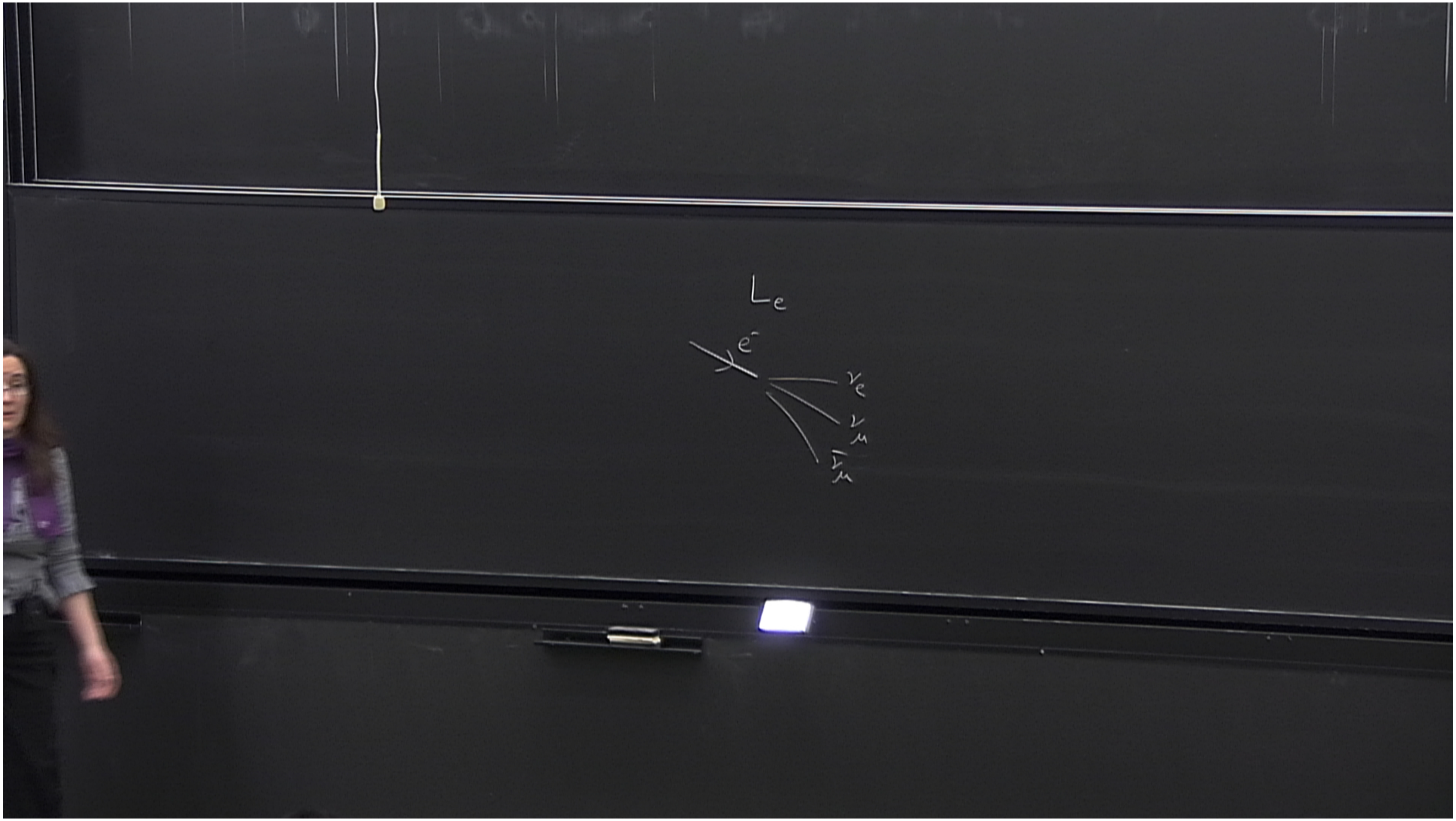
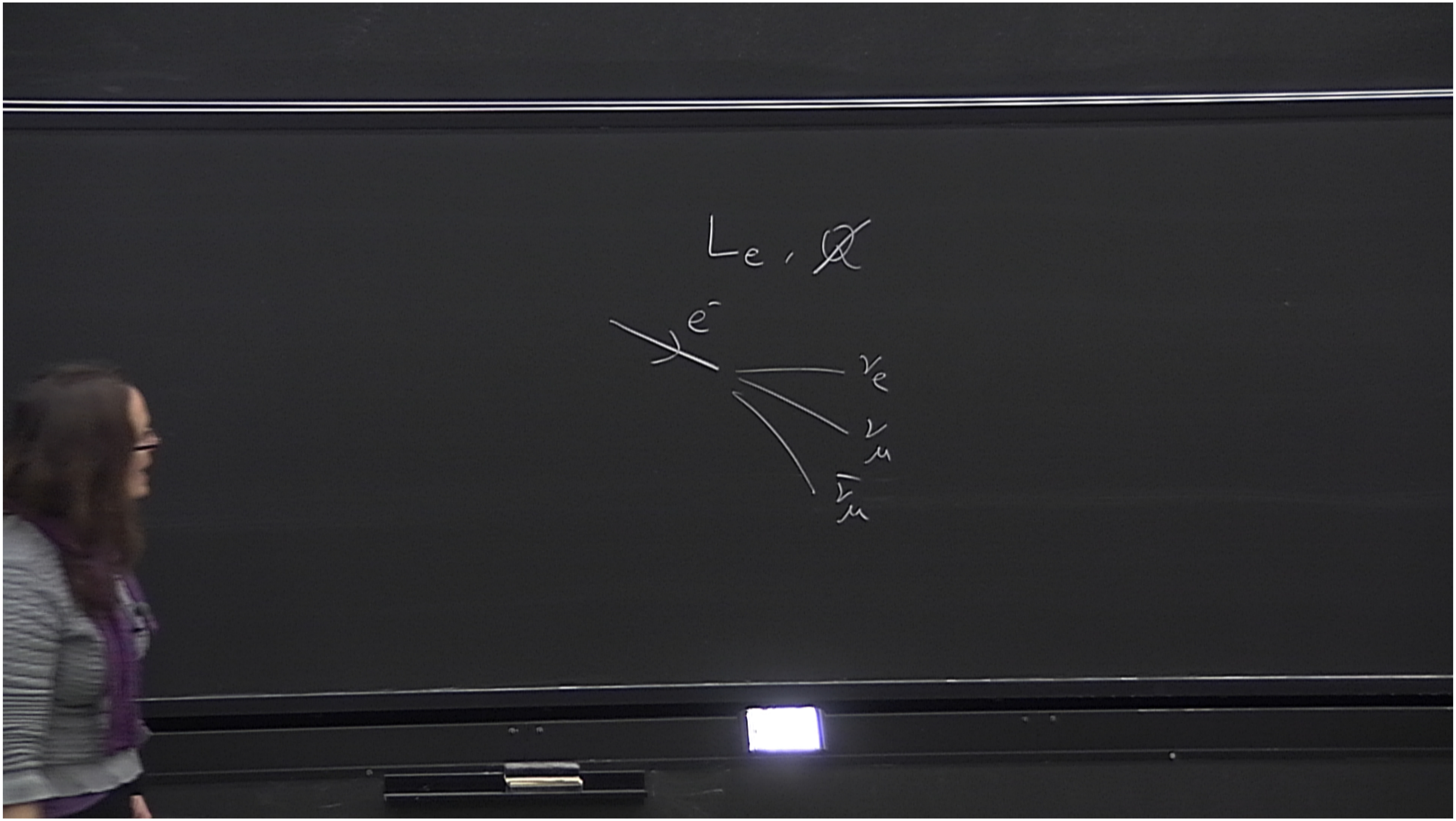
Title: Beyond the Standard Model (Review) - Lecture 6

Date: Feb 21, 2012 09:00 AM

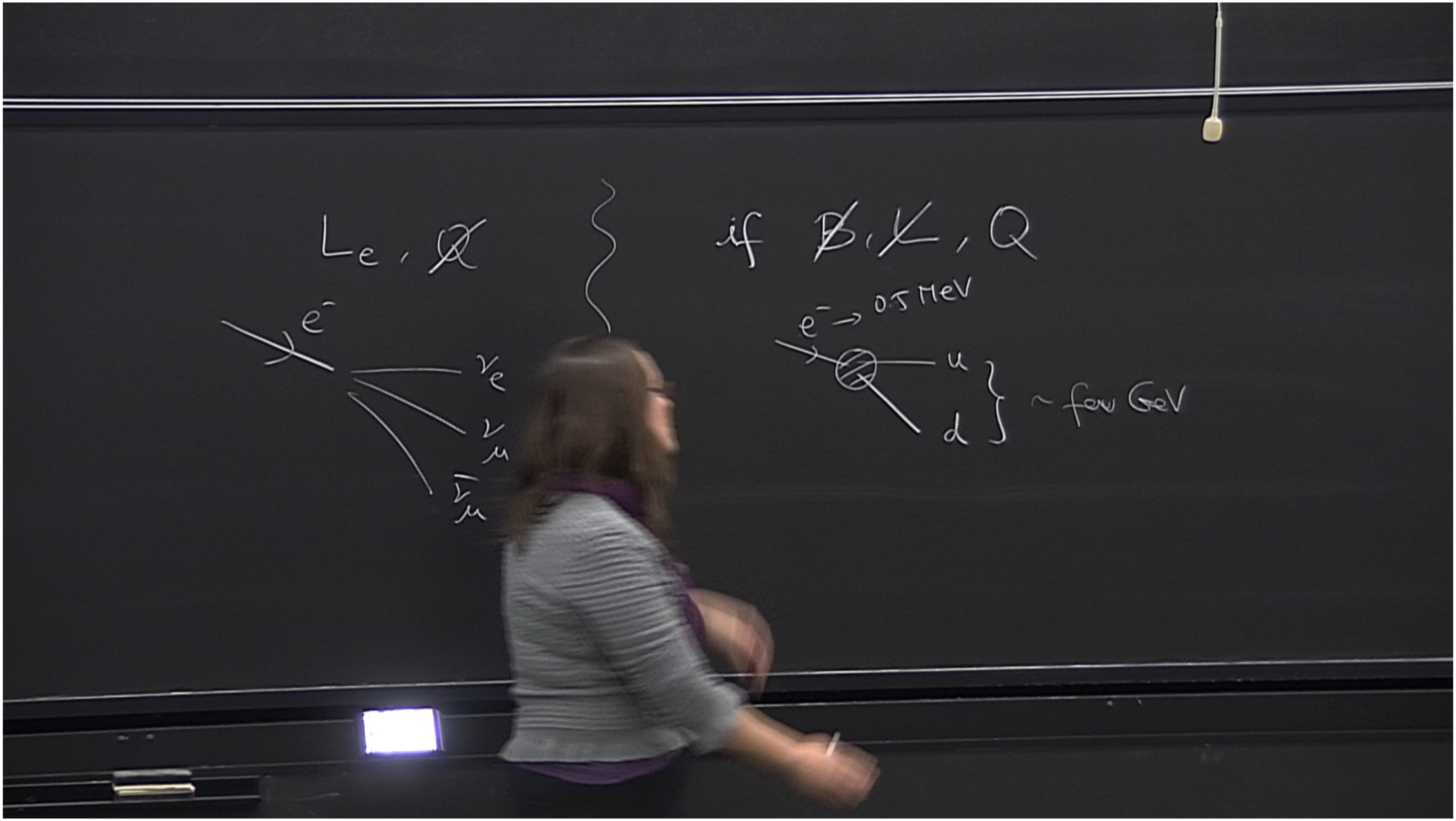
URL: http://pirsa.org/12020075

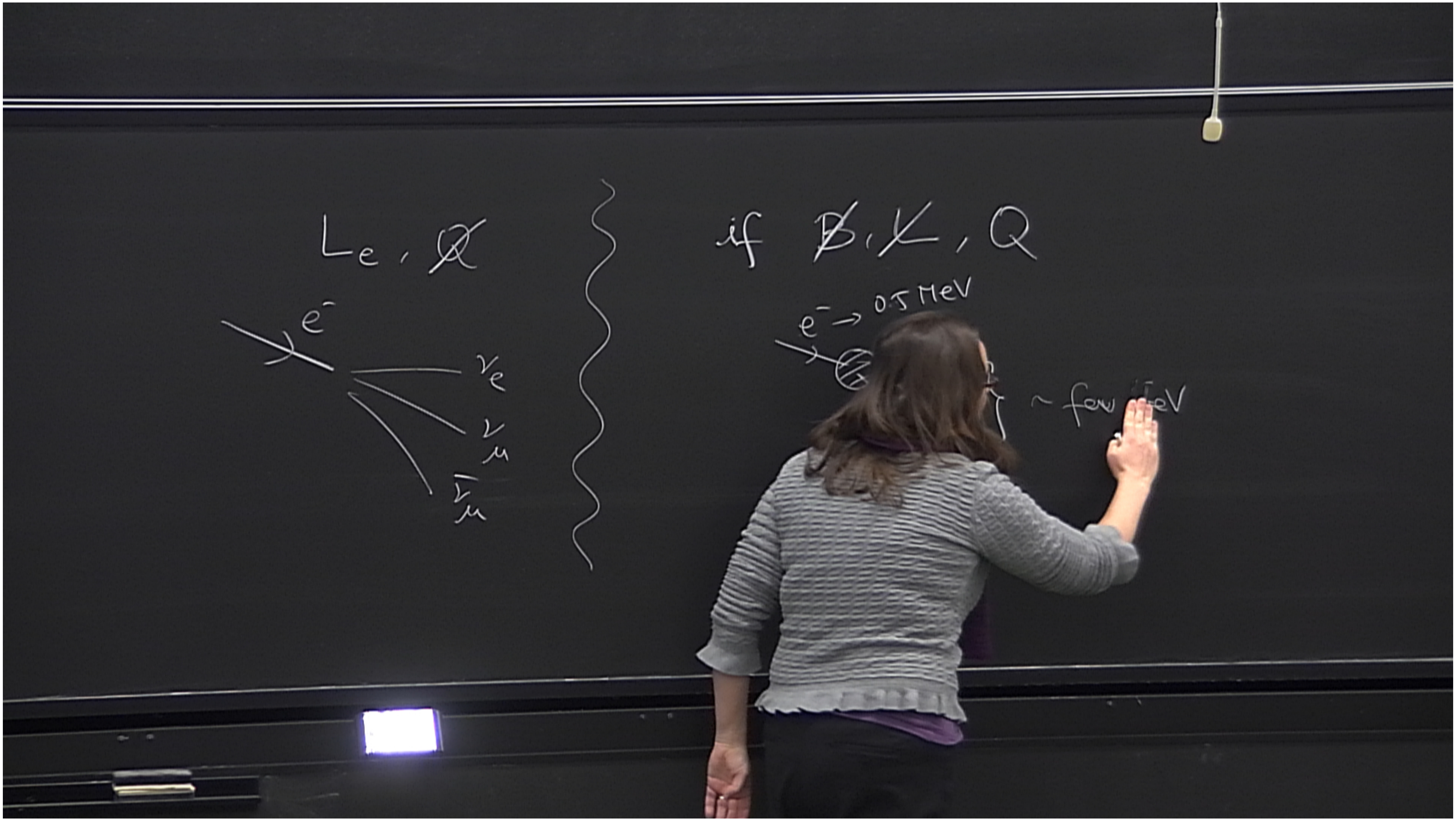
Abstract:


