Title: BSM Theory

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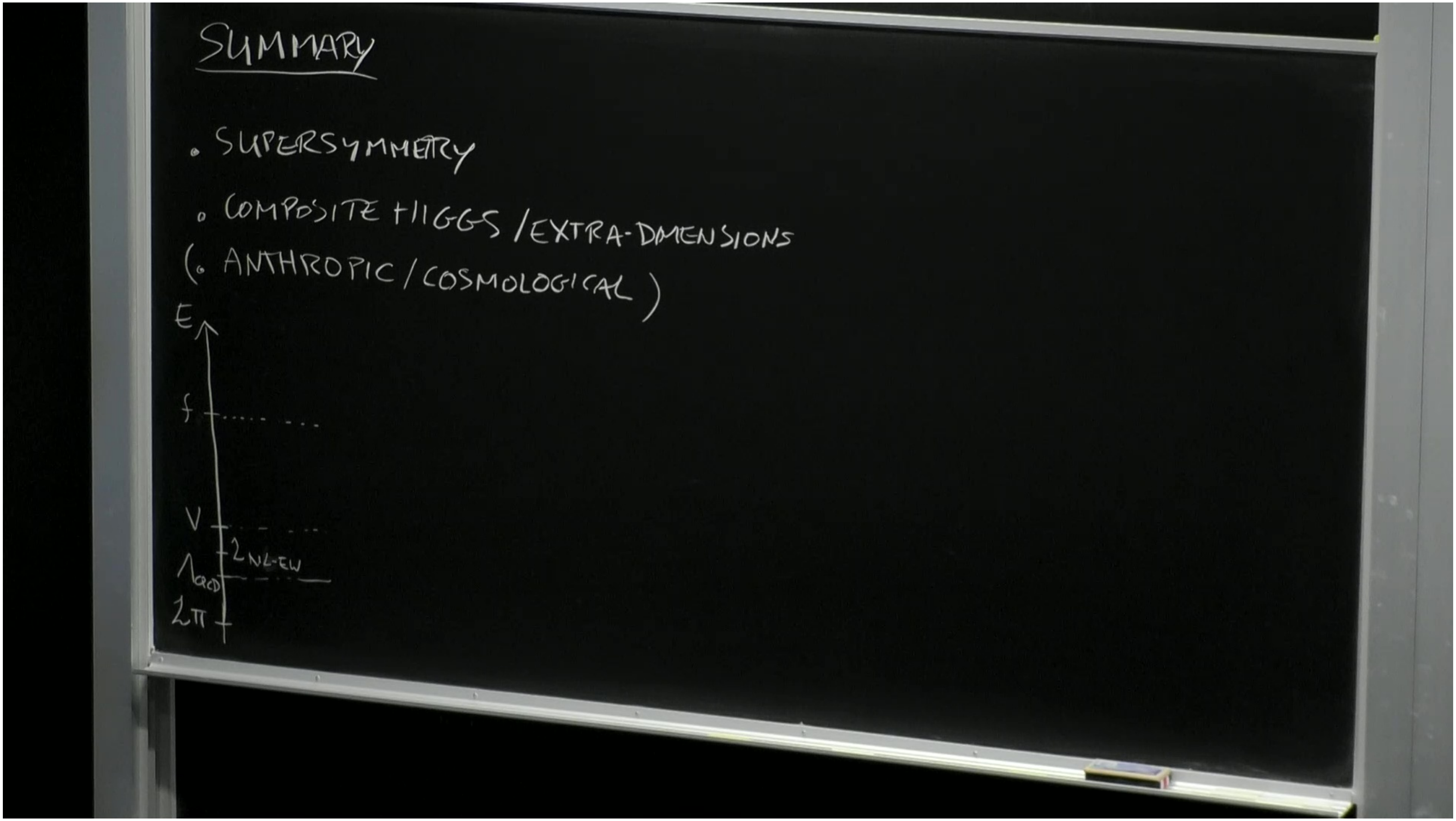
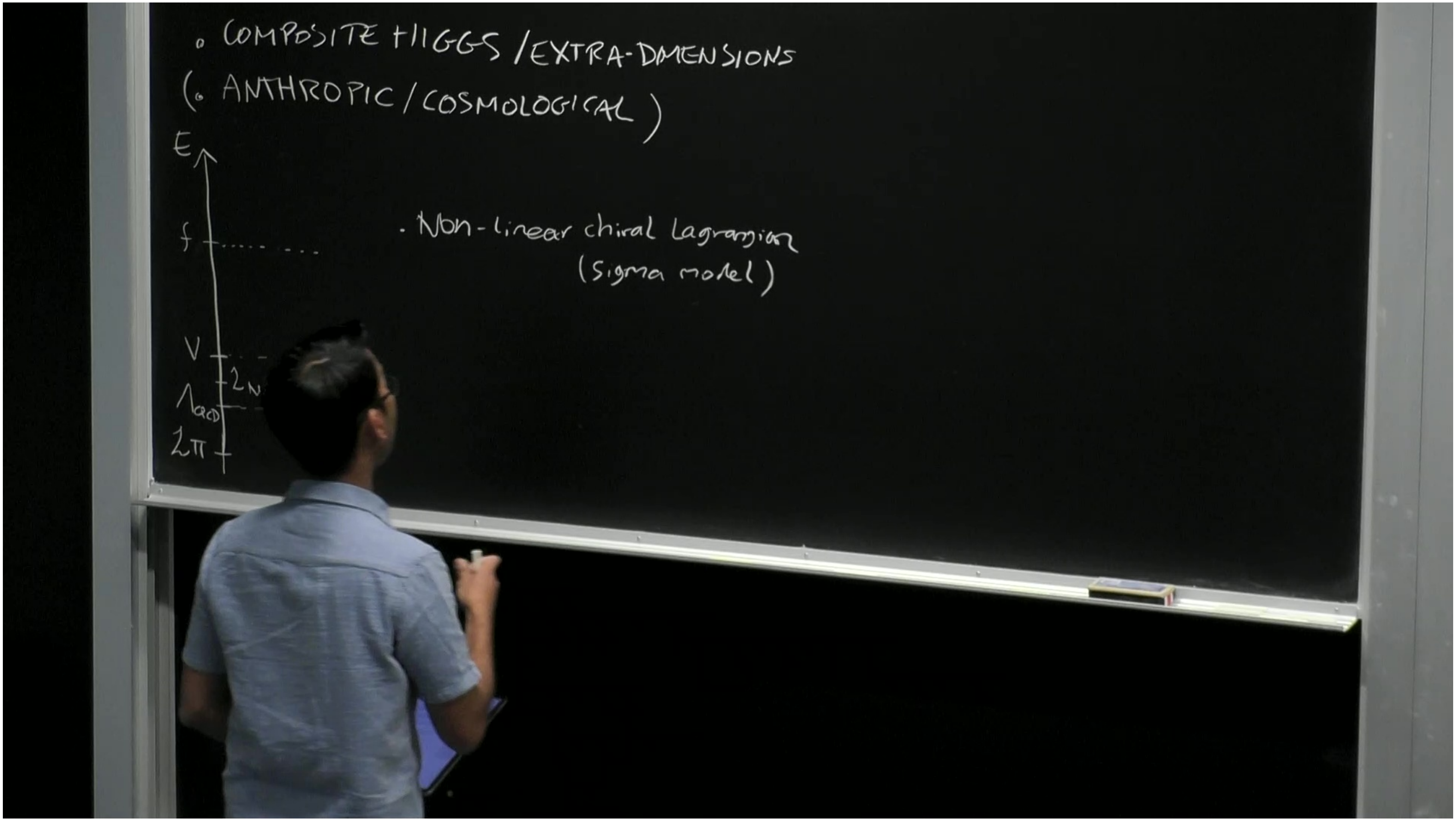

SUMMARY
• SUPERSYMMETRY
• COMPOSITE HIGGS / EXTRA-DIMENSIONS
(• ANTHROPIC / COSMOLOGICAL)
E
f
v
2π


. COMPOSITE HIGGS / EXTRA-DIMENSIONS
(. ANTHROPIC / COSMOLOGICAL)
E
f
. Non-linear chiral Lagrangian
(sigma model)
V
Λ_QCD
Λ_π

$\begin{pmatrix} u \\ d \end{pmatrix}$

2×2 MATRIX SCALARS

$$\mathcal{L} = \bar{\Psi} i \gamma^\mu \partial_\mu \Psi + g\left(\bar{\Psi}_L \Sigma \Psi_R + \bar{\Psi}_R \Sigma \Psi_L\right)$$

