Title: Standard Model & EDM, g-2

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Collection: School on Table-Top Experiments for Fundamental Physics

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More Standard Model

Last time: Massless spin-2 $\Rightarrow$ GR

Massless spin-1 $\Rightarrow$ YM

Spin-$\frac{1}{2}$, Spin-0 $\Rightarrow$ uncanstrained-ish

Today: Build the SM

The Higgs Mechanism

SM as an EFT

Building the SM

- spin-2 graviton (G_N)
- 12 massless spin-1 ($\alpha_Y, \alpha_W, \alpha_S$)
  - $1 + 3 + 8$
- 3 copies of 15 spin-$\frac{1}{2}$ Weyl fermions

	$U(1)_Y$	$SU(2)_L$
e^c		
e		
ν		
u^c		
d^c		
u		
d		

SM

...ton (G_N)

...ss spin-1 ($\alpha_Y, \alpha_W, \alpha_S$)

... = 8

... of 15 spin-$\frac{1}{2}$ Weyl fermi...

3x

	$U(1)_Y$	$SU(2)_L$	$SU(3)_C$
e^c	$+1$	—	
$l = \begin{pmatrix} e \\ \nu \end{pmatrix}$	$-1/2$	2	
u^c	$-2/3$	—	$\bar{3}$
d^c	$+1/3$	—	$\bar{3}$
$q = \begin{pmatrix} u \\ d \end{pmatrix}$	$+1/6$	2	3

Building the SM

- spin-2 graviton (G_N)
- 12 massless spin-1 ($\alpha_Y, \alpha_W, \alpha_S$)
  - ↳ $1 + 3 + 8$
- 3 copies of 15 spin-$\frac{1}{2}$ Weyl fermions
  - → No masses allowed ?!

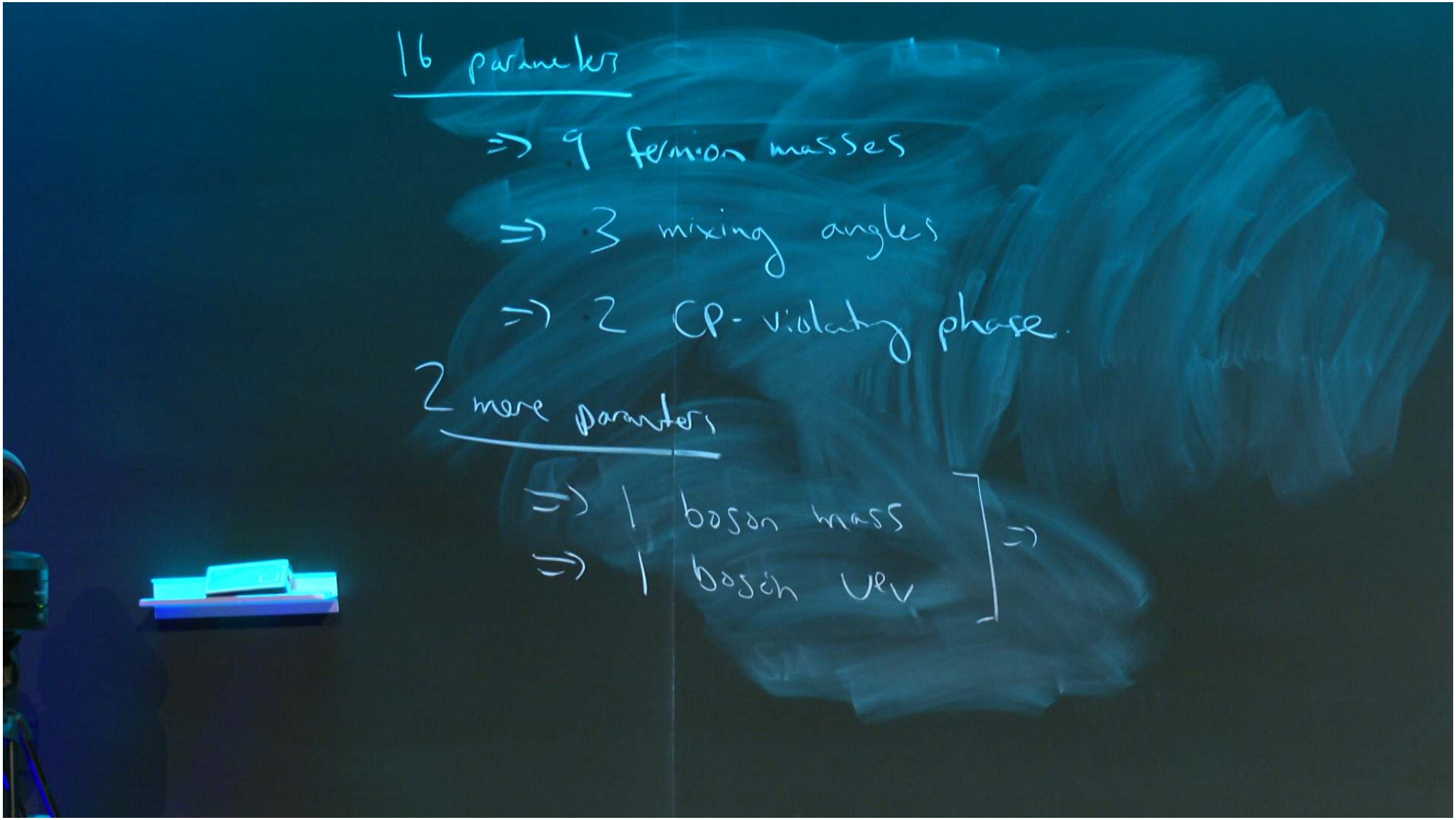
3×

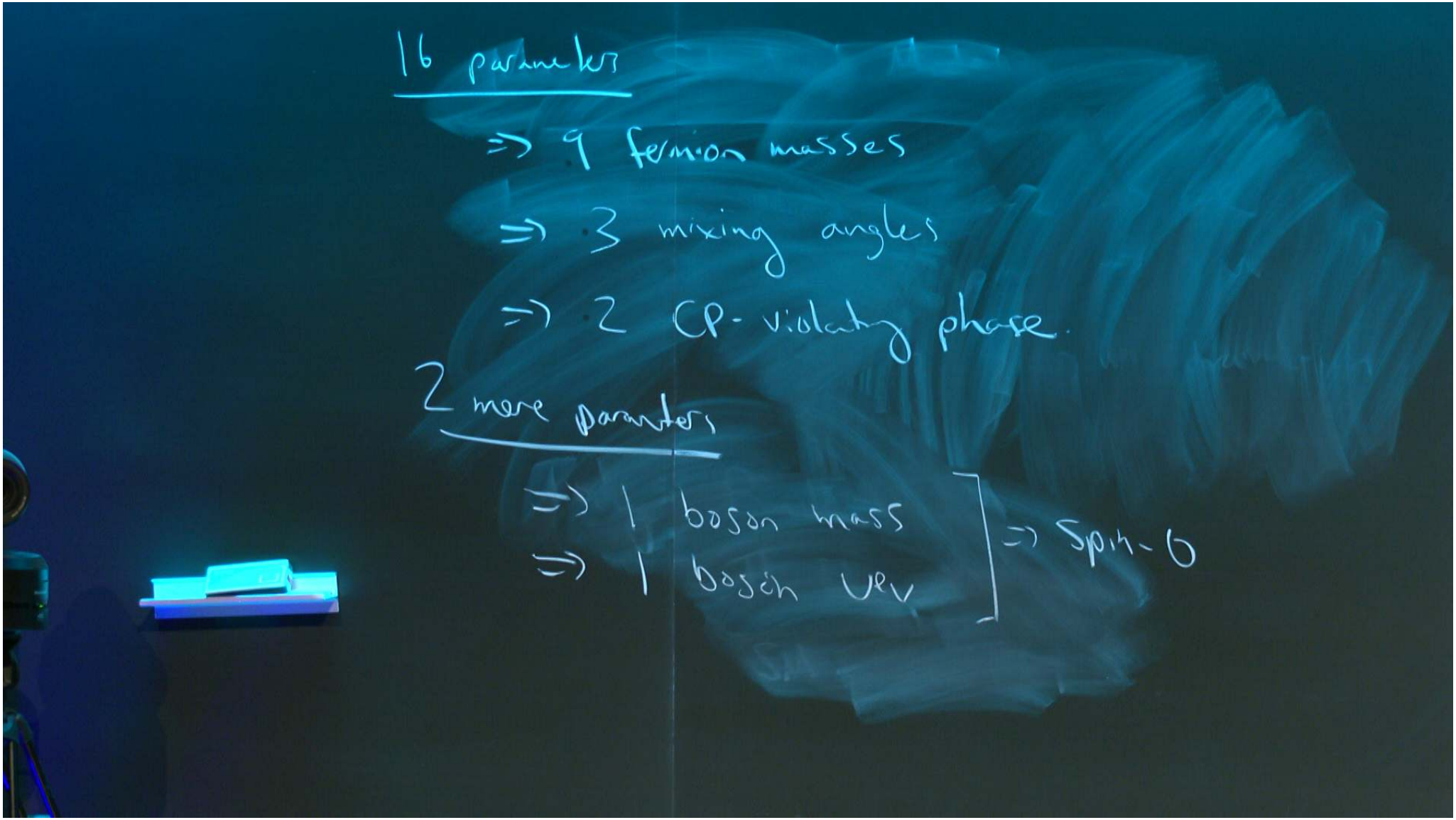
	$U(1)_Y$	SU
e^c	$+1$	—
$l = \begin{pmatrix} e \\ \nu \end{pmatrix}$	$-\frac{1}{2}$	2
u^c	$-\frac{2}{3}$	—
d^c	$+\frac{1}{3}$	—
$q = \begin{pmatrix} u \\ d \end{pmatrix}$	$+\frac{1}{6}$	2

Building the SM

- spin-2 graviton (G_N)
- 12 massless spin-1 ($\alpha_Y, \alpha_W, \alpha_S$)
  - $1 + 3 + 8$
- 3 copies of 15 spin-$\frac{1}{2}$ Weyl fermions
  - → No masses allowed ?!
- Where are the remaining 16 parameters?

	$U(1)_Y$	$SU(2)_L$
e^c	$+1$	—
$l = \begin{pmatrix} e \\ \nu \end{pmatrix}$	$-\frac{1}{2}$	2
u^c	$-\frac{2}{3}$	—
d^c	$+\frac{1}{3}$	—
$q = \begin{pmatrix} u \\ d \end{pmatrix}$	$+\frac{1}{6}$	2


16 parameters
=> 9 fermion masses
=> 3 mixing angles
=> 2 CP-violating phase.
2 more parameters
=> 1 boson mass
=> 1 bosch vev
=>


