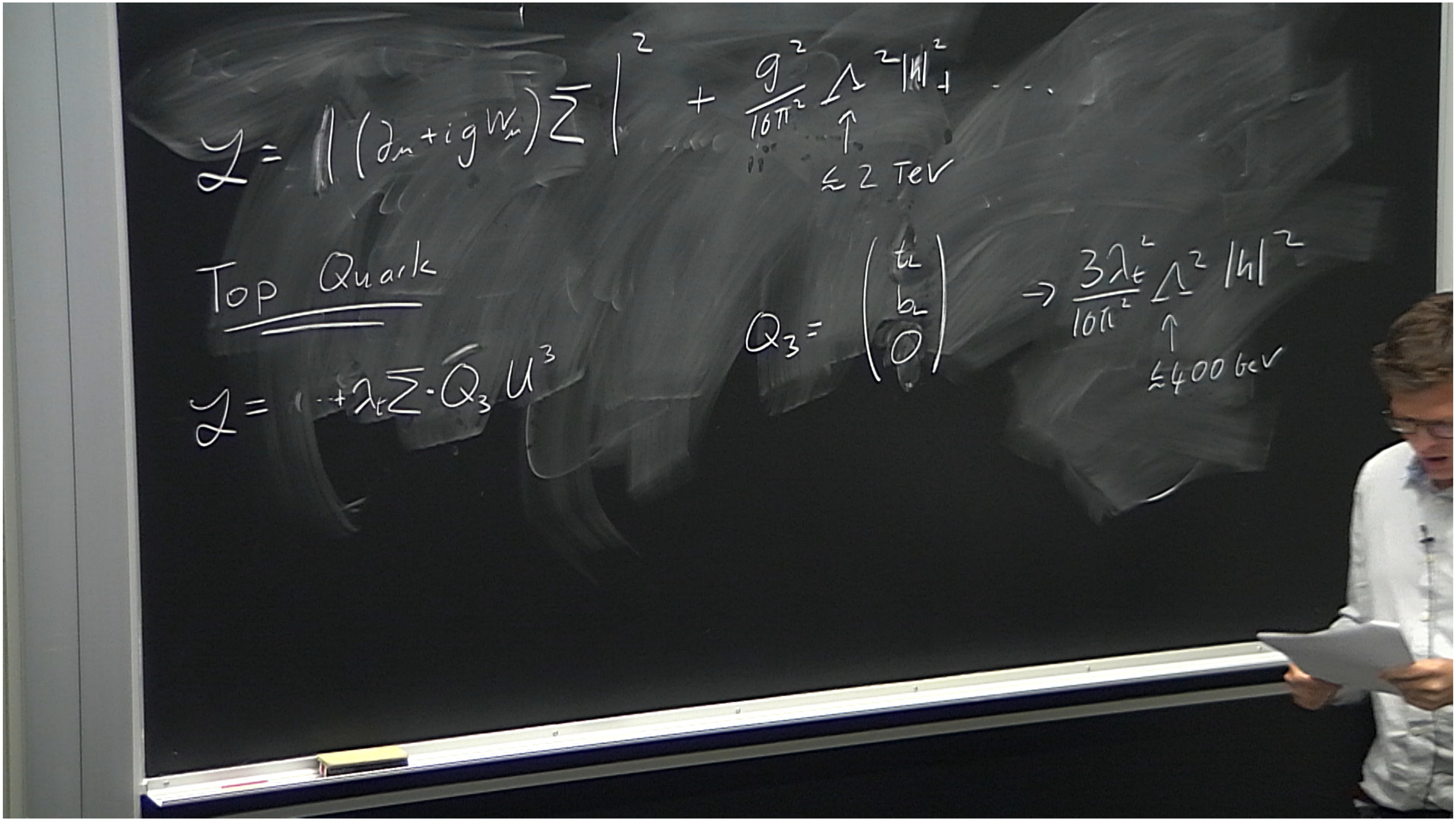
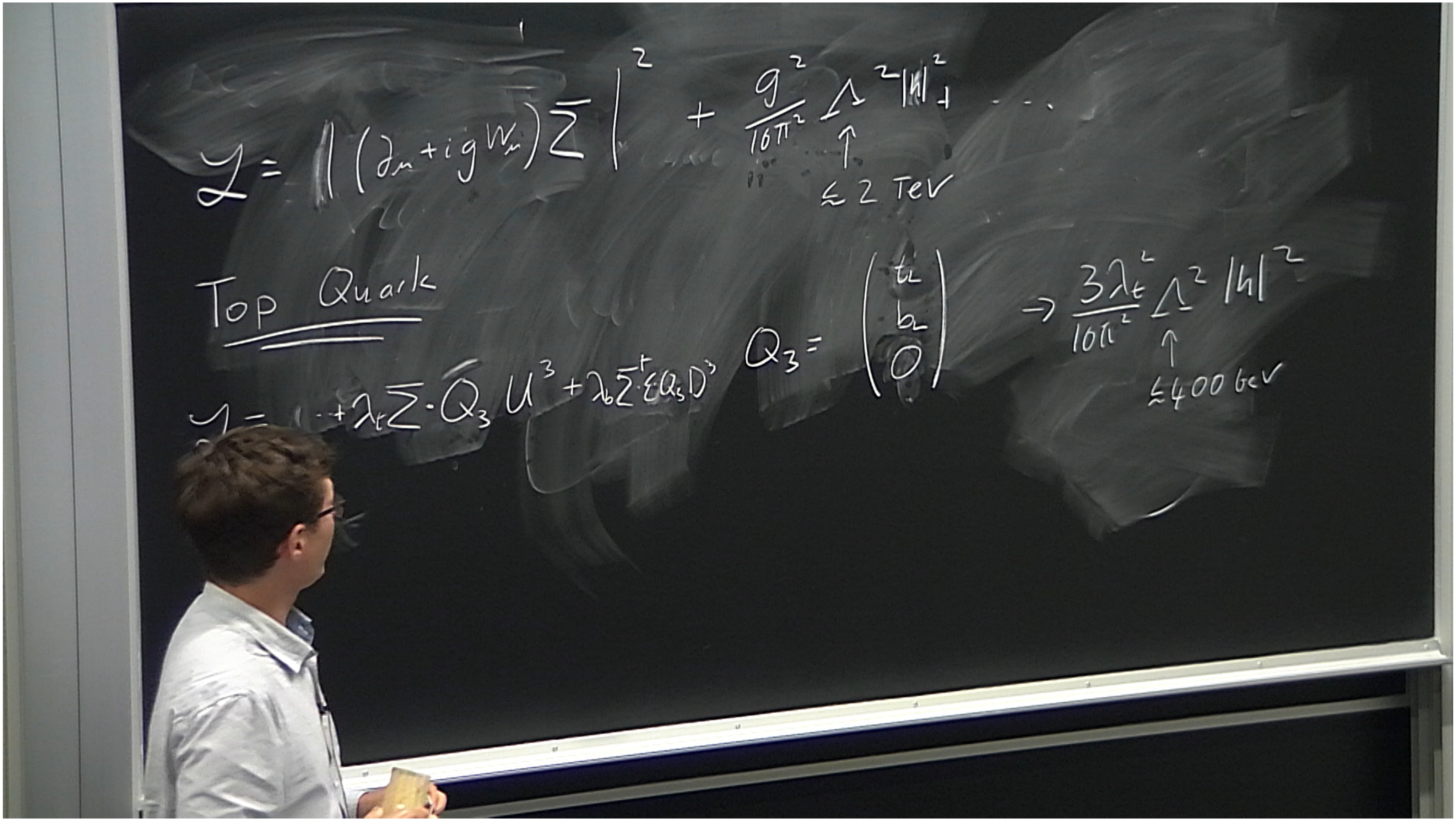
$\phi = \phi_R + i \phi_I$
$\phi = \rho e^{i\theta}$
$|h| = (h_1 h_1^+ + h_2 h_2^+)^{\frac{1}{2}}$
$\Sigma = \begin{pmatrix} i h_1 \frac{\sin(\frac{|h|}{f})}{|h|/f} \\ i h_2 \frac{\sin(|h|/f)}{|h|/f} \\ f \cos\left(\frac{|h|}{f}\right) \end{pmatrix}$



