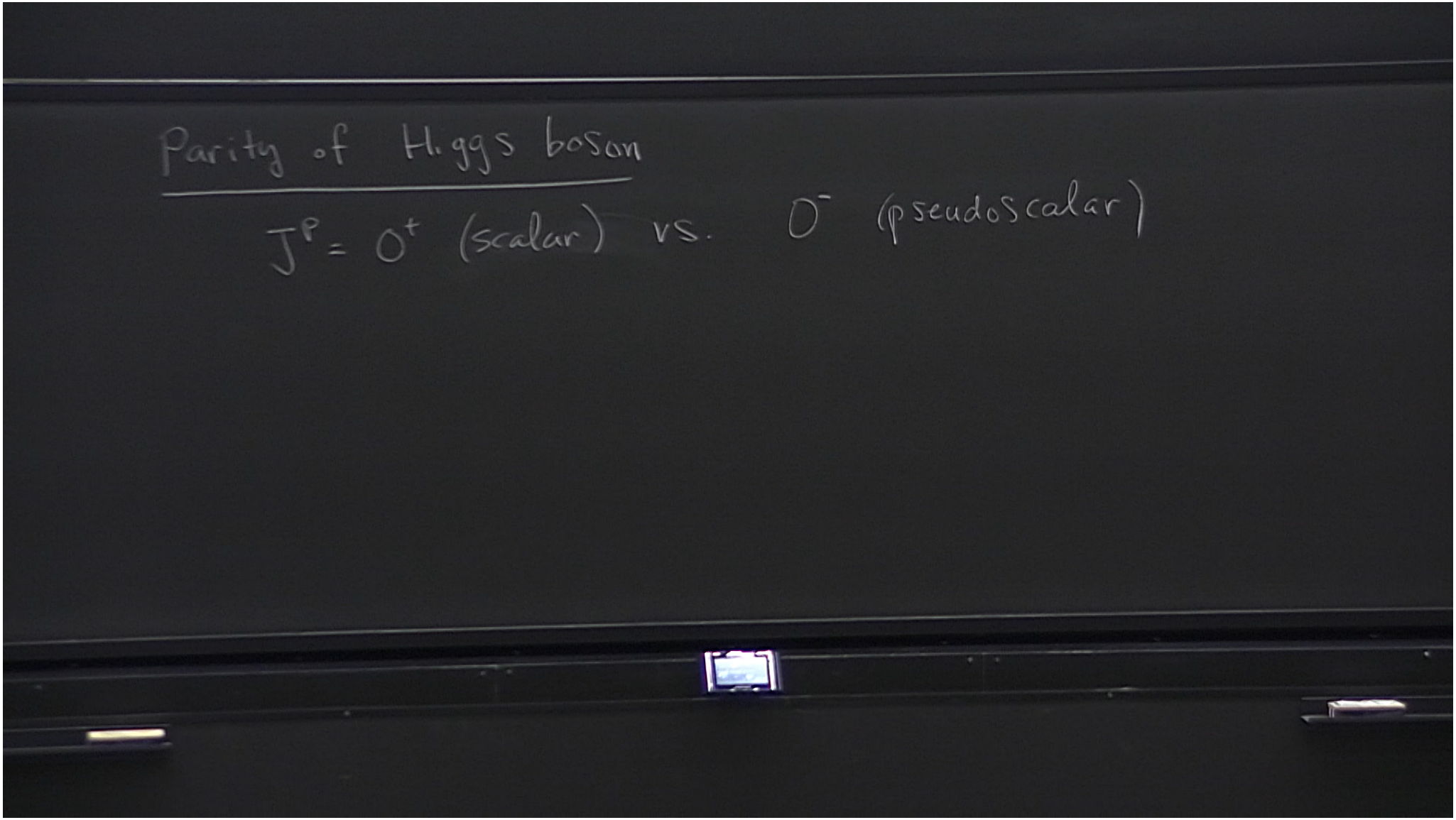
Title: PSI 17/18 - Standard Model - Lecture 11

Date: Jan 17, 2018 09:00 AM

URL: http://pirsa.org/18010018

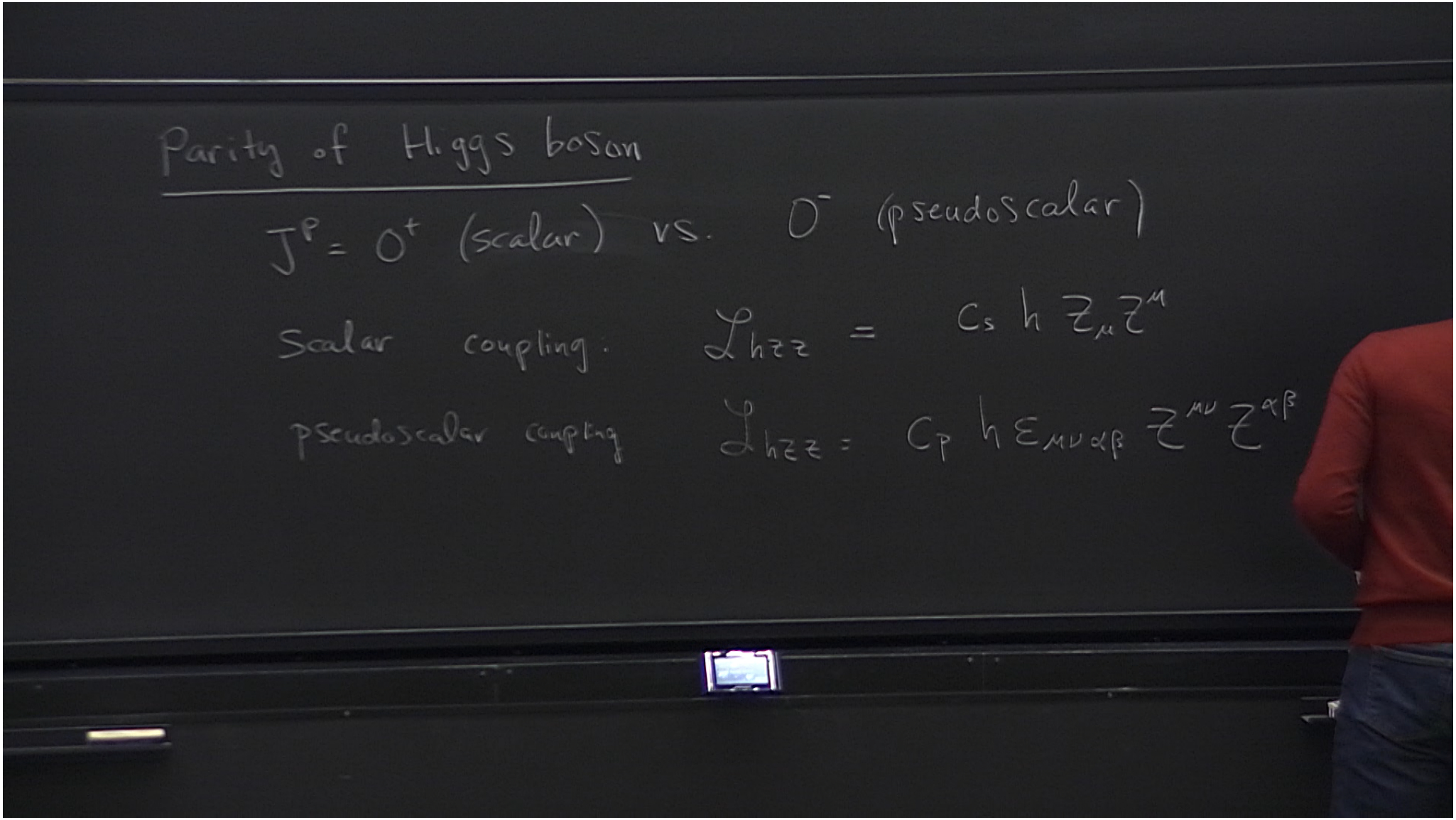
Abstract:


Parity of Higgs boson
$J^P = 0^+$ (scalar) vs. 0^- (pseudoscalar)

Parity of Higgs boson

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Scalar coupling: $\mathcal{L}_{hzz} = c_s\, h\, Z_\mu Z^\mu$


Parity of Higgs boson
$J^P = 0^+$ (scalar) vs. 0^- (pseudoscalar)
Scalar coupling: $\mathcal{L}_{hZZ} = c_s\, h\, Z_\mu Z^\mu$
pseudoscalar coupling $\mathcal{L}_{hZZ} = c_p\, h\, \varepsilon_{\mu\nu\alpha\beta} Z^{\mu\nu} Z^{\alpha\beta}$

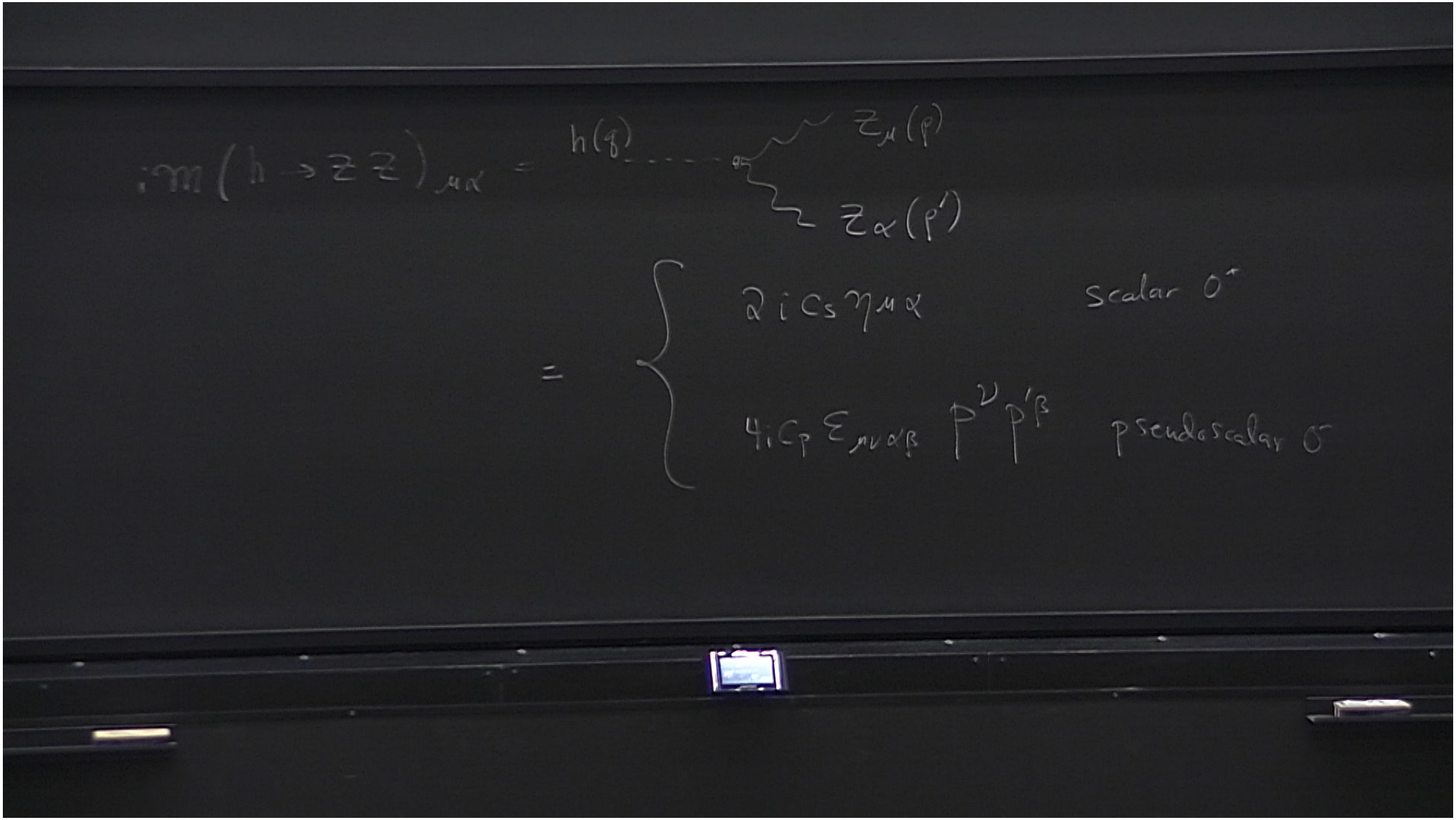
vs. 0^- (pseudoscalar)

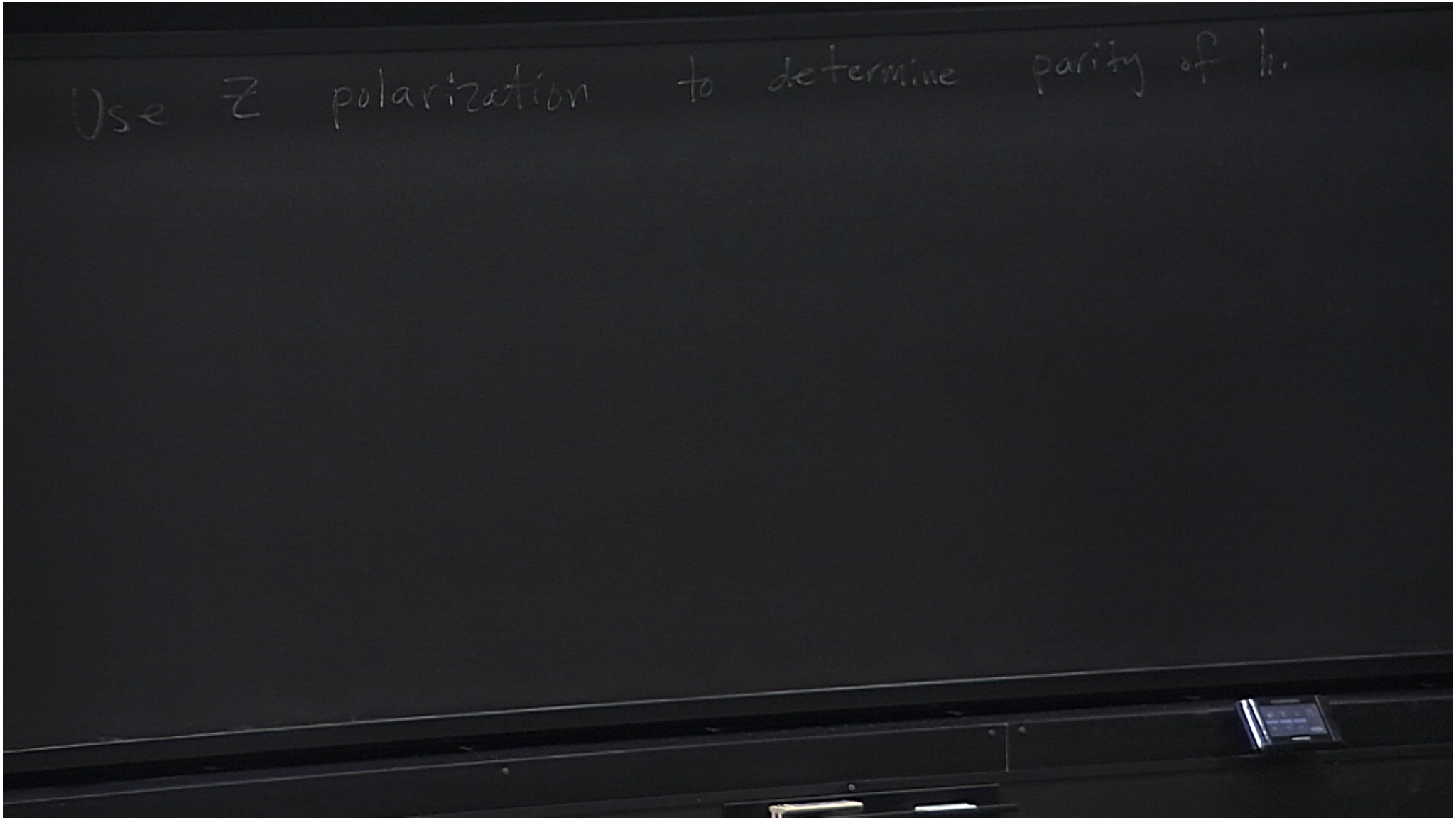
$$\mathcal{L}_{hZZ} = c_s\, h\, Z_\mu Z^\mu$$

$$\mathcal{L}_{hZZ} = c_p\, h\, \varepsilon_{\mu\nu\alpha\beta} Z^{\mu\nu} Z^{\alpha\beta}$$

$\varepsilon_{\mu\nu\alpha\beta}$ = antisym. tensor

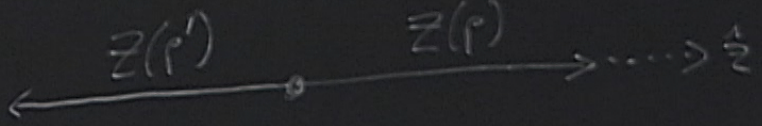
$Z^{\mu\nu} = \partial^\mu Z^\nu - \partial^\nu Z^\mu$


$i\mathcal{M}(h \to ZZ)_{\mu\alpha}$ =
h(q)
$Z_\mu(p)$
$Z_\alpha(p')$
$= \begin{cases} 2iC_S \eta_{\mu\alpha} & \text{scalar } 0^+ \\ 4iC_P \varepsilon_{\mu\nu\alpha\beta} p^\nu p'^\beta & \text{pseudoscalar } 0^- \end{cases}$


Use Z polarization to determine parity of h.

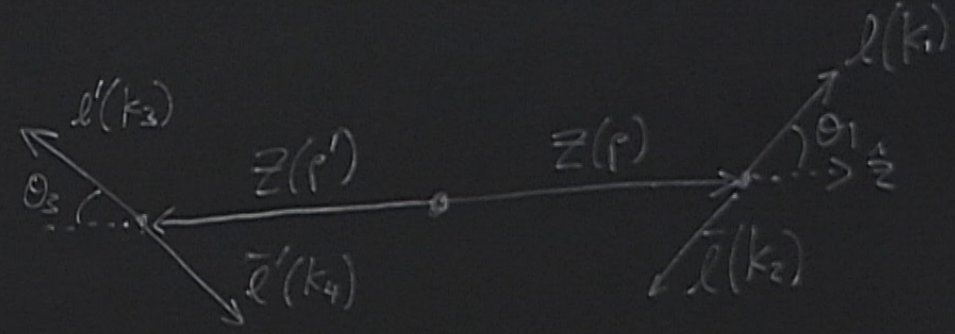
Use Z polarization to determine parity of h.

Consider $h \to ZZ \to l\bar{l}\,l'\bar{l}'$ where $l, l' = e, \mu$



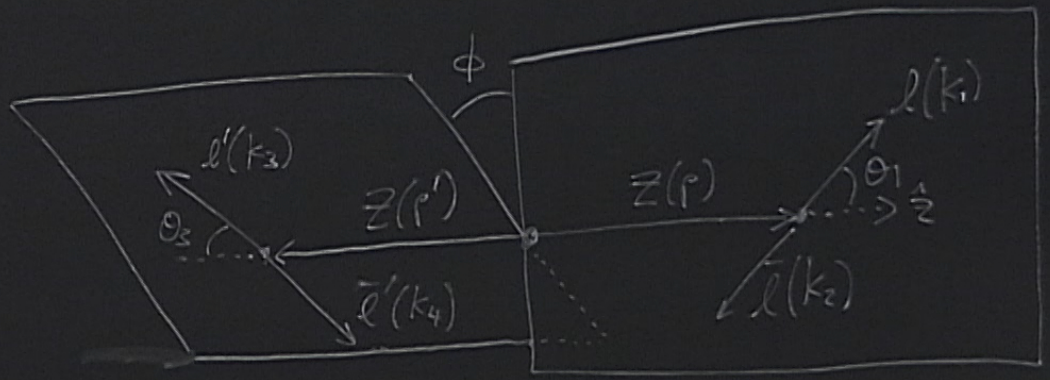
Use Z polarization to determine parity of h.