16 parameters
=> 9 fermion masses
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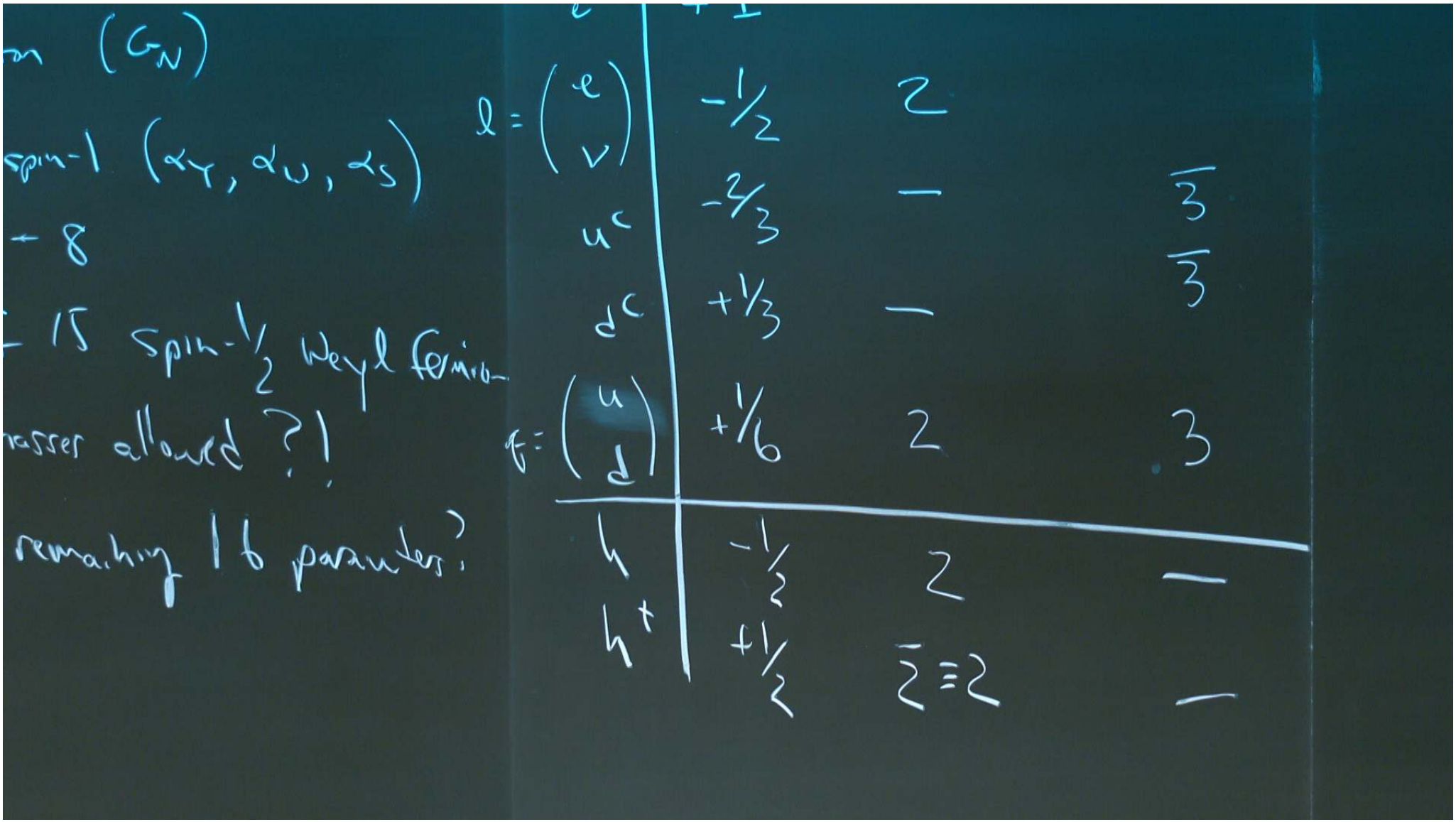
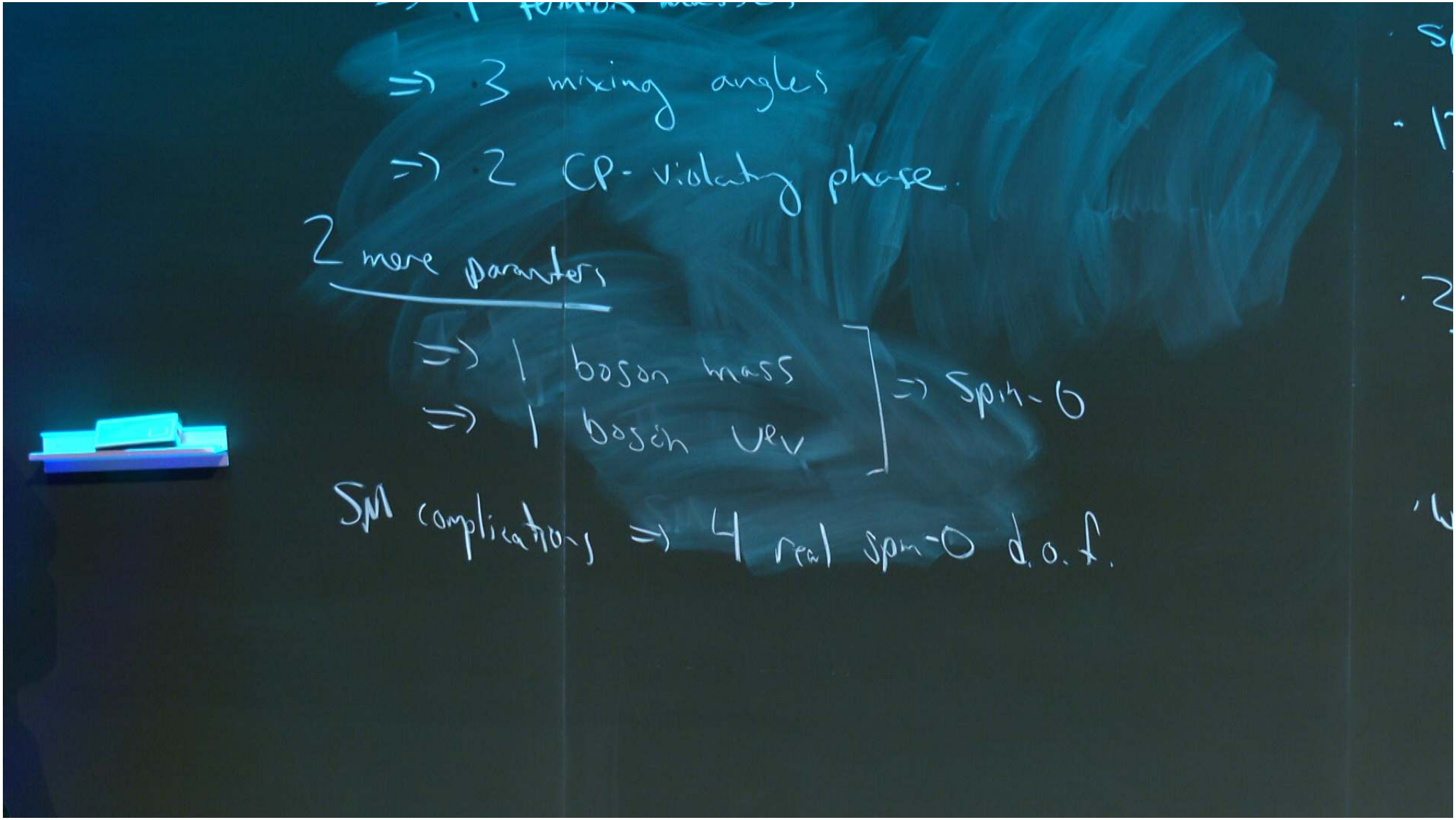
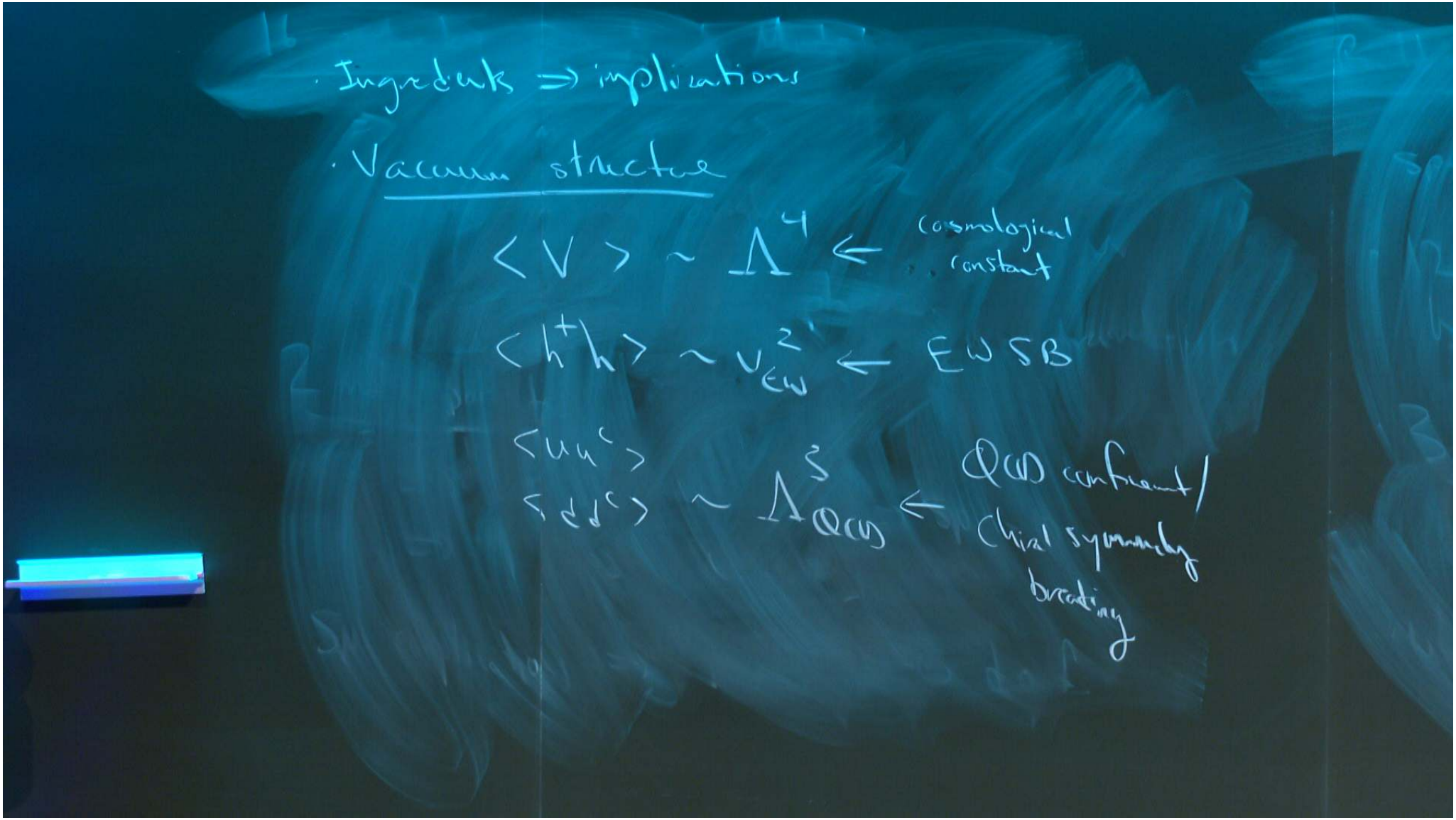
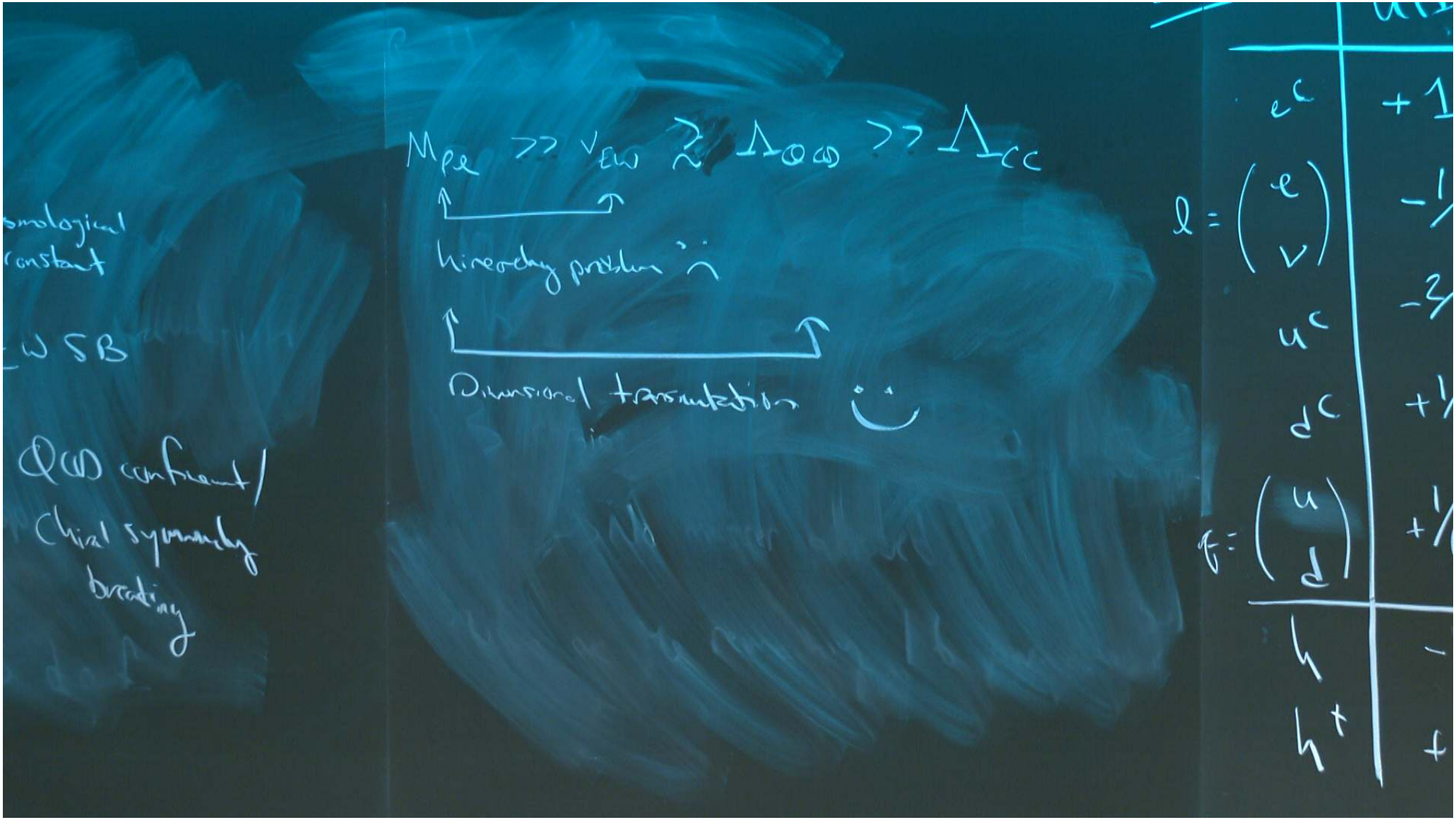
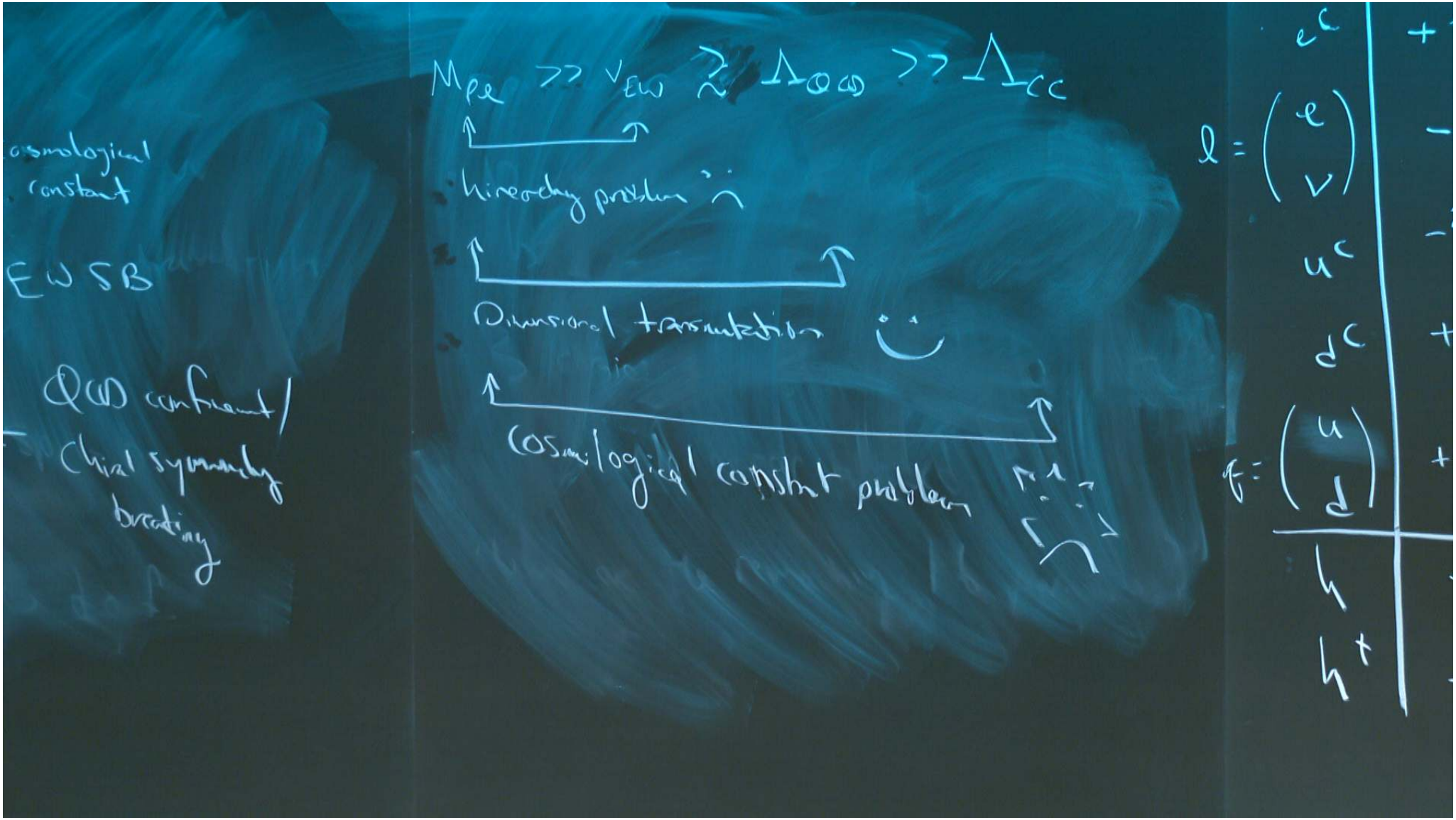
2 more parameters
=> 1 boson mass
=> 1 bosch vev
=> Spin-0