$\mathcal{L} = |(\partial_\mu + i g W_\mu)\Sigma|^2 + \frac{g^2}{16\pi^2}\Lambda^2 |h|^2 + \ldots$
$\lesssim 2$ TeV
Top Quark
$\mathcal{L} = \ldots + \lambda_t \Sigma \cdot Q_3 U^3$
$Q_3 = \begin{pmatrix} t_L \\ b_L \\ 0 \end{pmatrix}$
$\rightarrow \frac{3\lambda_t^2}{16\pi^2}\Lambda^2 |h|^2$
$\lesssim 400$ GeV


$\mathcal{L} = |(\partial_\mu + i g W_\mu)\Sigma|^2 + \frac{g^2}{16\pi^2}\Lambda^2 |h|^2 + \dots$
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Top Quark
$\mathcal{L} = \dots + \lambda_t \Sigma \cdot Q_3 U^3 + \lambda_b \Sigma^\dagger \cdot \epsilon Q_3 D^3$
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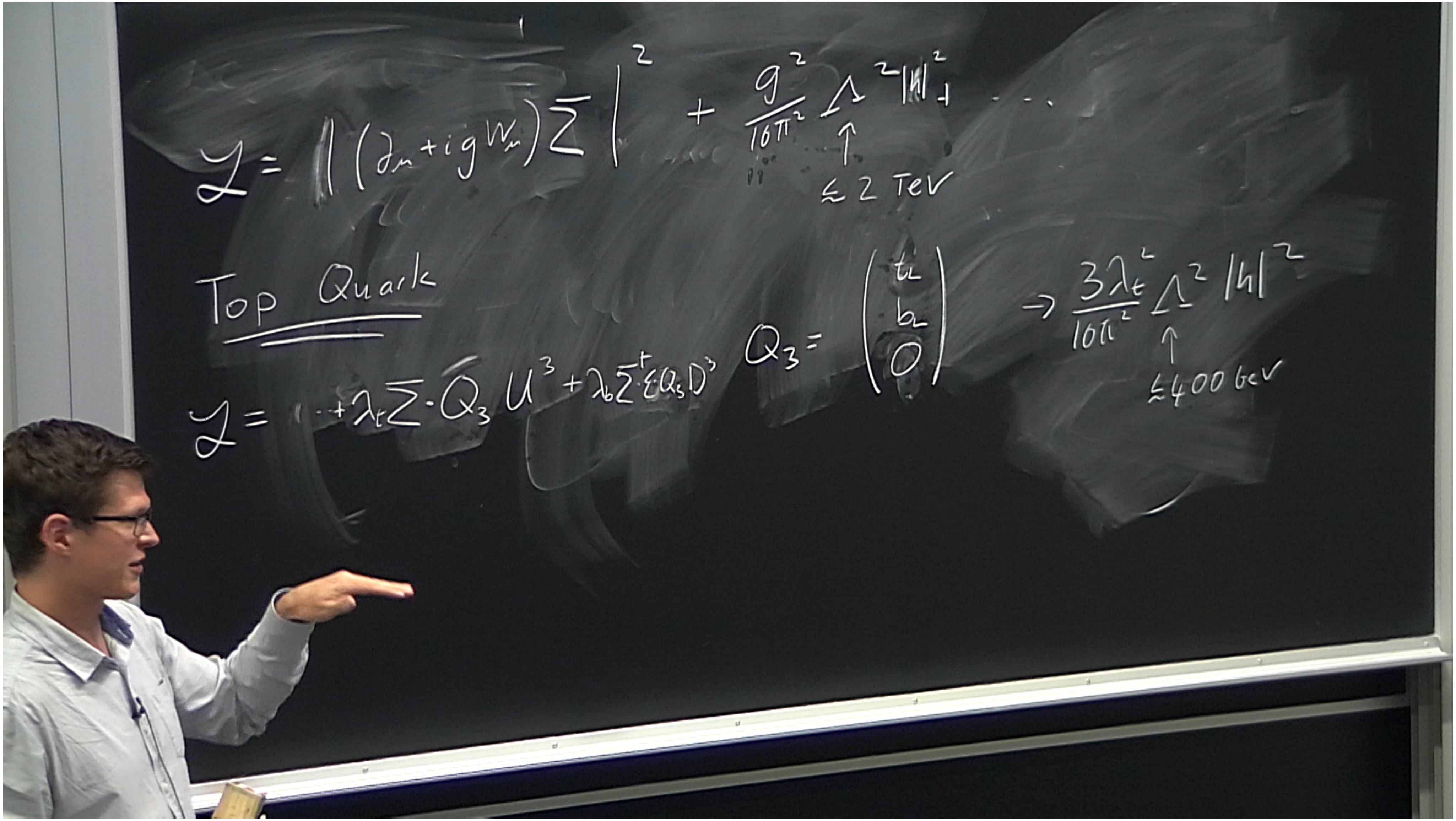
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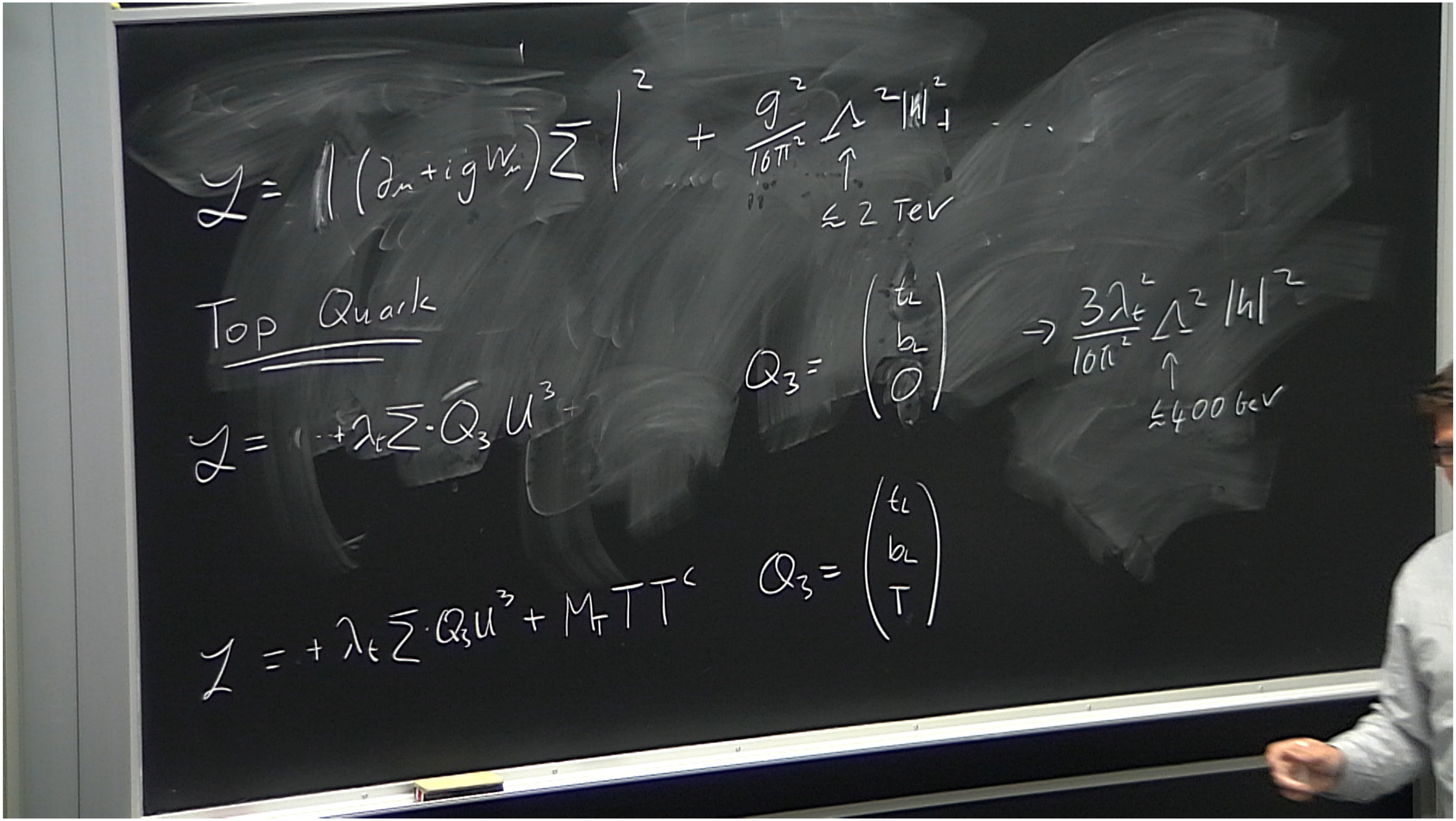