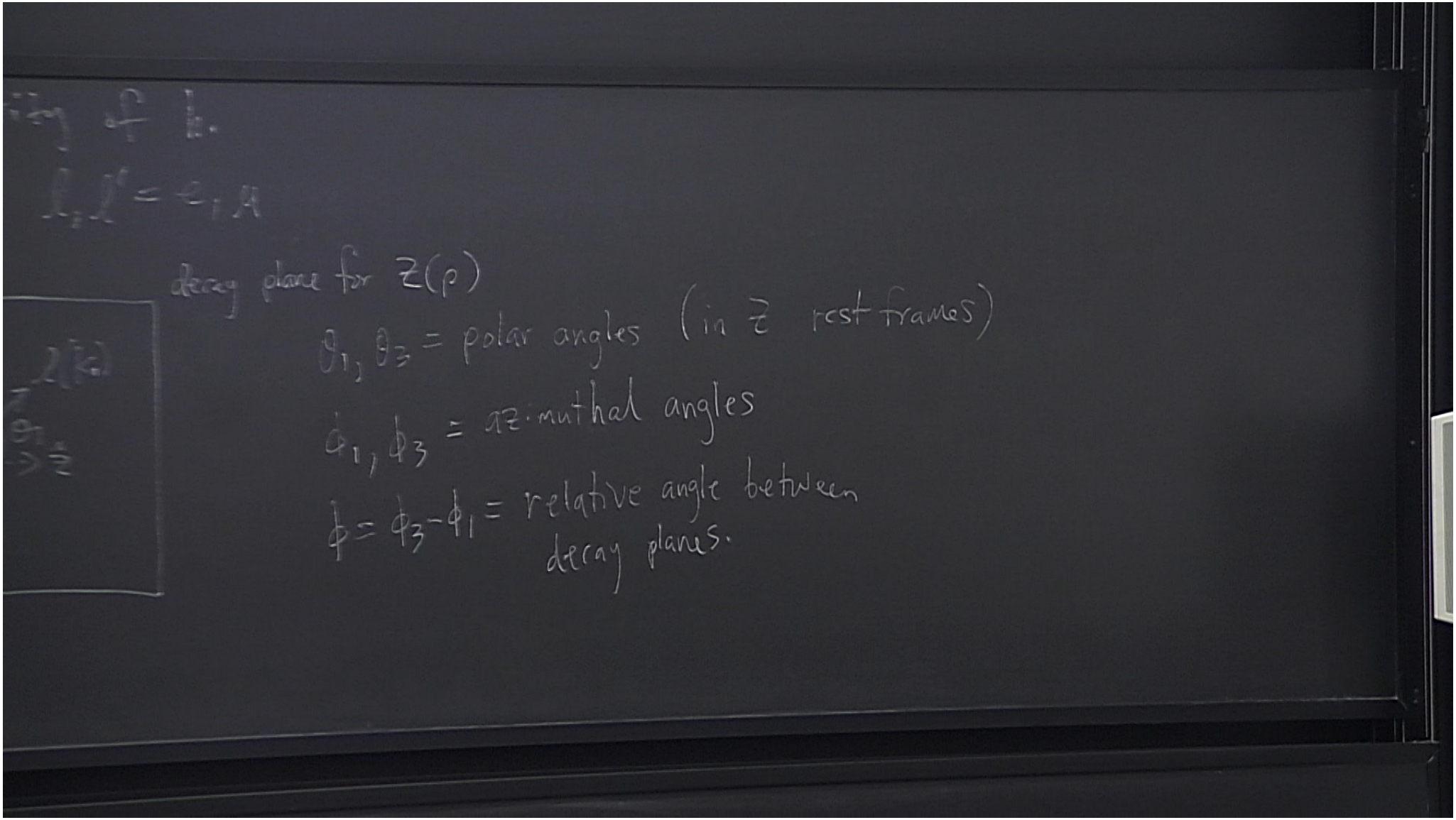
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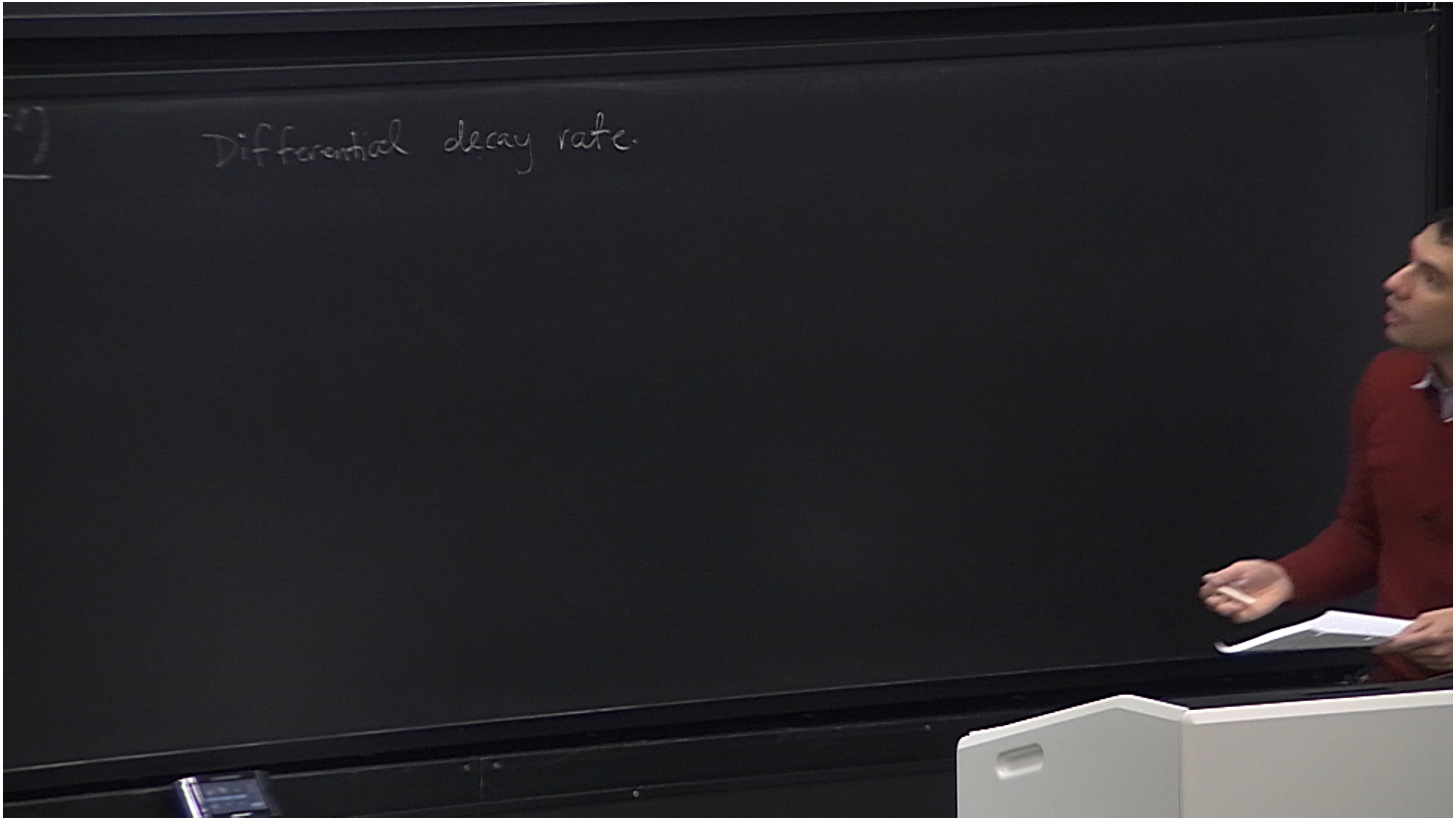
Use Z polarization to determine parity of h.

Consider $h \to ZZ \to l\bar{l}\,l'\bar{l}'$ where $l, l' = e, \mu$




decay plane for Z(ρ)
θ_1, θ_3 = polar angles (in Z rest frames)
ϕ_1, ϕ_3 = azimuthal angles
$\phi = \phi_3 - \phi_1$ = relative angle between decay planes.

Goal: Compute $\frac{d\Gamma(h \to ZZ \to l\bar{l}\, l'\bar{l}')}{d\phi}$


Differential decay rate.

Goal: Compute $\frac{d\Gamma(h \to ZZ \to \ell\bar{\ell}\,\ell'\bar{\ell}')}{d\phi}$

Illustrative limit: $m_h \gg m_Z \gg m_\ell$

$$\frac{d\Gamma(h \to ZZ \to l\bar{l}\, l'\bar{l}')}{d\phi}$$

Differential decay rate.

On-shell ZZ

$m_h \gg m_Z \gg m_l$.

Goal: Compute $\frac{d\Gamma(h \to ZZ \to \ell\bar{\ell}\,\ell'\bar{\ell}')}{d\phi}$ Differential decay rate.

Illustrative limit: $m_h \gg m_Z \gg m_\ell$. On-shell ZZ

Z polarizations: Z rest frame

$$\varepsilon_1^\mu = (0,1,0,0)$$
$$\varepsilon_2^\mu = (0,0,1,0)$$
$$\varepsilon_3^\mu = (0,0,1,0)$$

: Compute $\frac{d\Gamma(h \to ZZ \to \ell\bar{\ell}\,\ell'\bar{\ell}')}{d\phi}$ Differential decay rate.

trative limit: $m_h \gg m_Z \gg m_\ell$ On-shell ZZ

olarizations: Z rest frame $\xrightarrow{\text{boost}}$ Z with momentum $p^\mu = (Ep, 0, 0, p)$

$\varepsilon_1^\mu = (0,1,0,0)$

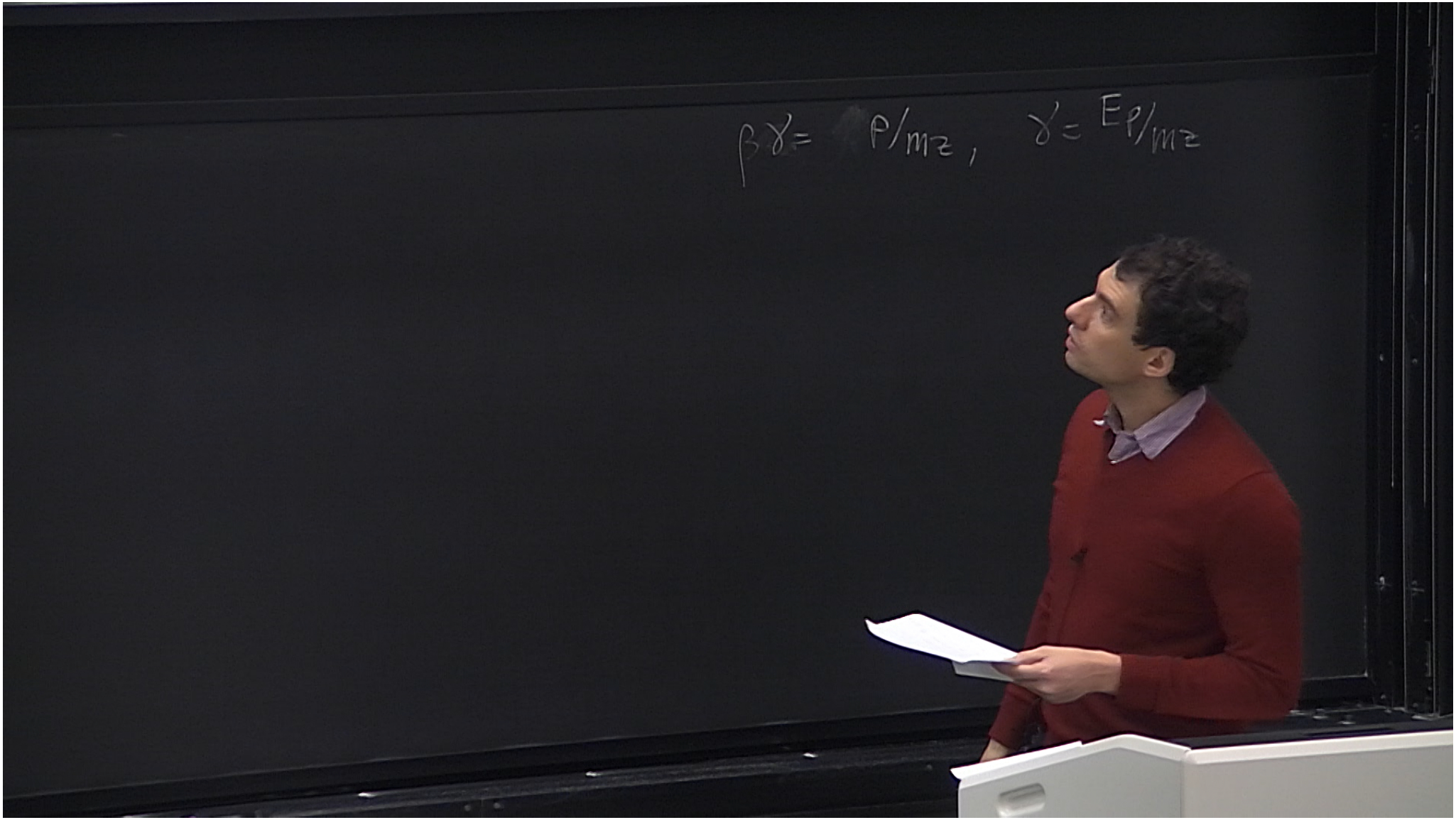
$\varepsilon_2^\mu = (0,0,1,0)$

$\varepsilon_3^\mu = (0,0,1,0)$

$\varepsilon_1^\mu(p) = (0,1,0,0)$ } transverse

$\varepsilon_2^\mu(p) = (0,0,1,0)$ }

$\varepsilon_3^\mu \to \varepsilon_L^\mu(p) = (\beta\gamma, 0, 0, \gamma)$ } Longitudinal


βγ= p/mc , γ= Ep/mc²

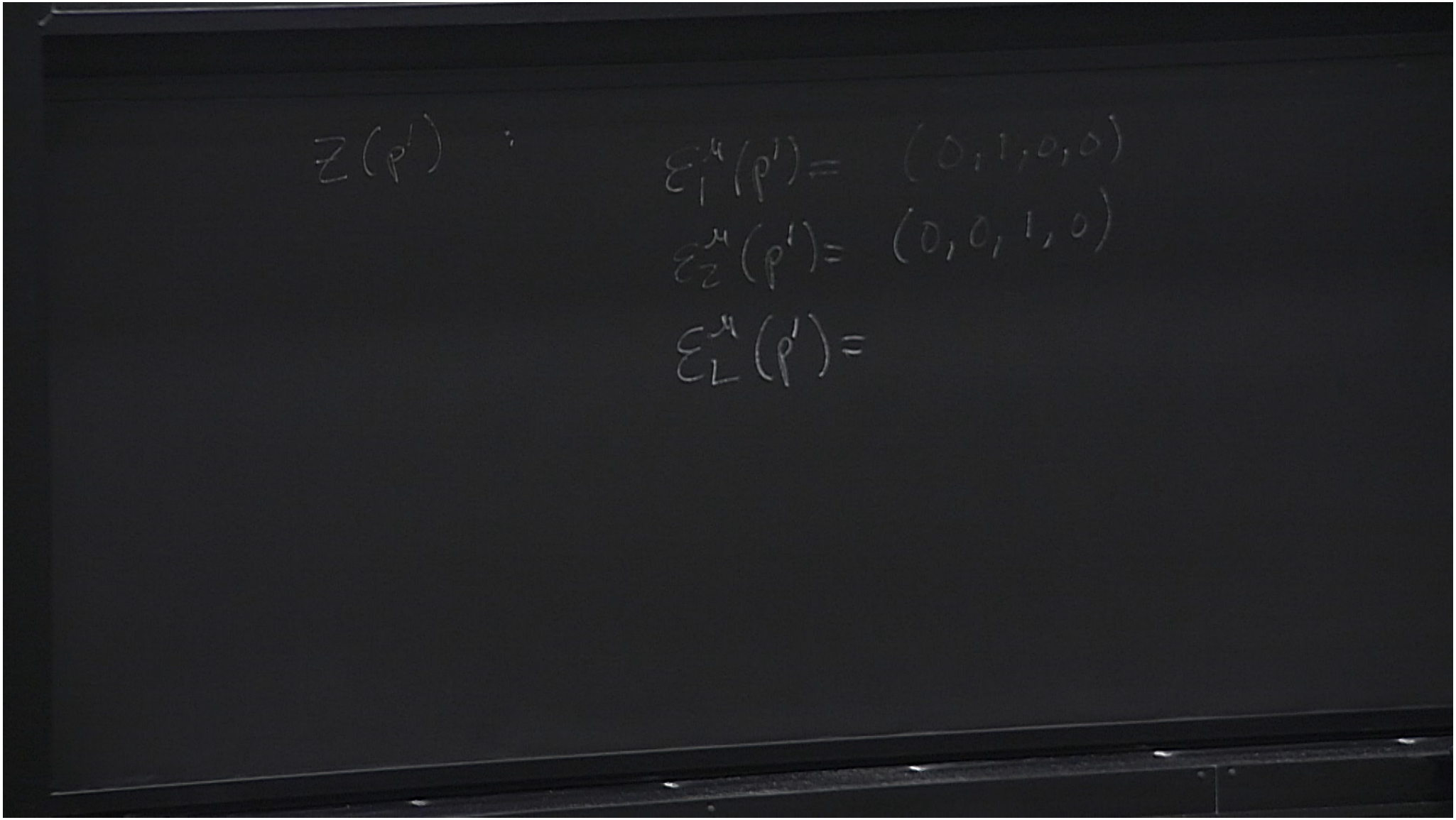
Goal: Compute $\frac{d\Gamma(h \to ZZ \to \ell\bar{\ell}\,\ell'\bar{\ell}')}{d\Phi}$

On-shel

Illustrative limit: $m_h \gg m_Z \gg m_\ell$

Z polarizations: Z rest frame — boost

$$\varepsilon_1^\mu = (0,1,0,0)$$
$$\varepsilon_2^\mu = (0,0,1,0)$$
$$\varepsilon_3^\mu = (0,0,0,1)$$


Z(p')
$\varepsilon_1^\mu(p') = (0,1,0,0)$
$\varepsilon_2^\mu(p') = (0,0,1,0)$
$\varepsilon_L^\mu(p') =$

$Z(p')$:

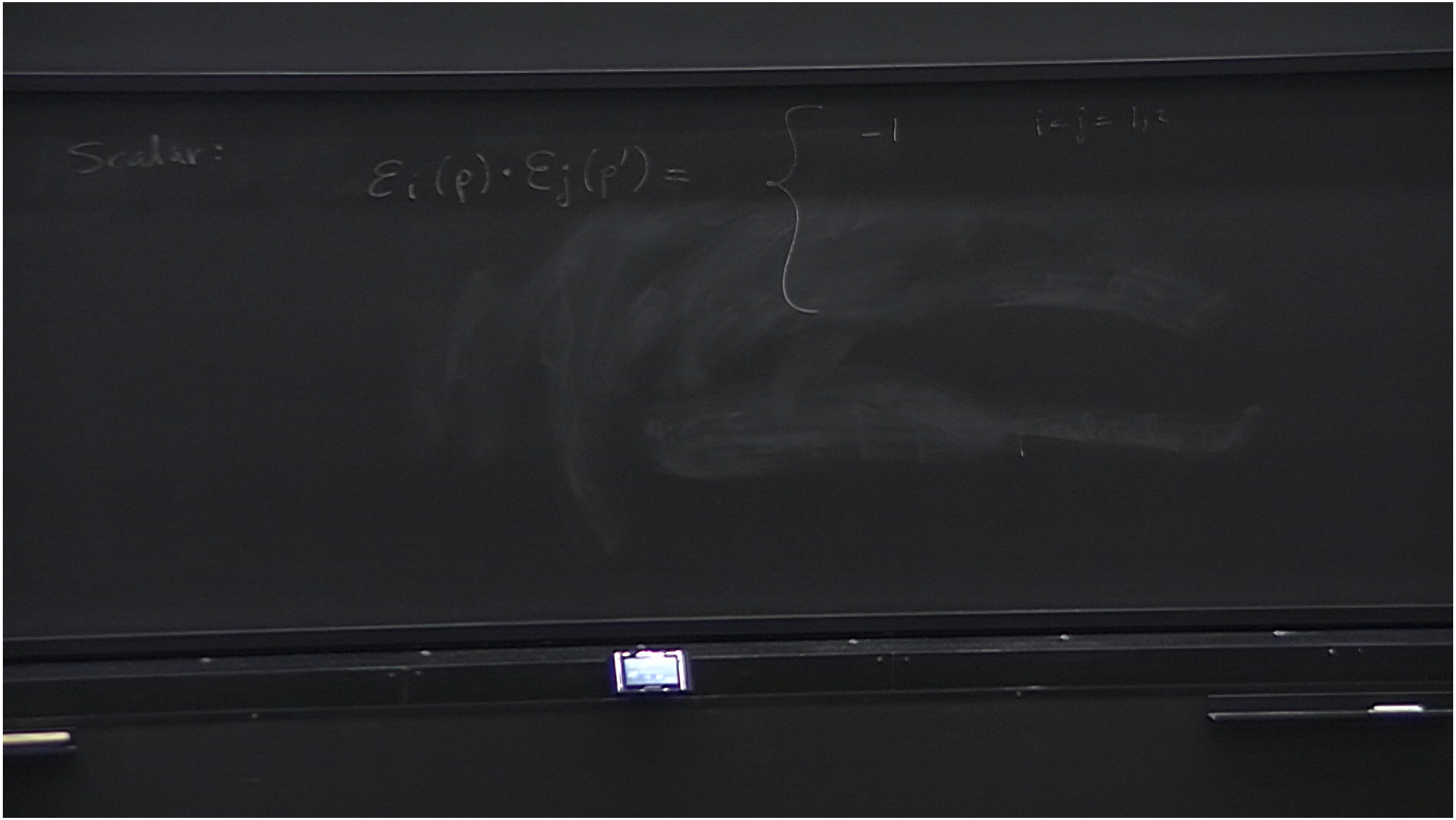
$\varepsilon_1^\mu(p') = (0, 1, 0, 0)$

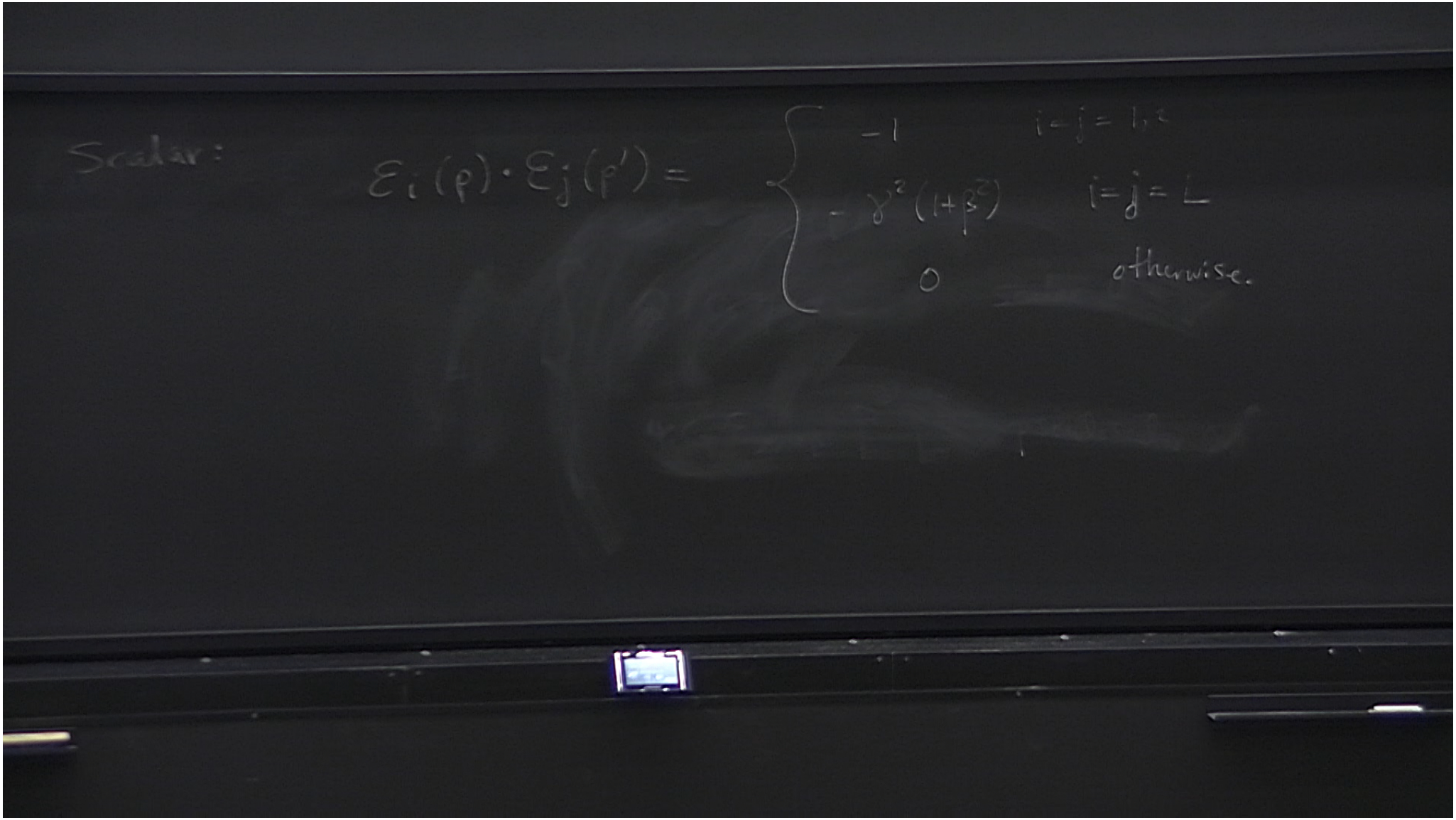
$\varepsilon_2^\mu(p') = (0, 0, 1, 0)$

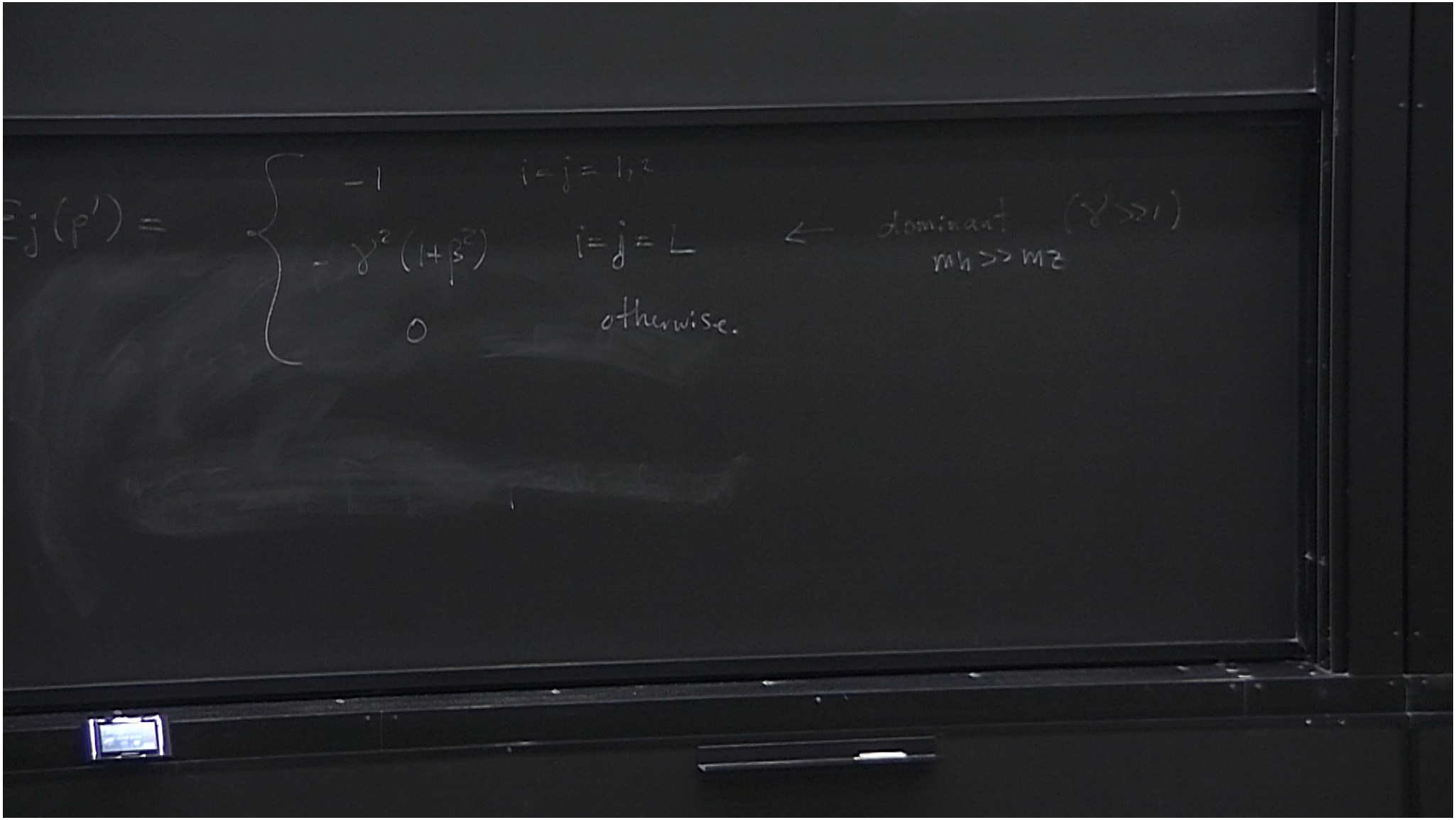
$\varepsilon_L^\mu(p') = (-\beta\gamma, 0, 0, \gamma)$

