Title: Standard Model Lecture

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Collection: Standard Model 2023/24

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Recall: $pp \to h \to$ final states

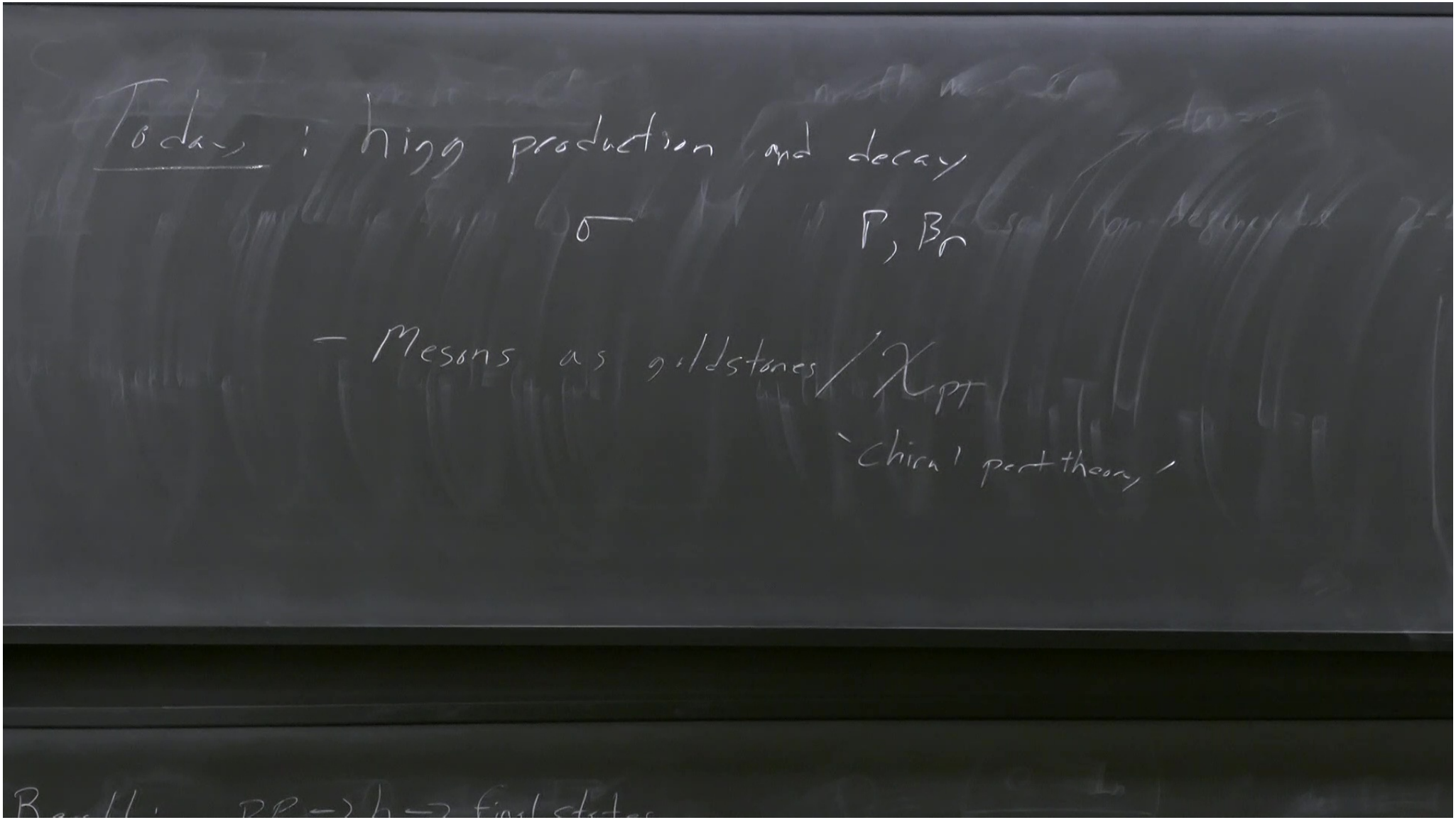
$$\sigma(pp \to h) = \int dx_1 f_1(x_1, M) \int dx_2 f_2(x_2, M) \, \hat{\sigma}(12 \to h)$$

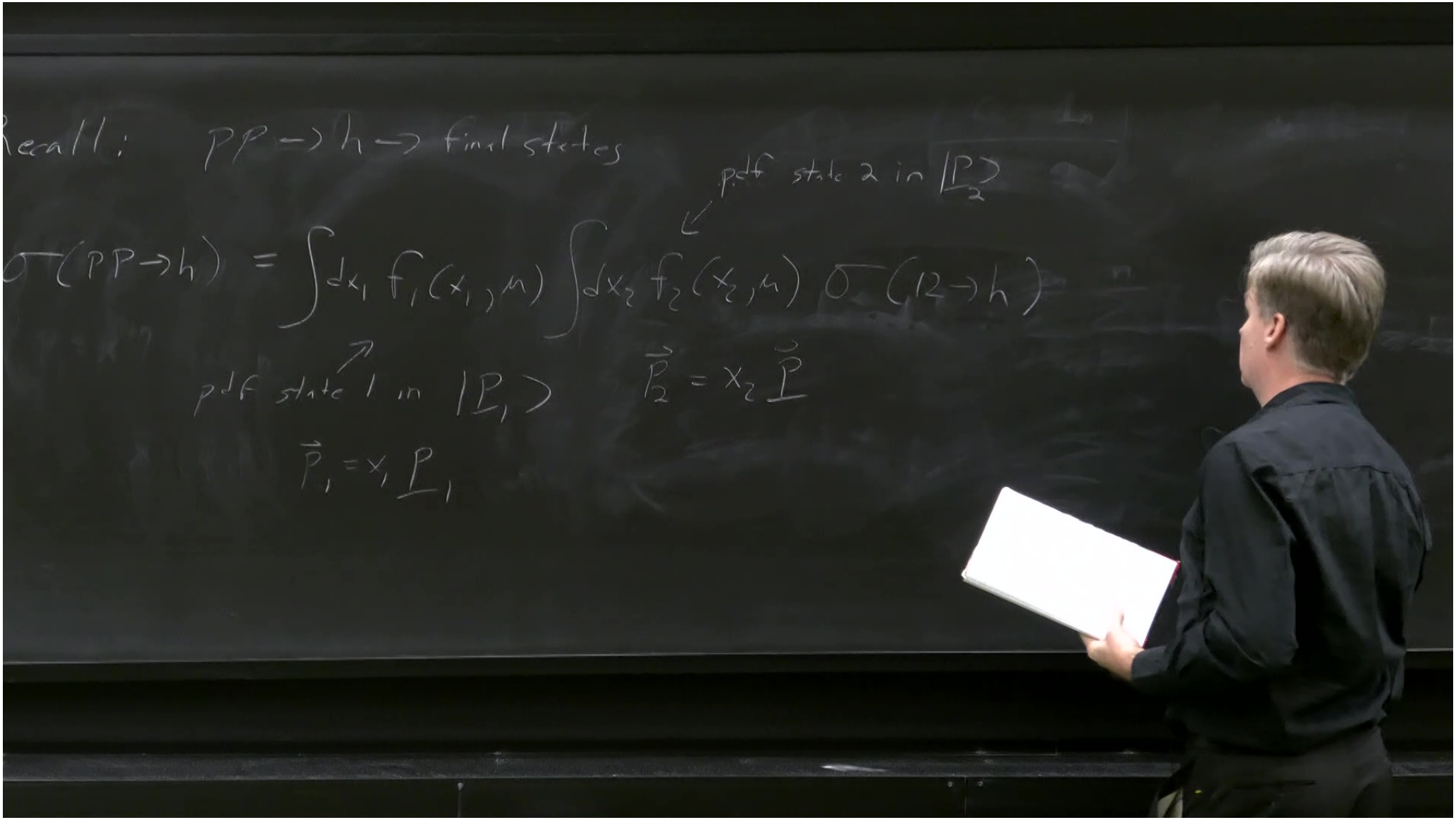
pdf state 2 in $|P_2\rangle$

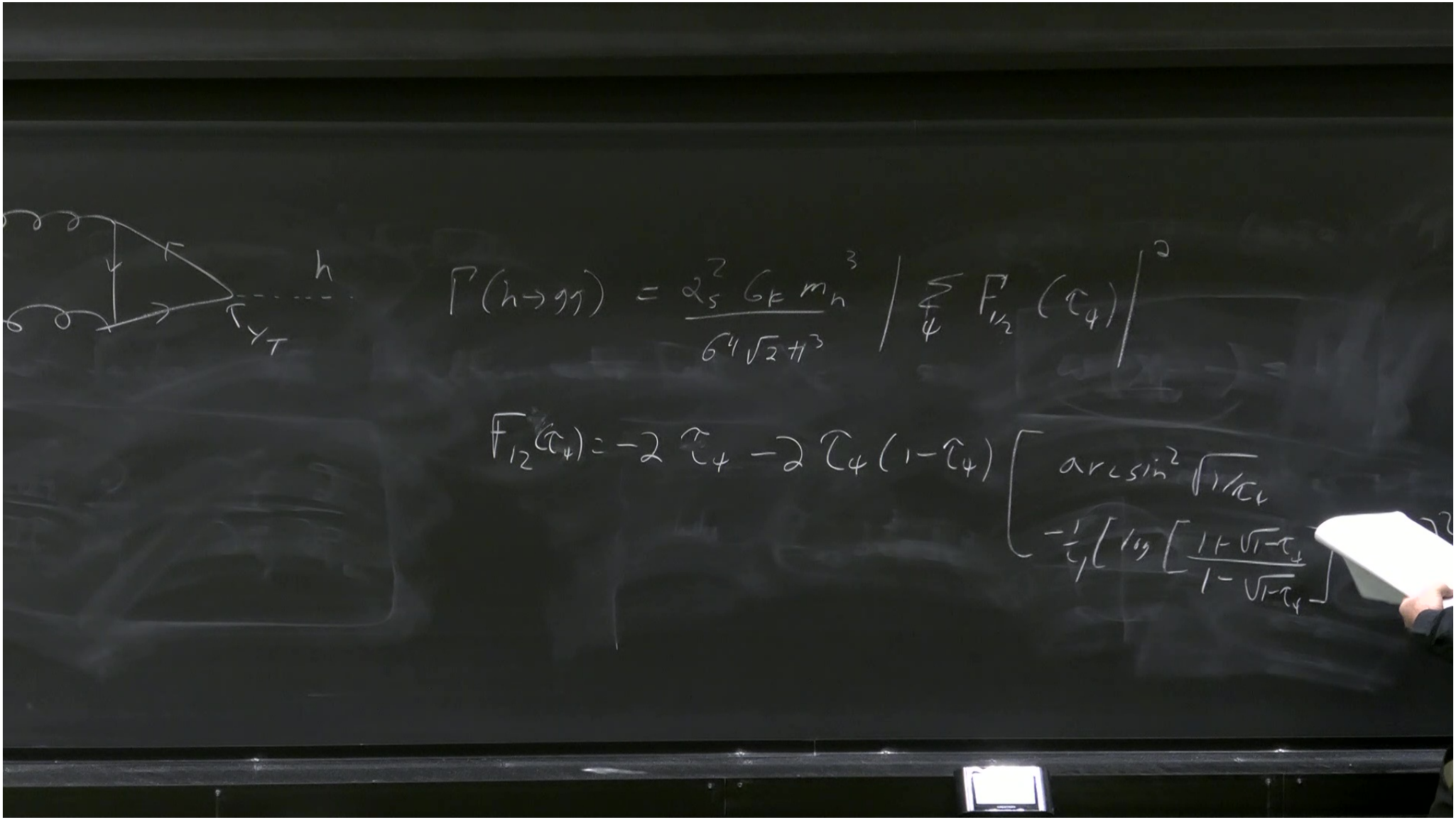
pdf state 1 in $|P_1\rangle$

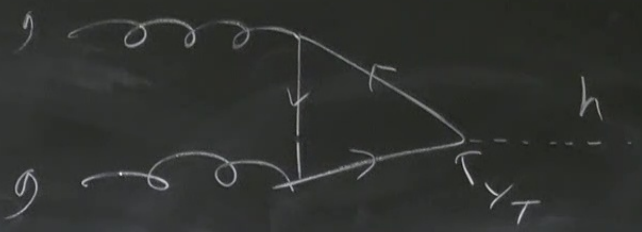
$\vec{P}_1 = x_1 \underline{P}_1$

$\vec{P}_2 = x_2 \underline{P}$


Today : higg production and decay
σ
Γ, BR
- Mesons as goldstones / χPT
`Chiral pert theory'

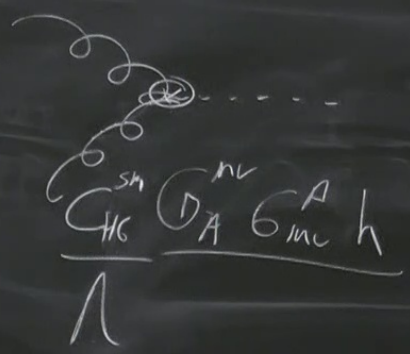

Recall: $pp \to h \to$ final states
pdf state 2 in $|P_2\rangle$
$\sigma(pp \to h) = \int dx_1 f_1(x_1, \mu) \int dx_2 f_2(x_2, \mu) \hat{\sigma}(12 \to h)$
pdf state 1 in $|P_1\rangle$
$\vec{p}_2 = x_2 \vec{P}$
$\vec{p}_1 = x_1 P_1$


h
γ_T
$\Gamma(h \to gg) = \frac{\alpha_s^2 G_F m_h^3}{64\sqrt{2}\pi^3} \left| \sum_q F_{1/2}(\tau_q) \right|^2$
$F_{1/2}(\tau_q) = -2\tau_q - 2\tau_q(1-\tau_q)\left[\arcsin^2\sqrt{1/\tau_q} \right.$
$\left. -\frac{1}{\tau_q}\left[\log\left[\frac{1+\sqrt{1-\tau_q}}{1-\sqrt{1-\tau_q}} \right] \right. \right.$



$$\Gamma(h \to gg) = \frac{\alpha_s^2 G_F m_h^3}{64\sqrt{2}\pi^3} \left| \sum_q F_{1/2}(\tau_q) \right|^2$$

