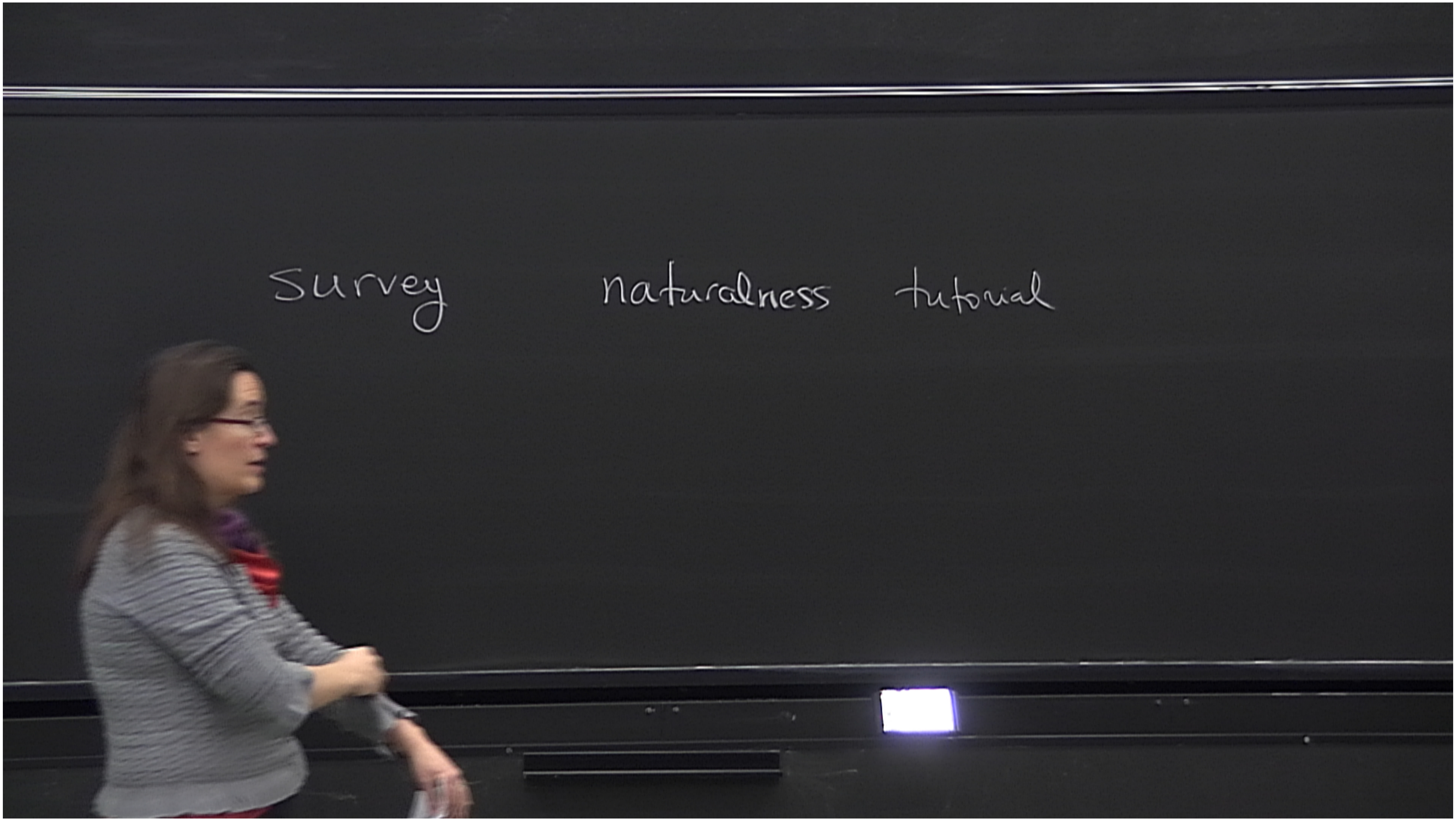
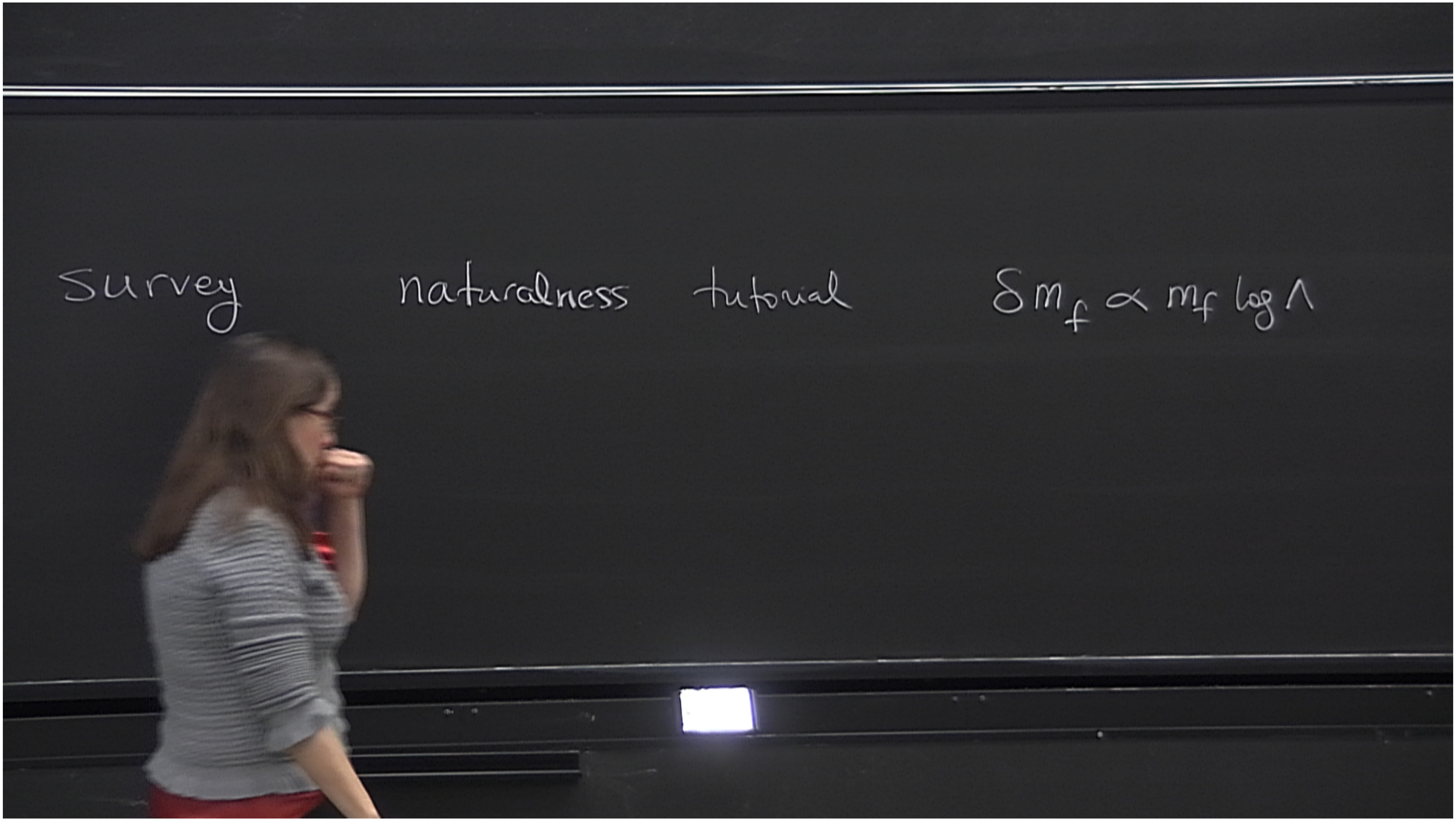
Title: Beyond the Standard Model (Review) - Lecture 9

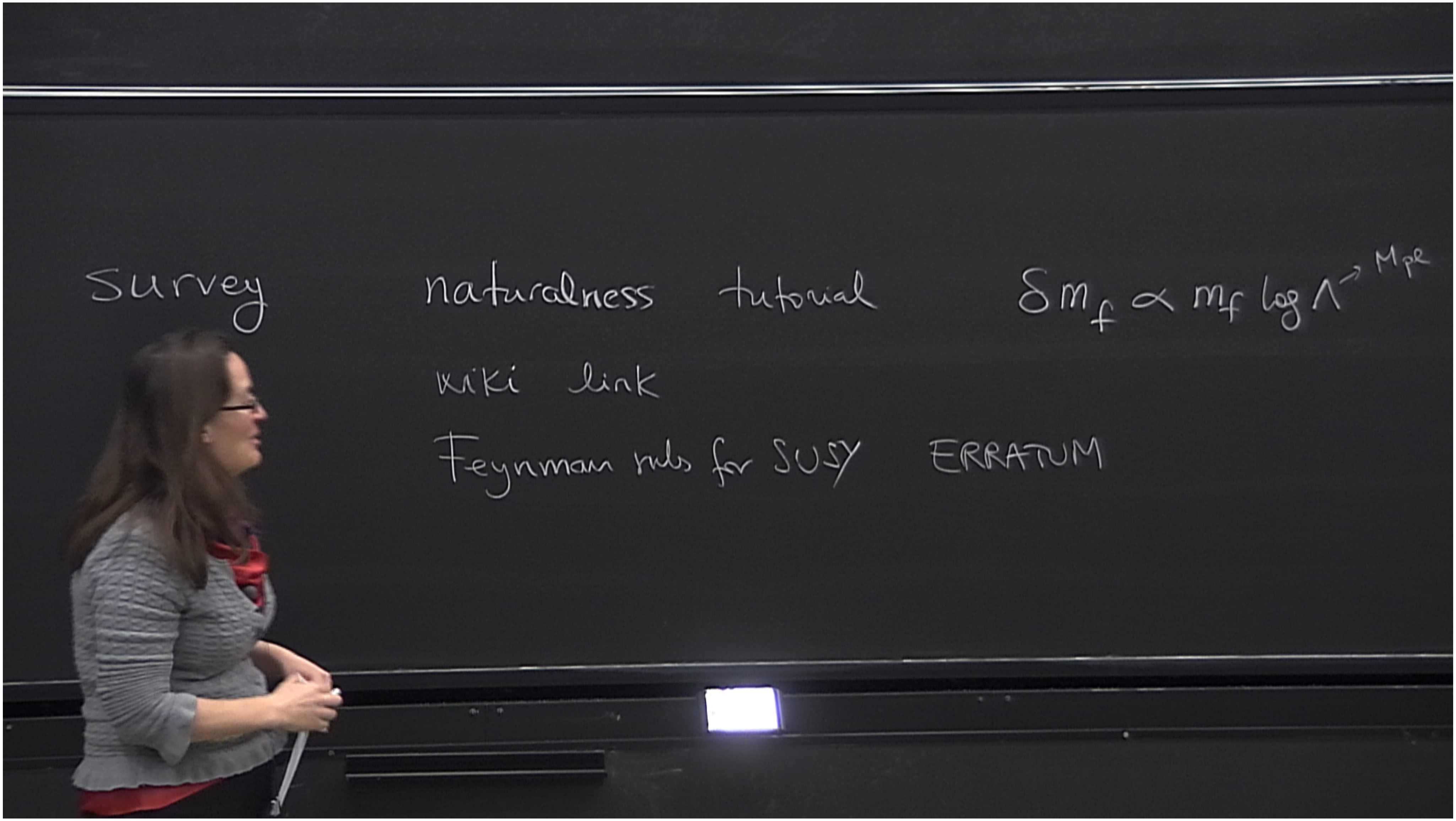
Date: Feb 24, 2012 09:00 AM

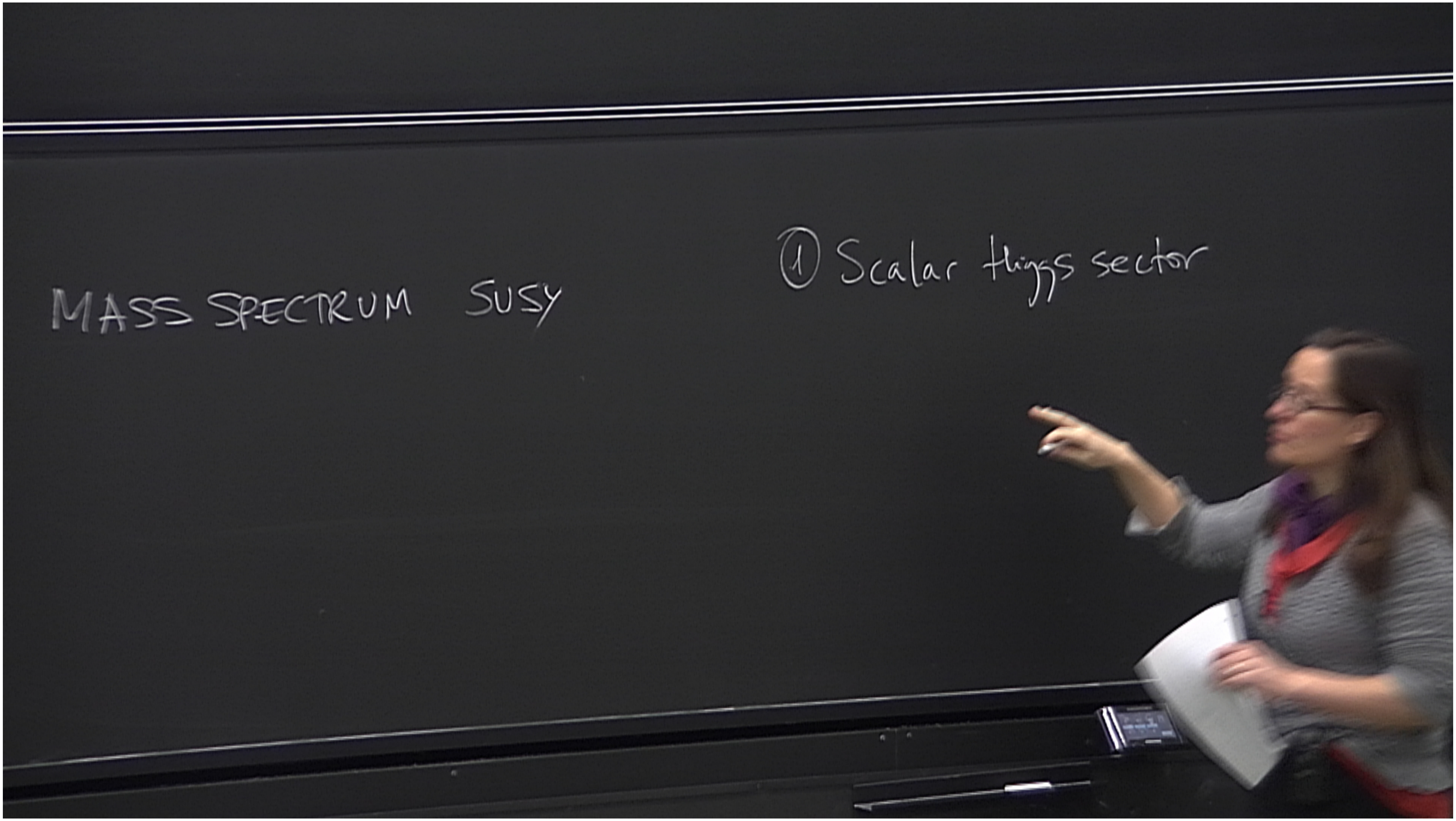
URL: http://pirsa.org/12020080

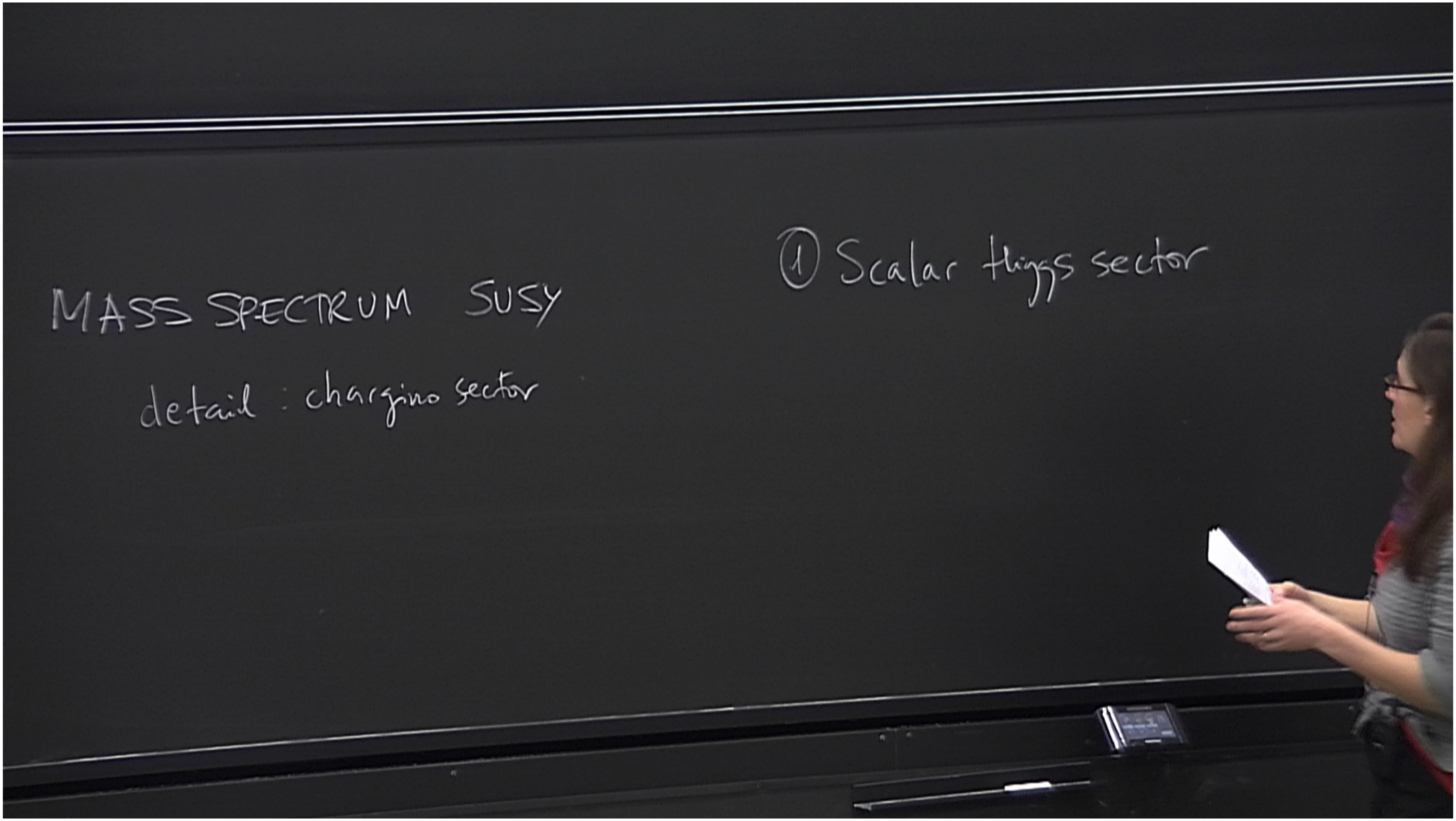
Abstract:

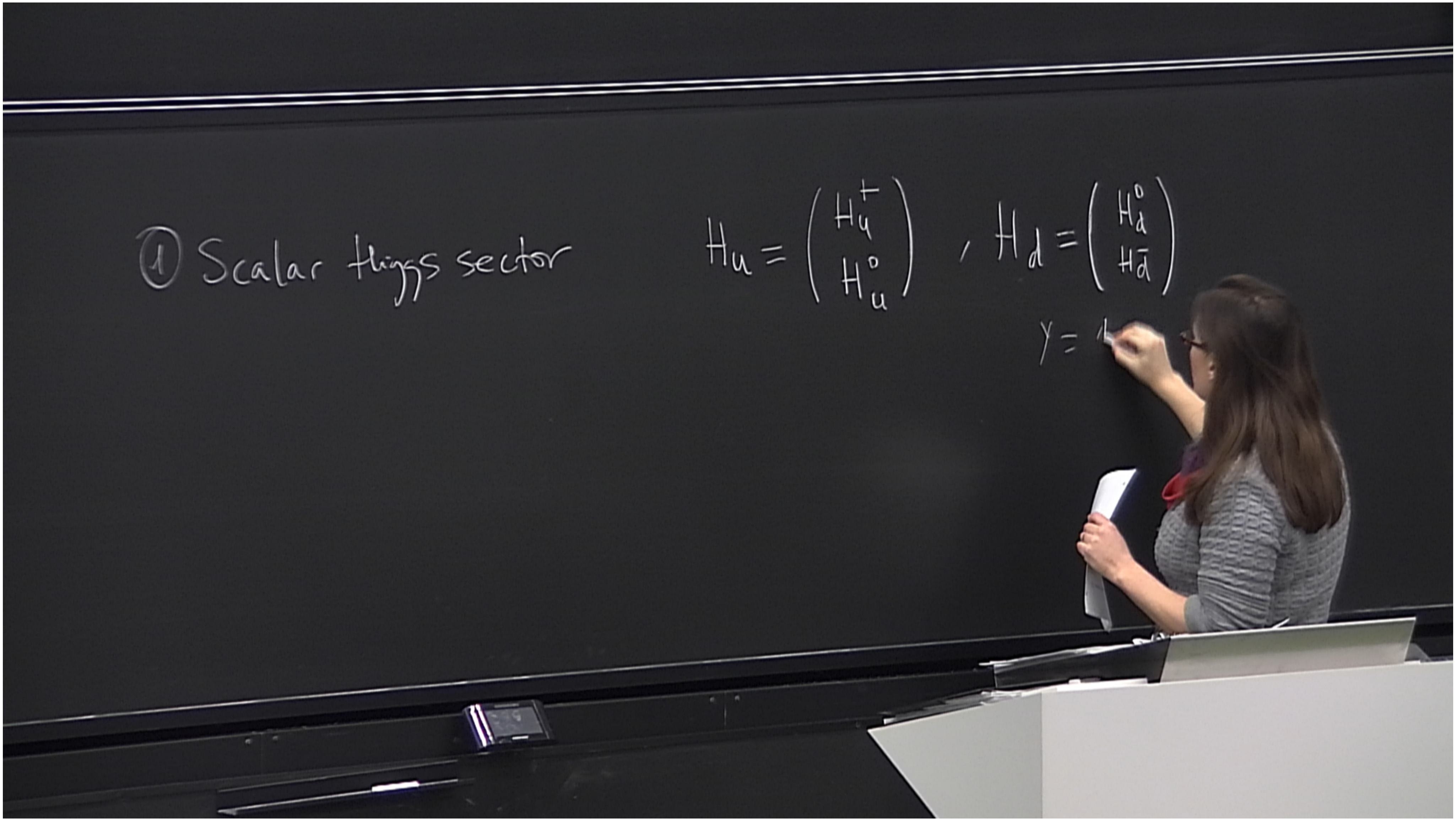

survey
naturalness tutorial

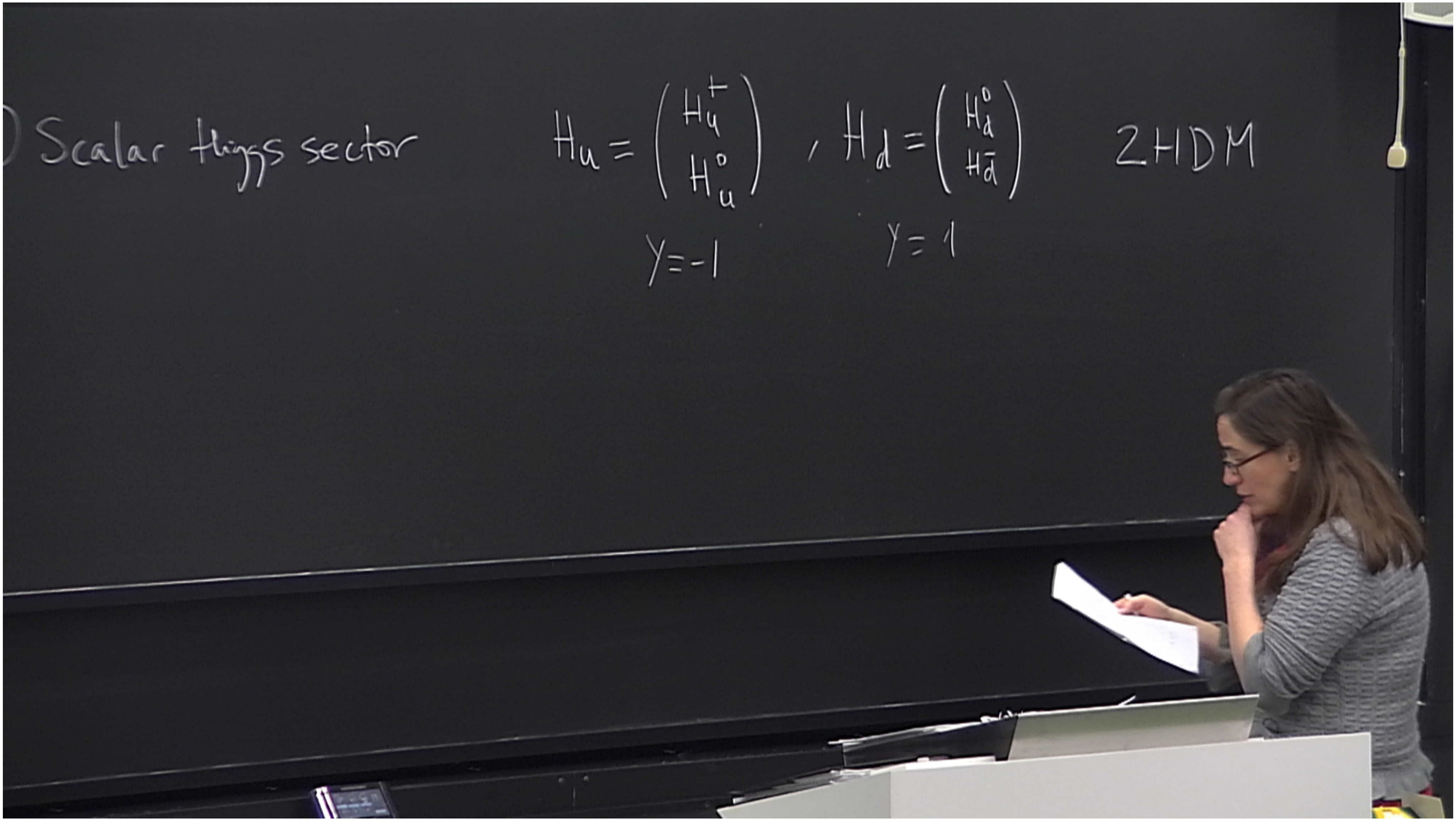

survey naturalness tutorial
$\delta m_f \propto m_f \log \Lambda$

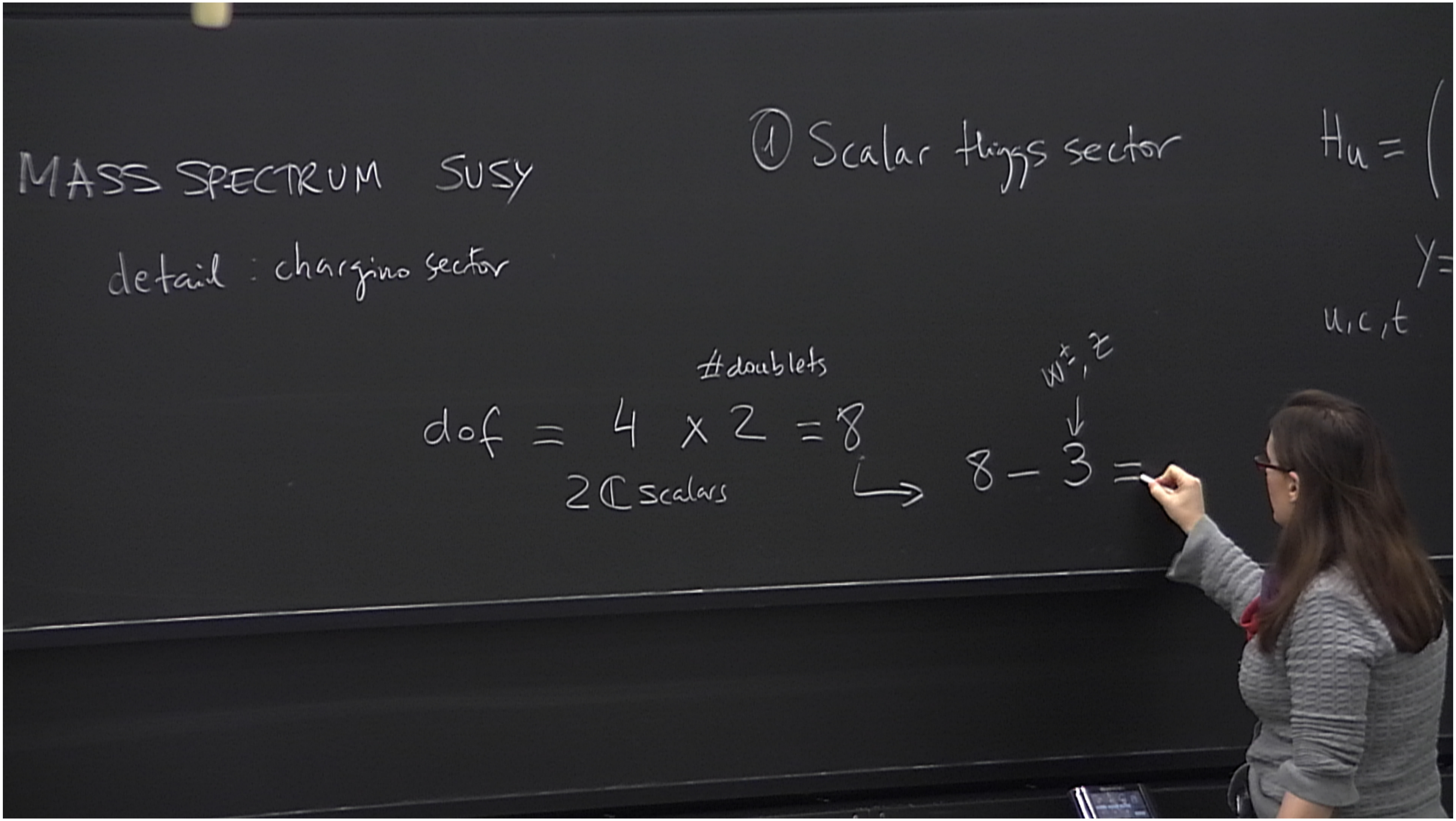

Survey
naturalness tutorial
$\delta m_f \propto m_f \log \Lambda \to M_{pl}$
wiki link
Feynman rules for SUSY ERRATUM


MASS SPECTRUM SUSY
① Scalar Higgs sector


MASS SPECTRUM SUSY
detail : chargino sector
1 Scalar Higgs sector


1 Scalar Higgs sector
$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$, $H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$
$Y =$


Scalar Higgs sector
$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$, $H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$
2HDM
$y = -1$
$y = 1$



MASS SPECTRUM SUSY
detail : chargino sector
① Scalar Higgs sector
$H_u = ($
$Y =$
u, c, t
#doublets
$W^{\pm}, Z$
dof = 4 x 2 = 8
2 ℂ scalars
8 − 3 =

SUSY

sector

① Scalar Higgs sector

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

$Y = -1$ $\qquad$ $Y = 1$

u, c, t $\qquad$ d, s, b

$$\text{dof} = \underbrace{4}_{\text{2 } \mathbb{C} \text{ scalars}} \times \overset{\#\text{doublets}}{2} = 8 \;\hookrightarrow\; 8 - \overset{W^\pm, Z}{\overset{\downarrow}{3}} = 5 \text{ physical dof}$$

SUSY

sector

① Scalar Higgs sector

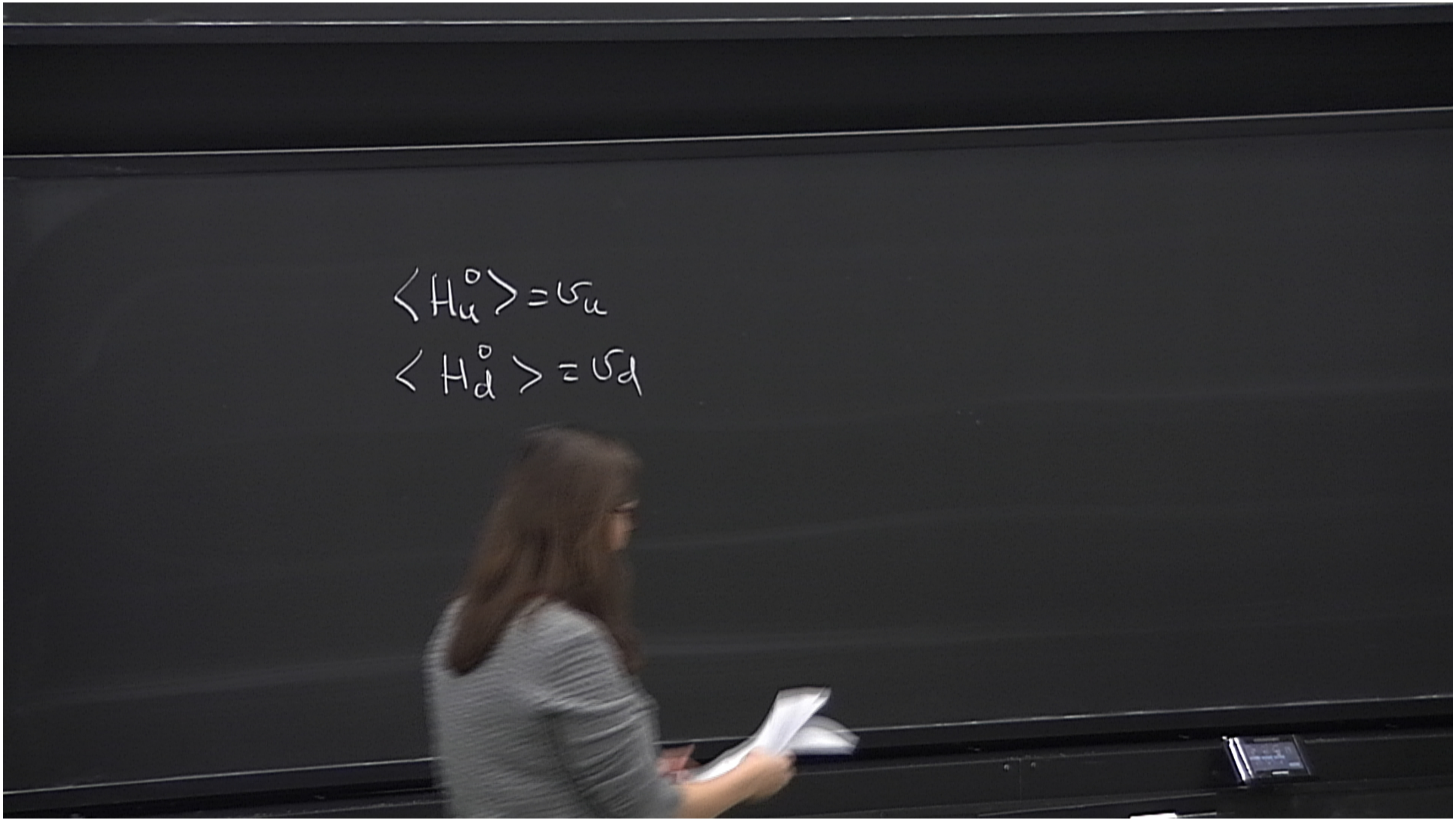
$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$, $H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$

$Y=-1$ $Y=1$

u, c, t d, s, b

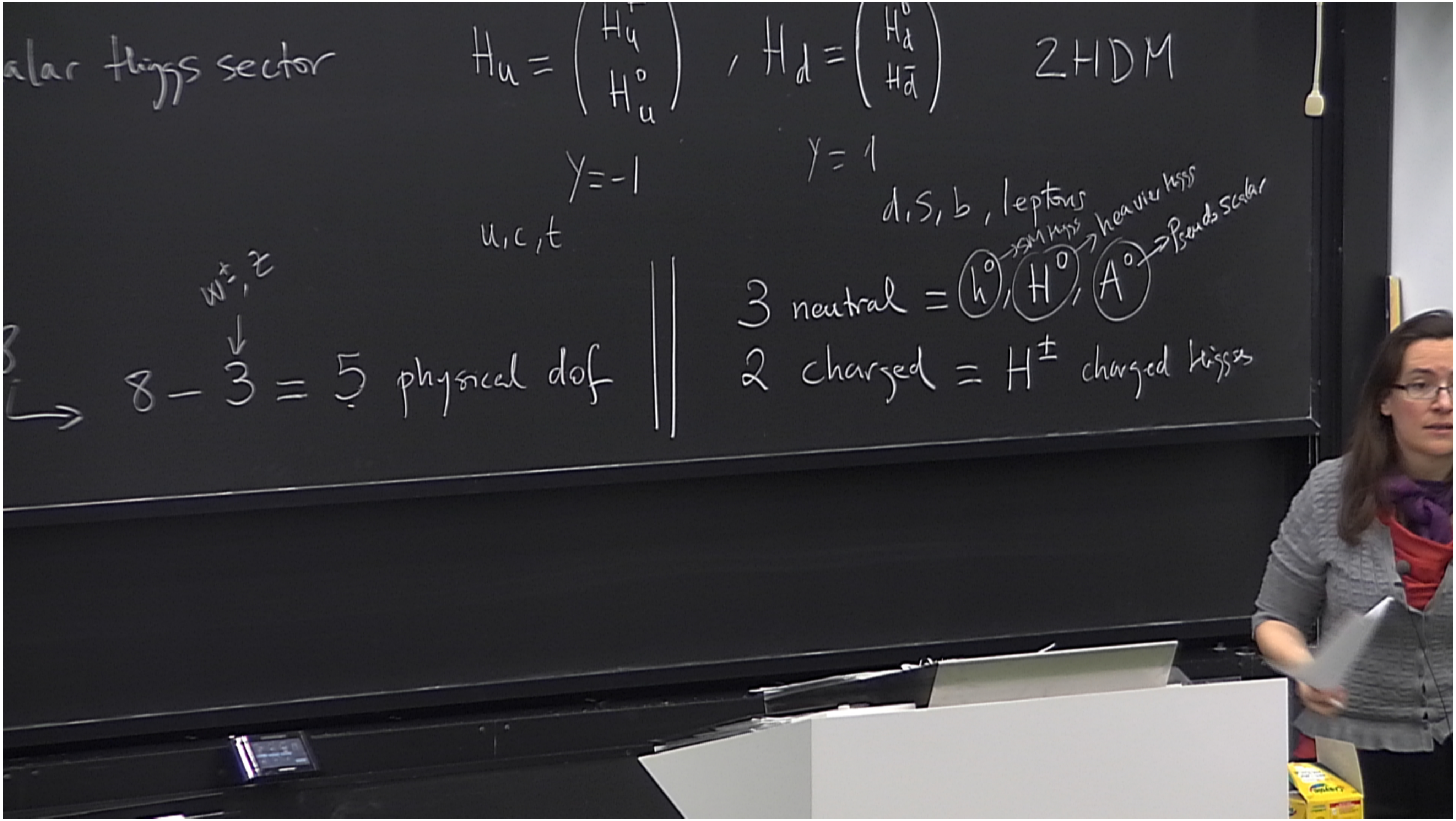
$$\text{dof} = \underset{2\,\mathbb{C}\text{ scalars}}{4} \times \overset{\#\text{doublets}}{2} = 8$$

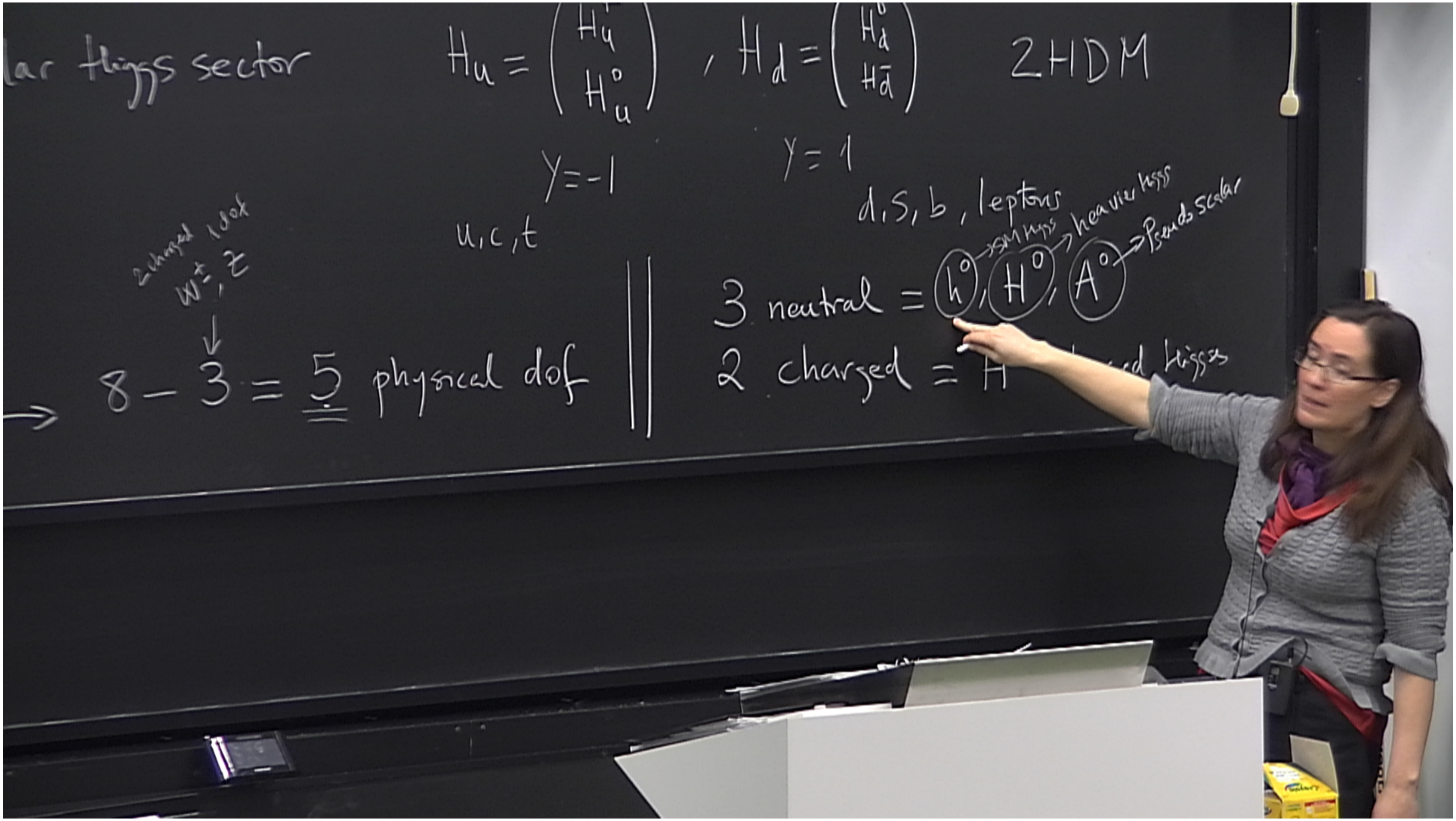
$$\hookrightarrow 8 - \overset{W^\pm, Z}{3} = 5 \text{ physical dof}$$