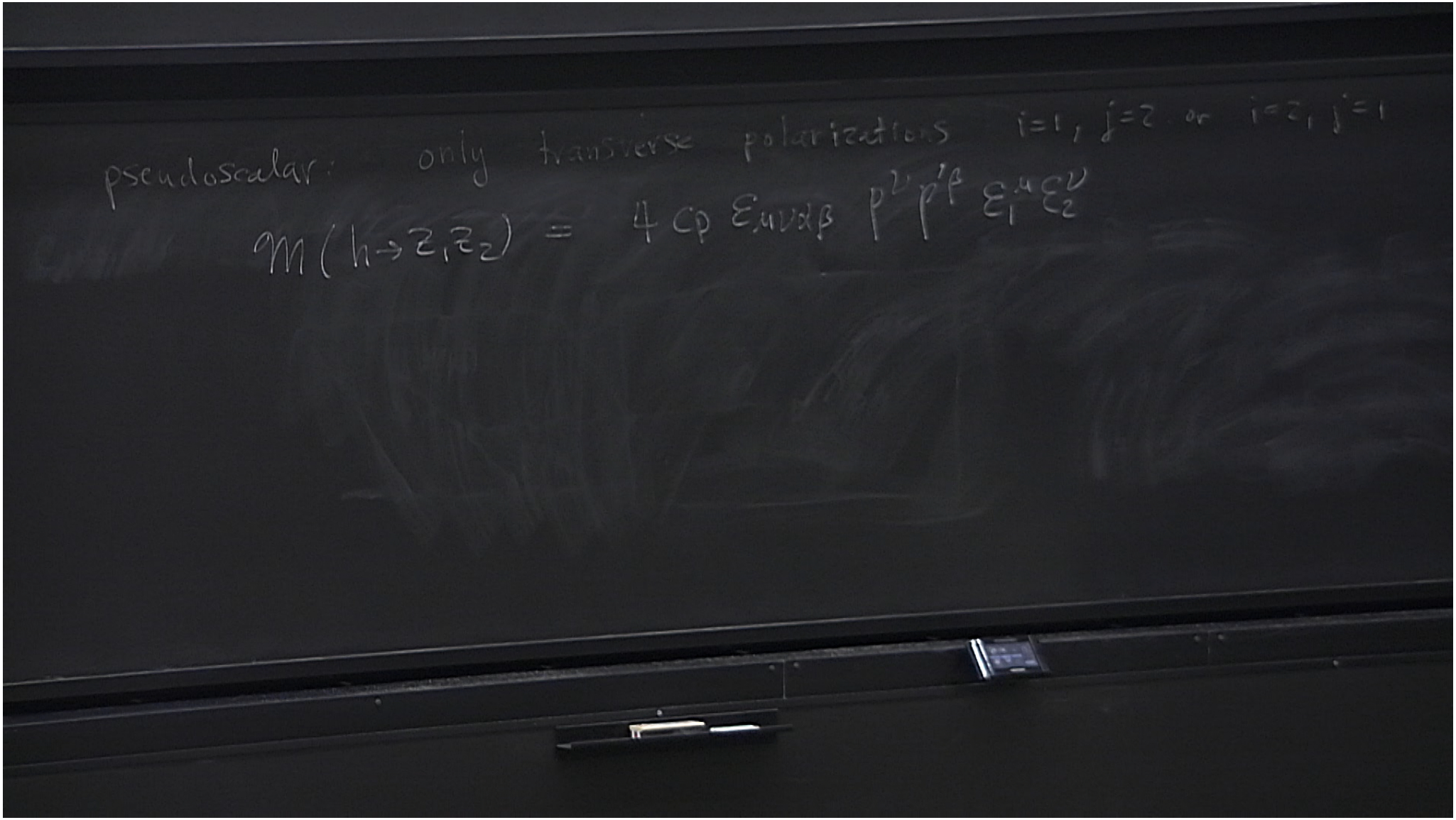
$$\mathcal{M}(h \to Z_i Z_j) = \mathcal{M}(h \to ZZ)_{\mu\nu}\, \varepsilon_i^{\mu}(p)\, \varepsilon_j^{\nu}(p')$$

$$= \begin{cases} 2C_S\, \varepsilon_i(p) \cdot \varepsilon_j(p') \\ 4C_P\, \varepsilon_{\mu\nu\alpha\beta}\, p^{\nu} p'^{\beta}\, \varepsilon_i^{\mu}(p)\, \varepsilon_j^{\alpha}(p') \end{cases}$$


Scalar:
$\varepsilon_i(p) \cdot \varepsilon_j(p') =$
-1
$i=j=1,2$


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$\varepsilon_i(p) \cdot \varepsilon_j(p') =$
-1 $i=j=1,2$
$-\gamma^2(1+\beta^2)$ $i=j=L$
0 otherwise.


$\Sigma_j(p') =$
-1 $i=j=1,2$
$-\gamma^2(1+\beta^2)$ $i=j=L$ ← dominant ($\gamma \gg 1$)
$m_h \gg m_Z$
0 otherwise.


pseudoscalar: only transverse polarizations i=1, j=2 or i=2, j=1
$\mathcal{M}(h \to Z_1 Z_2) = 4 c_{\tilde{B}} \varepsilon_{\mu\nu\alpha\beta} p^{\nu} p'^{\beta} \varepsilon_1^{*\mu} \varepsilon_2^{*\nu}$

pseudoscalar: only transverse polarizations $i=1, j=2$ or $i=2, j=1$

$$\mathcal{M}(h \to Z_1 Z_2) = 4 c_{\tilde{B}} \varepsilon_{\mu\nu\alpha\beta} p^{\nu} p'^{\beta} \varepsilon_1^{\mu} \varepsilon_2^{\nu}$$

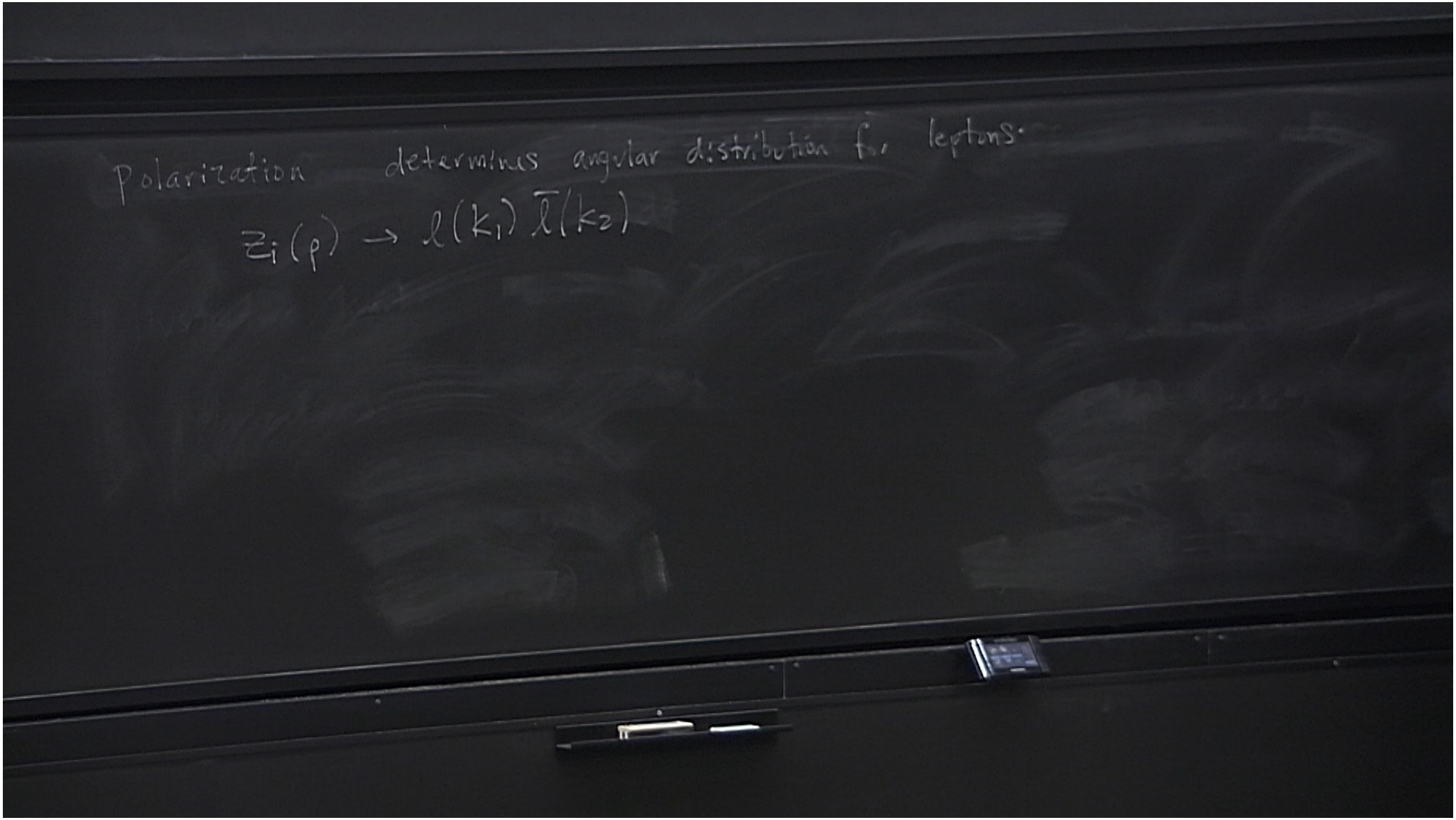
$$= - \mathcal{M}(h \to Z_2 Z_1)$$

pseudoscalar: only transverse polarizations $i=1, j=2$ or $i=2, j=1$

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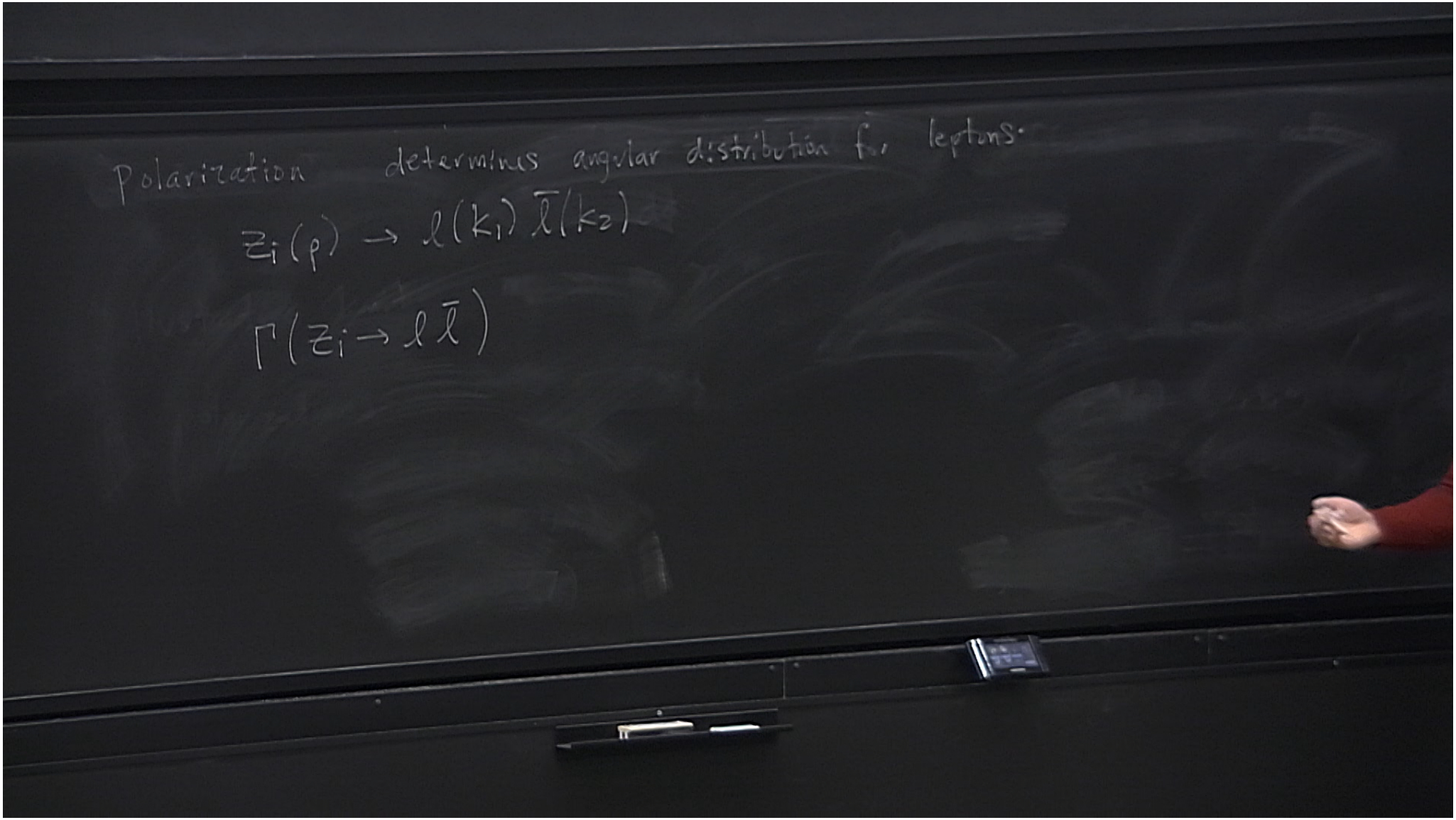
$$\mathcal{M}(h \to Z_1(p) Z_2(p')) = - \mathcal{M}(h \to Z_2(p) Z_1(p'))$$


Polarization determines angular distribution fn. leptons.
$Z_i(p) \to l(k_1)\,\bar{l}(k_2)$

Polarization determines angular distribution f. leptons.

$$Z_i(p) \to \ell(k_1)\,\bar{\ell}(k_2)$$

$$\Gamma(Z_i \to \ell\bar{\ell})$$



Polarization determines angular distribution for leptons.

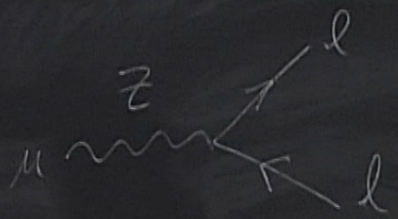
$$Z_i(p) \to \ell(k_1)\,\bar{\ell}(k_2)$$

$$\Gamma(Z_i \to \ell\bar{\ell}) = \frac{1}{64\pi^2 m_Z} \int d\cos\theta_1 \int d\phi_1 \sum_{\substack{\text{fermion} \\ \text{spins}}} |\mathcal{M}(Z_i \to \ell\bar{\ell})|^2$$

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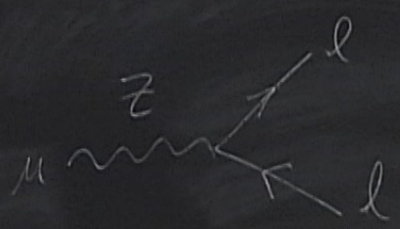
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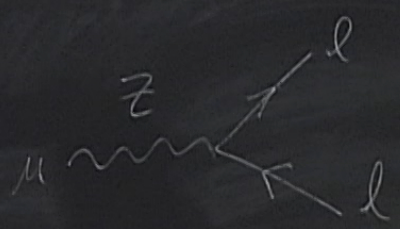


$$= \frac{ig}{4c_W}\gamma^\mu\left[(1-4s_W^2) - \gamma^5\right]$$

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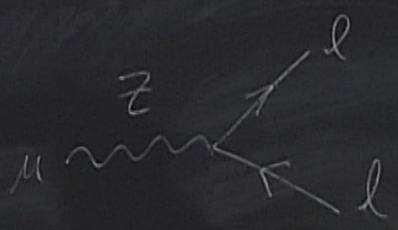
$$s_W^2 \simeq 0.23 \approx \frac{1}{4}$$

$$(1-4s_W^2) \approx 0$$

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$$= \frac{ig}{4c_W}\gamma^\mu\left[(1-4s_W^2) - \gamma^5\right]$$

$$= -\frac{ig}{4c_W}\gamma^\mu\gamma^5$$

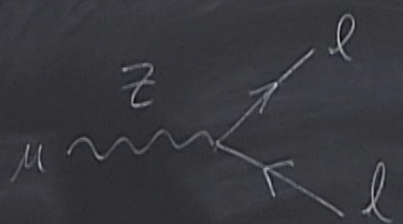
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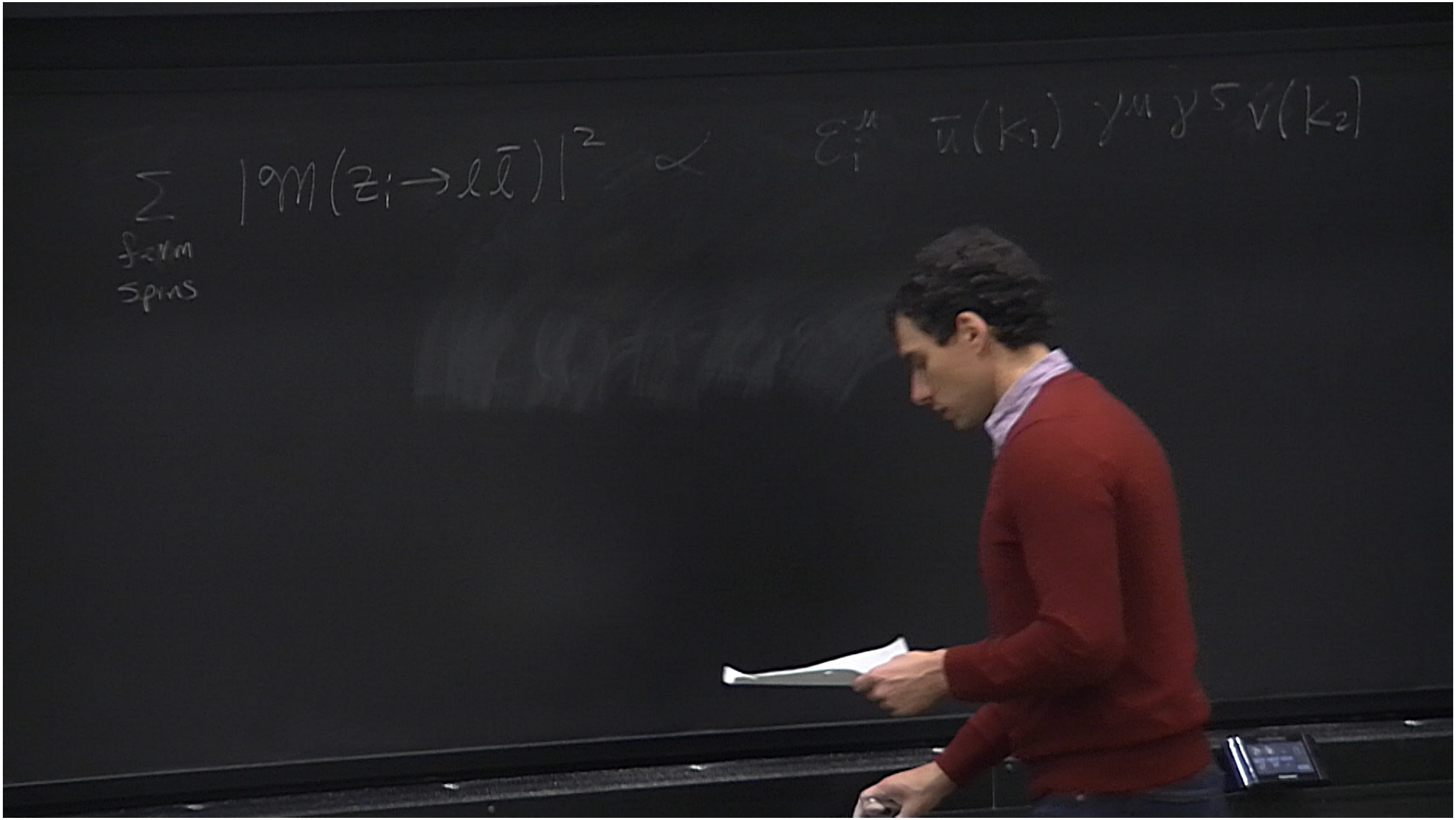