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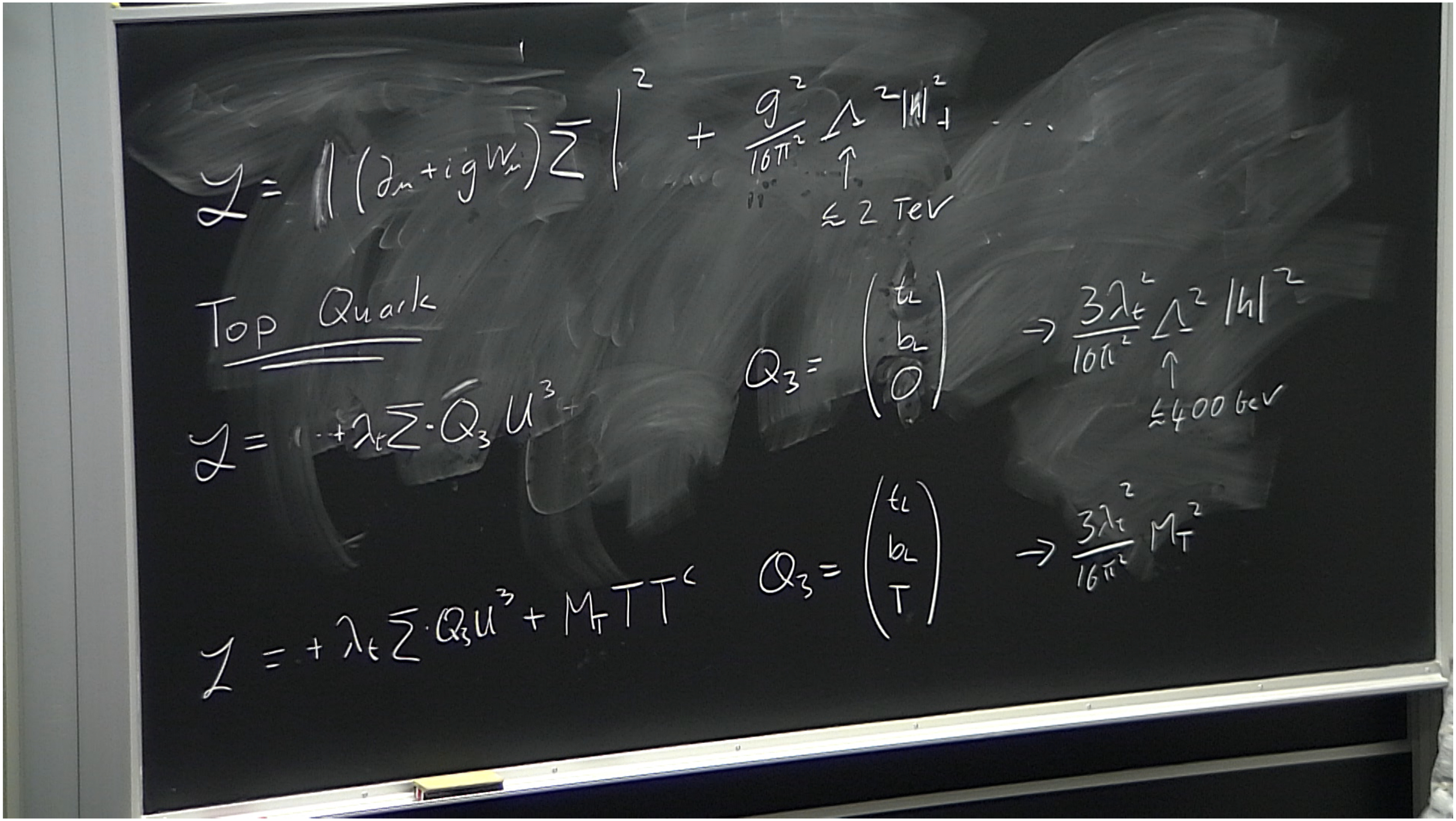
Top Quark
$Q_3 = \begin{pmatrix} t_L \\ b_L \\ 0 \end{pmatrix}$
$\rightarrow \frac{3\lambda_t^2}{16\pi^2}\Lambda^2 |h|^2$
$\lesssim 400$ GeV
$\mathcal{L} = \ldots + \lambda_t \Sigma \cdot Q_3 u^3 +$
$Q_3 = \begin{pmatrix} t_L \\ b_L \\ T \end{pmatrix}$
$\mathcal{L} = + \lambda_t \Sigma \cdot Q_3 u^3 + M_T T T^c$



$\mathcal{L} = |(\partial_\mu + i g W_\mu)\Sigma|^2 + \frac{g^2}{16\pi^2}\Lambda^2 |h|^2 + \ldots$
$\lesssim 2$ TeV
Top Quark
$\mathcal{L} = \cdots + \lambda_t \Sigma \cdot Q_3 u^3 +$
$Q_3 = \begin{pmatrix} t_L \\ b_L \\ 0 \end{pmatrix}$
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$\mathcal{L} = + \lambda_t \Sigma \cdot Q_3 u^3 + M_T T T^c$
$Q_3 = \begin{pmatrix} t_L \\ b_L \\ T \end{pmatrix}$
$\rightarrow \frac{3\lambda_t^2}{16\pi^2} M_T^2$

$$\mathcal{L} = \left|(\partial_\mu + i g W_\mu)\Sigma\right|^2 + \frac{g^2}{16\pi^2}\Lambda^2 |h|^2 + \ldots$$

$\Lambda \uparrow\ \lesssim 2\ \text{TeV}$

Top Quark

$$\mathcal{L} = \ldots + \lambda_t \Sigma \cdot Q_3\, u^3 \qquad Q_3 = \begin{pmatrix} t_L \\ b_L \\ 0 \end{pmatrix} \rightarrow \frac{3\lambda_t^2}{16\pi^2}\Lambda^2 |h|^2$$

