Title: BSM Theory

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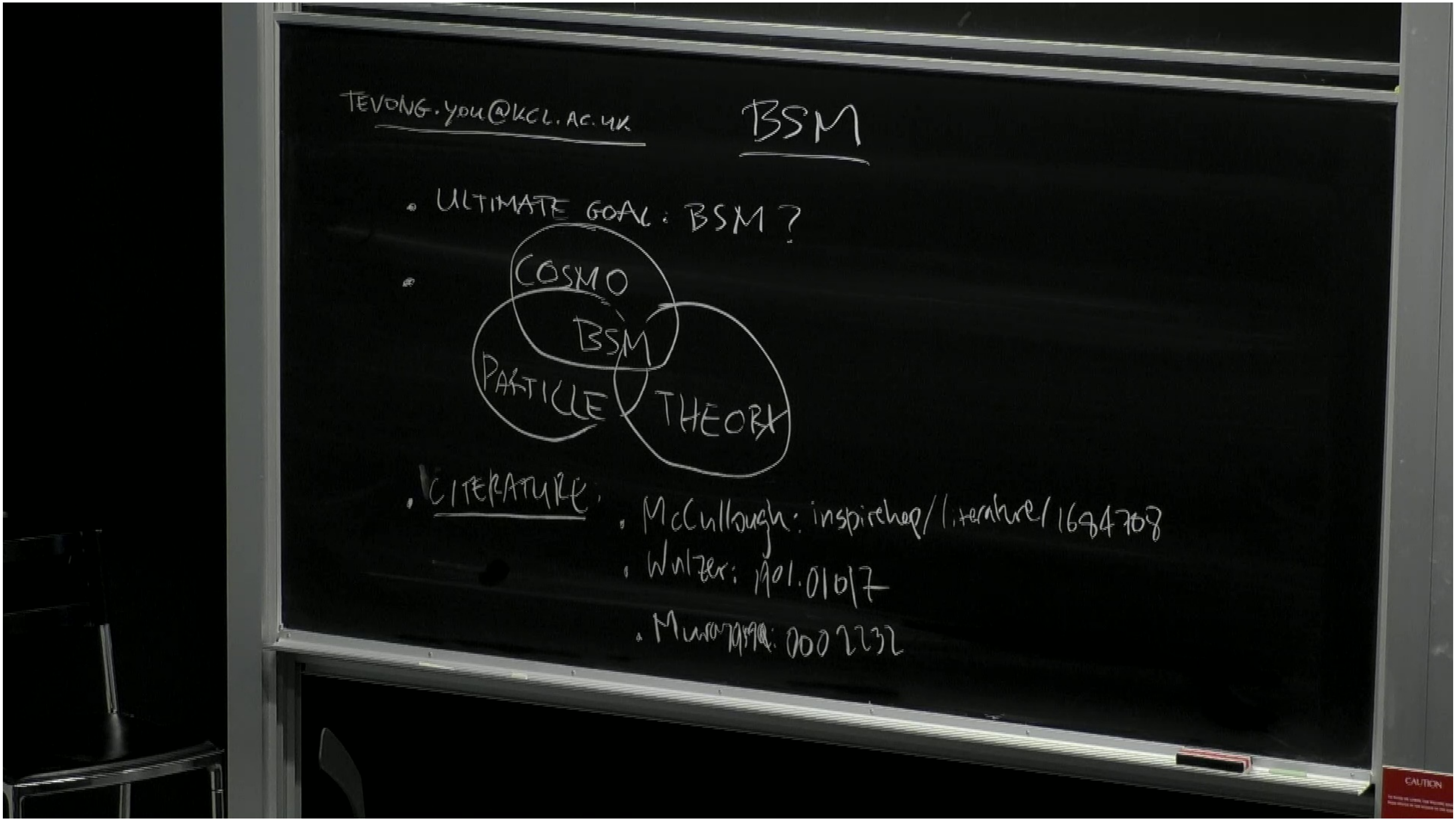
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