$(+ - - -)$

$$\Sigma = \sigma \mathbb{1}_{2\times 2} + i \vec{\pi} \cdot \vec{\sigma}$$

$$+ \frac{1}{2}(\partial_\mu \sigma)^2 + \frac{1}{2}(\partial_\mu \pi^i)^2 - \frac{\mu^2}{2}\left(\sigma^2 + \vec{\pi}^2\right) - \frac{\lambda}{4}\left(\sigma^2 + \vec{\pi}^2\right)^2$$

$$U_{L,R} = e^{-\frac{i}{2}\alpha^a_{L,R}\sigma^a}$$

- Σ transforms under $\underbrace{SU(2)_L \times SU(2)_R}_{SO(4)}$ $\qquad \Sigma \to U_L \Sigma U_R$

$$\phi = \begin{pmatrix} \pi_1 \\ \pi_2 \\ \pi_3 \\ \sigma \end{pmatrix} \qquad V = \frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$

- $\langle \phi \rangle = f \quad \Rightarrow \quad \sigma^2 + \vec{\pi}^2 = f^2$ choose $\langle \sigma \rangle = f \quad \langle \pi^i \rangle = 0$

$-\mu^2/\lambda$ shift $\sigma \to \sigma - f$

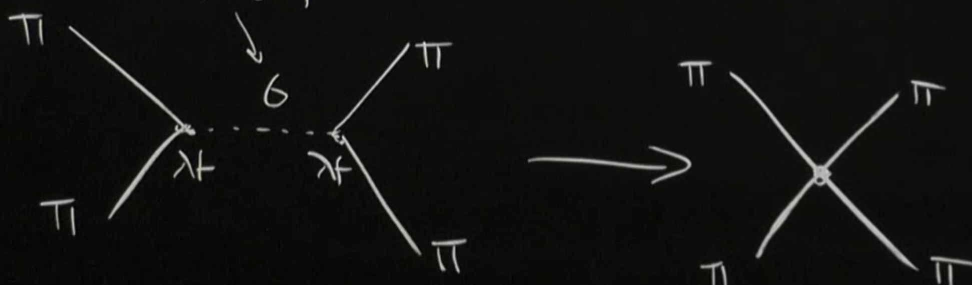
$$\mathcal{L} = \bar{\Psi} i \gamma^\mu \partial_\mu \Psi + g f \bar{\Psi}\Psi - \lambda f^2 \sigma^2 + g \bar{\Psi}(\sigma + i \vec{\tau}\cdot\vec{\pi})\Psi$$
$$- \frac{\lambda}{4}(\sigma^2 + \vec{\pi}^2)^2 - \lambda f \sigma(\sigma^2 + \vec{\pi}^2)$$

$-\mu^2/\lambda$

Shift $\sigma \to \sigma - f$

$$\mathcal{L} = \bar{\Psi} i\gamma^\mu \partial_\mu \Psi + gf\bar{\Psi}\Psi - \lambda f^2 \sigma^2 + g\bar{\Psi}(\sigma + i\vec{\tau}\cdot\vec{\pi})\Psi$$
$$- \frac{\lambda}{4}(\sigma^2 + \vec{\pi}^2)^2 - \lambda f \sigma(\sigma^2 + \vec{\pi}^2)$$

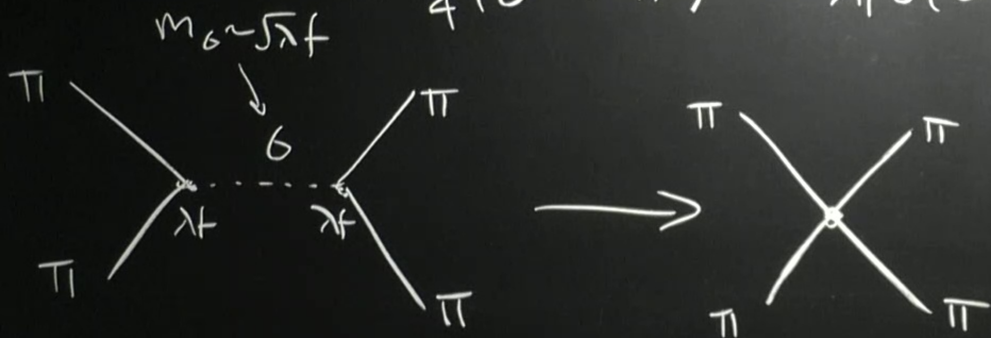
$m_\sigma \sim \sqrt{\lambda} f$



$-\mu^2/\lambda$

$\to \sigma - f$

$$\mathcal{L} = \bar\Psi i\gamma^\mu\partial_\mu\Psi + gf\bar\Psi\Psi - \lambda f^2\sigma^2 + g\bar\Psi(\sigma + i\vec\sigma\cdot\vec\pi)\Psi$$
$$- \frac{\lambda}{4}(\sigma^2+\vec\pi^2)^2 - \lambda f\sigma(\sigma^2+\vec\pi^2)$$



<u>But</u> As $f \to \infty$ coupling $\lambda f \to \infty$

• How to decouple heavy σ in a symmetry-respecting way?

$$\underbrace{\phi^2}_{\sigma^2+\vec{\pi}^2} = f^2 \Rightarrow \sigma = \sqrt{f^2-\vec{\pi}^2} \simeq f\left(1-\frac{1}{2}\frac{\vec{\pi}^2}{f^2}+\dots\right)$$

$$\mathcal{L}_\pi = \frac{1}{2}\left[(\partial_\mu\vec{\pi})^2 + \frac{(\vec{\pi}\cdot\partial_\mu\vec{\pi})^2}{f^2-\vec{\pi}^2}\right] + g\bar{\Psi}\left[\sqrt{f^2-\vec{\pi}^2}+i\vec{\sigma}\cdot\vec{\pi}\right]\Psi$$

• Use a different parametrisation of 4 scalar d.o.f:

$$\Sigma = \rho U \qquad U = e^{i\frac{\vec{\xi}\cdot\vec{\sigma}}{f}}$$

Singlet under full $SU(2)_L\times SU(2)_R$

triplet

$\rho^2 = \frac{1}{2}\mathrm{Tr}(\Sigma^\dagger\Sigma) = \sigma^2 + \pi^2 = f^2$ shift $\rho \to \rho - f$

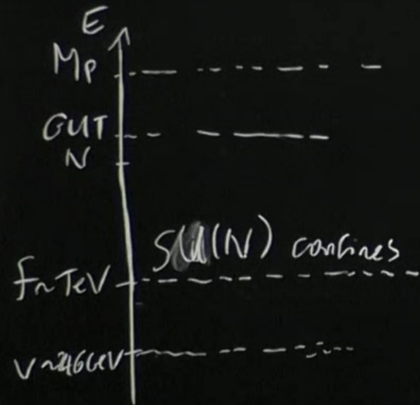
$$\mathcal{L} = \frac{f^2}{4}\mathrm{Tr}(\partial_\mu U^\dagger \partial^\mu U) + \bar{\Psi} i\gamma^\mu \partial_\mu \Psi + gf(\bar{\Psi}_L U \Psi_R + \bar{\Psi}_R U^\dagger \Psi_L)$$

- $\vec{\xi}$ transforms non-linearly under $SU(2)_L \times SU(2)_R$: $LUR^\dagger \Rightarrow \xi' = f(\xi)$
- $SU(2)_L \times SU(2)_R \to SU(2)_V$

in QCD: confinement of quarks $\langle \mathcal{O}_{QCD} \rangle \sim \langle \bar{q}_L q_R \rangle$

- $SU(3)_L \times SU(3)_R \to SU(3)_V$
- explicit breaking from quark masses

COMPOSITE HIGGS



Global symmetry G broken to H

$SO(5) \to SO(4) \Rightarrow$ no. of Goldstones $= 4$

$\Rightarrow$ Higgs as a pNGB

$$\vec{\phi} = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \end{pmatrix}$$

$$\Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \\ \sigma \end{pmatrix}$$

$$\Rightarrow \Phi^2 + \vec{\sigma}^2 = f^2 \Rightarrow \sigma = \sqrt{f^2 - \vec{\phi}^2}$$