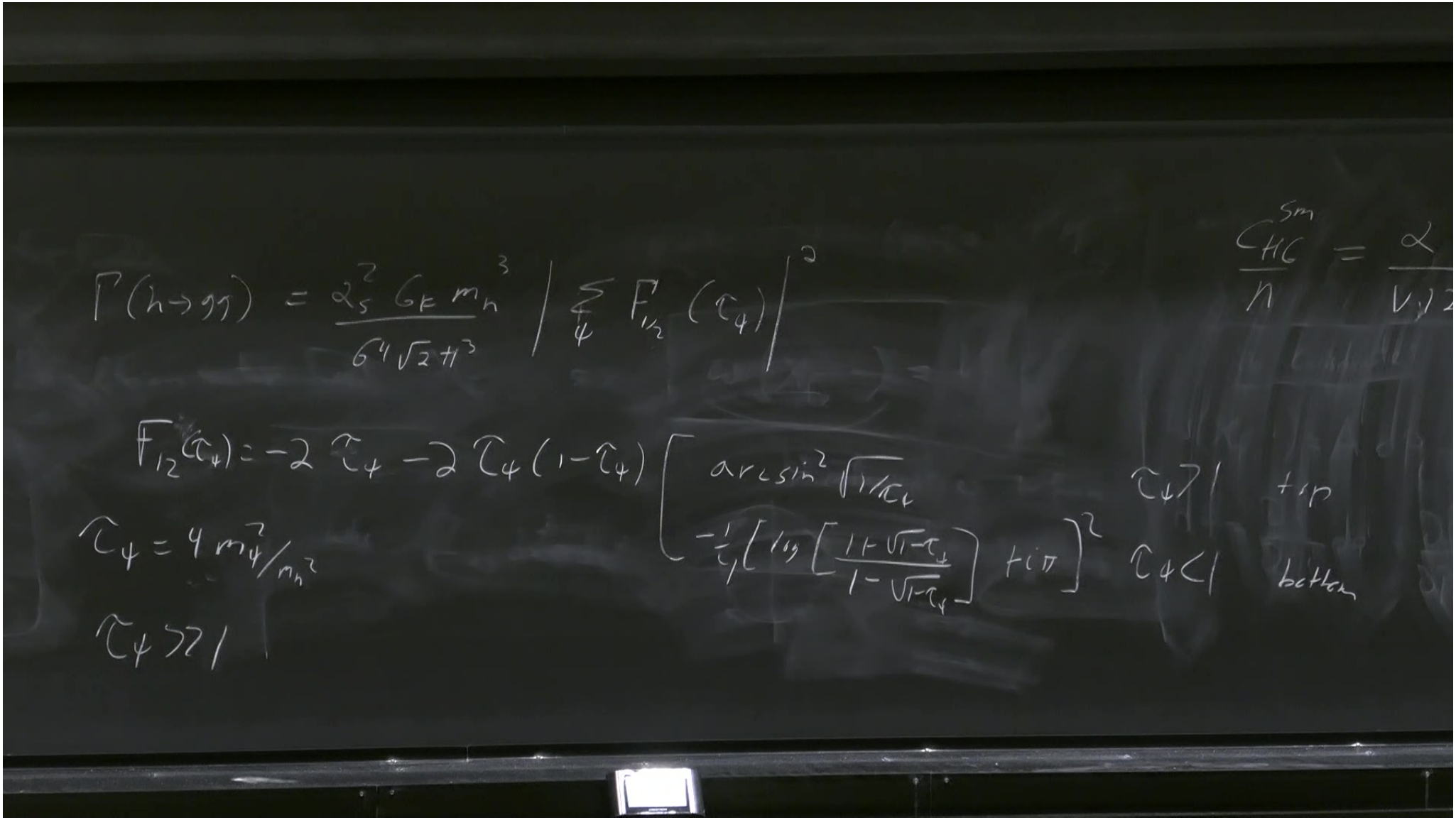
$$F_{1/2}(\tau_q) = -2\tau_q - 2\tau_q(1-\tau_q)\left[\arcsin^2\sqrt{1/\tau_q} \right.$$
$$\left. -\frac{1}{\tau_q}\left[\log\left[\frac{1+\sqrt{1-\tau_q}}{1-\sqrt{1-\tau_q}} \right. \right. \right.$$

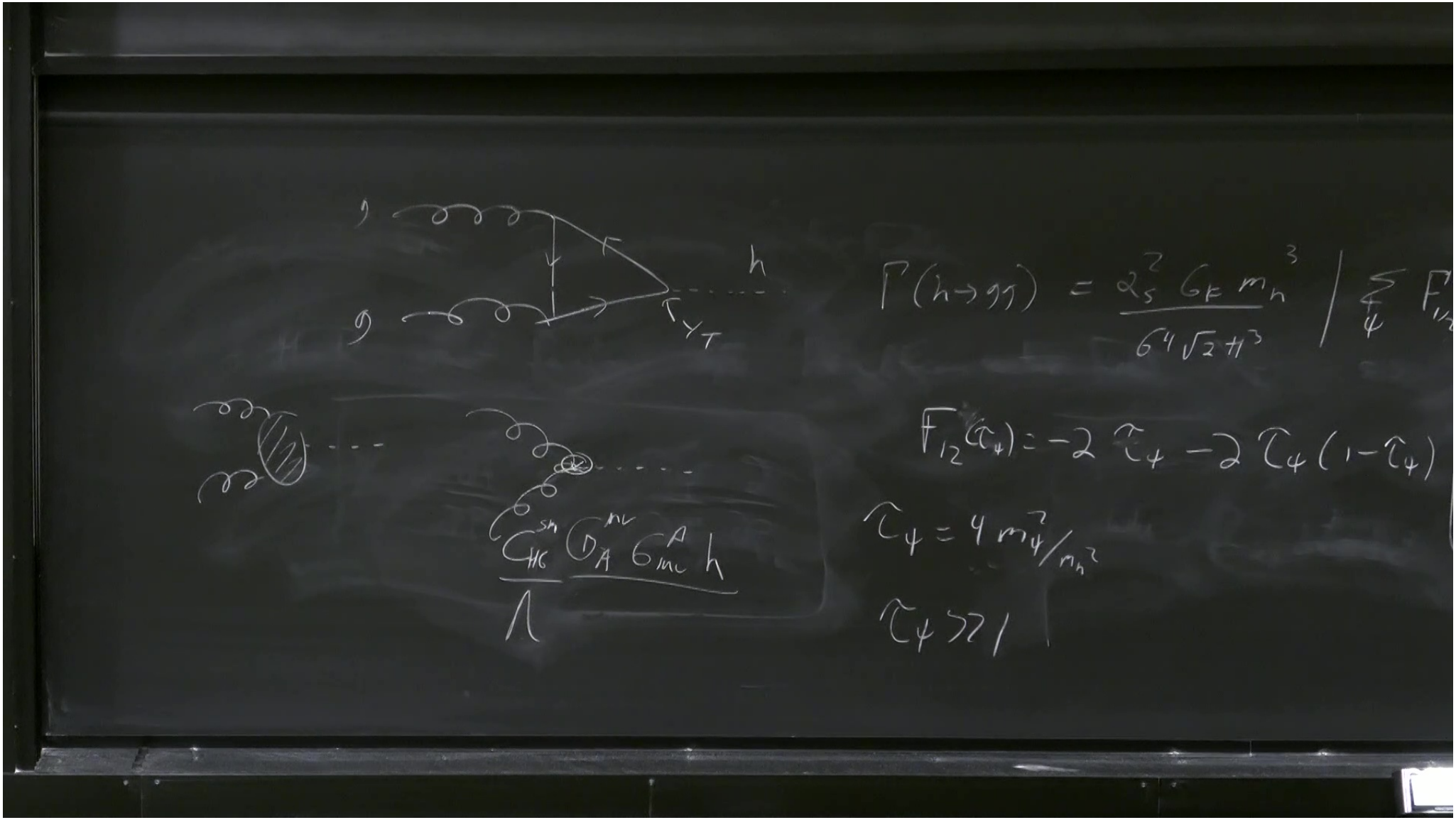


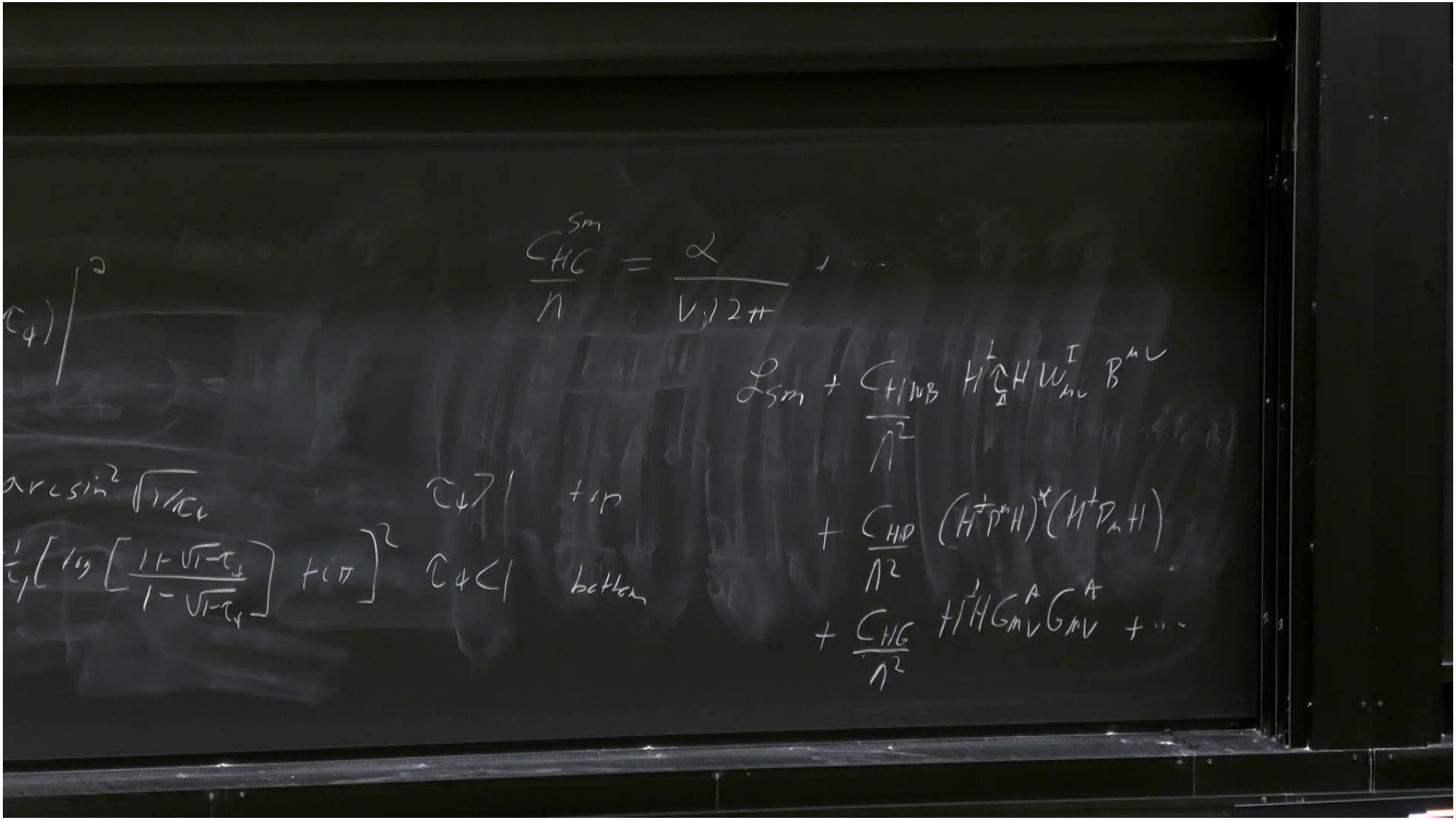
$$\frac{C_{HG}^{SM}}{\Lambda} G_A^{\mu\nu} G_{\mu\nu}^A h$$