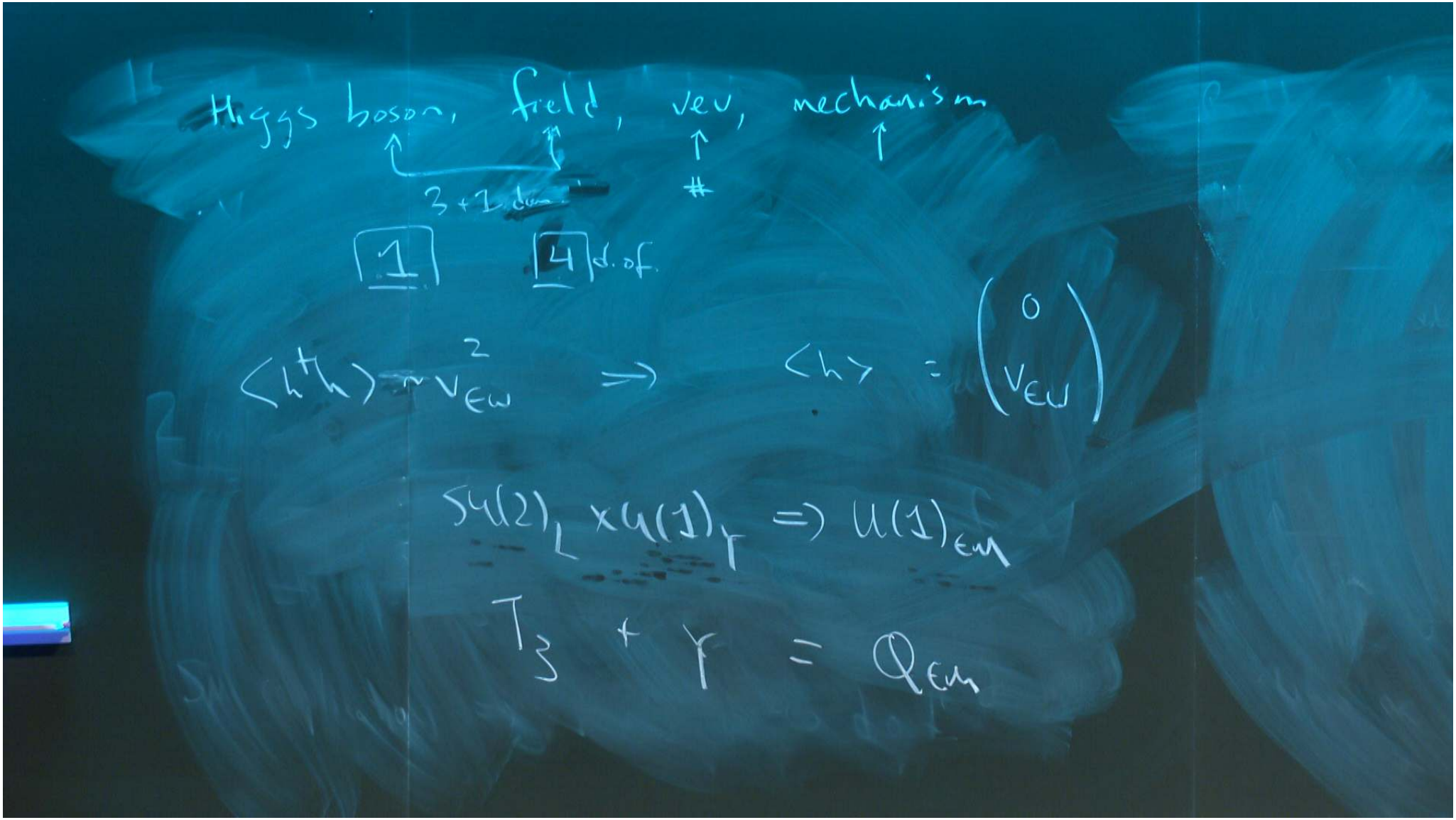

on (G_N)
spin-1 $(\alpha_Y, \alpha_W, \alpha_S)$
$= 8$
$= 15$ spin-$\frac{1}{2}$ Weyl fermi-
nasses allowed ?!
remaining 16 parameters?
$l = \begin{pmatrix} e \\ \nu \end{pmatrix}$
u^c
d^c
$q = \begin{pmatrix} u \\ d \end{pmatrix}$
h
h^+
$-1/2$
$-2/3$
$+1/3$
$+1/6$
$-1/2$
$+1/2$
2
1
1
2
2
$\bar{2} \equiv 2$
3
3
3
—
—

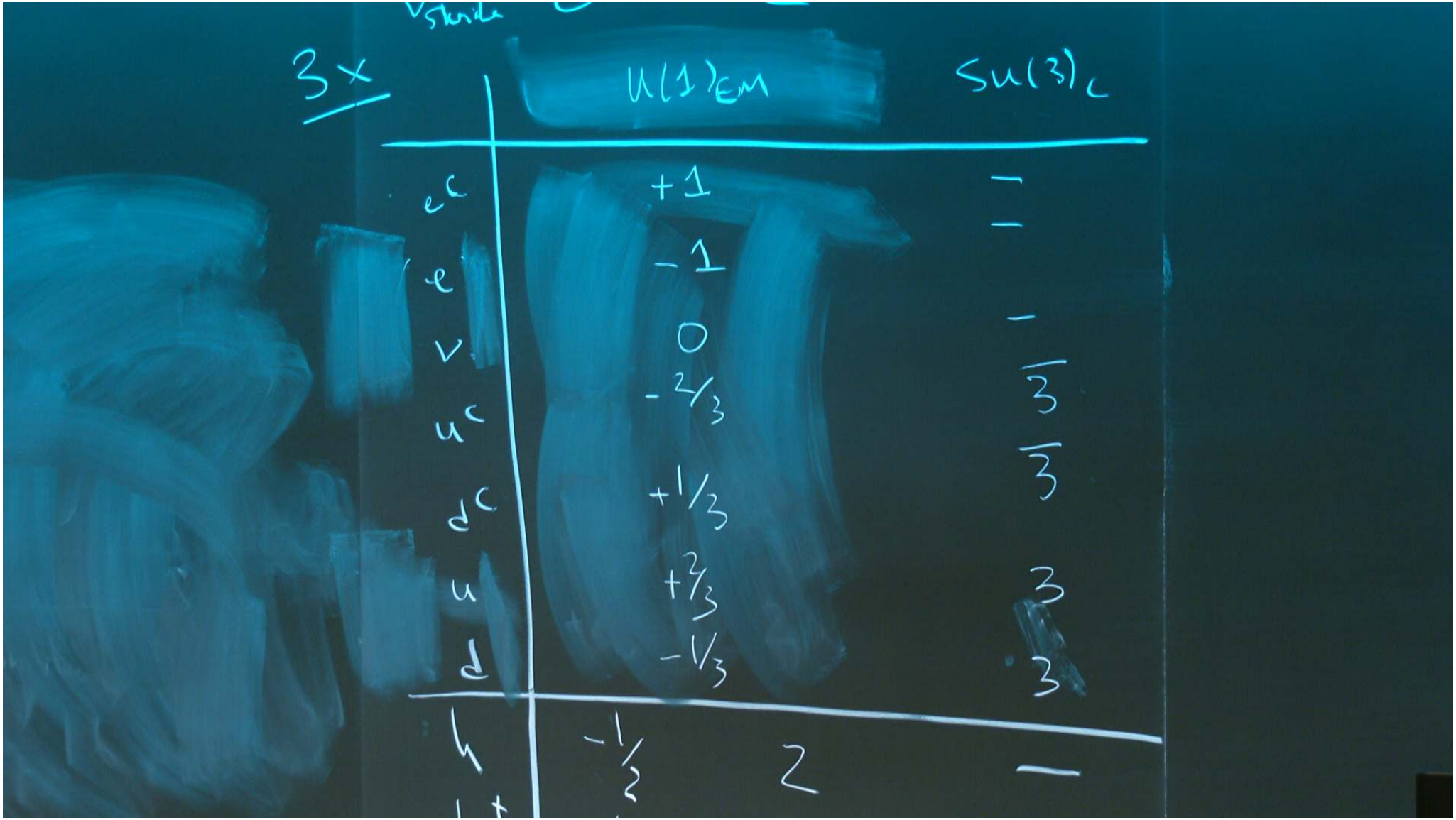

⇒ 3 mixing angles
⇒ 2 CP-violating phase.
2 more parameters
⇒ 1 boson mass
⇒ 1 boson vev
⇒ Spin-0
SM complications ⇒ 4 real spin-0 d.o.f.