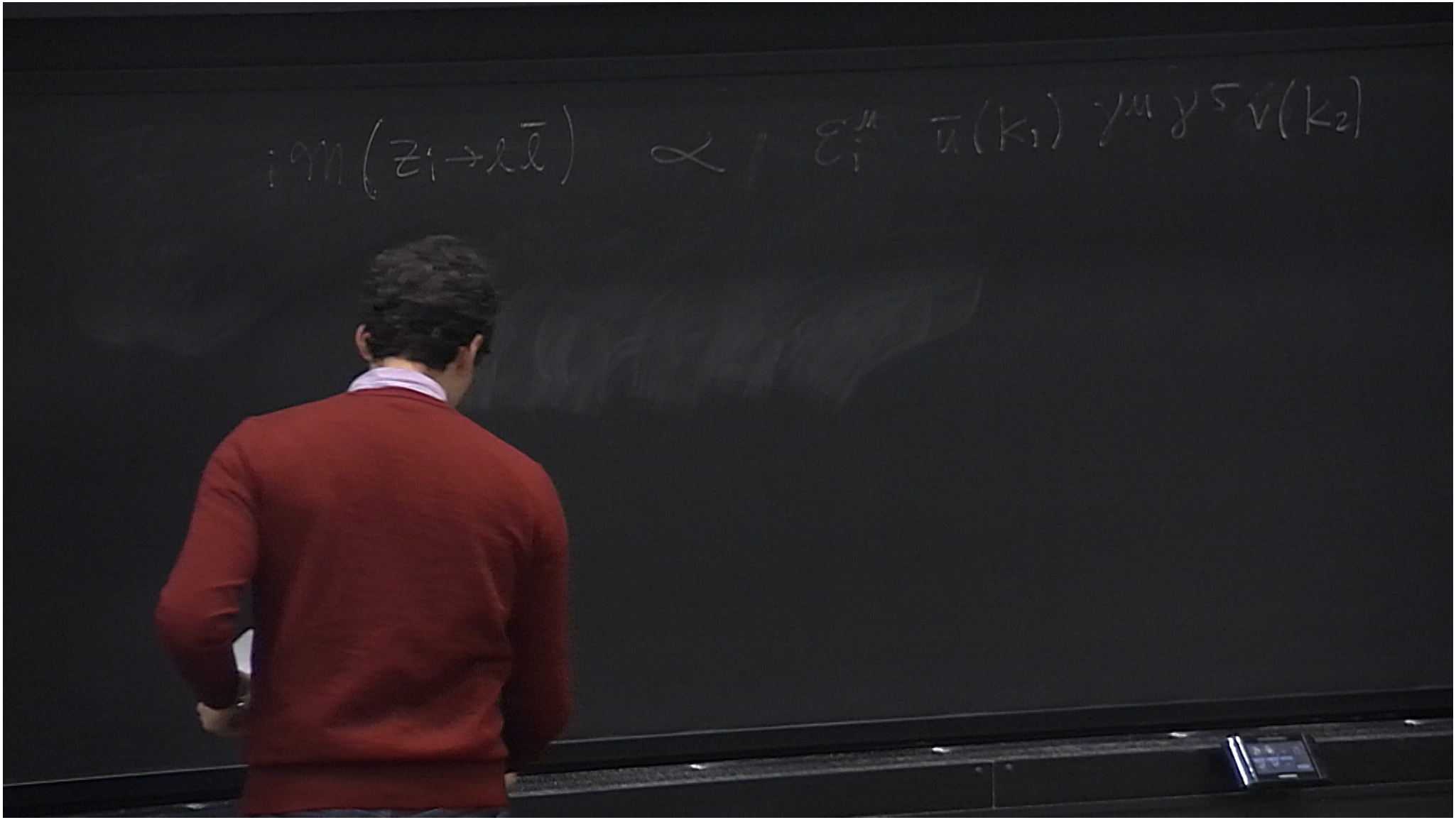
$$= \frac{ig}{4c_W}\gamma^\mu\left[(1-4s_W^2) - \gamma^5\right]$$

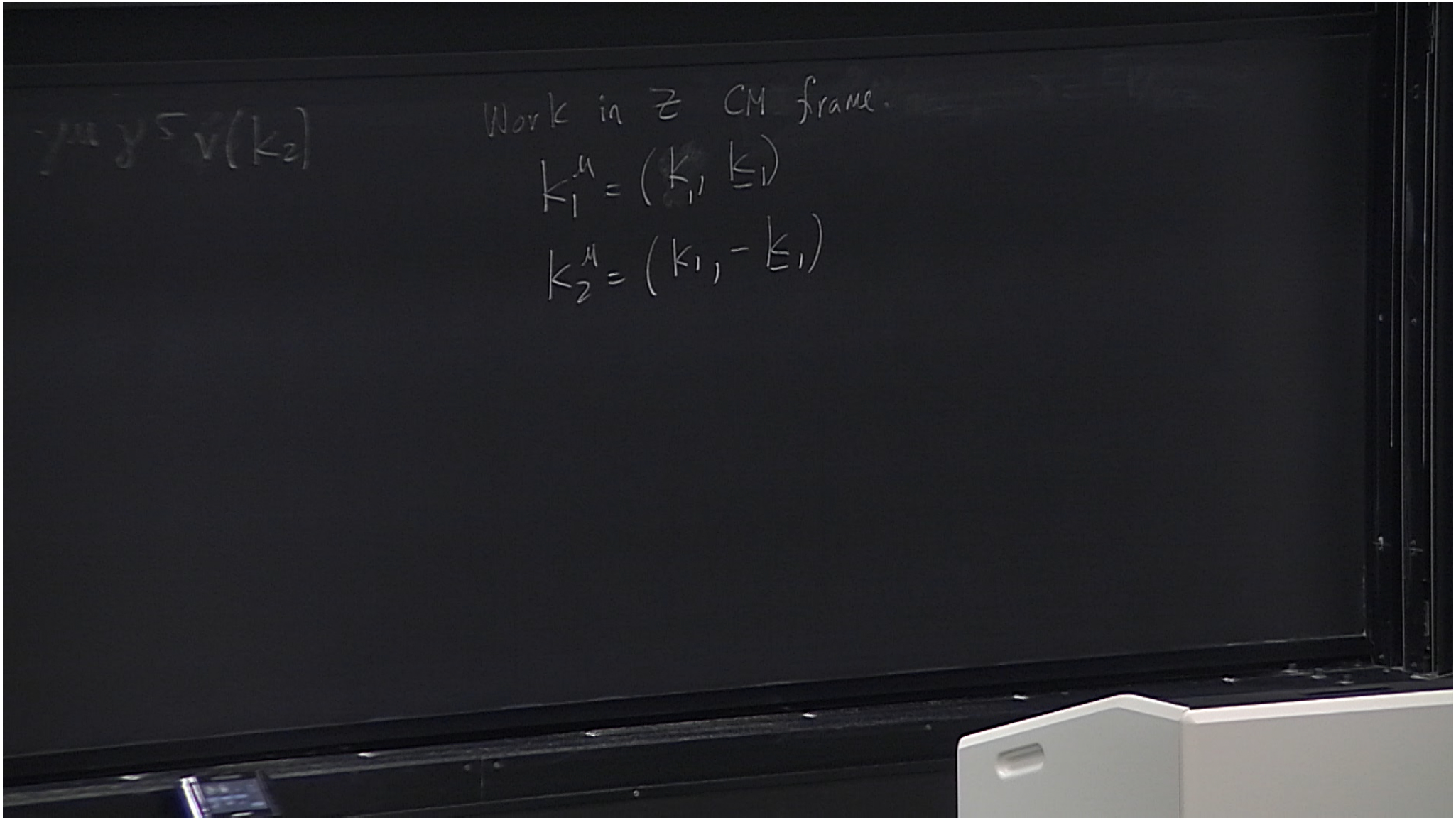
$$\cong -\frac{ig}{4c_W}\gamma^\mu\gamma^5$$

$s_W^2 \simeq 0.23 \approx \frac{1}{4}$

$(1-4s_W^2) \approx 0$


$\sum_{\text{f.v.m. spins}} |\mathcal{M}(Z_i \to l\bar{l})|^2 \propto \varepsilon_i^\mu \bar{u}(k_1) \gamma^\mu \gamma^5 v(k_2)$


$i\mathcal{M}(Z_1 \to l\bar{l}) \propto \epsilon_1^{\mu} \bar{u}(k_1) \gamma_\mu \gamma^5 v(k_2)$


$\gamma^\mu \gamma^5 v(k_2)$
Work in $\bar{z}$ CM frame.
$k_1^\mu = (k_1, \vec{k}_1)$
$k_2^\mu = (k_1, -\vec{k}_1)$

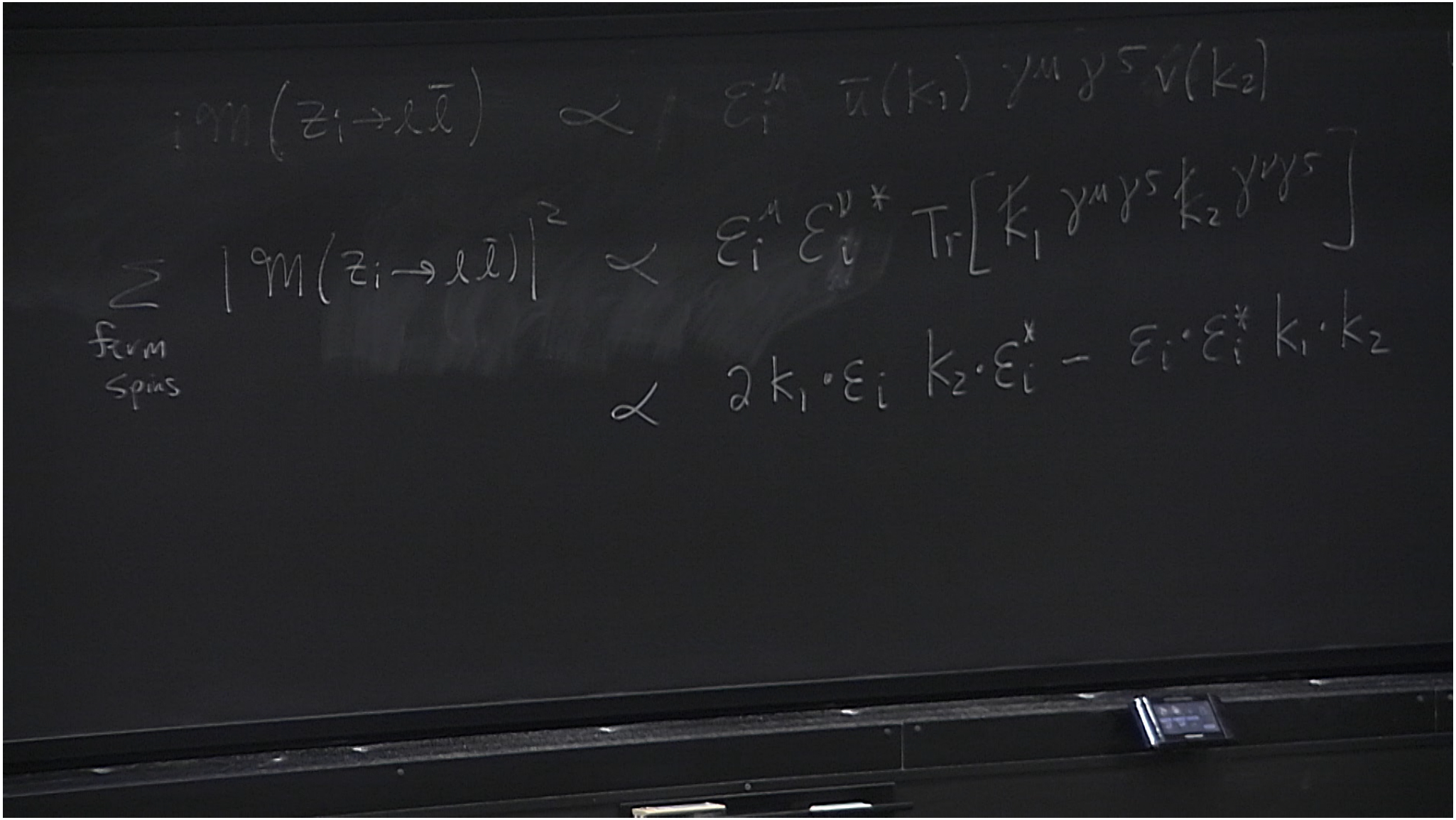
$$i\mathcal{M}(z_i \to l\bar{l}) \propto \varepsilon_i^{\mu}\, \bar{u}(k_1)\, \gamma_\mu \gamma_5\, v(k_2)$$

$$\sum_{\text{form spins}} |\mathcal{M}(z_i \to l\bar{l})|^2 \propto \varepsilon_i^{\mu}\, \varepsilon_i^{\nu *}\, \mathrm{Tr}\left[\not{k}_1 \gamma_\mu \gamma_5 \not{k}_2 \gamma_\nu \gamma_5 \right]$$

$$i\mathcal{M}(z_i \to l\bar{l}) \propto \varepsilon_i^{\mu}\, \bar{u}(k_1)\, \gamma_\mu \gamma_5\, v(k_2)$$

$$\sum_{\text{from spins}} |\mathcal{M}(z_i \to l\bar{l})|^2 \propto \varepsilon_i^{\mu}\, \varepsilon_i^{\nu *}\, \mathrm{Tr}\left[\not{k}_1 \gamma_\mu \gamma_5 \not{k}_2 \gamma_\nu \gamma_5 \right]$$

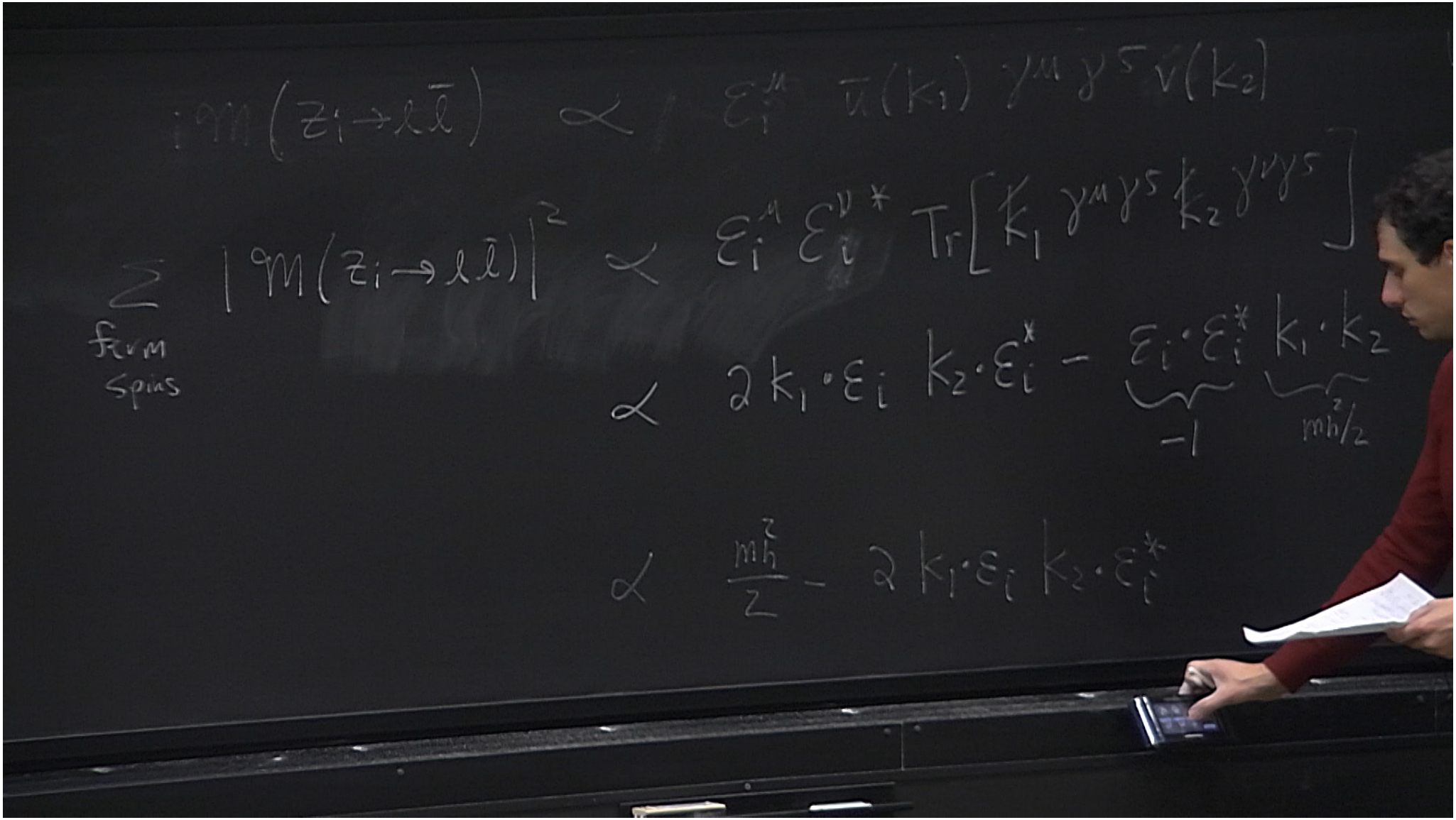
$$\propto 2\, k_1 \cdot \varepsilon_i\; k_2 \cdot \varepsilon_i^{*}$$

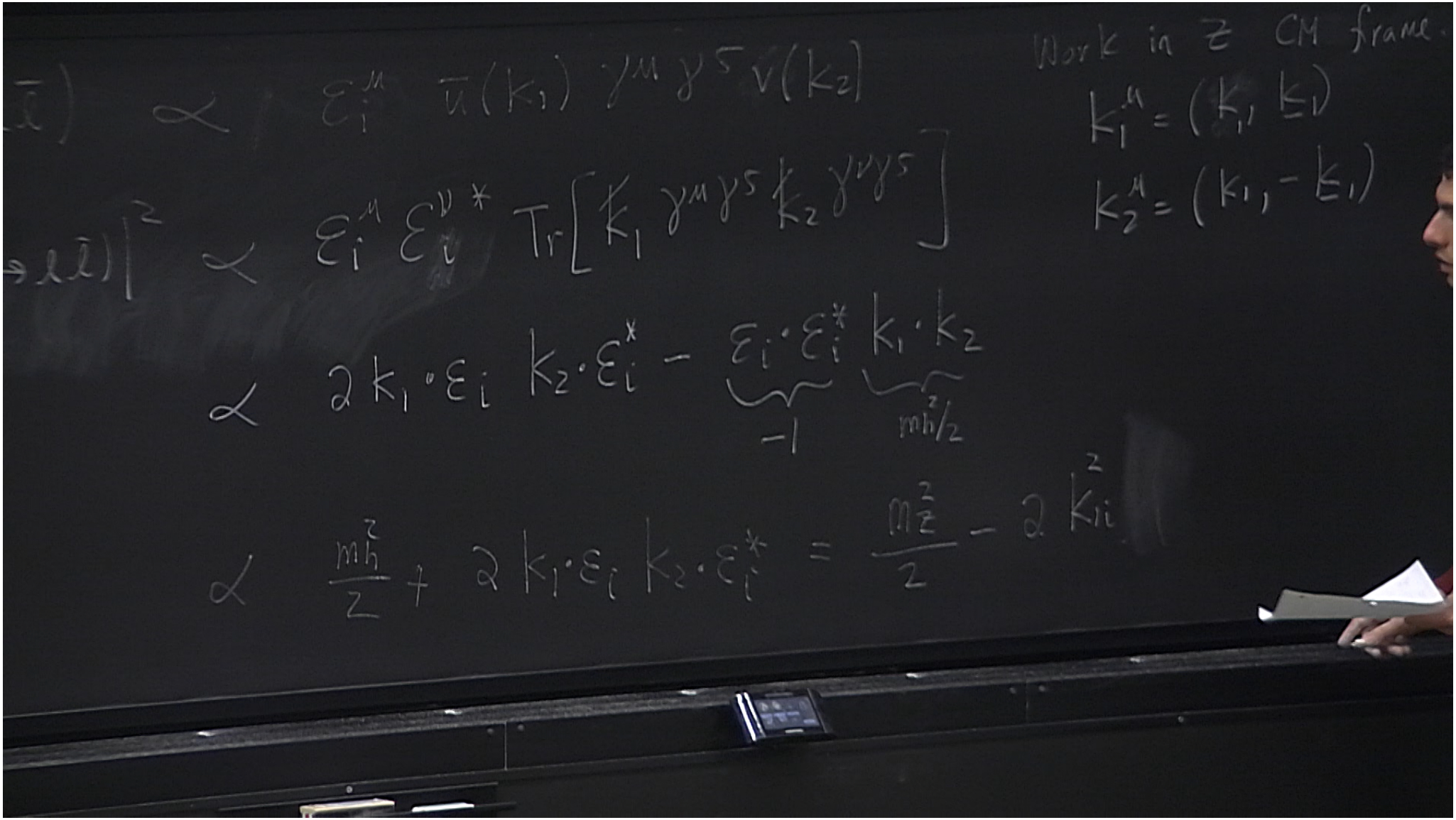

$i\mathcal{M}(Z_i \to l\bar{l}) \propto \varepsilon_i^\mu \, \bar{u}(k_1) \gamma_\mu \gamma^5 v(k_2)$
$\sum_{\text{form spins}} |\mathcal{M}(Z_i \to l\bar{l})|^2 \propto \varepsilon_i^\mu \varepsilon_i^{\nu *} \, \mathrm{Tr}[\not{k}_1 \gamma_\mu \gamma^5 \not{k}_2 \gamma_\nu \gamma^5]$
$\propto 2 k_1 \cdot \varepsilon_i \, k_2 \cdot \varepsilon_i^* - \varepsilon_i \cdot \varepsilon_i^* \, k_1 \cdot k_2$

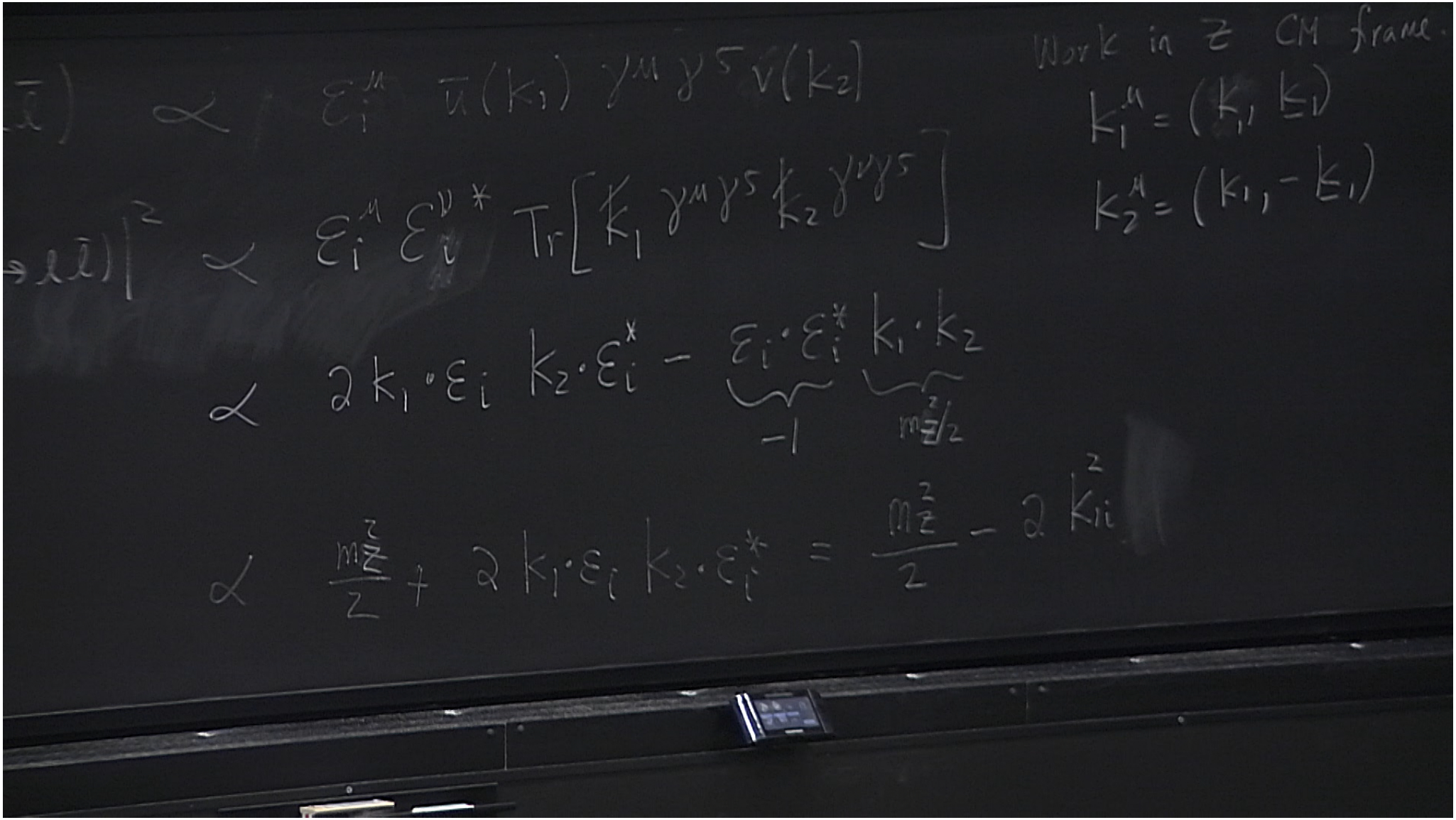
$$i\mathcal{M}(z_i \to l\bar{l}) \propto \varepsilon_i^{\mu}\, \bar{u}(k_1)\, \gamma_\mu \gamma^5\, v(k_2)$$