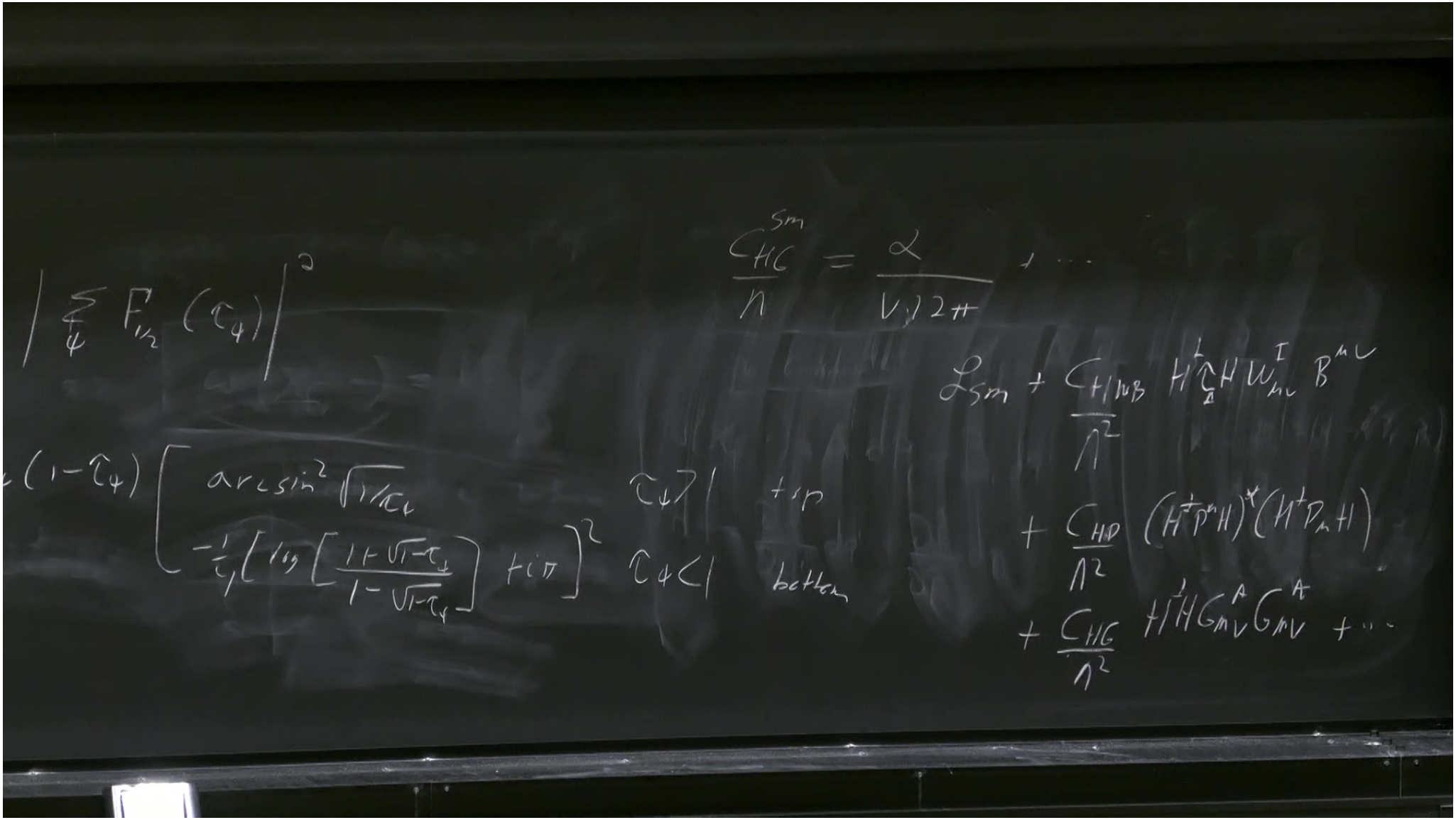
$$\tau_q = 4m_q^2/m_h^2$$

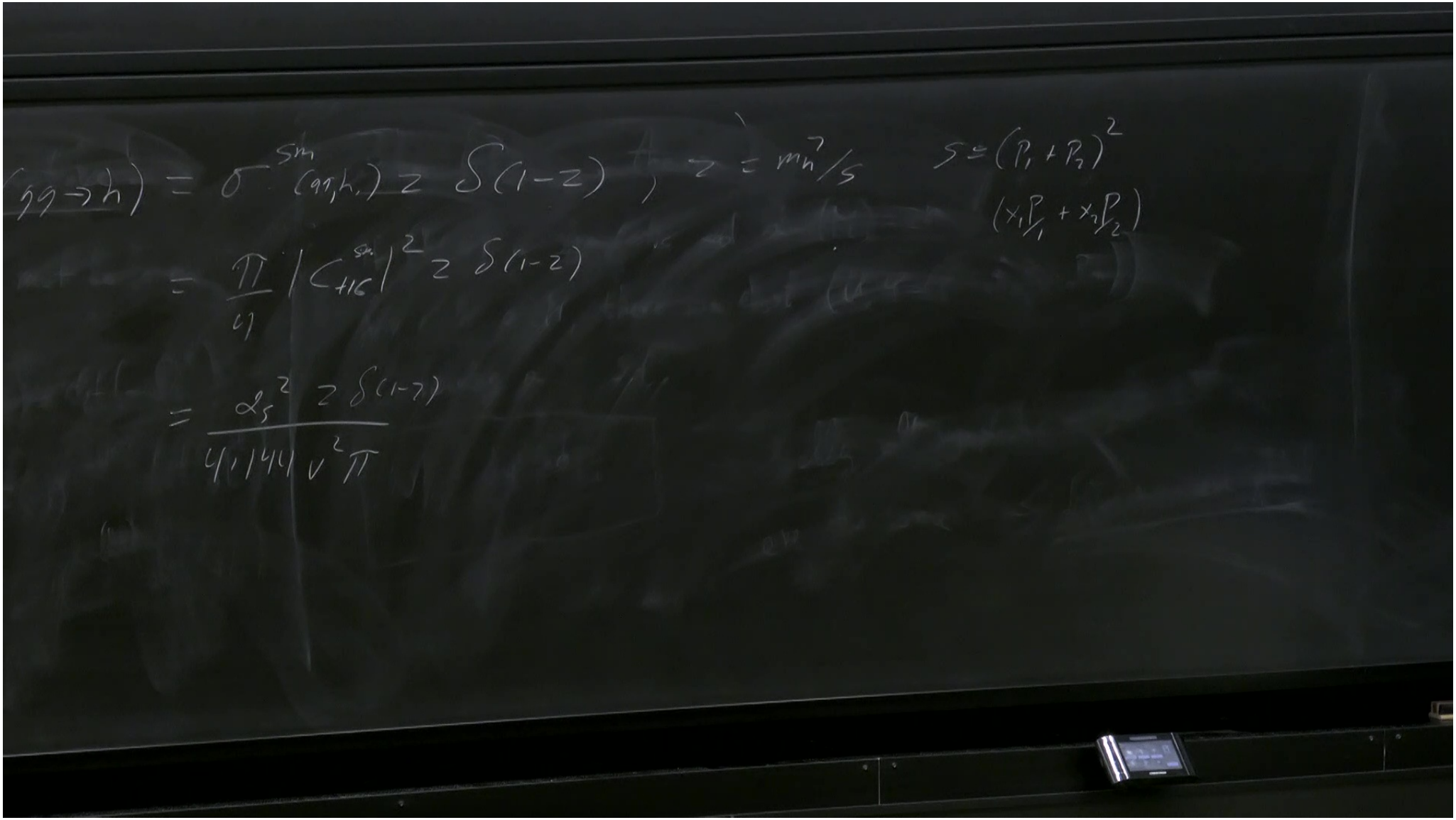
$$\tau_q \gg 1$$

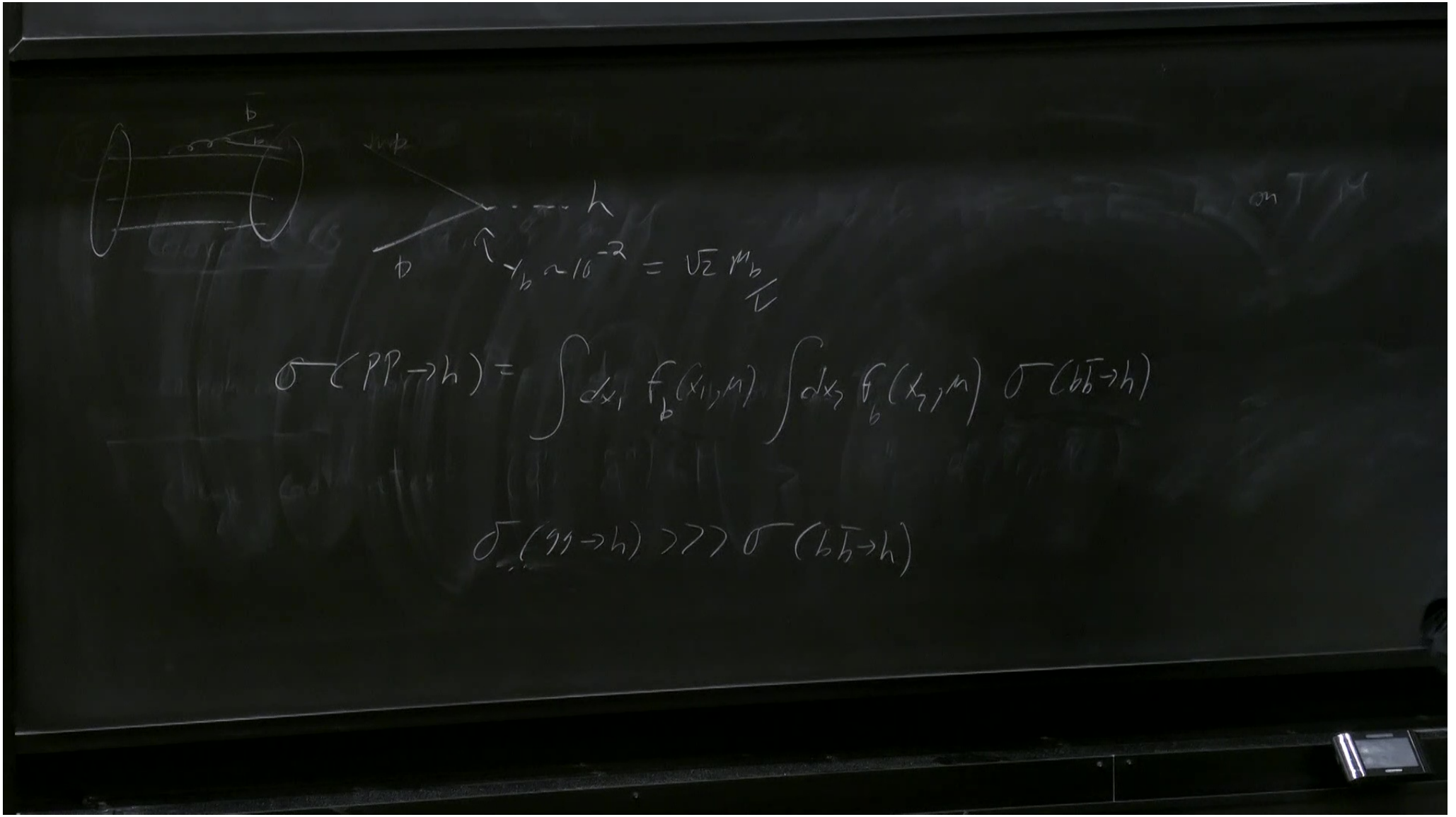

$\Gamma(h \to gg) = \frac{\alpha_s^2 G_F m_h^3}{64\sqrt{2}\pi^3} \left| \sum_q F_{1/2}(\tau_q) \right|^2$
$\frac{C_{HG}^{SM}}{\Lambda} = \frac{\alpha}{v}$
$F_{1/2}(\tau_q) = -2\tau_q - 2\tau_q(1-\tau_q)\left[\arcsin^2\sqrt{1/\tau_q} \quad \tau_q > 1 \text{ top}\right.$
$\left. -\frac{1}{4}\left[\log\left[\frac{1+\sqrt{1-\tau_q}}{1-\sqrt{1-\tau_q}}\right] + i\pi\right]^2 \quad \tau_q < 1 \text{ bottom}\right]$
$\tau_q = 4m_q^2/m_h^2$
$\tau_q \gg 1$

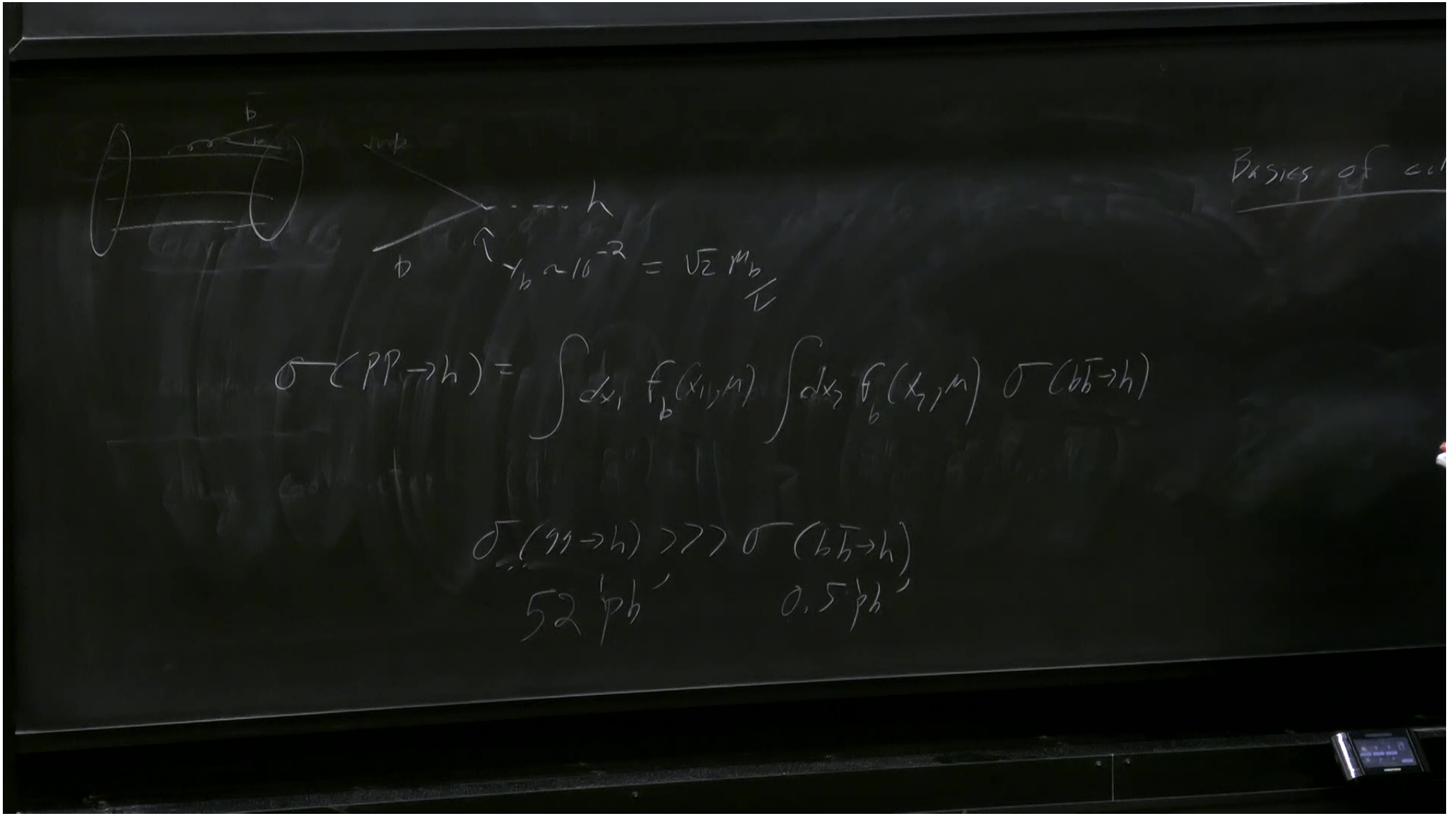

g
g
h
τ_{y_T}
$\Gamma(h \to gg) = \frac{\alpha_s^2 G_F m_h^3}{64\sqrt{2}\pi^3} \left| \sum_f F_{1/2}$
$F_{1/2}(\tau_f) = -2\tau_f - 2\tau_f(1-\tau_f)$
$\frac{C_{HG}^{SM} G_A^{NP} G_{MC}^A h}{\Lambda}$
$\tau_f = 4m_f^2/m_h^2$
$\tau_f \gg 1$

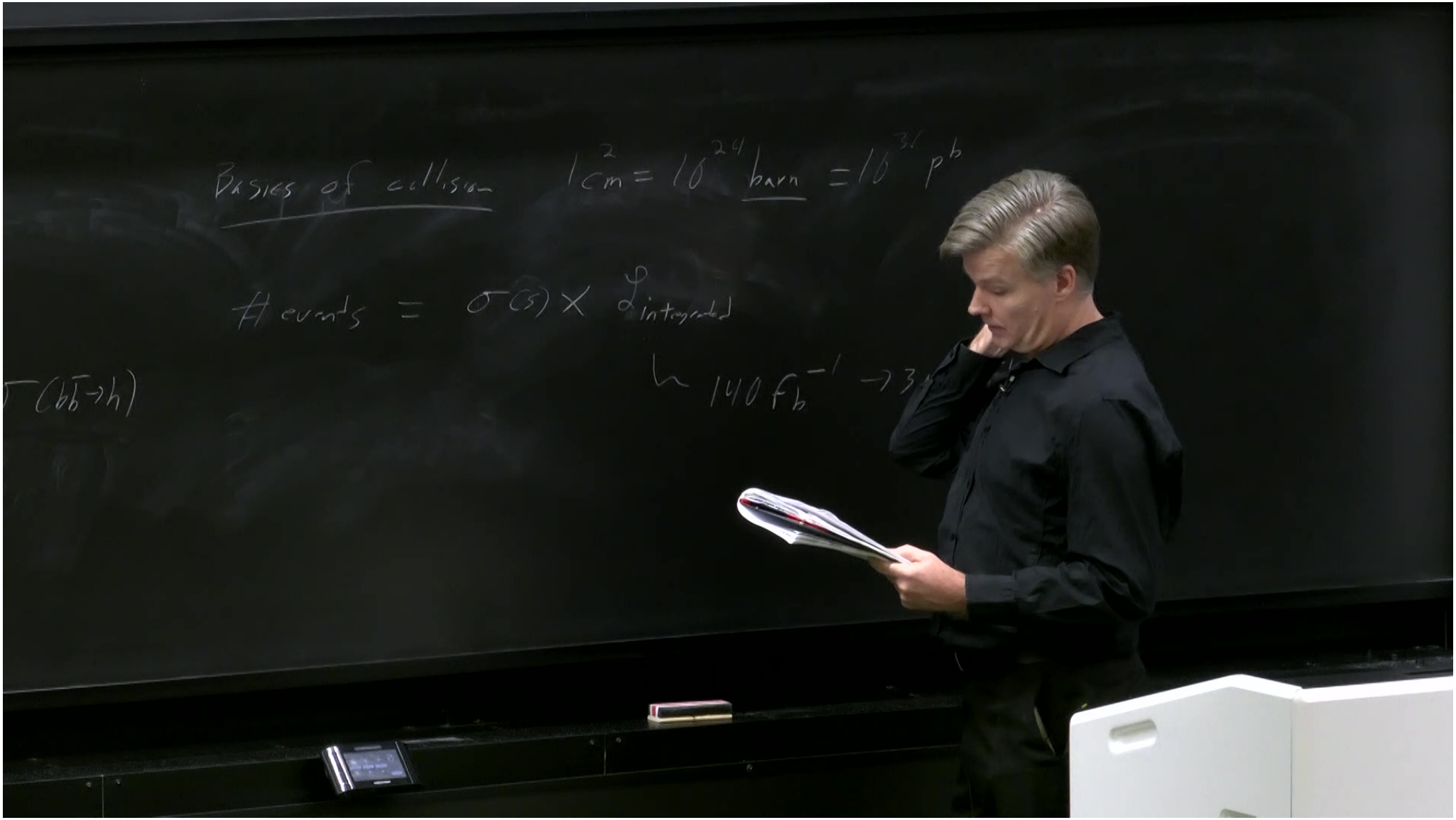

$\frac{C_{HG}^{SM}}{\Lambda} = \frac{\alpha}{V^2 12\pi}$ + ...
$\mathcal{L}_{SM} + \frac{C_{HWB}}{\Lambda^2} H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$
$+ \frac{C_{HD}}{\Lambda^2} (H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$
$+ \frac{C_{HG}}{\Lambda^2} H^\dagger H G^A_{\mu\nu} G^{A\mu\nu}$ + ...
$\arcsin^2 \sqrt{\tau_4}$
$\tau_4 > 1$ top
$\frac{1}{\tau_4}\left[\log\left[\frac{1+\sqrt{1-\tau_4}}{1-\sqrt{1-\tau_4}}\right] + i\pi\right]^2$
$\tau_4 < 1$ bottom