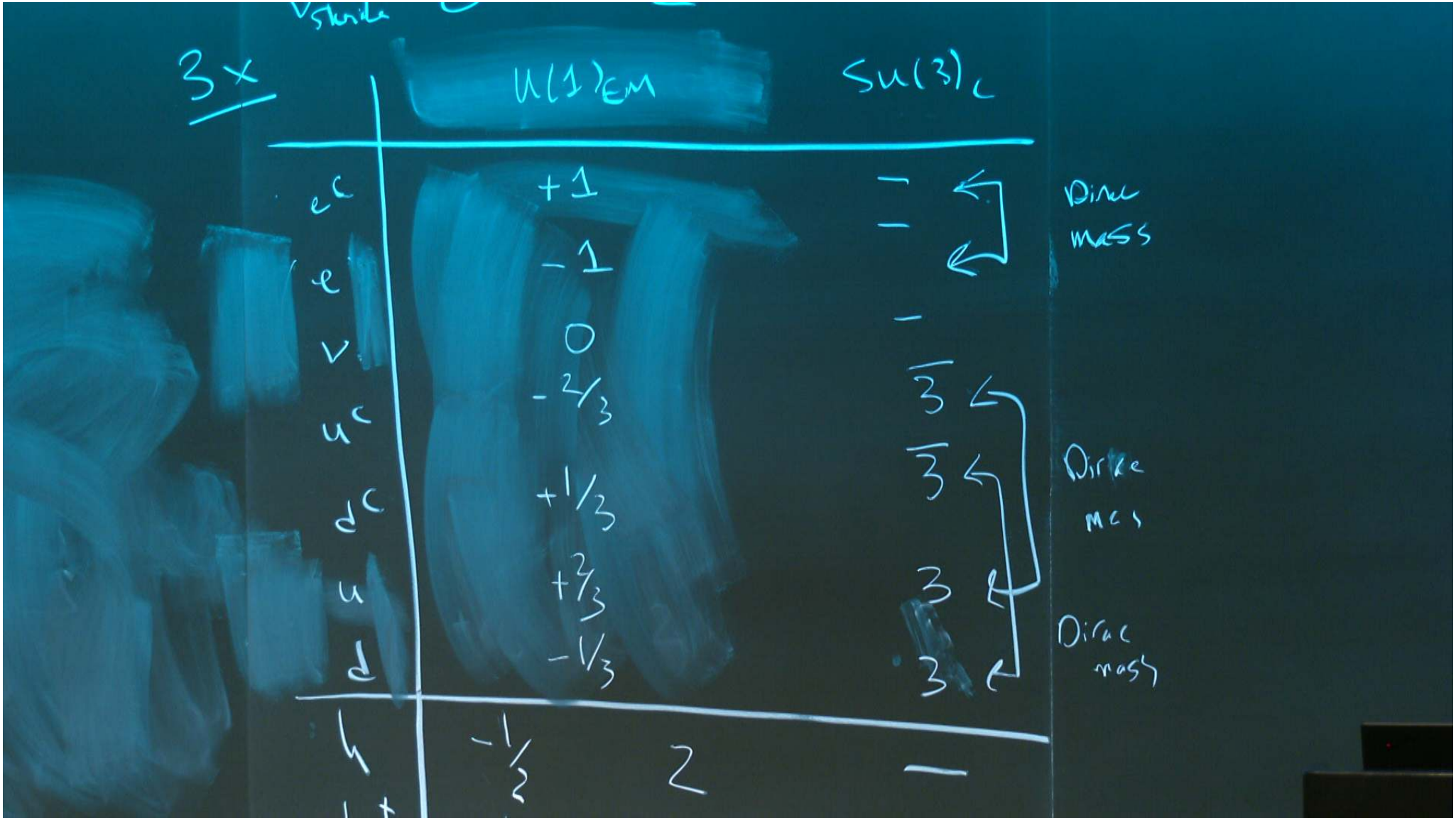

· Ingredients ⇒ implications
· Vacuum structure
$\langle V \rangle \sim \Lambda^4$ ← cosmological constant
$\langle h^\dagger h \rangle \sim v_{EW}^2$ ← EWSB
$\langle u u^c \rangle$
$\langle d d^c \rangle \sim \Lambda_{QCD}^3$ ← QCD confinement / Chiral symmetry breaking

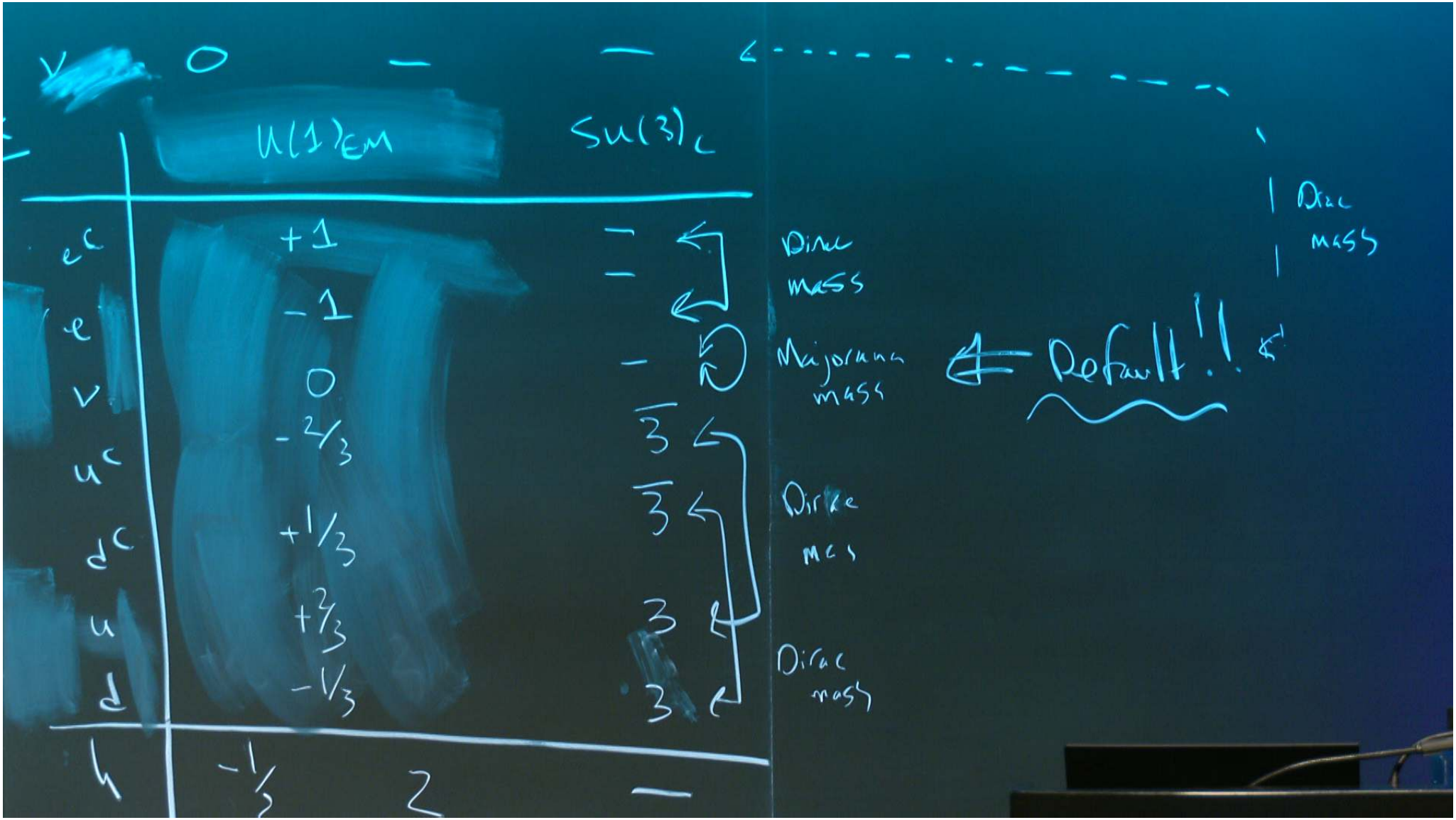

$M_{Pl} >> v_{EW} \gtrsim \Lambda_{QCD} >> \Lambda_{CC}$
hierarchy problem
Dimensional transmutation
QCD confinement/
Chiral symmetry
breaking
e^c
$+1$
$l = \begin{pmatrix} e \\ \nu \end{pmatrix}$
u^c
d^c
$q = \begin{pmatrix} u \\ d \end{pmatrix}$
h
$h^\dagger$

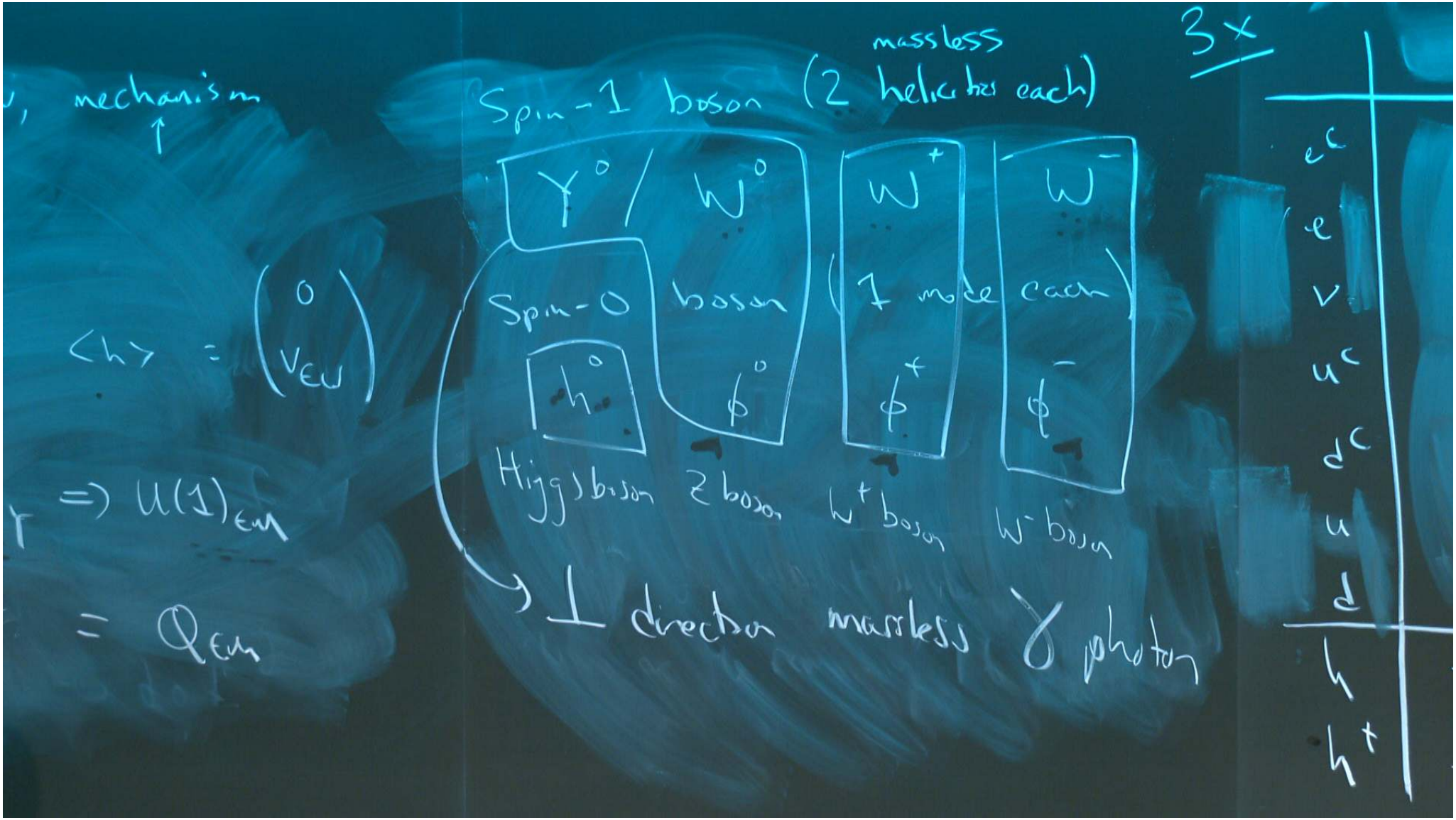

$M_{Pl} >> v_{EW} \gtrsim \Lambda_{QCD} >> \Lambda_{CC}$
hierarchy problem
Dimensional transmutation
cosmological constant problem
cosmological constant
EWSB
QCD confinement/
Chiral symmetry
breaking
$l = \begin{pmatrix} e \\ \nu \end{pmatrix}$
e^c
u^c
d^c
$q = \begin{pmatrix} u \\ d \end{pmatrix}$
H
$H^\dagger$