L_e
e^-
ν_e
ν_μ
$\bar{\nu}_\mu$

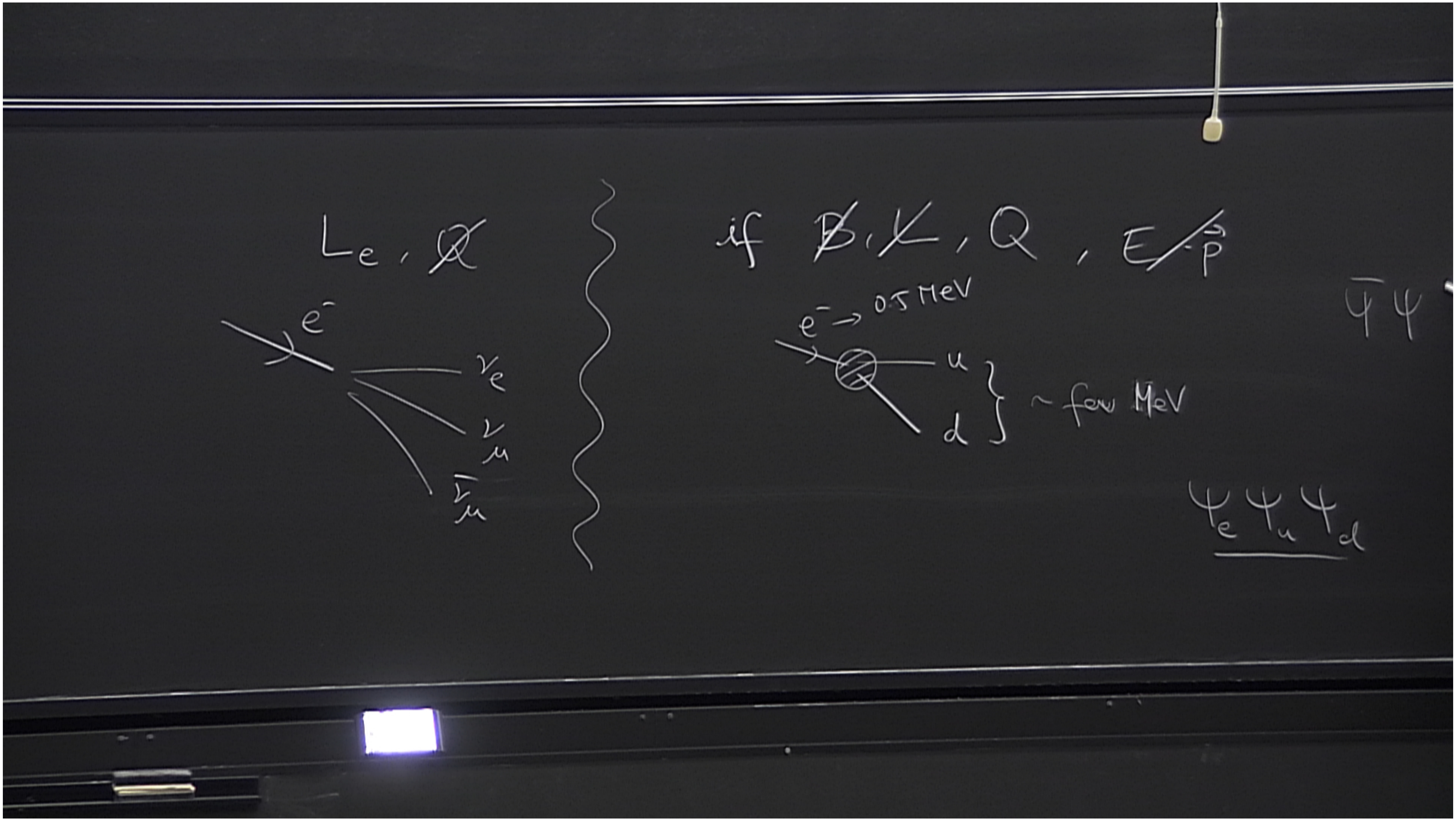

L_e ,
e^-
ν_e
ν_μ
$\bar{\nu}_\mu$

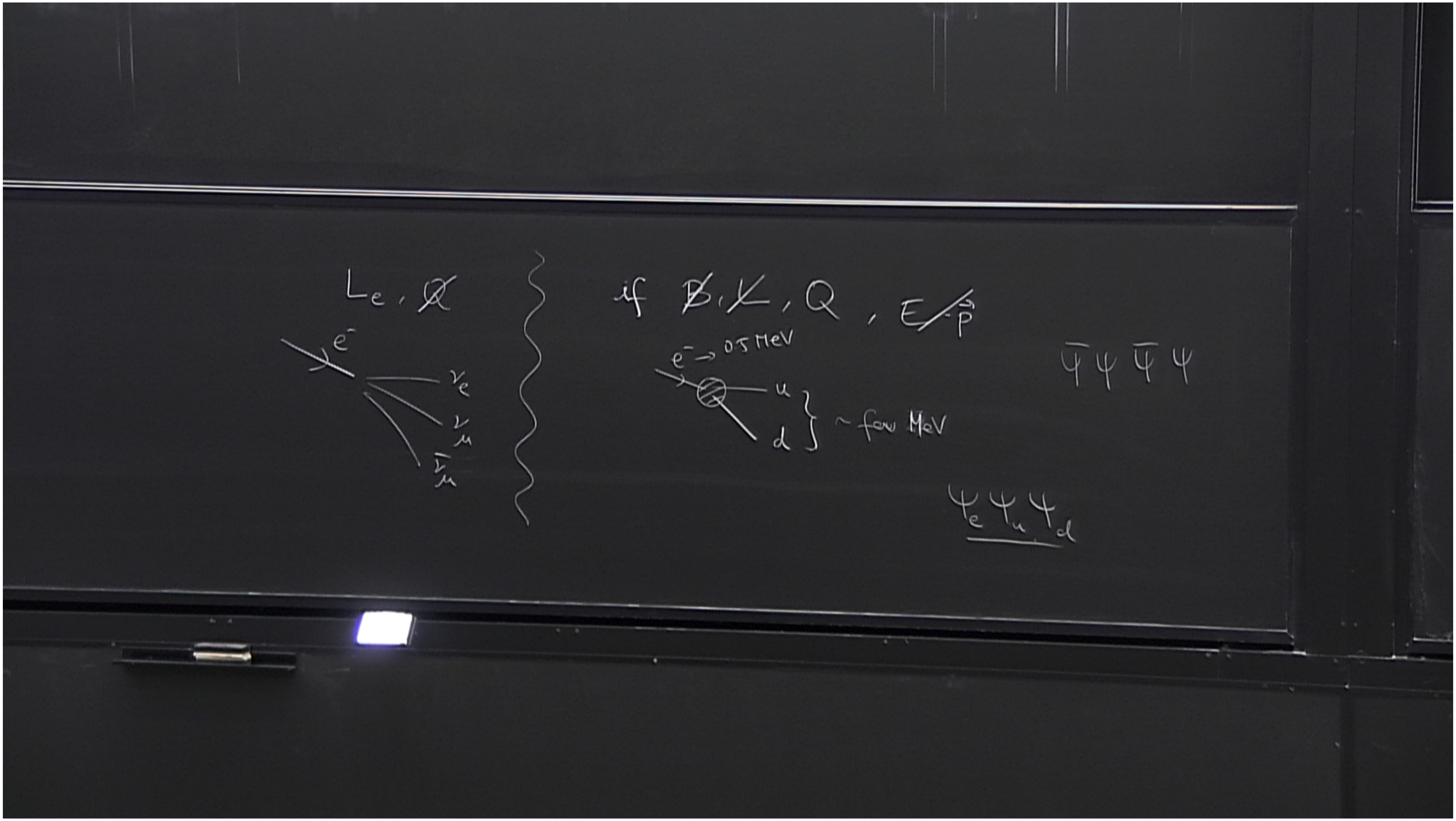

L_e , $\cancel{Q}$
e^-
ν_e
ν
if $\cancel{B}$, $\cancel{L}$, Q
e^-


Le, Q
if B, L, Q
e⁻
νe
νμ
ν̄μ
e⁻ → 0.5 MeV
u
d
~ few GeV



$L_e, \not{Q}$
e^-
ν_e
ν_μ
$\bar{\nu}_\mu$
if $\not{B}, \not{L}, Q$
$e^- \to 0.5$ MeV
~ few MeV


$L_e, \cancel{Q}$
e^-
ν_e
ν_μ
$\bar{\nu}_\mu$
if $\cancel{B}, \cancel{K}, Q, \cancel{E}, \cancel{\vec{p}}$
$e^- \to 0.5$ MeV
u
d
~ few MeV
$\bar{\psi}\psi$
$\psi_e \psi_u \psi_d$


L_e, $\cancel{Q}$
e^-
ν_e
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$\bar{\nu}_\mu$
if $\cancel{B}$, $\cancel{L}$, Q, E, $\vec{p}$
$e^- \to$ 0.5 MeV
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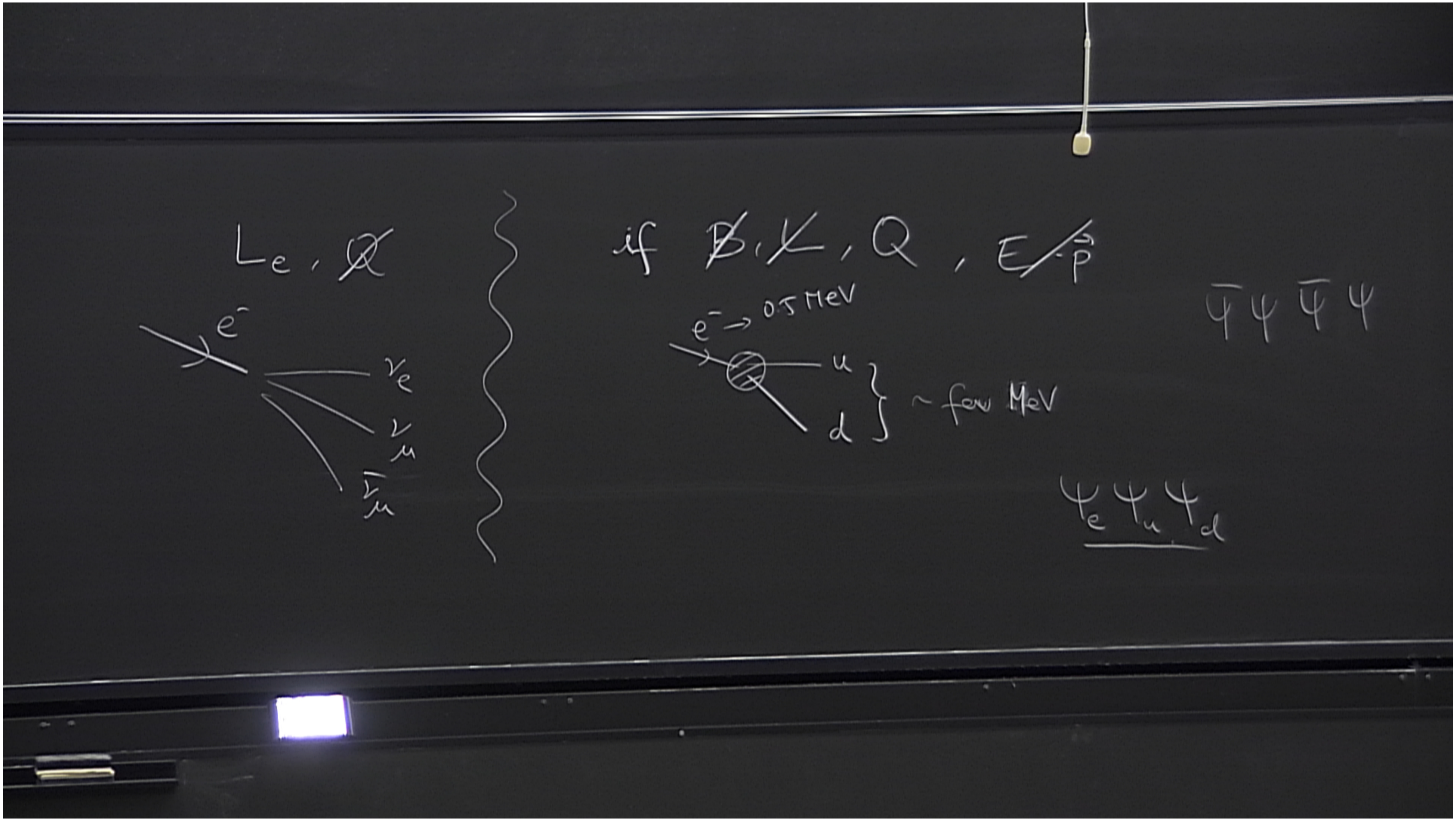
d
~ few MeV
$\bar\psi \psi \bar\psi \psi$
$\psi_e \psi_u \psi_d$


L_e, $\cancel{Q}$
e^-
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if $\cancel{B}$, $\cancel{L}$, Q, $E/\vec{p}$
$e^- \to$ 0.5 MeV
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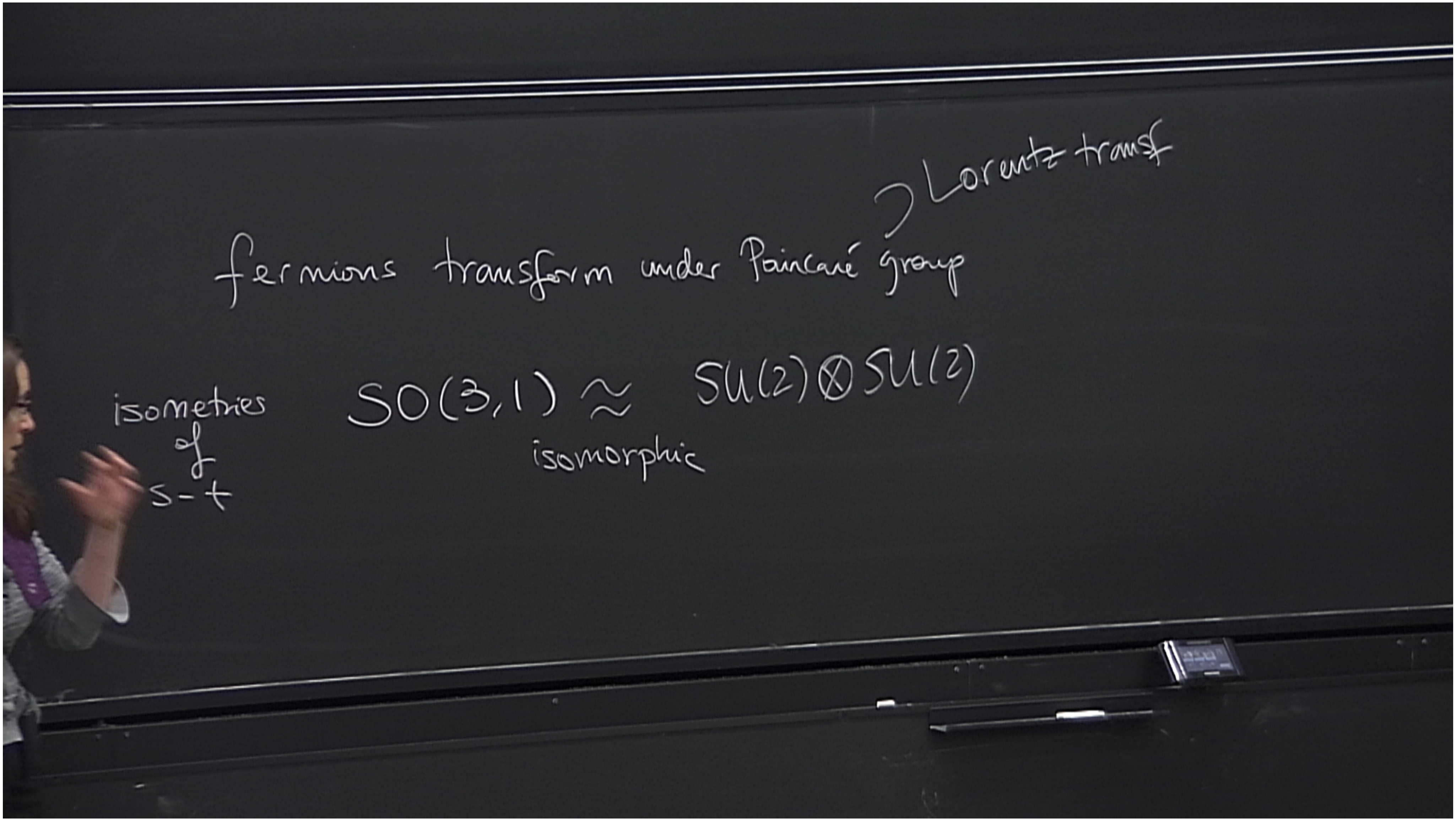
~ few MeV
$\bar{\psi}\psi\bar{\psi}\psi$
$\psi_e\psi_u\psi_d$