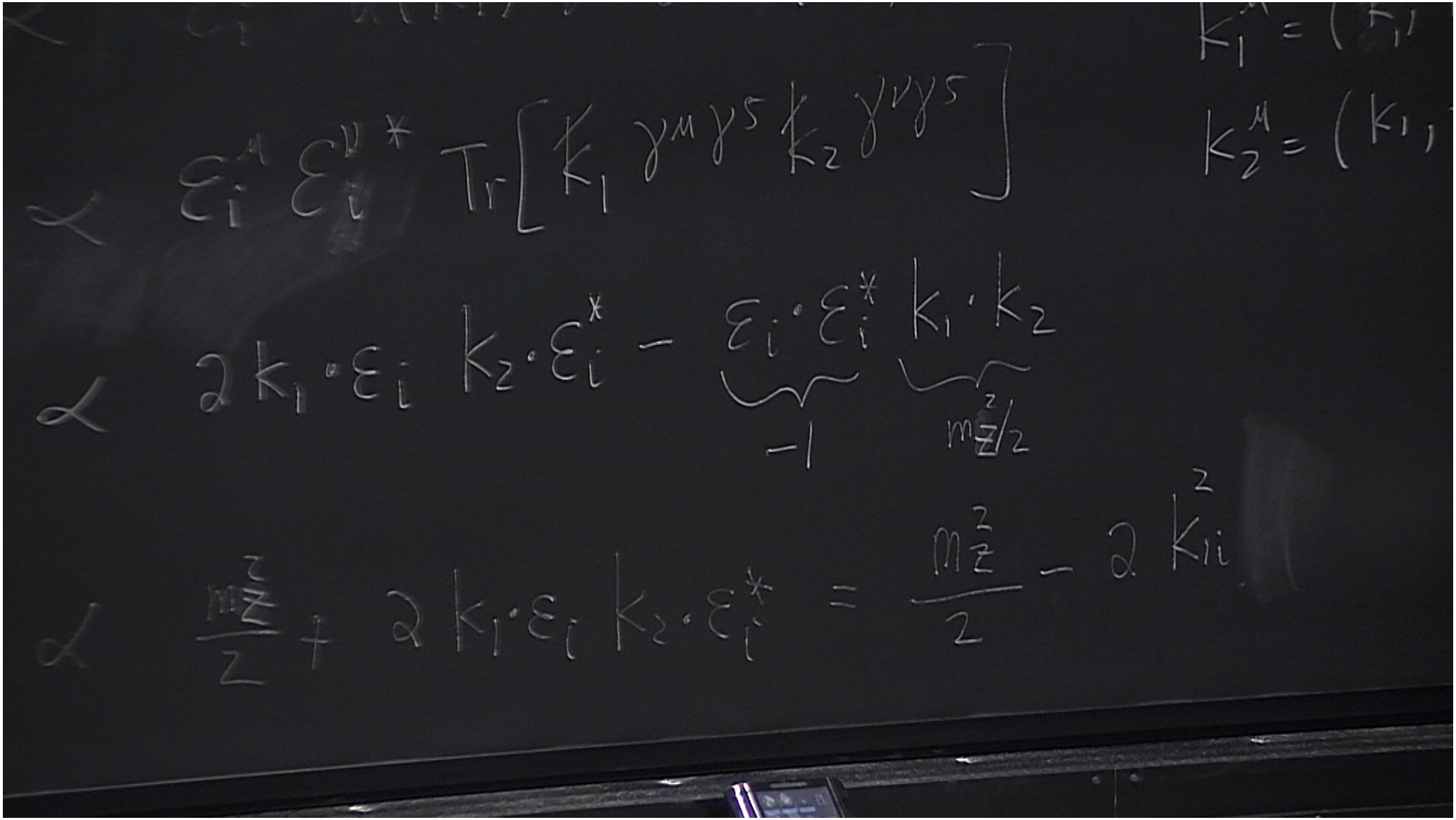
$$\sum_{\text{from spins}} |\mathcal{M}(z_i \to l\bar{l})|^2 \propto \varepsilon_i^{\mu} \varepsilon_i^{\nu *}\, \mathrm{Tr}\left[\not{k}_1 \gamma_\mu \gamma^5 \not{k}_2 \gamma_\nu \gamma^5 \right]$$

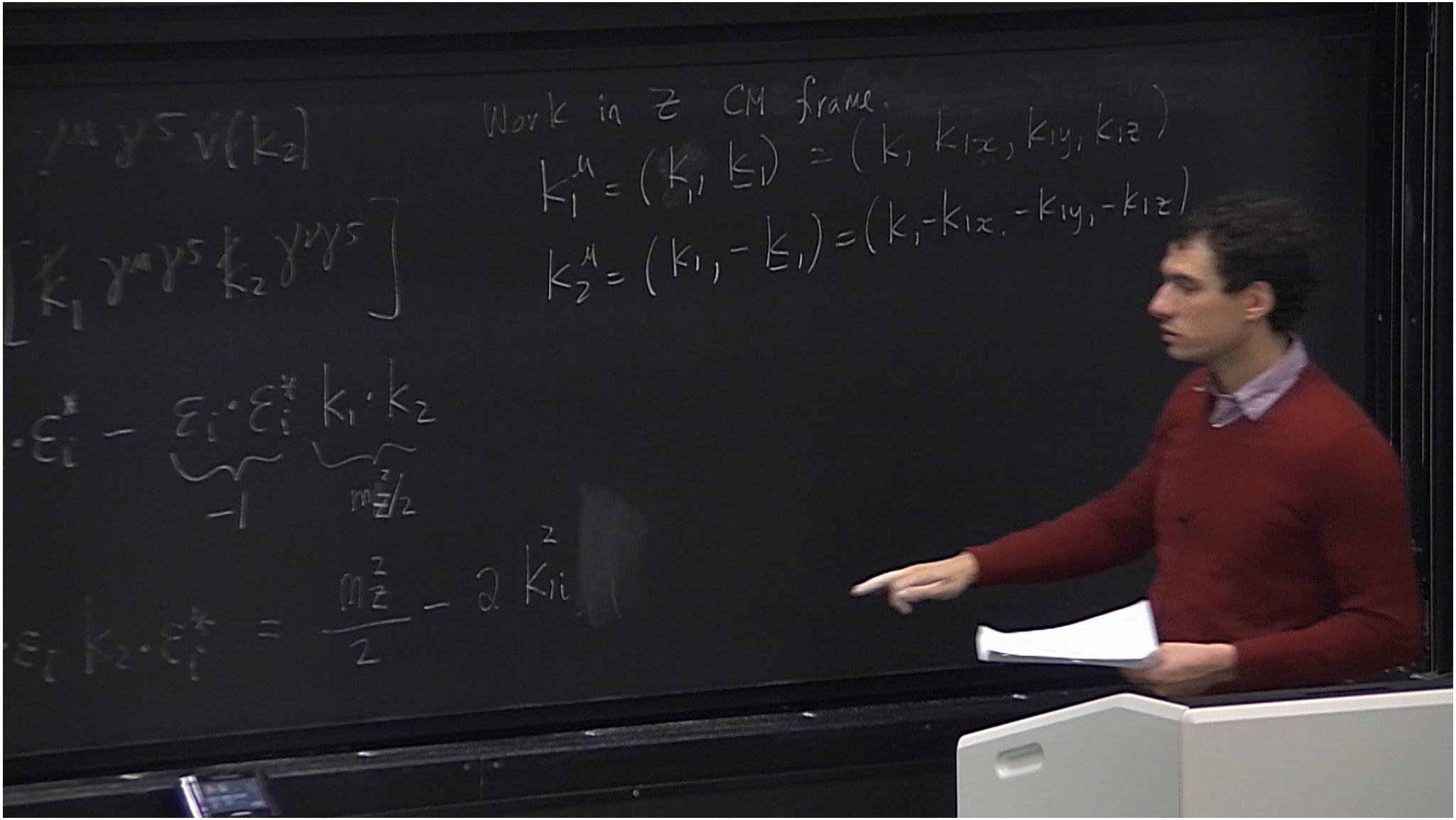
$$\propto 2 k_1 \cdot \varepsilon_i\, k_2 \cdot \varepsilon_i^* - \underbrace{\varepsilon_i \cdot \varepsilon_i^*}_{-1} \underbrace{k_1 \cdot k_2}_{m_h^2/2}$$


$i\mathcal{M}(z_i \to l\bar{l}) \propto \varepsilon_i^\mu \bar{u}(k_1)\gamma_\mu\gamma_5 v(k_2)$
$\sum_{\text{form spins}} |\mathcal{M}(z_i \to l\bar{l})|^2 \propto \varepsilon_i^\mu \varepsilon_i^{\nu *} \mathrm{Tr}[\not{k}_1 \gamma_\mu\gamma_5 \not{k}_2 \gamma_\nu\gamma_5]$
$\propto 2k_1\cdot\varepsilon_i\, k_2\cdot\varepsilon_i^* - \underbrace{\varepsilon_i\cdot\varepsilon_i^*}_{-1}\underbrace{k_1\cdot k_2}_{m_h^2/2}$
$\propto \frac{m_h^2}{2} - 2k_1\cdot\varepsilon_i\, k_2\cdot\varepsilon_i^*$

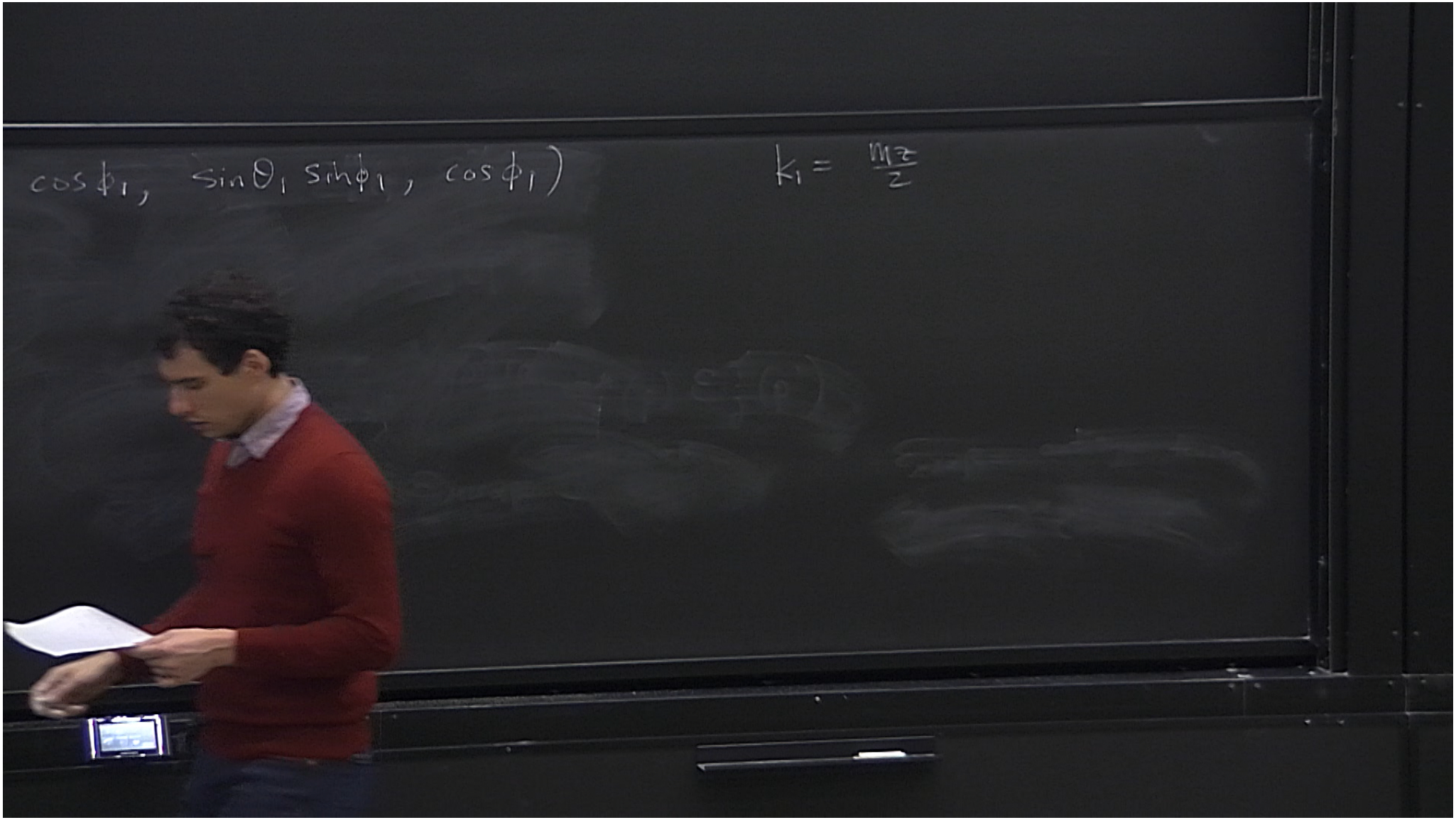

Work in Z CM frame.
$k_1^\mu = (k_1, \vec{k}_1)$
$k_2^\mu = (k_1, -\vec{k}_1)$
$\bar{u}(k_1)\,\gamma^\mu\gamma^5\,v(k_2)$
ε_i^μ
$\varepsilon_i^\mu\,\varepsilon_i^{\nu *}\,\mathrm{Tr}\left[\not{k}_1\,\gamma^\mu\gamma^5\,\not{k}_2\,\gamma^\nu\gamma^5\right]$
$2\,k_1\cdot\varepsilon_i\;k_2\cdot\varepsilon_i^* - \underbrace{\varepsilon_i\cdot\varepsilon_i^*}_{-1}\;\underbrace{k_1\cdot k_2}_{m_h^2/2}$
$\frac{m_h^2}{2} + 2\,k_1\cdot\varepsilon_i\;k_2\cdot\varepsilon_i^* = \frac{m_Z^2}{2} - 2\,k_{1i}^2$


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$2\,k_1\cdot\varepsilon_i\;k_2\cdot\varepsilon_i^* - \underbrace{\varepsilon_i\cdot\varepsilon_i^*}_{-1}\;\underbrace{k_1\cdot k_2}_{m_Z^2/2}$
$\frac{m_Z^2}{2} + 2\,k_1\cdot\varepsilon_i\;k_2\cdot\varepsilon_i^* = \frac{m_Z^2}{2} - 2\,\vec{k}_{1i}^{\,2}$


$k_1^\mu = (k_1$
$k_2^\mu = (k_1,$
$\propto \varepsilon_i^\mu \varepsilon_i^{\nu *} \mathrm{Tr}\left[\not{k}_1 \gamma_\mu \gamma_5 \not{k}_2 \gamma_\nu \gamma_5 \right]$
$\propto 2 k_1 \cdot \varepsilon_i \, k_2 \cdot \varepsilon_i^* - \underbrace{\varepsilon_i \cdot \varepsilon_i^*}_{-1} \underbrace{k_1 \cdot k_2}_{m_Z^2/2}$
$\propto \frac{m_Z^2}{2} + 2 k_1 \cdot \varepsilon_i \, k_2 \cdot \varepsilon_i^* = \frac{m_Z^2}{2} - 2 k_{1i}^2$


Work in Z CM frame.
$k_1^\mu = (k_1, \vec{k}_1) = (k_1, k_{1x}, k_{1y}, k_{1z})$
$k_2^\mu = (k_1, -\vec{k}_1) = (k_1, -k_{1x}, -k_{1y}, -k_{1z})$
$\cdot \varepsilon_i^* - \varepsilon_i \cdot \varepsilon_i^* \; k_1 \cdot k_2$
-1
$m_Z^2/2$
$\varepsilon_i \; k_2 \cdot \varepsilon_i^* = \frac{m_Z^2}{2} - 2 k_{1i}^2$

$$\underline{k}_1 = k_1 \left(\sin\theta_1 \cos\phi_1, \sin\theta_1 \sin\phi_1, \cos\phi_1 \right)$$


cos φ1, sin θ1 sin φ1, cos φ1)
k1 = nπ/2

$$\underline{k}_1 = k_1 \left(\sin\theta_1 \cos\phi_1,\ \sin\theta_1 \sin\phi_1,\ \cos\phi_1 \right) \qquad k_1 = \frac{m_Z}{2}$$

$$\sum_{\text{fermi spins}} |\mathcal{M}(Z_L \to \ell\bar{\ell})|^2$$

$$\underline{k}_1 = k_1 \left(\sin\theta_1 \cos\phi_1,\ \sin\theta_1 \sin\phi_1,\ \cos\theta_1 \right) \qquad k_1 = \frac{m_Z}{2}$$

$$\sum_{\text{ferm spins}} |\mathcal{M}(Z_L \to \ell\bar{\ell})|^2 \propto \frac{m_Z^2}{2}\left(1 - \cos^2\theta_1\right)$$

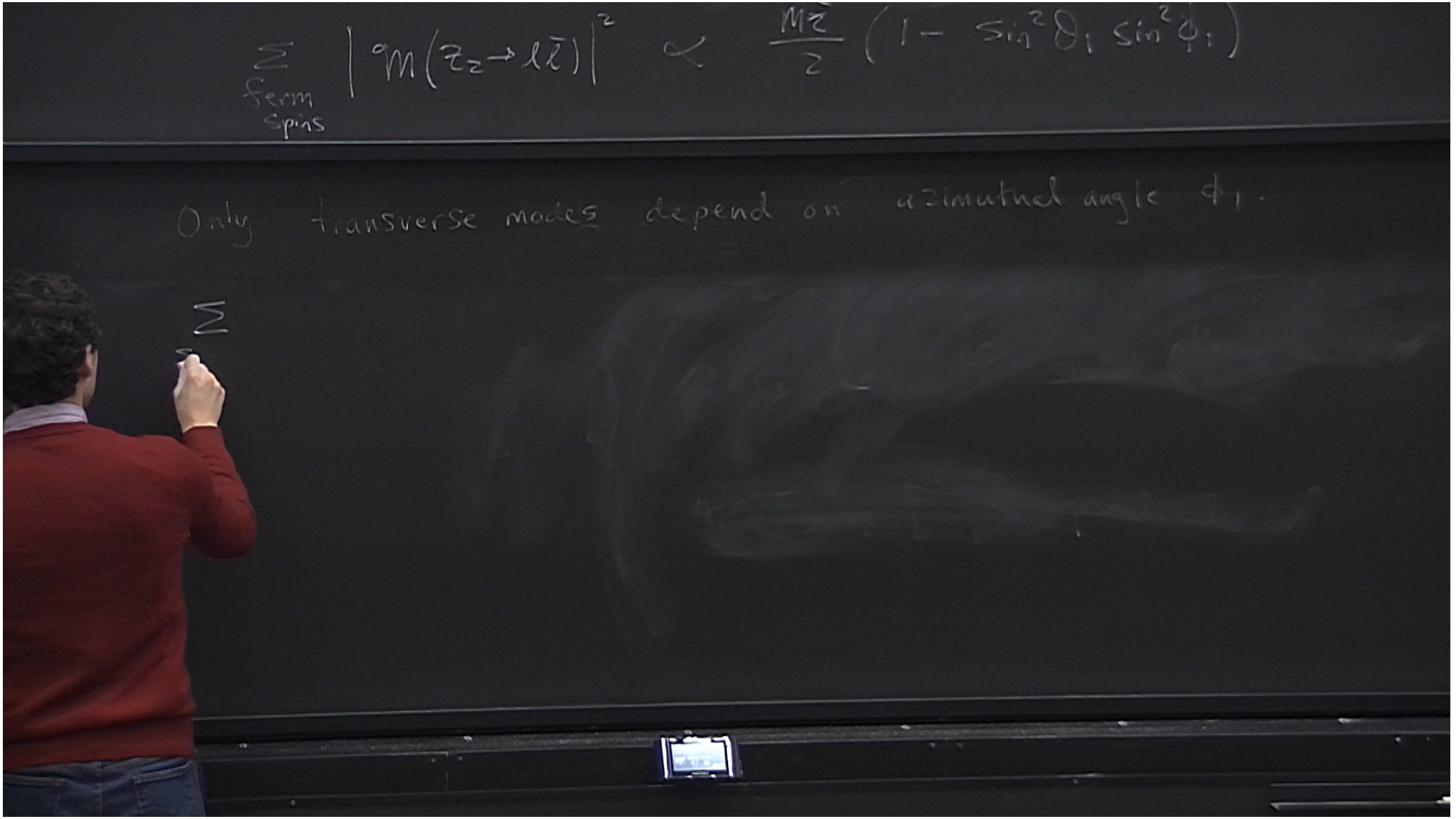
$$\sum_{\text{ferm spins}} |\mathcal{M}(Z_1 \to \ell\bar{\ell})|^2 \propto \frac{m_Z^2}{2}\left(1 - \sin^2\theta_1 \cos^2\phi_1\right)$$

$$\sum_{\text{ferm spins}} |\mathcal{M}(Z_2 \to \ell\bar{\ell})|^2 \propto \frac{m_Z^2}{2}\left(1 - \sin^2\theta_1 \sin^2\phi_1\right)$$

$$\sum_{\text{ferm spins}} \left| \mathcal{M}(Z_2 \to l\bar{l}) \right|^2 \propto \frac{M_Z^2}{2} \left(1 - \sin^2\theta_1 \sin^2\phi_1\right)$$

Only transverse modes depend on azimuthal angle ϕ_1.