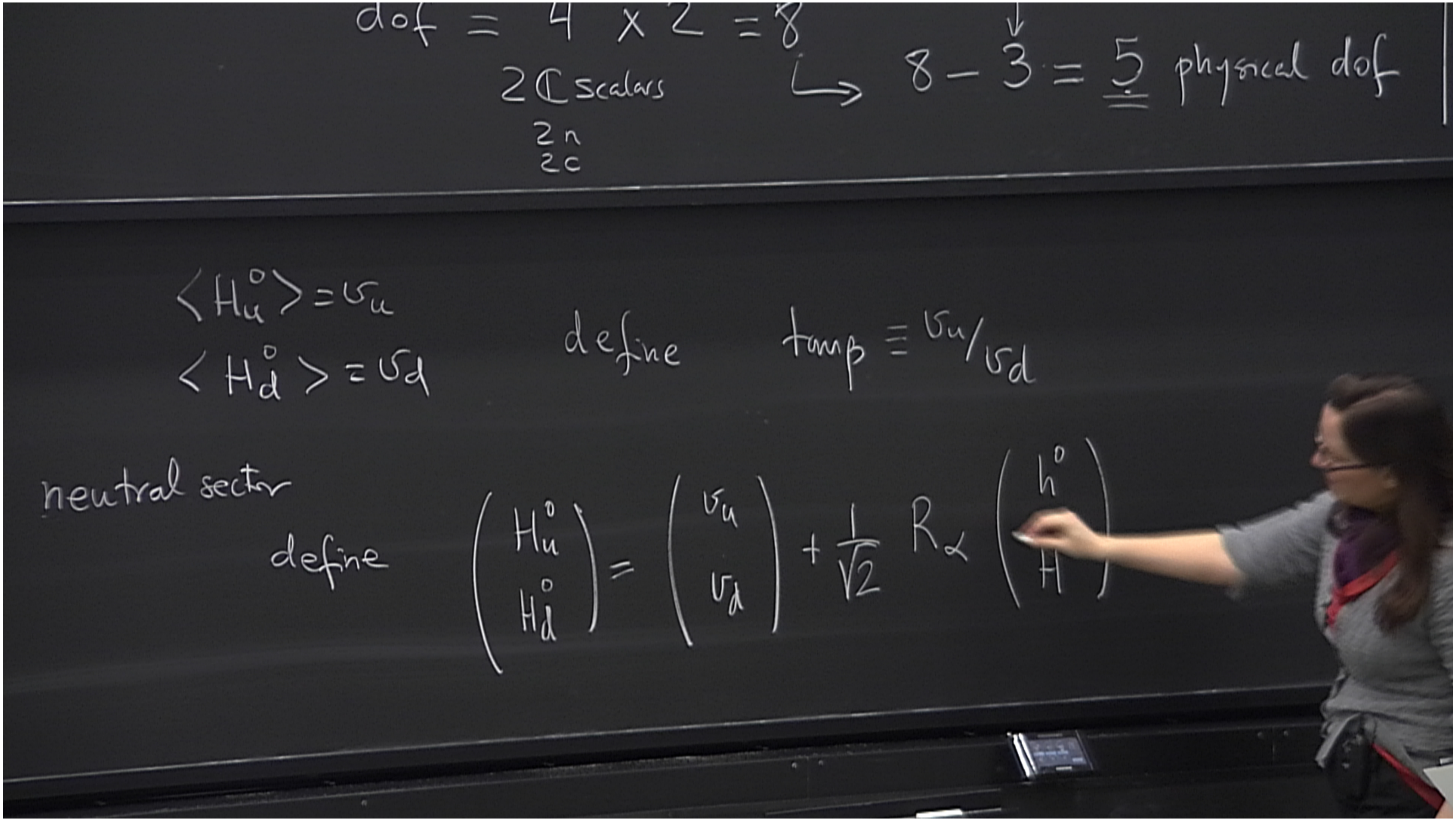

$\langle H_u^0 \rangle = v_u$
$\langle H_d^0 \rangle = v_d$

$$\langle H_u^0 \rangle = v_u$$
$$\langle H_d^0 \rangle = v_d$$

define $\tan\beta \equiv v_u / v_d$


alar Higgs sector
$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$, $H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$
2HDM
$Y = -1$
$Y = 1$
u, c, t
d, s, b, leptons
$W^\pm, Z$
$8 - 3 = 5$ physical dof
3 neutral = h^0, H^0, A^0
SM higgs
heavier higgs
pseudo scalar
2 charged = $H^\pm$ charged Higgses


lar Higgs sector
2HDM
Y=-1
Y=1
u,c,t
d,s,b, leptons
W±, Z
8 − 3 = 5 physical dof
3 neutral = h0, H0, A0
SM higgs
heavier higgs
Pseudo scalar
2 charged = H
Higgses


dof = 4 x 2 = 8
2 ℂ scalars
2 n
2 c
↳ 8 − 3 = 5 physical dof
⟨H_u^0⟩ = v_u
⟨H_d^0⟩ = v_d
define
tan β ≡ v_u/v_d
neutral sector
define
(H_u^0, H_d^0) = (v_u, v_d) + 1/√2 R_α (h^0, H)

$$\text{dof} = 4 \times 2 = 8$$

$2\,\mathbb{C}$ scalars $\hookrightarrow 8 - 3 = \underline{\underline{5}}$ physical dof

$2n$

$2c$

3 neu

2 cha

$\langle H_u^0 \rangle = v_u$

$\langle H_d^0 \rangle = v_d$

define $\tan\beta \equiv v_u / v_d$

$$R_\theta \equiv \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix}$$

ector

define
$$\begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix} = \begin{pmatrix} v_u \\ v_d \end{pmatrix} + \frac{1}{\sqrt{2}} R_\alpha \begin{pmatrix} h^0 \\ H^0 \end{pmatrix}$$

$\mathrm{dof} = 4 \times 2 = 8$

$2\,\mathbb{C}$ scalars $\hookrightarrow 8 - 3 = \underline{\underline{5}}$ physical dof

2 n
2 c

3 neu
2 cha

$\langle H_u^0 \rangle = v_u$

$\langle H_d^0 \rangle = v_d$

define $\tan\beta \equiv v_u / v_d$

$$R_\theta \equiv \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix}$$

ector

define

$$\begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix} = \begin{pmatrix} v_u \\ v_d \end{pmatrix} + \frac{1}{\sqrt{2}} R_\alpha \begin{pmatrix} h^0 \\ H^0 \end{pmatrix} + \frac{i}{\sqrt{2}} R_\beta \begin{pmatrix} G^0 \\ A^0 \end{pmatrix}$$

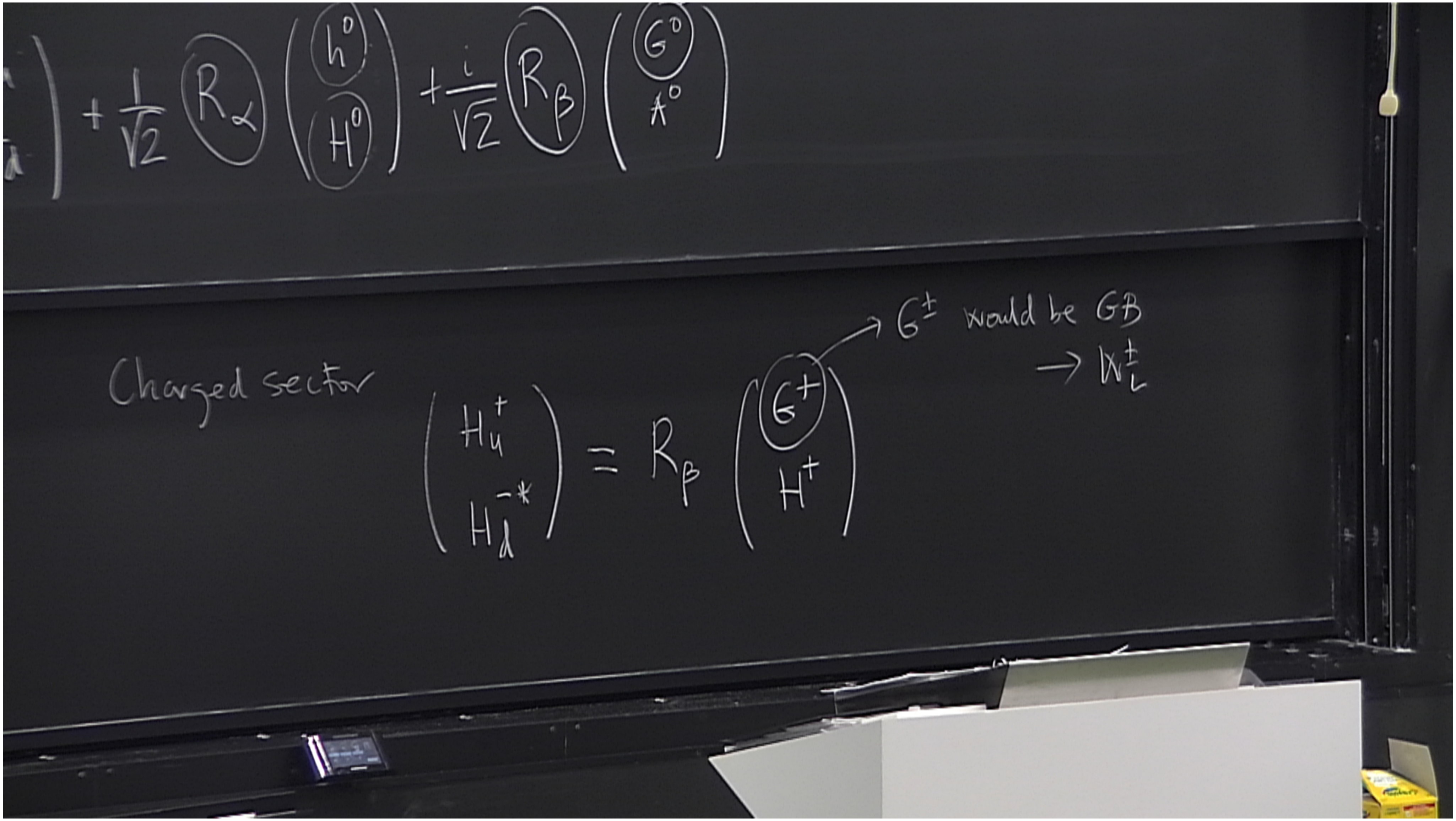
neutral sector

define $\begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix} = \begin{pmatrix} v_u \\ v_d \end{pmatrix} + \frac{1}{\sqrt{2}} R_\alpha \begin{pmatrix} h^0 \\ H^0 \end{pmatrix} + \frac{i}{\sqrt{2}}$

$$\tan 2\alpha = \tan 2\beta \cdot \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}$$

Charged sector

$\Big(H_u$


$+\frac{1}{\sqrt{2}} R_\alpha \begin{pmatrix} h^0 \\ H^0 \end{pmatrix} + \frac{i}{\sqrt{2}} R_\beta \begin{pmatrix} G^0 \\ A^0 \end{pmatrix}$
Charged sector
$\begin{pmatrix} H_u^+ \\ H_d^{-*} \end{pmatrix} = R_\beta \begin{pmatrix} G^+ \\ H^+ \end{pmatrix}$
$\rightarrow G^\pm$ would be GB
$\rightarrow W_L^\pm$

$$R_\alpha \begin{pmatrix} h \\ H^0 \end{pmatrix} + \frac{i}{\sqrt{2}} R_\beta \begin{pmatrix} G^0 \\ A^0 \end{pmatrix}$$

rged sector

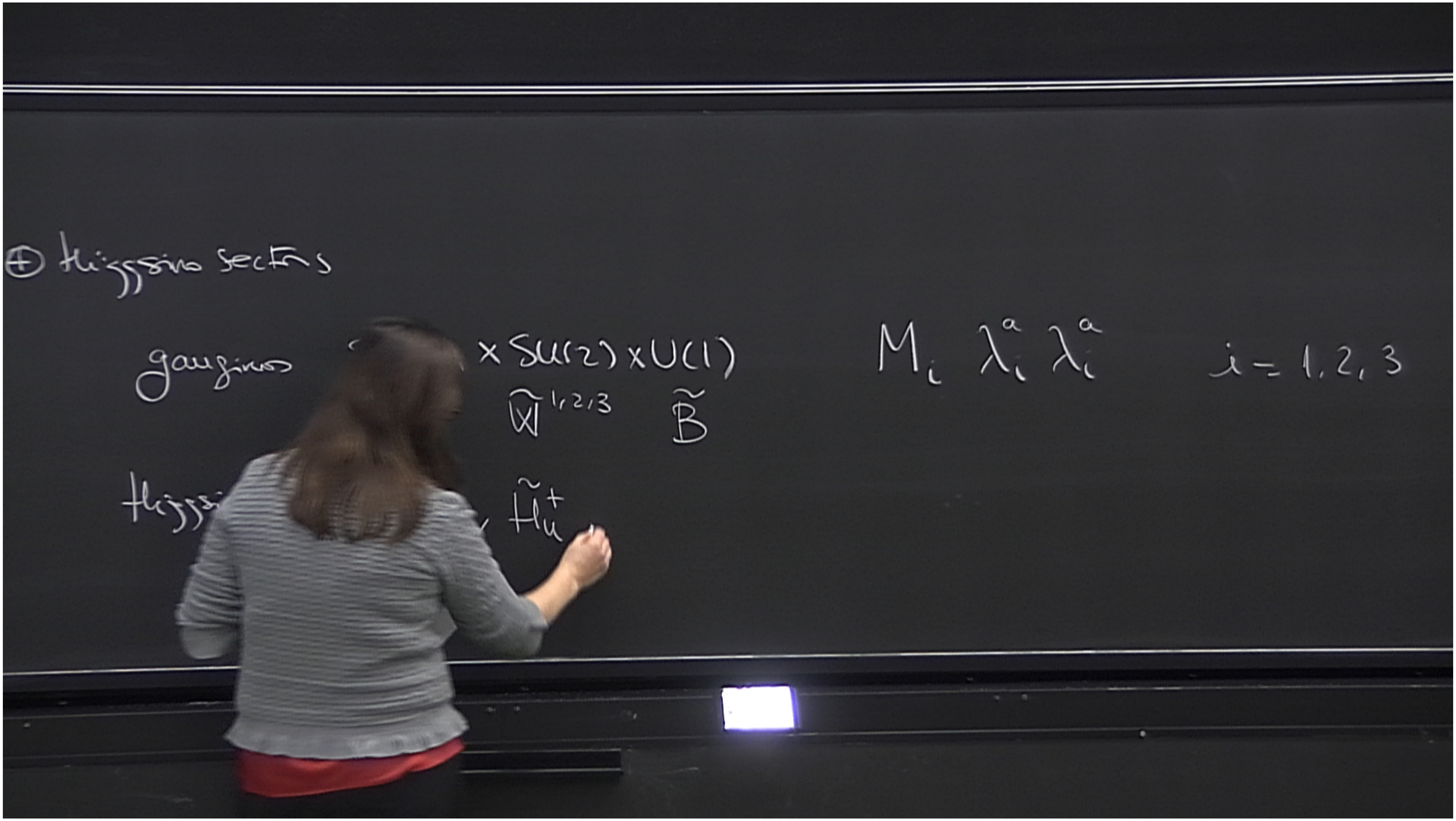
$$\begin{pmatrix} H_u^+ \\ H_d^{-*} \end{pmatrix} = R_\beta \begin{pmatrix} G^+ \\ H^+ \end{pmatrix}$$

$\to G^\pm$ would be GB

$\to W^\pm_L$ longitudinal

② gaugino ⊕ higgsino sectors

gauginos $SU(3) \times SU(2) \times U(1)$


④ Higgsino sectors
gauginos × SU(2) × U(1)
$M_i \lambda_i^a \lambda_i^a$
$i = 1, 2, 3$
$\tilde{W}^{1,2,3}$ $\tilde{B}$
$\tilde{H}_u^+$

⊙ Higgsino sectors

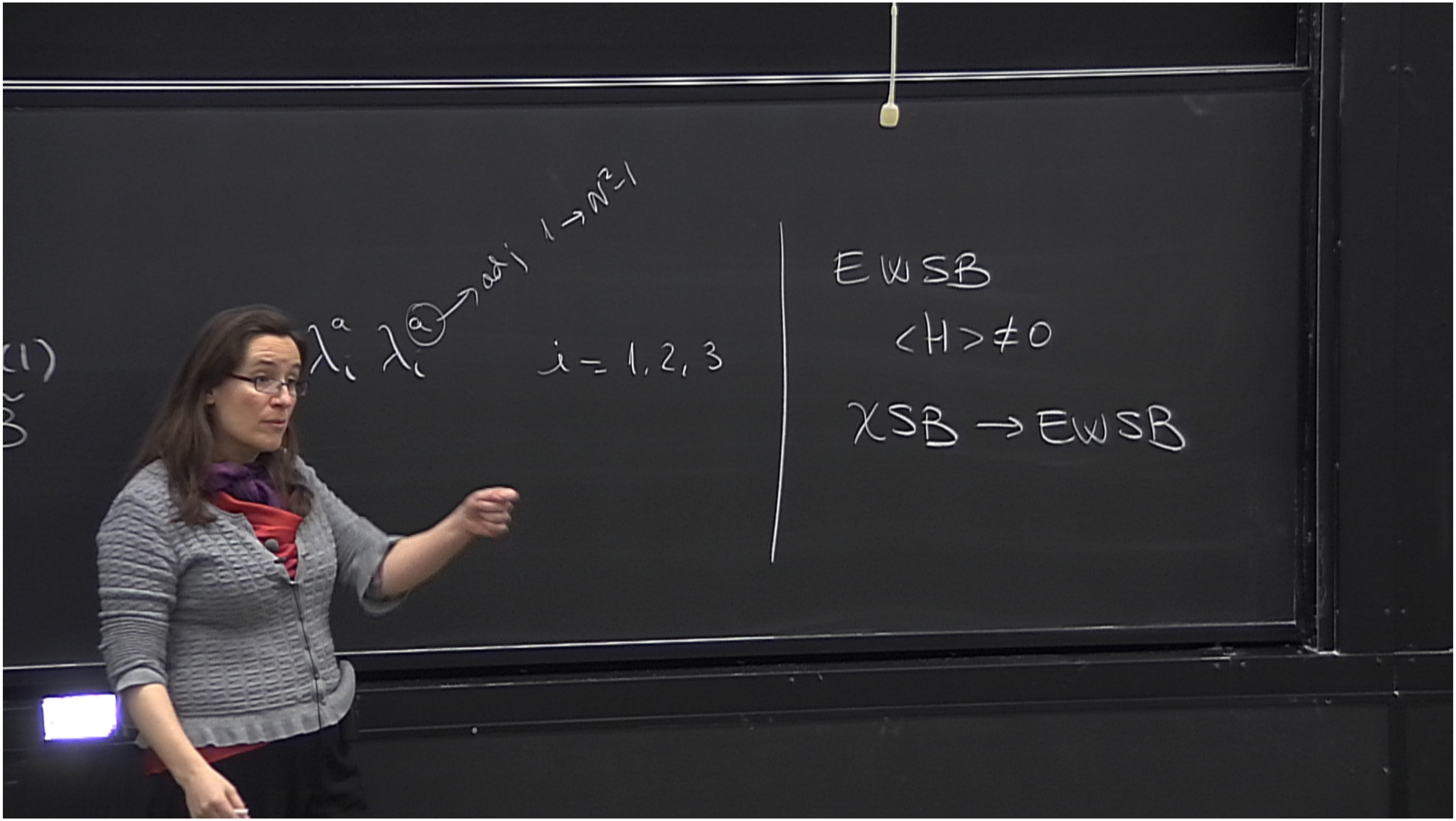
gauginos $SU(3) \times SU(2) \times U(1)$