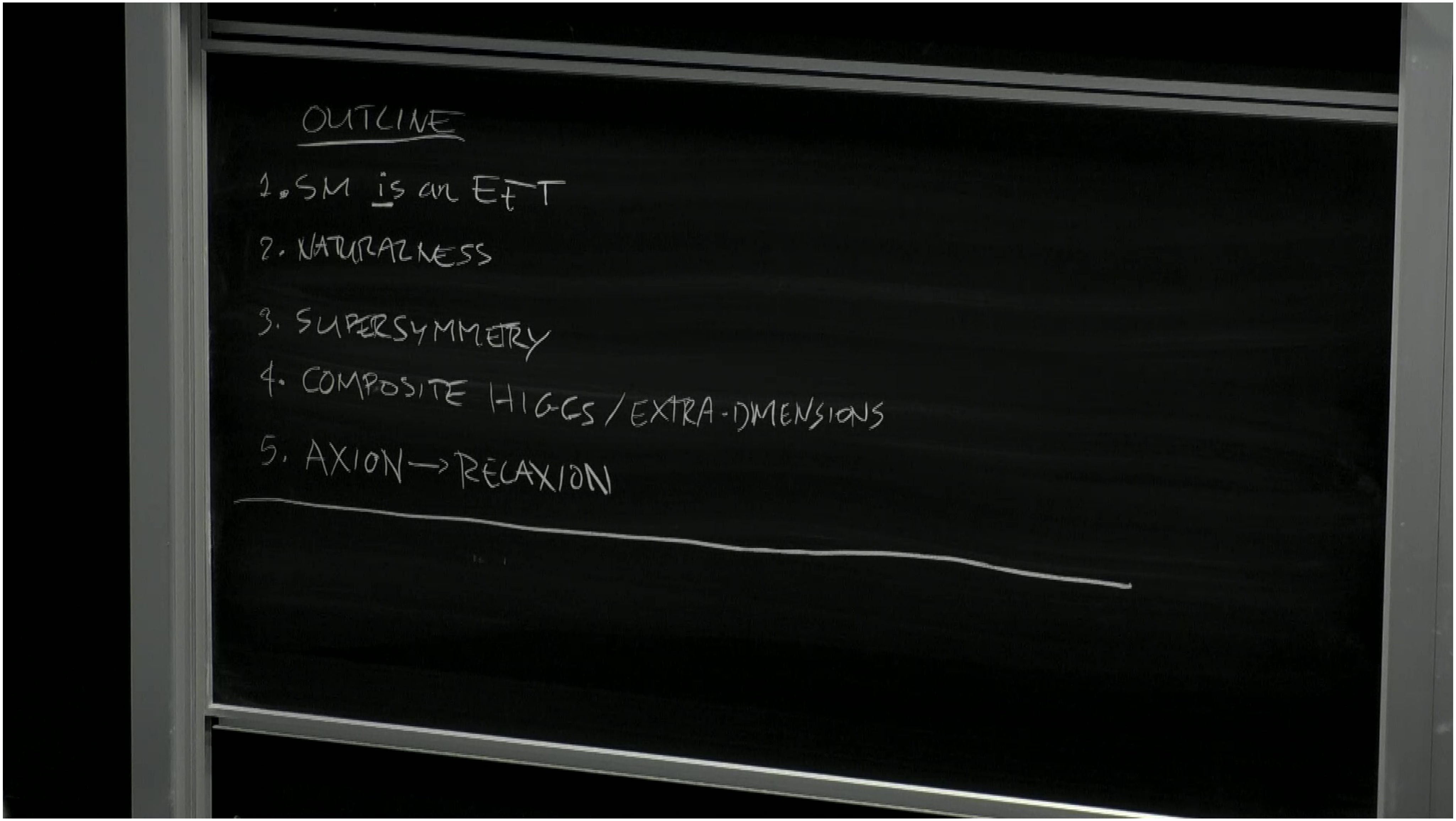
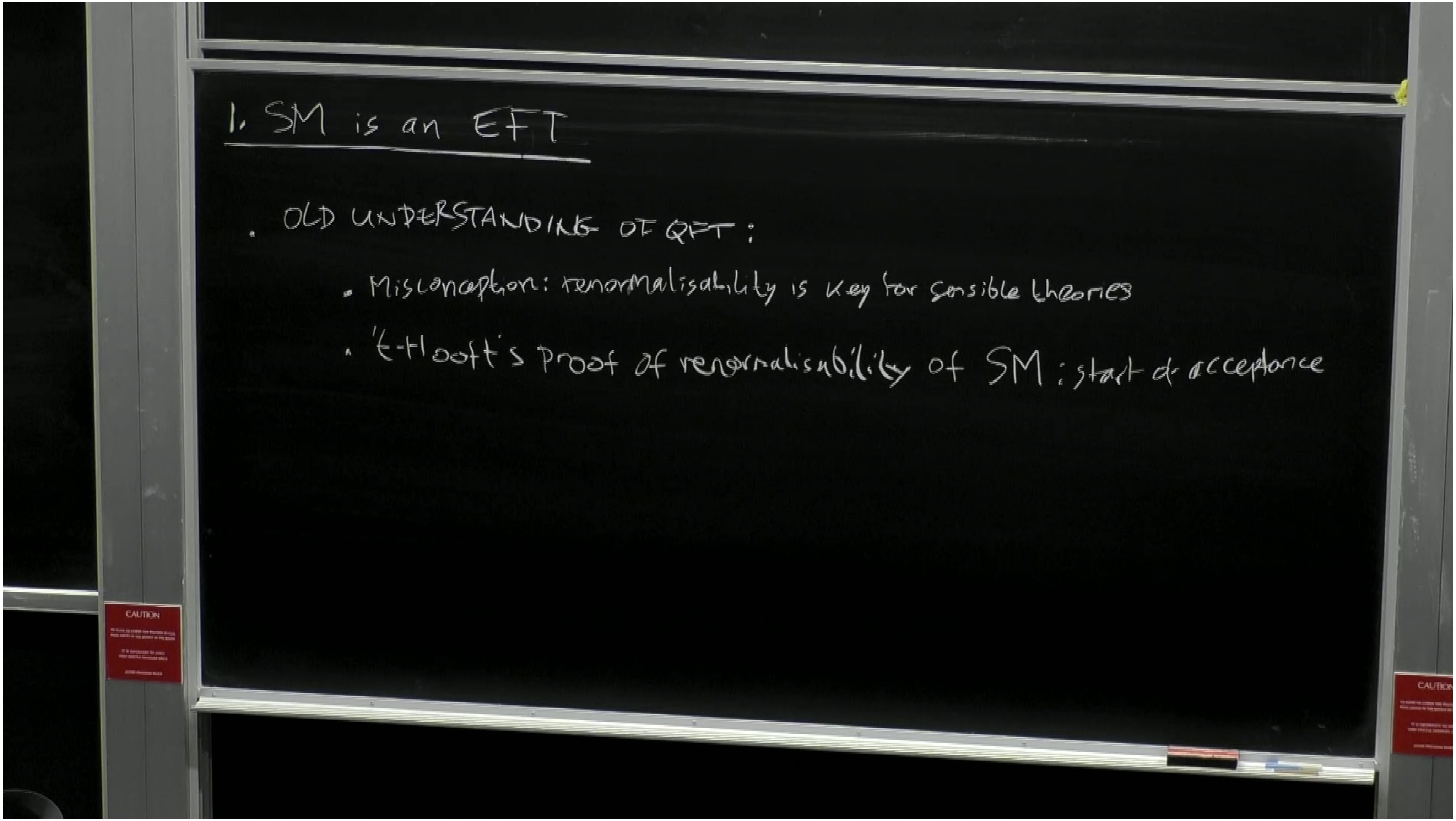
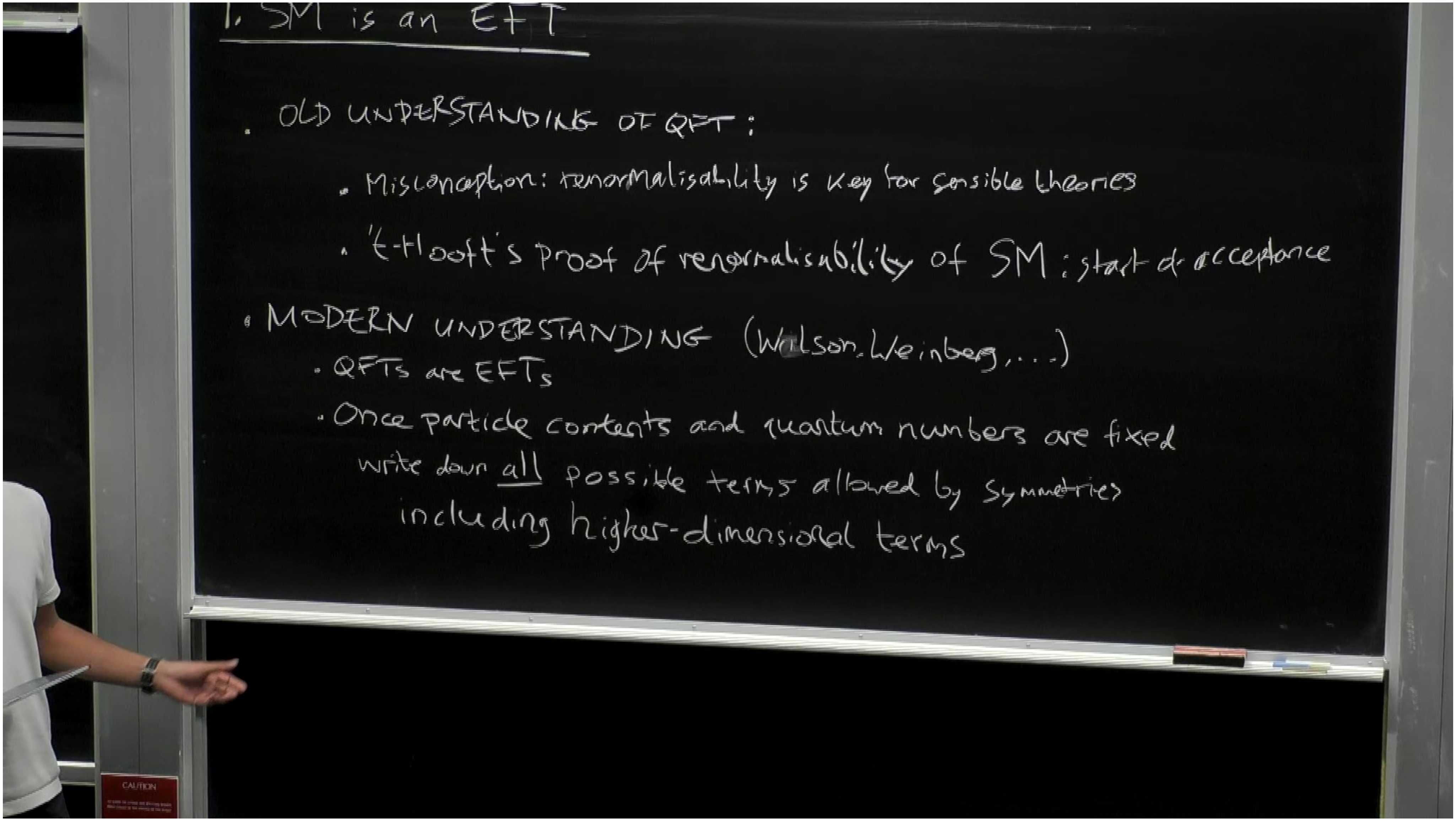
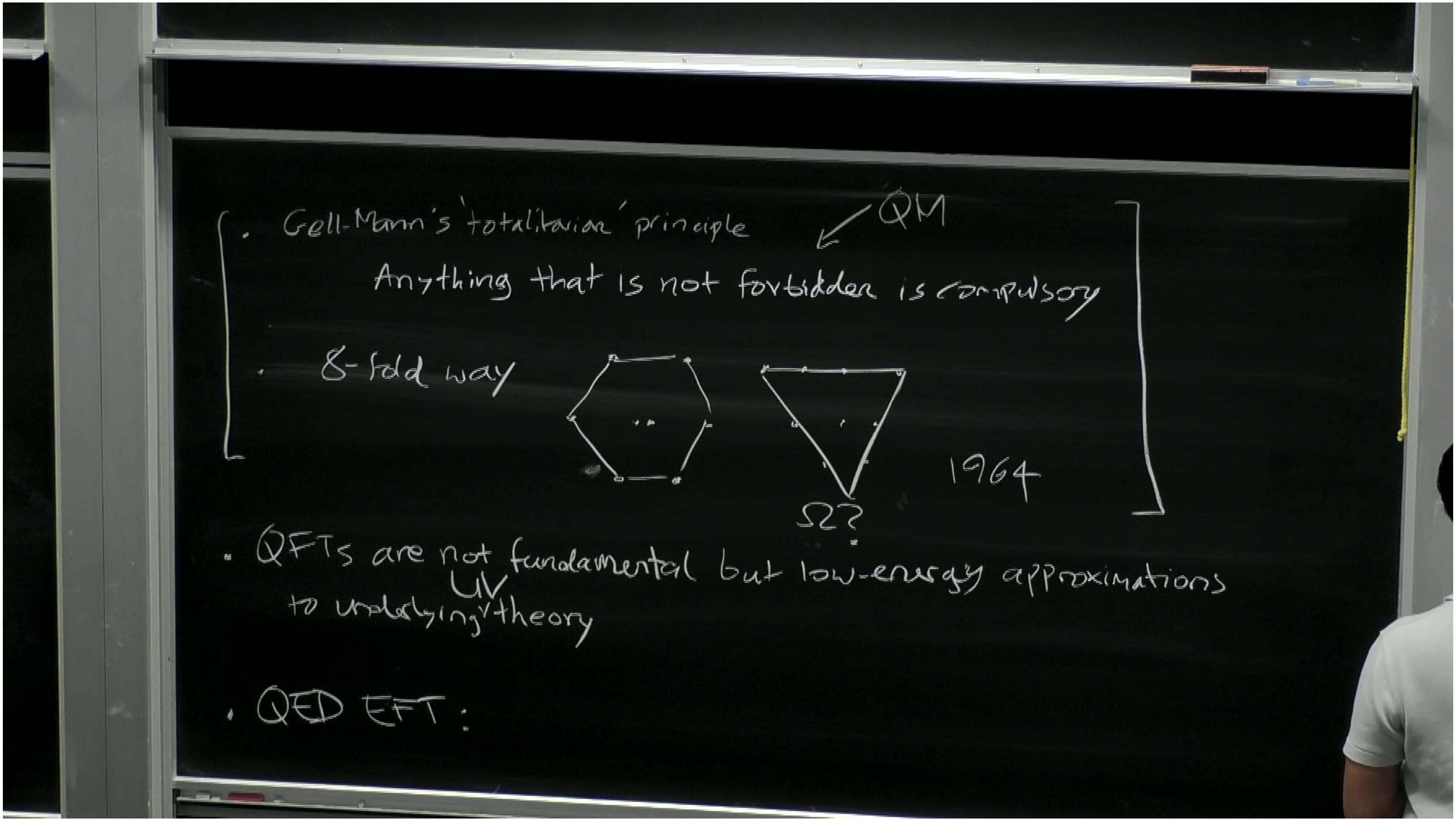
BSM
ULTIMATE GOAL: BSM?
COSMO
BSM
PARTICLE
THEORY
LITERATURE:
McCullough: inspirehep/literature/1684708
Wulzer: 1901.01017
Murayama: 0002232