Lorentz transf
fermions transform under Poincaré group
isometries of s-t
SO(3,1) ≈ SU(2) ⊗ SU(2)
isomorphic

fermions transform under Poincaré group $\supset$ Lorentz transf

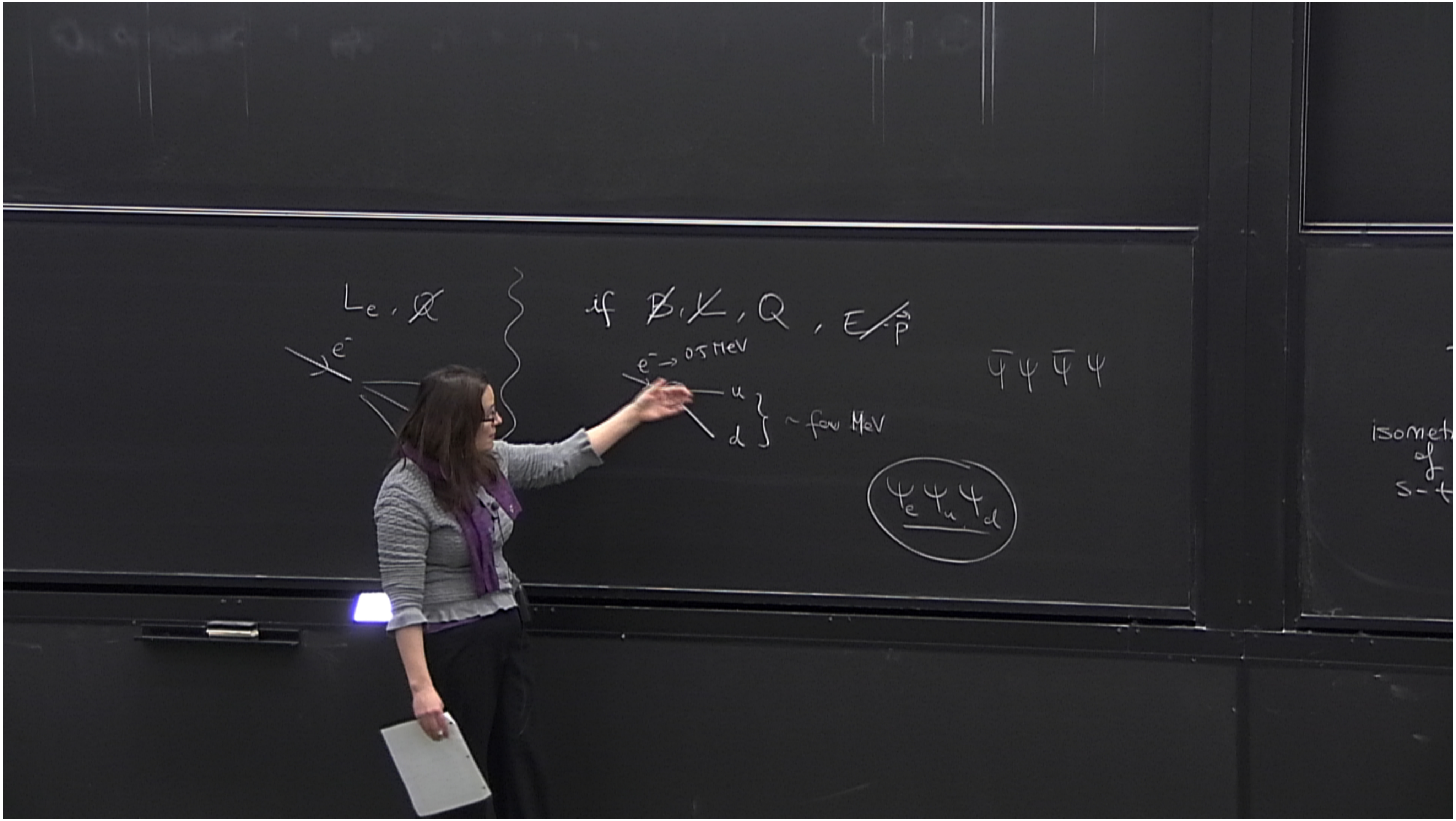
isometries of s-t $\quad SO(3,1) \approx SU(2)_L \otimes SU(2)_R$

isomorphic

$\psi_L \, (2,1)$

$\psi_R \, (1,2)$

$$\Psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$


L_e, $\cancel{Q}$
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$e^- \to$ 0.5 MeV
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$\bar{\psi}\psi\bar{\psi}\psi$
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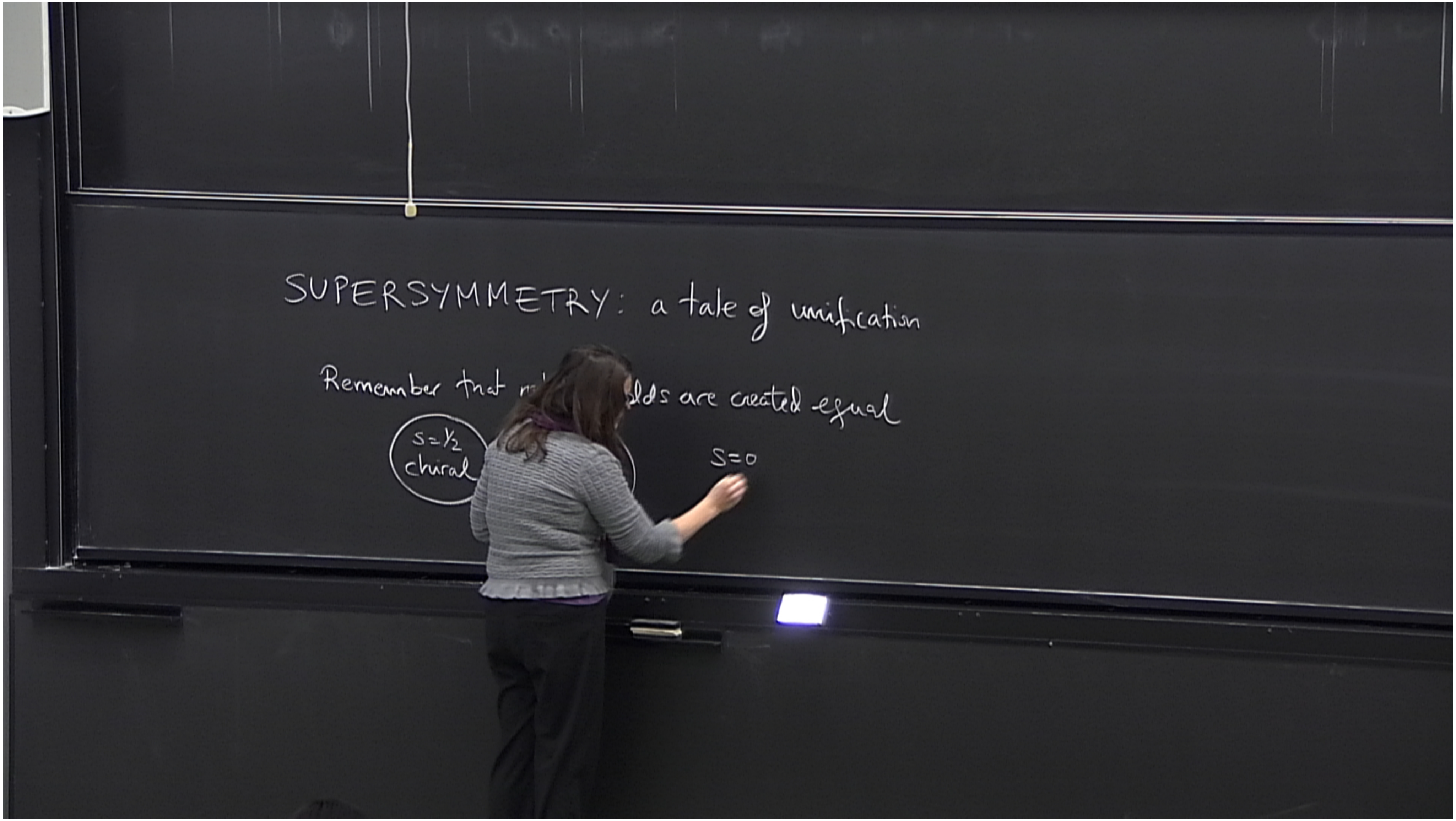

SUPERSYMMETRY: a tale of unification
Remember that
are created equal
s=½
chiral
s=0

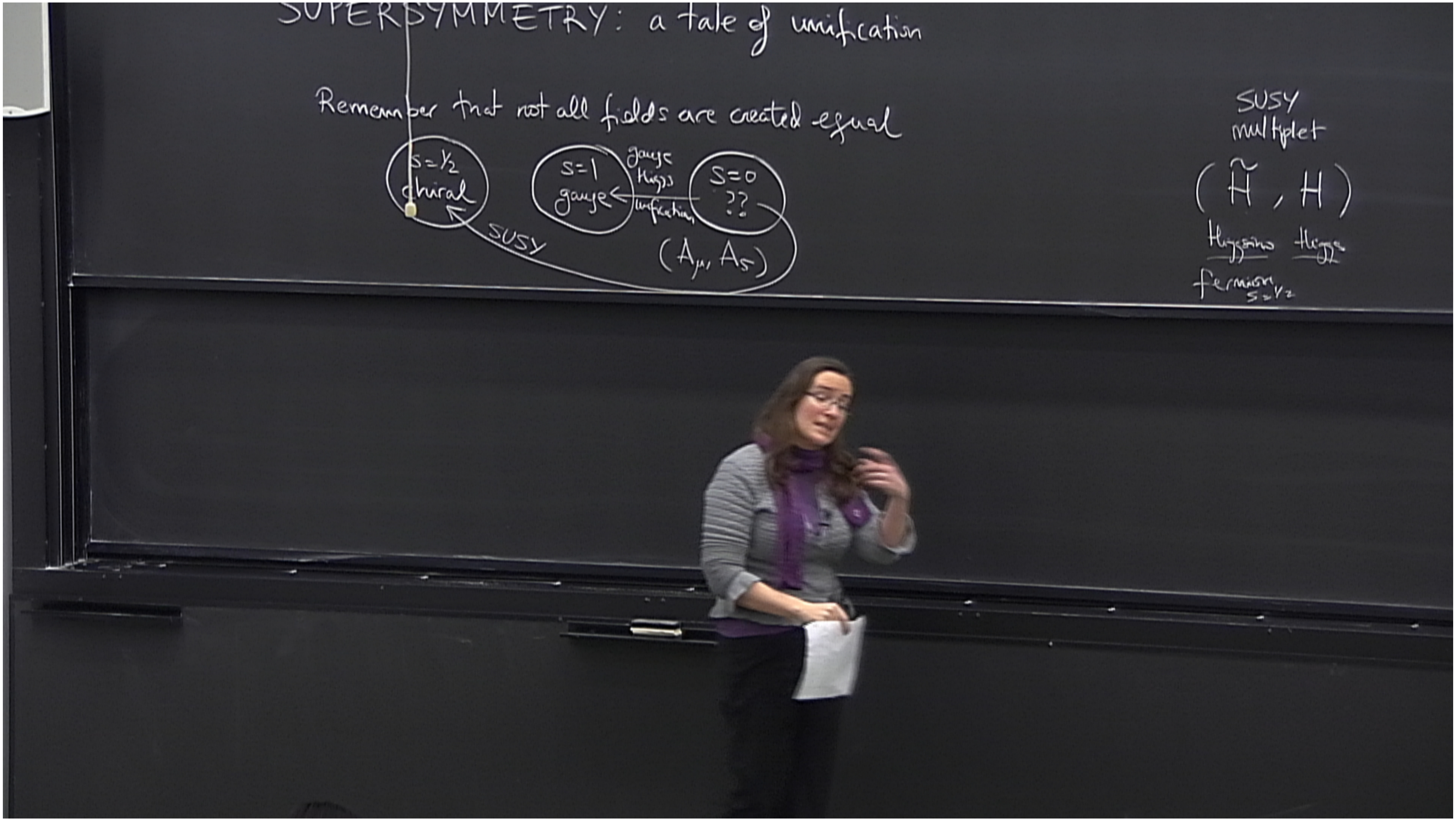
SUPERSYMMETRY: a tale of unification

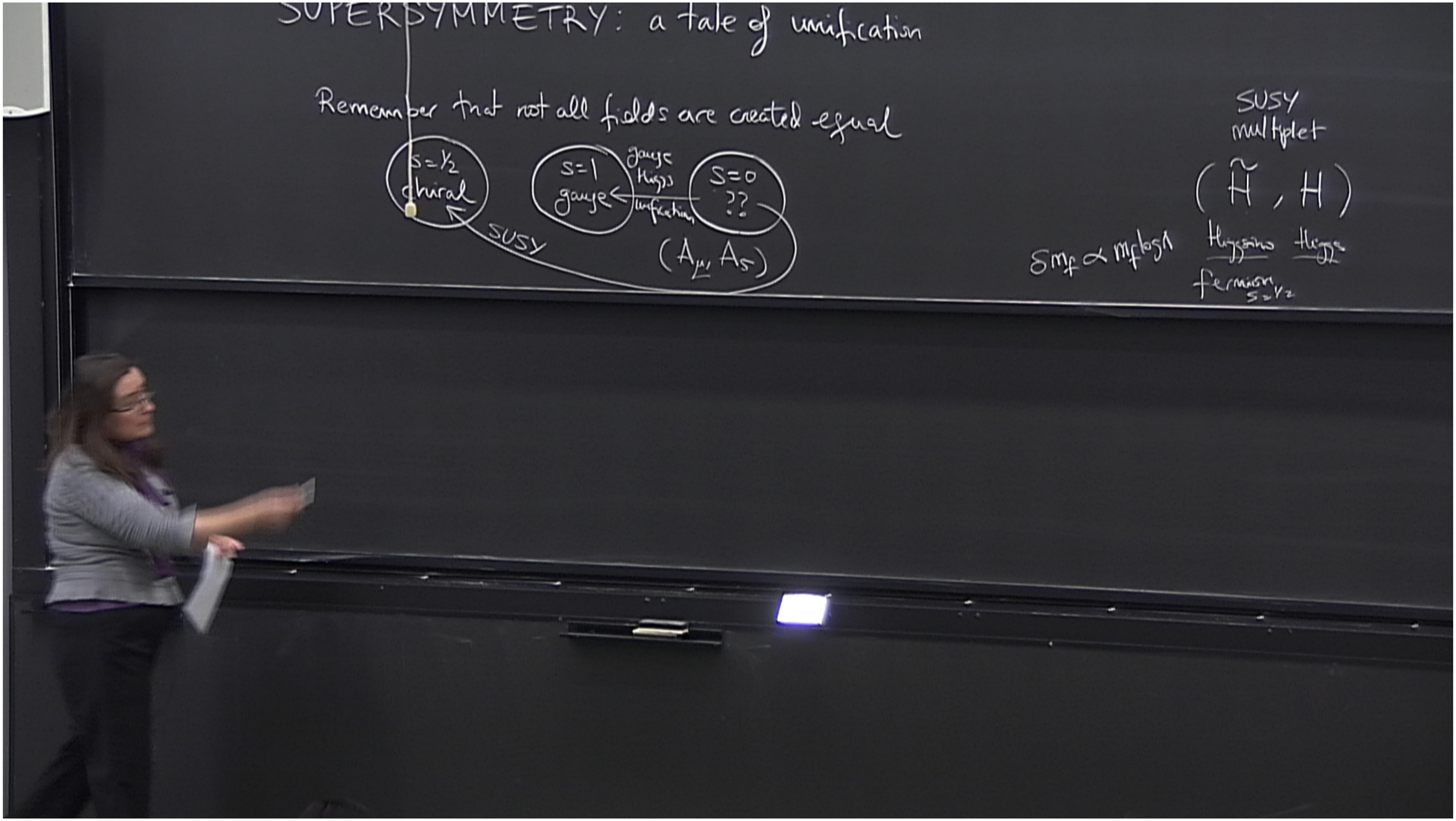
Remember that not all fields are created equal

$s = 1/2$ chiral

$s = 1$ gauge

$s = 0$??


SUPERSYMMETRY: a tale of unification
Remember that not all fields are created equal
s = 1/2
chiral
s = 1
gauge
gauge Higgs unification
S = 0
??
SUSY
(A_μ, A_5)
SUSY multiplet
(H̃ , H)
Higgsino Higgs
fermion s = 1/2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Higgs
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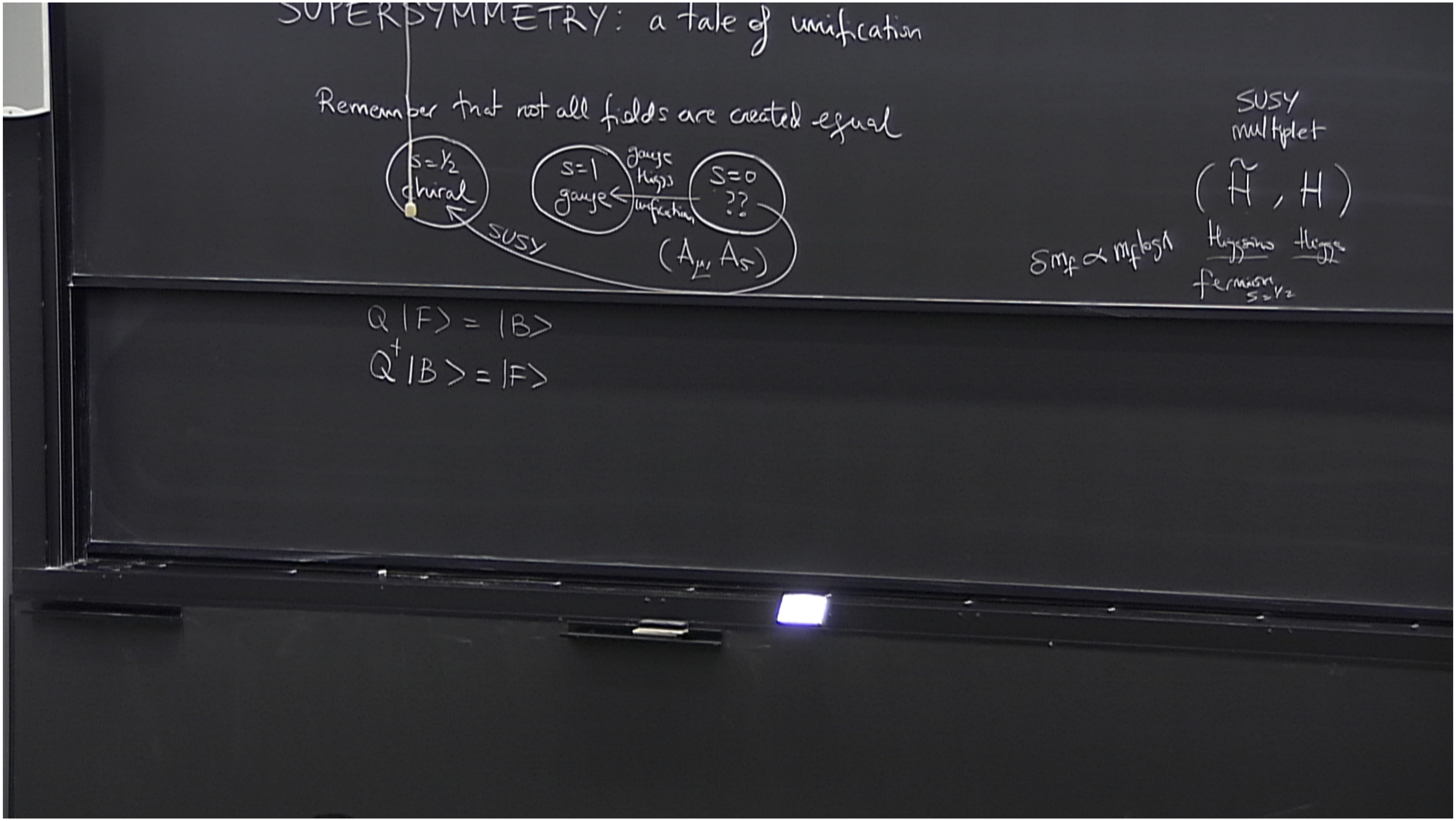
s=1/2
δm_f ∝ m_f log Λ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Q |F> = |B>
Q† |B> = |F>