$\Lambda \uparrow\ \lesssim 400\ \text{GeV}$

$$\mathcal{L} = \ldots + \lambda_t \Sigma \cdot Q_3 u^3 + M_T T T^c \qquad Q_3 = \begin{pmatrix} t_L \\ b_L \\ T \end{pmatrix} \rightarrow \frac{3\lambda_t^2}{16\pi^2} M_T^2 |h|^2$$

$$\mathcal{L} = \left|(\partial_\mu + i g W_\mu)\Sigma\right|^2 + \frac{g^2}{16\pi^2}\Lambda^2 |h|^2 + \cdots$$

$\Lambda \lesssim 2$ TeV

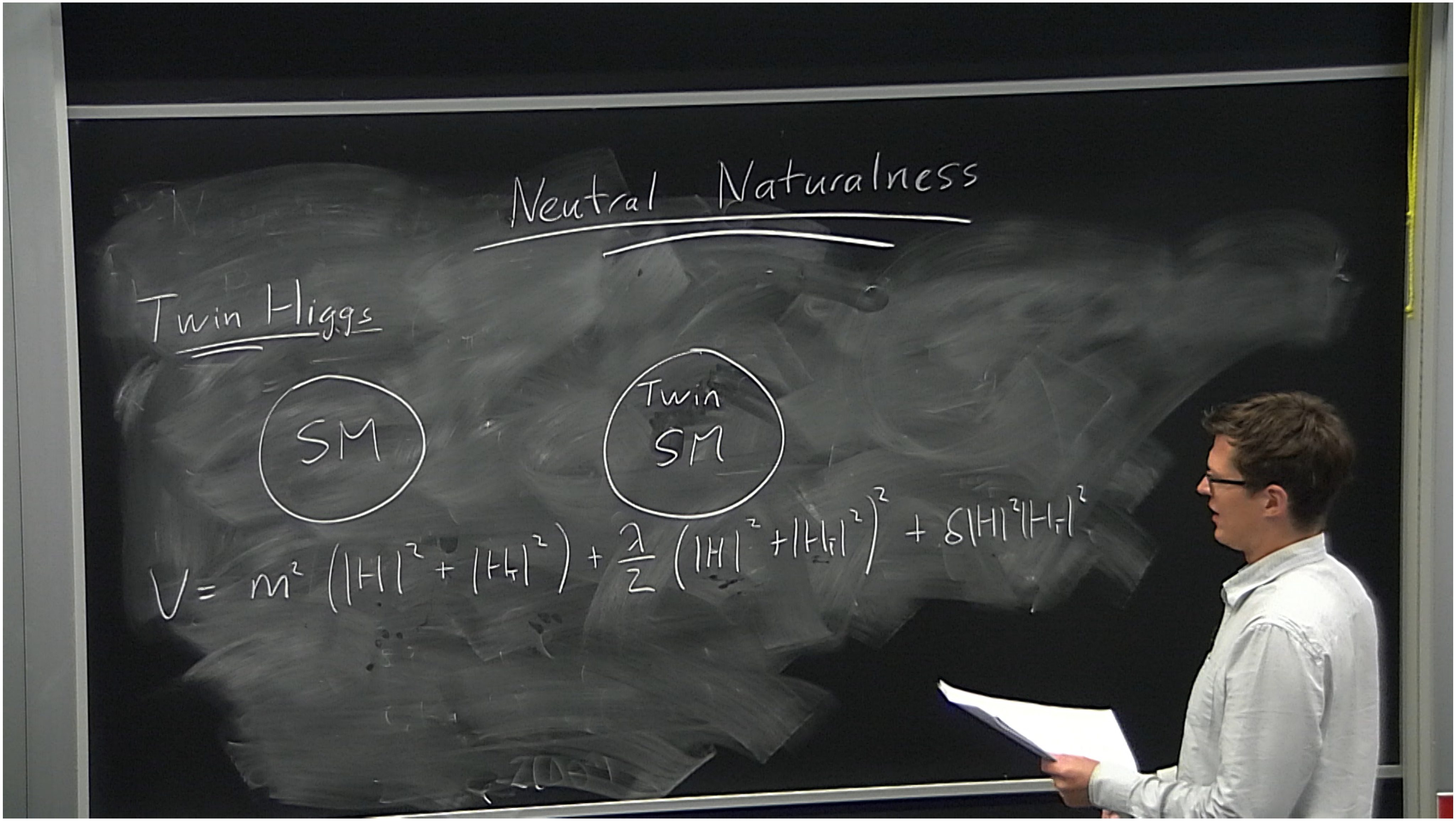
Top Quark

$$\mathcal{L} = \cdots + \lambda_t \Sigma \cdot Q_3 u^3 + \qquad Q_3 = \begin{pmatrix} t_L \\ b_L \\ 0 \end{pmatrix} \rightarrow \frac{3\lambda_t^2}{16\pi^2}\Lambda^2 |h|^2$$