OUTLINE
1. SM is an EFT
2. NATURALNESS
3. SUPERSYMMETRY
4. COMPOSITE HIGGS / EXTRA-DIMENSIONS
5. AXION → RELAXION


1. SM is an EFT
. OLD UNDERSTANDING OF QFT:
. Misconception: renormalisability is key for sensible theories
. 't Hooft's proof of renormalisability of SM: start of acceptance


1. SM is an EFT
. OLD UNDERSTANDING OF QFT:
. Misconception: renormalisability is key for sensible theories
. 't-Hooft's proof of renormalisability of SM: start of acceptance
. MODERN UNDERSTANDING (Wilson, Weinberg, ...)
. QFTs are EFTs
. Once particle contents and quantum numbers are fixed
write down all possible terms allowed by symmetries
including higher-dimensional terms
CAUTION


Gell-Mann's 'totalitarian' principle
QM
Anything that is not forbidden is compulsory
8-fold way
Ω?
1964
QFTs are not fundamental but low-energy approximations
to underlying UV theory
QED EFT:

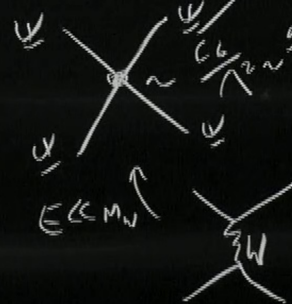
$$\mathcal{L}^{EFT}_{QED} = \bar{\Psi} i\gamma D_\mu \Psi - m\bar{\Psi}\Psi - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{c_6}{\Lambda^2}(\bar{\Psi}\Gamma\Psi)^2 + \frac{c_8}{\Lambda^4}(F_{\mu\nu}F^{\mu\nu})^2 + \dots$$

← Wilson coefficients

$\Gamma = \{\mathbb{1}, \gamma^\mu, \gamma_5, \gamma^\mu\gamma_5, \sigma_{\mu\nu}\}$

↑ GeV

Λ EFT cut-off $\gg$ GeV

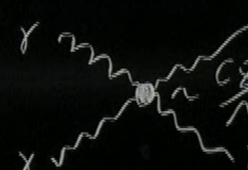


$\sim \frac{c_6}{\Lambda^2} \sim \frac{g^2}{M_W^2}$

$E \ll M_W$

$\sim \frac{g^2}{p^2 - M_W^2} = \frac{g^2}{M_W^2}\left(\frac{1}{p^2/M_W^2 - 1}\right)$

↑ Euler-Heisenberg 1933



$\sim \frac{c_8}{\Lambda^4} \sim \frac{e^4}{16\pi^2}\frac{1}{m_e^4}$

$E \ll m_e$

- SM as an EFT

$SU(3)_c \quad SU(2)_L \quad U(1)_Y$

$$\mathcal{L}^{EFT}_{QED} = \bar\Psi i\gamma D_\mu \Psi - m\bar\Psi\Psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{C_6}{\Lambda^2}(\bar\Psi\Gamma\Psi)^2 + \frac{C_8}{\Lambda^4}(F_{\mu\nu}F^{\mu\nu})^2 + \dots$$

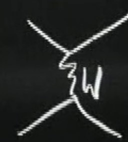
$\uparrow$ GeV (C_6: $\leftarrow$ Wilson coefficients)

$\Gamma = \{\mathbb{1}, \gamma^\mu, \gamma_5, \gamma^\mu\gamma_5, \sigma_{\mu\nu}\}$