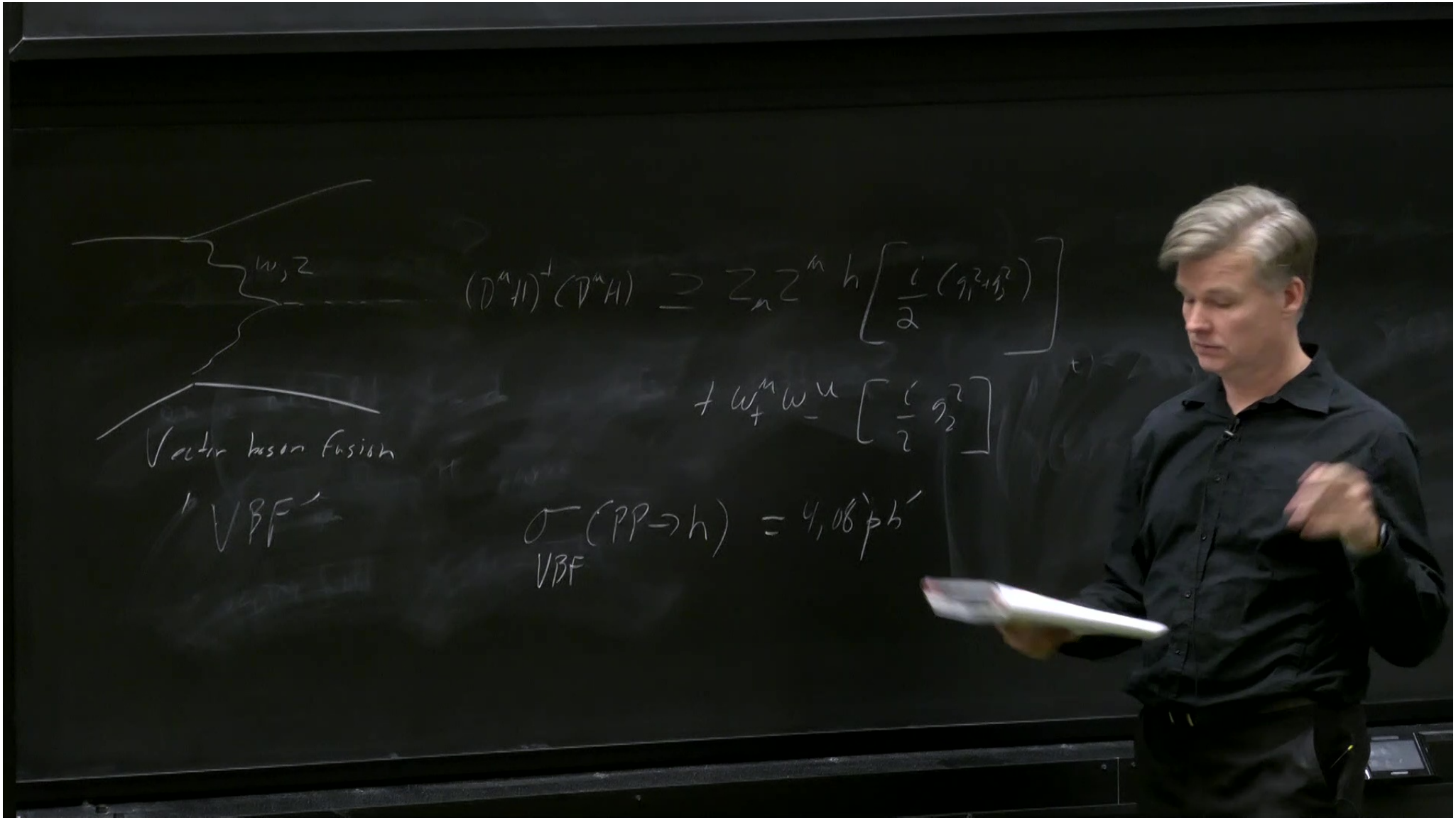

$\left| \sum_\psi F_{1/2}(\tau_4) \right|^2$
$\frac{C_{HG}^{SM}}{\Lambda} = \frac{\alpha}{V} \frac{1}{12\pi} \cdots$
$\mathcal{L}_{SM} + \frac{C_{HWB}}{\Lambda^2} H^\dagger \hat{\tau}^I H W^I_{\mu\nu} B^{\mu\nu}$
$+ \frac{C_{HD}}{\Lambda^2} (H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$
$+ \frac{C_{HG}}{\Lambda^2} H^\dagger H G^A_{\mu\nu} G^{A\mu\nu} + \cdots$
$(1-\tau_4)\left[\arcsin^2 \sqrt{1/\tau_4} \right.$
$\left. -\frac{1}{4}\left[\log\left[\frac{1+\sqrt{1-\tau_4}}{1-\sqrt{1-\tau_4}} \right] + i\pi \right]^2 \right.$
$\tau_4 > 1$ top
$\tau_4 < 1$ bottom

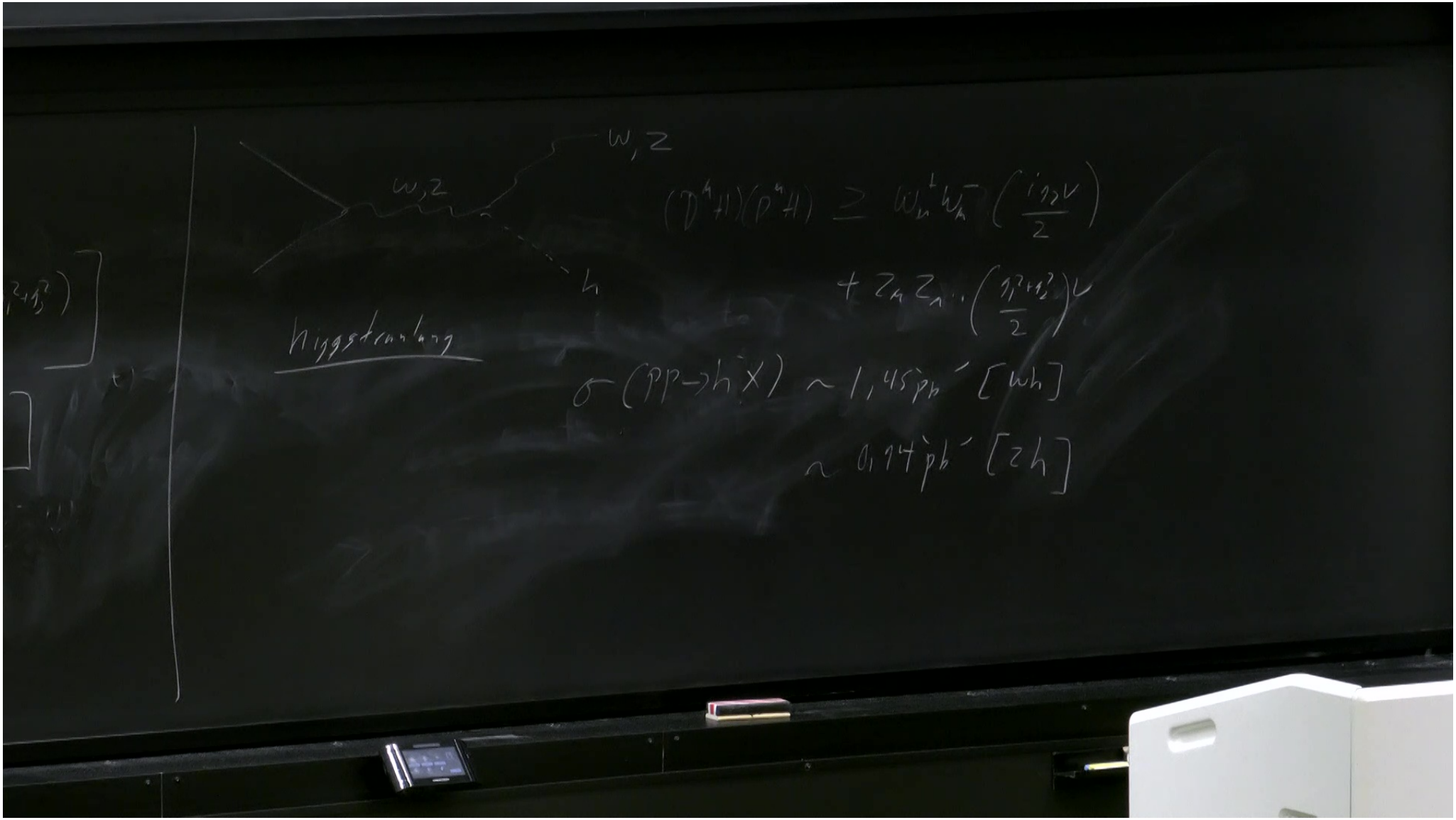

$\sigma^{SM}(gg \to h) = \sigma^{SM}(gg \to h) \propto \delta(1-z)$, $z = m_h^2/s$
$s = (P_1 + P_2)^2$
$(x_1 P_1 + x_2 P_2)$
$= \frac{\pi}{4} |C_{ttG}^{SM}|^2 \propto \delta(1-z)$
$= \frac{\alpha_s^2 \propto \delta(1-z)}{4.144 v^2 \pi}$

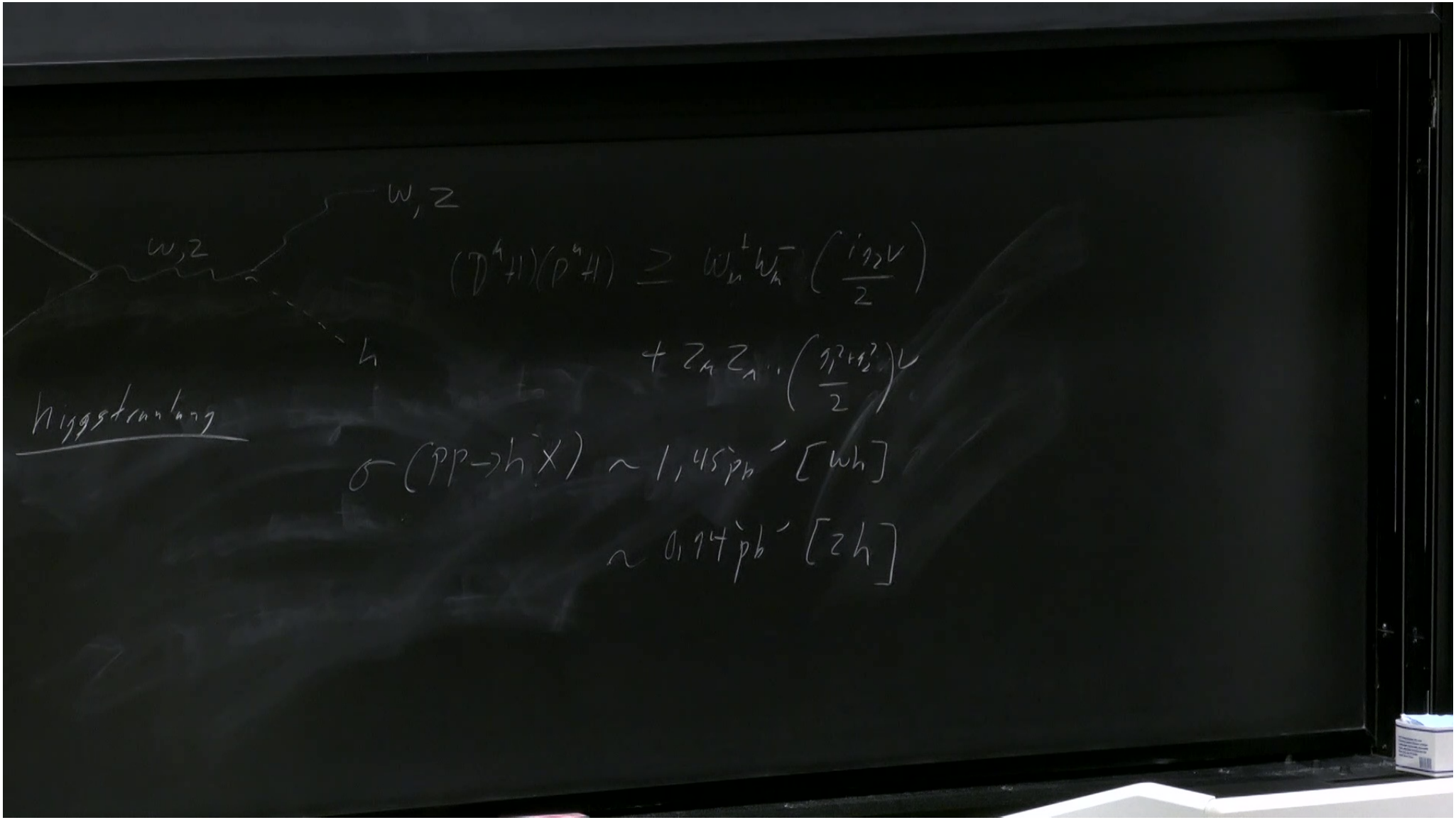

b
b
h
$y_b \sim 10^{-2} = \sqrt{2}\, m_b / v$
$\sigma(pp \to h) = \int dx_1\, f_b(x_1, m) \int dx_2\, f_b(x_2, m)\, \sigma(b\bar{b} \to h)$
$\sigma(gg \to h) >>> \sigma(b\bar{b} \to h)$