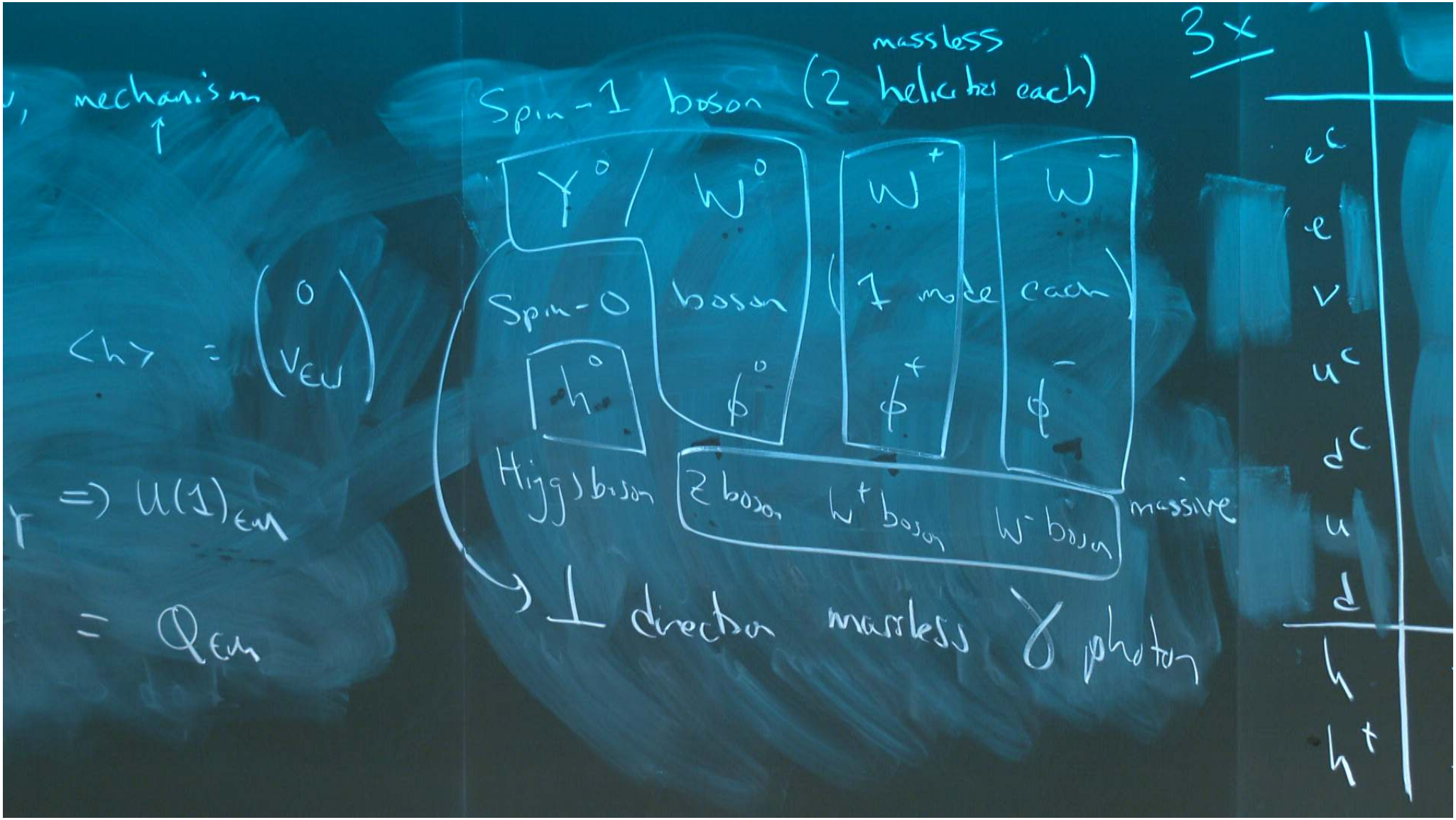

Higgs boson, field, vev, mechanism
3 + 1 d.o.f.
1
4 d.o.f.
$\langle h^\dagger h \rangle \sim v_{EW}^2 \Rightarrow \langle h \rangle = \begin{pmatrix} 0 \\ v_{EW} \end{pmatrix}$
$SU(2)_L \times U(1)_Y \Rightarrow U(1)_{EM}$
$T_3 + Y = Q_{EM}$

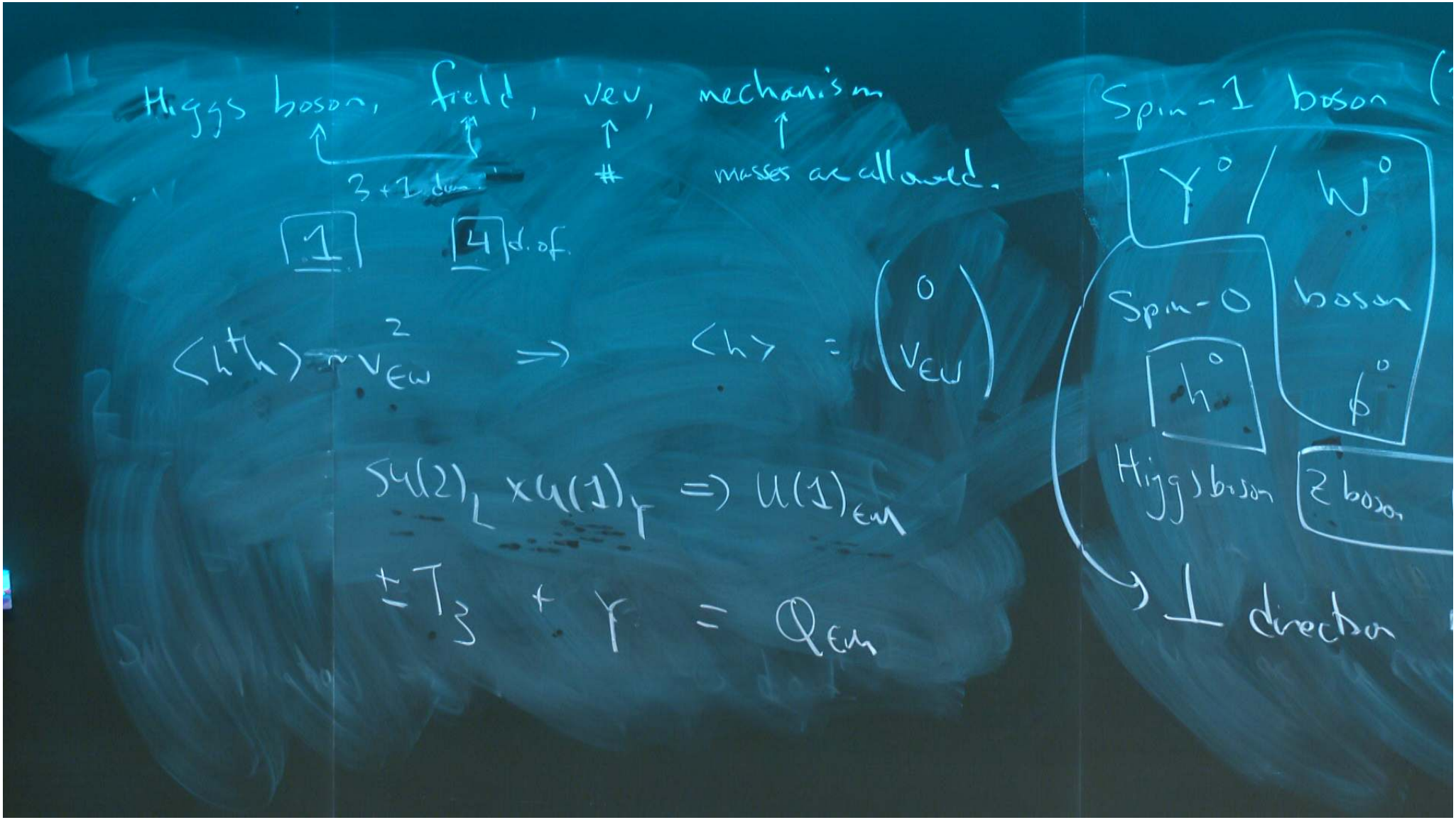

3x
$U(1)_{EM}$
$SU(3)_C$
e^c
$+1$
-1
ν
0
u^c
$-2/3$
d^c
$+1/3$
u
$+2/3$
d
$-1/3$
$-1/2$
2
1

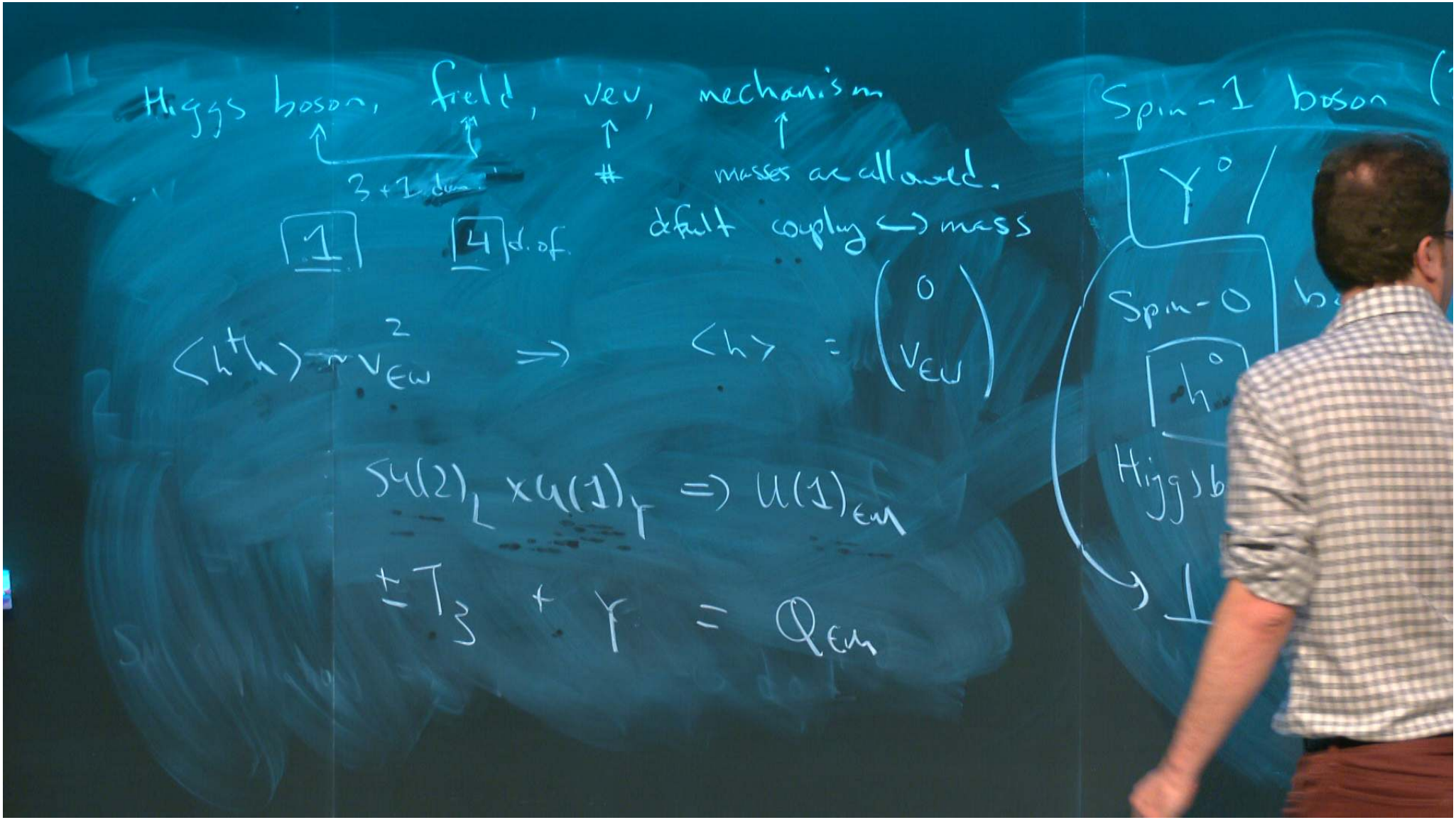

3x
U(1)EM
SU(3)C
eC
e
ν
uC
dC
u
d
+1
−1
0
−2/3
+1/3
+2/3
−1/3
3
3
3
3
Dirac mass
Dirac mass
Dirac mass
−1/2
2