$\begin{pmatrix} u \\ d \end{pmatrix}$

2×2 MATRIX SCALARS

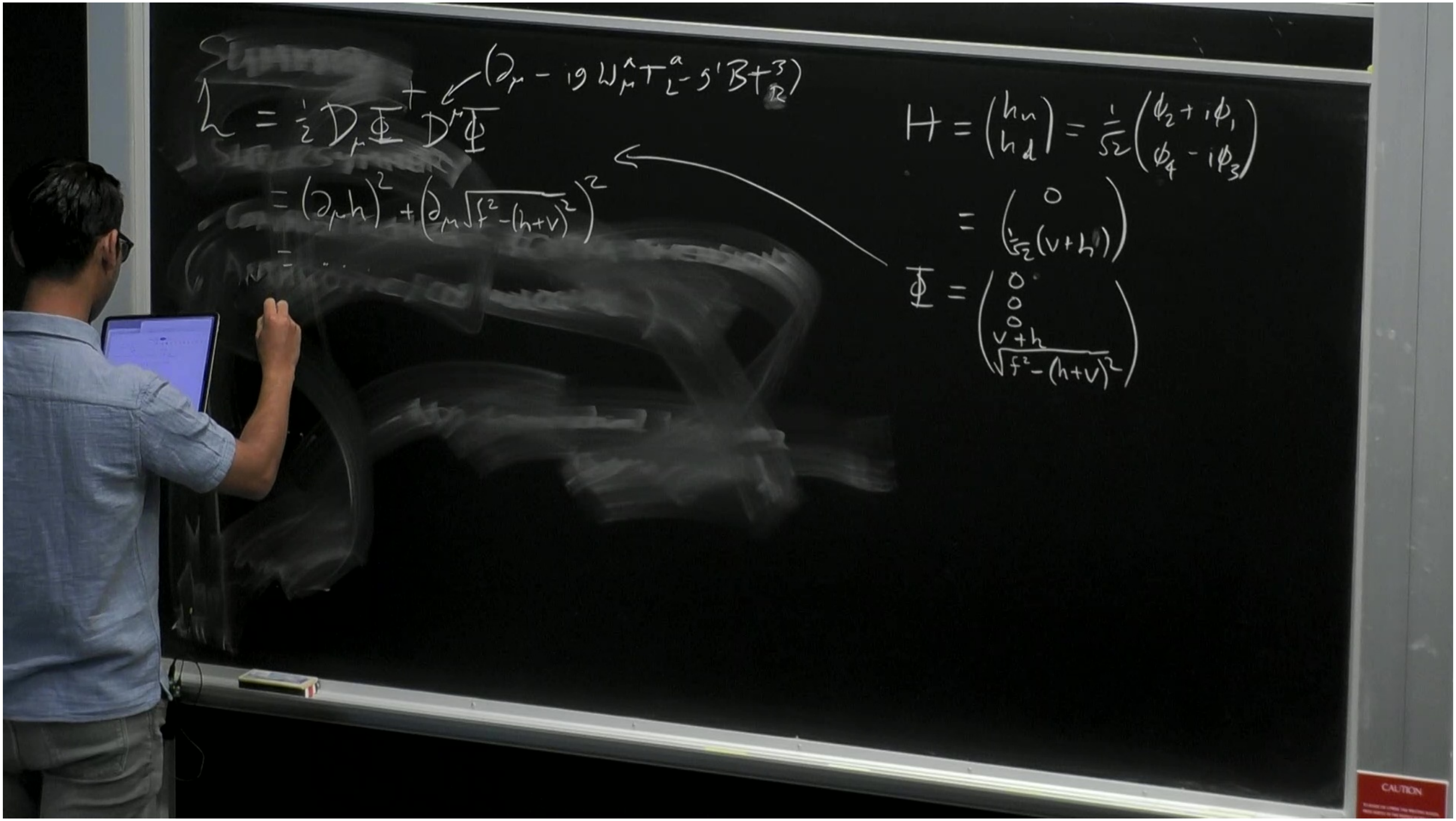
$$\mathcal{L} = \bar{\Psi} i\gamma^\mu \partial_\mu \Psi + g\left(\bar{\Psi}_L \Sigma \Psi_R + \bar{\Psi}_R \Sigma \Psi_L\right) \qquad (+\,-\,-\,-)$$

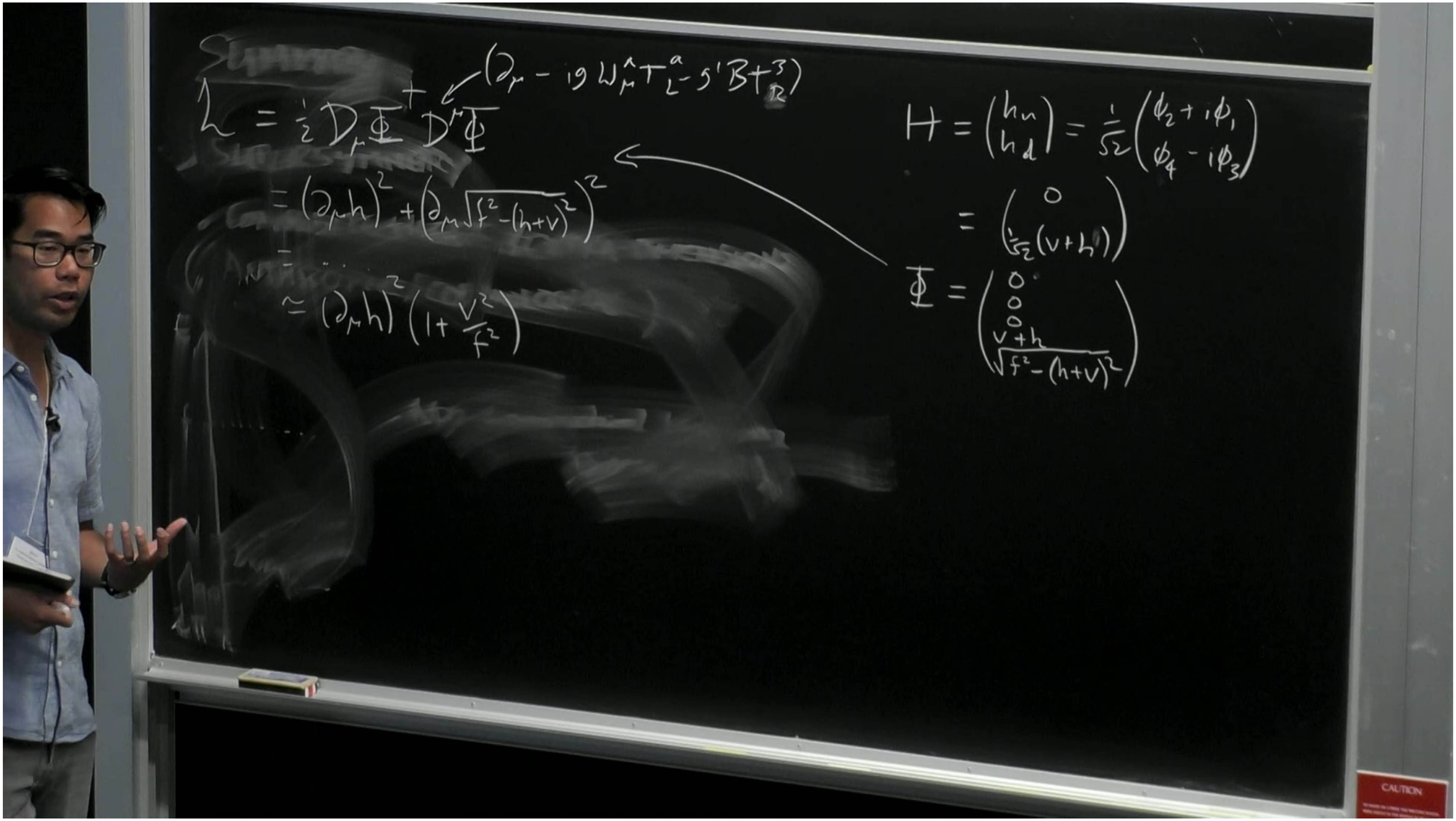
$$\Sigma = \sigma \mathbb{1}_{2\times 2} + i\vec{\pi}\cdot\vec{\sigma}$$

$$+ \frac{1}{2}(\partial_\mu \sigma)^2 + \frac{1}{2}(\partial_\mu \vec{\pi})^2 - \frac{\mu^2}{2}\left(\sigma^2 + \vec{\pi}^2\right) - \frac{\lambda}{4}\left(\sigma^2 + \vec{\pi}^2\right)^2 \qquad U_{L,R} = e^{-\frac{i}{2}\alpha^a_{L,R}\sigma^a}$$