Λ EFT cutoff $\gg$ GeV

$\sim \frac{C_6}{\Lambda^2} \sim \frac{g^2}{M_W^2}$

$\uparrow E \ll M_W$

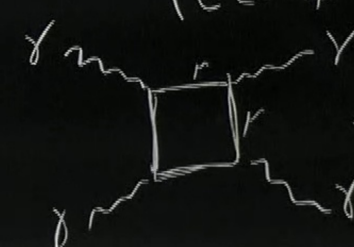


$\sim \frac{g^2}{p^2 - M_W^2} = \frac{g^2}{M_W^2}\left(\frac{1}{\frac{p^2}{M_W^2} - 1}\right)$

$\uparrow$ Euler-Heisenberg 1933

$\sim \frac{C_8}{\Lambda^4} \sim \frac{e^4}{16\pi^2}\frac{1}{m_\mu^4}$

$\uparrow E \ll m_\mu$



$E \gg m_\mu$

- SM as an EFT

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q_L	3	2	$\frac{1}{6}$
u_R	3	1	$\frac{2}{3}$
d_R	3	1	$-\frac{1}{3}$
L_L	1	2	$-\frac{1}{2}$
l_R	1	1	-1
H	1	2	$\frac{1}{2}$

- $d < 4$: 'relevant'
- $d = 4$: marginal
- $d > 4$: 'irrelevant'

$\theta < 10^{-9}$

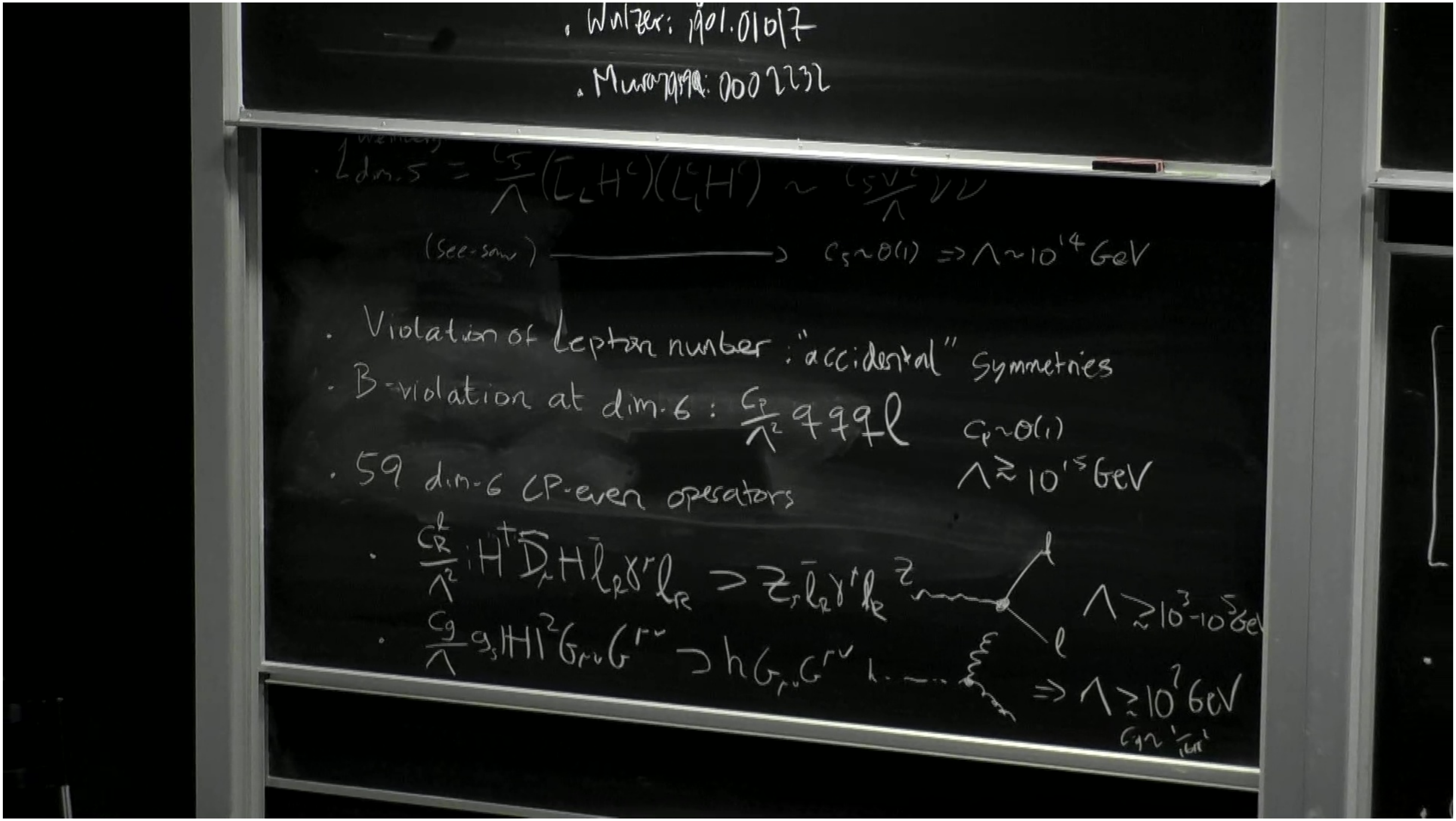
θ strong CP problem

$$\mathcal{L}_{SM}^{EFT} = \bar{Q}_L i\gamma^\mu D_\mu Q_L + \bar{q}_R i\gamma^\mu D_\mu q_R + \bar{L}_L i\gamma^\mu D_\mu L_L + \bar{\ell}_R i\gamma^\mu D_\mu \ell_R$$