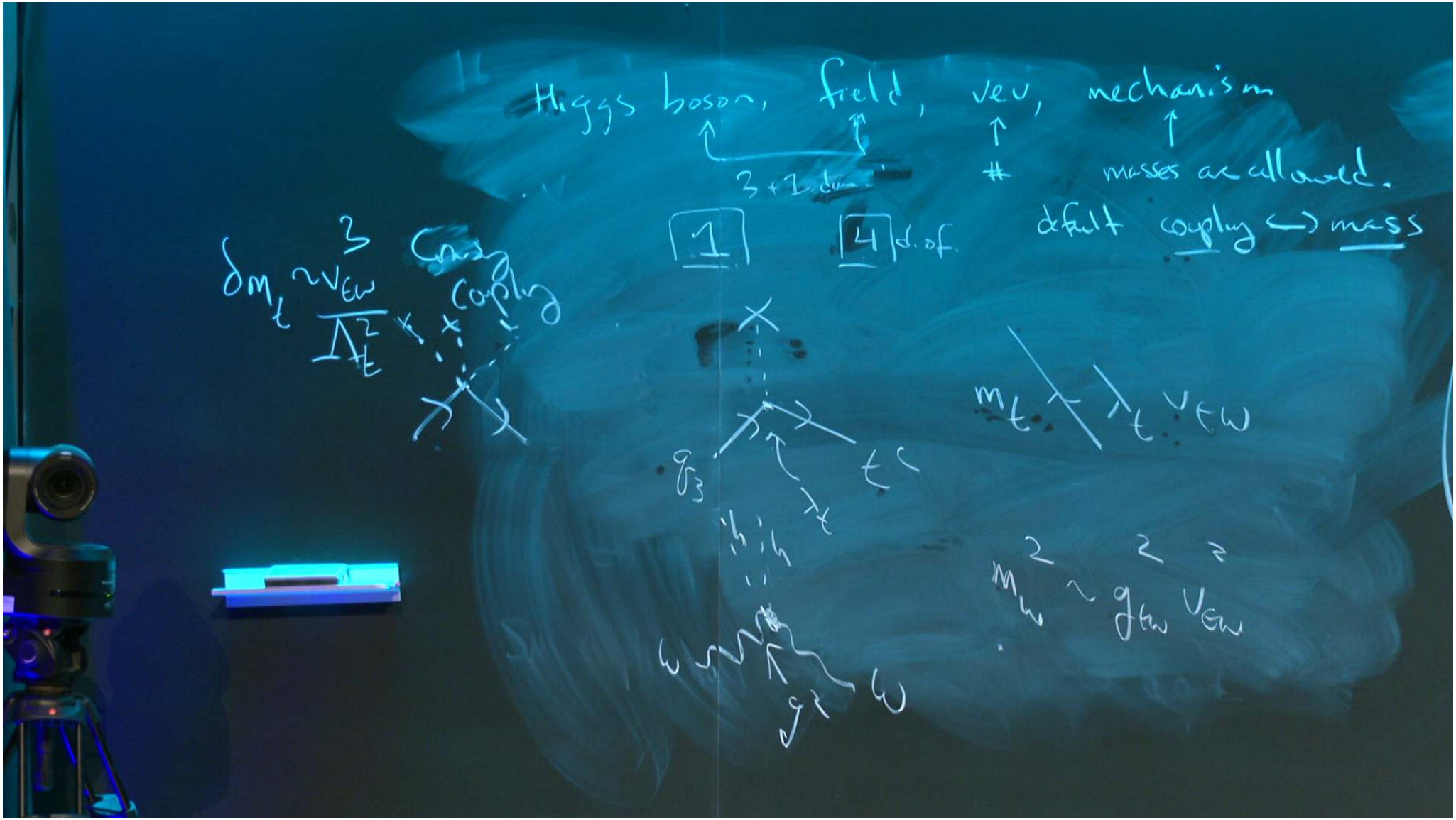

U(1)EM
SU(3)C
+1
-1
0
-2/3
+1/3
+2/3
-1/3
Dirac mass
Majorana mass
Default!!
Dirac mass
Dirac mass
Dirac mass

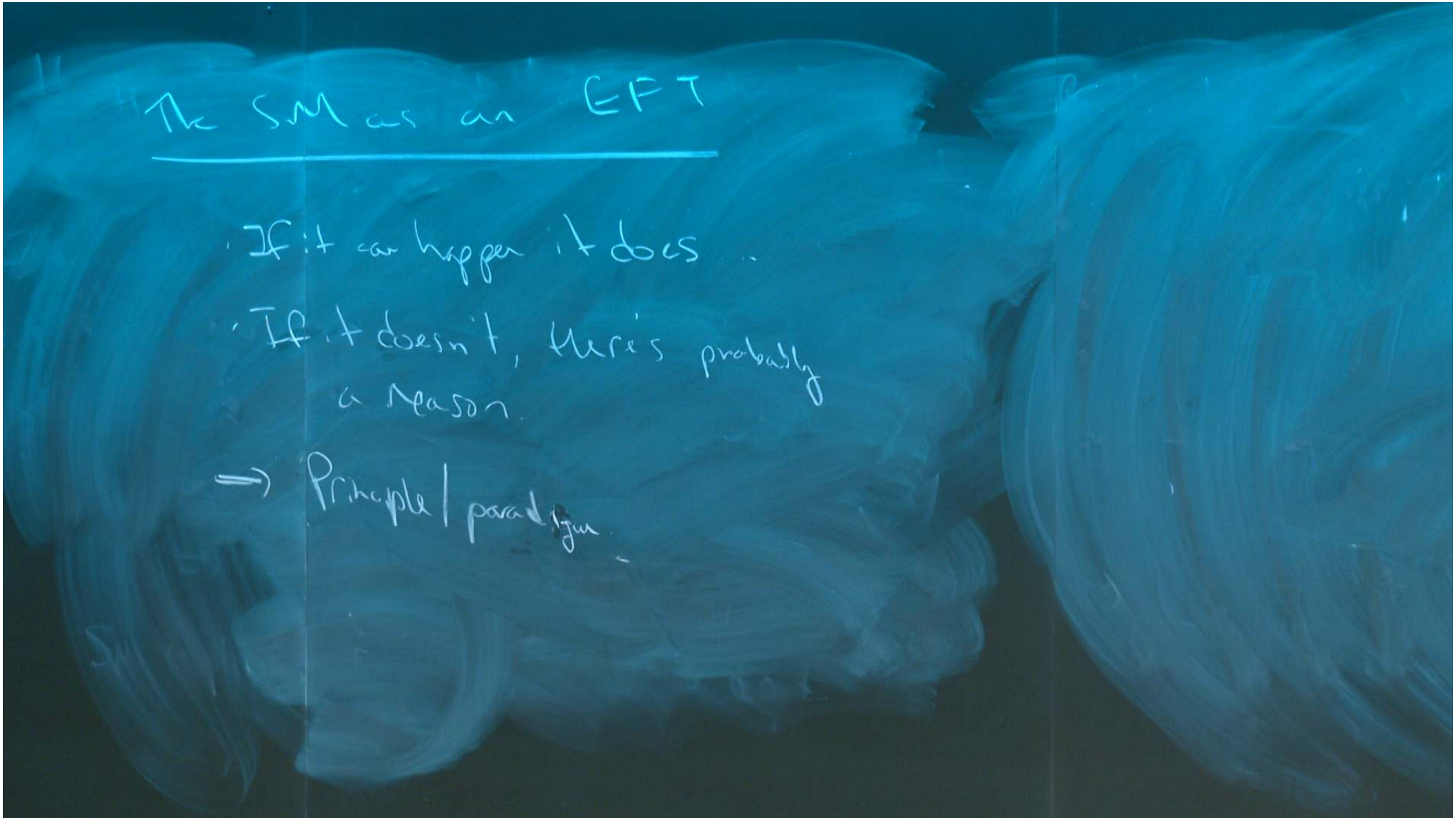

mechanism
Spin-1 boson (2 helicities each)
massless
3x
Spin-0 boson
(1 mode each)
Higgs boson
Z boson
W+ boson
W- boson
massless photon
=> U(1)EM
= QEM

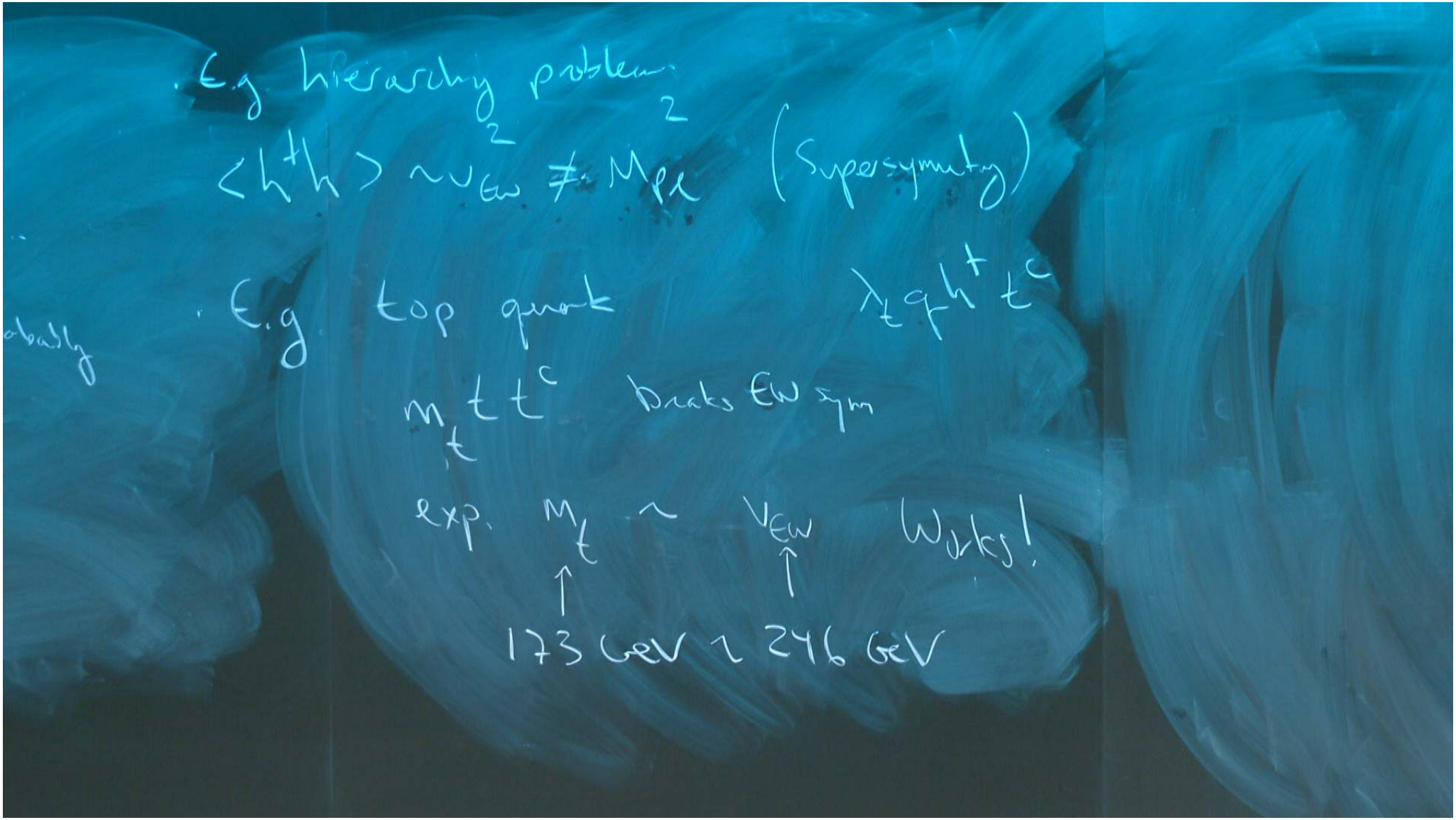

mechanism
massless
Spin-1 boson (2 helicities each)
3x
Y^0 / W^0 W^+ W^-
Spin-0 boson (1 mode each)
h^0 ϕ^0 ϕ^+ ϕ^-
Higgs boson
Z boson
W^+ boson
W^- boson
massive
$\langle h \rangle = \begin{pmatrix} 0 \\ v_{EW} \end{pmatrix}$
$\Rightarrow U(1)_{EM}$
$= Q_{EM}$
$\perp$ direction massless γ photon
e^c
e
ν
u^c
d^c
u
d
h
h^+