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gauge Higgs unification

SUSY

(A_μ, A_5)

SUSY multiplet

$(\tilde{H}, H)$

Higgsino Higgs

fermion $s=1/2$

$\delta m_f \propto m_f \log \Lambda$

$Q^\alpha |F_\alpha\rangle = |B\rangle$

$Q^\dagger_\alpha |B\rangle = |F_\alpha\rangle$

SUSY transf are fermionic

fermions transform under Poincaré group $\supset$ Lorentz transf

isometries of s-t

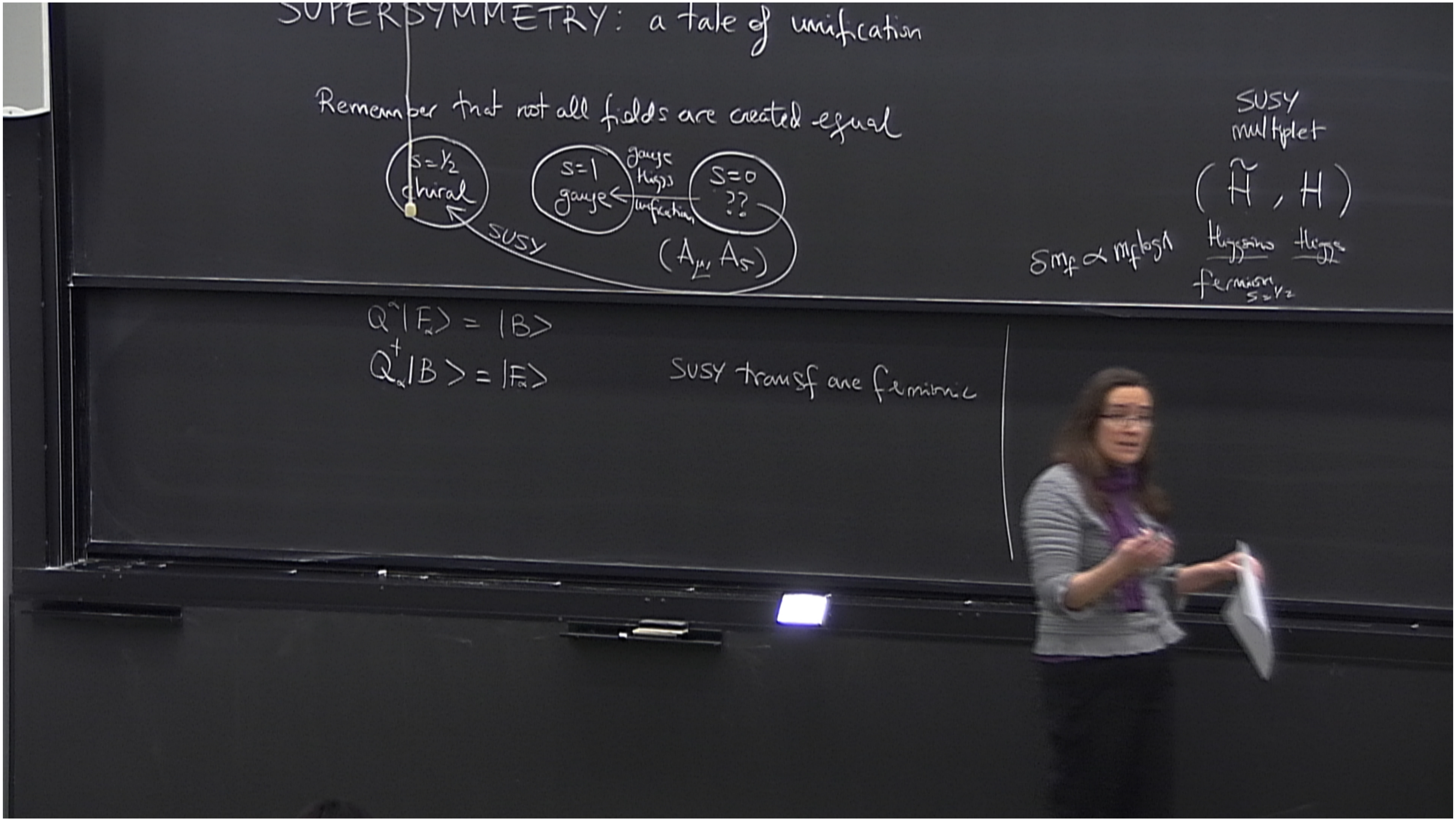
$$SO(3,1) \approx SU(2)_L \otimes SU(2)_R$$

isomorphic

$$\psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

$\psi_L \, (2,1)$

$\psi_R \, (1,2)$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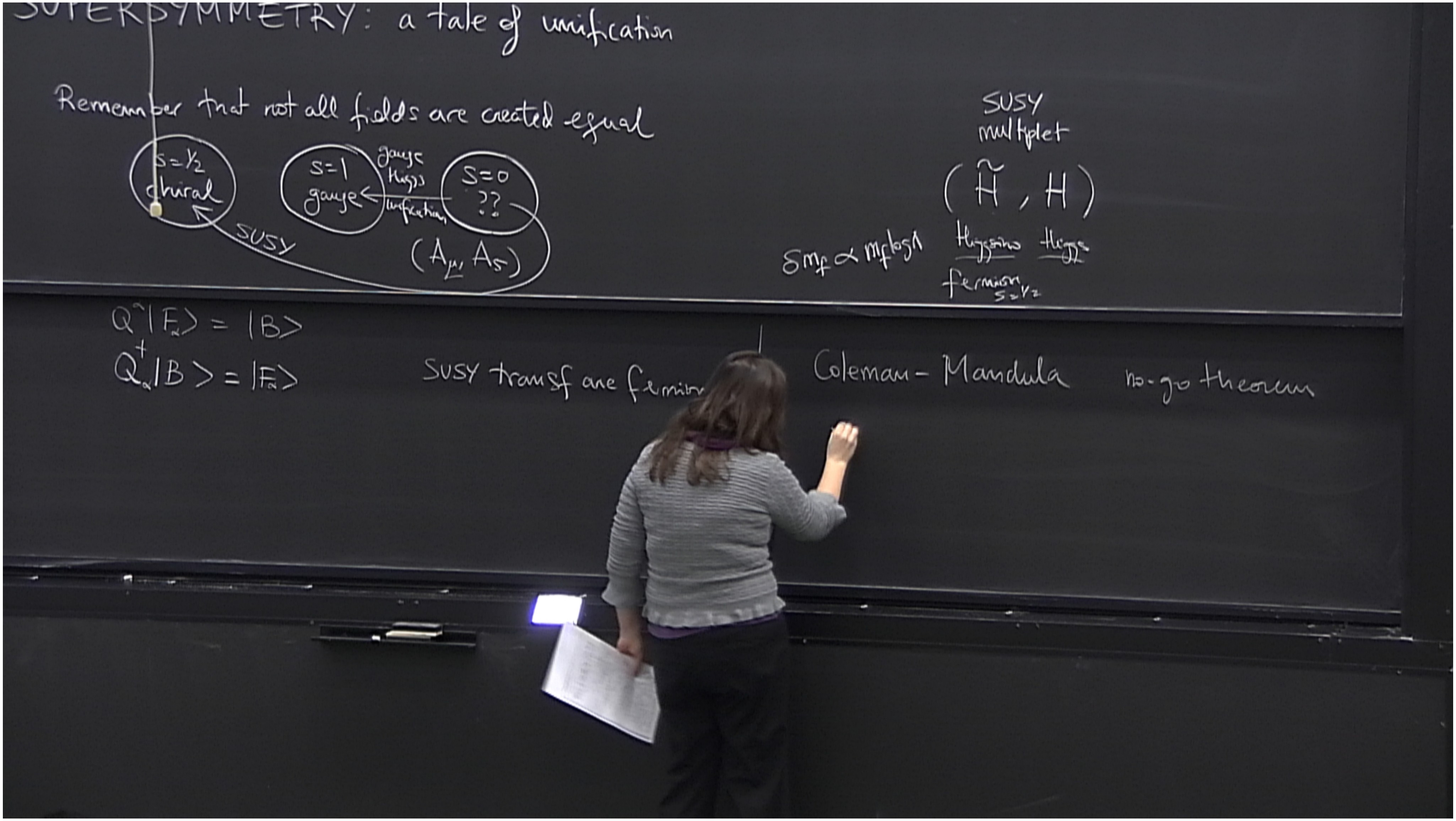
Q^α|F_α> = |B>
Q†_α|B> = |F_α>
SUSY transf are fermionic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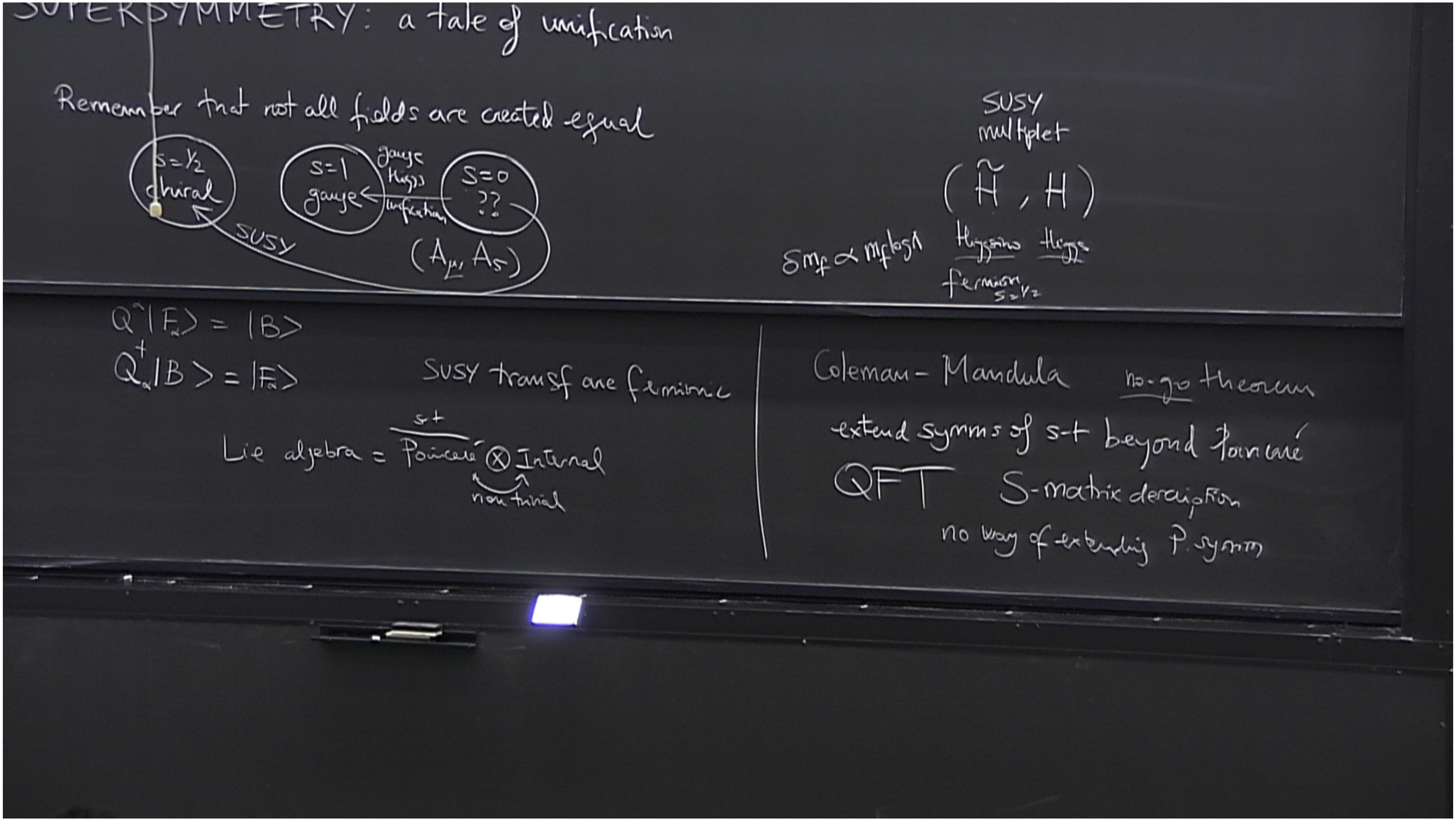
SUSY transf are fermion
Coleman - Mandula
no-go theorem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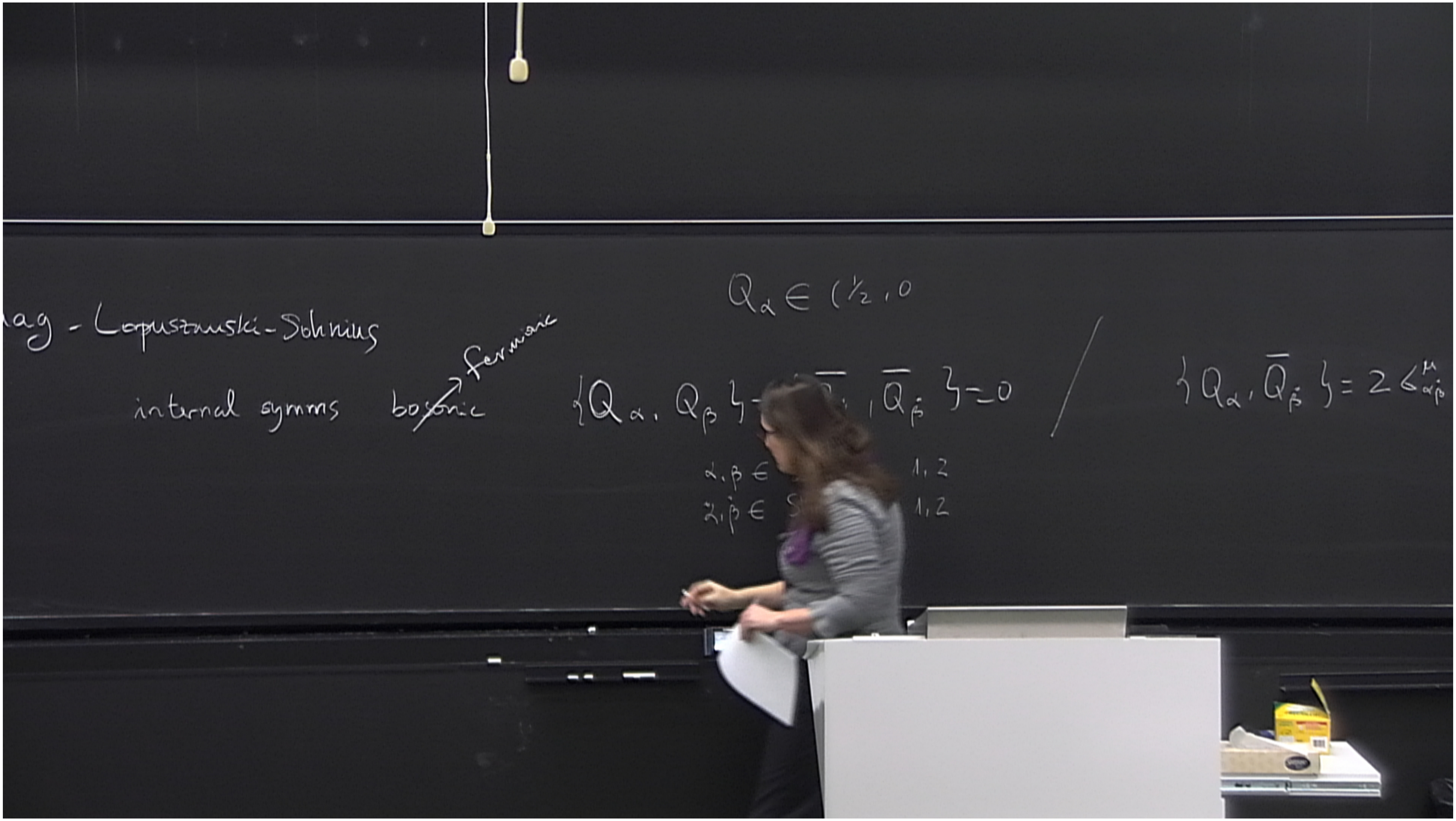
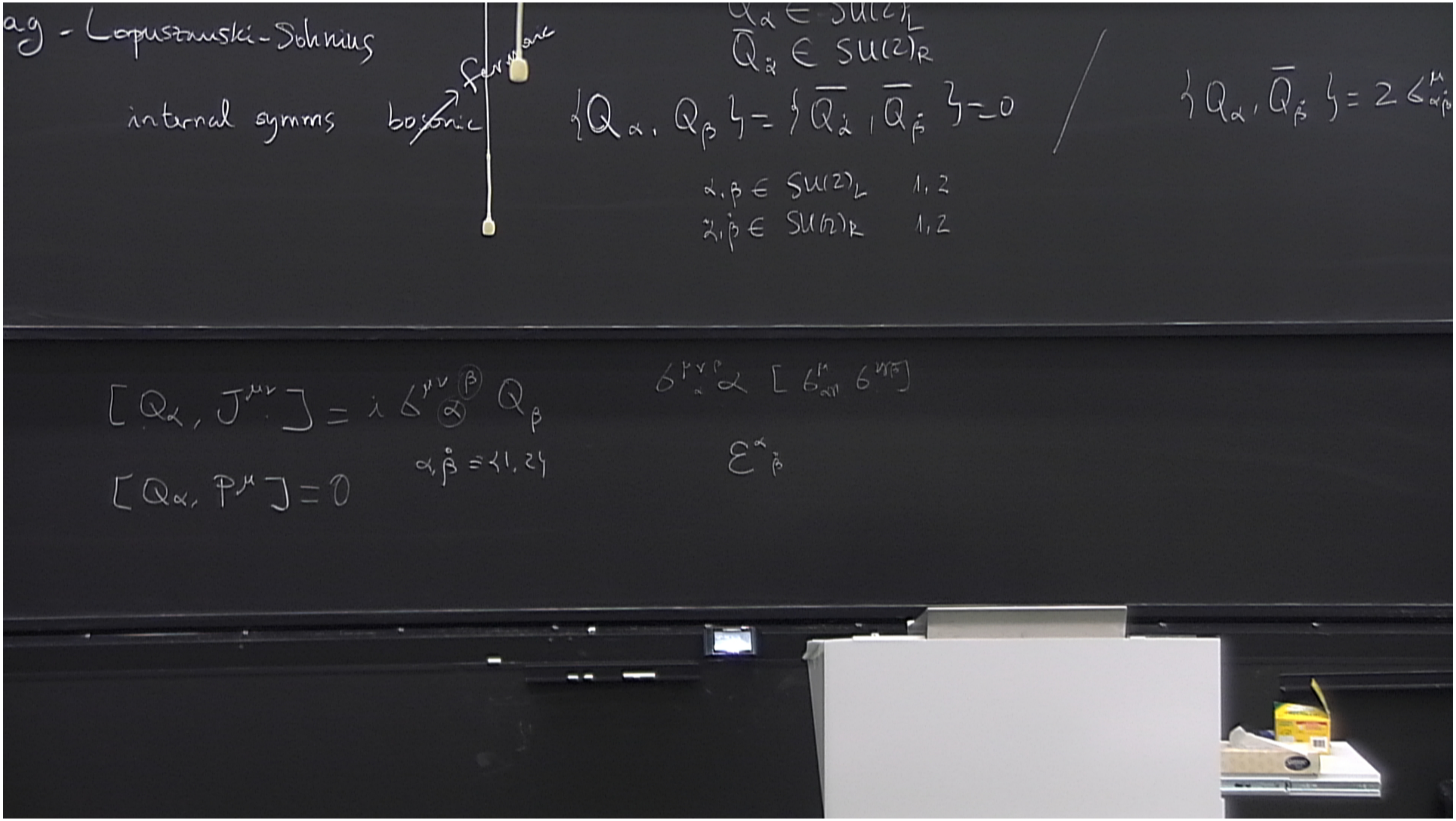
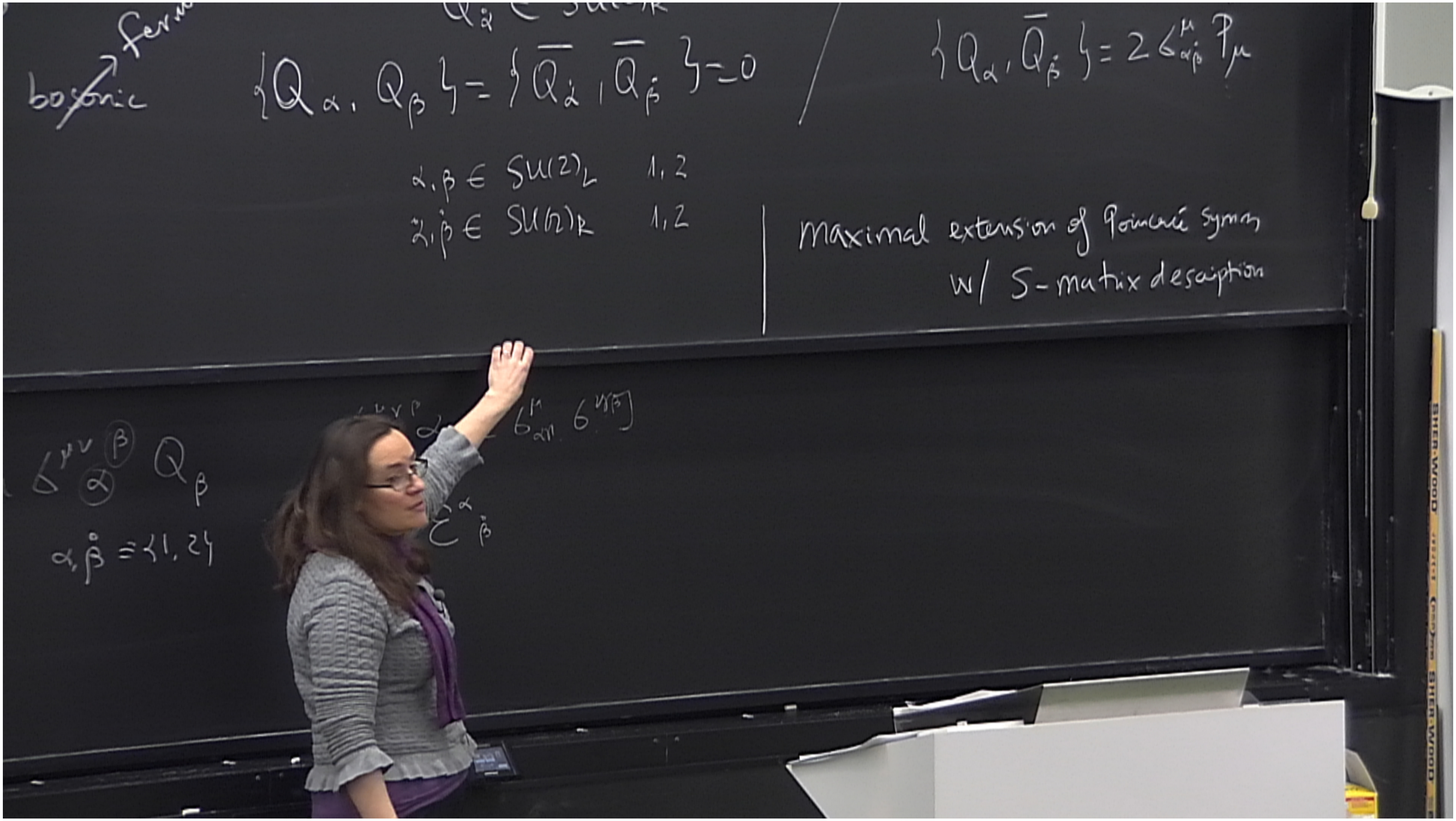
δm_f ∝ m_f log Λ
Q^α|F_α> = |B>
Q^†_α|B> = |F_α>
SUSY transf are fermionic
Lie algebra = Poincaré ⊗ Internal
s-t
non trivial
Coleman-Mandula no-go theorem
extend symms of s-t beyond Poincaré
QFT S-matrix description
no way of extending P. symm