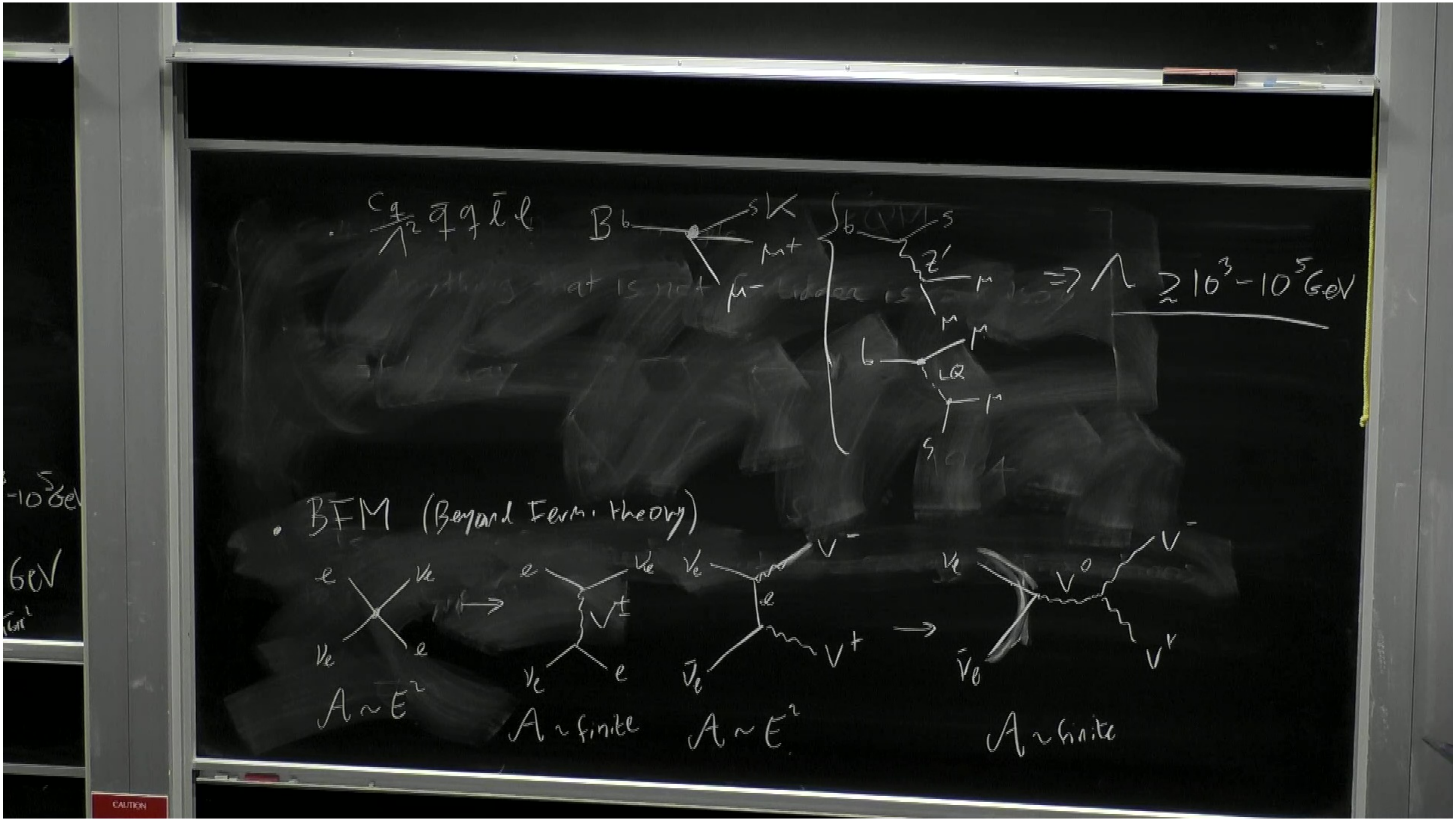
$$- \frac{1}{4} B_{\mu\nu}B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4} G^i_{\mu\nu}G^{i\mu\nu} \boxed{+ \frac{\theta}{16\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}}$$

$$(D_\mu H)^\dagger (D^\mu H) - V(H) + y_d \bar{Q}_L H u_R + y_u \bar{Q}_L H^c u_R + y_e \bar{L}_L H \ell_R + h.c.$$

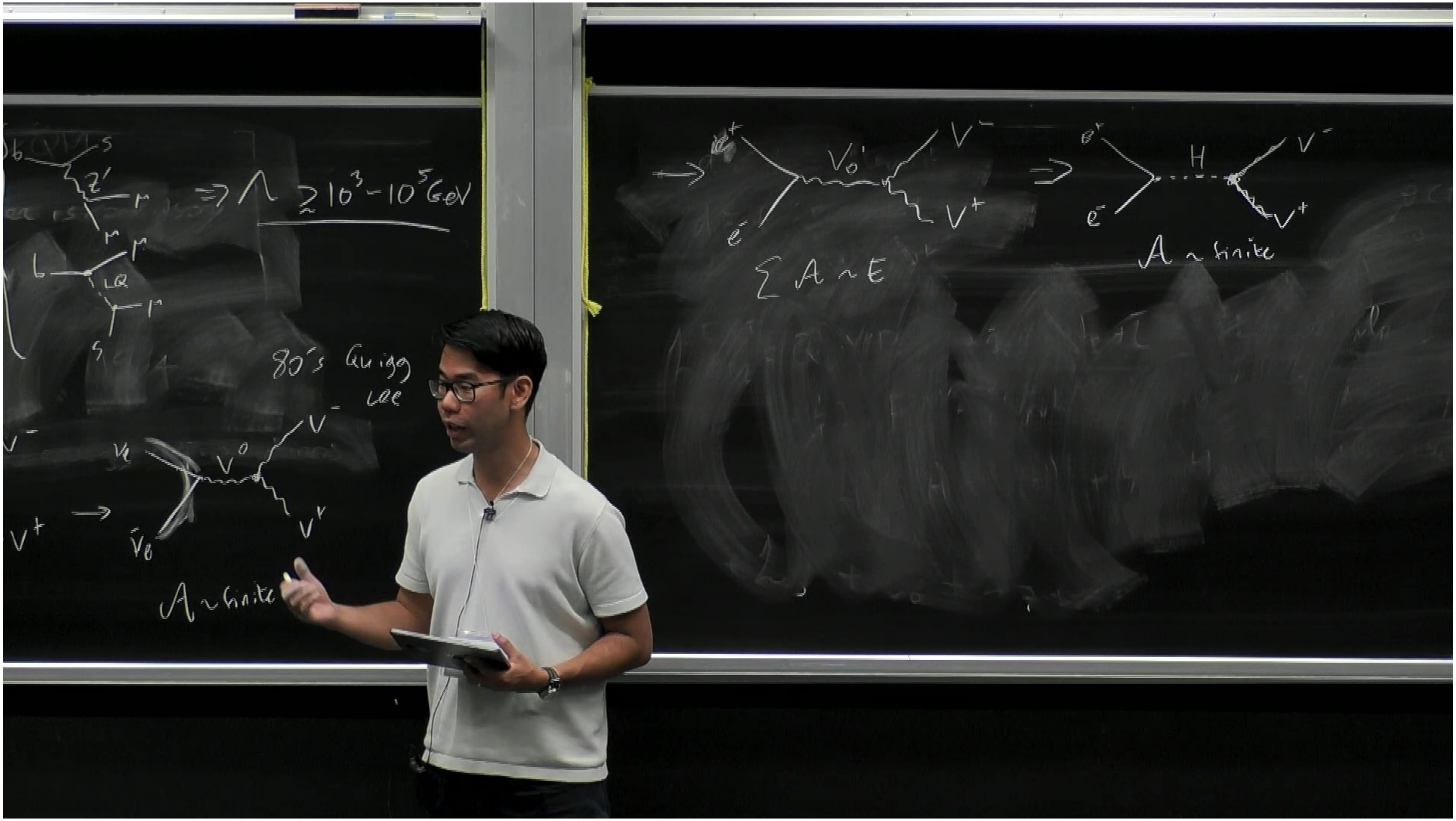
$$+ \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \dots$$