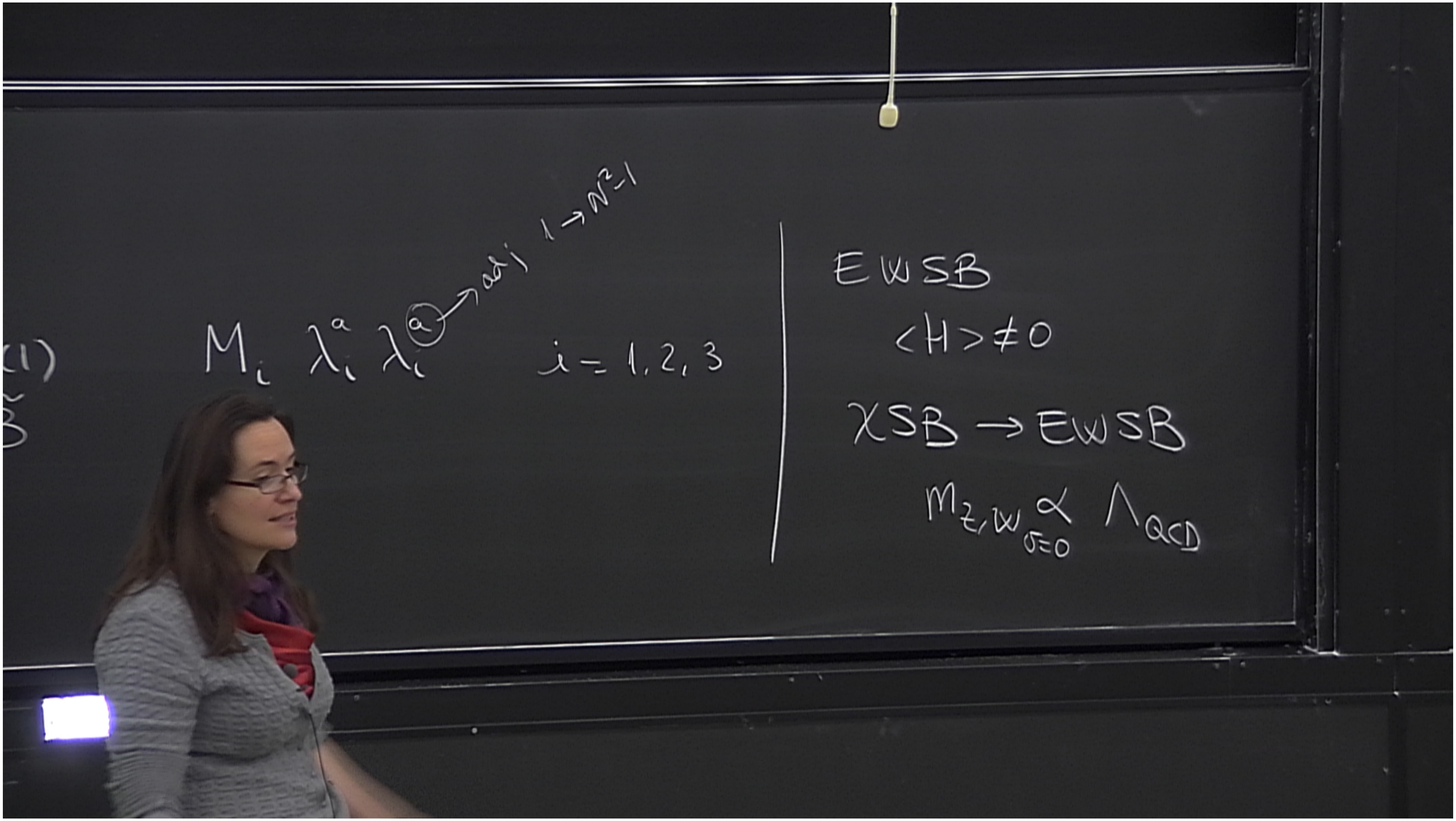
$\tilde{g} \qquad \tilde{W}^{1,2,3} \qquad \tilde{B}$

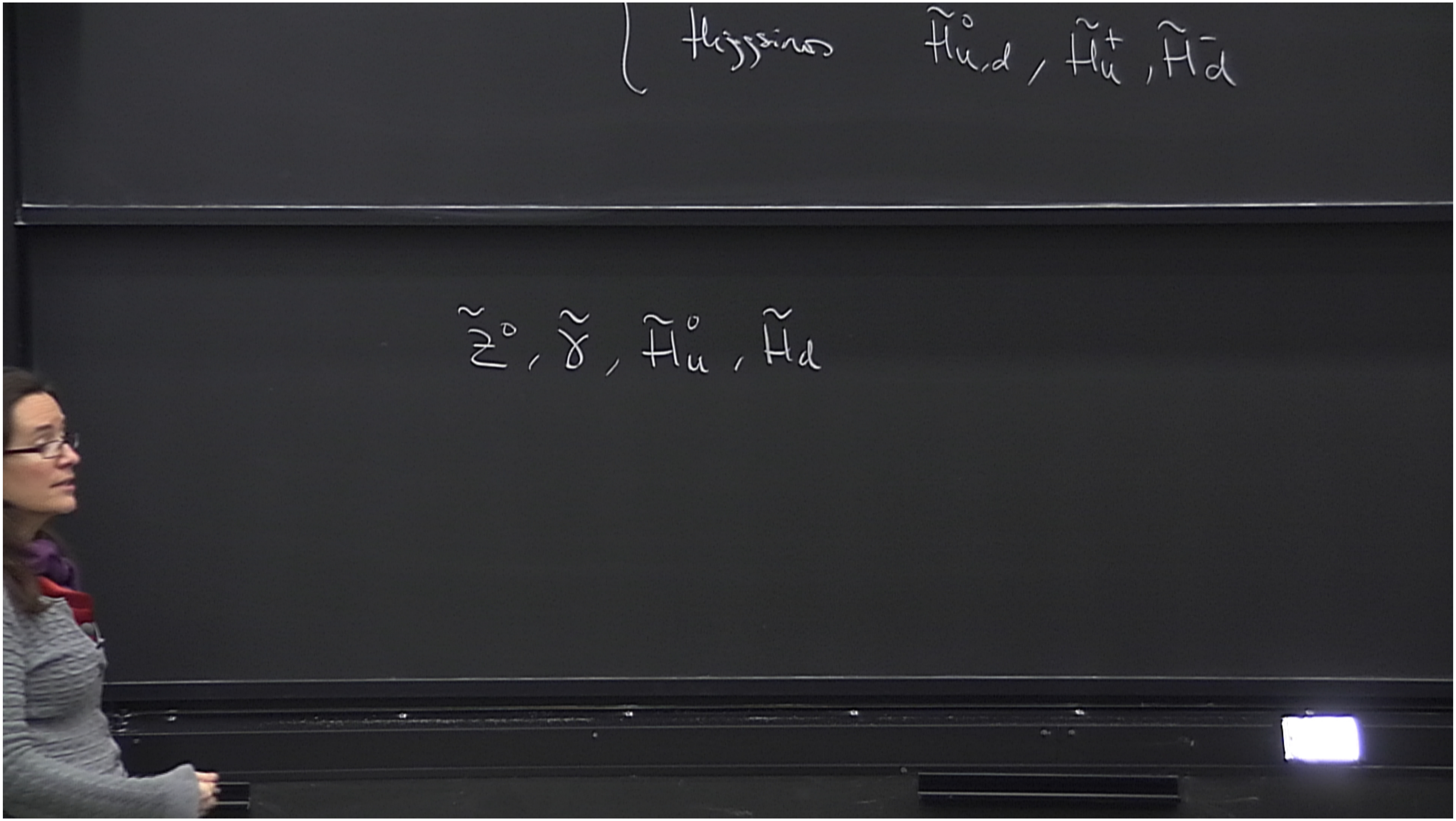
Higgsinos $\tilde{H}^0_{u,d}$, $\tilde{H}^+_u$, $\tilde{H}^-_d$

$M_i \lambda_i^a \lambda_i^a$ → adj $1 \to N^2-1$

$i = 1, 2, 3$


(1)
λ λ → adj 1 → N²-1
i = 1, 2, 3
EWSB
<H> ≠ 0
χSB → EWSB


(1)
Mi λi^a λi^a → adj 1 → N²-1
i = 1, 2, 3
EWSB
<H> ≠ 0
χSB → EWSB
M_Z,W ∝_σ=0 Λ_QCD

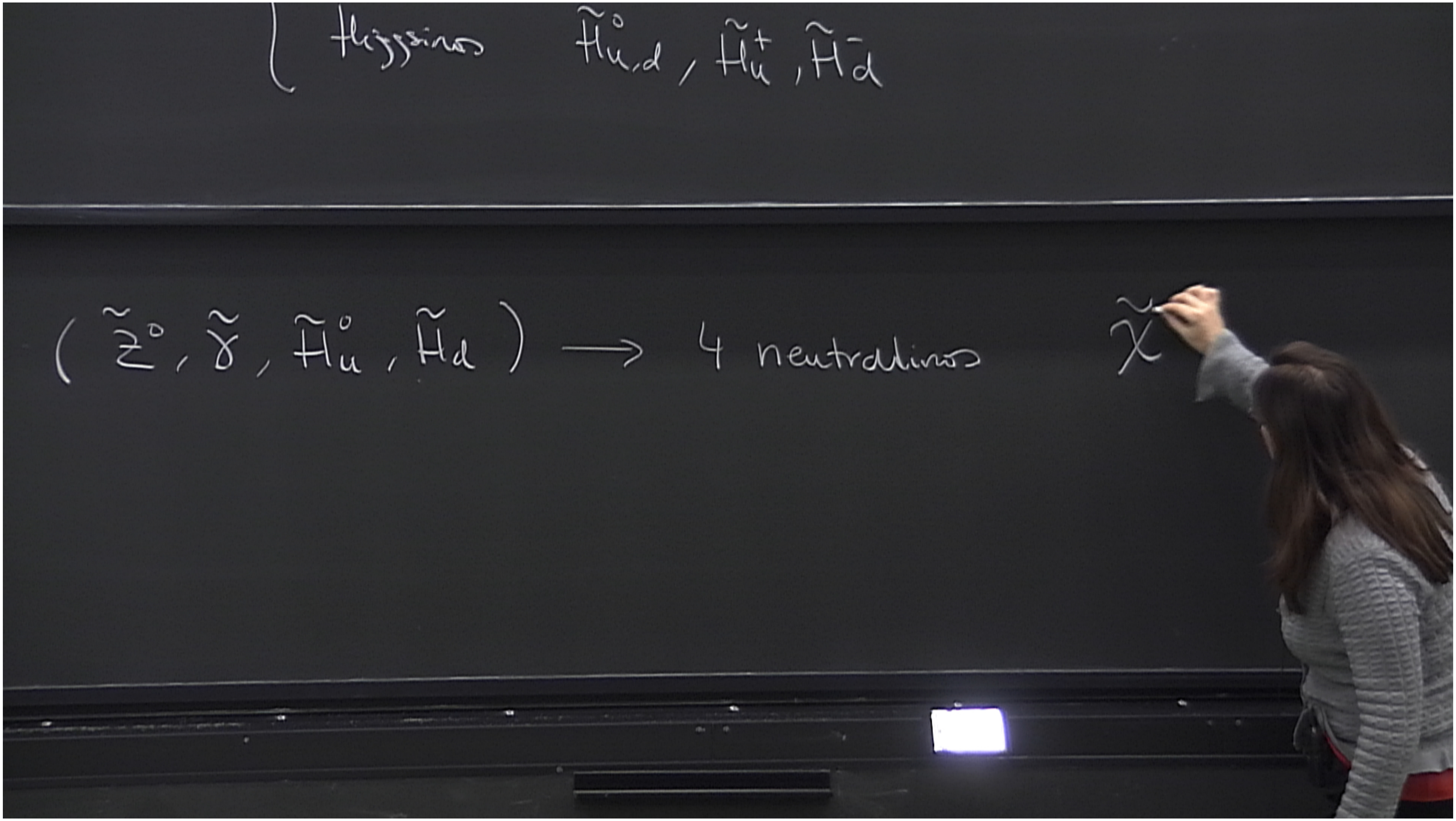

Higgsinos $\tilde{H}^0_{u,d}$, $\tilde{H}_u^+$, $\tilde{H}_d^-$
$\tilde{Z}^0$, $\tilde{\gamma}$, $\tilde{H}^0_u$, $\tilde{H}_d$

Higgsinos $\tilde{H}^0_{u,d}, \tilde{H}^+_u, \tilde{H}^-_d$

$(\tilde{Z}^0, \tilde{\gamma}, \tilde{H}^0_u, \tilde{H}_d) \longrightarrow$ 4 neutrali

Higgsinos $\tilde{H}^0_{u,d}$, $\tilde{H}^+_u$, $\tilde{H}^-_d$

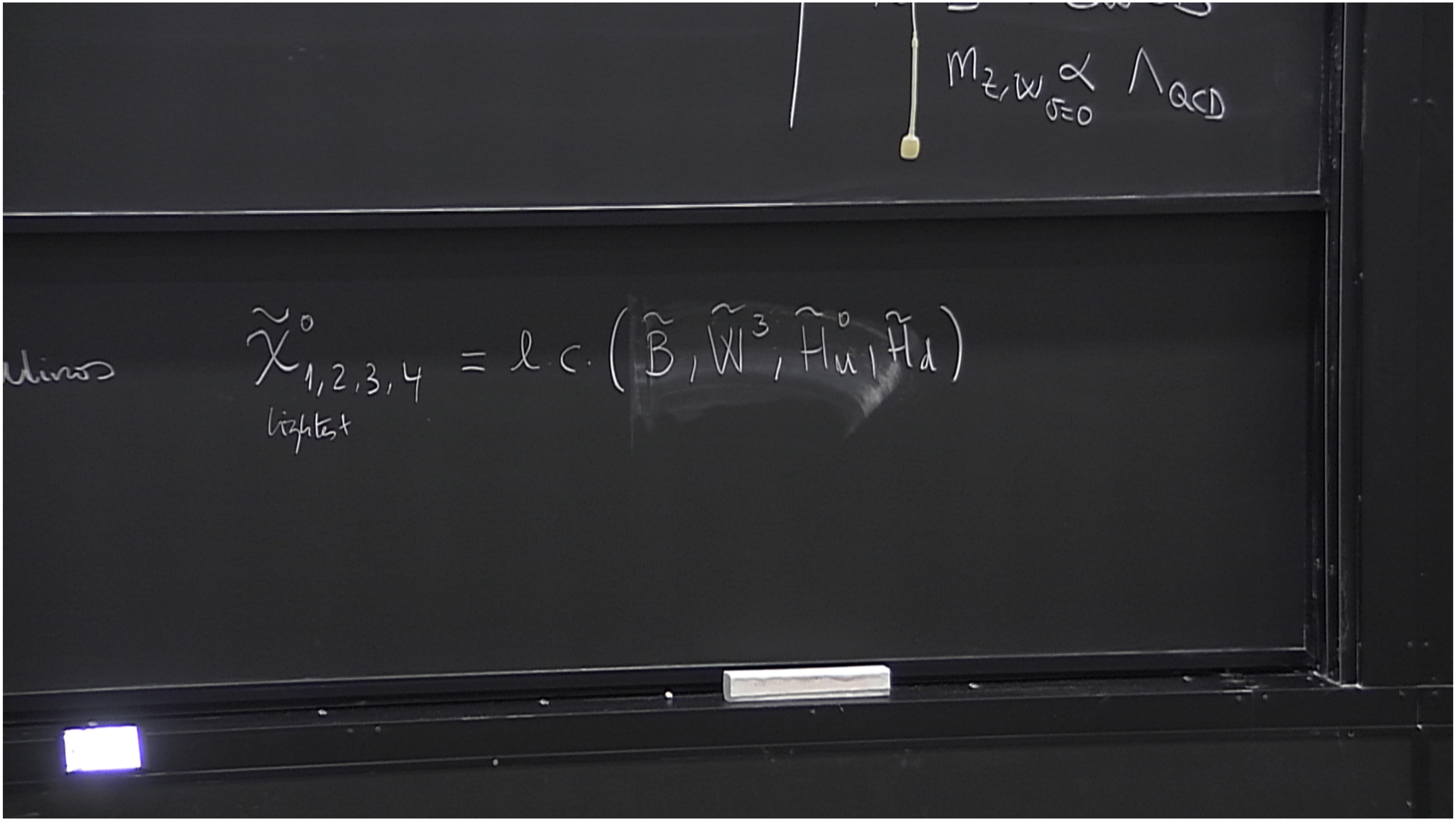
$(\tilde{Z}^0, \tilde{\gamma}, \tilde{H}^0_u, \tilde{H}_d) \longrightarrow$ 4 neutralinos

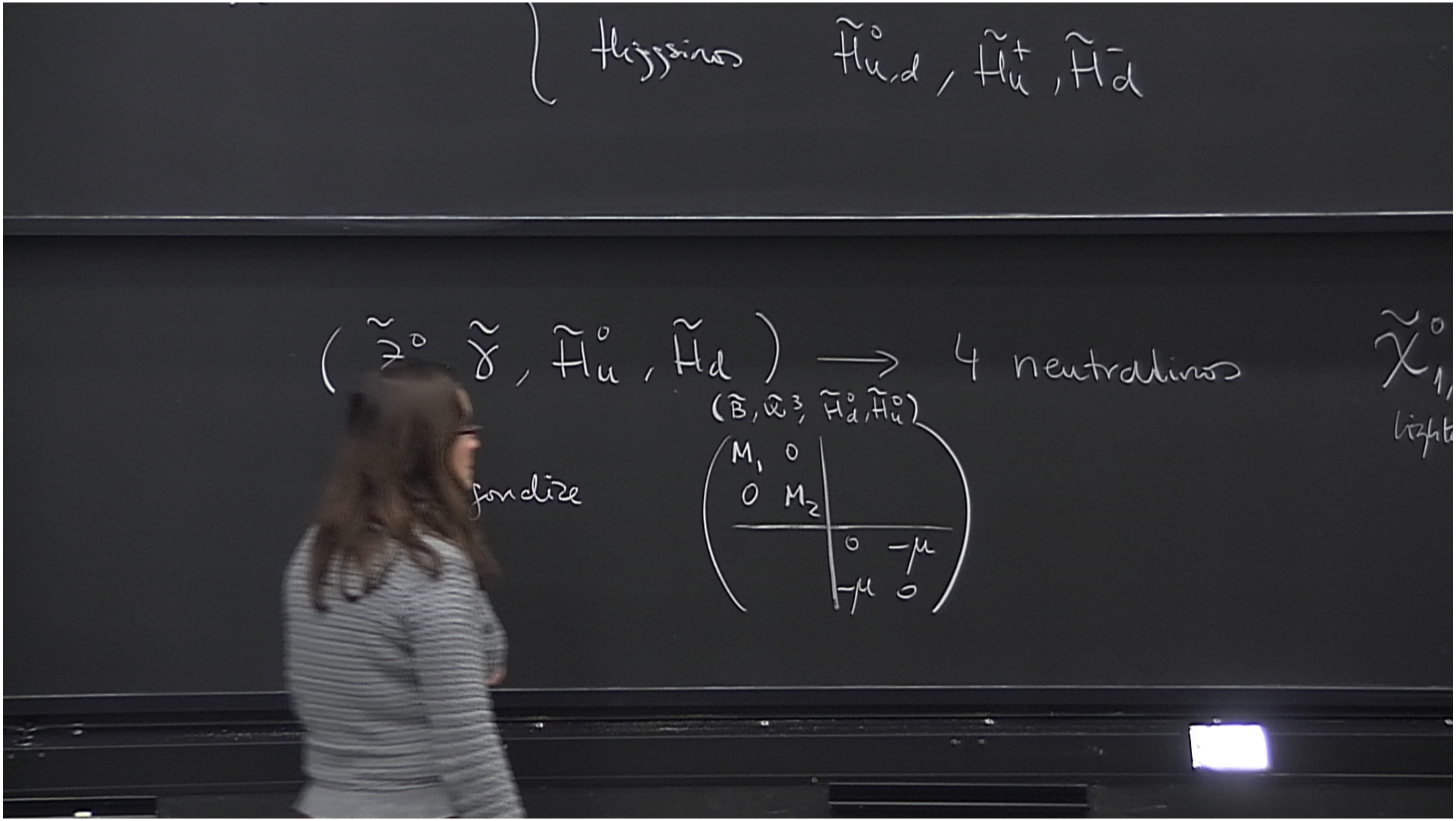

Higgsinos $\tilde{H}^0_{u,d}$, $\tilde{H}_u^+$, $\tilde{H}_d^-$
$(\tilde{Z}^0, \tilde{\gamma}, \tilde{H}_u^0, \tilde{H}_d) \longrightarrow$ 4 neutralinos $\tilde{\chi}$