ag - Lopuszanski - Sohnius
internal symms
bosonic
fermionic
$Q_\alpha \in (1/2, 0$
$\{Q_\alpha, Q_\beta\} =$
$, \bar{Q}_{\dot\beta}\} = 0$
$\{Q_\alpha, \bar{Q}_{\dot\beta}\} = 2\sigma^\mu_{\alpha\dot\beta}$
$\alpha, \beta \in$
$1, 2$
$\dot\alpha, \dot\beta \in$
$1, 2$


ag - Lopuszanski - Sohnius
internal symms bosonic fermionic
$Q_\alpha \in SU(2)_L$
$\bar{Q}_{\dot\alpha} \in SU(2)_R$
$\{Q_\alpha, Q_\beta\} = \{\bar{Q}_{\dot\alpha}, \bar{Q}_{\dot\beta}\} = 0$
$\{Q_\alpha, \bar{Q}_{\dot\beta}\} = 2\sigma^\mu_{\alpha\dot\beta}$
$\alpha, \beta \in SU(2)_L$ 1, 2
$\dot\alpha, \dot\beta \in SU(2)_R$ 1, 2
$[Q_\alpha, J^{\mu\nu}] = i\,\sigma^{\mu\nu}{}_\alpha{}^\beta\, Q_\beta$
$\alpha, \dot\beta = \{1, 2\}$
$[Q_\alpha, P^\mu] = 0$
$\sigma^{\mu\nu}{}_\alpha{}^\beta \propto [\sigma^\mu_{\alpha\dot\alpha}\, \sigma^{\nu\dot\alpha\beta}]$
$\varepsilon^\alpha{}_{\dot\beta}$


bosonic
$\{Q_\alpha, Q_\beta\} = \{\bar{Q}_{\dot\alpha}, \bar{Q}_{\dot\beta}\} = 0$
$\{Q_\alpha, \bar{Q}_{\dot\beta}\} = 2\sigma^\mu_{\alpha\dot\beta} P_\mu$
$\alpha, \beta \in SU(2)_L$ 1, 2
$\dot\alpha, \dot\beta \in SU(2)_R$ 1, 2
maximal extension of Poincaré symm
w/ S-matrix description
$\alpha, \dot\beta = \{1, 2\}$

fermionic
~~bosonic~~

$\{Q_\alpha, Q_\beta\} = \{\bar{Q}_{\dot\alpha}, \bar{Q}_{\dot\beta}\} = 0$

$\{Q_\alpha, \bar{Q}_{\dot\beta}\} = 2\sigma^\mu_{\alpha\dot\beta} P_\mu$

$\alpha, \beta \in SU(2)_L \quad 1, 2$

$\dot\alpha, \dot\beta \in SU(2)_R \quad 1, 2$

Q^i_α

maximal extension of Poincaré symm
w/ S-matrix description

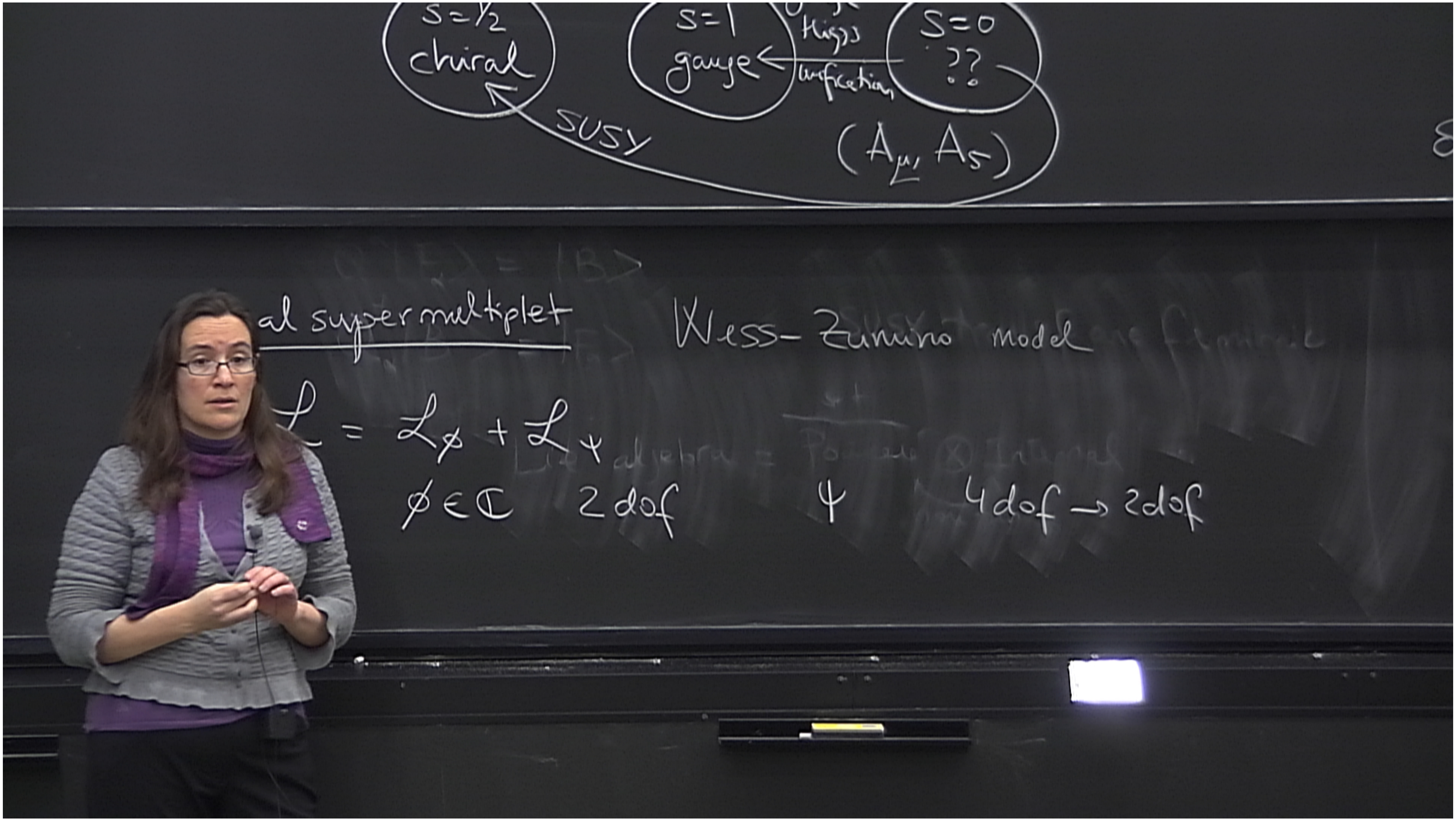
$\sigma^{\mu\nu}{}_\alpha{}^\beta \, Q_\beta$