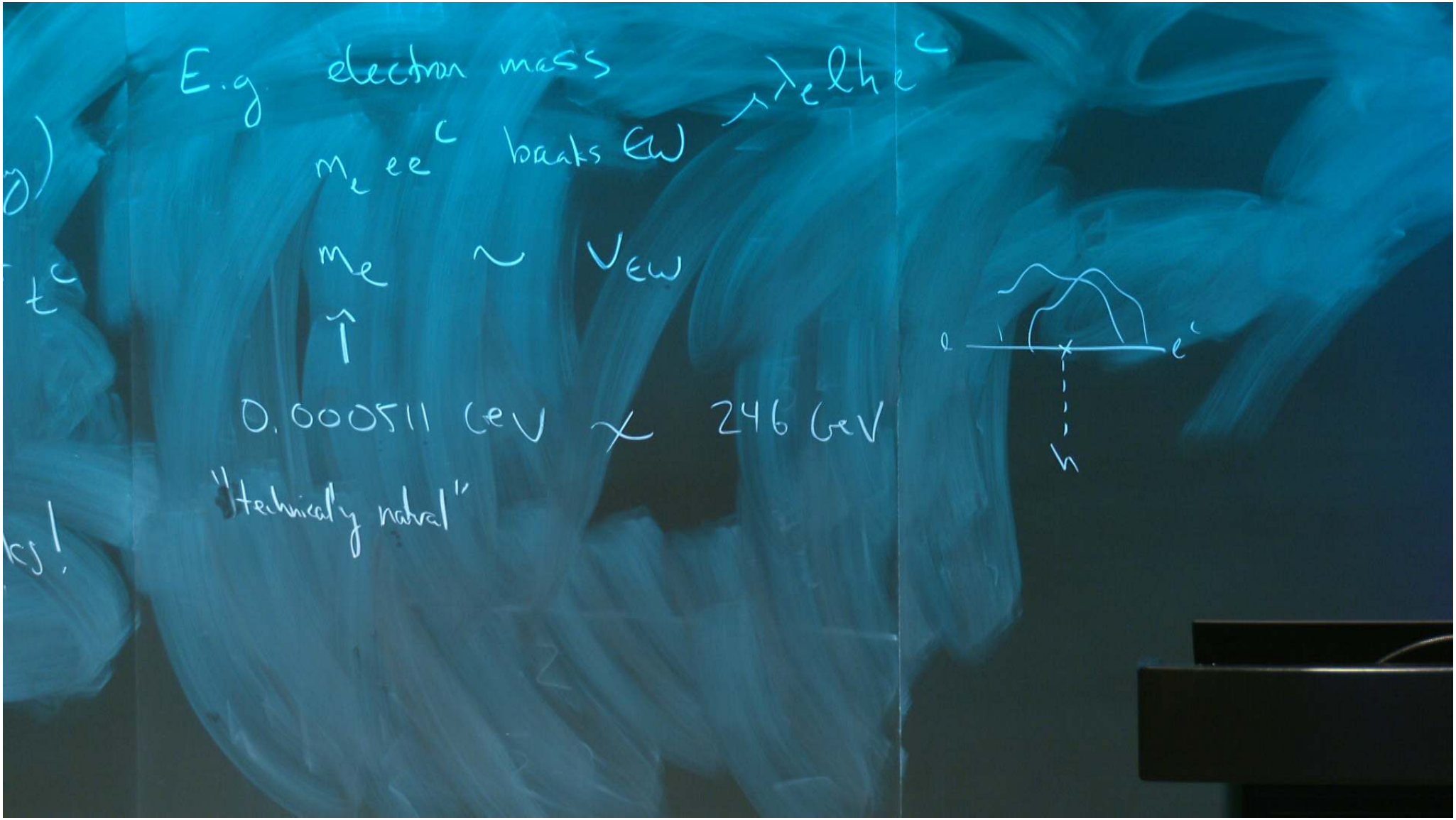

Higgs boson, field, vev, mechanism
3 + 1 dim.
#
masses are allowed.
1
4 d. of
$\langle h^\dagger h \rangle = \frac{1}{2} v_{EW}^2 \Rightarrow \langle h \rangle = \begin{pmatrix} 0 \\ v_{EW} \end{pmatrix}$
$SU(2)_L \times U(1)_Y \Rightarrow U(1)_{EM}$
$\pm T_3 + Y = Q_{EM}$
Spin-1 boson
Y^0 / W^0
Spin-0 boson
h^0
ϕ^0
Higgs boson
Z boson
⊥ direction

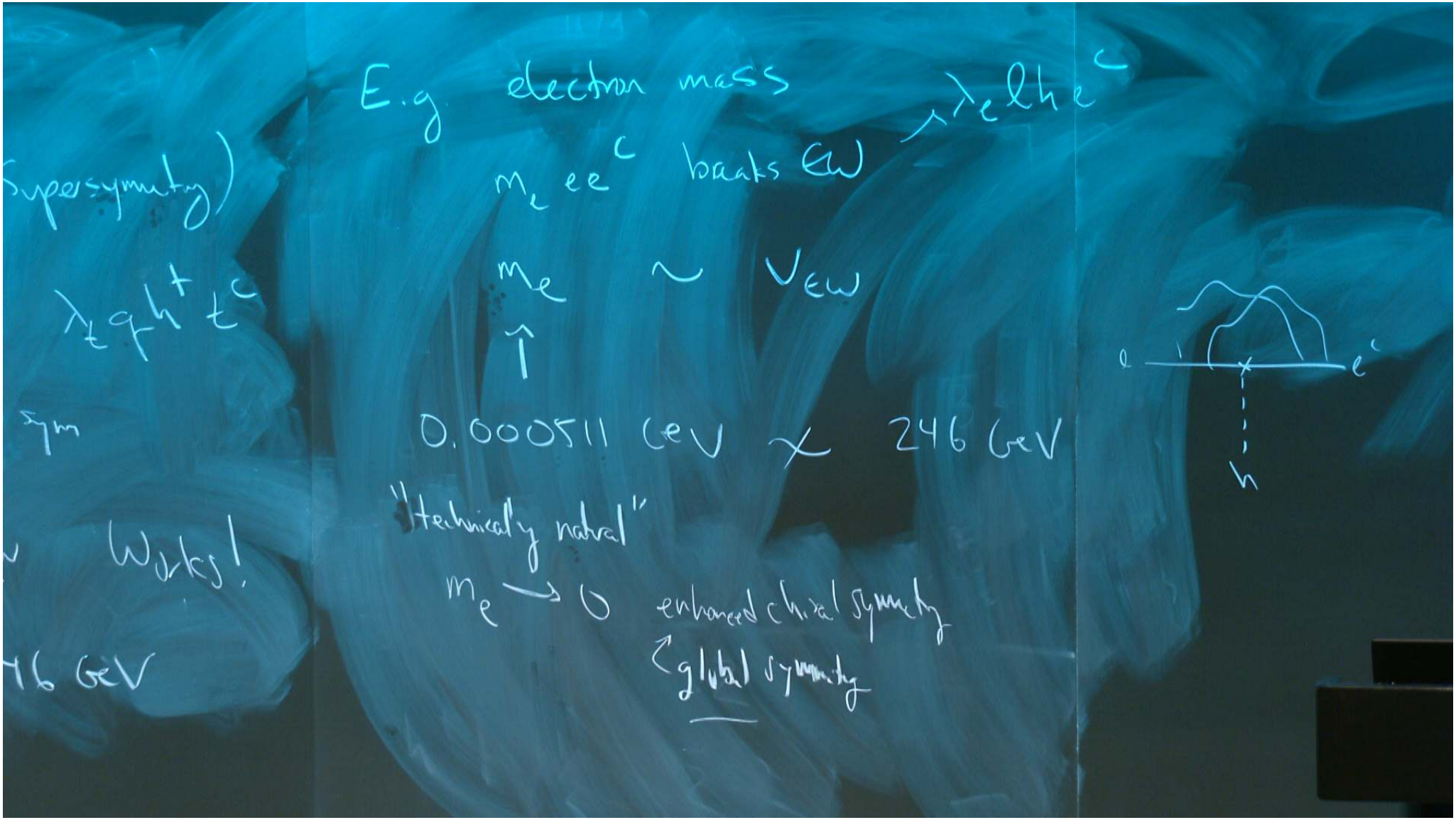

Higgs boson, field, vev, mechanism
3+1 dim.
#
masses are allowed.
1
4 d. of
default coupling ↔ mass
$\langle h^\dagger h \rangle = \frac{1}{2} v_{EW}^2 \Rightarrow \langle h \rangle = \begin{pmatrix} 0 \\ v_{EW} \end{pmatrix}$
$SU(2)_L \times U(1)_Y \Rightarrow U(1)_{EM}$
$\pm T_3 + Y = Q_{EM}$
Spin-1 boson
Y^0
Spin-0
h^0
Higgs b
1

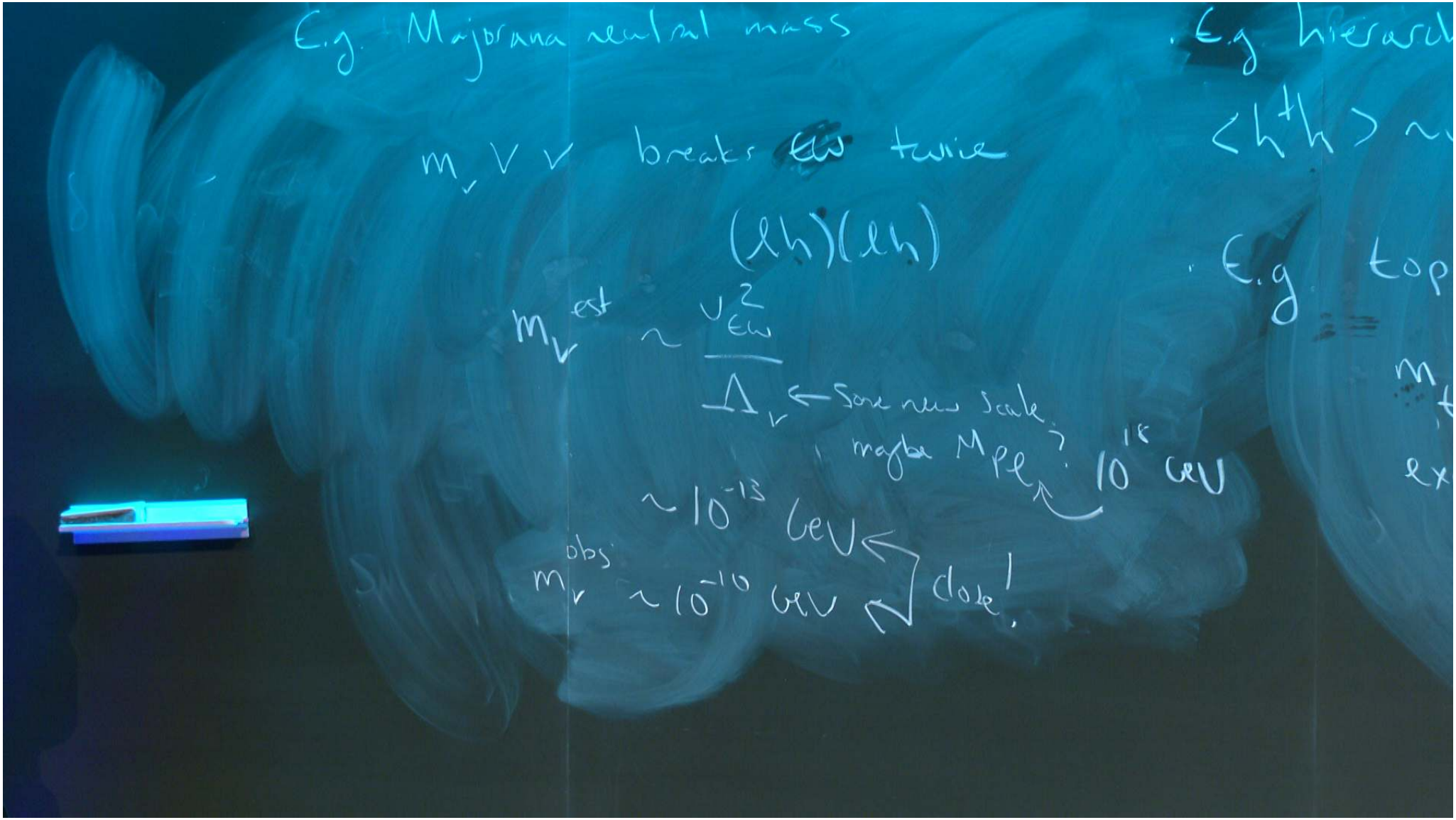

Higgs boson, field, vev, mechanism
3 + 1 dim.
#
masses are allowed.
default coupling ↔ mass
1
4 d.o.f.
Gauge coupling
$\delta m_t \sim \frac{v_{EW}^3}{\Lambda_t^2}$
$m_t = \lambda_t v_{EW}$
$m_W^2 \sim g_{EW}^2 v_{EW}^2$