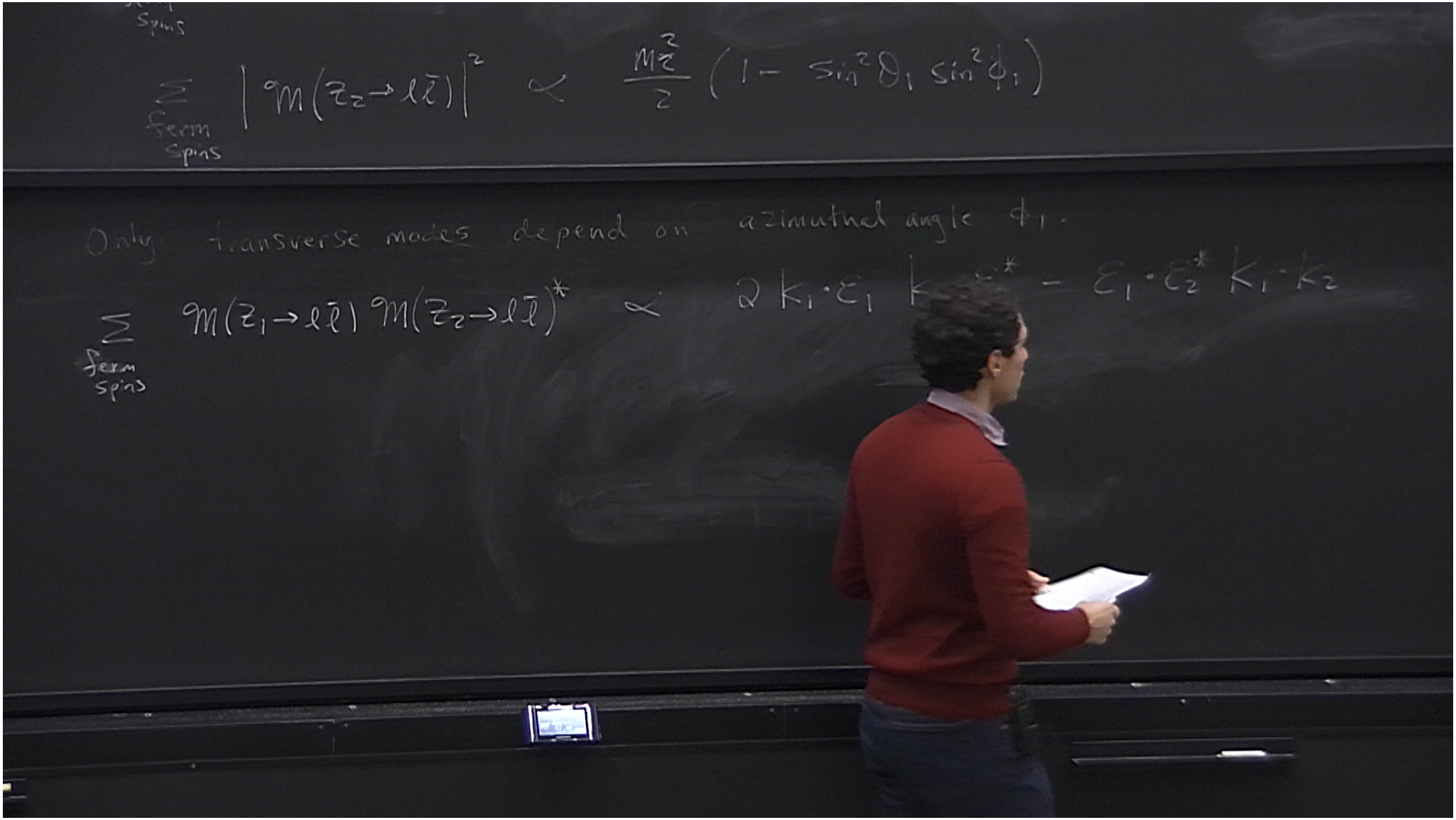
$$\sum_{s}$$



$$\sum_{\text{ferm spins}} \left| \mathcal{M}(Z_2 \to l\bar{l}) \right|^2 \propto \frac{M_Z}{2}\left(1 - \sin^2\theta_1 \sin^2\phi_1\right)$$

Only transverse modes depend on azimuthal angle ϕ_1.

$$\sum_{\text{ferm spins}} \mathcal{M}(Z_1 \to l\bar{l})\, \mathcal{M}(Z_2 \to l\bar{l})^* \propto$$


Spins
$\sum_{\text{ferm spins}} |\mathcal{M}(Z_2 \to l\bar{l})|^2 \propto \frac{M_Z^2}{2}(1 - \sin^2\theta_1 \sin^2\phi_1)$
Only transverse modes depend on azimuthal angle ϕ_1.
$\sum_{\text{ferm spins}} \mathcal{M}(Z_1 \to l\bar{l})\,\mathcal{M}(Z_2 \to l\bar{l})^* \propto 2\,k_1\cdot\varepsilon_1\, k$ $- \varepsilon_1\cdot\varepsilon_2^*\, k_1\cdot k_2$

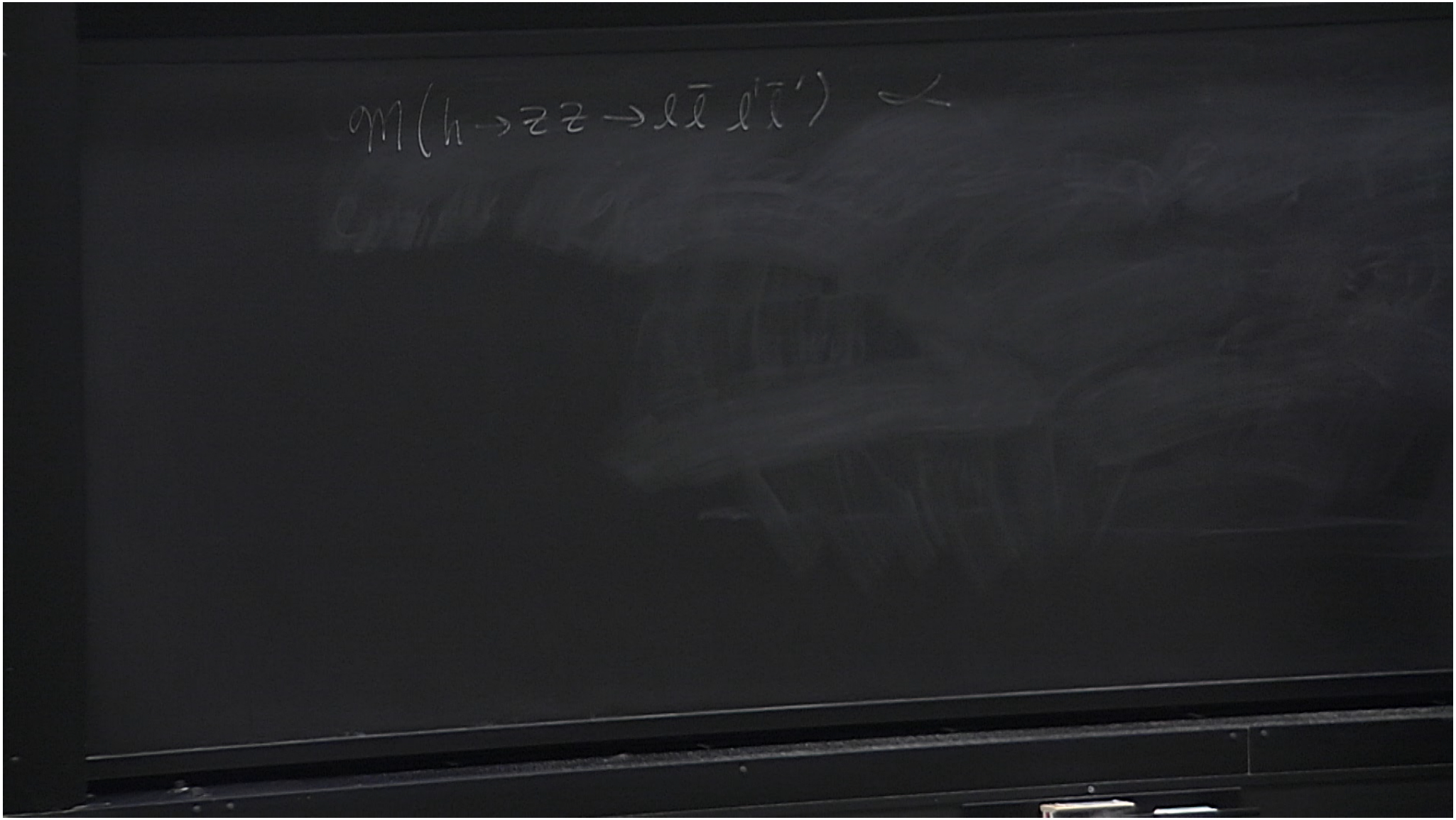
$$\sum_{\text{ferm spins}} |\mathcal{M}(Z_2 \to l\bar{l})|^2 \propto \frac{m_Z^2}{2}\left(1 - \sin^2\theta_1 \sin^2\phi_1\right)$$

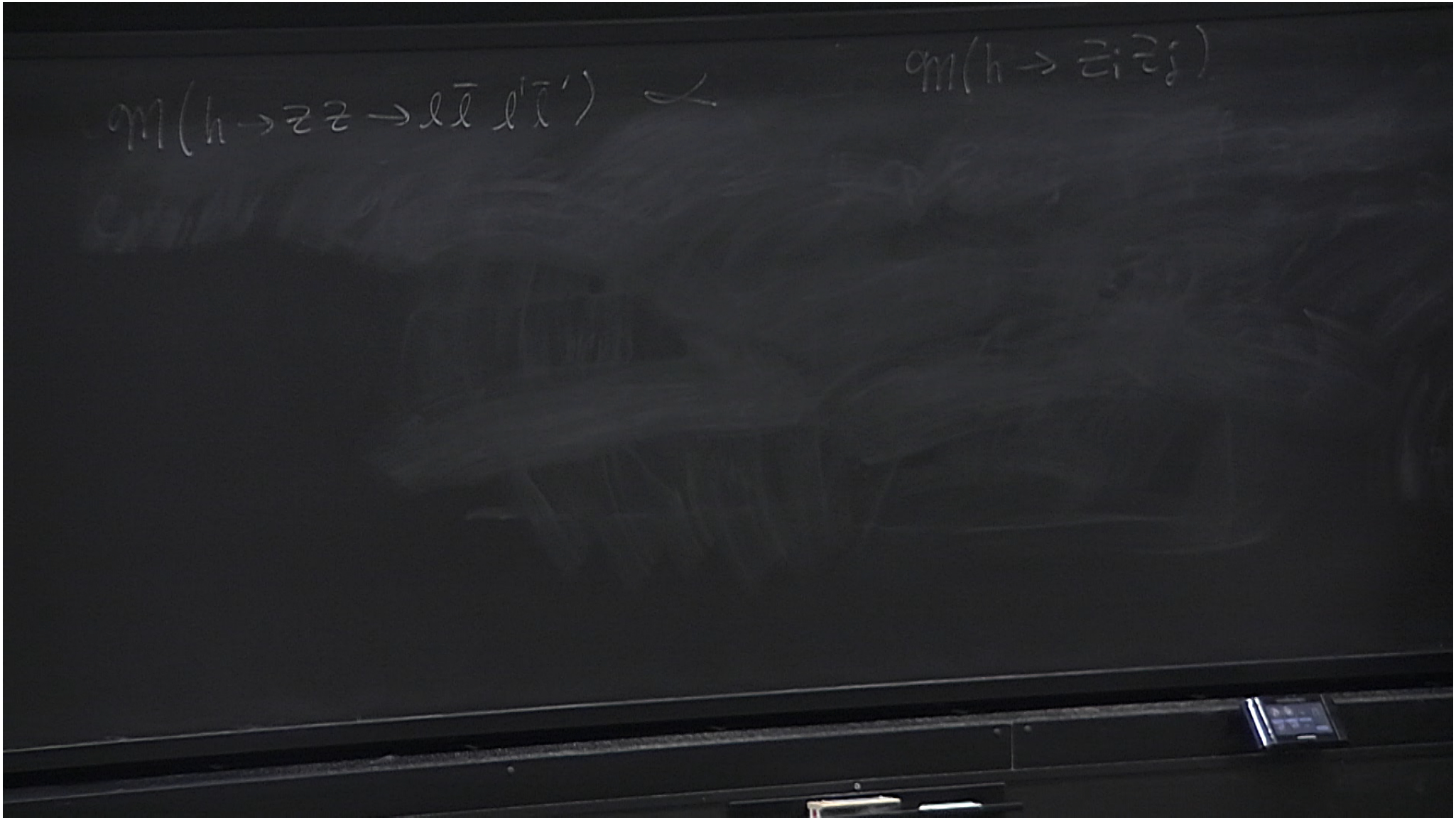
Only transverse modes depend on azimuthal angle ϕ_1.

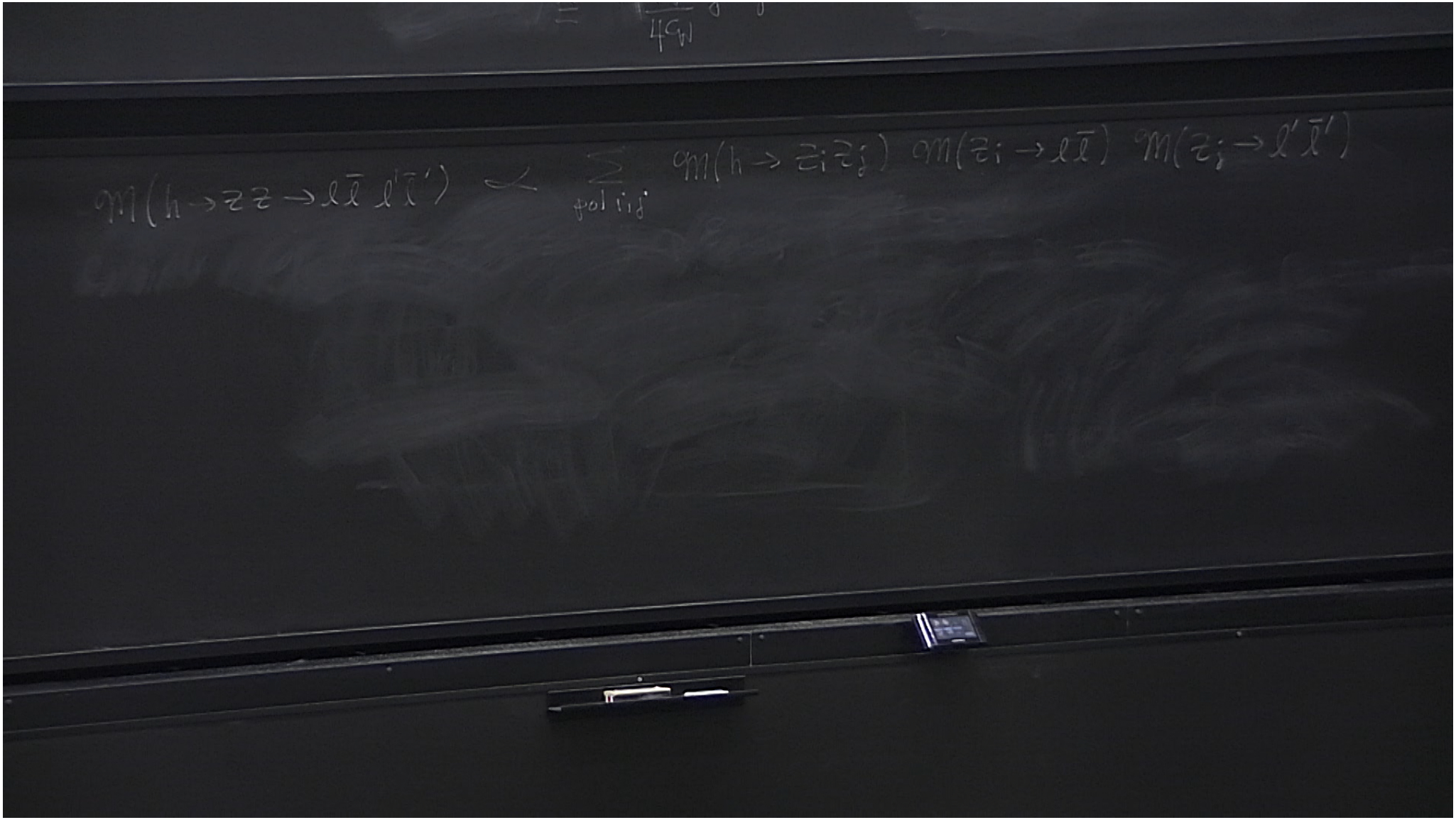
$$\sum_{\text{ferm spins}} \mathcal{M}(Z_1 \to l\bar{l})\,\mathcal{M}(Z_2 \to l\bar{l})^* \propto 2\,k_1\cdot\varepsilon_1\; k_2\cdot\varepsilon_2^* - \cancel{\varepsilon_1\cdot\varepsilon_2^*}^{\to 0}\, k_1\cdot k_2$$

$$\propto -2\,k_{1x}k_{1y}$$

$$\propto -\frac{m_Z^2}{2}\sin^2\theta_1 \sin\phi_1\cos\phi_1$$


$m(h \to ZZ \to l\bar{l}\, l'\bar{l}')$

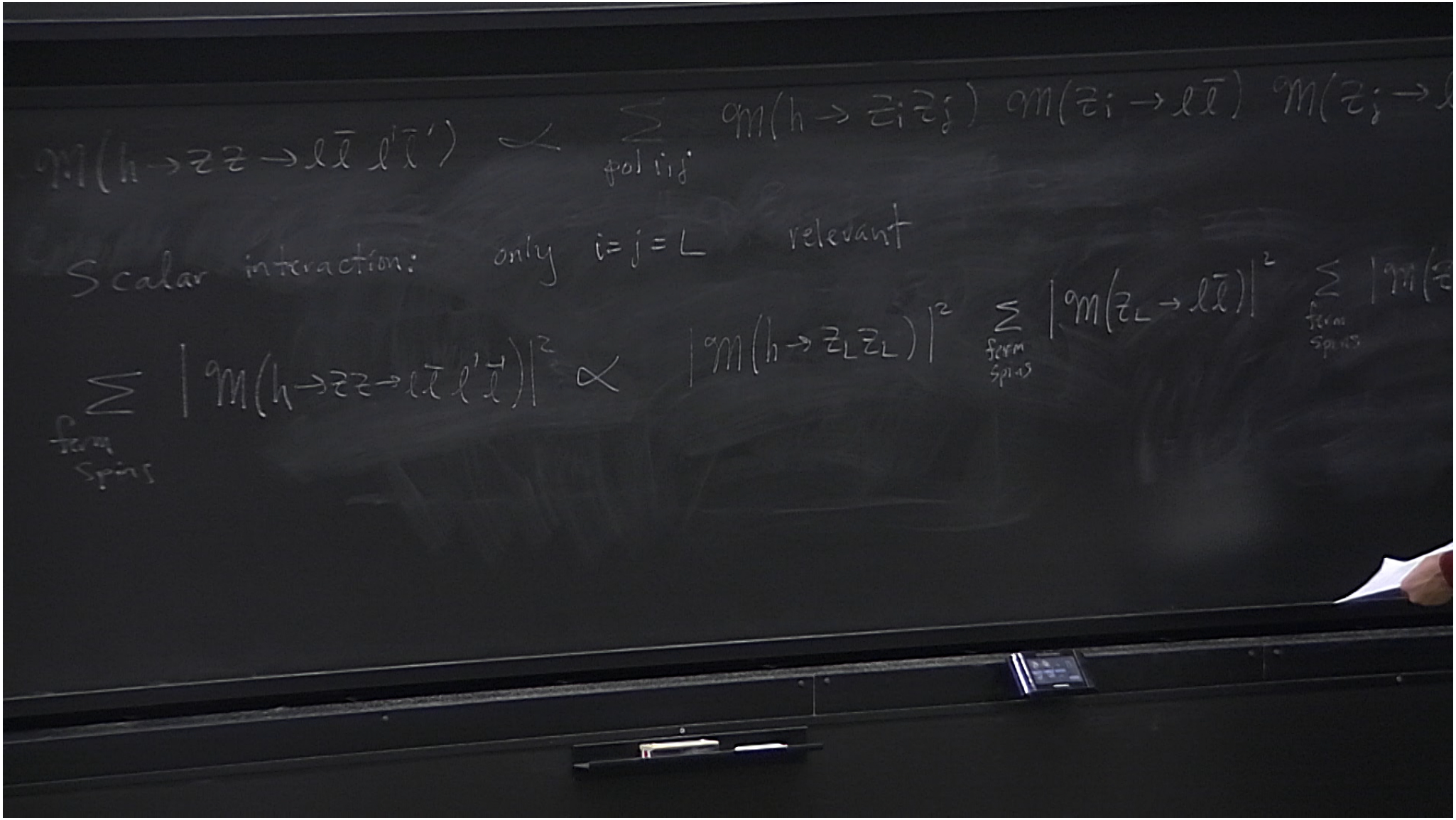

$gg(h \to ZZ \to l\bar{l}\, l'\bar{l}')$
$gg(h \to Z_i Z_j)$

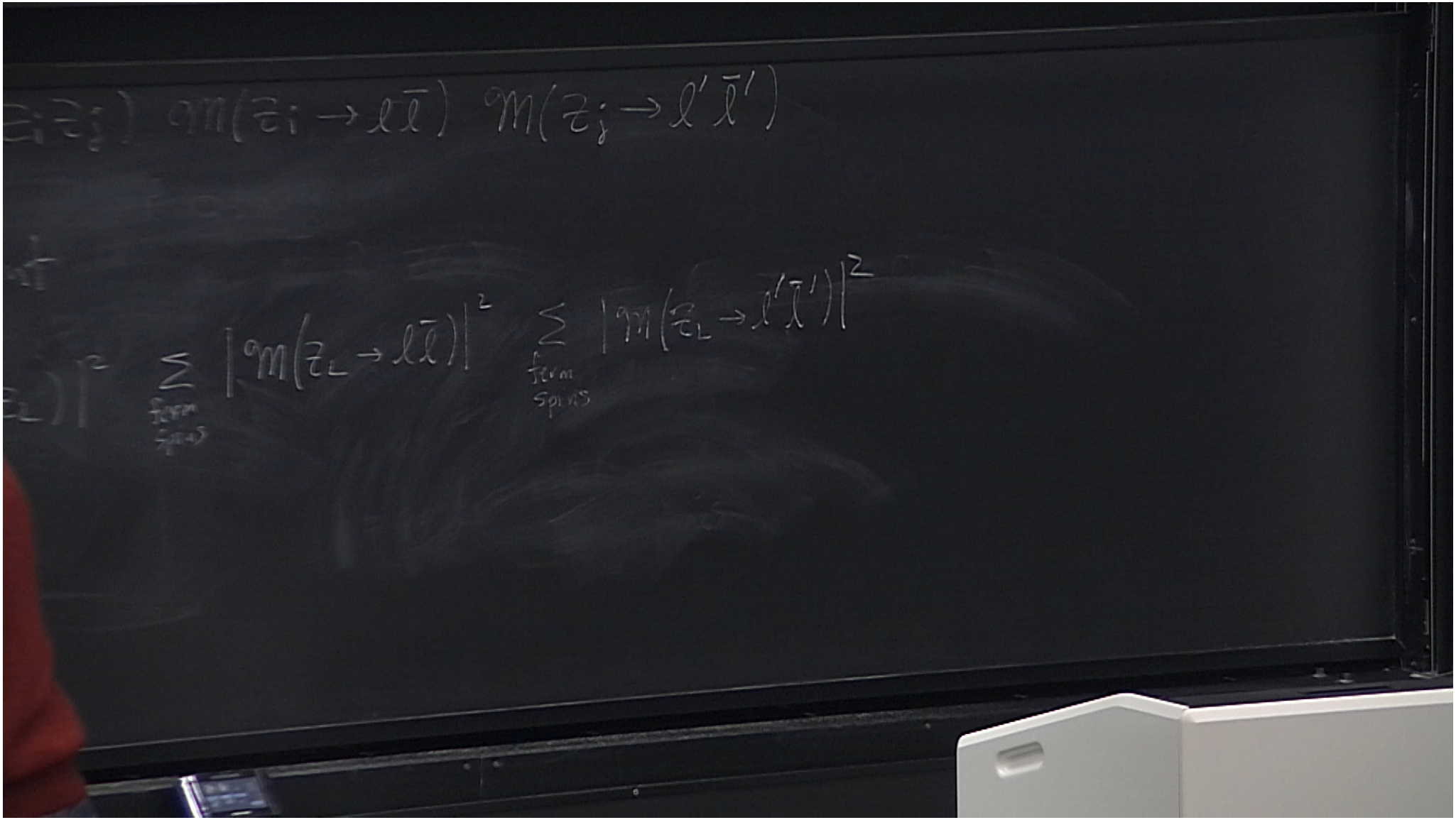

$\mathcal{M}(h \to ZZ \to l\bar{l}\, l'\bar{l}') \propto \sum_{pol\ i,j} \mathcal{M}(h \to Z_i Z_j)\, \mathcal{M}(Z_i \to l\bar{l})\, \mathcal{M}(Z_j \to l'\bar{l}')$