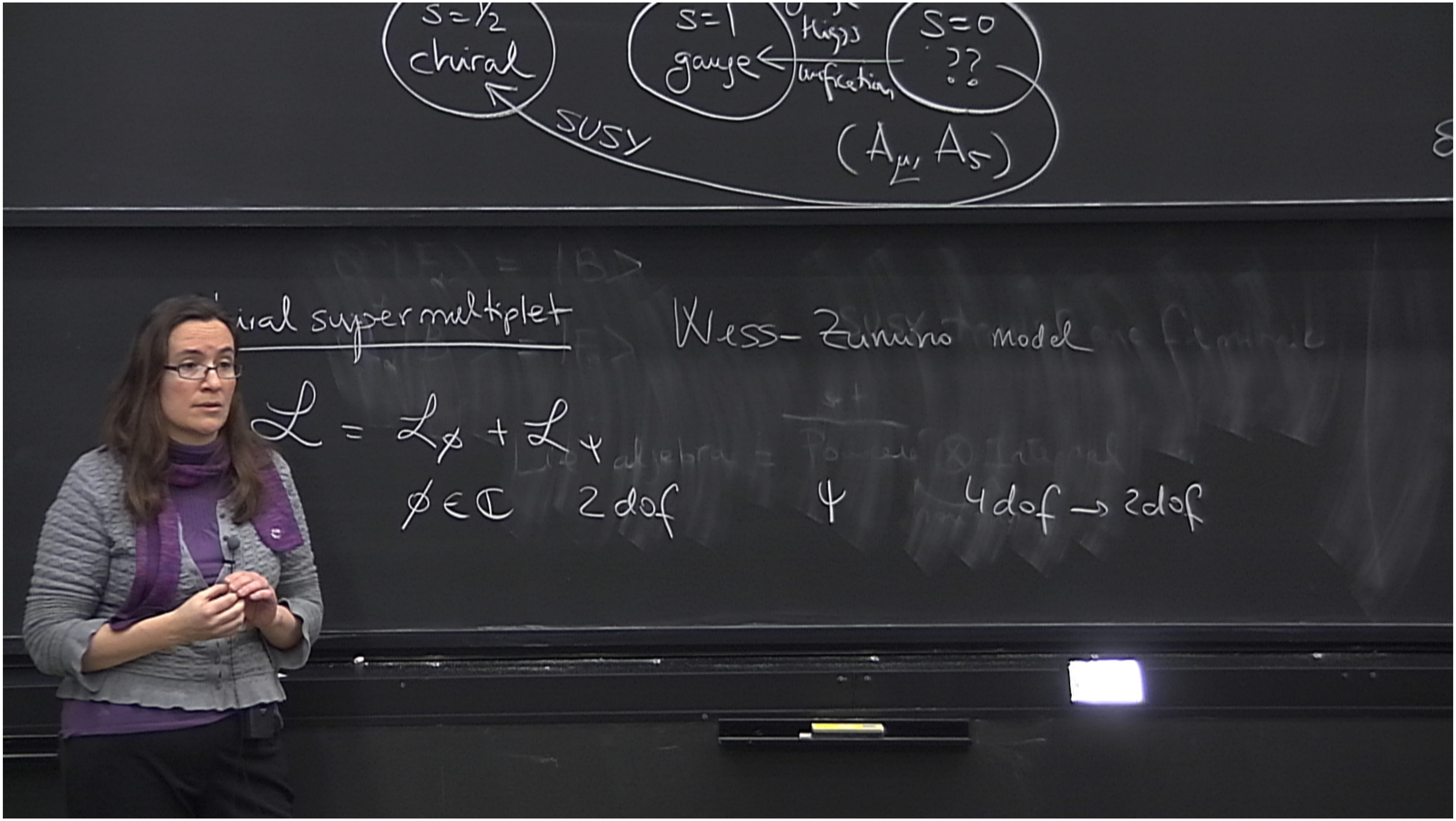
$\alpha, \dot\beta = \{1, 2\}$

$\sigma^{\mu\nu\rho}{}_\alpha \propto [\sigma^\mu_{\alpha\dot\gamma}, \sigma^{\nu\dot\gamma\beta}]$

$\varepsilon^\alpha{}_{\dot\beta}$

SUSY $\mathcal{N} = 1, 2, 4, 8$


s=½
chiral
s=1
gauge
Higgs
unification
s=0
??
SUSY
(A_μ, A_5)
al supermultiplet
Wess-Zumino model
L = L_φ + L_ψ
φ ∈ ℂ 2 dof
ψ 4dof → 2dof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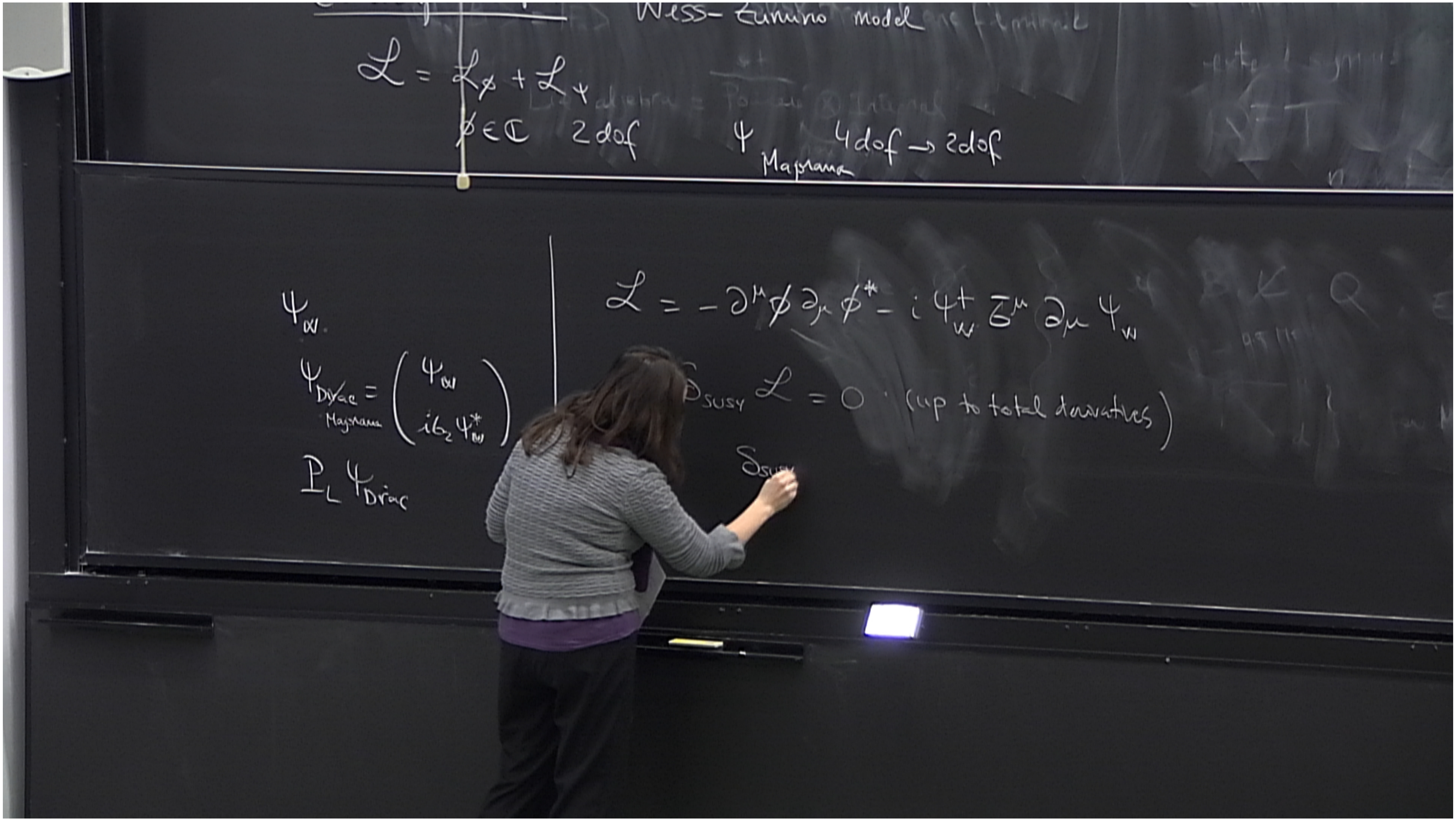
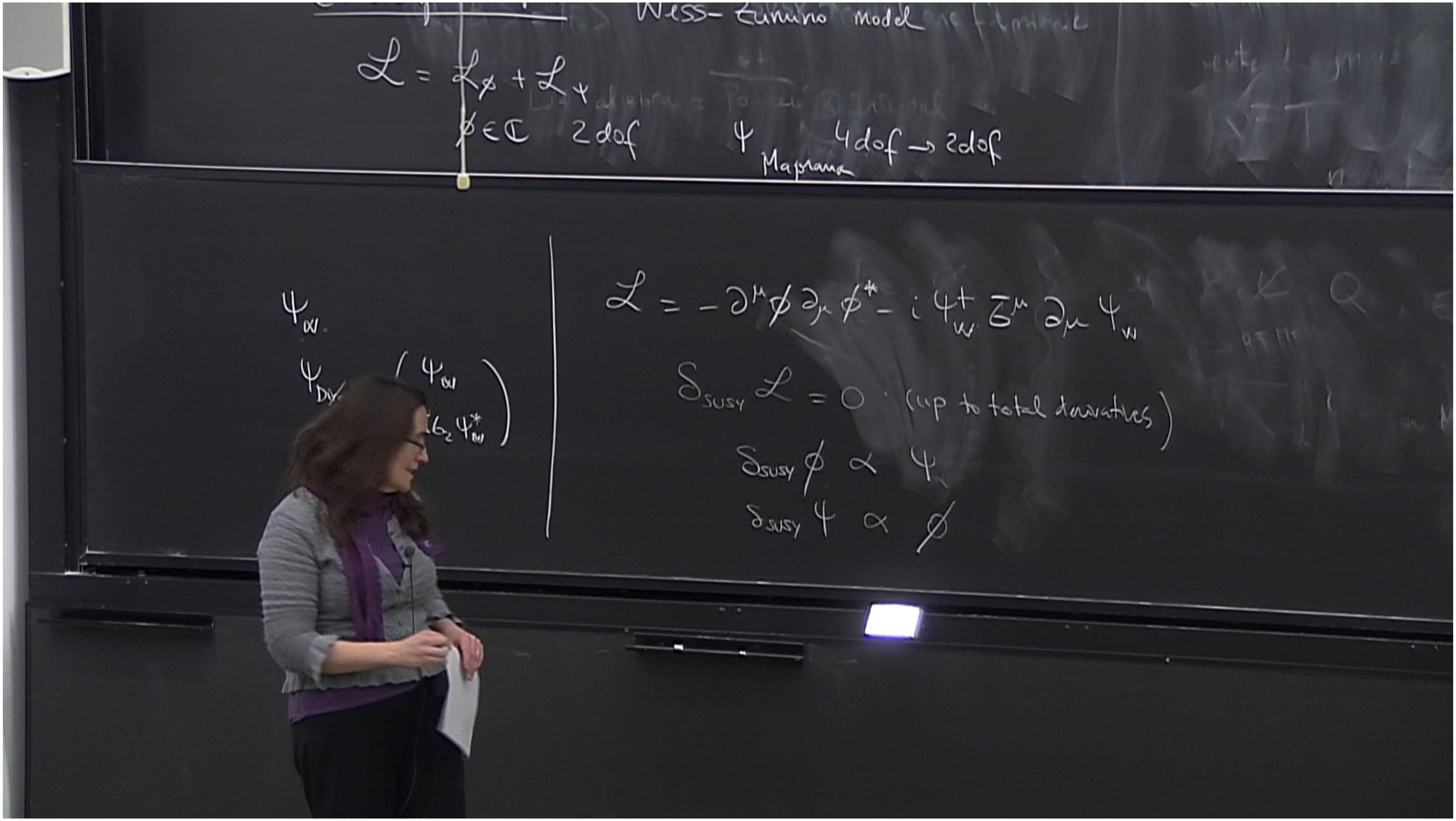

Wess-Zumino model
$\mathcal{L} = \mathcal{L}_\phi + \mathcal{L}_\psi$
$\phi \in \mathbb{C}$ 2 dof
ψ_{Majorana} 4 dof → 2 dof
ψ_α
$\psi_{\text{Dirac/Majorana}} = \begin{pmatrix} \psi_\alpha \\ i\sigma_2 \psi^*_\alpha \end{pmatrix}$
$P_L \psi_{\text{Dirac}}$
$\mathcal{L} = -\partial^\mu \phi \, \partial_\mu \phi^* - i \psi^\dagger_\alpha \bar{\sigma}^\mu \partial_\mu \psi_\alpha$
$\delta_{SUSY} \mathcal{L} = 0$ (up to total derivatives)
δ_{SUSY}


Wess- Zumino model
$\mathcal{L} = \mathcal{L}_\phi + \mathcal{L}_\psi$
$\phi \in \mathbb{C}$ 2 dof
ψ 4 dof $\to$ 2 dof
Majorana
ψ_α
$\mathcal{L} = -\partial^\mu \phi \, \partial_\mu \phi^* - i \psi^\dagger_\alpha \bar{\sigma}^\mu \partial_\mu \psi_\alpha$
$\delta_{susy} \mathcal{L} = 0$ (up to total derivatives)
$\delta_{susy} \phi \propto \psi$
$\delta_{susy} \psi \propto \phi$

Wess-Zumino model

$$\mathcal{L} = \mathcal{L}_\phi + \mathcal{L}_\psi$$

$\phi \in \mathbb{C}$ 2 dof $\quad \psi_{\text{Majorana}}$ 4 dof $\to$ 2 dof

ψ_w

$$\psi_{\text{Dirac/Majorana}} = \begin{pmatrix} \psi_w \\ i\sigma_2 \psi_w^* \end{pmatrix}$$

$P_L \psi_{\text{Dirac}}$

$$\mathcal{L} = -\partial^\mu \phi \, \partial_\mu \phi^* - i \psi_w^\dagger \bar{\sigma}^\mu \partial_\mu \psi_w$$

$\delta_{SUSY} \mathcal{L} = 0$ (up to total derivatives)

$$\delta_{susy} \underset{1}{\phi} = \varepsilon^\alpha \underset{3/2}{\psi_\alpha} \qquad \varepsilon^\alpha \text{ spinor SUSY transf.}$$

$$\delta_{susy} \psi \propto \phi$$

$\dot{\alpha}, \dot{\beta} \in SU(2)_R$ 1, 2

Q^i_α

$$\delta\phi = \varepsilon\psi \,, \quad \delta\phi^* = \varepsilon^+ \psi^+$$

$$\delta \mathcal{L}_\phi = - \varepsilon\, \partial_\mu \phi^* \partial^\mu \psi + h.c$$

we want $\delta\mathcal{L}_\psi = -\delta\mathcal{L}_\phi$ up to total derivatives

$\alpha, \dot{\beta} \in SU(2)_R$ $\quad 1,2$

Q^i_α

$$\delta\phi = \varepsilon\psi \,, \quad \delta\phi^* = \varepsilon^+_\alpha \psi^+_\alpha = \psi^+ \varepsilon^+ \qquad (\varepsilon^+_1 \; \varepsilon^+_2)\begin{pmatrix}\psi^+_1 \\ \psi^+_2\end{pmatrix}$$

$$\delta \mathcal{L}_\phi = - \varepsilon \, \underbrace{\partial_\mu \phi^*}\, \partial^\mu \psi + h.c$$