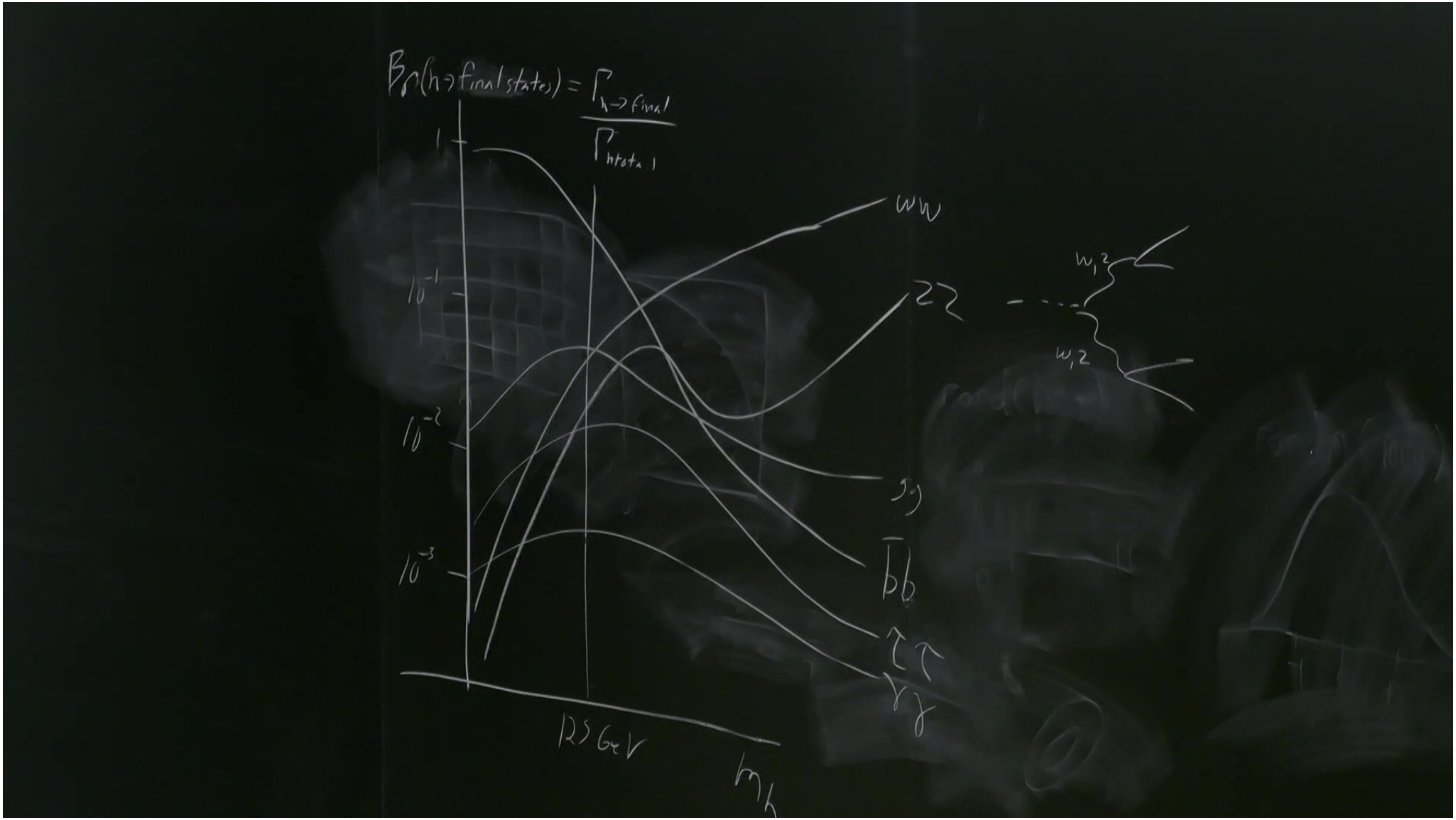

b
b
h
$y_b \sim 10^{-2} = \sqrt{2}\, m_b / v$
$\sigma(pp \to h) = \int dx_1\, f_b(x_1, m) \int dx_2\, f_b(x_2, m)\, \sigma(b\bar{b} \to h)$
$\sigma(gg \to h) \gg\gg \sigma(b\bar{b} \to h)$
$52\ pb$
$0.5\ pb$

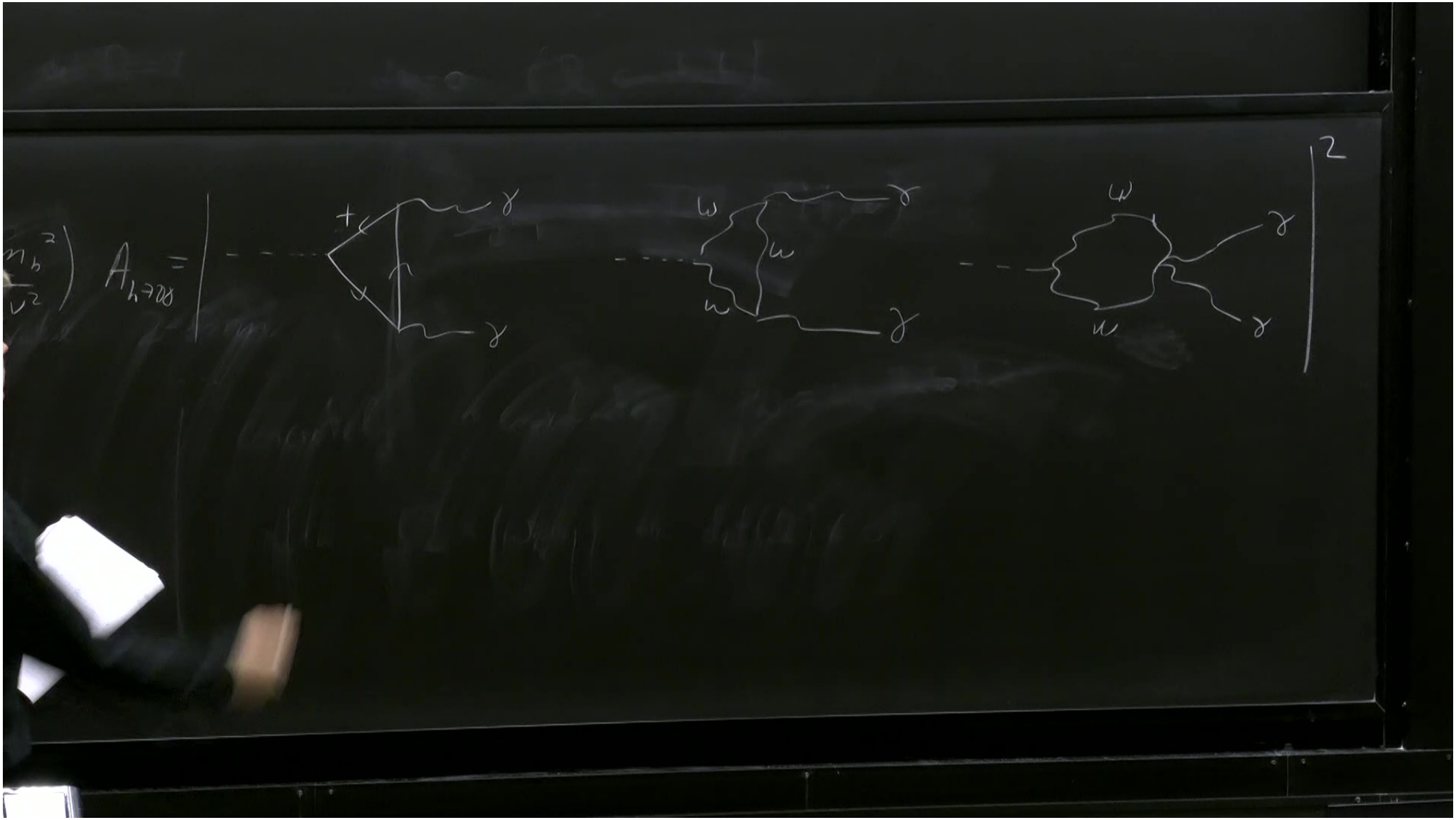

Basics of collision
1 cm = 10^24 barn = 10^36 pb
events = σ(s) × ∫ L dt integrated
↳ 140 fb^-1 → 3
σ(bb̄→h)

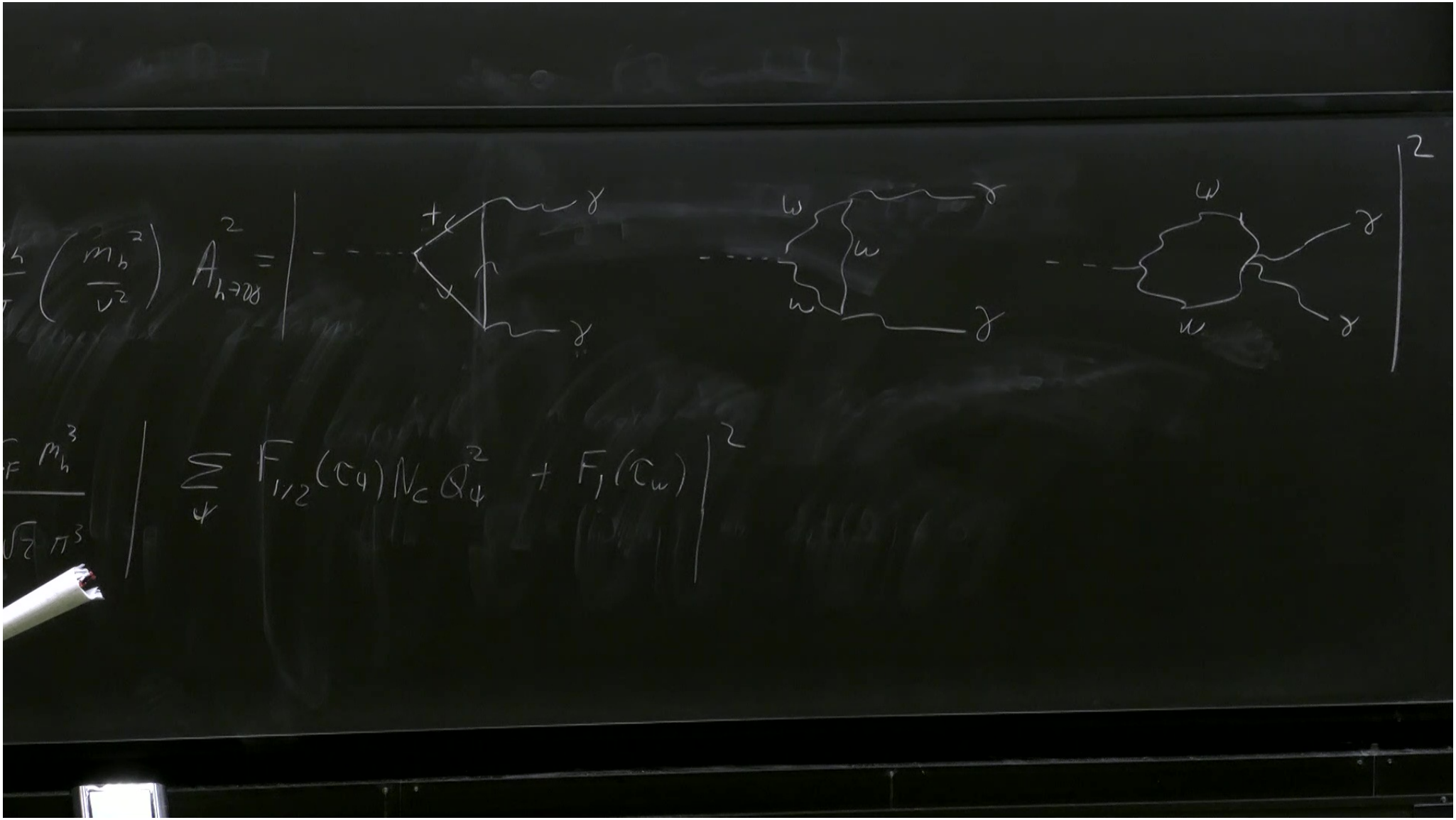

W, Z
Vector boson fusion
"VBF"
$(D^\mu H)^\dagger (D^\mu H) \supset Z_\mu Z^\mu h \left[\frac{i}{2}(g_1^2+g_2^2)\right]$
$+ W_+^\mu W_-^\mu \left[\frac{i}{2} g_2^2\right]$
$\sigma_{VBF}(PP \to h) = 4{,}08\,pb$

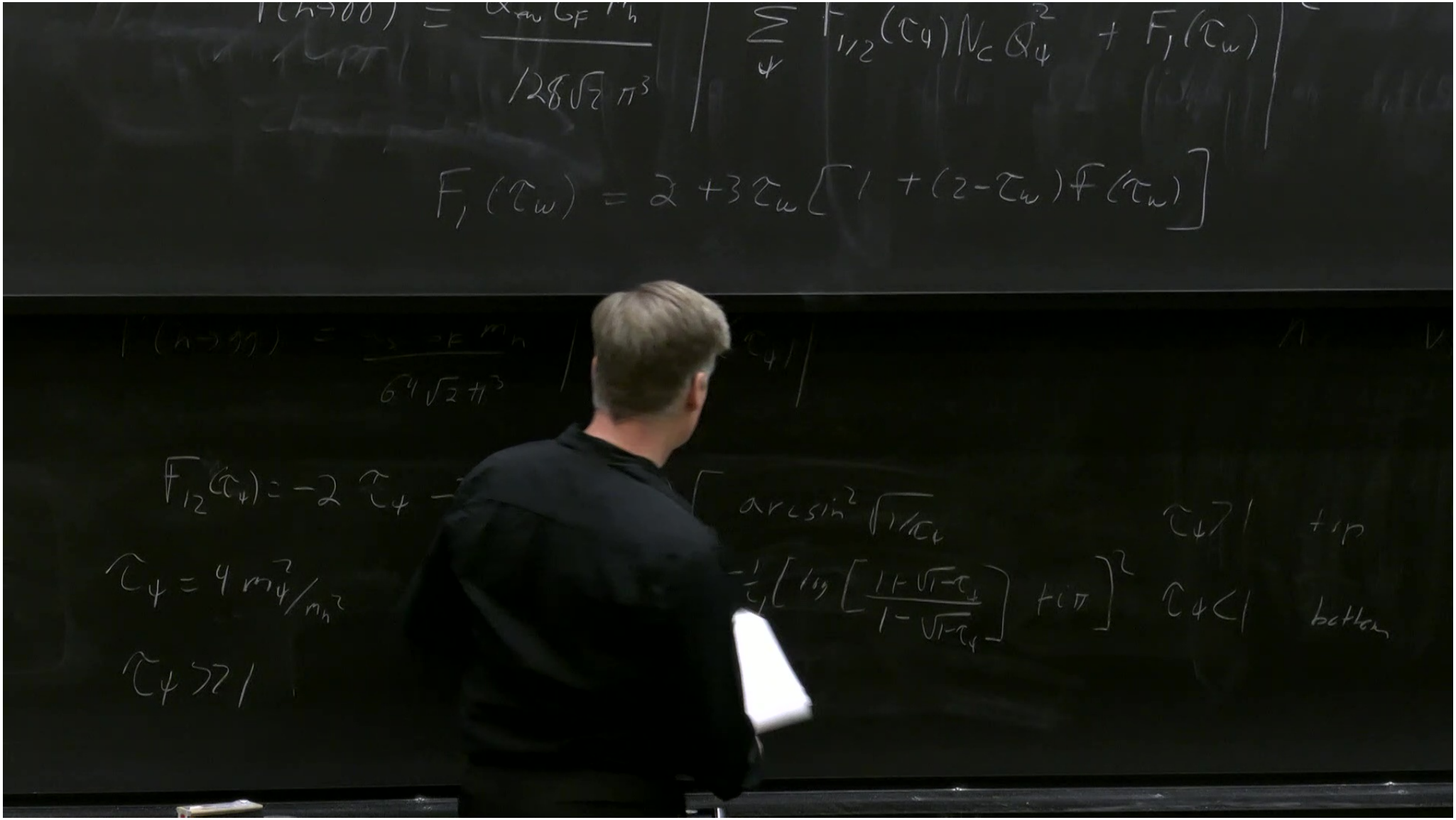

W, Z
W, Z
h
Higgsstrahlung
$(D^\mu H)(D_\mu H) \supset W_\mu^+ W_\mu^- \left(\frac{i g_2 v}{2}\right)$
$+ Z_\mu Z_\mu \left(\frac{g_1^2 + g_2^2}{2}\right) v$
$\sigma(pp \to hX) \sim 1{,}45\,\text{pb}\ [Wh]$
$\sim 0{,}94\,\text{pb}\ [Zh]$