- Σ transforms under $\underbrace{SU(2)_L \times SU(2)_R}_{SO(4)}$ $\qquad \Sigma \to U_L \Sigma U_R^\dagger$

$$\phi = \begin{pmatrix} \pi_1 \\ \pi_2 \\ \pi_3 \\ \sigma \end{pmatrix} \qquad V = \frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$


$(\partial_\mu - ig W_\mu^a T_L^a - g' B T_R^3)$
$\mathcal{L} = \frac{1}{2} D_\mu \Phi^\dagger D^\mu \Phi$
$= (\partial_\mu h)^2 + (\partial_\mu \sqrt{f^2-(h+v)^2})^2$
$= \ldots$
$H = \begin{pmatrix} h_u \\ h_d \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_2 + i\phi_1 \\ \phi_4 - i\phi_3 \end{pmatrix}$
$= \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+h) \end{pmatrix}$
$\Phi = \begin{pmatrix} 0 \\ 0 \\ 0 \\ v+h \\ \sqrt{f^2-(h+v)^2} \end{pmatrix}$



$(\partial_\mu - ig W_\mu^a T_L^a - g' B T_R^3)$
$\mathcal{L} = \frac{1}{2} D_\mu \Phi^\dagger D^\mu \Phi$
$= (\partial_\mu h)^2 + \left(\partial_\mu \sqrt{f^2 - (h+v)^2}\right)^2$
$= \ldots$