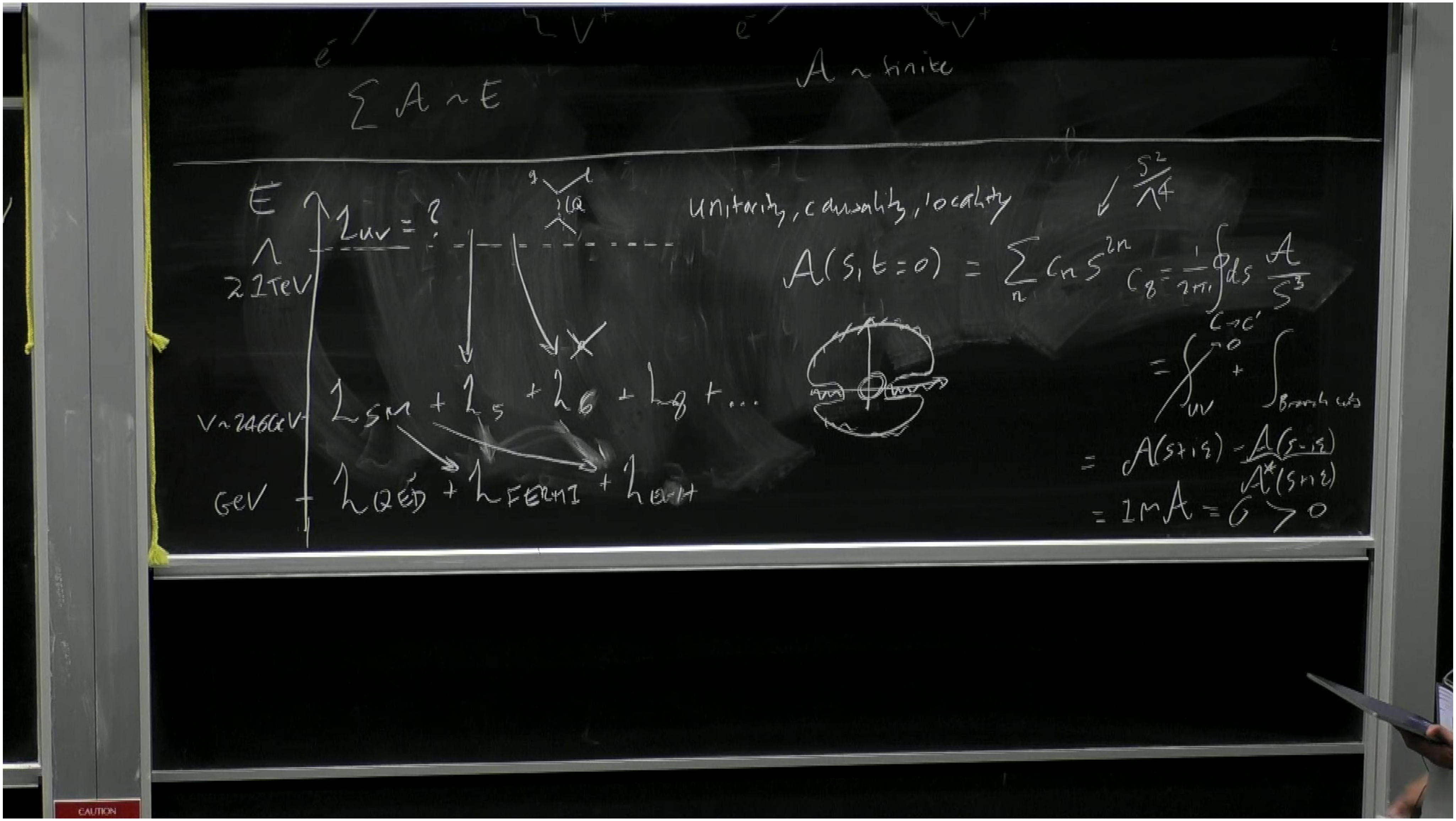
. Walzer: 1901.01017
. Murayama: 0002232
$\mathcal{L}_{dim.5} = \frac{c_5}{\Lambda}(\bar{L}_L H^c)(L_L^c H^\dagger) \sim \frac{c_5 v^2}{\Lambda} \nu\nu$
(see-saw) → $c_5 \sim O(1) \Rightarrow \Lambda \sim 10^{14}$ GeV
. Violation of lepton number: "accidental" symmetries
. B-violation at dim-6: $\frac{c_p}{\Lambda^2} qqql$
$c_p \sim O(1)$
$\Lambda \gtrsim 10^{15}$ GeV
. 59 dim-6 CP-even operators
$\frac{c_R^l}{\Lambda^2} i H^\dagger \overleftrightarrow{D}_\mu H \bar{l}_R \gamma^\mu l_R \supset Z_\mu \bar{l}_R \gamma^\mu l_R$
$\frac{c_g}{\Lambda} g_s |H|^2 G_{\mu\nu} G^{\mu\nu} \supset h G_{\mu\nu} G^{\mu\nu}$
$\Lambda \gtrsim 10^3 - 10^5$ GeV
$\Rightarrow \Lambda \gtrsim 10^7$ GeV