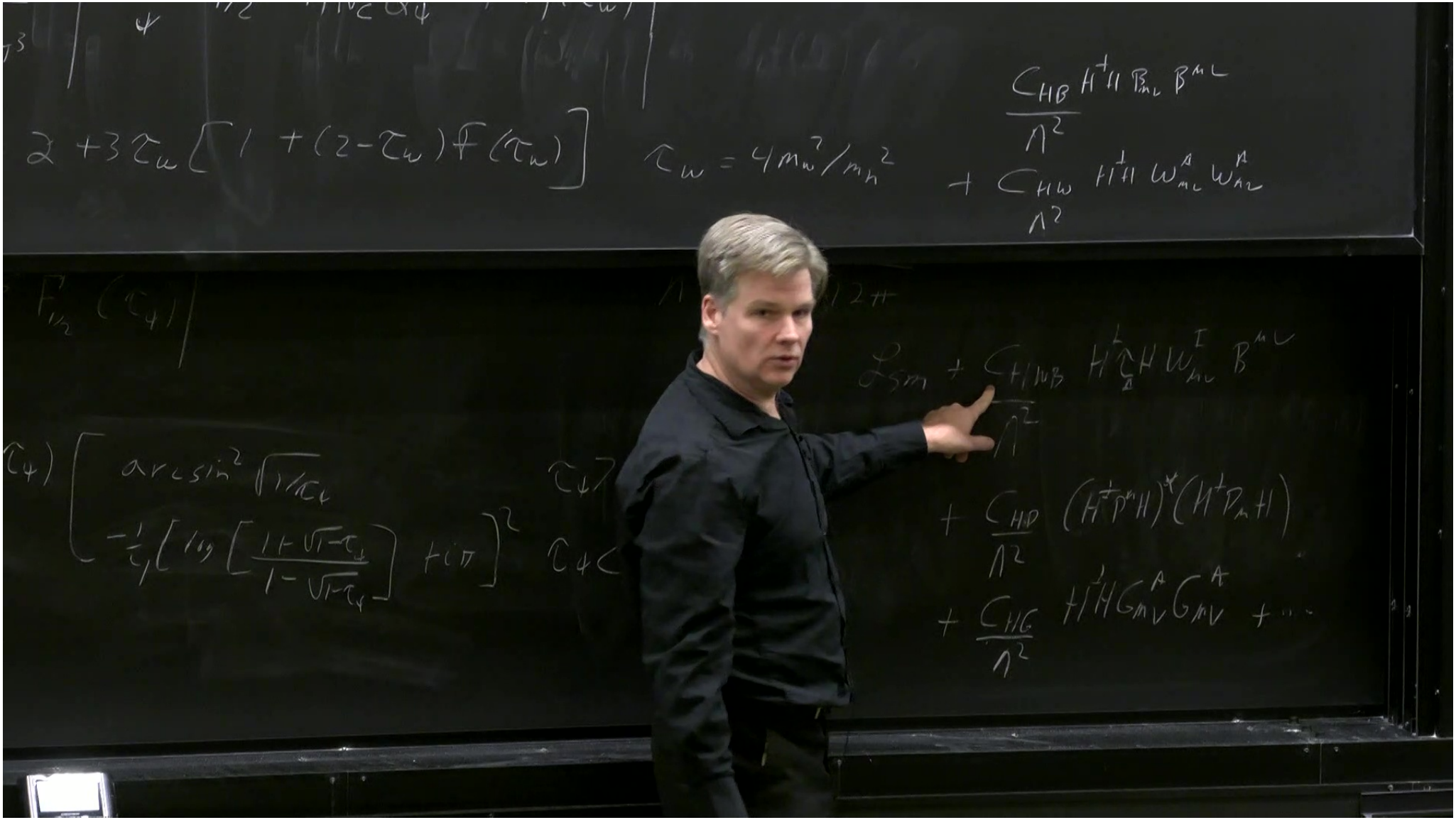

W, Z
W, Z
h
Higgsstrahlung
$(D^\mu H)(D_\mu H) \supset W_\mu^+ W_\mu^- \left(\frac{i g_2 v}{2}\right)^2$
$+ Z_\mu Z_\mu \cdot \left(\frac{g_1^2 + g_2^2}{2}\right) v^2$
$\sigma(pp \to h X) \sim 1{,}45\,\text{pb}\;[Wh]$
$\sim 0{,}94\,\text{pb}\;[Zh]$

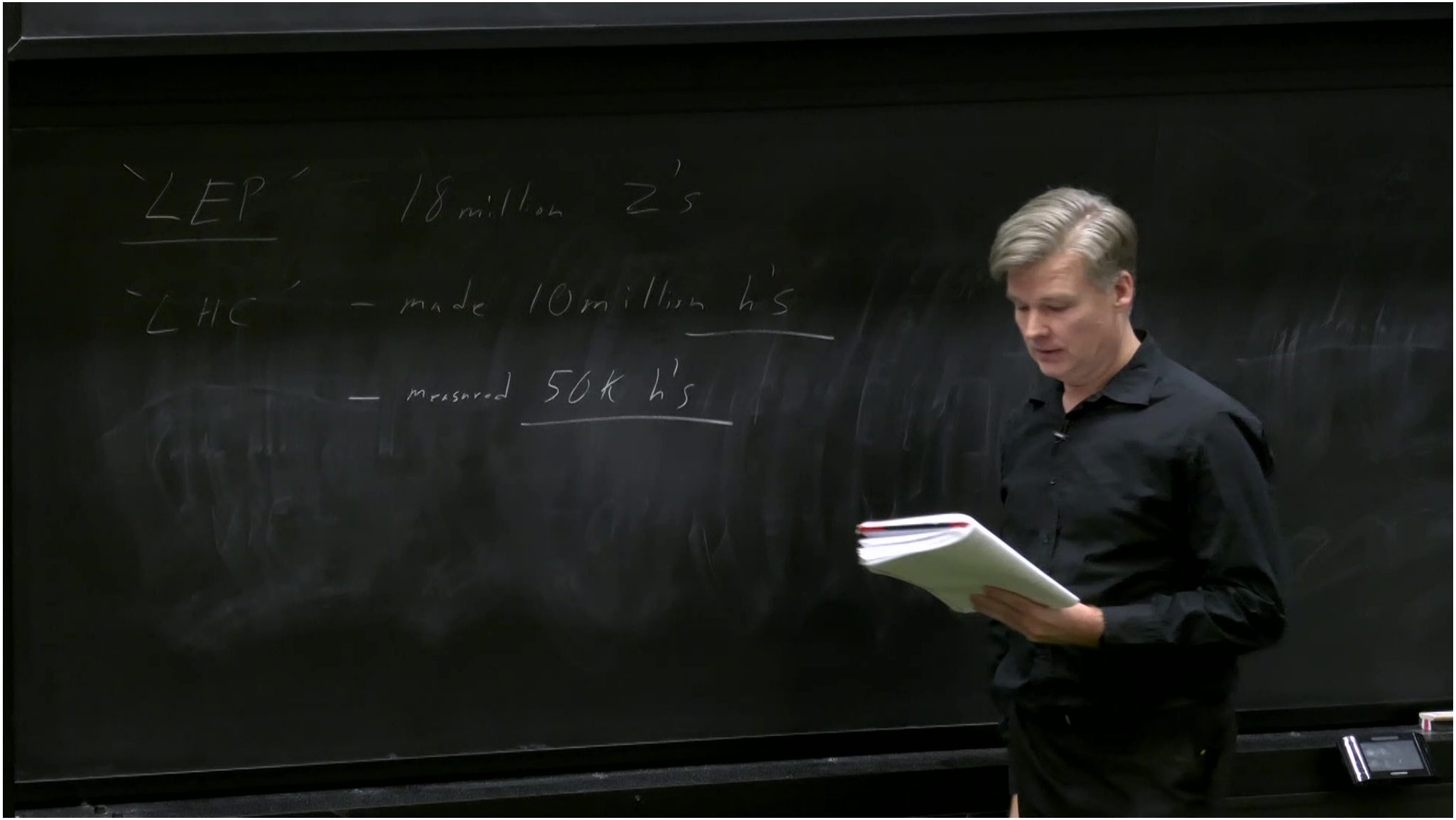

$Br(h \to \text{final states}) = \frac{\Gamma_{h \to \text{final}}}{\Gamma_{h\,\text{total}}}$
1
10^{-1}
10^{-2}
10^{-3}
WW
ZZ
W,Z
W,Z
gg
$\bar{b}b$
$\tau\tau$
$\gamma\gamma$
125 GeV
m_h

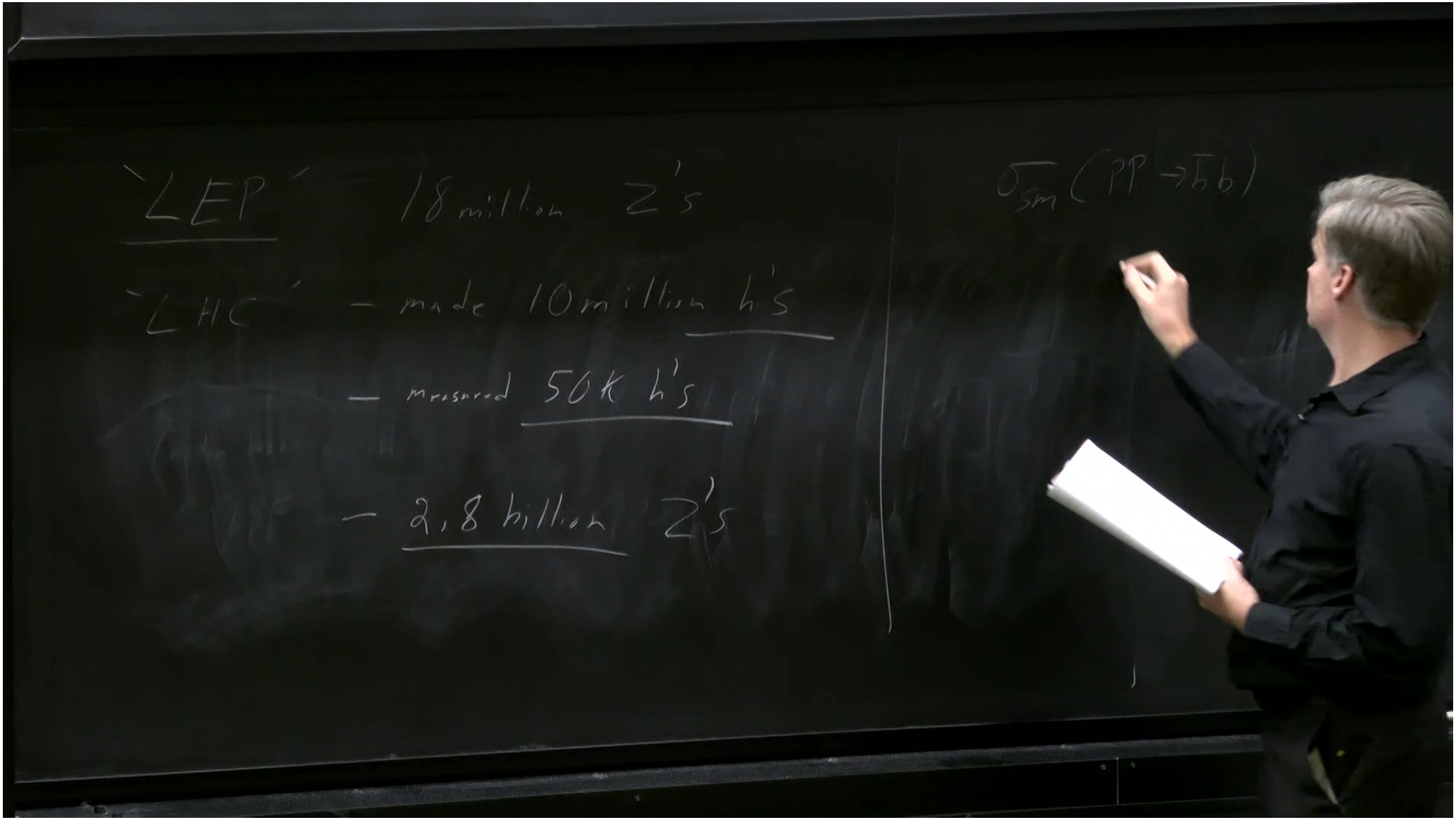

$\left(\frac{m_h^2}{v^2}\right) A_{h\to\gamma\gamma} =$
+
γ
γ
W
W
W
γ
γ
W
γ
γ
2

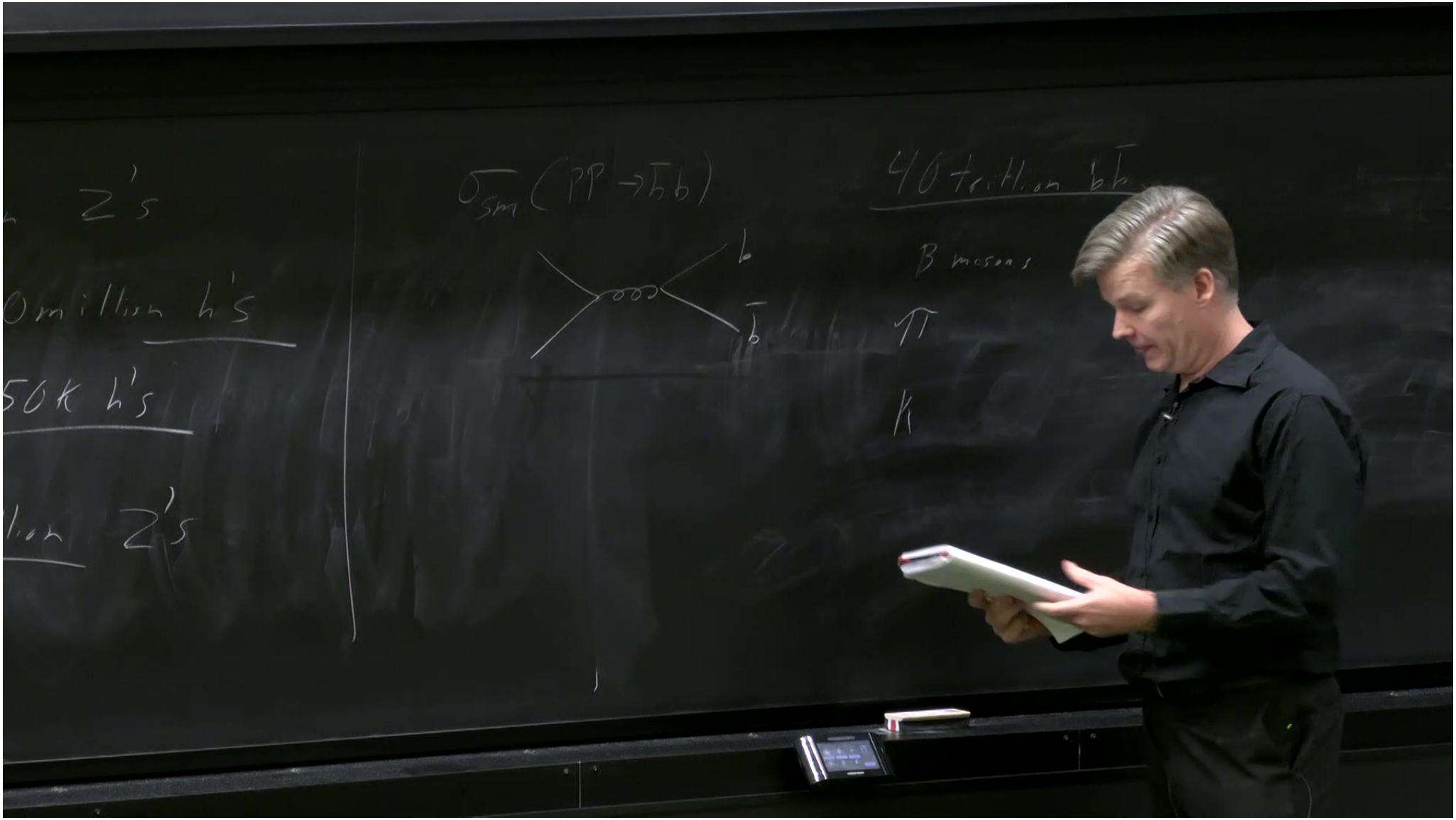

$\left(\frac{m_h^2}{v^2}\right) A_{h\to\gamma\gamma}^2 =$
t
W
W
W
W
γ
γ
γ
γ
$\frac{G_F m_h^3}{\sqrt{2}\,\pi^3}$
$\sum_\psi F_{1/2}(\tau_\psi) N_c Q_\psi^2 + F_1(\tau_W)$
2
2