Higgsinos $\tilde{H}^0_{u,d}$, $\tilde{H}^+_u$, $\tilde{H}^-_d$

$(\tilde{Z}^0, \tilde{\gamma}, \tilde{H}^0_u, \tilde{H}_d) \longrightarrow$ 4 neutralinos $\tilde{\chi}^0_{1,2,3,4}$

lightest


$m_{Z,W} \underset{\sigma=0}{\propto} \Lambda_{QCD}$
$\tilde{\chi}^0_{1,2,3,4} = l.c.(\tilde{B}, \tilde{W}^3, \tilde{H}_u^0, \tilde{H}_d)$
lightest


Higgsinos $\tilde{H}^0_{u,d}$, $\tilde{H}_u^+$, $\tilde{H}_d^-$
$\tilde{\gamma}$, $\tilde{H}_u^0$, $\tilde{H}_d$) $\longrightarrow$ 4 neutralinos
$(\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0)$
$\begin{pmatrix} M_1 & 0 & & \\ 0 & M_2 & & \\ & & 0 & -\mu \\ & & -\mu & 0 \end{pmatrix}$

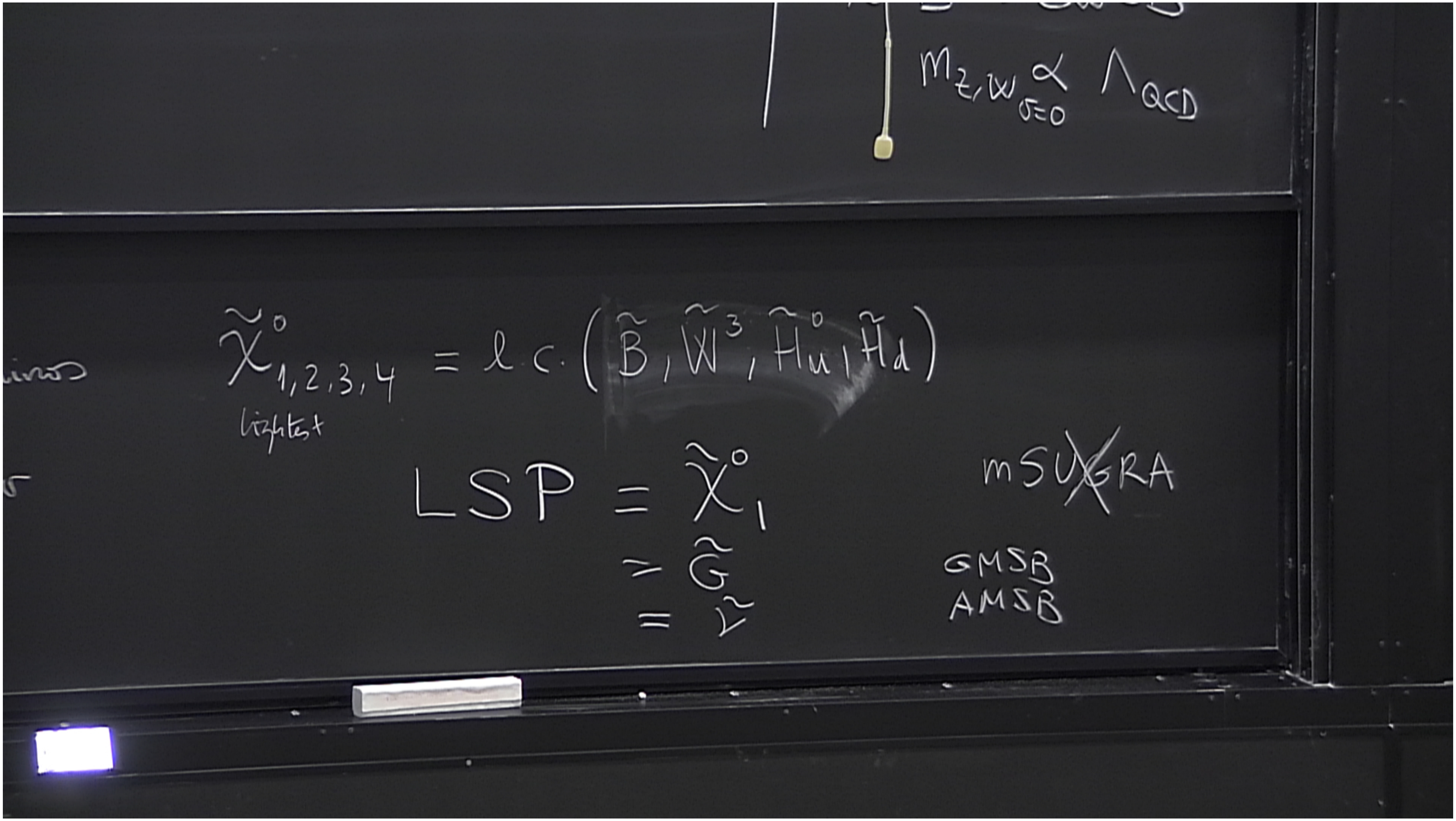
Higgsinos $\tilde{H}^0_{u,d}$, $\tilde{H}_u^+$, $\tilde{H}_d^-$

$(\tilde{Z}^0, \tilde{\gamma}, \tilde{H}_u^0, \tilde{H}_d) \longrightarrow$ 4 neutralinos $\tilde{\chi}^0_{1,}$

lightest

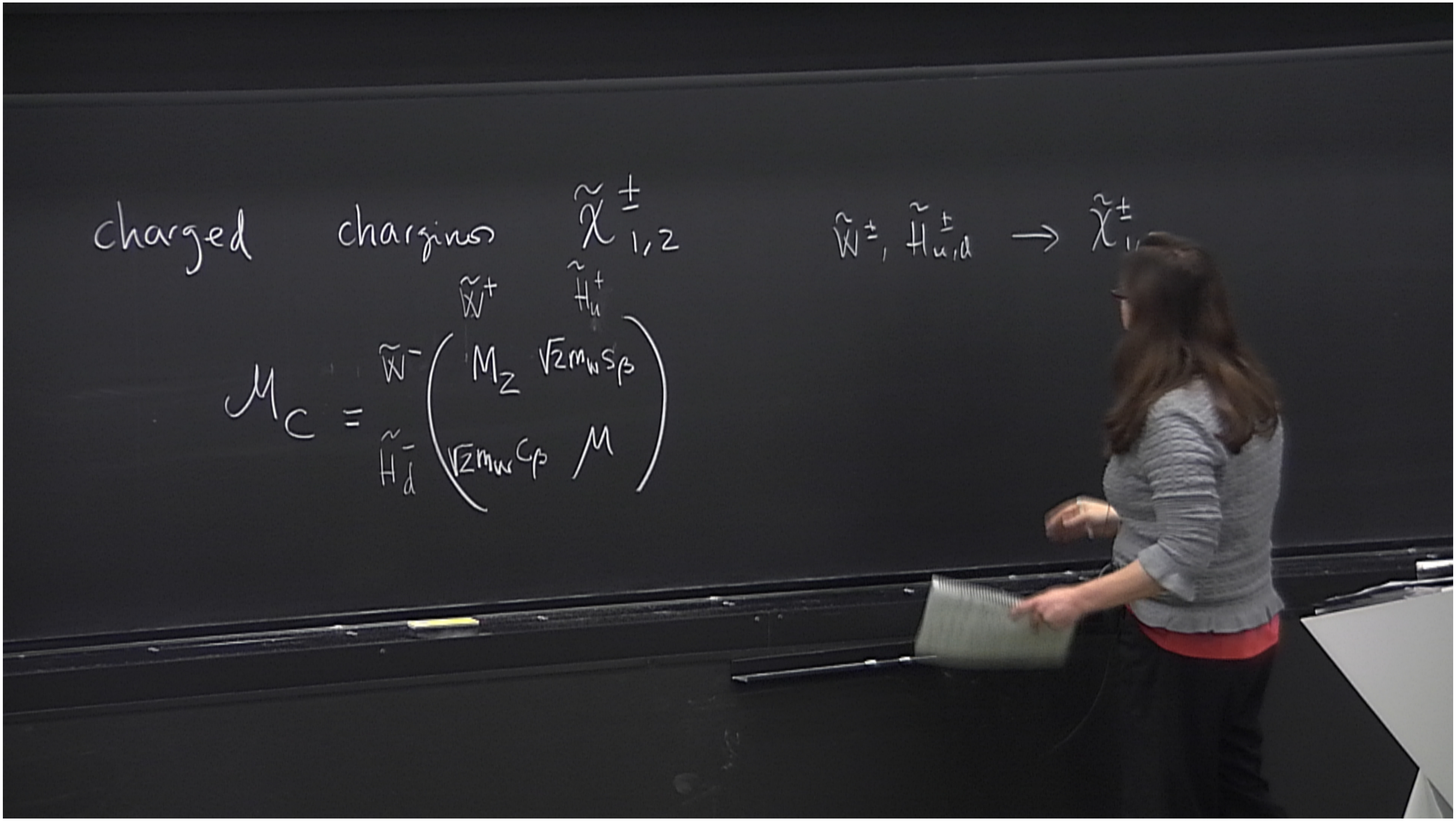
diagonalize

$$
\begin{array}{c}
(\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0) \\
\left(\begin{array}{cc|cc}
M_1 & 0 & \multicolumn{2}{c}{\text{EWSB}} \\
0 & M_2 & & \\
\hline
\multicolumn{2}{c|}{\text{EWSB}} & 0 & -\mu \\
 & & -\mu & 0
\end{array}\right)
\end{array}
\qquad \text{EWSB} \to \propto (g, g')v
$$

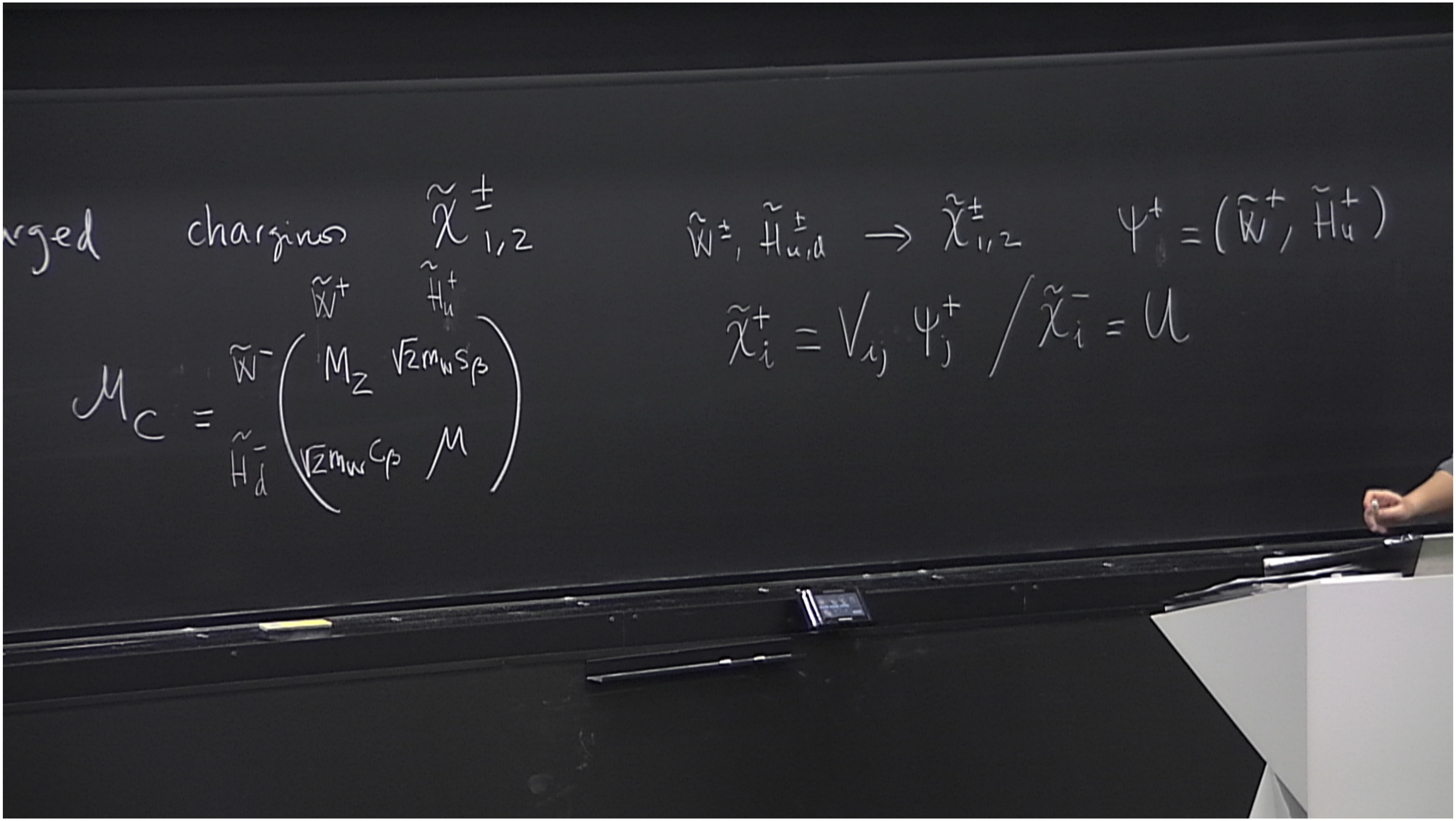

$m_{Z,W} \underset{\sigma=0}{\propto} \Lambda_{QCD}$
$\tilde{\chi}^0_{1,2,3,4} = l.c.(\tilde{B}, \tilde{W}^3, \tilde{H}^0_u, \tilde{H}_d)$
lightest
$LSP = \tilde{\chi}^0_1$
$= \tilde{G}$
$= \tilde{\nu}$
mSUGRA
GMSB
AMSB

charged charginos $\tilde{\chi}^{\pm}_{1,2}$

$$\mathcal{M}_C = \begin{pmatrix} M_2 & \sqrt{2}\, m_W s_\beta \\ \sqrt{2}\, m_W c_\beta & \mu \end{pmatrix}$$



charged charginos $\tilde{\chi}^{\pm}_{1,2}$
$\tilde{W}^{\pm}, \tilde{H}^{\pm}_{u,d} \rightarrow \tilde{\chi}^{\pm}_{1,}$
$$\mathcal{M}_C = \begin{array}{c c} & \begin{array}{cc} \tilde{W}^+ & \tilde{H}_u^+ \end{array} \\ \begin{array}{c} \tilde{W}^- \\ \tilde{H}_d^- \end{array} & \begin{pmatrix} M_2 & \sqrt{2} m_W s_\beta \\ \sqrt{2} m_W c_\beta & \mu \end{pmatrix} \end{array}$$


rged charginos $\tilde{\chi}^{\pm}_{1,2}$
$\tilde{W}^{\pm}, \tilde{H}^{\pm}_{u,d} \rightarrow \tilde{\chi}^{\pm}_{1,2}$
$\psi^{+} = (\tilde{W}^{+}, \tilde{H}^{+}_{u})$
$\tilde{\chi}^{+}_{i} = V_{ij}\, \psi^{+}_{j} \;/\; \tilde{\chi}^{-}_{i} = U$
$\mathcal{M}_C = \begin{array}{c|cc} & \tilde{W}^{+} & \tilde{H}^{+}_{u} \\ \tilde{W}^{-} & M_2 & \sqrt{2} m_W s_\beta \\ \tilde{H}^{-}_{d} & \sqrt{2} m_W c_\beta & \mu \end{array}$

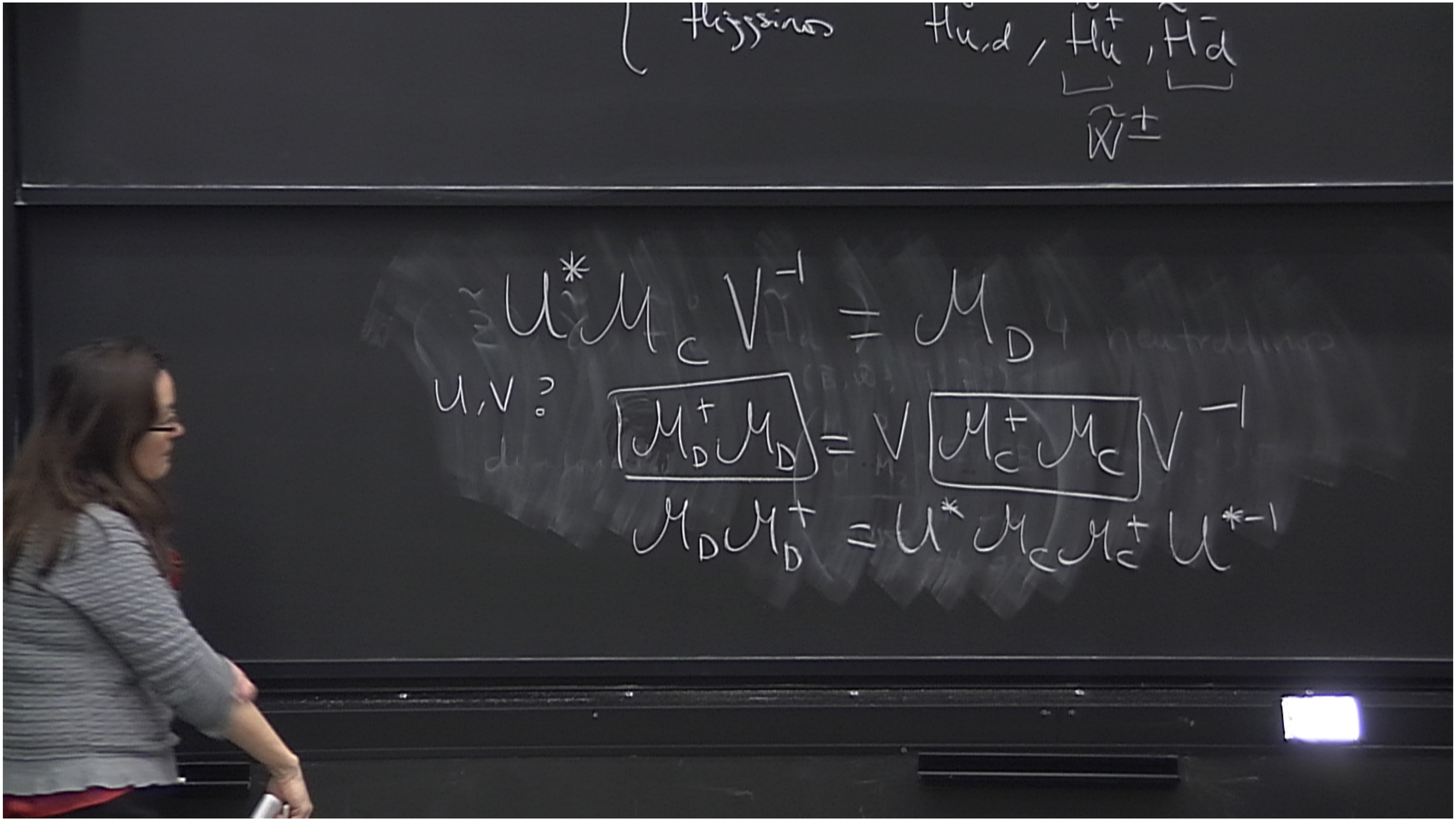
Higgsinos $\tilde{H}_{u,d}$, $\underbrace{\tilde{H}_u^+}$, $\underbrace{\tilde{H}_d^-}$