$\simeq (\partial_\mu h)^2 \left(1 + \frac{v^2}{f^2}\right)$
$H = \begin{pmatrix} h_u \\ h_d \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_2 + i\phi_1 \\ \phi_4 - i\phi_3 \end{pmatrix}$
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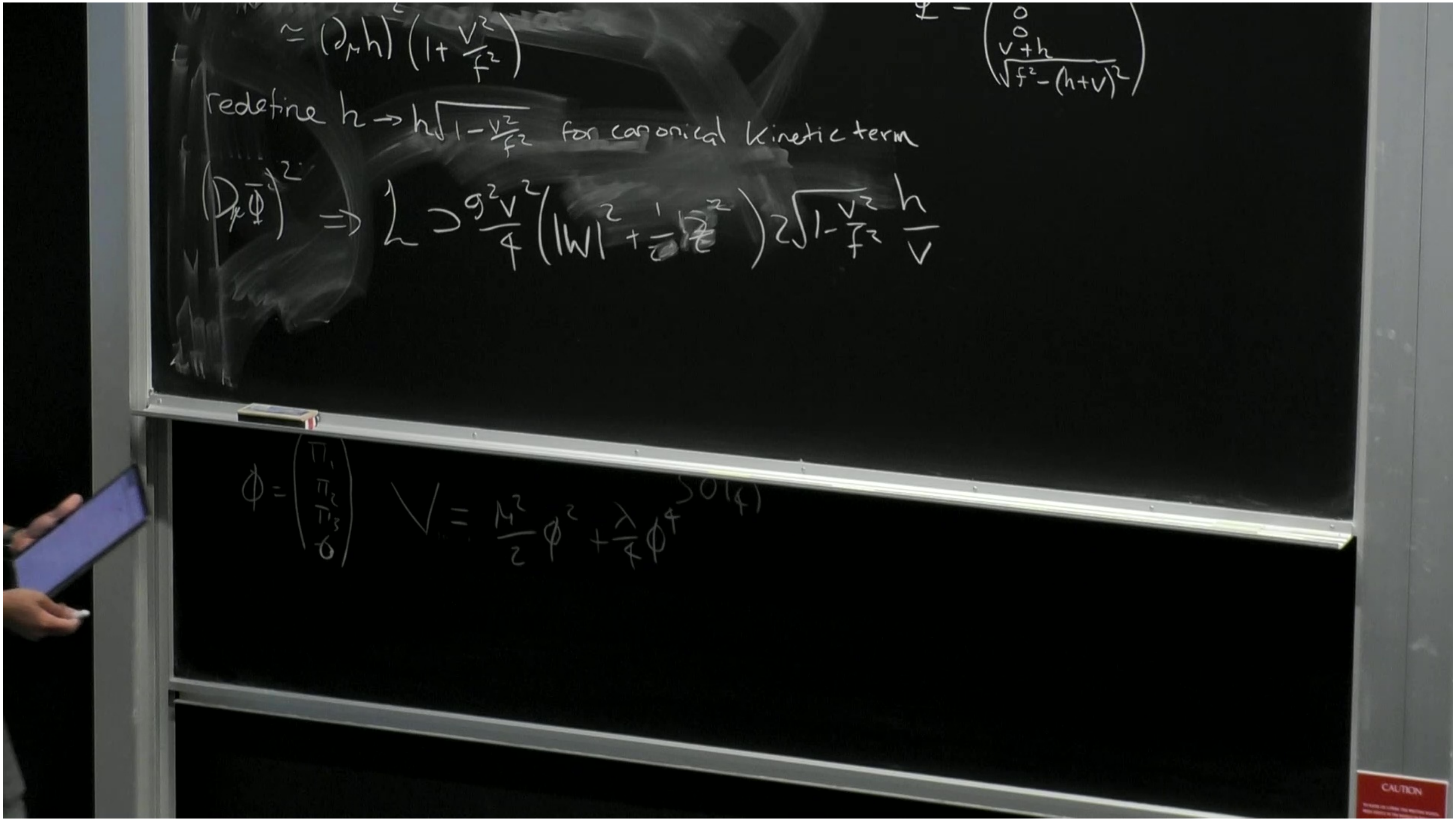
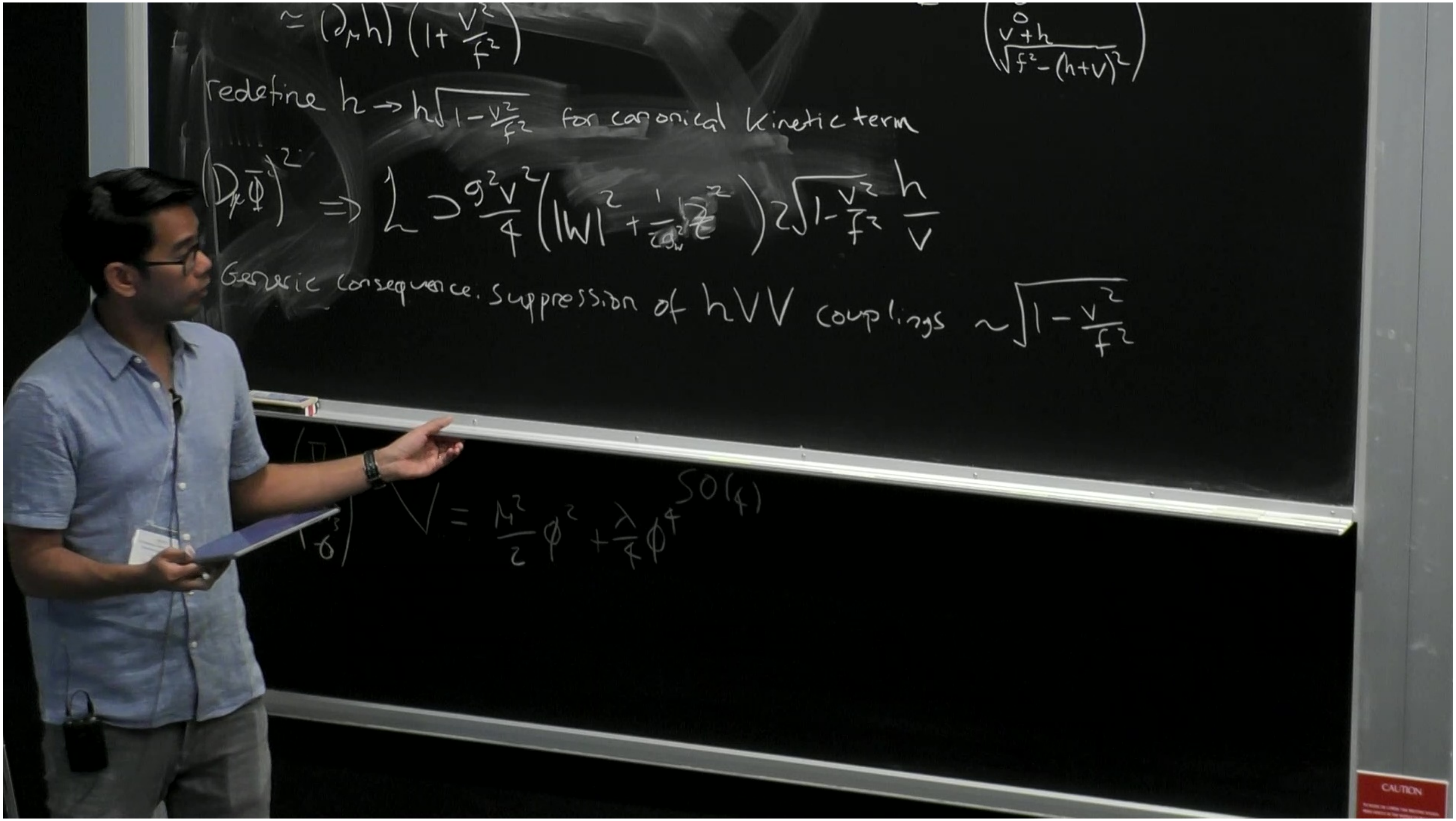
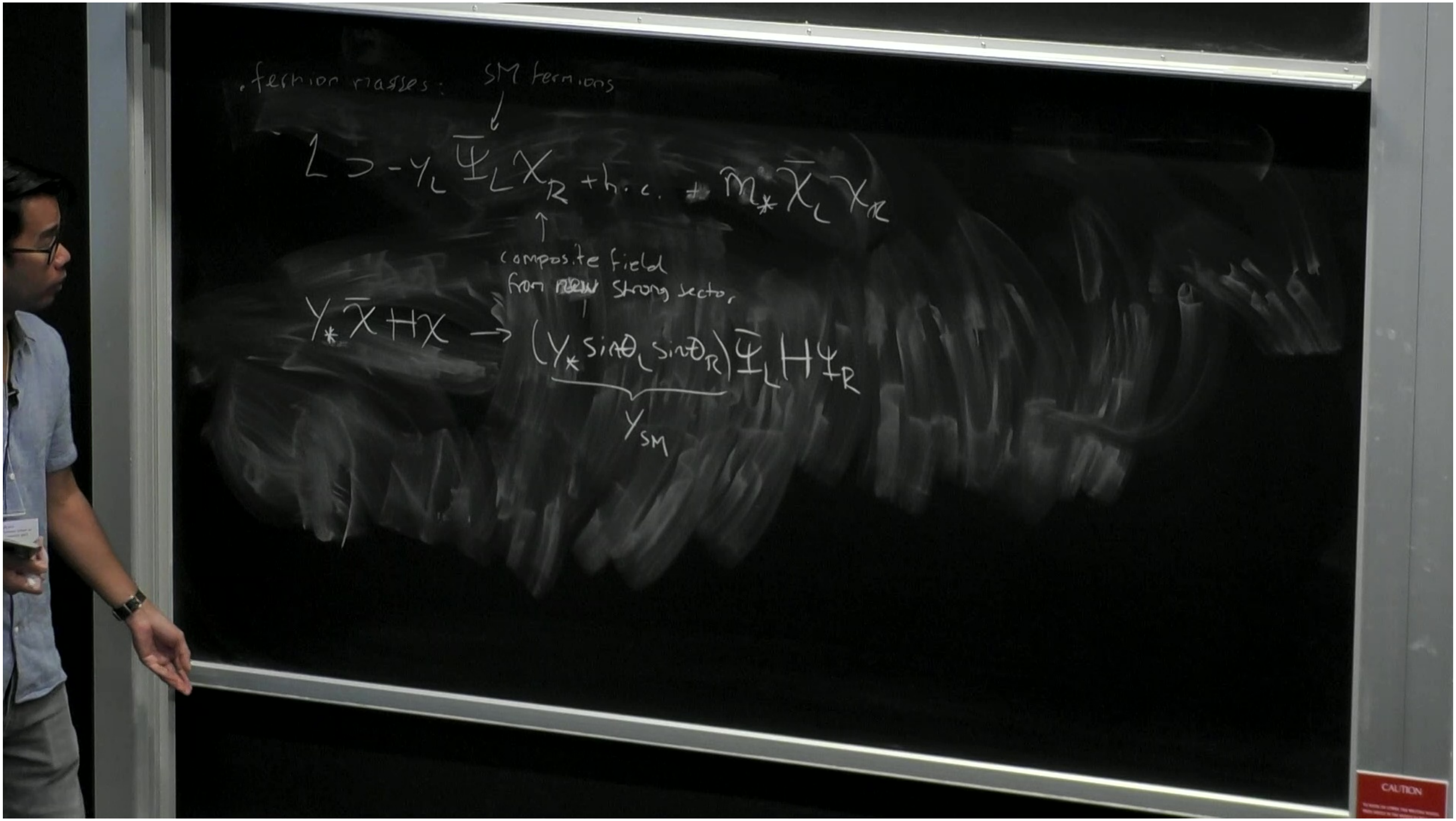
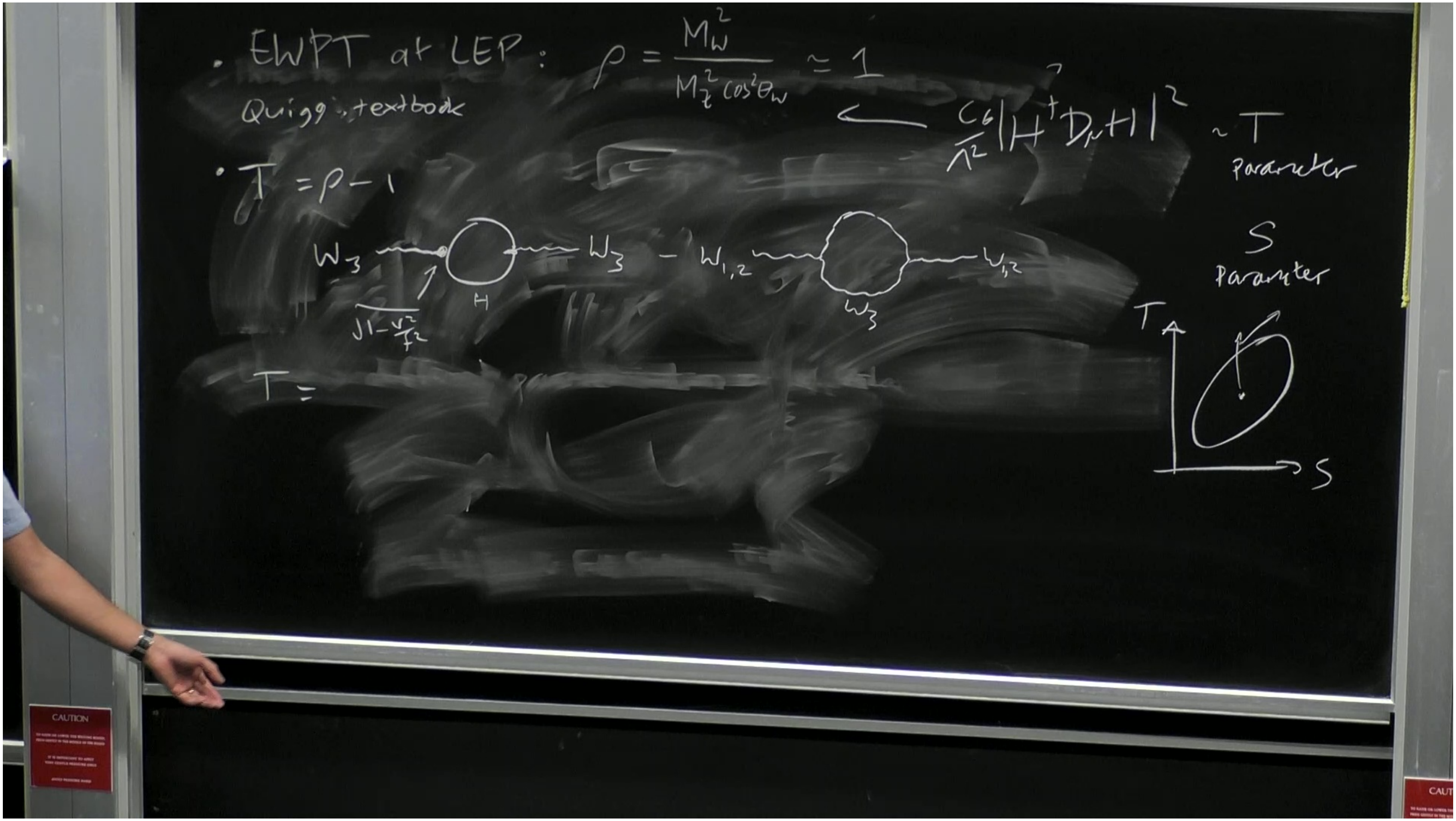
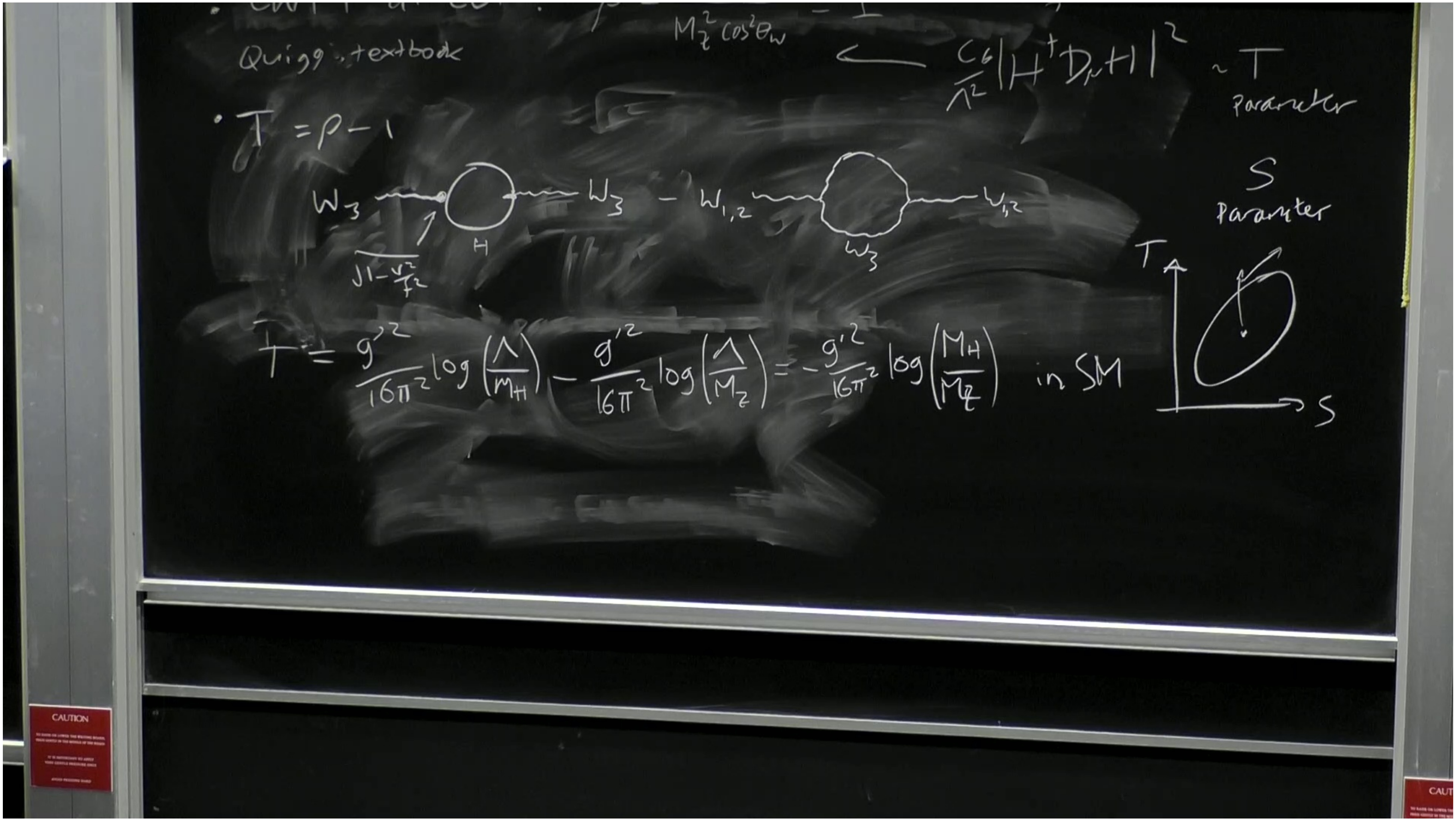
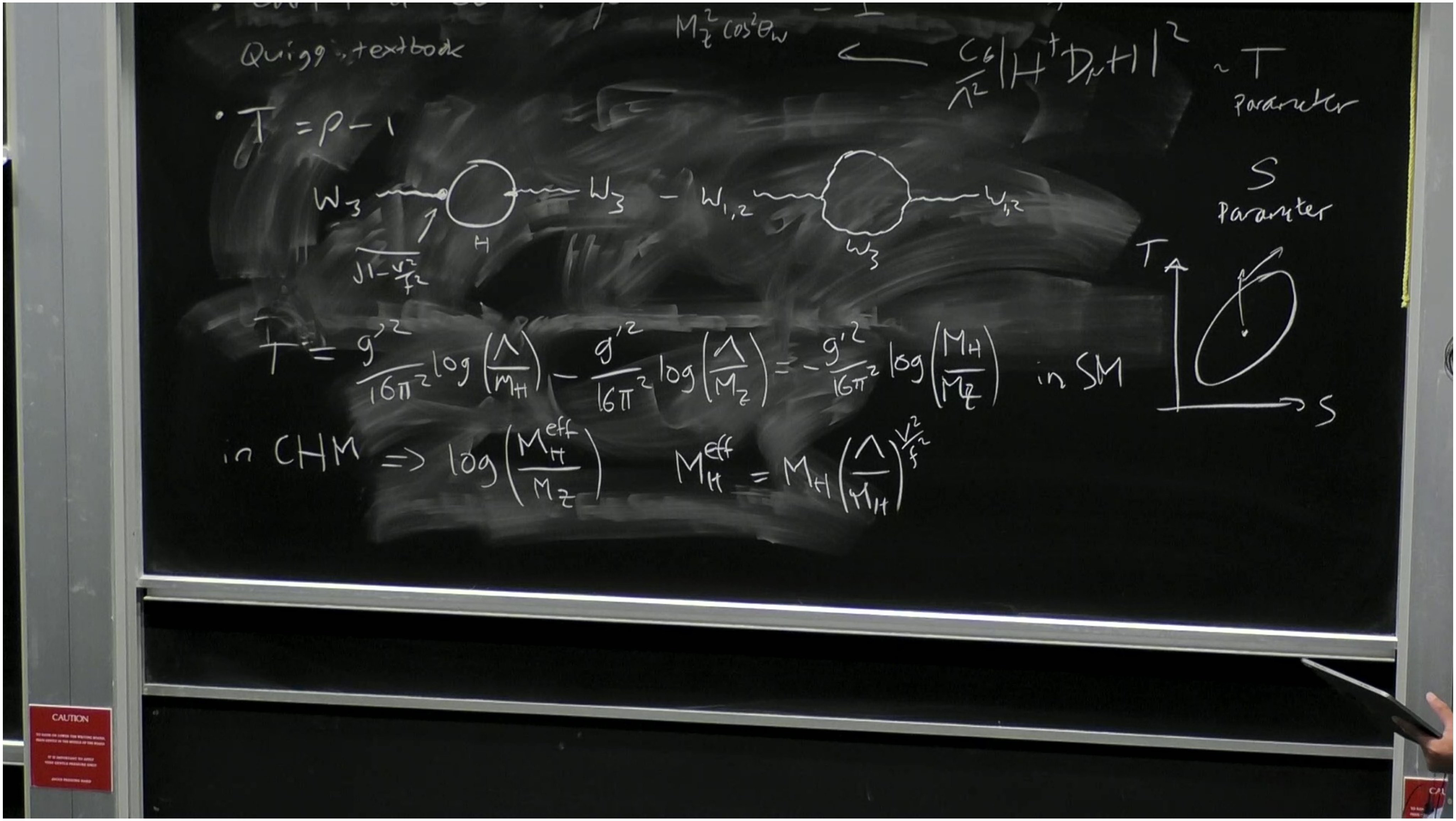