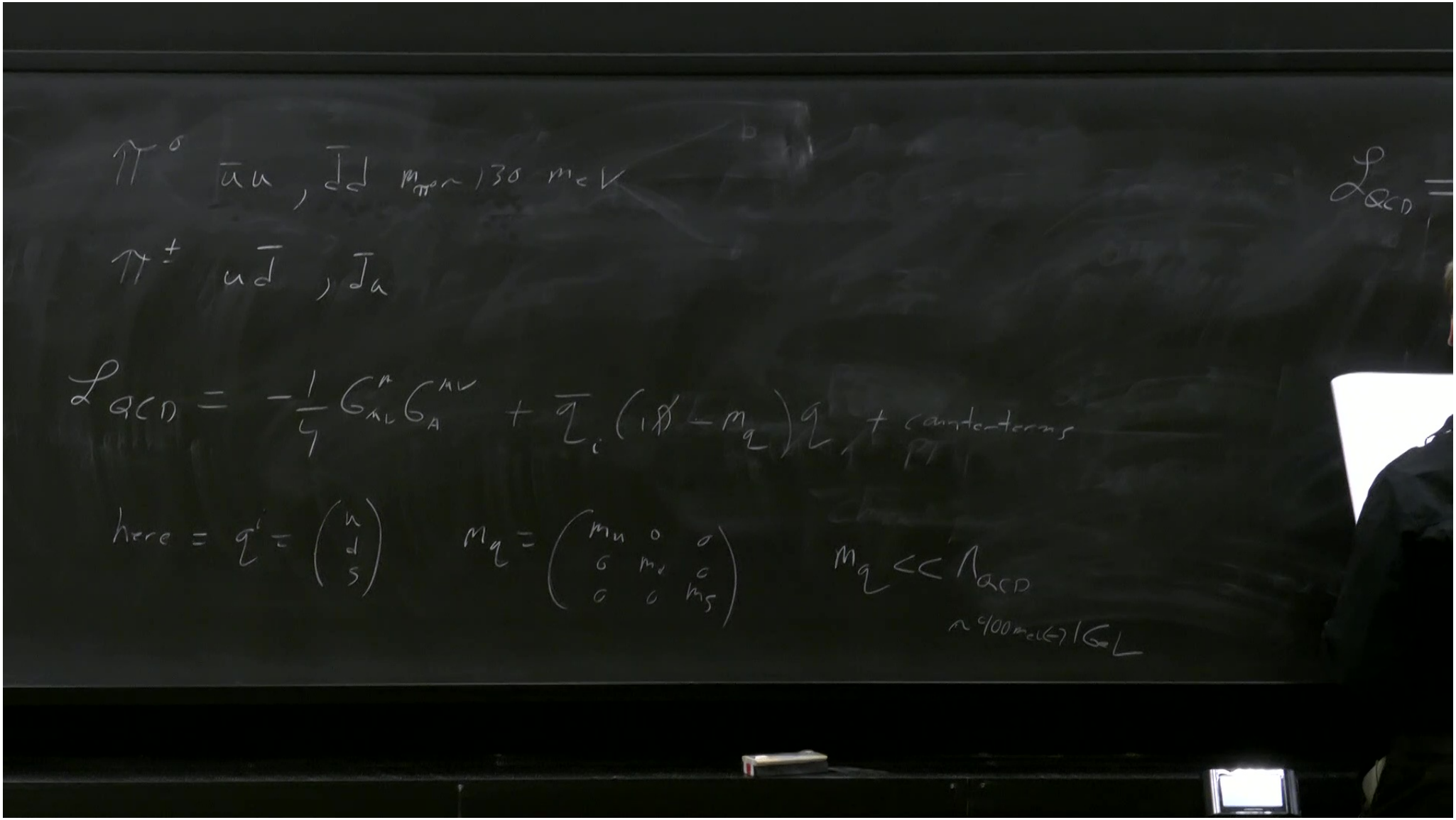

$\Gamma(h \to gg) = \frac{\alpha_s^2 G_F m_h^3}{128\sqrt{2}\pi^3}$
$\left| \sum_\psi F_{1/2}(\tau_\psi) N_c Q_\psi^2 + F_1(\tau_W) \right|^2$
$F_1(\tau_W) = 2 + 3\tau_W [1 + (2-\tau_W) f(\tau_W)]$
$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 G_F m_h^3}{64\sqrt{2}\pi^3}$
$F_{1/2}(\tau_\psi) = -2\tau_\psi [$
$\arcsin^2 \sqrt{1/\tau_\psi}$
$\tau_\psi > 1$ tip
$\tau_\psi = 4m_\psi^2/m_h^2$
$-\frac{1}{2}\left[\log\left[\frac{1+\sqrt{1-\tau_\psi}}{1-\sqrt{1-\tau_\psi}}\right] + i\pi\right]^2$
$\tau_\psi < 1$ bottom
$\tau_\psi \gg 1$

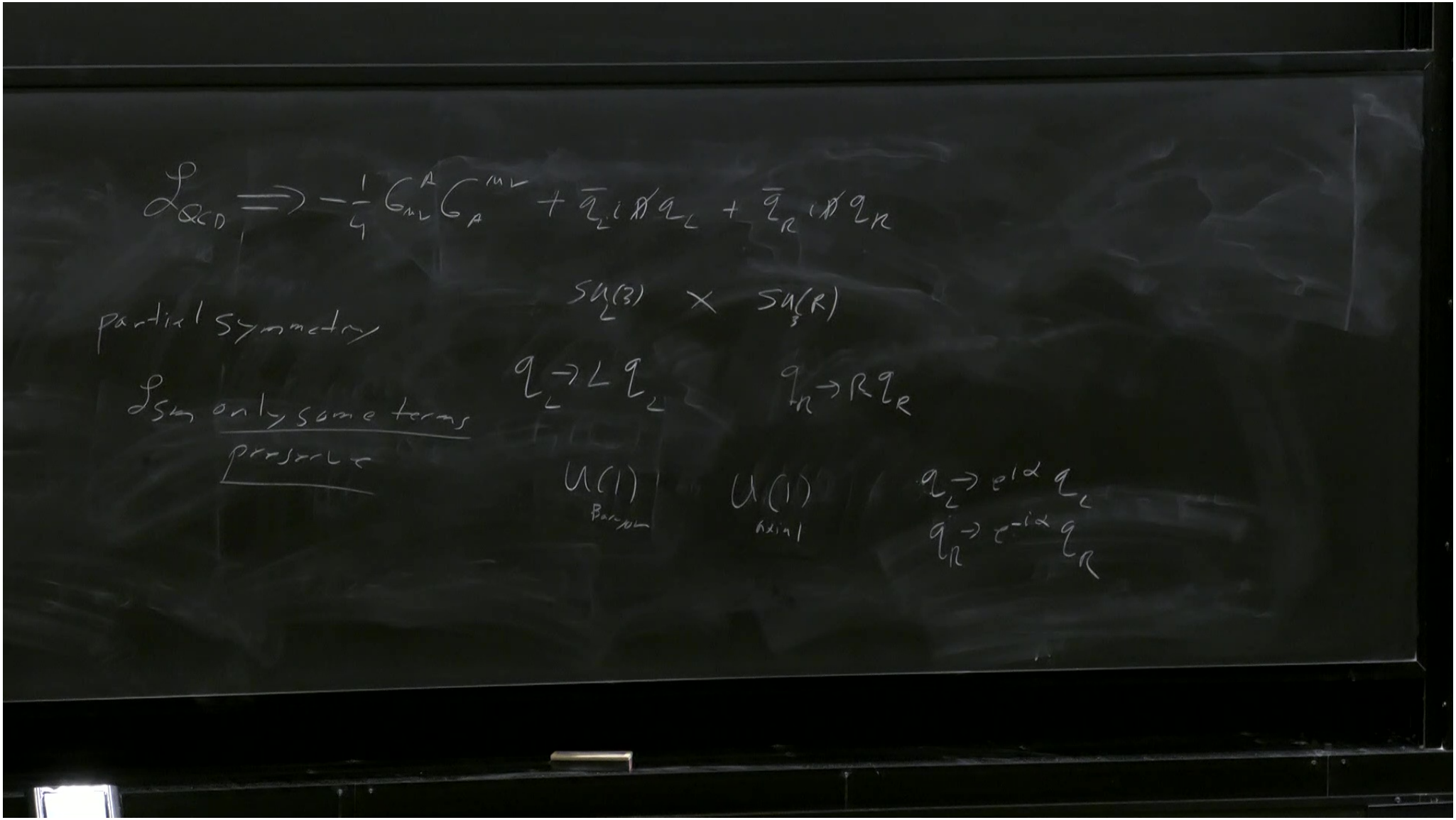

$\frac{C_{HB}}{\Lambda^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}$
$+ \frac{C_{HW}}{\Lambda^2} H^\dagger H W^A_{\mu\nu} W^{A\mu\nu}$
$\mathcal{L}_{SM} + \frac{C_{HWB}}{\Lambda^2} H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$
$+ \frac{C_{HD}}{\Lambda^2} (H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$
$+ \frac{C_{HG}}{\Lambda^2} H^\dagger H G^A_{\mu\nu} G^{A\mu\nu} + \dots$
$\tau_W = 4m_W^2/m_H^2$
$2 + 3\tau_W [1 + (2-\tau_W) f(\tau_W)]$

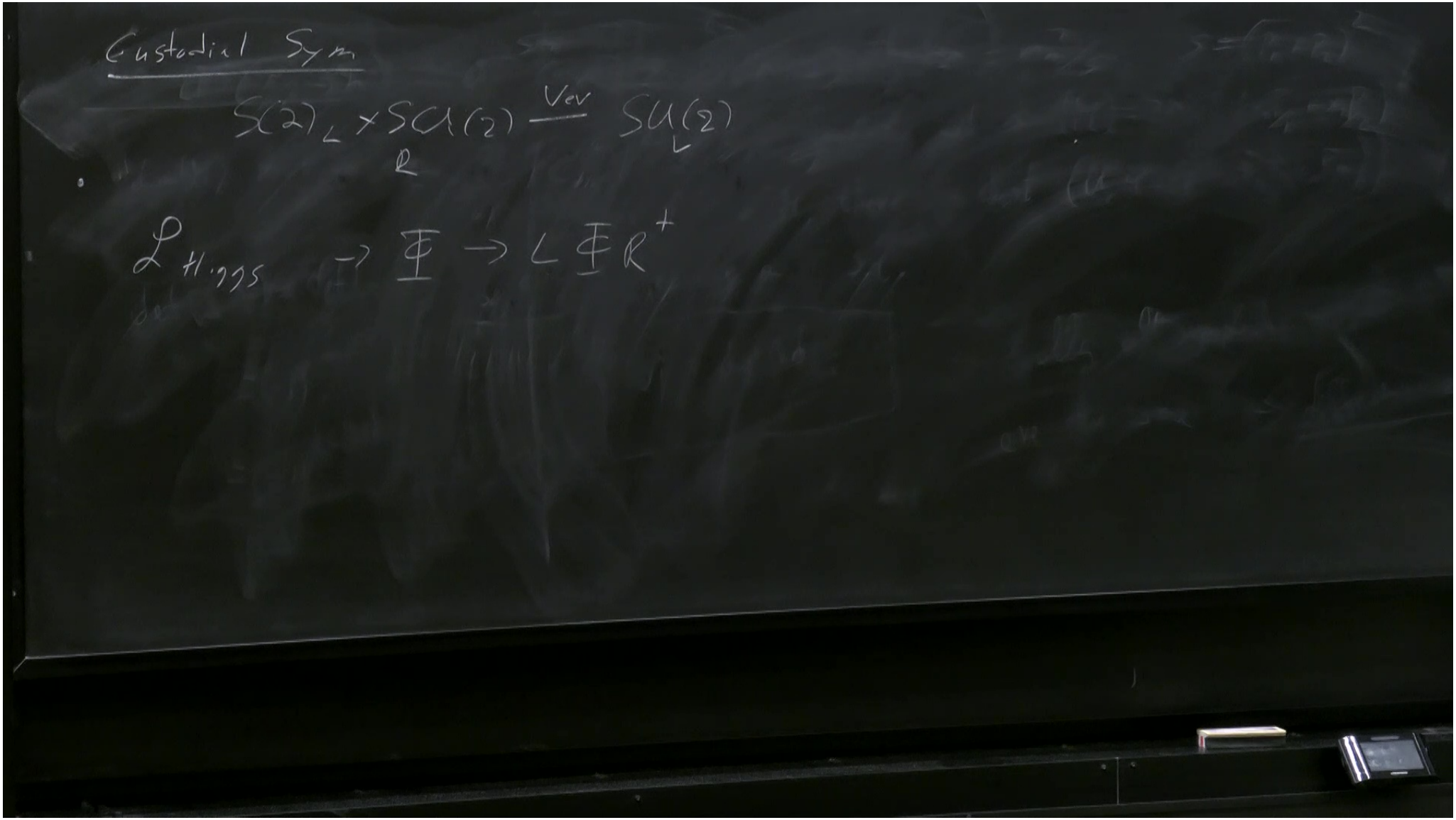

`LEP' 18 million Z's
`LHC' - made 10 million h's
- measured 50k h's

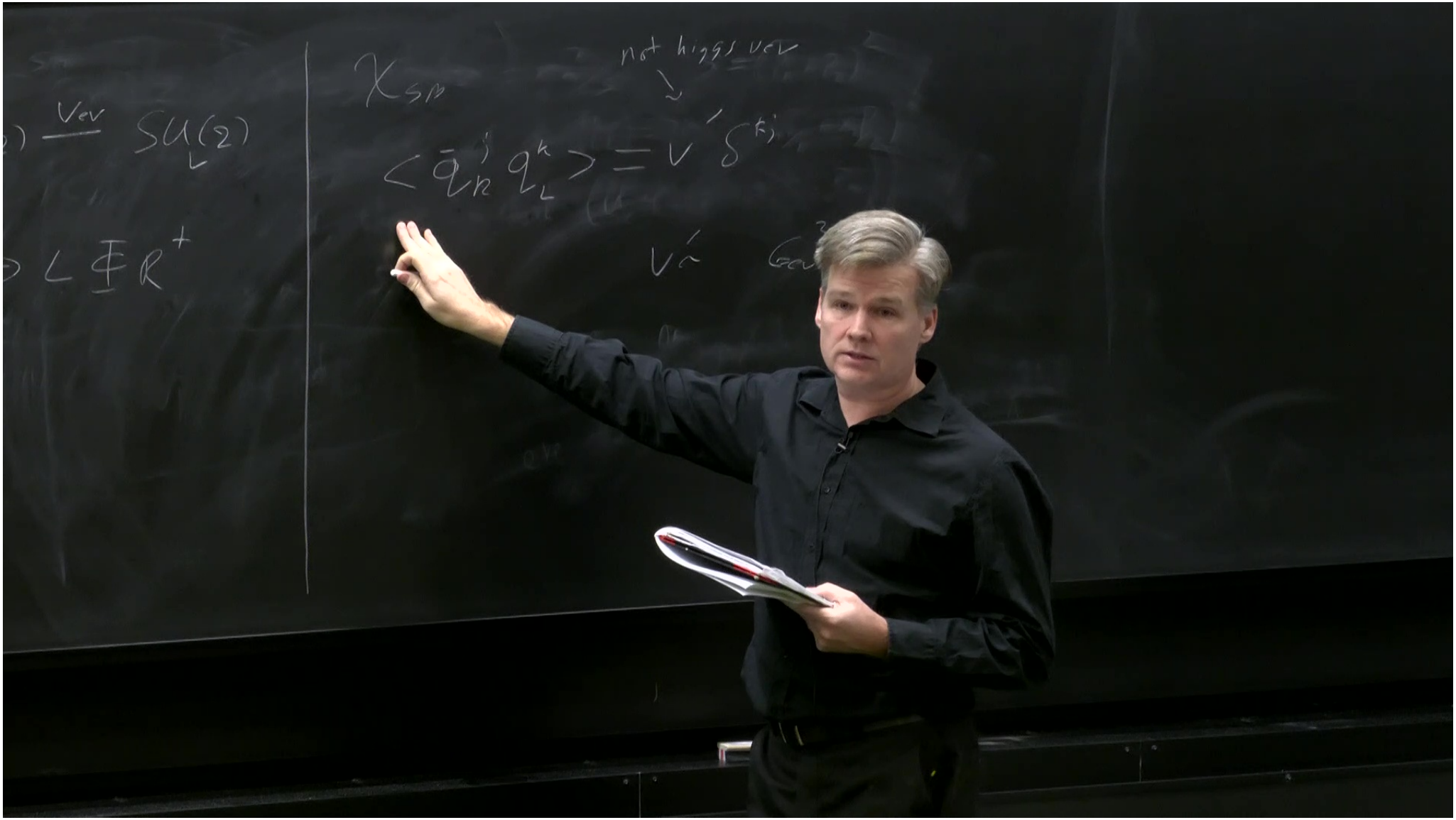

`LEP' – 18 million Z's
`LHC' – made 10 million h's
– measured 50k h's
– 2,8 billion Z's
$\sigma_{SM}(PP \to \bar{t}b)$