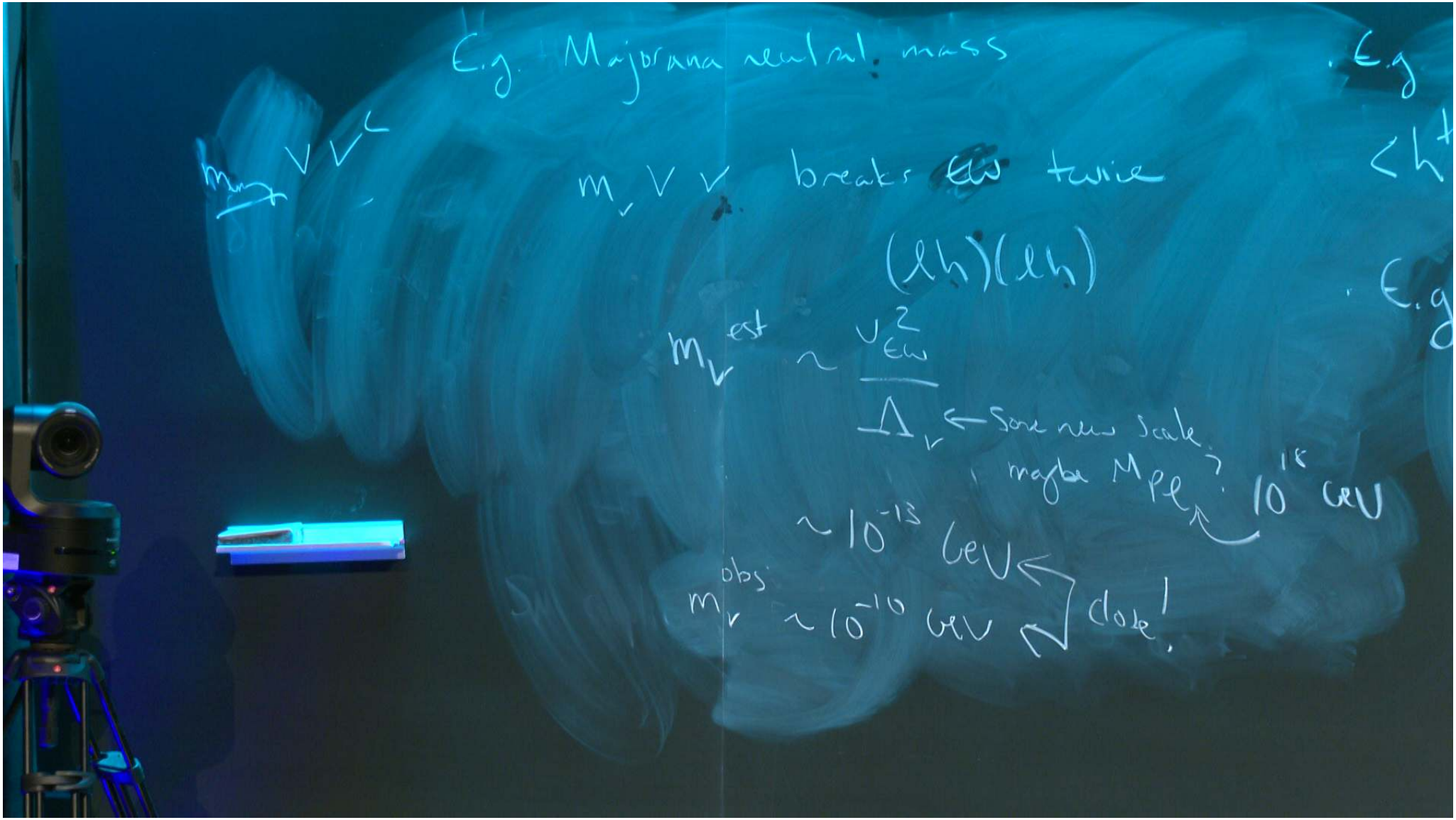

The SM as an EFT
· If it can happen, it does
· If it doesn't, there's probably a reason
⟹ Principle / paradigm

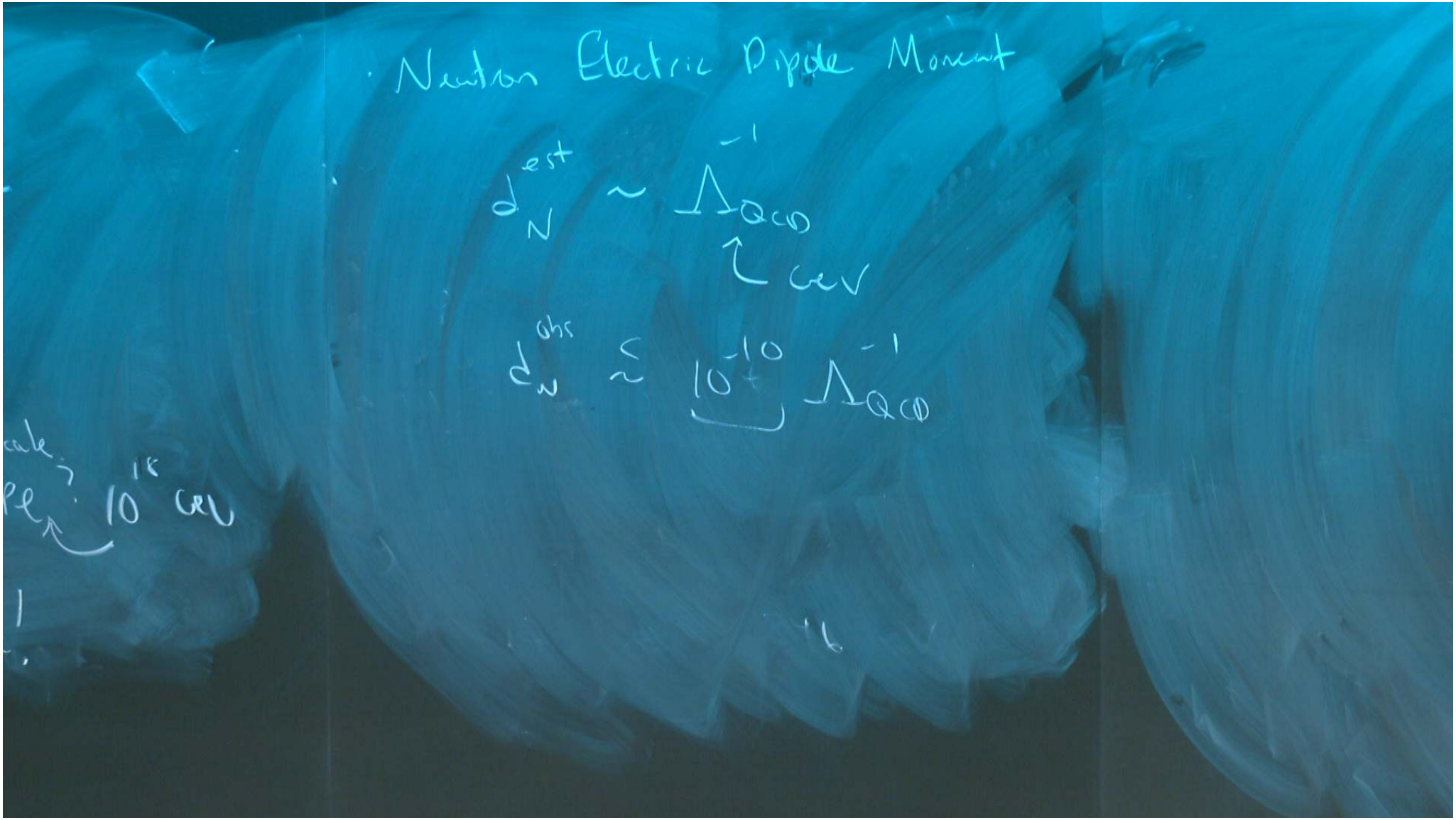

E.g. hierarchy problem:
$\langle h^\dagger h \rangle \sim v_{EW}^2 \neq M_{Pl}^2$ (Supersymmetry)
E.g. top quark
$\lambda_t q h^\dagger t^c$
$m_t t t^c$ breaks EW sym
exp. $m_t \sim v_{EW}$ Works!
173 GeV ≈ 246 GeV

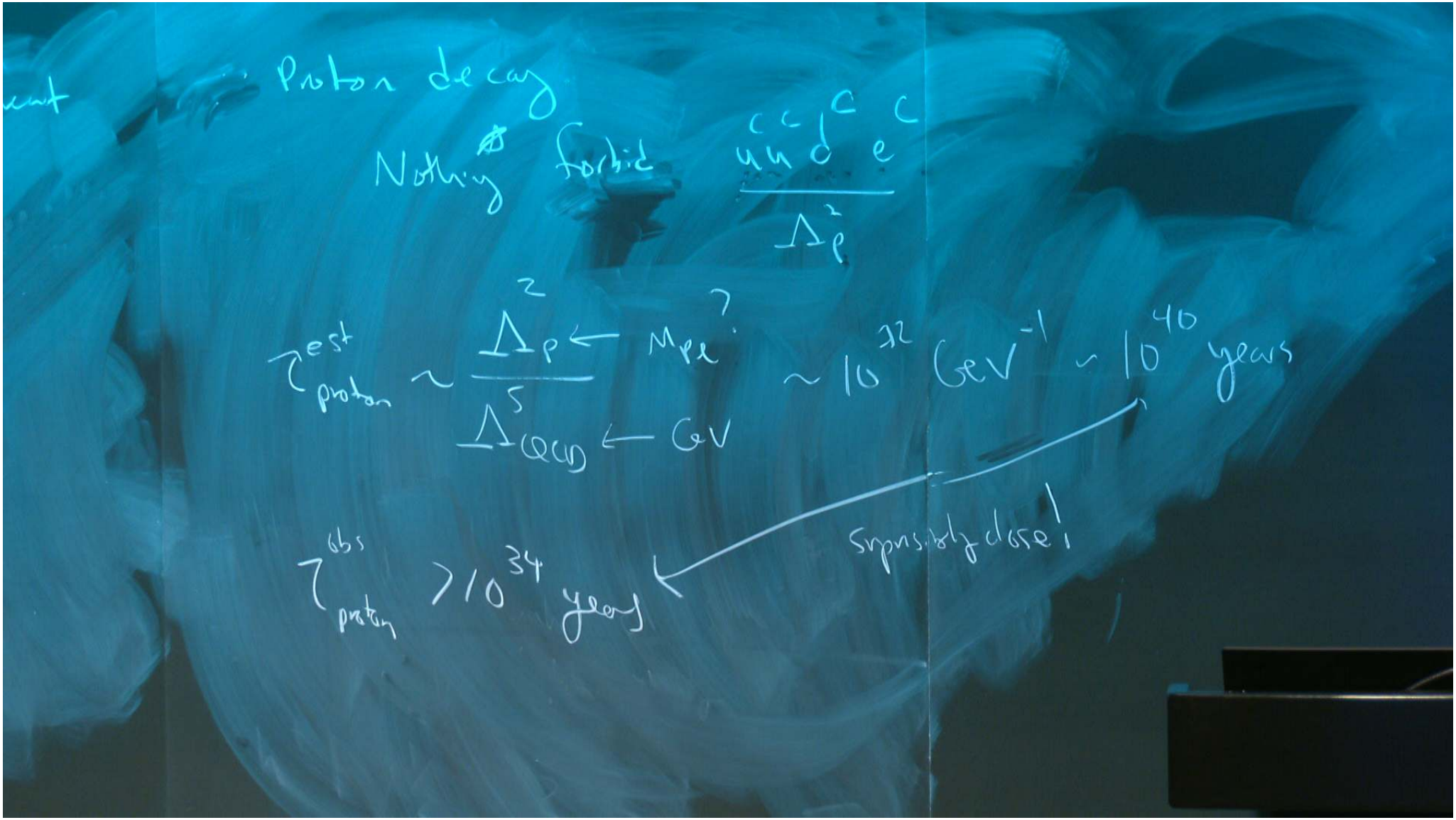

E.g. electron mass
$m_e e e^c$ breaks EW
$\lambda_e l h e^c$
$m_e \sim v_{EW}$
0.000511 GeV $\times$ 246 GeV
"Technically natural"
e
e
h


E.g. electron mass
$m_e ee^c$ breaks EW
$\lambda_e l h e^c$
supersymmetry)
$\lambda_t q h^t t^c$
$m_e \sim v_{EW}$
0.000511 GeV × 246 GeV
"Technically natural"
$m_e \to 0$ enhanced chiral symmetry
global symmetry
Works!
246 GeV
e
e'
h


E.g. Majorana neutrino mass
E.g. hierarch
breaks EW twice
(lh)(lh)
E.g. top
Some new scale
maybe M_Pl ? 10^18 GeV
~10^-13 GeV
~10^-10 GeV
close!


E.g. Majorana neutrino mass
E.g
$m_\nu \nu\nu$
$m_\nu \nu\nu$ breaks EW twice
$\langle h$
$(lh)(lh)$
E.g
$m_\nu^{est} \sim \frac{v_{EW}^2}{\Lambda_\nu}$
$\Lambda_\nu \leftarrow$ some new scale
maybe M_{Pl}? 10^{18} GeV
$\sim 10^{-13}$ GeV
$m_\nu^{obs} \sim 10^{-10}$ GeV
close!


Neutron Electric Dipole Moment
$d_N^{est} \sim \Lambda_{QCD}^{-1}$
$\sim$ GeV
$d_N^{obs} \lesssim 10^{-10}\ \Lambda_{QCD}^{-1}$
10^{15} GeV


Proton decay
Nothing forbid
$\frac{uudeccc}{\Lambda_p^2}$
$\tau^{est}_{proton} \sim \frac{\Lambda_p^2 \leftarrow M_{Pl}^2}{\Lambda_{QCD}^5 \leftarrow GeV} \sim 10^{32} GeV^{-1} \sim 10^{40}$ years
$\tau^{obs}_{proton} > 10^{34}$ years
Suprisingly close!