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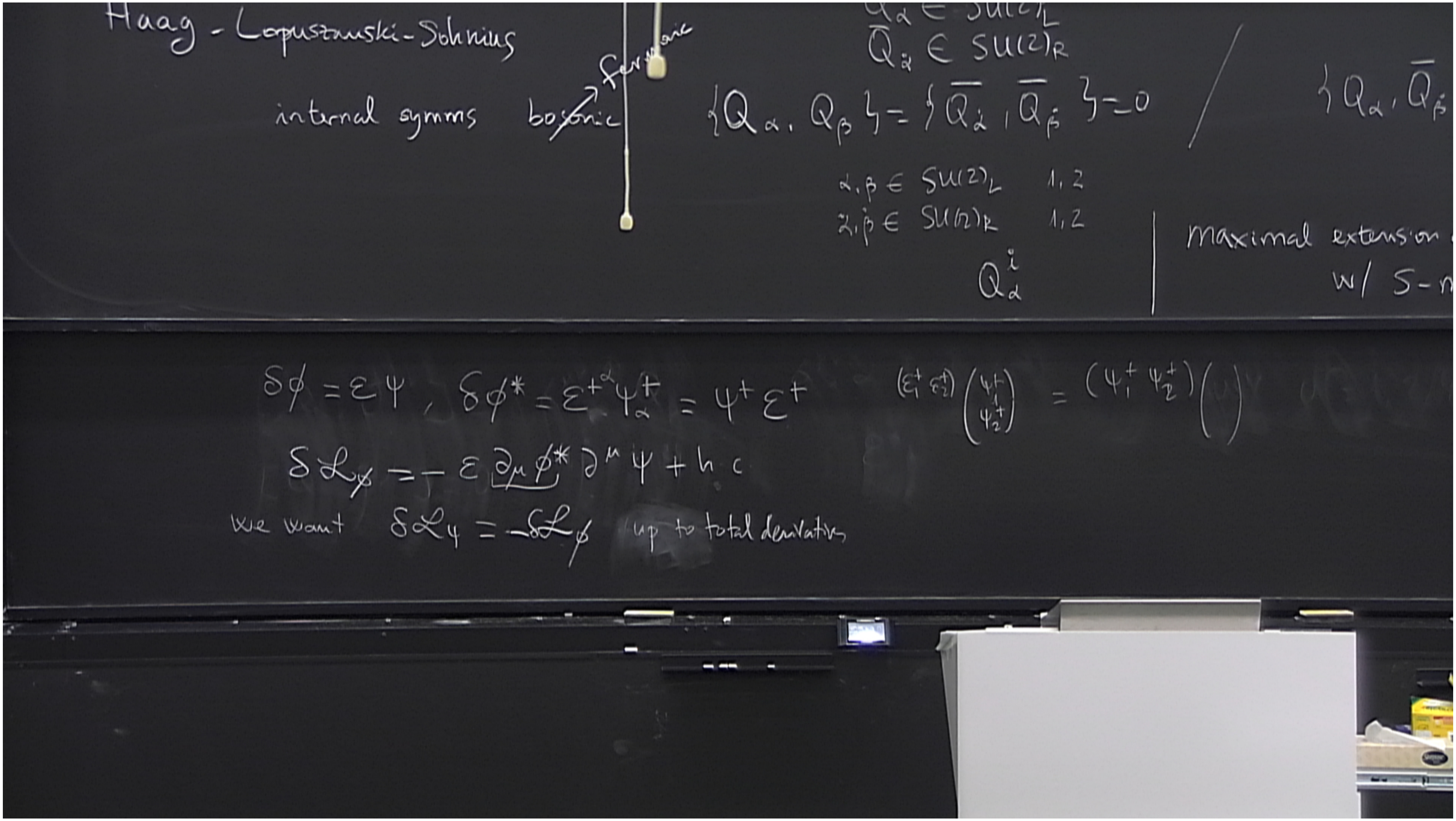
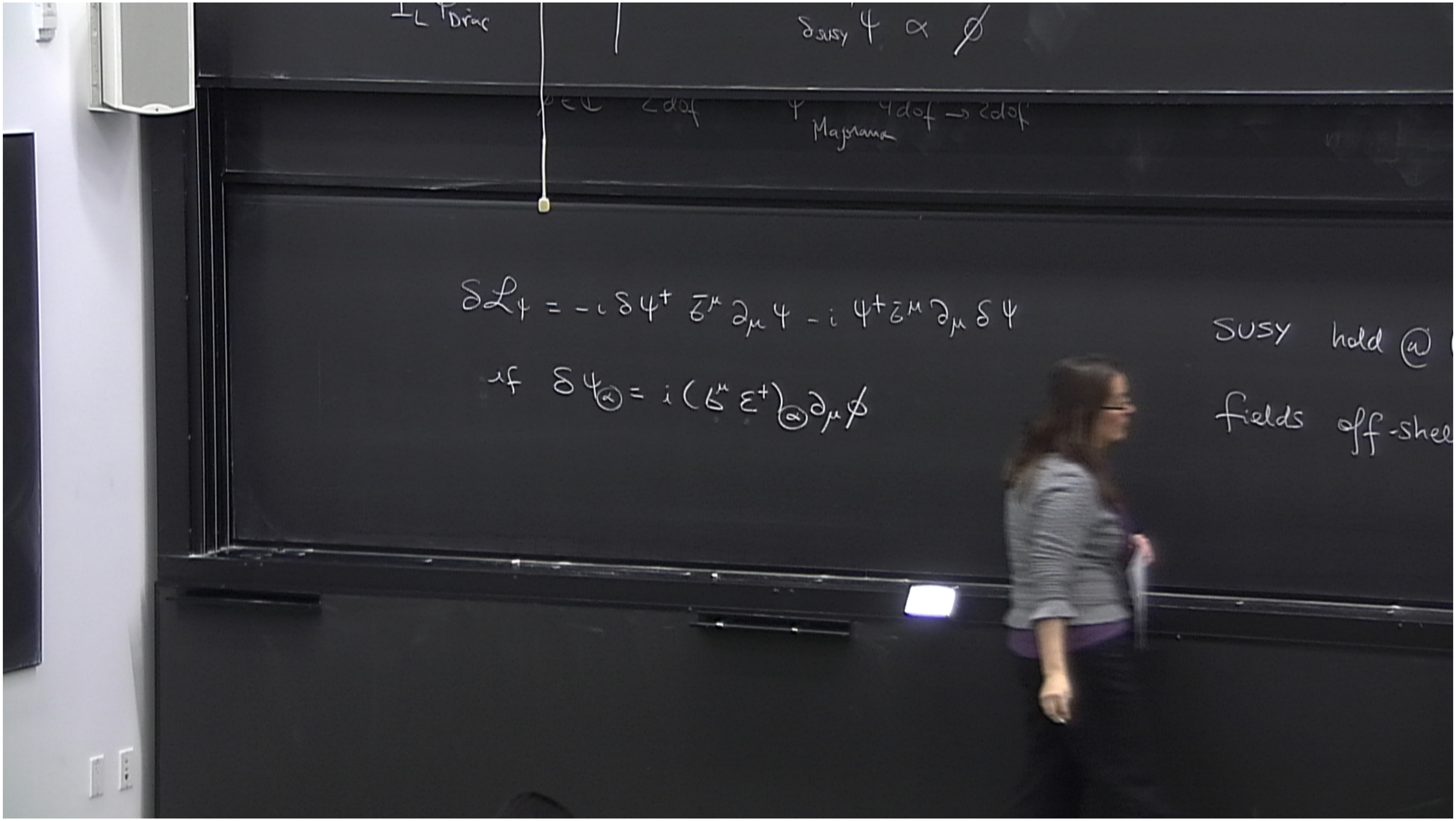

Haag - Lopuszanski - Sohnius
internal symms bosonic fermionic
$\bar{Q}_{\dot\alpha} \in SU(2)_R$
$\{Q_\alpha, Q_\beta\} = \{\bar{Q}_{\dot\alpha}, \bar{Q}_{\dot\beta}\} = 0$
$\alpha, \beta \in SU(2)_L$ 1, 2
$\dot\alpha, \dot\beta \in SU(2)_R$ 1, 2
Q^i_α
maximal extension
$\delta\phi = \varepsilon\psi$, $\delta\phi^* = \varepsilon^{\dagger\alpha}\psi^\dagger_\alpha = \psi^\dagger\varepsilon^\dagger$
$(\varepsilon_1^\dagger\ \varepsilon_2^\dagger)\begin{pmatrix}\psi_1^\dagger\\ \psi_2^\dagger\end{pmatrix} = (\psi_1^\dagger\ \psi_2^\dagger)$
$\delta\mathcal{L}_\phi = -\varepsilon\,\partial_\mu\phi^*\,\partial^\mu\psi + h.c$
We want $\delta\mathcal{L}_\psi = -\delta\mathcal{L}_\phi$ up to total derivatives


$\delta_{susy} \psi \propto \phi$
ψ Majorana 4 dof → 2 dof
$\delta \mathcal{L}_\psi = -i \delta\psi^\dagger \bar{\sigma}^\mu \partial_\mu \psi - i \psi^\dagger \bar{\sigma}^\mu \partial_\mu \delta\psi$
if $\delta\psi_\alpha = i(\sigma^\mu \epsilon^\dagger)_\alpha \partial_\mu \phi$
SUSY hold @
fields off-shel

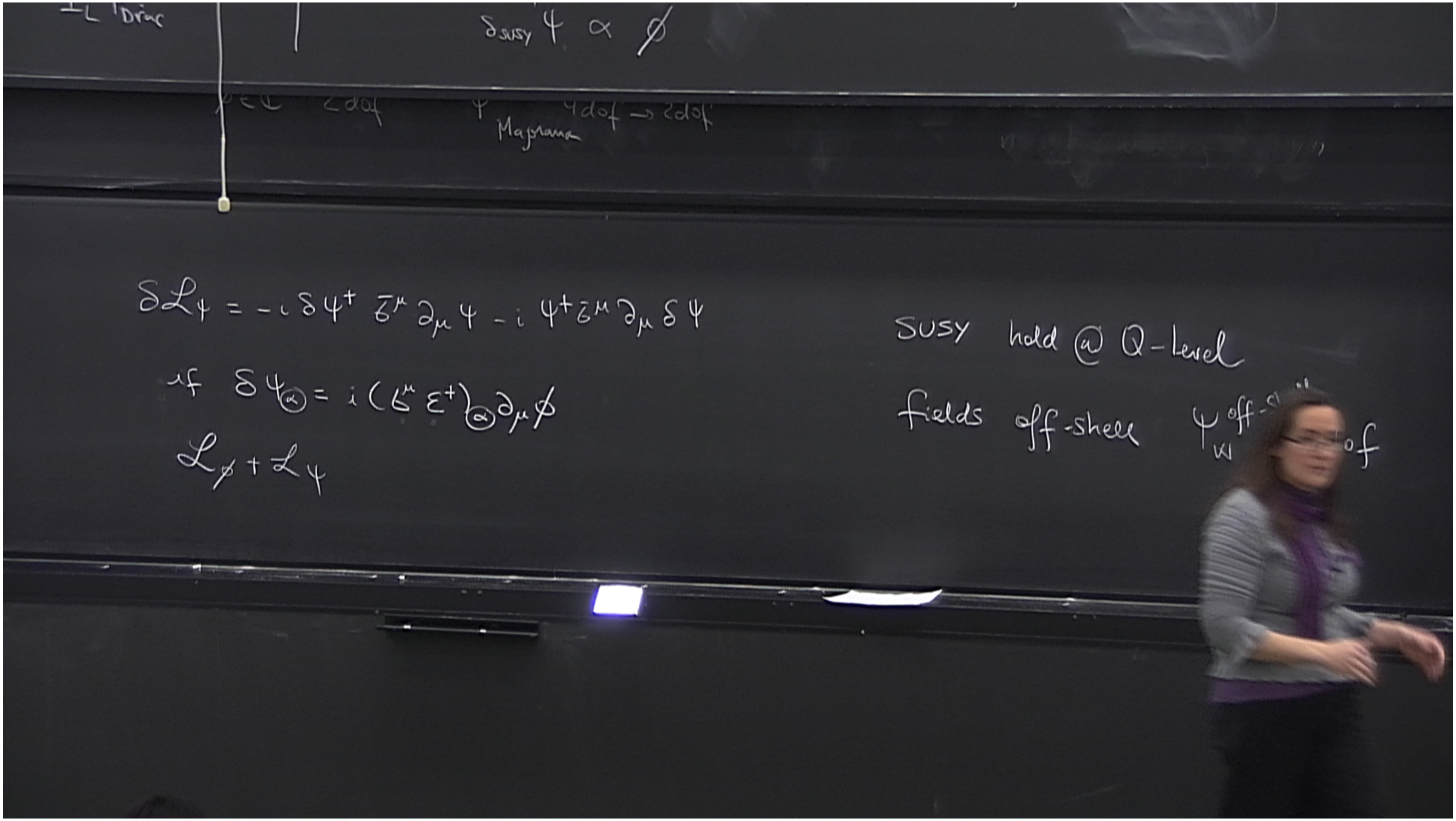
$$\delta_{susy}\,\psi \;\propto\; \cancel{\phi}$$

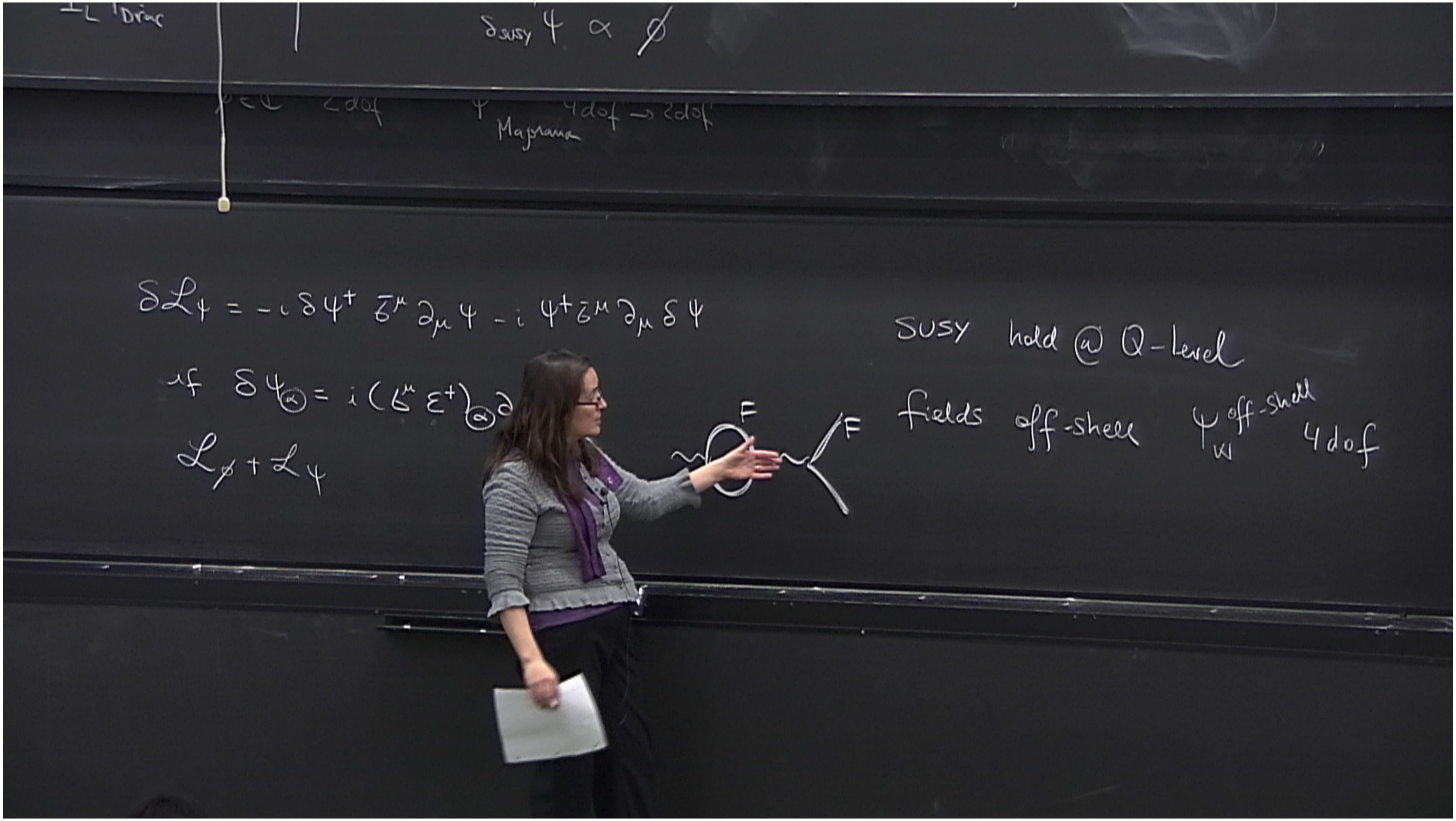
$$\delta \mathcal{L}_\psi = -i\,\delta\psi^\dagger \bar{\sigma}^\mu \partial_\mu \psi - i\,\psi^\dagger \bar{\sigma}^\mu \partial_\mu \delta\psi$$

if $\delta \psi_{\alpha} = i(\sigma^\mu \varepsilon^\dagger)_{\alpha} \partial_\mu \phi$

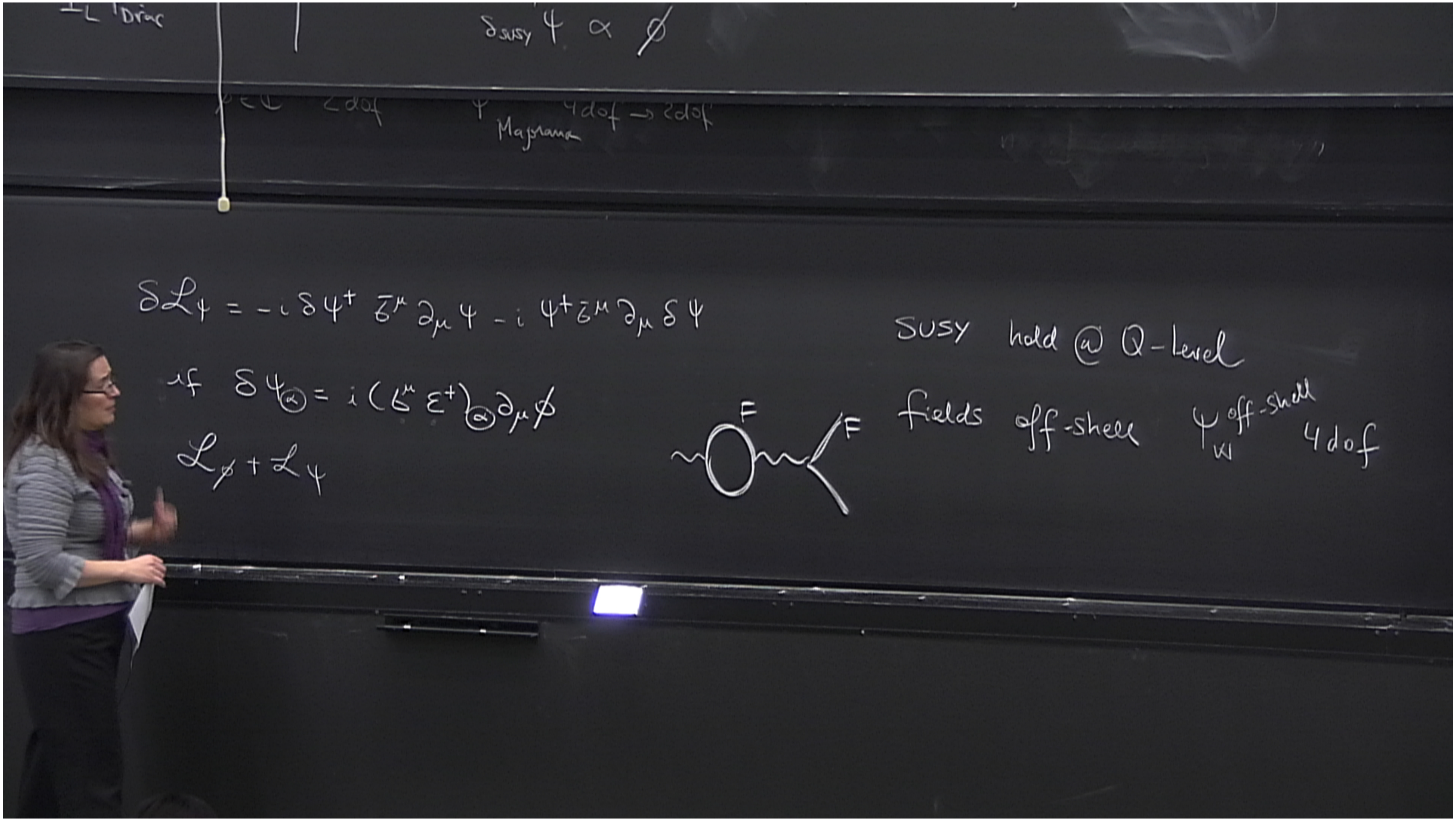
SUSY hold @ Q-level

fields off-shell


$\delta_{susy}\psi \propto \phi$
$\psi_{Majorana}$ 4 dof → 2 dof
$\delta\mathcal{L}_\psi = -i\,\delta\psi^\dagger\bar{\sigma}^\mu\partial_\mu\psi - i\,\psi^\dagger\bar{\sigma}^\mu\partial_\mu\delta\psi$
if $\delta\psi_\alpha = i(\sigma^\mu\varepsilon^\dagger)_\alpha\partial_\mu\phi$
$\mathcal{L}_\phi + \mathcal{L}_\psi$
SUSY hold @ Q-level
fields off-shell