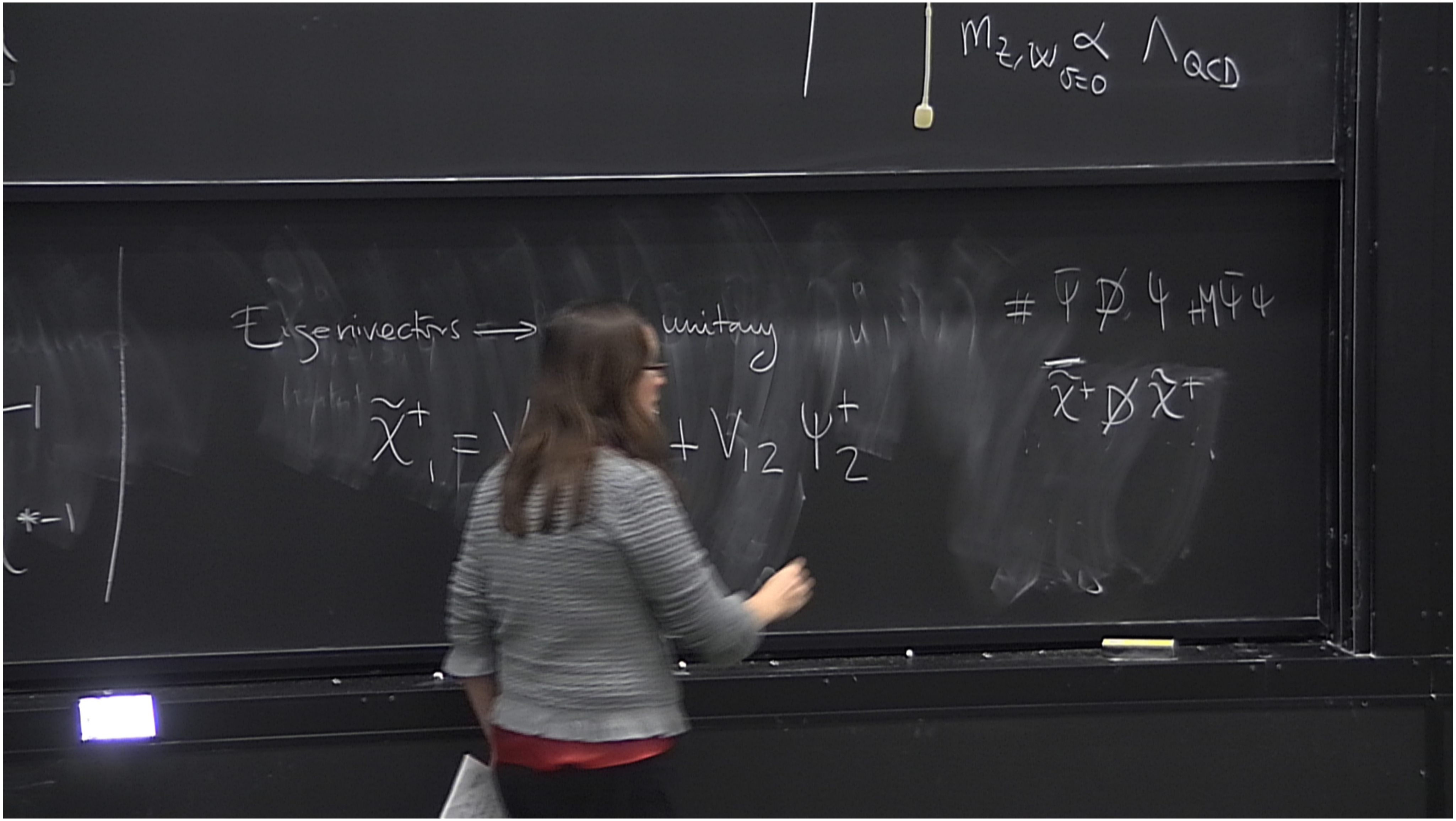
$\tilde{W}^{\pm}$

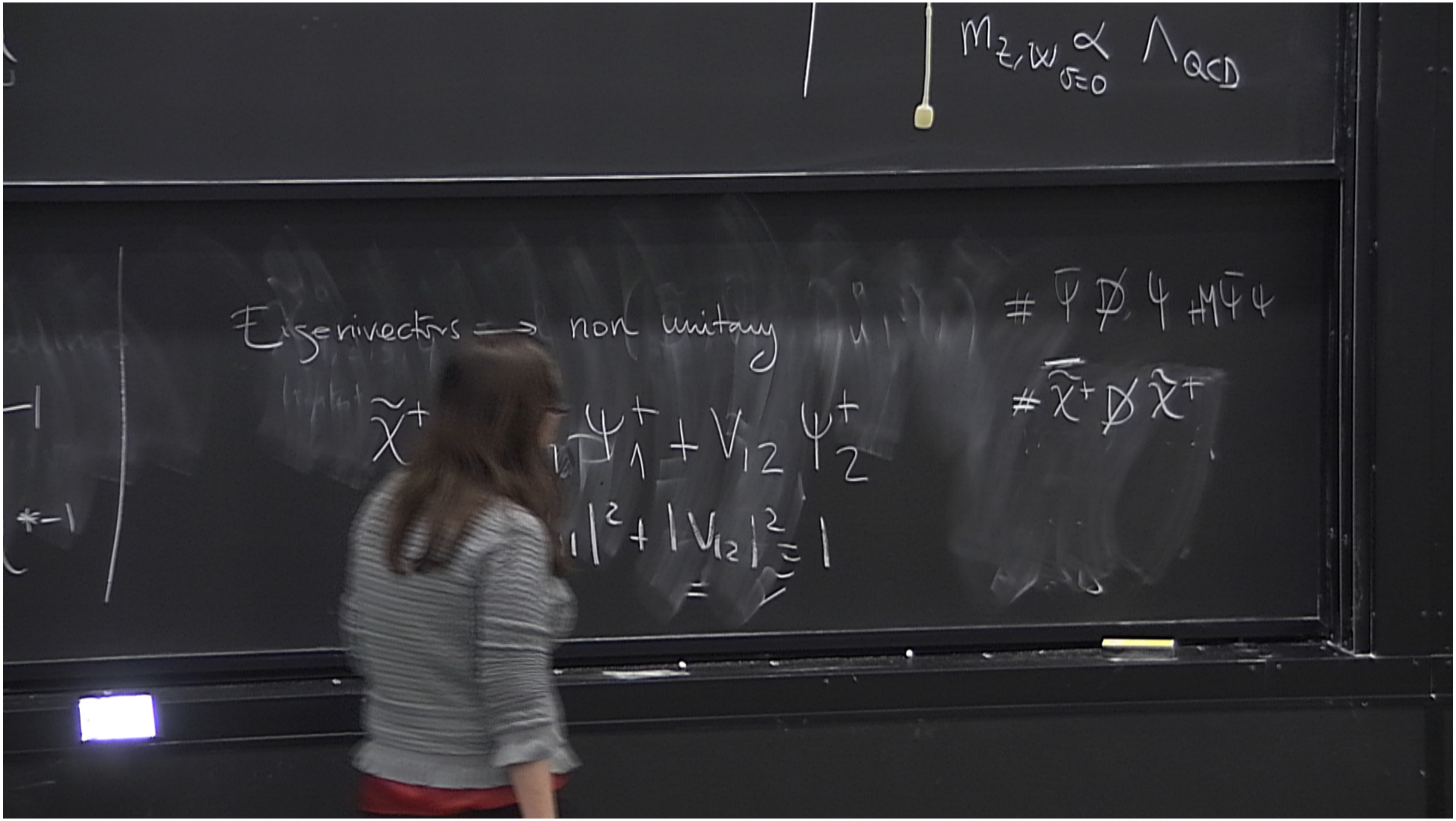
$$U^* M_C V^{-1} = M_D$$

U, V ?

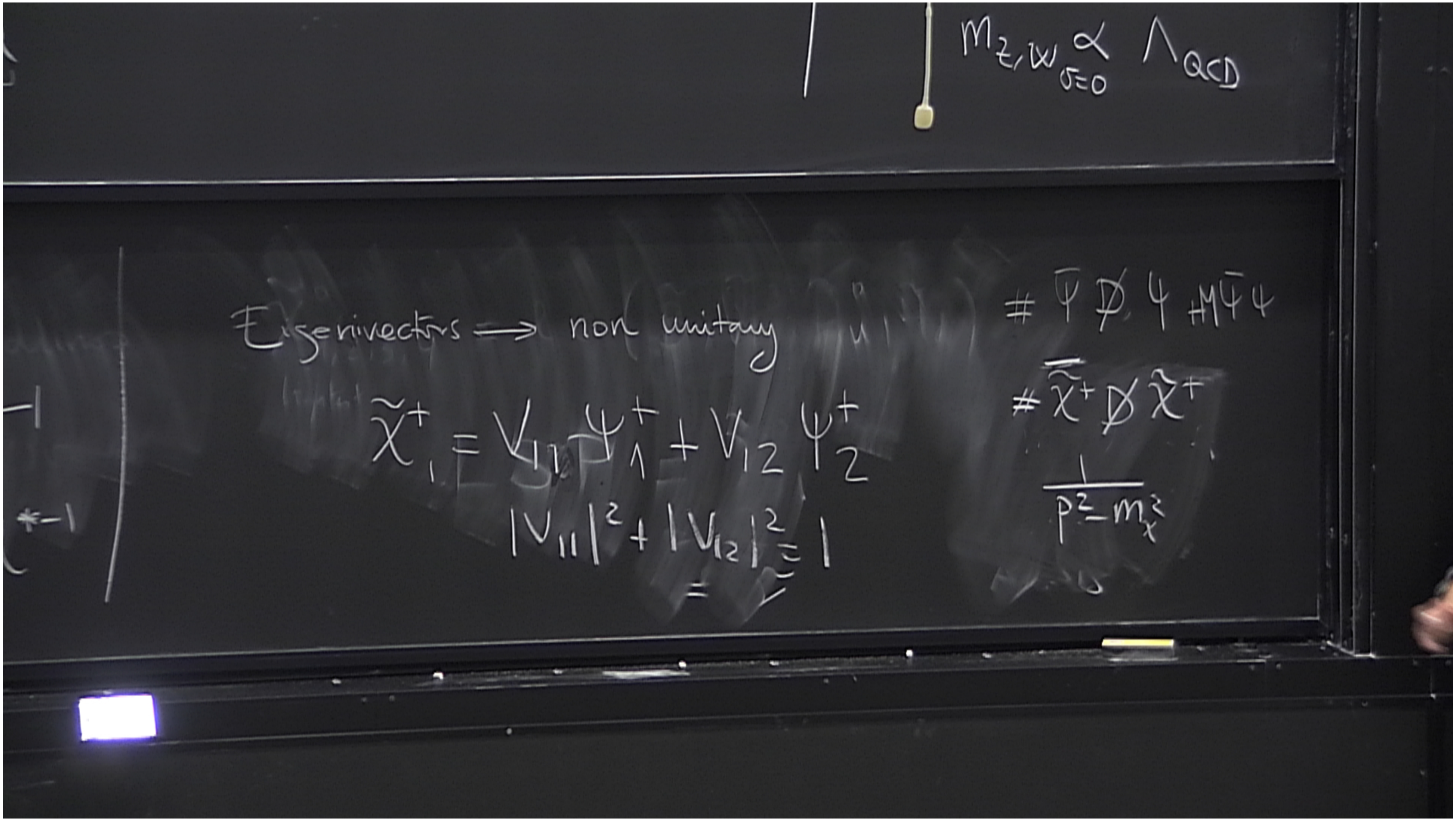
$$M_D^+ M_D = V\, M_C^+ M_C\, V^{-1}$$

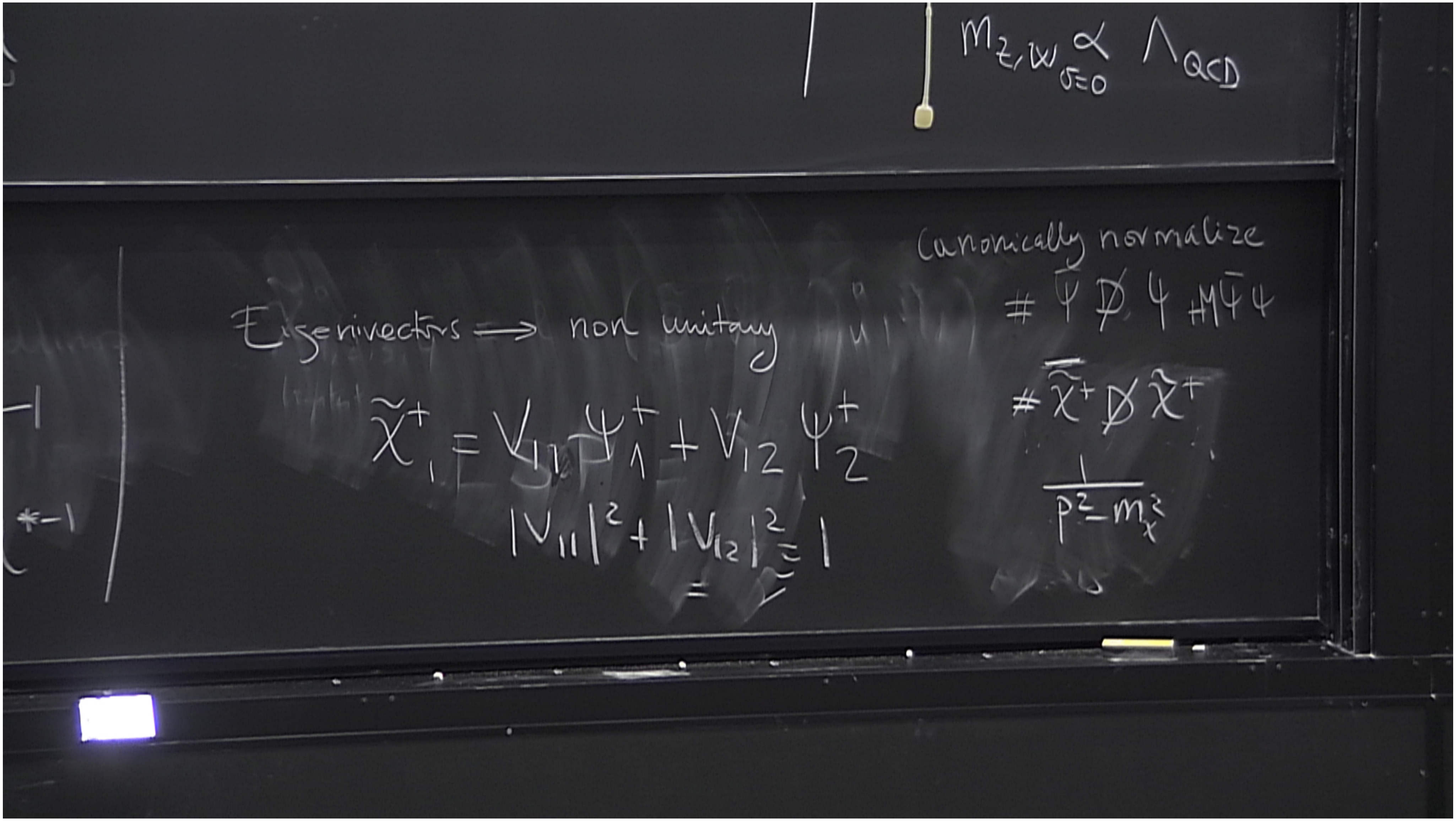

Higgsinos $H_{u,d}$, $\tilde{H}_u^+$, $\tilde{H}_d^-$
$\tilde{W}^\pm$
$U^* M_C V^{-1} = M_D$
U, V ?
$M_D^\dagger M_D = V\, M_C^\dagger M_C\, V^{-1}$
$M_D M_D^\dagger = U^* M_C M_C^\dagger U^{*-1}$

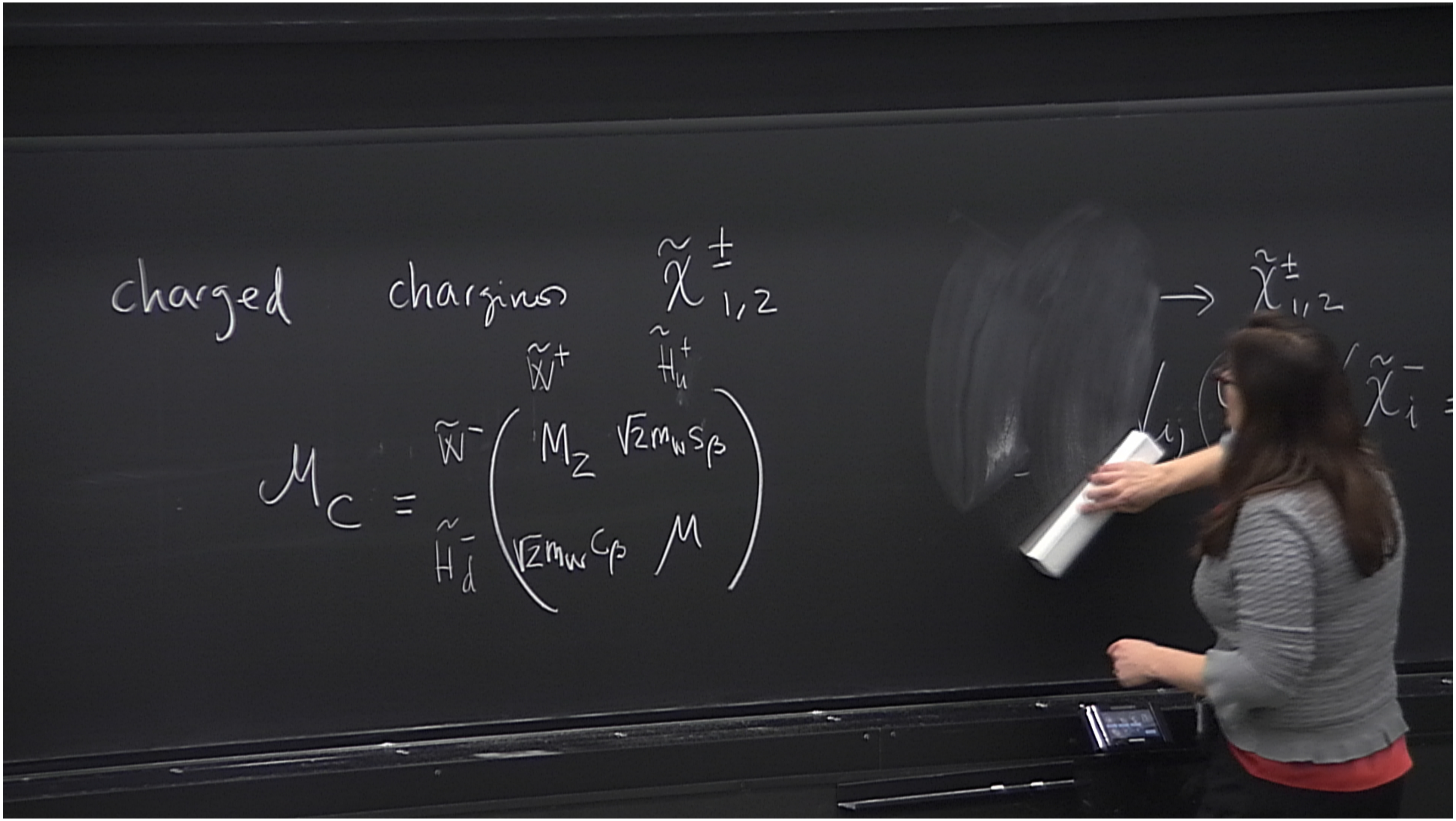

Eigenvectors ⟶
unitary



M Z,W ∝ σ=0 Λ QCD
Eigenvectors → non unitary
Ψ̄ D̸ ψ + MΨ̄ψ
χ̃+ D̸ χ̃+
χ̃+
ψ1+ + V12 ψ2+
|² + |V12|² = 1


$m_{Z,W} \underset{\sigma=0}{\propto} \Lambda_{QCD}$
Eigenvectors $\longrightarrow$ non unitary
$\tilde{\chi}^+_1 = V_{11}\psi^+_1 + V_{12}\psi^+_2$
$|V_{11}|^2 + |V_{12}|^2 = 1$
$\# \bar{\Psi} \not{D} \Psi + M\bar{\Psi}\Psi$
$\# \bar{\tilde{\chi}}^+ \not{D} \tilde{\chi}^+$
$\frac{1}{p^2 - m_\chi^2}$


$m_{Z,W} \underset{\sigma=0}{\propto} \Lambda_{QCD}$
Eigenvectors ⟹ non unitary
$\tilde{\chi}^+_1 = V_{11}\psi^+_1 + V_{12}\psi^+_2$
$|V_{11}|^2 + |V_{12}|^2 = 1$
Canonically normalize
$\# \bar{\psi} \not{D} \psi + M\bar{\psi}\psi$
$\# \bar{\tilde{\chi}}^+ \not{D} \tilde{\chi}^+$
$\frac{1}{p^2 - m_\chi^2}$


charged charginos $\tilde{\chi}^{\pm}_{1,2}$
$$\mathcal{M}_C = \begin{array}{c|cc} & \tilde{W}^+ & \tilde{H}_u^+ \\ \hline \tilde{W}^- & & \\ \tilde{H}_d^- & & \end{array} \begin{pmatrix} M_2 & \sqrt{2}m_W s_\beta \\ \sqrt{2}m_W c_\beta & \mu \end{pmatrix}$$
$\rightarrow \tilde{\chi}^{\pm}_{1,2}$

$,2$

$M_2, \mu \gg \text{EWSB}$

$$m_{\tilde{\chi}^\pm_{1,2}} \approx M_2, |\mu| \quad \text{if } |\mu| > M_2$$

$$m_{\tilde{\chi}^\pm_{1,2}} \approx M_2 - \# \frac{M_2 m_W}{\mu}, \mu + \# m_W$$