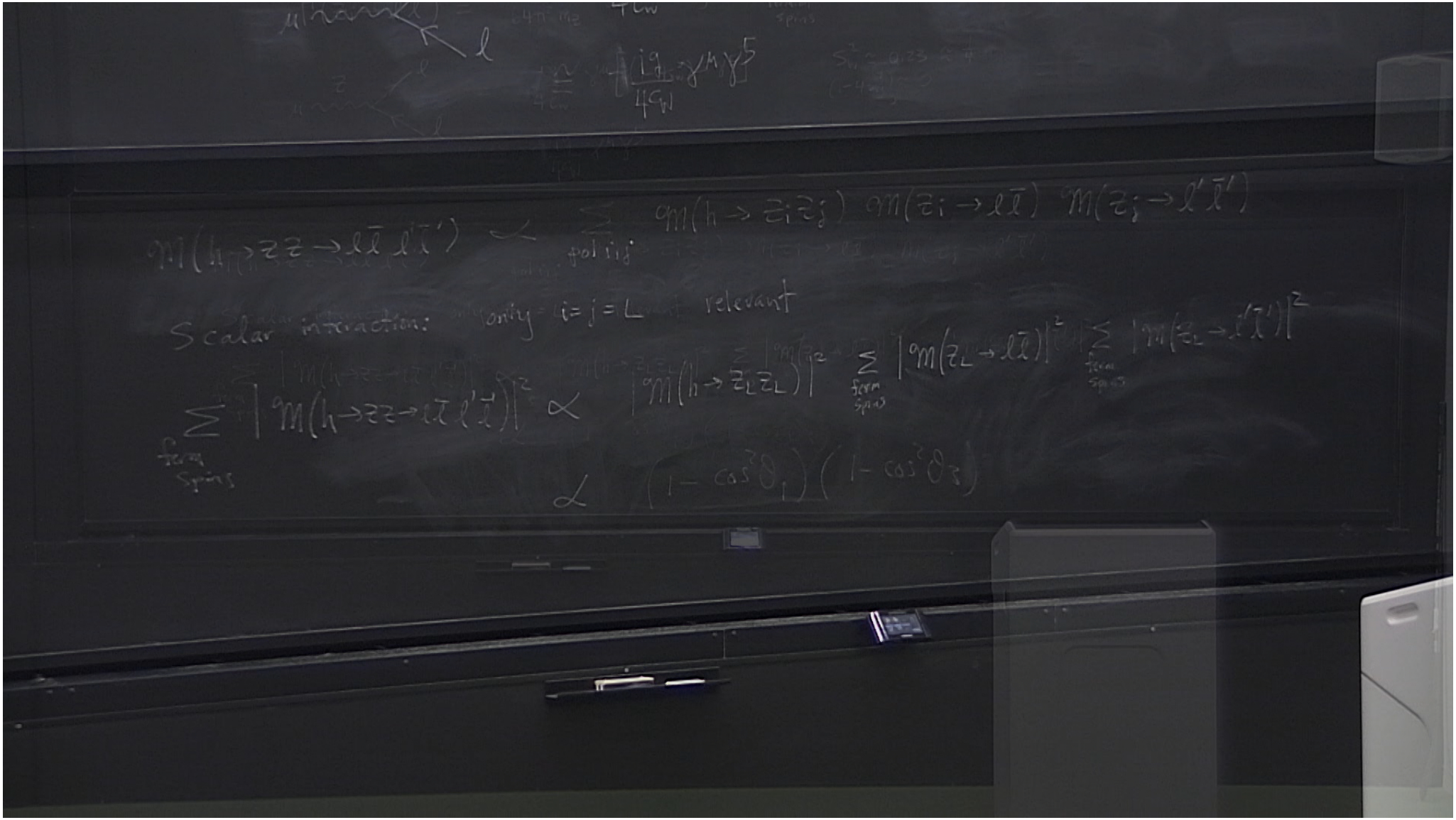
$\mathcal{M}(h \to ZZ \to l\bar{l}\, l'\bar{l}') \propto \sum_{\text{pol } i,j} \mathcal{M}(h \to Z_i Z_j)\, \mathcal{M}(Z_i \to$

Scalar interaction: only $i = j = L$ relevant

$$\sum_{\substack{\text{ferm} \\ \text{spins}}} \left| \mathcal{M}(h \to ZZ \to l\bar{l}\, l'\bar{l}') \right|^2 \propto$$


$\mathcal{M}(h \to ZZ \to l\bar{l}\, l'\bar{l}') \propto \sum_{\text{pol } i,j} \mathcal{M}(h \to Z_i Z_j)\, \mathcal{M}(Z_i \to l\bar{l})\, \mathcal{M}(Z_j \to$
Scalar interaction: only $i=j=L$ relevant
$\sum_{\text{ferm spins}} |\mathcal{M}(h \to ZZ \to l\bar{l}\, l'\bar{l}')|^2 \propto |\mathcal{M}(h \to Z_L Z_L)|^2 \sum_{\text{ferm spins}} |\mathcal{M}(Z_L \to l\bar{l})|^2 \sum_{\text{ferm spins}} |\mathcal{M}($


$\mathcal{M}(\bar{z}_i \to l\bar{l})\ \mathcal{M}(z_j \to l'\bar{l}')$
$\sum_{\text{fermi spins}} |\mathcal{M}(\bar{z}_L \to l\bar{l})|^2 \sum_{\text{fermi spins}} |\mathcal{M}(z_L \to l'\bar{l}')|^2$


$\mathcal{M}(h \to ZZ \to l\bar{l}\, l'\bar{l}') \propto \sum_{pol\, i,j} \mathcal{M}(h \to Z_i Z_j)\, \mathcal{M}(Z_i \to l\bar{l})\, \mathcal{M}(Z_j \to l'\bar{l}')$
Scalar interaction: only $i=j=L$ relevant
$\sum_{\text{form spins}} |\mathcal{M}(h \to ZZ \to l\bar{l}\, l'\bar{l}')|^2 \propto |\mathcal{M}(h \to Z_L Z_L)|^2 \sum_{\text{form spins}} |\mathcal{M}(Z_L \to l\bar{l})|^2 \sum_{\text{form spins}} |\mathcal{M}(Z_L \to l'\bar{l}')|^2$
$\propto (1-\cos^2\theta_1)(1-\cos^2\theta_2)$

$$\mathcal{M}(h \to ZZ \to l\bar{l}\, l'\bar{l}') \propto \sum_{pol\ i,j} \mathcal{M}(h \to Z_i Z_j)\, \mathcal{M}(Z_i \to l\bar{l})\, \mathcal{M}(Z_j \to l'\bar{l}')$$

Scalar interaction: only $i = j = L$ relevant

$$\sum_{ferm\ spins} |\mathcal{M}(h \to ZZ \to l\bar{l}\, l'\bar{l}')|^2 \propto |\mathcal{M}(h \to Z_L Z_L)|^2 \sum_{ferm\ spins} |\mathcal{M}(Z_L \to l\bar{l})|^2 \sum_{ferm\ spins} |\mathcal{M}(Z_L \to l'\bar{l}')|^2$$

$$\propto (1 - \cos^2\theta_1)(1 - \cos^2\theta_2)$$

f. leptons.

$$\sum |\mathcal{M}(Z_i \to l\bar{l})|^2$$

No dependence on ϕ_1, ϕ_3 : $\Rightarrow \frac{d\Gamma}{d\phi}$

No dependence on ϕ_1, ϕ_3 : $\Rightarrow \quad \frac{dP}{d\phi} = \text{const}$

No dependence on ϕ_1, ϕ_3 : $\Rightarrow \frac{d\Gamma}{d\phi} =$

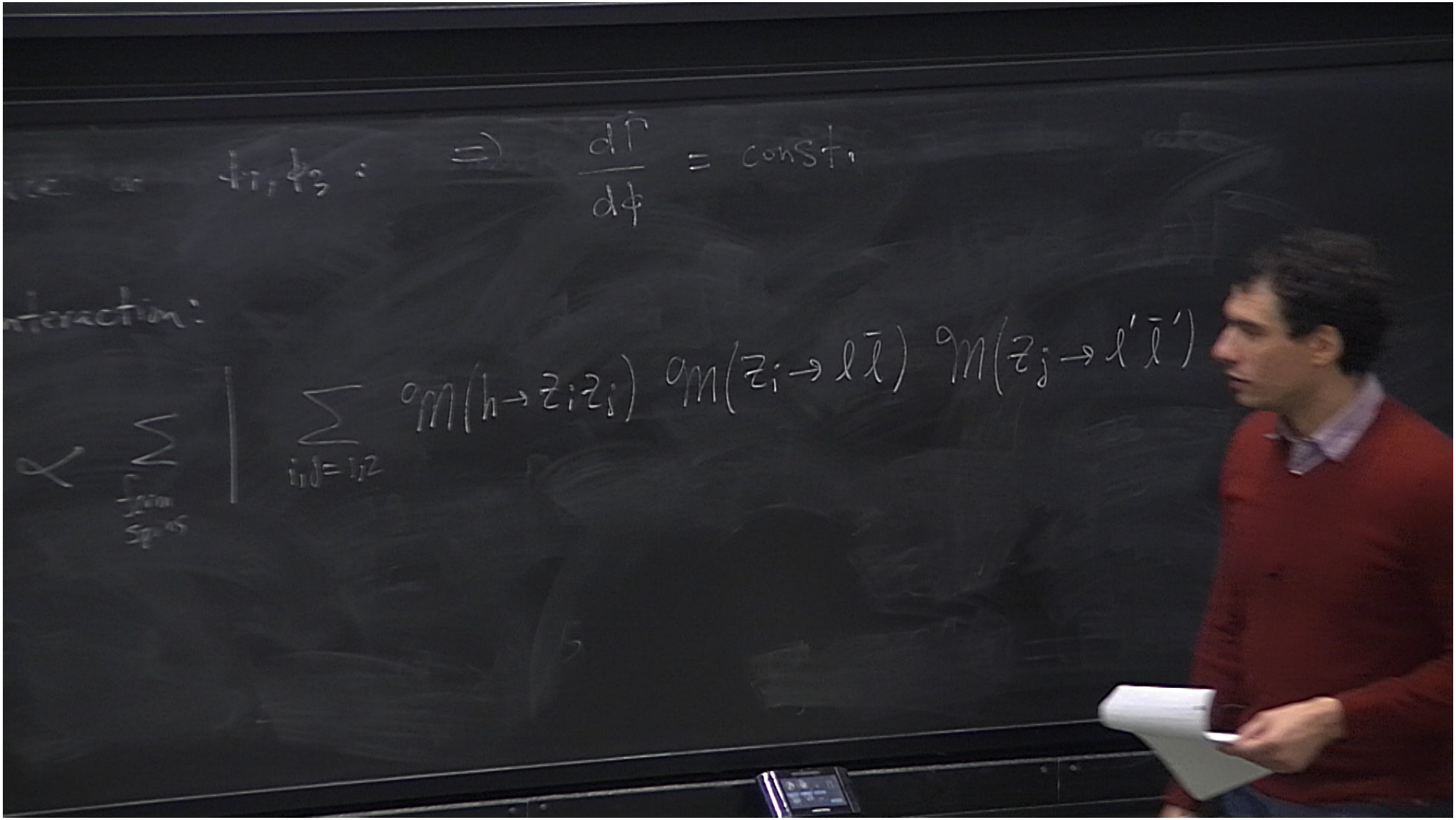
Pseudoscalar interaction:

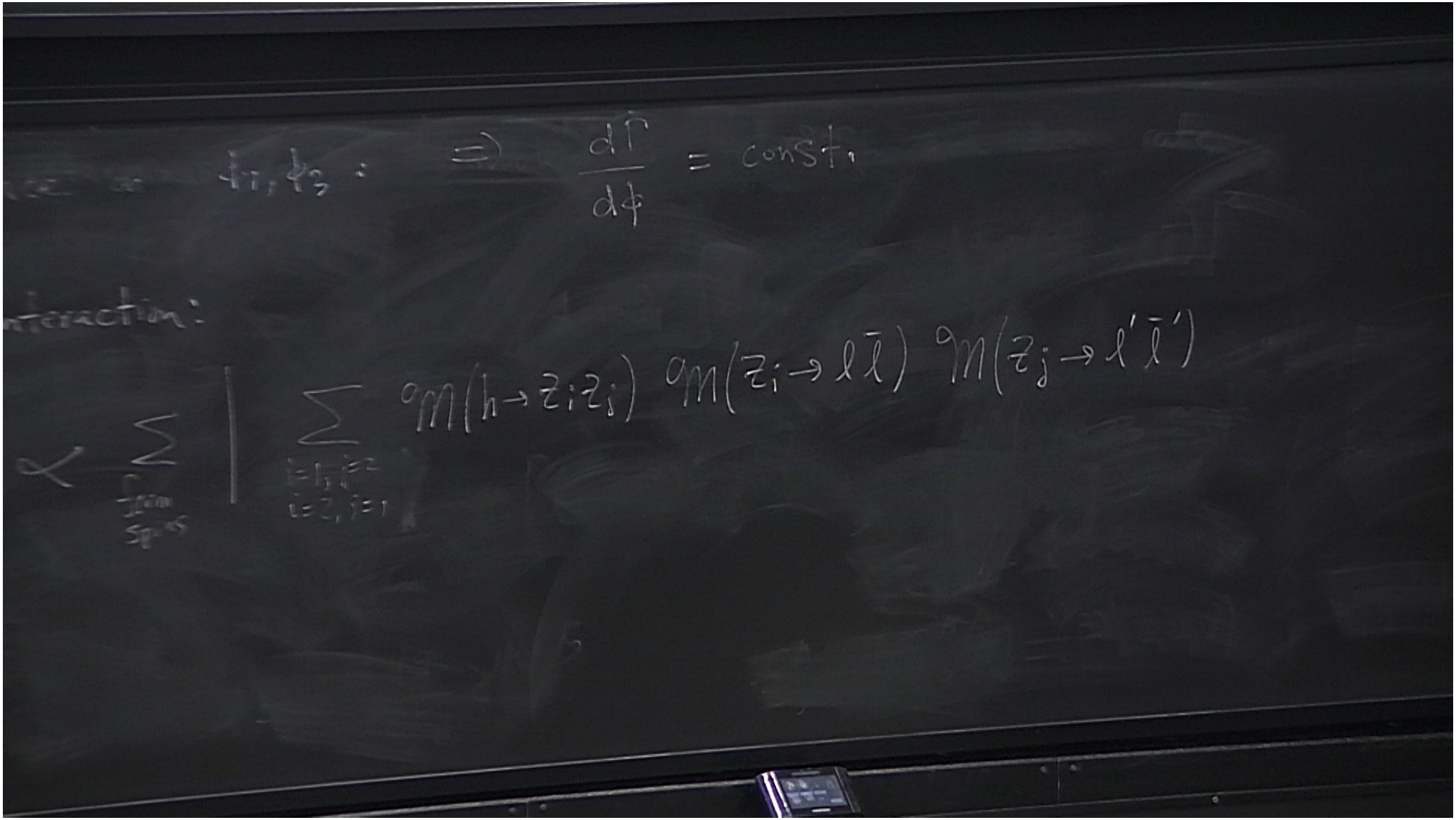
$$\sum_{\substack{\text{fermi}\\ \text{spins}}} \left| \mathcal{M}(h \to ZZ \to l\bar{l}\, l'\bar{l}') \right|^2 \propto \sum_{\substack{\text{fermi}\\ \text{spins}}} \left| \mathcal{M}(h \to Z_i Z_i) \, \mathcal{M}(\bar{Z} \right.$$

ϕ_1, ϕ_2 : $\Rightarrow$ $\frac{d\Gamma}{d\phi} = \text{const.}$

nteraction:

$$\propto \sum_{\substack{\text{final} \\ \text{spins}}} \left| \sum_{i,j=} g_m(h \to z_i z_j)\, g_m(z_i \to l\bar{l})\, g_m(z_j \to l'\bar{l}') \right.$$


ϕ_1, ϕ_2 : $\Rightarrow$ $\frac{d\Gamma}{d\phi}$ = const.
interaction:
$\propto \sum_{\text{spins}} \left| \sum_{i,j=1,2} g_m(h \to z_i z_j)\, g_m(z_i \to l\bar{l})\, g_m(z_j \to l'\bar{l}') \right.$

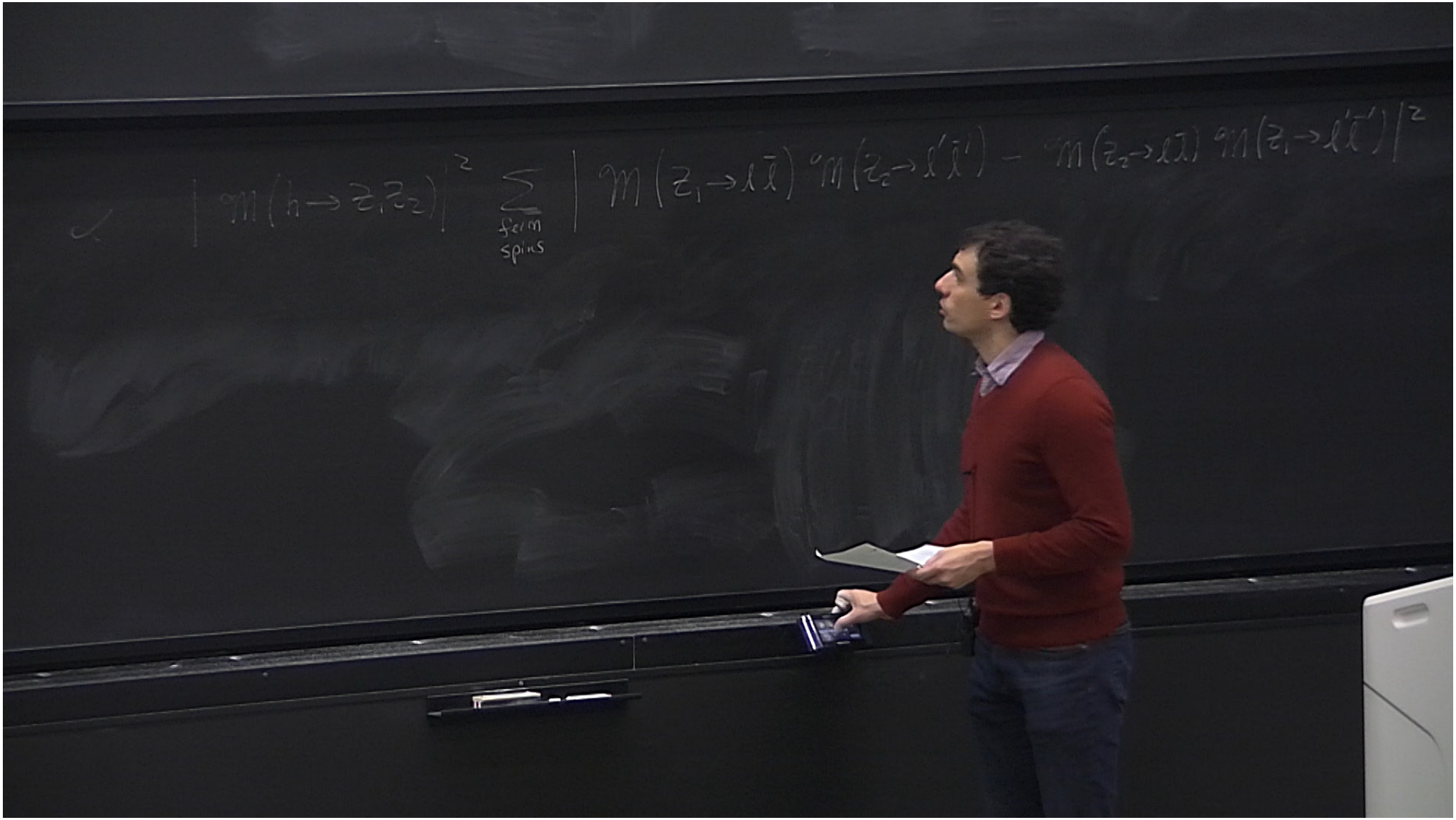

ϕ_1, ϕ_2 : $\Rightarrow$ $\frac{d\Gamma}{d\phi}$ = const.
interaction:
$\propto \sum_{\substack{\text{diagrams} \\ \text{spins}}} \left| \sum_{\substack{i=1,2 \\ i=2,j=1}} \right.$
$g_n(h \to z_i z_j)\ g_n(z_i \to l\bar{l})\ g_n(z_j \to l'\bar{l}')$