$\simeq (\partial_\mu h)^2 \left(1+\frac{v^2}{f^2}\right)$
redefine $h \to h\sqrt{1-\frac{v^2}{f^2}}$ for canonical kinetic term
$(D_\mu \bar{\Phi})^2 \Rightarrow \mathcal{L} \supset \frac{g^2 v^2}{4}\left(|W|^2+\frac{1}{2}|Z|^2\right) 2\sqrt{1-\frac{v^2}{f^2}}\,\frac{h}{v}$
$\Phi = \begin{pmatrix} 0 \\ 0 \\ v+h \\ \sqrt{f^2-(h+v)^2} \end{pmatrix}$
$\phi = \begin{pmatrix} \pi_1 \\ \pi_2 \\ \pi_3 \\ \sigma \end{pmatrix}$
$V = \frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$
SO(4)
CAUTION

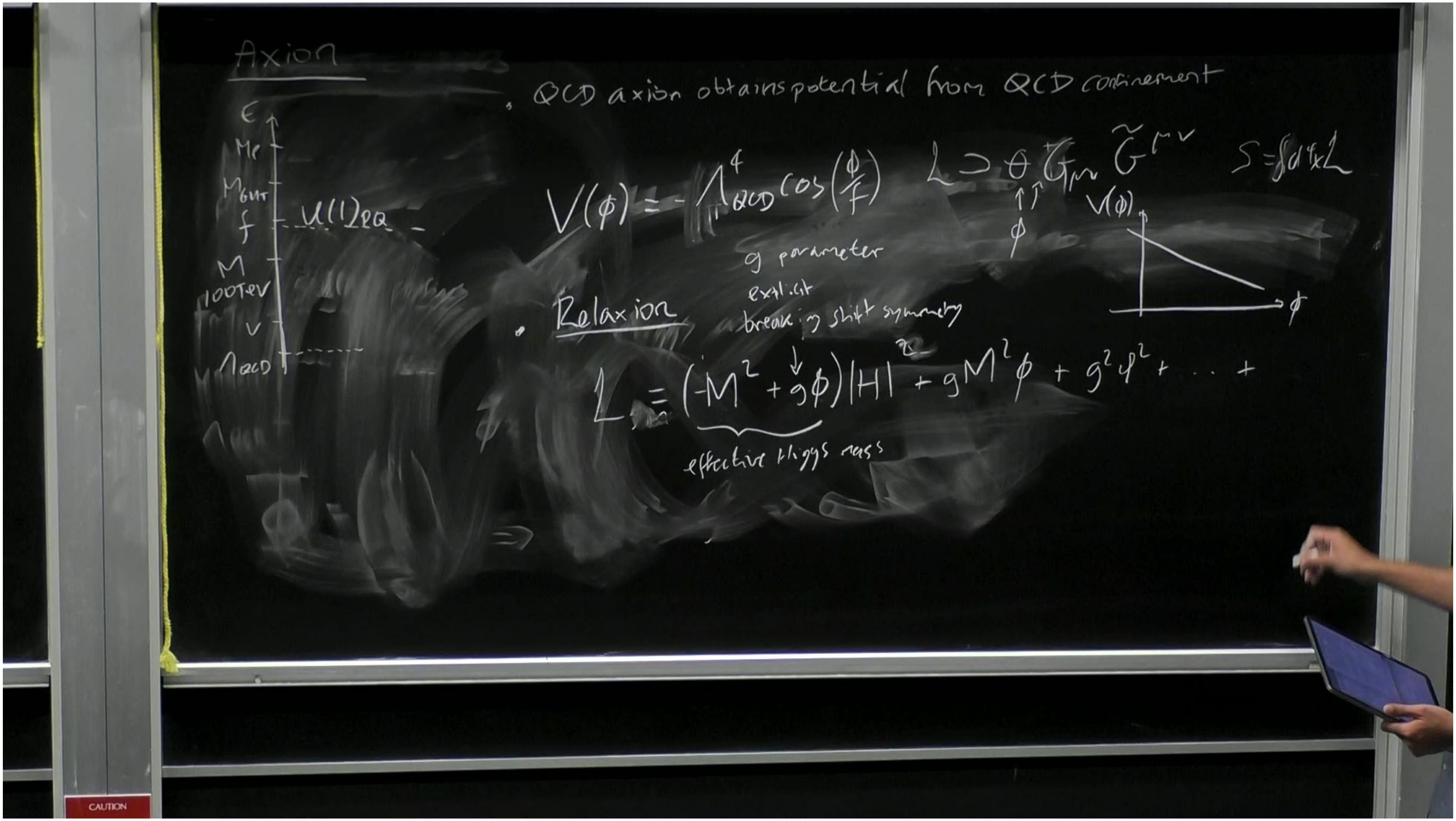

$\simeq (\partial_\mu h)\left(1+\frac{v^2}{f^2}\right)$
$\begin{pmatrix} 0 \\ v+h \\ \sqrt{f^2-(h+v)^2} \end{pmatrix}$
redefine $h \to h\sqrt{1-\frac{v^2}{f^2}}$ for canonical kinetic term
$(D_\mu \vec{\Phi})^2 \Rightarrow \mathcal{L} \supset \frac{g^2 v^2}{4}\left(|W|^2 + \frac{1}{2 c_W^2} Z^2\right) 2\sqrt{1-\frac{v^2}{f^2}}\,\frac{h}{v}$
Generic consequence: suppression of hVV couplings $\sim \sqrt{1-\frac{v^2}{f^2}}$
$V = \frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$ SO(4)

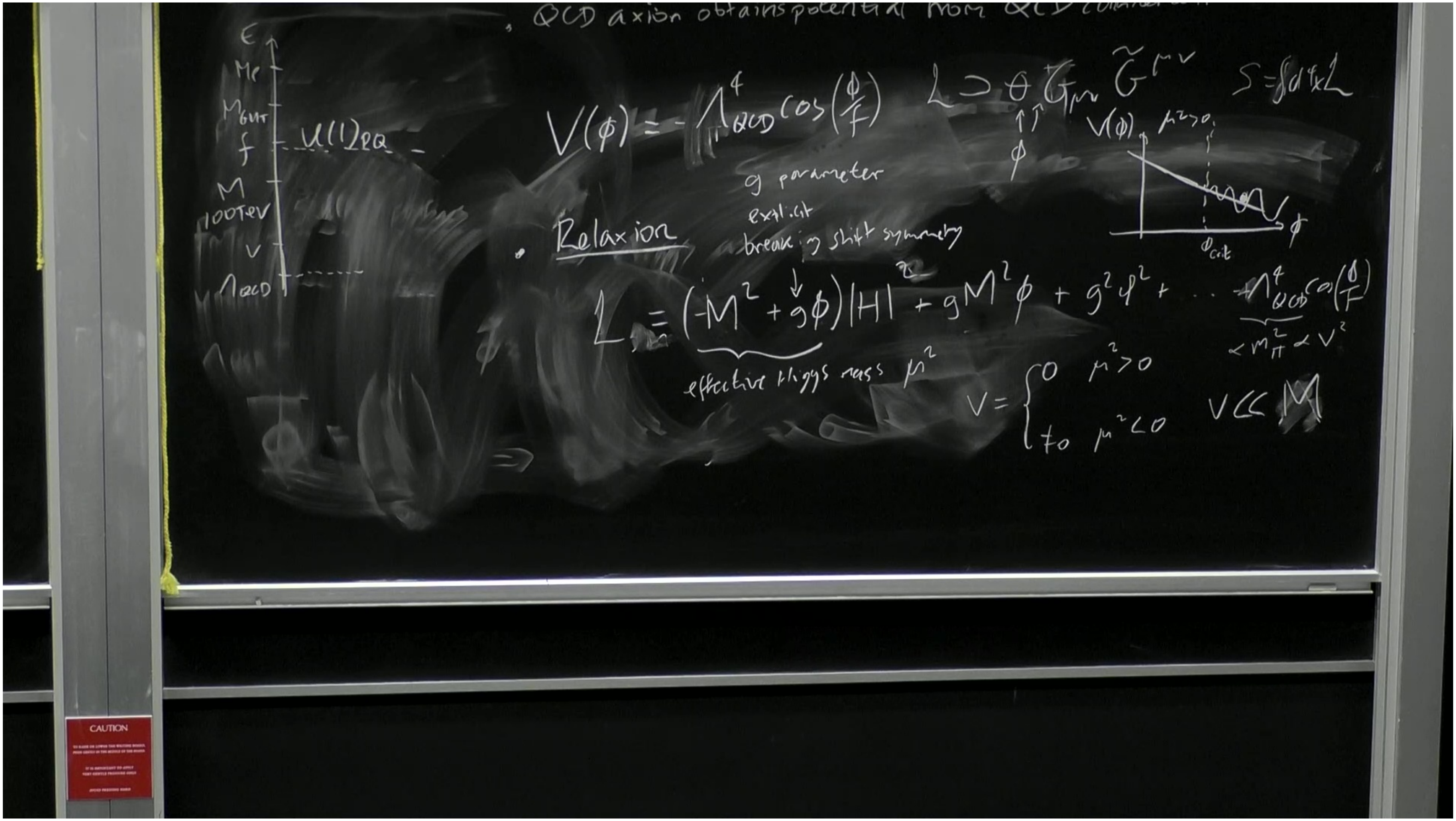

. fermion masses :
SM fermions
$\mathcal{L} \supset -y_L \bar{\Psi}_L \chi_R + h.c. + m_* \bar{\chi}_L \chi_R$
composite field
from new strong sector
$Y_* \bar{\chi} H \chi \longrightarrow \underbrace{(Y_* \sin\theta_L \sin\theta_R)}_{y_{SM}} \bar{\Psi}_L H \Psi_R$