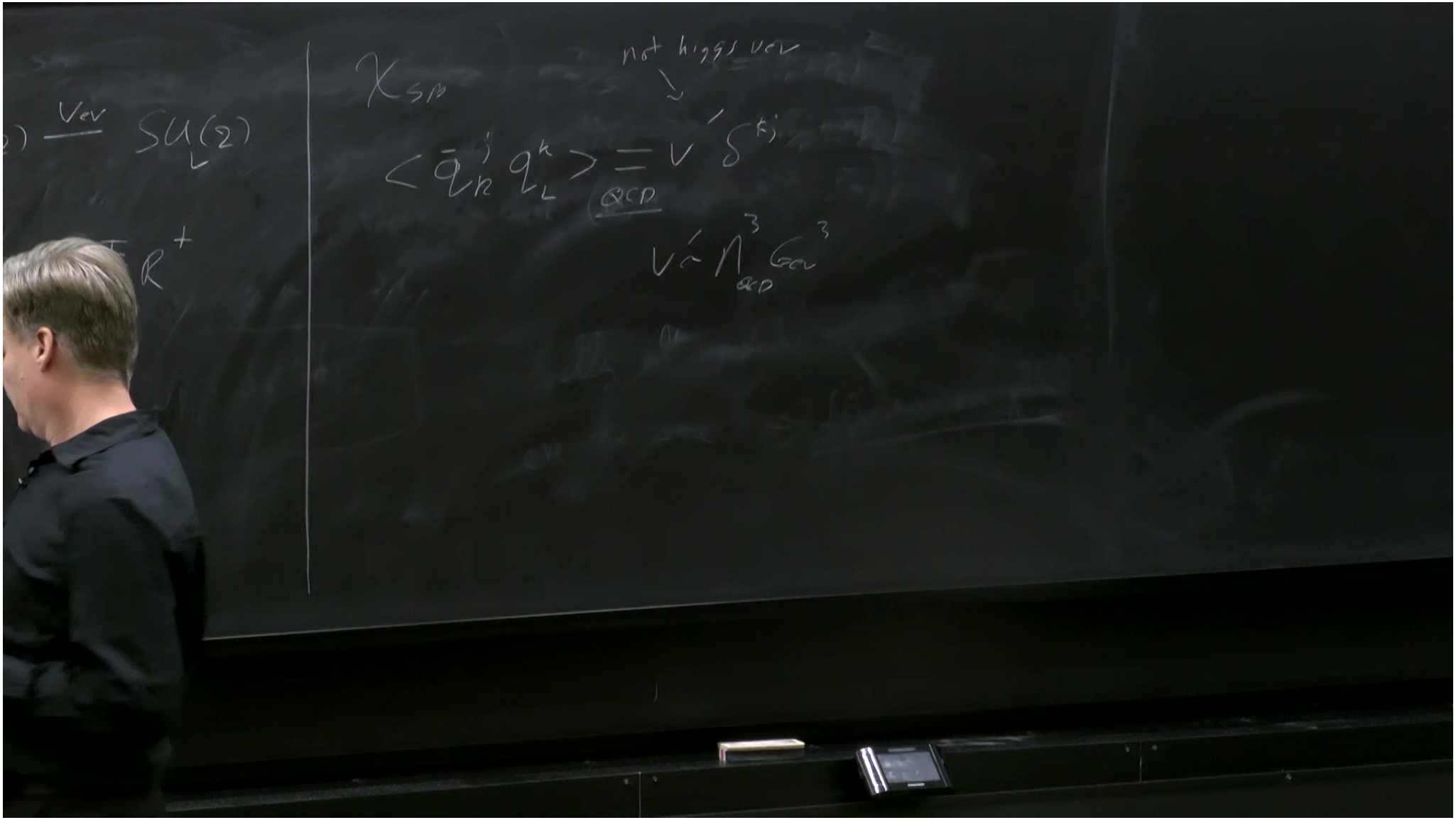

Z's
Omillion h's
50k h's
Z's
$\sigma_{SM}(pp \to b\bar{b}b)$
b
$\bar{b}$
40 Trillion $b\bar{b}$
B mesons
π
K

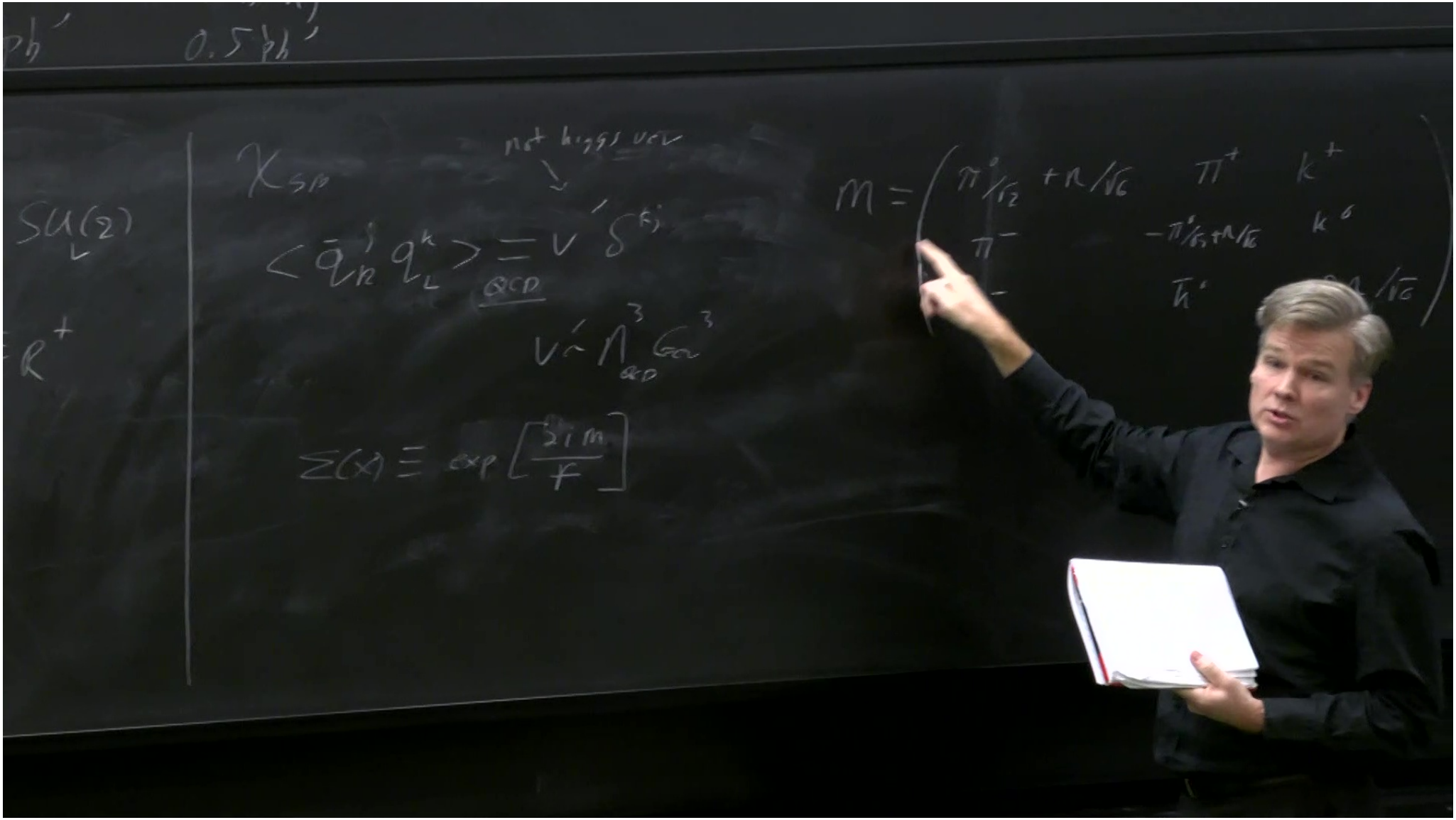

π^0 $\bar{u}u$, $\bar{d}d$ $m_{\pi^0} \sim 130$ MeV
$\pi^\pm$ $u\bar{d}$, $\bar{d}u$
$\mathcal{L}_{QCD} =$
$\mathcal{L}_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu} + \bar{q}_i (i\not{D} - m_q) q_i$ + counterterms
here $q^i = \begin{pmatrix} u \\ d \\ s \end{pmatrix}$ $m_q = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}$ $m_q \ll \Lambda_{QCD}$
~ 400 MeV ~ 1 GeV

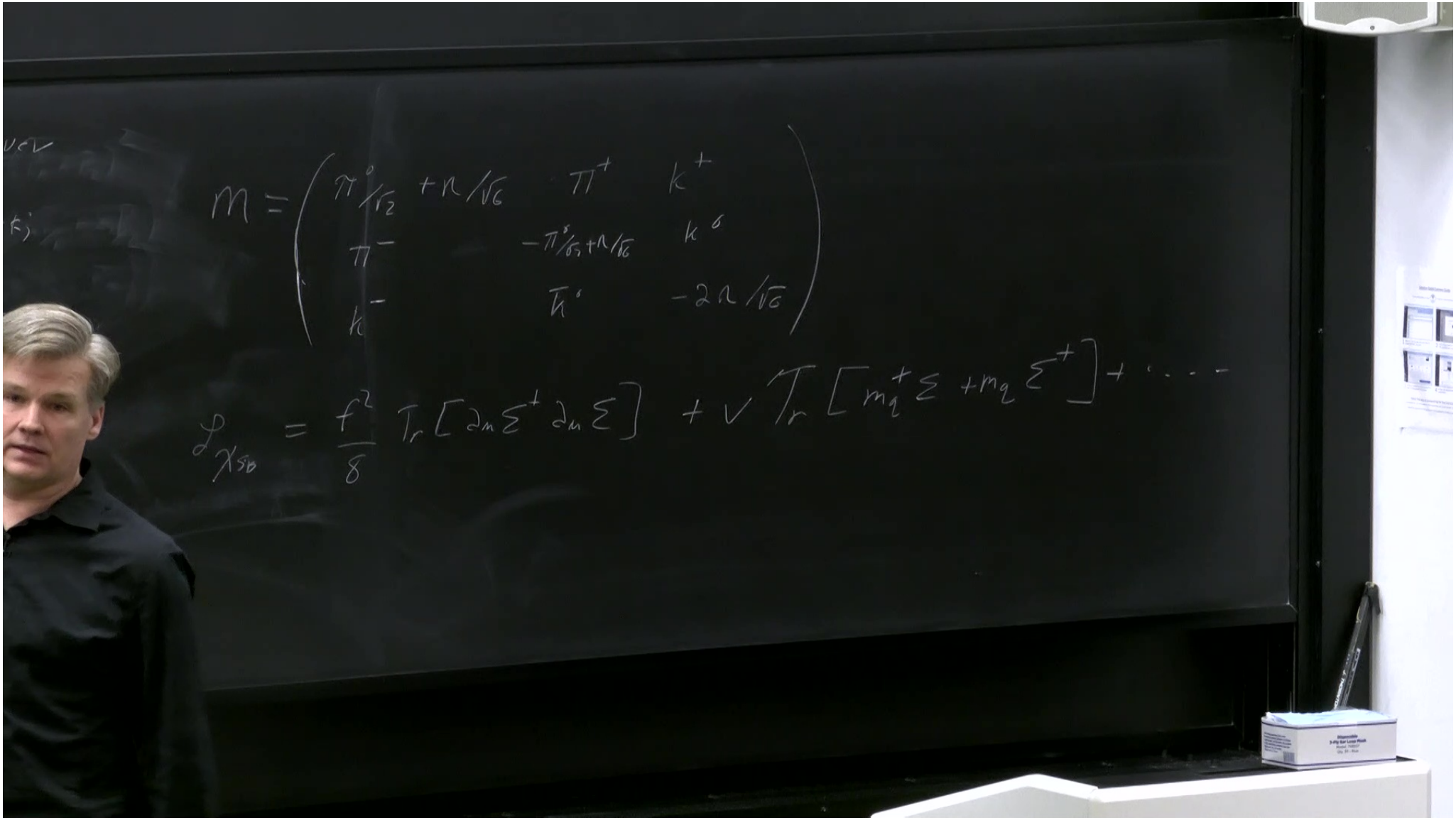

$\mathcal{L}_{QCD} \Longrightarrow -\frac{1}{4} G^A_{\mu\nu} G_A^{\mu\nu} + \bar{q}_L i \not{D} q_L + \bar{q}_R i \not{D} q_R$
$SU_L(3) \times SU_R(3)$
Partial symmetry
$\mathcal{L}_{SM}$ only some terms preserve
$q_L \to L q_L$
$q_R \to R q_R$
$U(1)$ Baryon
$U(1)$ Axial
$q_L \to e^{i\alpha} q_L$
$q_R \to e^{-i\alpha} q_R$


Custodial Sym
$SU(2)_L \times SU(2)_R \xrightarrow{Vev} SU(2)_{L+R}$
$\mathcal{L}_{Higgs} \to \Phi \to L \Phi R^+$


not higgs vev
χ_{SB}
$\langle \bar{q}_R^i q_L^k \rangle = v' \delta^{ki}$
vev
$SU(2)_L$
$L \Phi R^+$


not higgs vev
QCD


0.5 fb
SU(2)
R+
χSB
not higgs vev
<q̄R^i qL^k> = v' δ^ki
QCD
v' ~ Λ_QCD^3 Gαν^3
Σ(x) = exp[2i π / f]
M = (π^0/√2 + η/√6 π+ k+
π− −π^0/√6+η/√6 k0
η' η/√6)


$M = \begin{pmatrix} \pi^0/\sqrt{2} + \eta/\sqrt{6} & \pi^+ & K^+ \\ \pi^- & -\pi^0/\sqrt{2} + \eta/\sqrt{6} & K^0 \\ K^- & \bar{K}^0 & -2\eta/\sqrt{6} \end{pmatrix}$
$\mathcal{L}_{\chi SB} = \frac{f^2}{8} Tr[\partial_\mu \Sigma^\dagger \partial_\mu \Sigma] + v\, Tr[m_q^\dagger \Sigma + m_q \Sigma^\dagger] + \ldots$