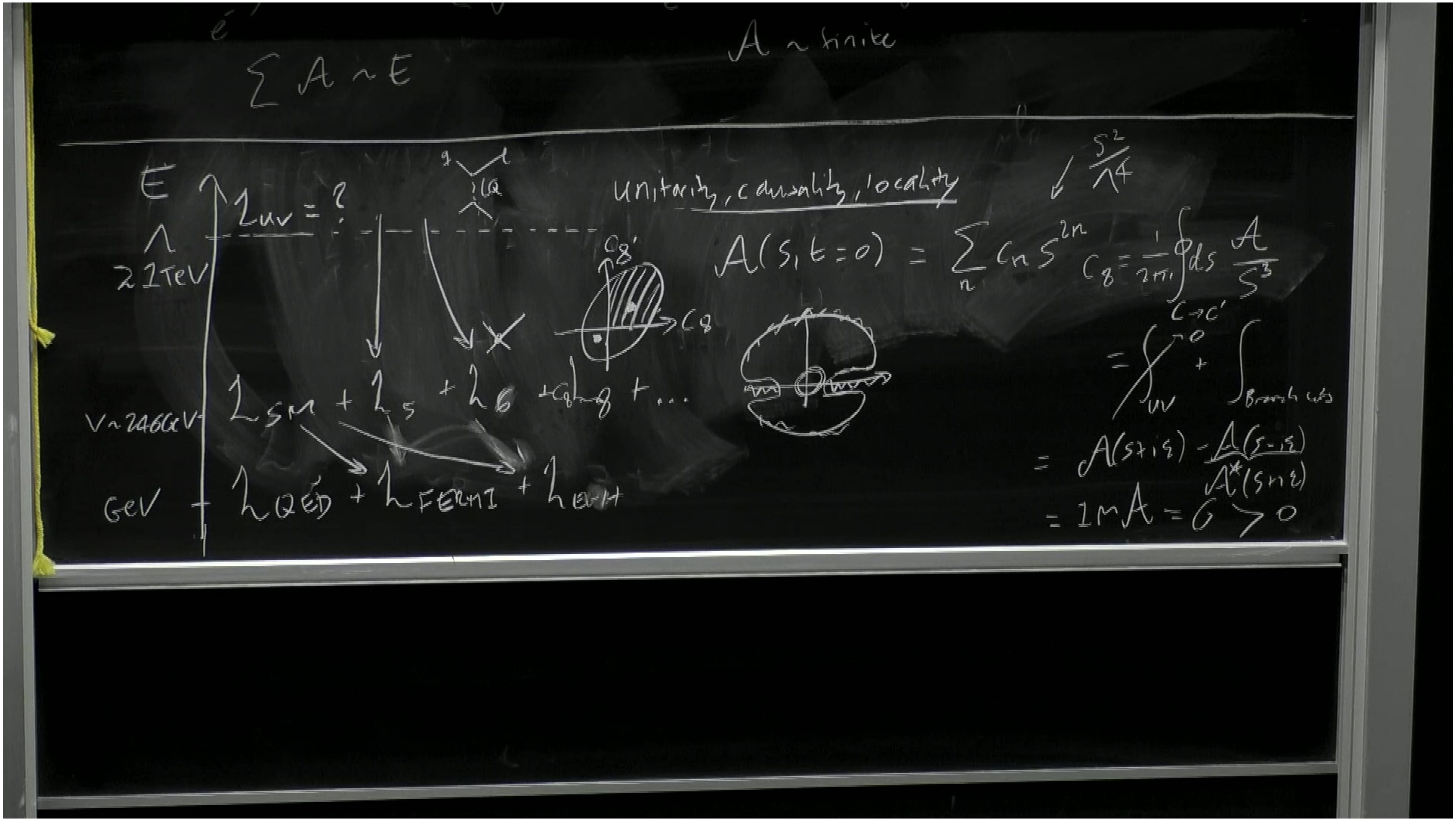


B
μ+
μ−
Z′
LQ
⇒ Λ ≳ 10^3 − 10^5 GeV
• BFM (Beyond Fermi theory)
A ~ E^2
A ~ finite
A ~ E^2
A ~ finite



⇒ Λ ≳ 10^3 - 10^5 GeV
80's Quigg Lee
A ~ finite
Σ A ~ E
A ~ finite


Σ A ~ E
A ~ finite
unitarity, causality, locality
E
L_UV = ?
Λ
≳ 1TeV
v ~ 246GeV
GeV
L_SM + L_5 + L_6 + L_8 + ...
L_QED + L_FERMI
A(s, t=0) = Σ_n c_n s^2n
= Im A = σ > 0
CAUTION


Σ A ~ E
A ~ finite
unitarity, causality, locality
A(s, t=0) = Σ c_n s^{2n}
≥ 1 TeV
V ~ 246 GeV
GeV
= Im A = σ > 0