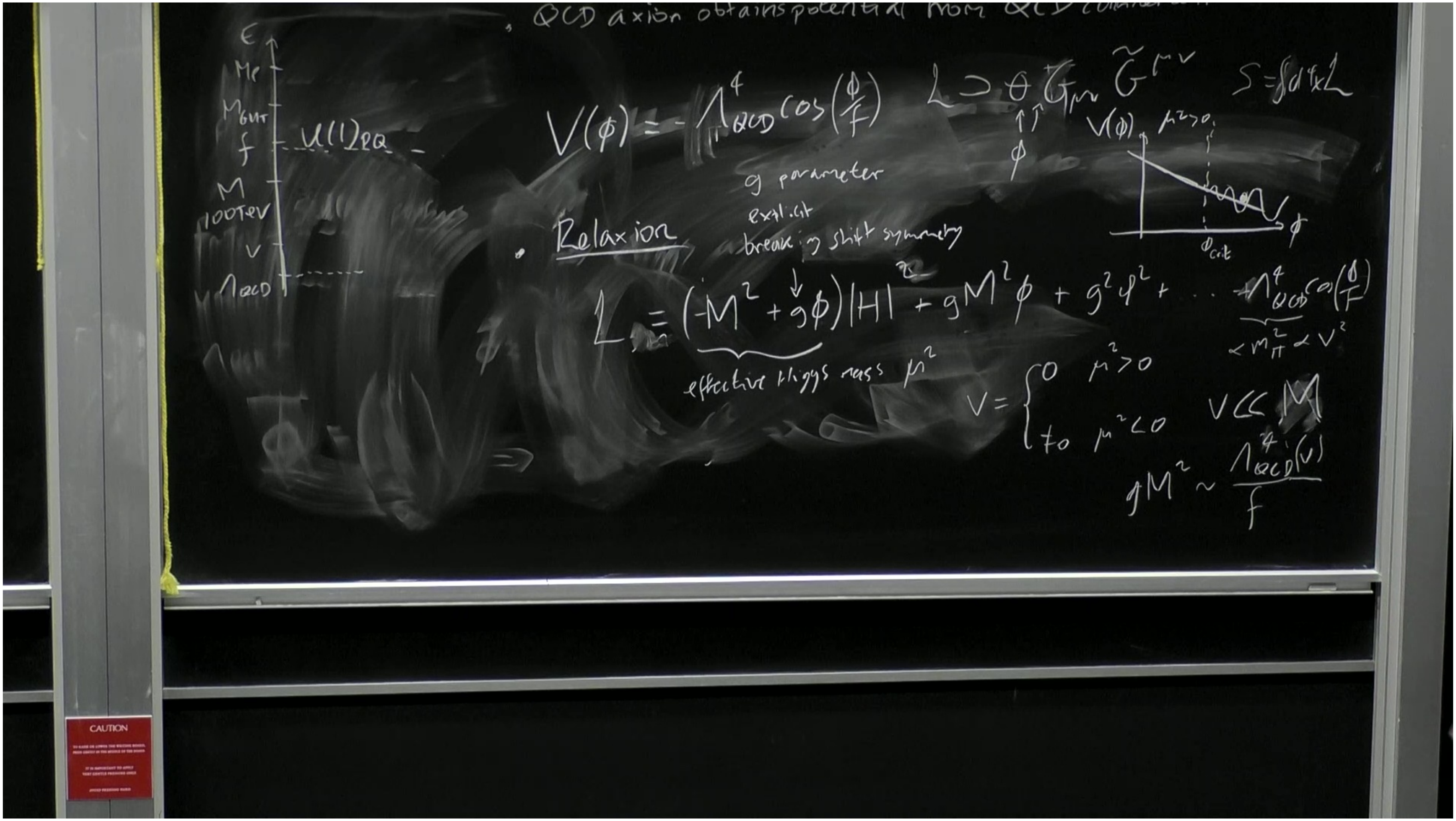

• EWPT at LEP : $\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} \simeq 1$
Quigg's textbook
$\frac{c_6}{\Lambda^2} |H^\dagger D_\mu H|^2 \sim T$
parameter
• $T = \rho - 1$
W_3
W_3
$-$ $W_{1,2}$
$W_{1,2}$
H
W_3
$\sqrt{1 - \frac{v^2}{f^2}}$
$T =$
S
parameter
T
S
CAUTION


Quigg: textbook
$M_Z^2 \cos^2\theta_W$
$\frac{c_6}{\Lambda^2}|H^\dagger D_\mu H|^2 \sim T$ parameter
• $T = \rho - 1$
W_3 H W_3 $-$ $W_{1,2}$ W_3 $W_{1,2}$
$\sqrt{1-\frac{v^2}{f^2}}$
$T = \frac{g'^2}{16\pi^2}\log\left(\frac{\Lambda}{M_H}\right) - \frac{g'^2}{16\pi^2}\log\left(\frac{\Lambda}{M_Z}\right) = -\frac{g'^2}{16\pi^2}\log\left(\frac{M_H}{M_Z}\right)$ in SM
S parameter
T
S
CAUTION


Quigg's textbook
$M_Z^2 \cos^2\theta_W$
$\frac{C_6}{\Lambda^2}|H^\dagger D_\mu H|^2 \sim T$
parameter
• $T = \rho - 1$
W_3 — W_3 − $W_{1,2}$ — $W_{1,2}$
H
W_3
$\sqrt{1-\frac{v^2}{f^2}}$
S
parameter
T
S
$T = \frac{g'^2}{16\pi^2}\log\left(\frac{\Lambda}{M_H}\right) - \frac{g'^2}{16\pi^2}\log\left(\frac{\Lambda}{M_Z}\right) = -\frac{g'^2}{16\pi^2}\log\left(\frac{M_H}{M_Z}\right)$ in SM
in CHM $\Rightarrow \log\left(\frac{M_H^{eff}}{M_Z}\right)$ $M_H^{eff} = M_H\left(\frac{\Lambda}{M_H}\right)^{\frac{v^2}{f^2}}$
CAUTION


Axion
QCD axion obtains potential from QCD confinement
E
M_P
M_{GUT}
f $U(1)_{PQ}$
M
100TeV
v
Λ_{QCD}
$V(\phi) = -\Lambda_{QCD}^4 \cos\left(\frac{\phi}{f}\right)$
$\mathcal{L} \supset \theta\, G_{\mu\nu} \tilde{G}^{\mu\nu}$
ϕ
$S = \int d^4x \mathcal{L}$
$V(\phi)$
ϕ
Relaxion
g parameter
explicit
breaking shift symmetry
$\mathcal{L} = \underbrace{(-M^2 + g\phi)}_{\text{effective Higgs mass}} |H|^2 + gM^2\phi + g^2\phi^2 + \dots +$
CAUTION


QCD axion obtains potential from QCD
$V(\phi) = -\Lambda_{QCD}^4 \cos(\phi/f)$
$\mathcal{L} \supset \theta G_{\mu\nu} \tilde{G}^{\mu\nu}$
$S = \int d^4x \mathcal{L}$
U(1)PQ
Relaxion
g parameter
explicit
breaking shift symmetry
$\mathcal{L} = (-M^2 + g\phi)|H|^2 + gM^2\phi + g^2\phi^2 + \ldots + \Lambda_{QCD}^4 \cos(\phi/f)$
effective Higgs mass μ^2
$\propto m_\pi^2 \propto v^2$
$v = 0$, $\mu^2 > 0$
$v \neq 0$, $\mu^2 < 0$
$v \ll M$
ϕ_{crit}
CAUTION


QCD axion obtains potential from QCD
V(φ) = -Λ⁴QCD cos(φ/f)
L ⊃ θ Gμν G̃μν
S = ∫d⁴x L
g parameter
explicit
breaking shift symmetry
Relaxion
L = (-M² + gφ)|H|² + gM²φ + g²φ² + ... - Λ⁴QCD cos(φ/f)
effective Higgs mass μ²
V = 0 μ² > 0
≠ 0 μ² < 0
v << M
gM² ~ Λ⁴QCD(v) / f
φcrit
U(1)PQ
CAUTION