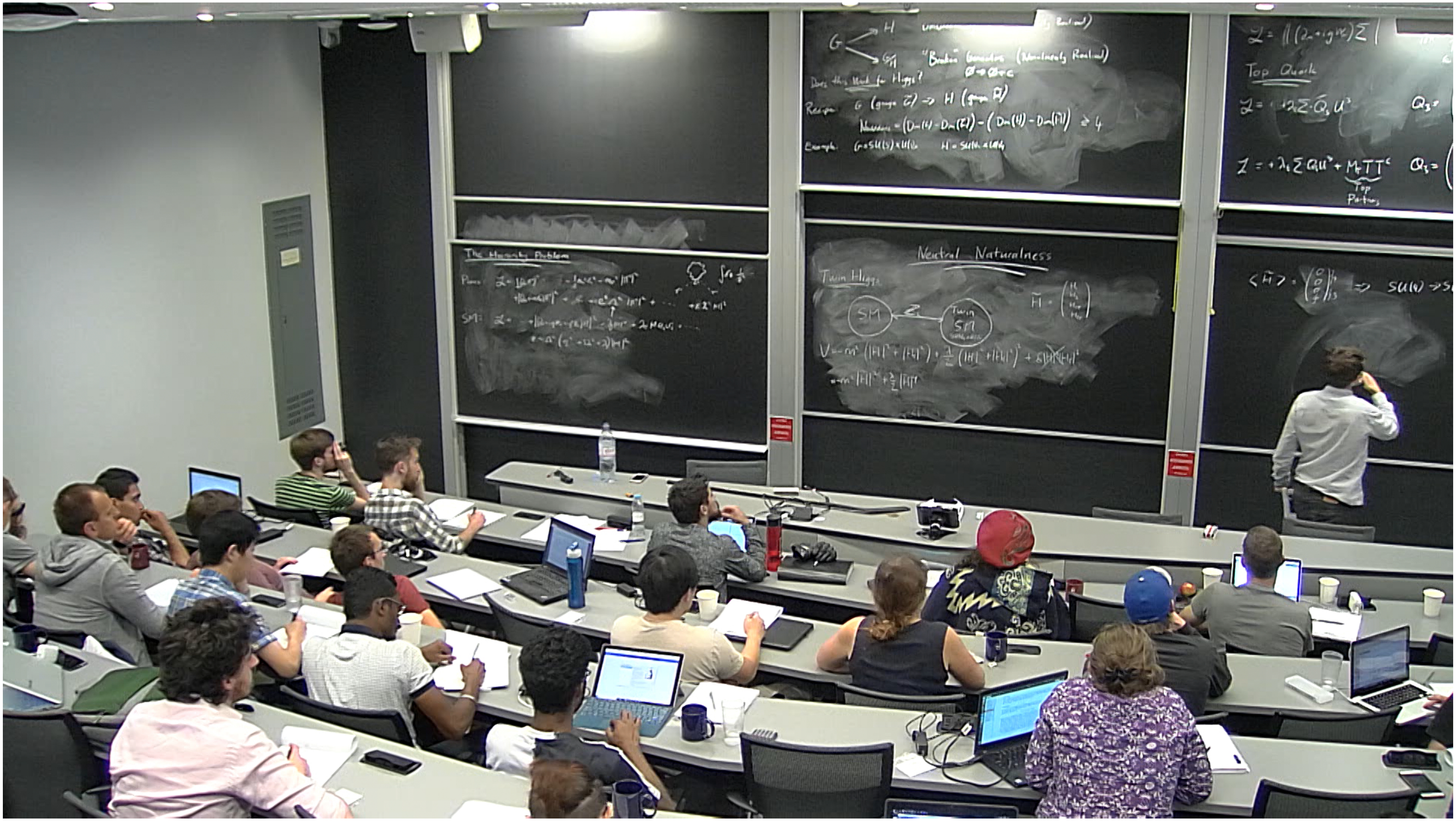
$\Lambda \lesssim 400$ GeV

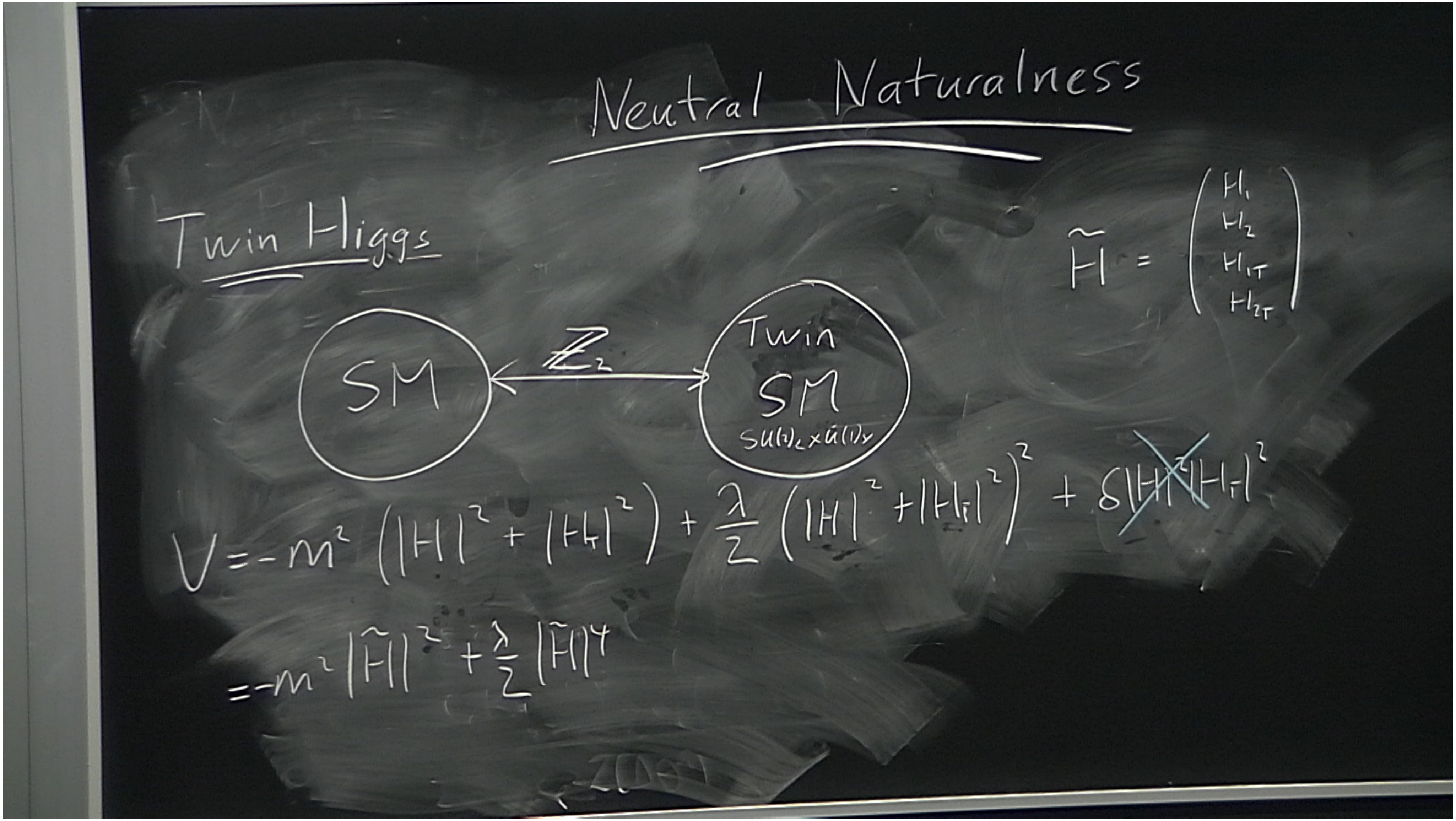
$$\mathcal{L} = + \lambda_t \Sigma \cdot Q_3 u^3 + \underbrace{M_T T T^c}_{\text{Top Partners}} \qquad Q_3 = \begin{pmatrix} t_L \\ b_L \\ T \end{pmatrix} \rightarrow \frac{3\lambda_t^2}{16\pi^2} M_T^2 |h|^2$$