δsusy ψ ∝ ϕ
Majorana
4dof → 2dof
δℒψ = −i δψ† σ̄μ ∂μ ψ − i ψ† σ̄μ ∂μ δψ
if δψα = i (σμ ε†)α ∂
ℒϕ + ℒψ
F
F
SUSY hold @ Q-level
fields off-shell ψ off-shell 4dof



$\delta_{susy} \psi \propto \phi$
ψ Majorana 4 dof → 2 dof
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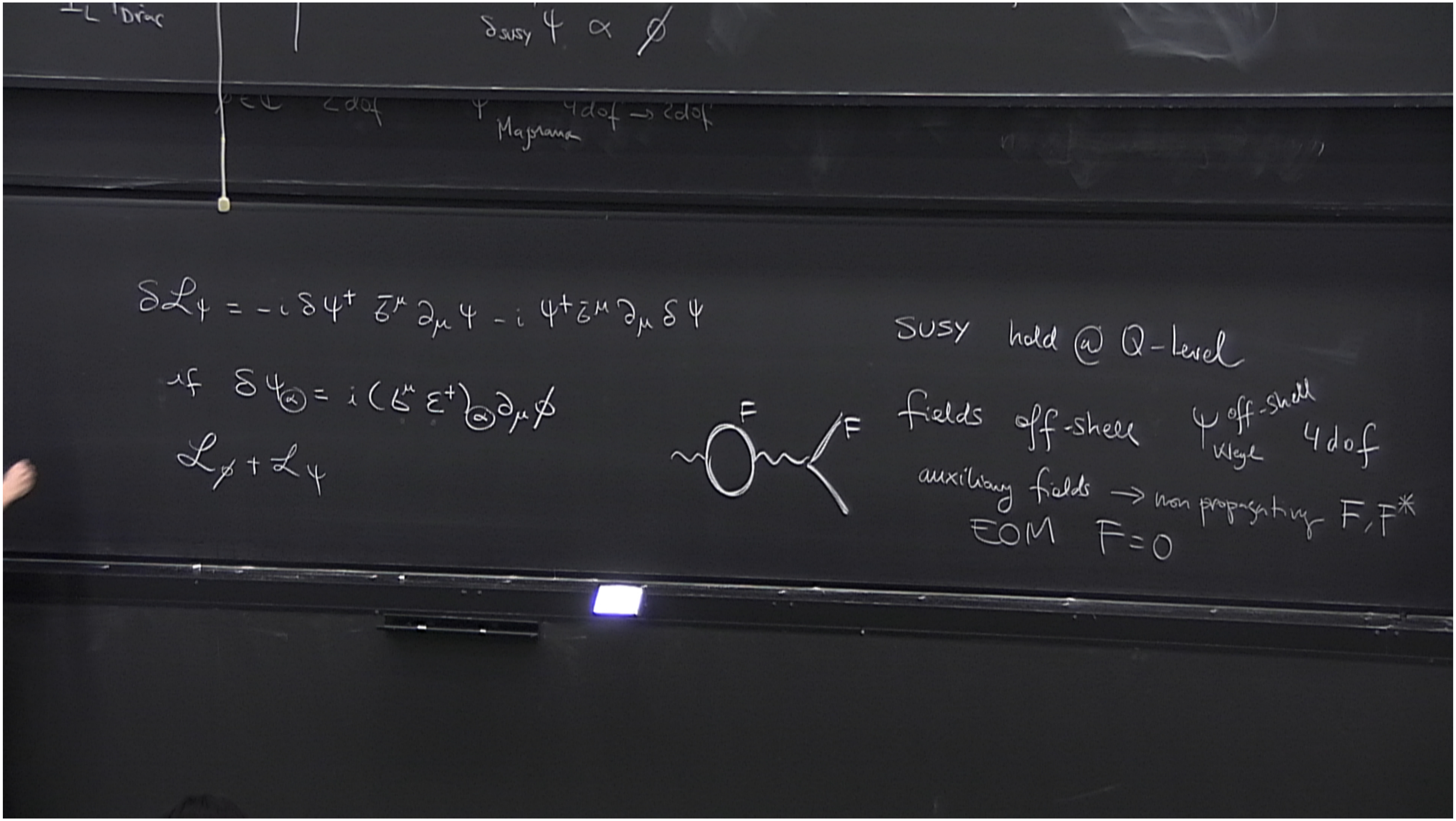
$\mathcal{L}_\phi + \mathcal{L}_\psi$
F
F
SUSY hold @ Q-level
fields off-shell ψ_{W} off-shell 4 dof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if $\delta\psi_\alpha = i(\sigma^\mu\varepsilon^\dagger)_\alpha\partial_\mu\phi$
$\mathcal{L}_\phi + \mathcal{L}_\psi$
F
F
SUSY hold @ Q-Level
fields off-shell
ψ off-shell Weyl 4dof
auxiliary fields → non propagating F, F^*
EOM $F=0$

Ψ_L Dirac

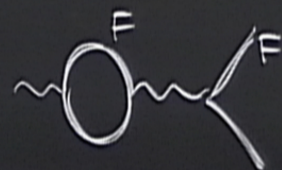
$\delta_{susy}\psi \propto \phi$

$\phi \in \mathbb{C}$ 2 dof ψ Majorana 4 dof $\to$ 2 dof

$$\delta\mathcal{L}_\psi = -i\,\delta\psi^\dagger \bar{\sigma}^\mu \partial_\mu \psi - i\,\psi^\dagger \bar{\sigma}^\mu \partial_\mu \delta\psi$$

if $\delta\psi_\alpha = i(\sigma^\mu \epsilon^\dagger)_\alpha \partial_\mu \phi$

$$\mathcal{L} = \mathcal{L}_\phi + \mathcal{L}_\psi + \mathcal{L}_F \supset FF^*$$



SUSY hold @ Q-level

fields off-shell ψ_{Weyl} off-shell 4 dof

auxiliary fields $\to$ non propagating F, F^*

EOM $\boxed{F=0}$

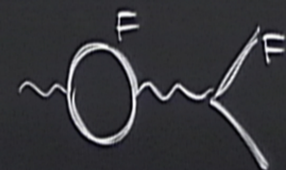
$\delta_{susy}\psi \propto \phi$

ψ 4 dof $\to$ 2 dof Majorana

$$\delta\mathcal{L}_\psi = -i\,\delta\psi^\dagger\bar{\sigma}^\mu\partial_\mu\psi - i\,\psi^\dagger\bar{\sigma}^\mu\partial_\mu\delta\psi$$

if $\delta\psi_\alpha = i(\sigma^\mu\varepsilon^\dagger)_\alpha\partial_\mu\phi$

$$\mathcal{L} = \mathcal{L}_\phi + \mathcal{L}_\psi + \mathcal{L}_F \supset FF^*$$



SUSY hold @ Q-level

fields off-shell ψ_{Weyl} off-shell 4 dof

auxiliary fields $\to$ non propagating F, F^*

EOM $\boxed{F=0}$

I_L Dirac

$\delta_{susy}\psi \propto \phi$

$\phi \in \mathbb{C}$ 2 dof ψ Majorana 4 dof $\to$ 2 dof

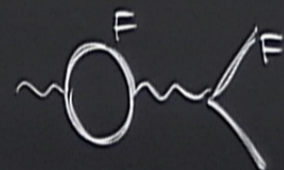
$$\delta\mathcal{L}_\psi = -i\,\delta\psi^\dagger\bar{\sigma}^\mu\partial_\mu\psi - i\,\psi^\dagger\bar{\sigma}^\mu\partial_\mu\delta\psi$$

if $\delta\psi_\alpha = i(\sigma^\mu\epsilon^\dagger)_\alpha\partial_\mu\phi$

$$\mathcal{L} = \mathcal{L}_\phi + \mathcal{L}_\psi + \mathcal{L}_F \supset FF^*$$

chiral supermultiplet (ϕ, ψ, F)

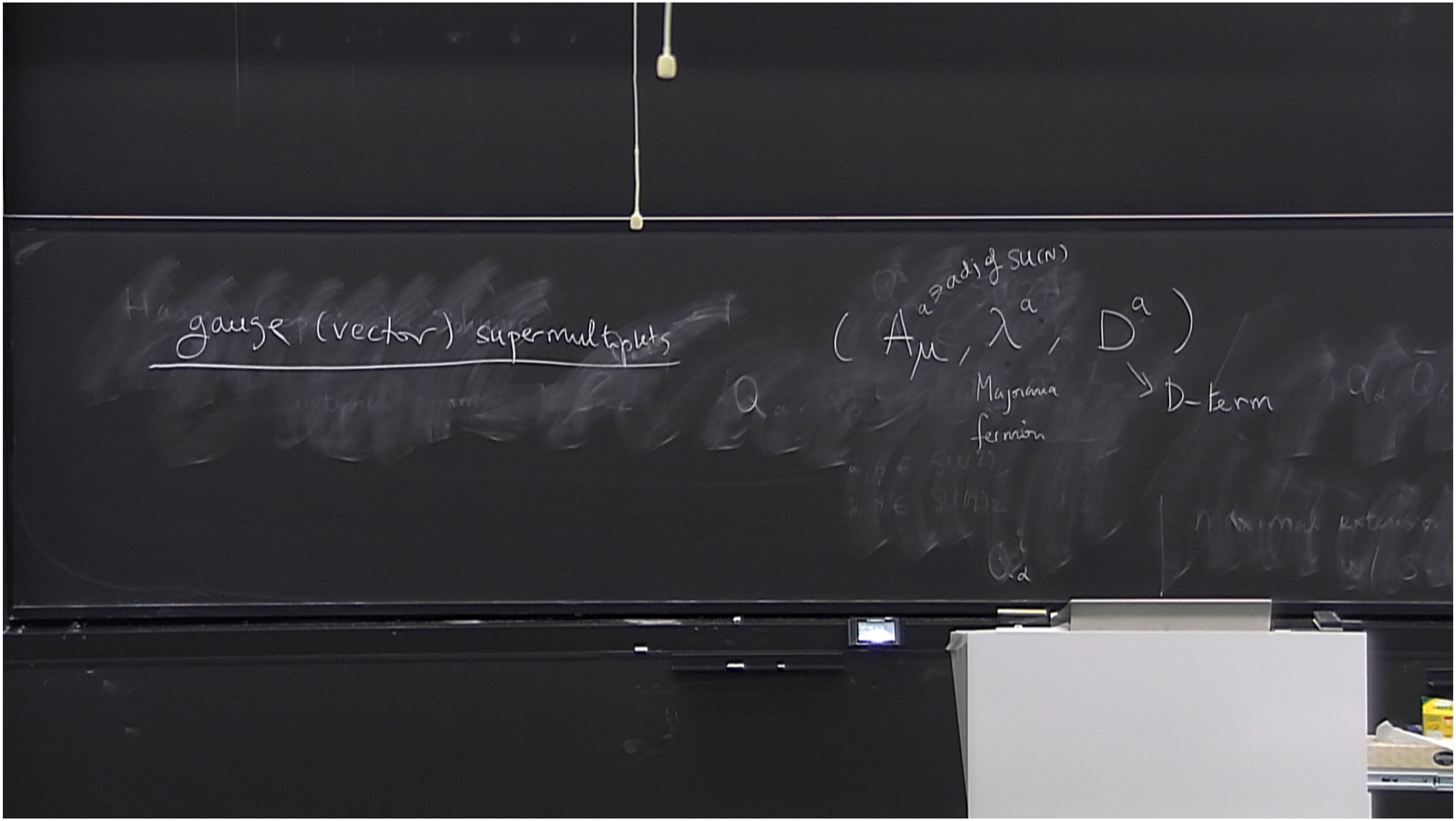
SUSY hold @ Q-level

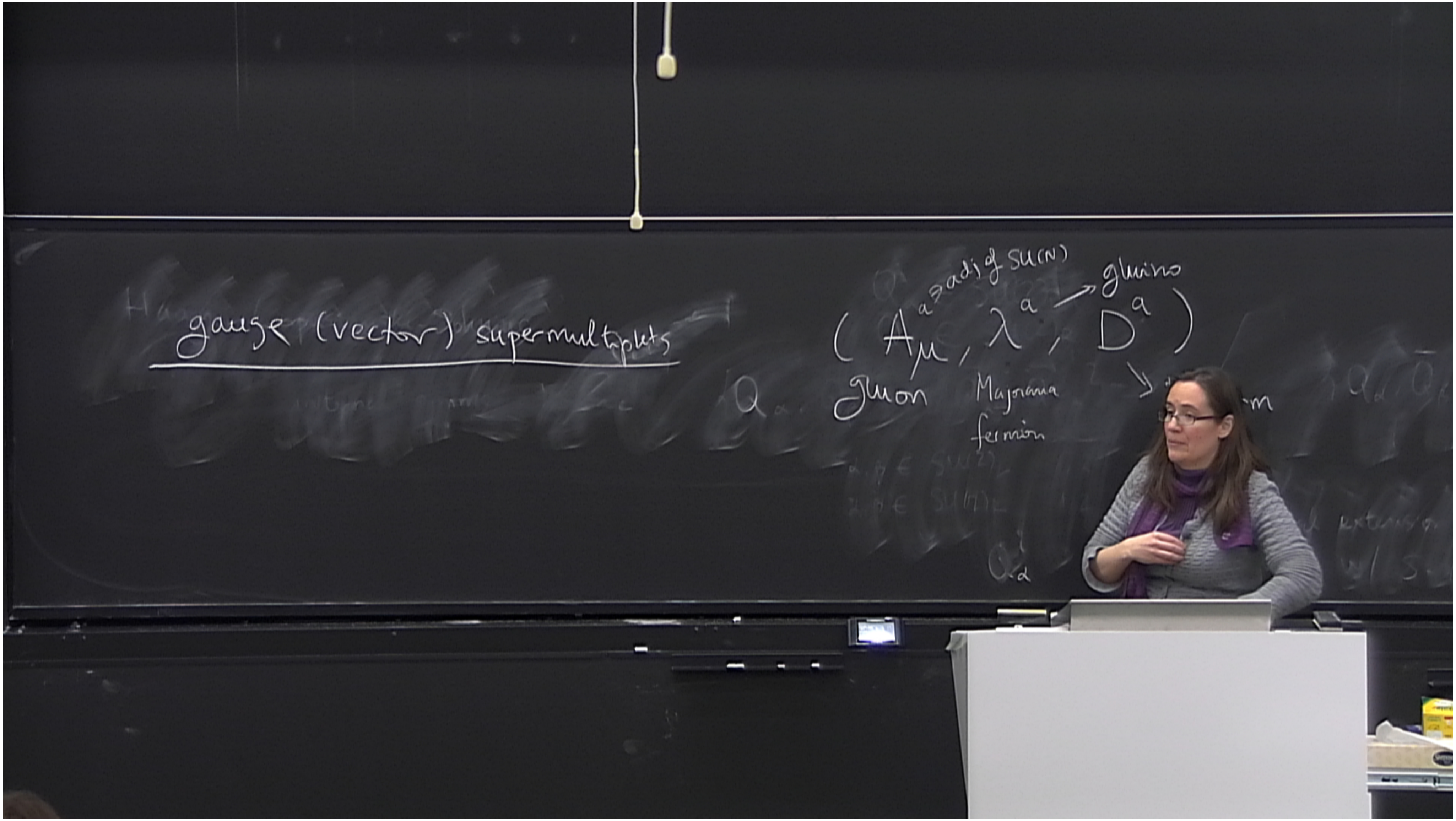


fields off-shell ψ_{Weyl} off-shell 4 dof

auxiliary fields $\to$ non propagating F, F^*

EOM $\boxed{F=0}$


gauge (vector) supermultiplets
a ∋ adj of SU(N)
(A_μ^a , λ^a , D^a)
Majorana fermion
D-term


gauge (vector) supermultiplets
a = adj of SU(N)
gluino
(A^a_μ , λ^a , D^a)
gluon
Majorana
fermion