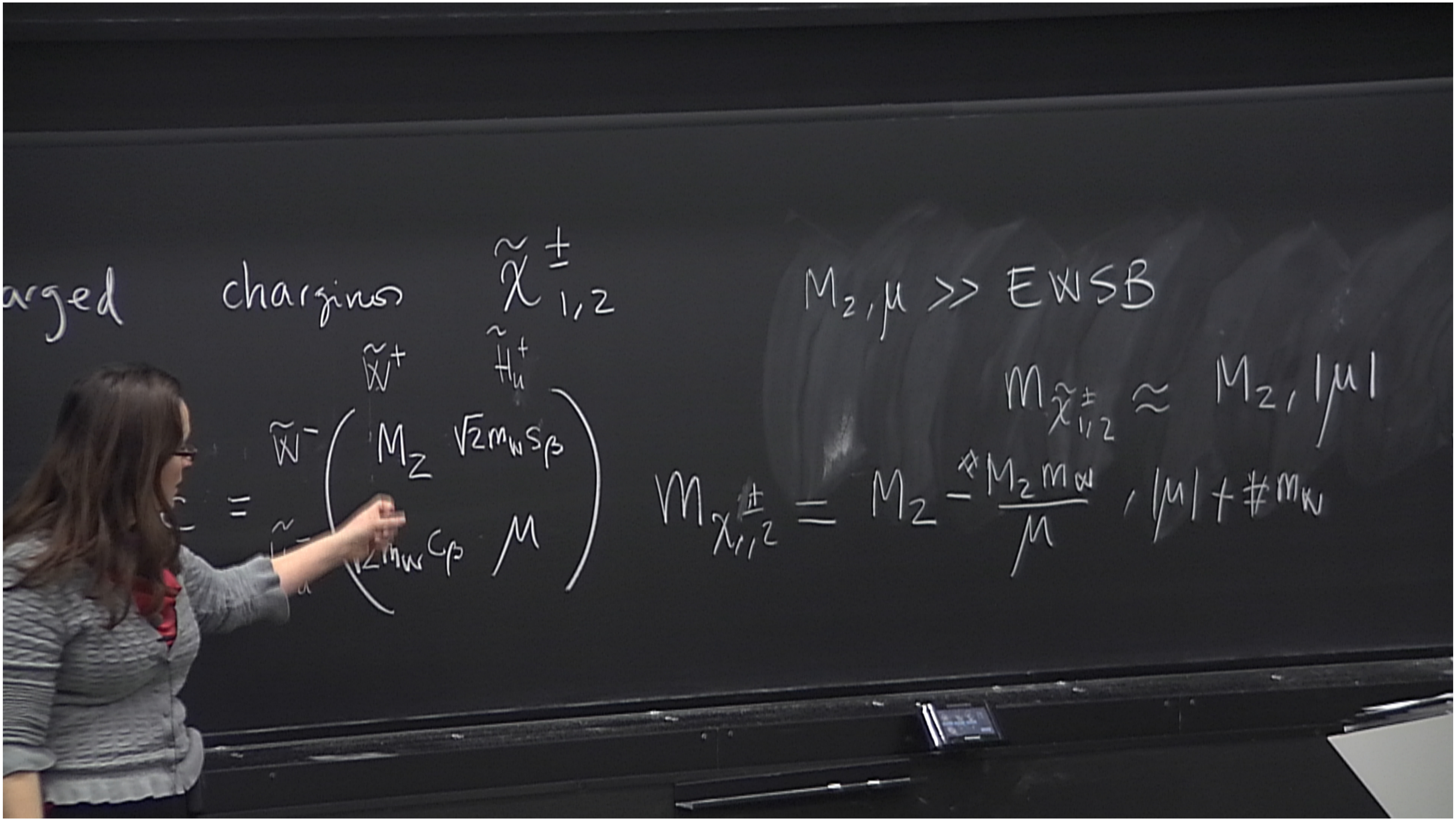
charged charginos $\tilde{\chi}^{\pm}_{1,2}$

$M_2, \mu \gg$ EWSB

$m_{\tilde{\chi}^{\pm}_{1,2}} \approx M_2, |\mu|$

$$\mathcal{M}_C = \begin{array}{c|c} & \begin{array}{cc} \tilde{W}^+ & \tilde{H}_u^+ \end{array} \\ \begin{array}{c} \tilde{W}^- \\ \tilde{H}_d^- \end{array} & \begin{pmatrix} M_2 & \sqrt{2}\, m_W s_\beta \\ \sqrt{2}\, m_W c_\beta & \mu \end{pmatrix} \end{array}$$

$m_{\chi^{\pm}_{1,2}} =$


arged
charginos $\tilde{\chi}^{\pm}_{1,2}$
$M_2, \mu \gg$ EWSB
$m_{\tilde{\chi}^{\pm}_{1,2}} \approx M_2, |\mu|$
$\tilde{W}^+$ $\tilde{H}_u^+$
$\tilde{W}^-$ M_2 $\sqrt{2} m_W s_\beta$
$\sqrt{2} m_W c_\beta$ μ
$m_{\chi^{\pm}_{1,2}} = M_2 - \# \frac{M_2 m_W}{\mu}, |\mu| + \# m_W$

arged charginos $\tilde{\chi}^{\pm}_{1,2}$

$M_2, \mu \gg$ EWSB

$$\begin{array}{c|cc} & \tilde{W}^+ & \tilde{H}_u^+ \\ \hline \tilde{W}^- & & \\ \tilde{H}_d^- & & \end{array}$$

$$\mathcal{M}_C = \begin{pmatrix} M_2 & \sqrt{2} m_W s_\beta \\ \sqrt{2} m_W c_\beta & \mu \end{pmatrix}$$

$$m_{\tilde{\chi}^{\pm}_{1,2}} \approx M_2, |\mu|$$

$$m_{\chi^{\pm}_{1,2}} = M_2 - \# \frac{M_2 m_W}{\mu}, \ |\mu| + \# m_W$$

charginos $\tilde{\chi}^{\pm}_{1,2}$

$$M_C = \begin{array}{c|cc} & \tilde{W}^+ & \tilde{H}_u^+ \\ \hline \tilde{W}^- & M_2 & \sqrt{2}\, m_W s_\beta \\ \tilde{H}_d^- & \sqrt{2}\, m_W c_\beta & \mu \end{array}$$

$M_2, \mu \gg$ EWSB

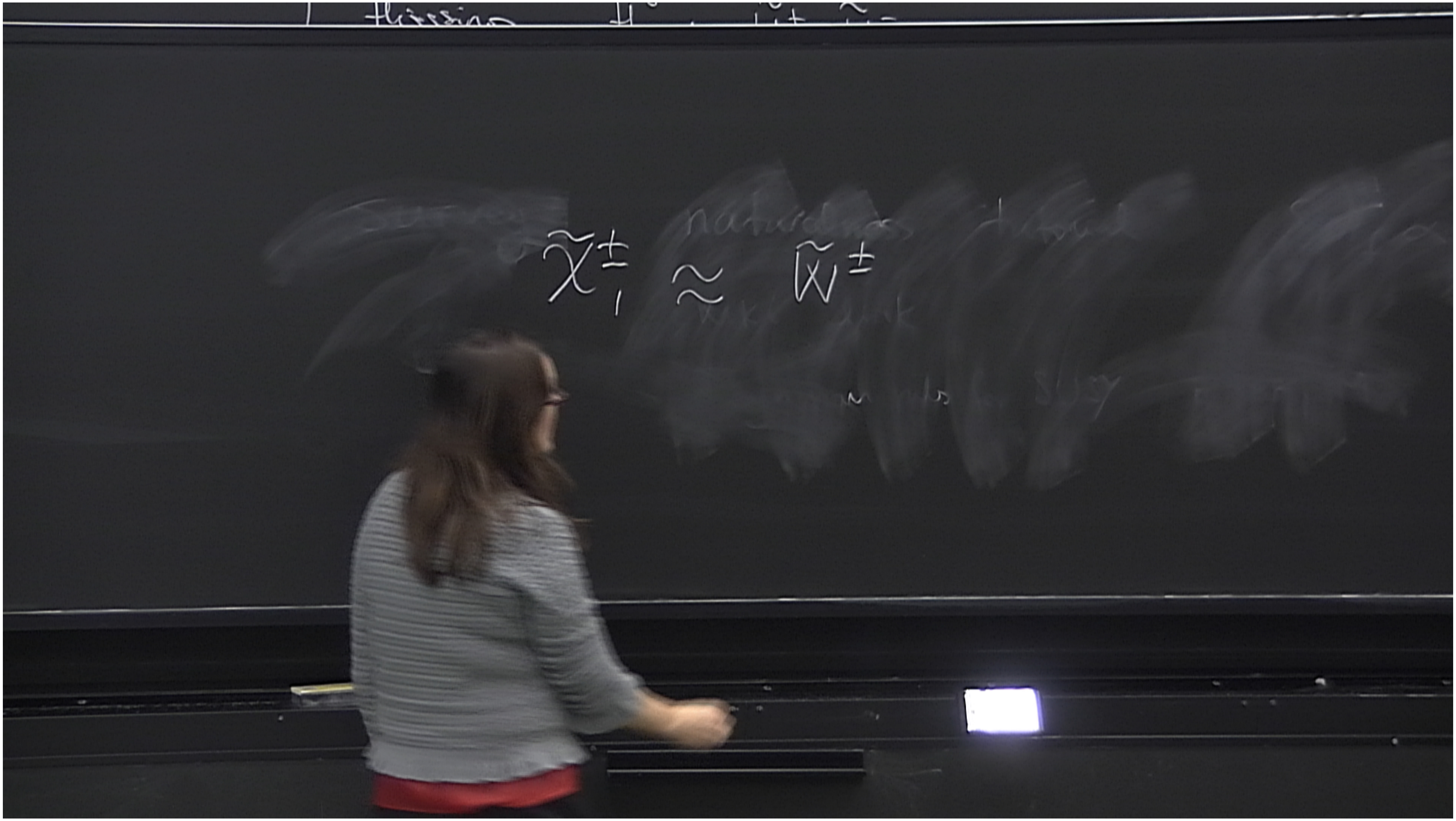
$$m_{\tilde{\chi}^{\pm}_{1,2}} \approx M_2, |\mu|$$

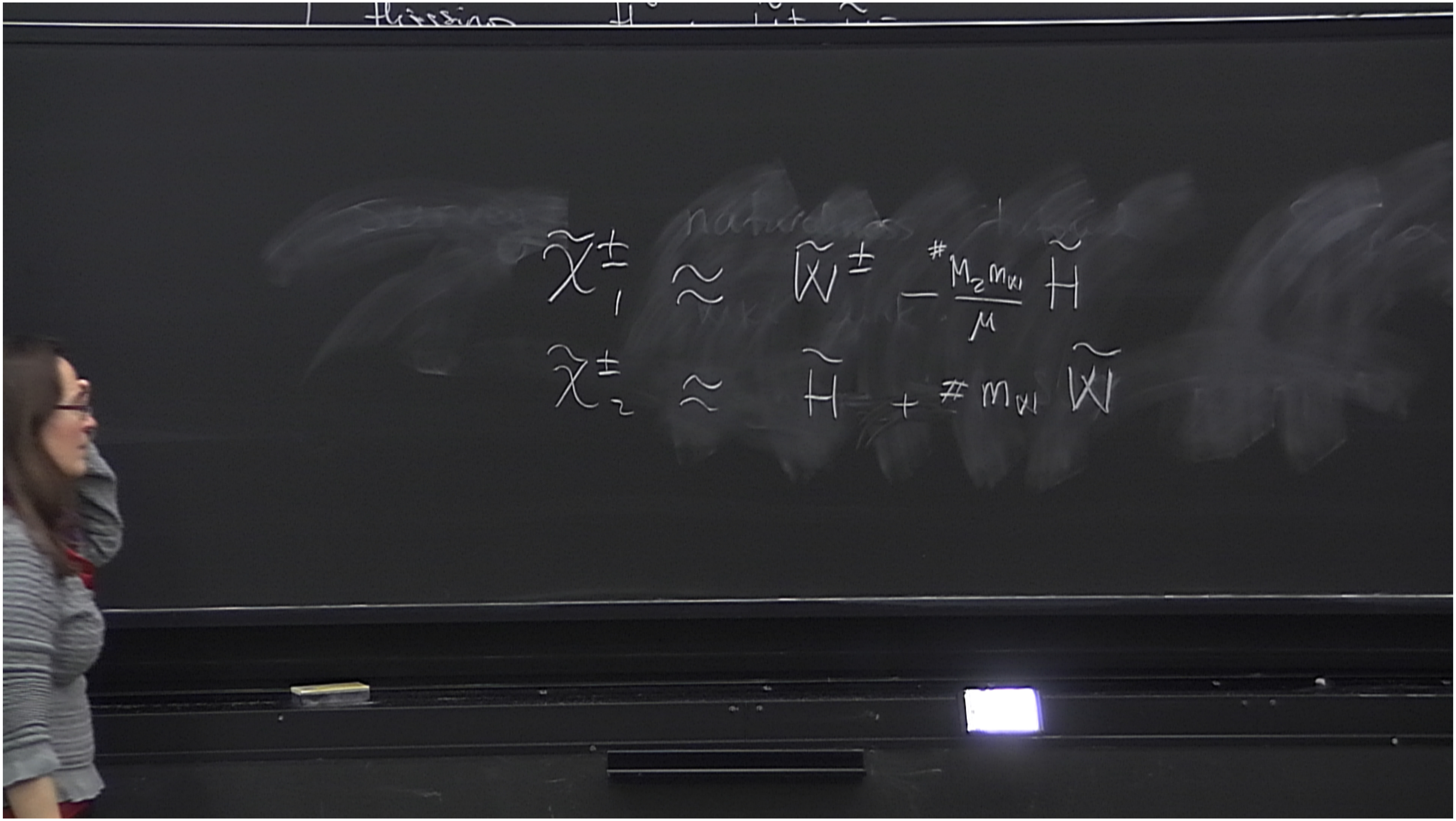
if

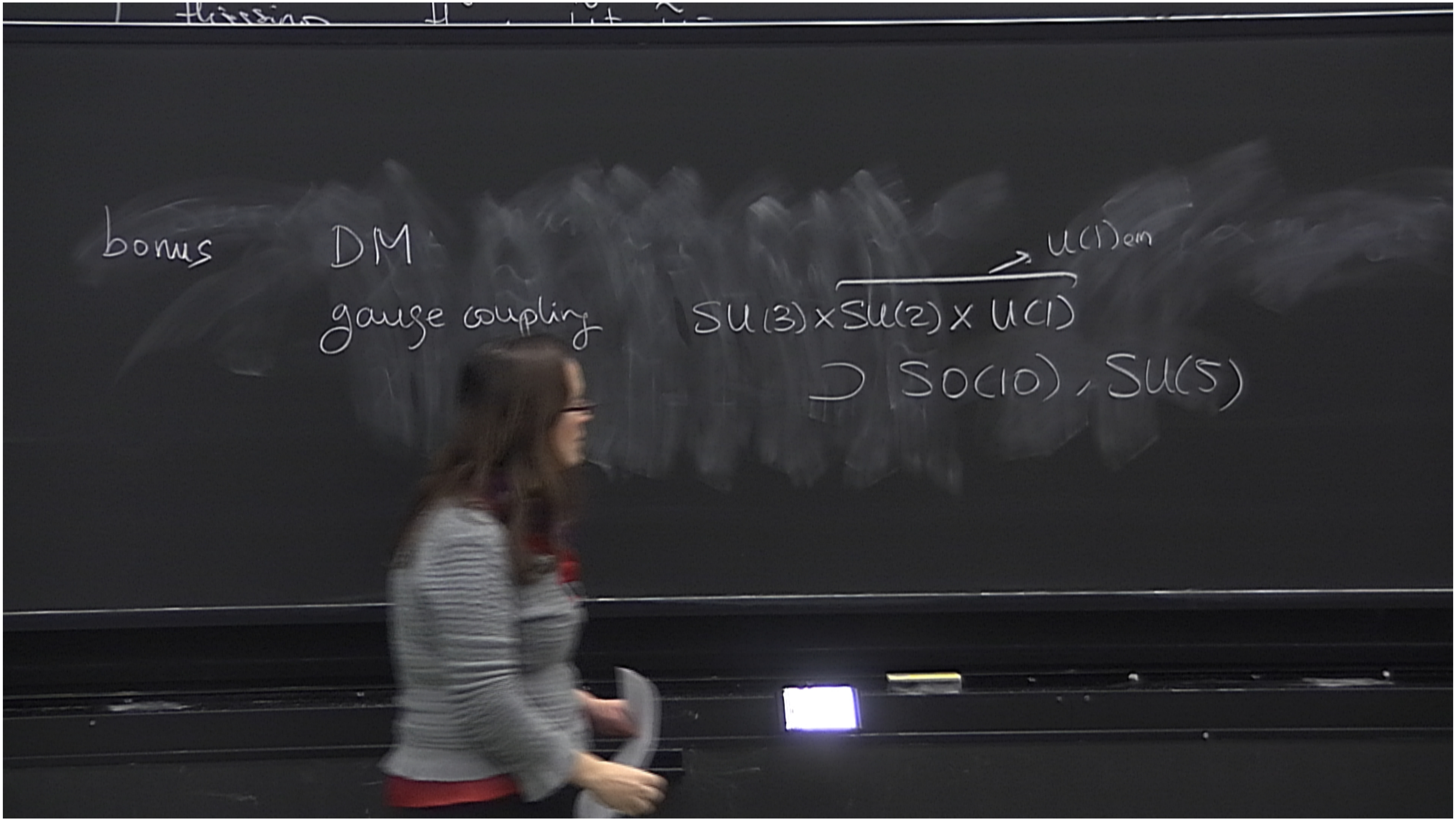
$$m_{\chi^{\pm}_{1,2}} = M_2 - \# \frac{M_2 m_W}{\mu}, \quad |\mu| + \# m_W \sim$$