$M_T \lesssim 400$ GeV

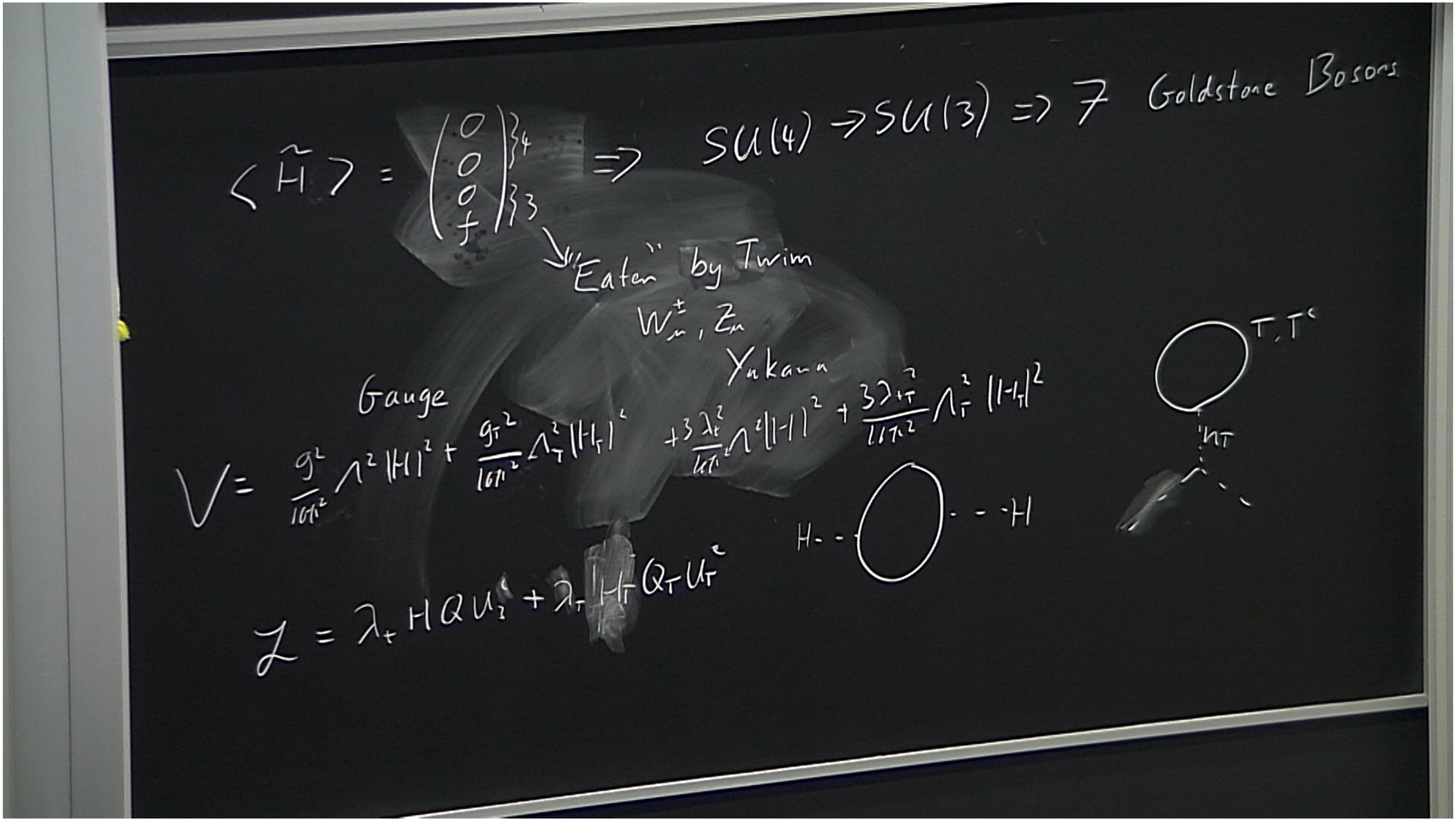


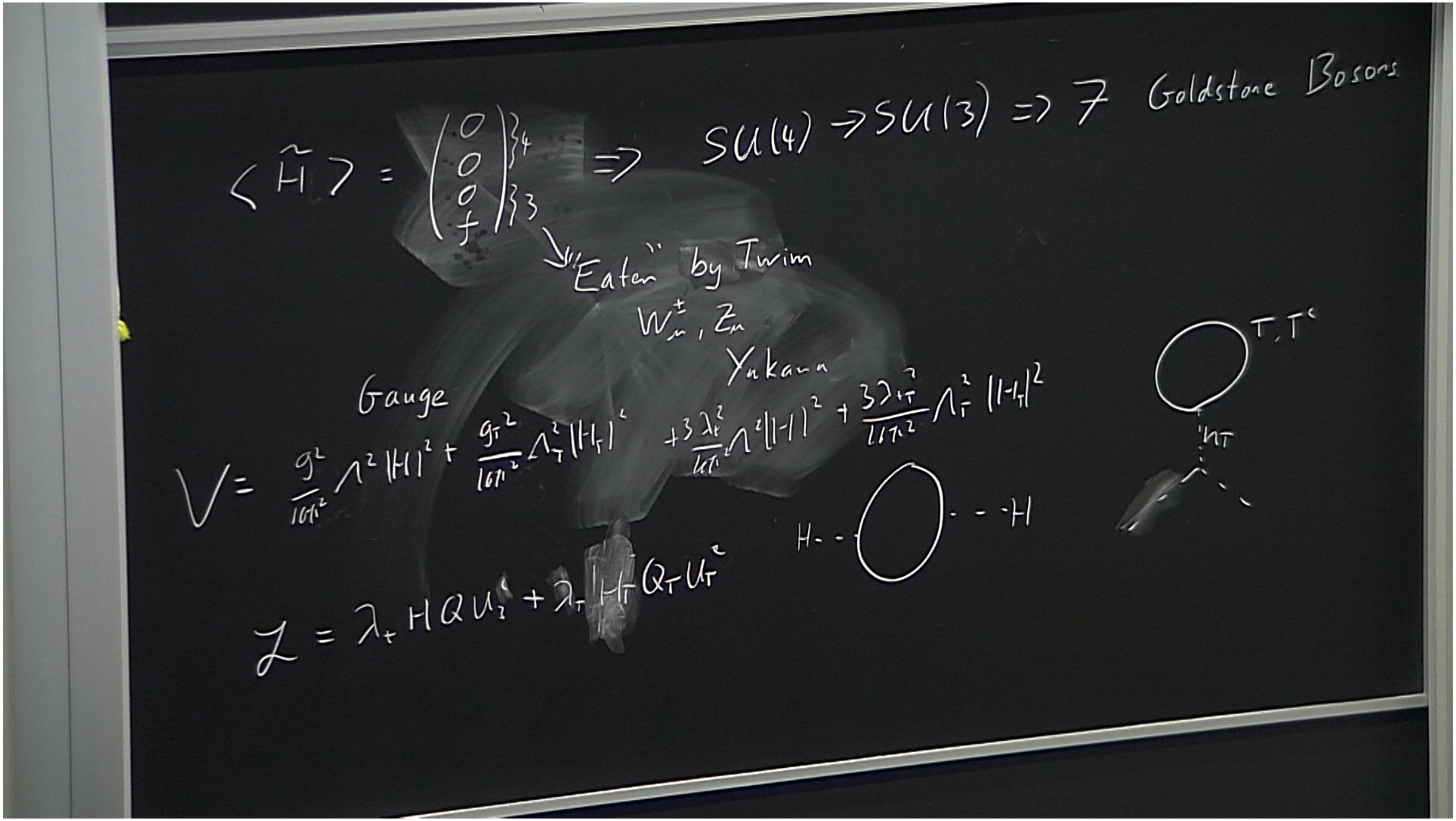
Neutral Naturalness
Twin Higgs
SM
Twin SM
$V = m^2 (|H|^2 + |H_T|^2) + \frac{\lambda}{2} (|H|^2 + |H_T|^2)^2 + \delta |H|^2 |H_T|^2$


"Broken" Generators (Nonlinearly Realized)
Does this Work for Higgs?
Recipe:
Example:
Top Quark
Top Partners
The Hierarchy Problem
Neutral Naturalness
Twin Higgs
SM
Twin SM



Neutral Naturalness
Twin Higgs
SM
Z_2
Twin SM
SU(2)_L × U(1)_Y
H̃ = (H_1, H_2, H_1T, H_2T)
V = -m² (|H|² + |H_T|²) + λ/2 (|H|² + |H_T|²)² + δ|H|²|H_T|²
= -m² |H̃|² + λ/2 |H̃|⁴


SU(4) → SU(3) ⇒ 7 Goldstone Bosons
⟨H̃⟩ = (0, 0, 0, f) }4 }3 ⇒
"Eaten" by Twin
W±μ, Zμ
Gauge
Yukawa
T, Tc
hT
H - - - H


SU(4) → SU(3) ⇒ 7 Goldstone Bosons
"Eaten" by Twin
$W^{\pm}_{\mu}, Z_{\mu}$
Gauge
Yukawa
$V = \frac{g^2}{16\pi^2}\Lambda^2|H|^2 + \frac{g_T^2}{16\pi^2}\Lambda_T^2|H_T|^2 + \frac{3\lambda_t^2}{16\pi^2}\Lambda^2|H|^2 + \frac{3\lambda_T^2}{16\pi^2}\Lambda_T^2|H_T|^2$
T, T^c
h_T
H
H
$\mathcal{L} = \lambda_t H Q U_3^c + \lambda_T H_T Q_T U_T^c$