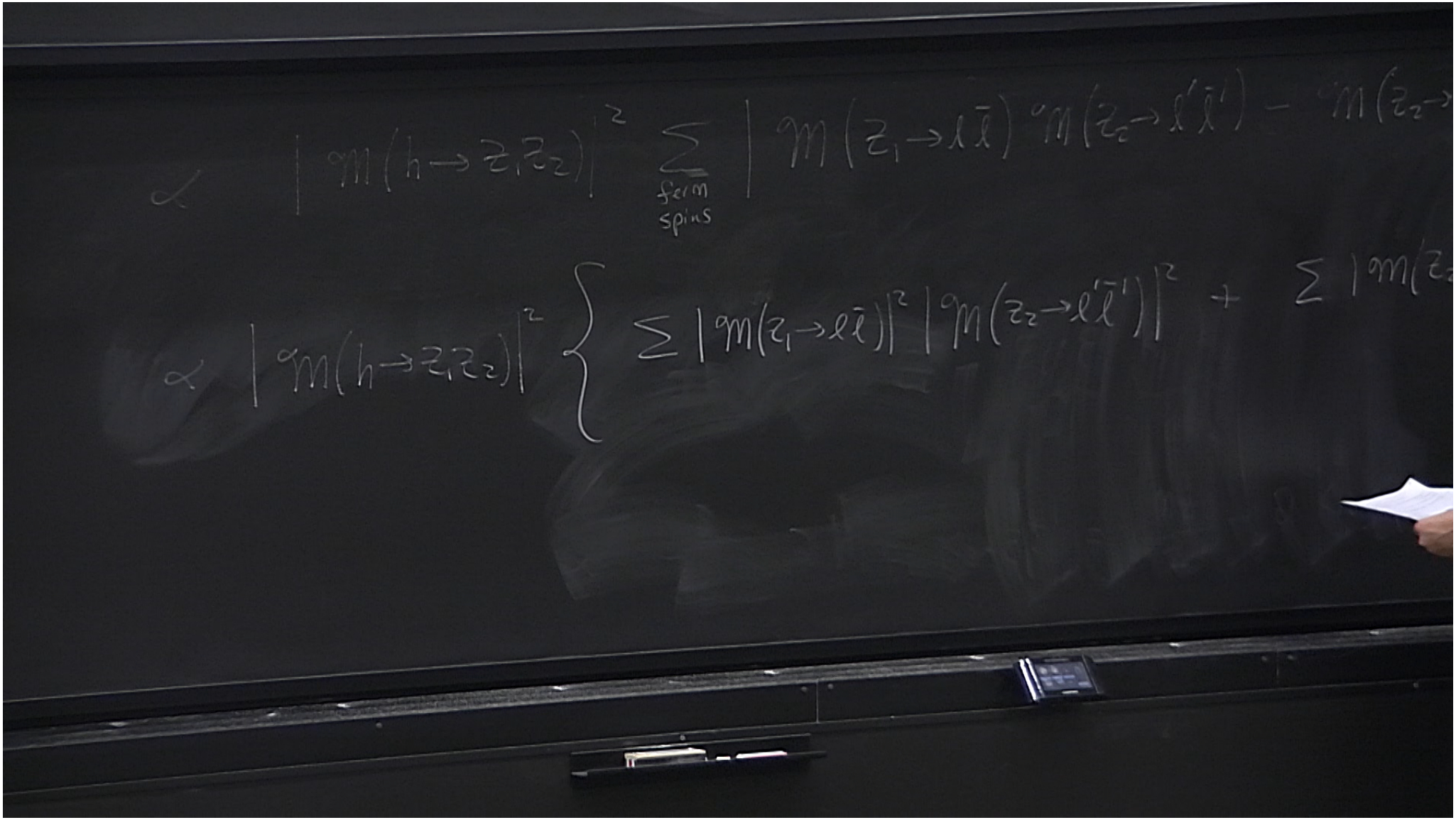
No dependence on ϕ_1, ϕ_3 : $\Rightarrow \quad \frac{d\hat{\Gamma}}{d\phi} = \text{const.}$

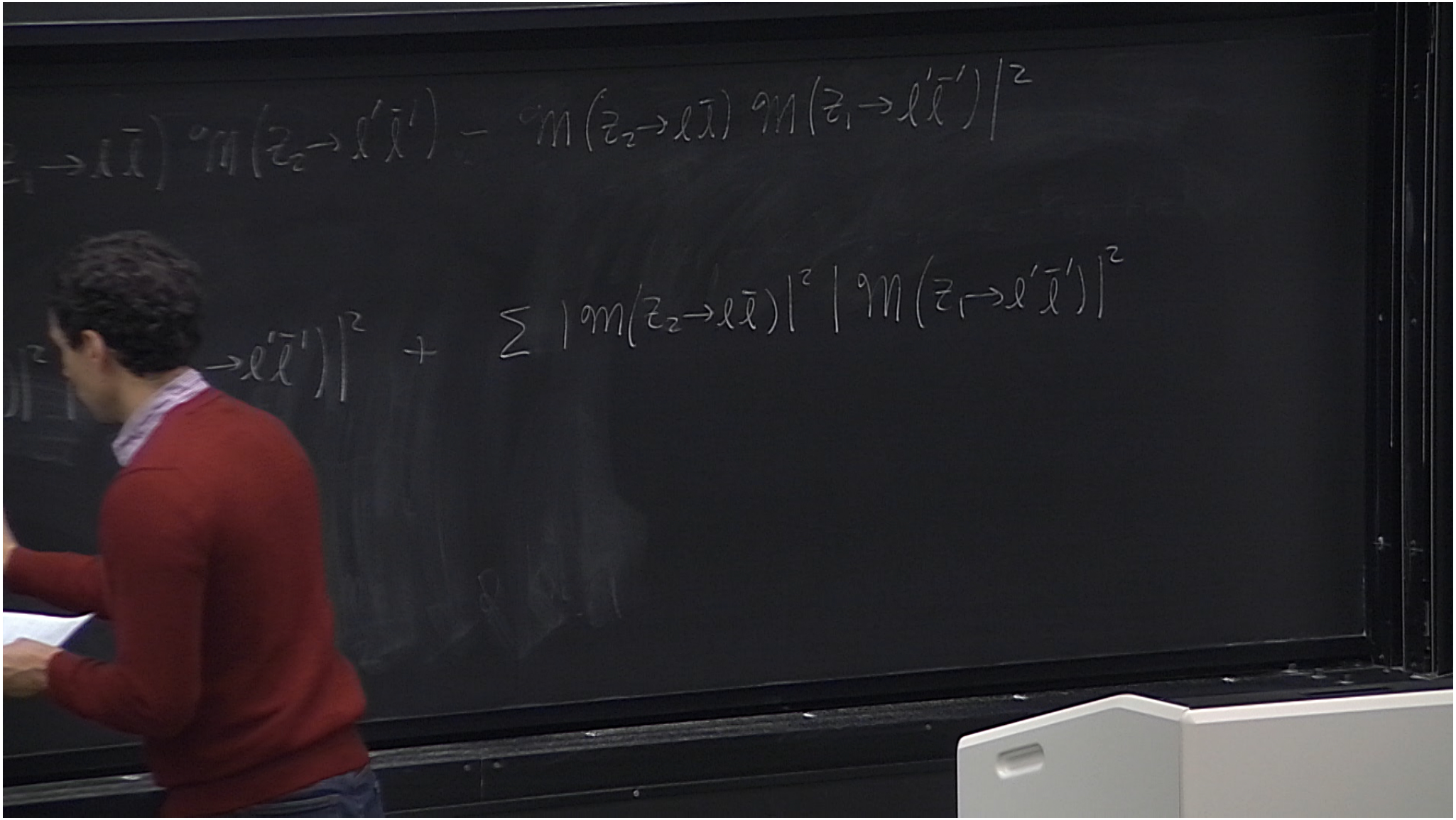
Pseudoscalar interaction:

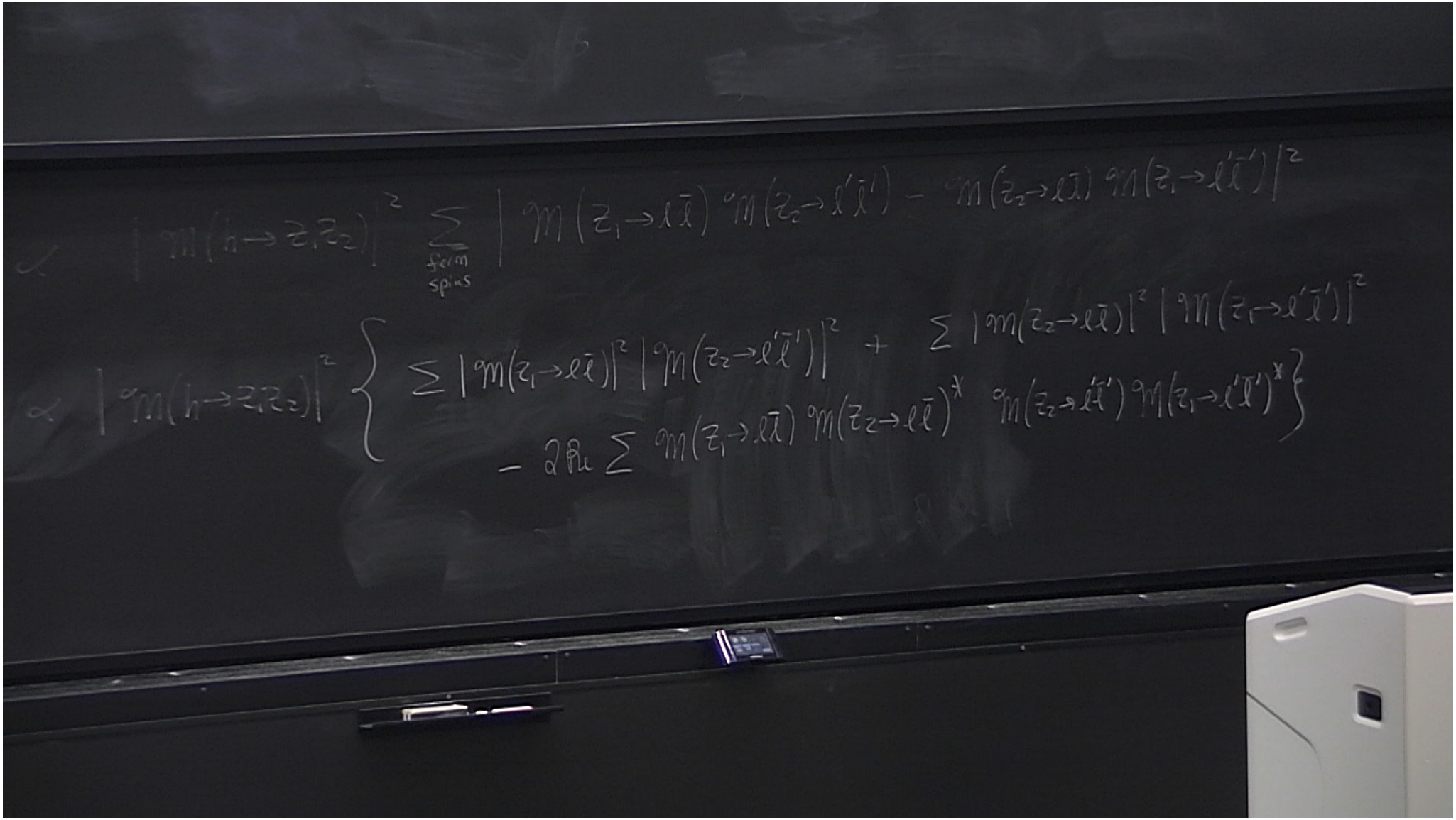
$$\sum_{\text{fermi spins}} \left| \mathcal{M}(h \to ZZ \to l\bar{l}\, l'\bar{l}') \right|^2 \propto \sum_{\text{fermi spins}} \left| \sum_{\substack{i=1,j=2 \\ i=2,j=1}} \mathcal{M}(h \to Z_i Z_j)\, \mathcal{M}(Z_i \to l\bar{l})\, \mathcal{M}(Z_j \to l'\bar{l}') \right|^2$$

Work in Z CM


$\propto |\mathcal{M}(h \to Z_1 Z_2)|^2 \sum_{\text{ferm spins}} |\mathcal{M}(Z_1 \to l\bar{l}) \mathcal{M}(Z_2 \to l'\bar{l}') - \mathcal{M}(Z_2 \to l\bar{l}) \mathcal{M}(Z_1 \to l'\bar{l}')|^2$


$\propto |\mathcal{M}(h \to Z_1 Z_2)|^2 \sum_{\text{ferm spins}} |\mathcal{M}(Z_1 \to l\bar{l})\,\mathcal{M}(Z_2 \to l'\bar{l}') - \mathcal{M}(Z_2 \to$
$\propto |\mathcal{M}(h \to Z_1 Z_2)|^2 \left\{ \sum |\mathcal{M}(Z_1 \to l\bar{l})|^2 |\mathcal{M}(Z_2 \to l'\bar{l}')|^2 + \sum |\mathcal{M}(Z_2$


$\mathcal{M}(z_2 \to \ell\bar{\ell})\,\mathcal{M}(z_1 \to \ell'\bar{\ell}') \Big|^2$
$\to \ell\bar{\ell}') \Big|^2 + \sum |\mathcal{M}(z_2 \to \ell\bar{\ell})|^2 \, |\mathcal{M}(z_1 \to \ell'\bar{\ell}')|^2$


$\propto |\mathcal{M}(h \to z_1 z_2)|^2 \sum_{\text{ferm spins}} |\mathcal{M}(z_1 \to l\bar{l})\,\mathcal{M}(z_2 \to l'\bar{l}') - \mathcal{M}(z_2 \to l\bar{l})\,\mathcal{M}(z_1 \to l'\bar{l}')|^2$
$\propto |\mathcal{M}(h \to z_1 z_2)|^2 \Big\{ \sum |\mathcal{M}(z_1 \to l\bar{l})|^2 |\mathcal{M}(z_2 \to l'\bar{l}')|^2 + \sum |\mathcal{M}(z_2 \to l\bar{l})|^2 |\mathcal{M}(z_1 \to l'\bar{l}')|^2$
$- 2\,\mathrm{Re} \sum \mathcal{M}(z_1 \to l\bar{l})\,\mathcal{M}(z_2 \to l\bar{l})^* \,\mathcal{M}(z_2 \to l'\bar{l}')\,\mathcal{M}(z_1 \to l'\bar{l}')^* \Big\}$

$$\propto \text{const.} \times \Big\{ (1 - \sin^2\theta_1 \cos^2\phi_1)(1 - \sin^2\theta_3 \sin^2\phi_3)$$
$$+ (1 - \sin^2\theta_1 \sin^2\phi_1)(1 - \sin^2\theta_3 \cos^2\phi_3)$$
$$- 2 \sin^2\theta_1 \sin^2\theta_3 \sin\phi_1 \cos\phi_1 \sin\phi_3 \cos\phi_3 \Big\}$$

$$\propto \text{const.} \times \Big\{ (1 - \sin^2\theta_1 \cos^2\phi_1)(1 - \sin^2\theta_3 \sin^2\phi_3)$$
$$+ (1 - \sin^2\theta_1 \sin^2\phi_1)(1 - \sin^2\theta_3 \cos^2\phi_3)$$
$$- 2 \sin^2\theta_1 \sin^2\theta_3 \sin\phi_1 \cos\phi_1 \sin\phi_3 \cos\phi_3 \Big\}$$
$$\propto \text{const.} \Big\{ \cos^2\theta_1 + \cos^2\theta_3 + \sin^2\theta_1 \sin^2\theta_3 \sin^2(\underbrace{\phi_3 - \phi_1}_{\phi}) \Big\}$$

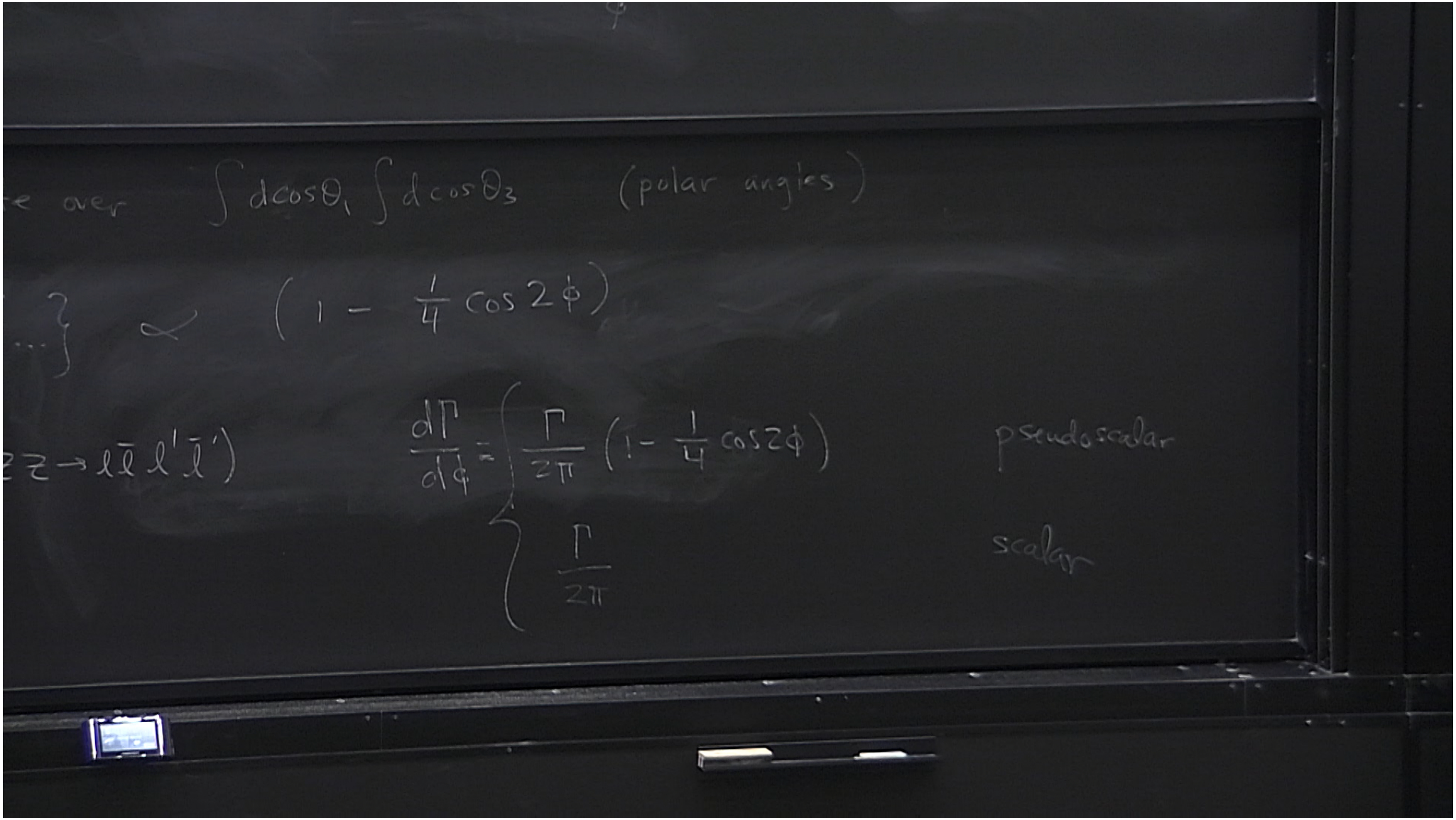
Compute $\frac{d\Gamma}{d\phi}$. Integrate over $\int d\cos\theta_1 \int d\cos\theta_3$ (polar angles)

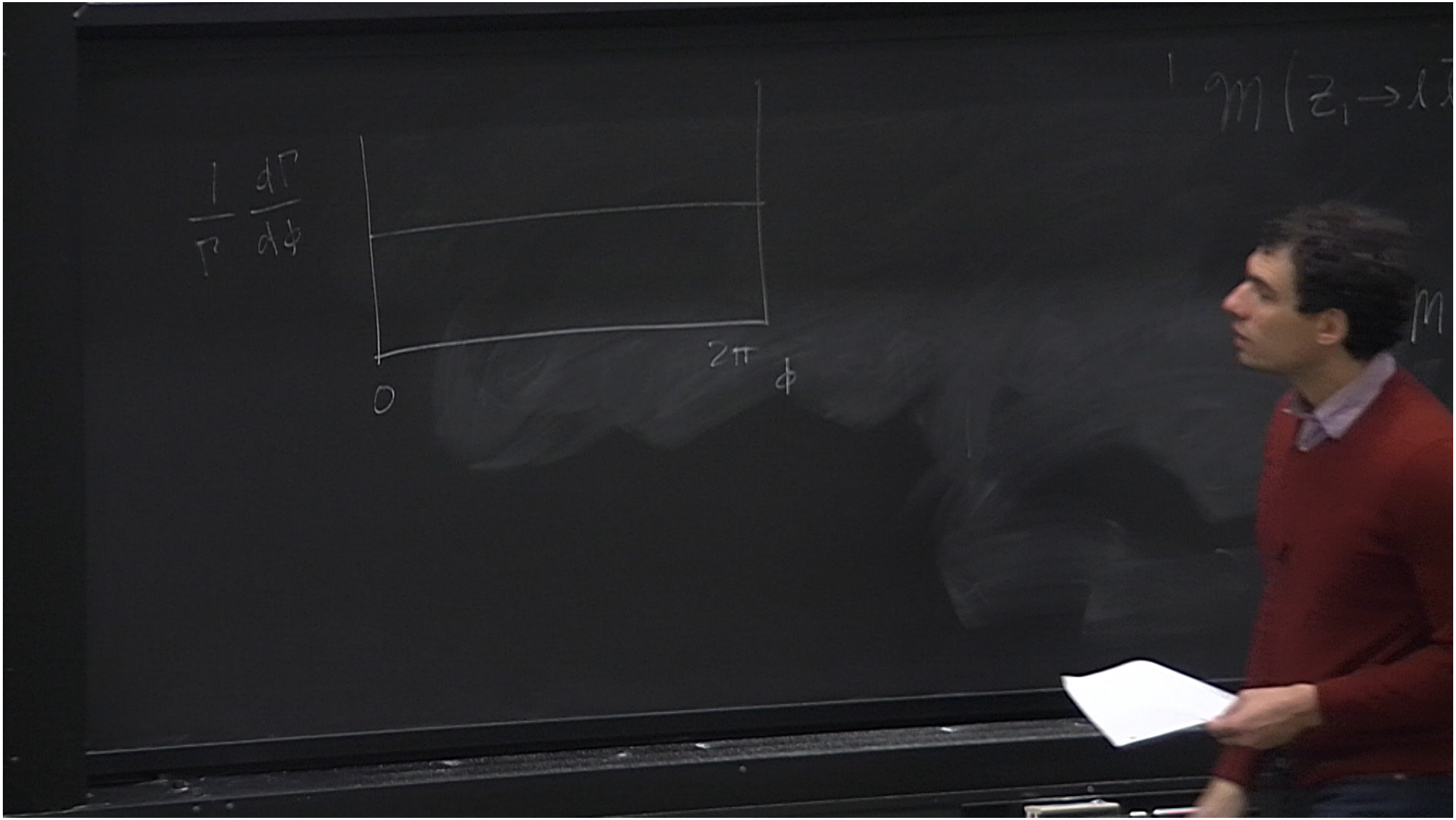
$$\Rightarrow \int d\cos\theta_1 \int d\cos\theta_3 \{\ldots\} \propto \left(1 - \frac{1}{4}\cos 2\phi\right)$$

Compute $\frac{d\Gamma}{d\phi}$. Integrate over $\int d\cos\theta_1 \int d\cos\theta_3$ (polar angles)

$$\Rightarrow \int d\cos\theta_1 \int d\cos\theta_3 \{\ldots\} \propto \left(1 - \frac{1}{4}\cos 2\phi\right)$$

$$\Rightarrow \Gamma = \Gamma(h \to ZZ \to l\bar{l}\,l'\bar{l}') \qquad \frac{d\Gamma}{d\phi} = \frac{\Gamma}{2\pi}\left(1 - \frac{1}{4}\cos 2\phi\right)$$


e over $\int d\cos\theta_1 \int d\cos\theta_3$ (polar angles)
$\cdots\} \propto \left(1 - \frac{1}{4}\cos 2\phi\right)$
$ZZ \to l\bar{l}\, l'\bar{l}')$
$\frac{d\Gamma}{d\phi} = \begin{cases} \frac{\Gamma}{2\pi}\left(1 - \frac{1}{4}\cos 2\phi\right) \\ \frac{\Gamma}{2\pi} \end{cases}$
pseudoscalar
scalar


$\frac{1}{r}\frac{dr}{d\phi}$
0
2π
ϕ

$\frac{1}{r}\frac{dr}{d\phi}$