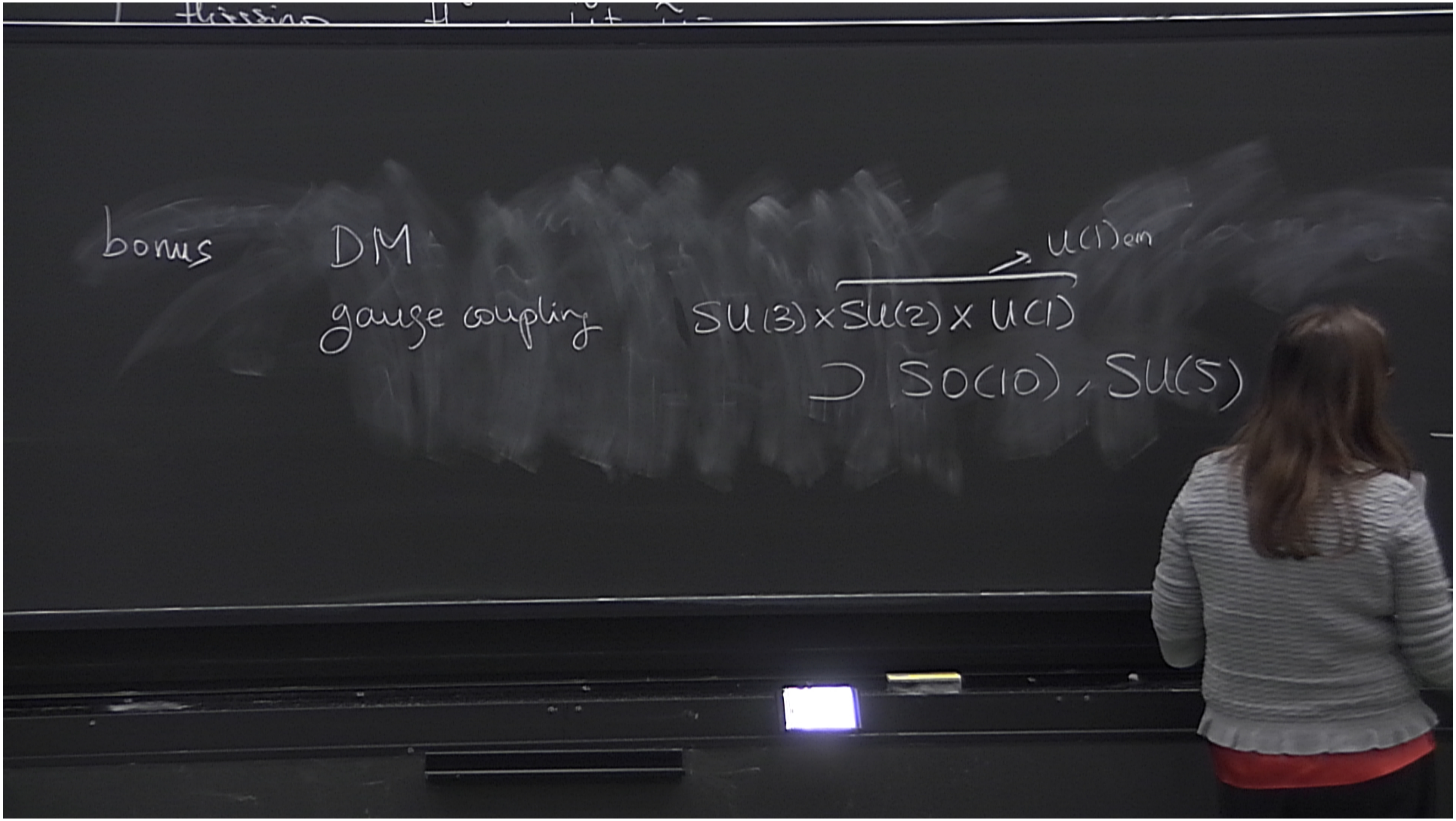
mostly $\tilde{W}$ mostly $\tilde{H}$

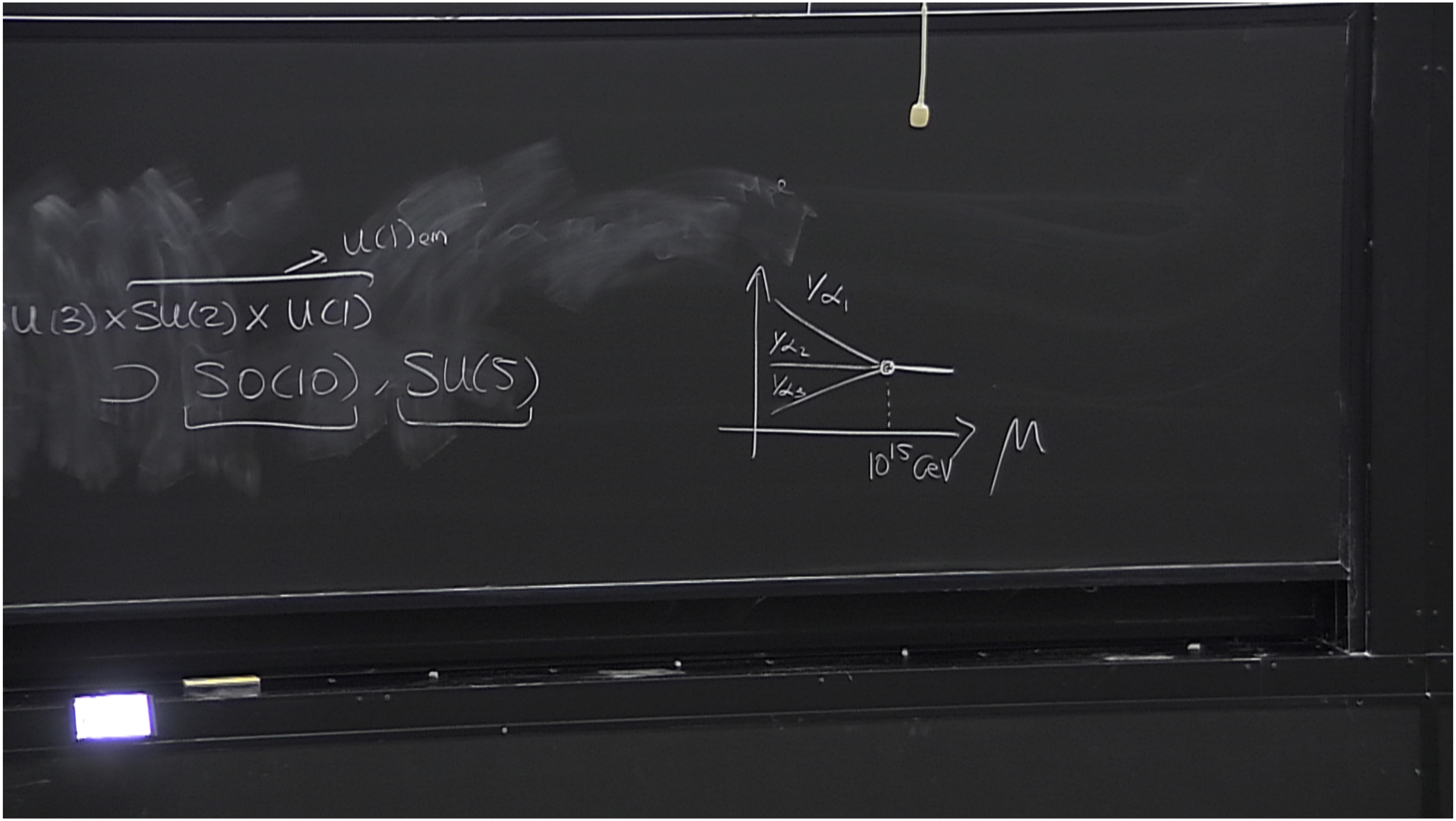
$m_{\tilde{\chi}^{\pm}_{1,2}} \approx$

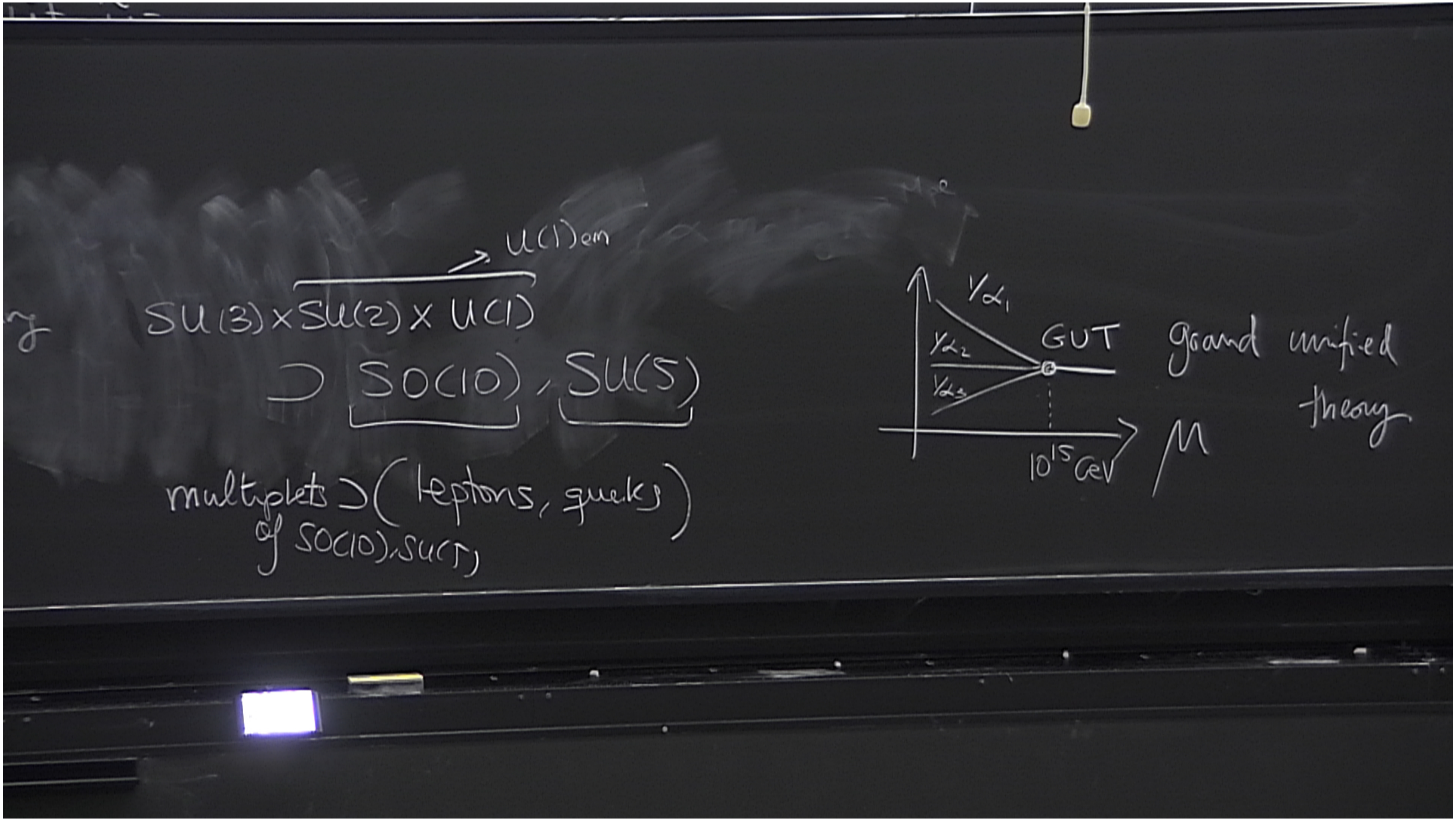

$\tilde{\chi}^{\pm}_{1} \approx \tilde{W}^{\pm}$

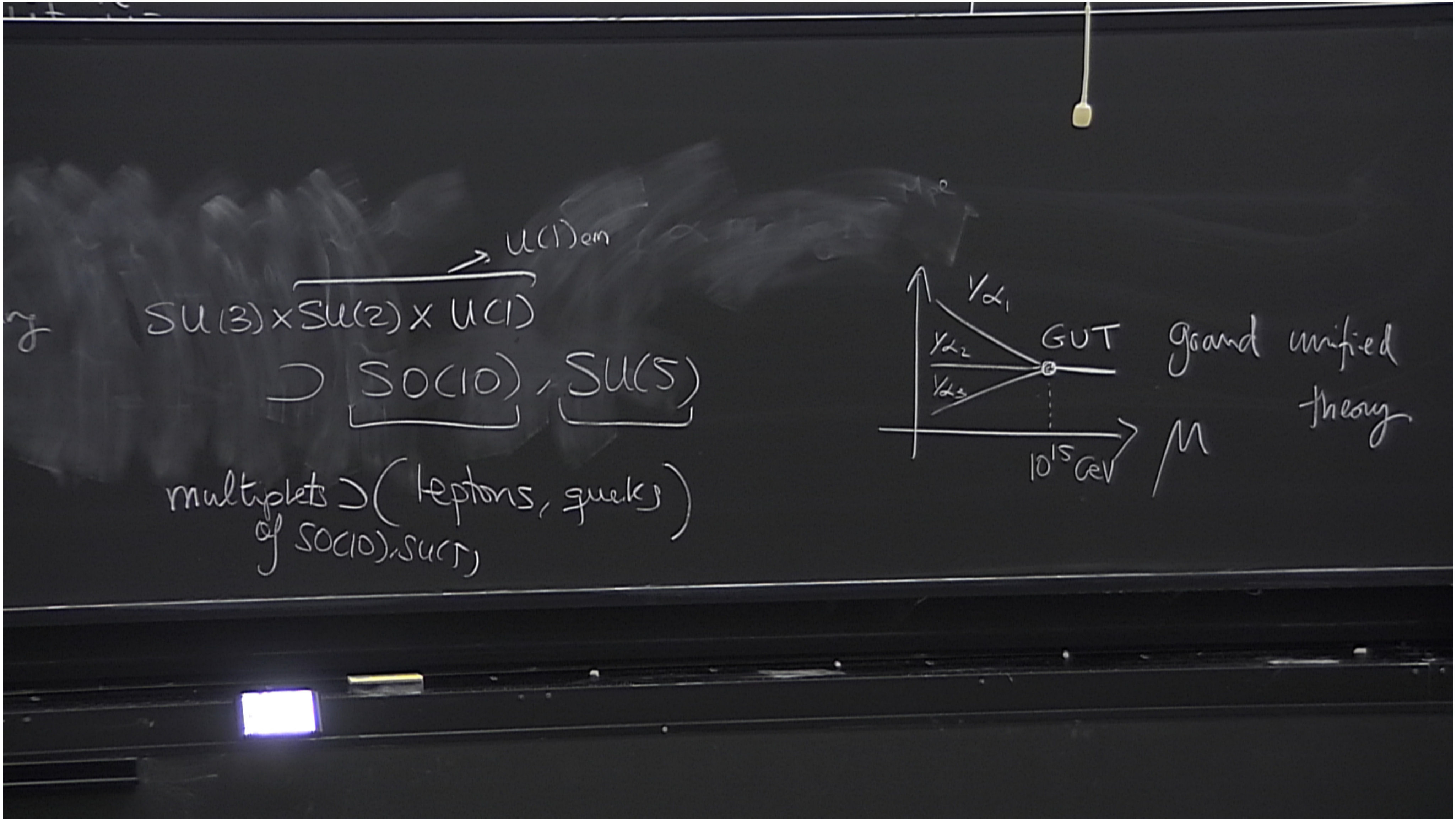

$\tilde{\chi}^{\pm}_{1} \approx \tilde{W}^{\pm} - \# \frac{M_2 m_W}{\mu} \tilde{H}$
$\tilde{\chi}^{\pm}_{2} \approx \tilde{H} + \# m_W \tilde{W}$


bonus
DM
gauge coupling
SU(3) x SU(2) x U(1)
U(1)em
⊃ SO(10), SU(5)


bonus
DM
U(1)em
gauge coupling SU(3) x SU(2) x U(1)
⊃ SO(10), SU(5)


U(1)em
SU(3) x SU(2) x U(1)
⊃ SO(10), SU(5)
1/α1
1/α2
1/α3
10^15 GeV
μ


U(1)em
SU(3) x SU(2) x U(1)
⊃ SO(10), SU(5)
multiplets ⊃ (leptons, quarks)
of SO(10), SU(5)
1/α1
1/α2
1/α3
GUT
10^15 GeV
μ
grand unified
theory

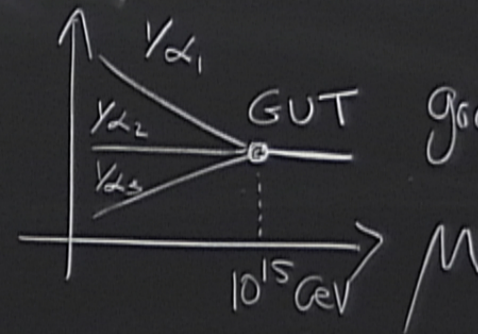

U(1)em
SU(3) × SU(2) × U(1)
⊃ SO(10), SU(5)
multiplets ⊃ (leptons, quarks)
of SO(10), SU(5)
1/α1
1/α2
1/α3
GUT
10^15 GeV
μ
grand unified theory

$$SU(3) \times \overbrace{SU(2) \times U(1)}^{\to\, U(1)_{em}}$$

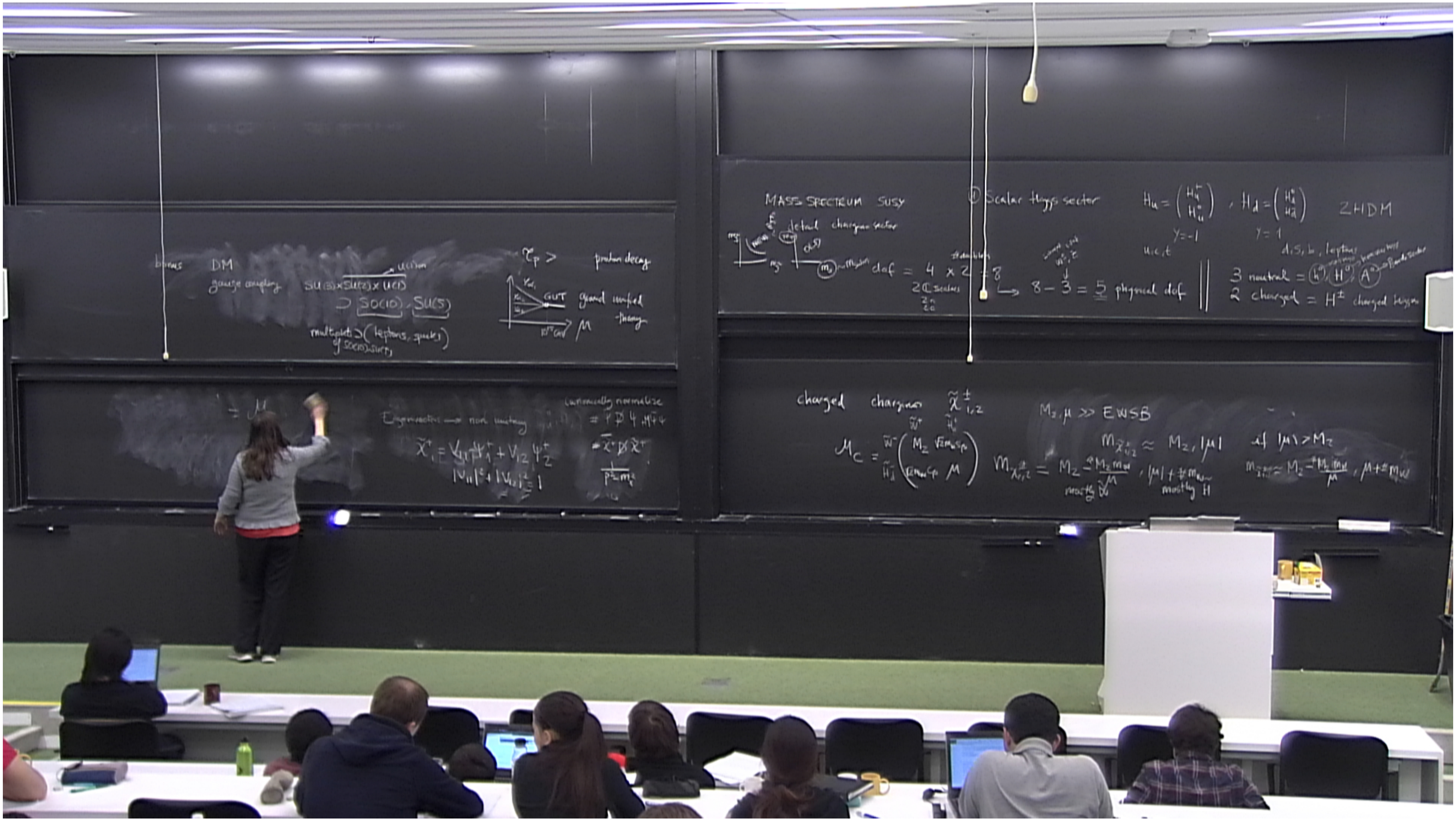
$$\supset \underbrace{SO(10)}, \underbrace{SU(5)}$$

multiplets $\supset$ (leptons, quarks)
of $SO(10), SU(5)$

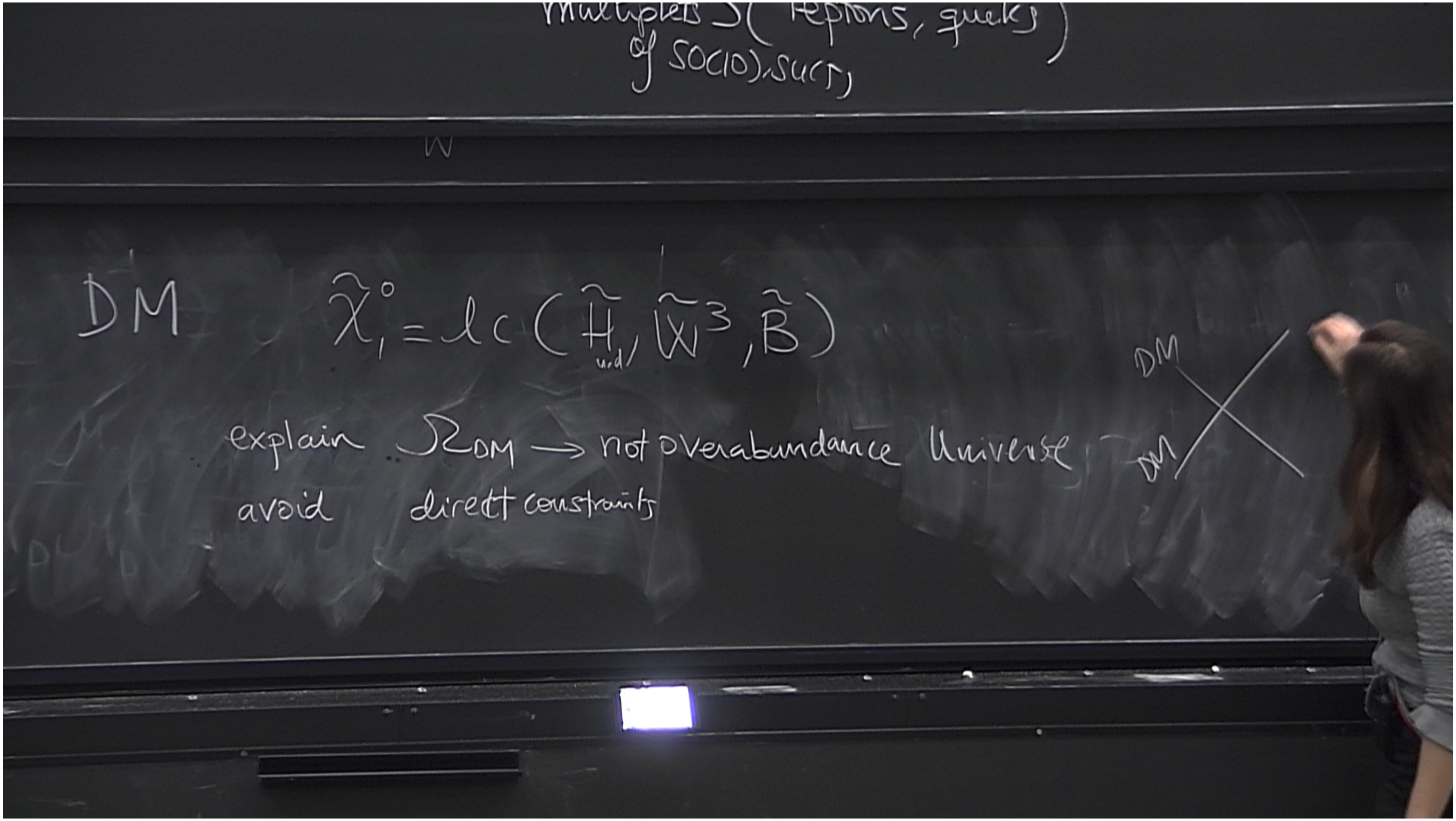
$\tau_p >$ proton decay



grand unified theory



MASS SPECTRUM SUSY
Scalar Higgs sector
2HDM
8 − 3 = 5 physical dof
3 neutral
2 charged
charged Higgs
proton decay
GUT
grand unified theory
SU(5)
SO(10)
charged
M2, μ >> EWSB
mostly H


multiplets (leptons, quarks)
of SO(10), SU(5)
DM
$\tilde{\chi}^0_1 = lc(\tilde{H}_{u,d}, \tilde{W}^3, \tilde{B})$
explain $\Omega_{DM} \rightarrow$ not overabundance Universe
avoid direct constraints
DM
DM