Title: The Standard Model â€“ Theory: The Higgs boson

Date: Jul 08, 2015 02:30 PM

URL: http://pirsa.org/15070024

Abstract:

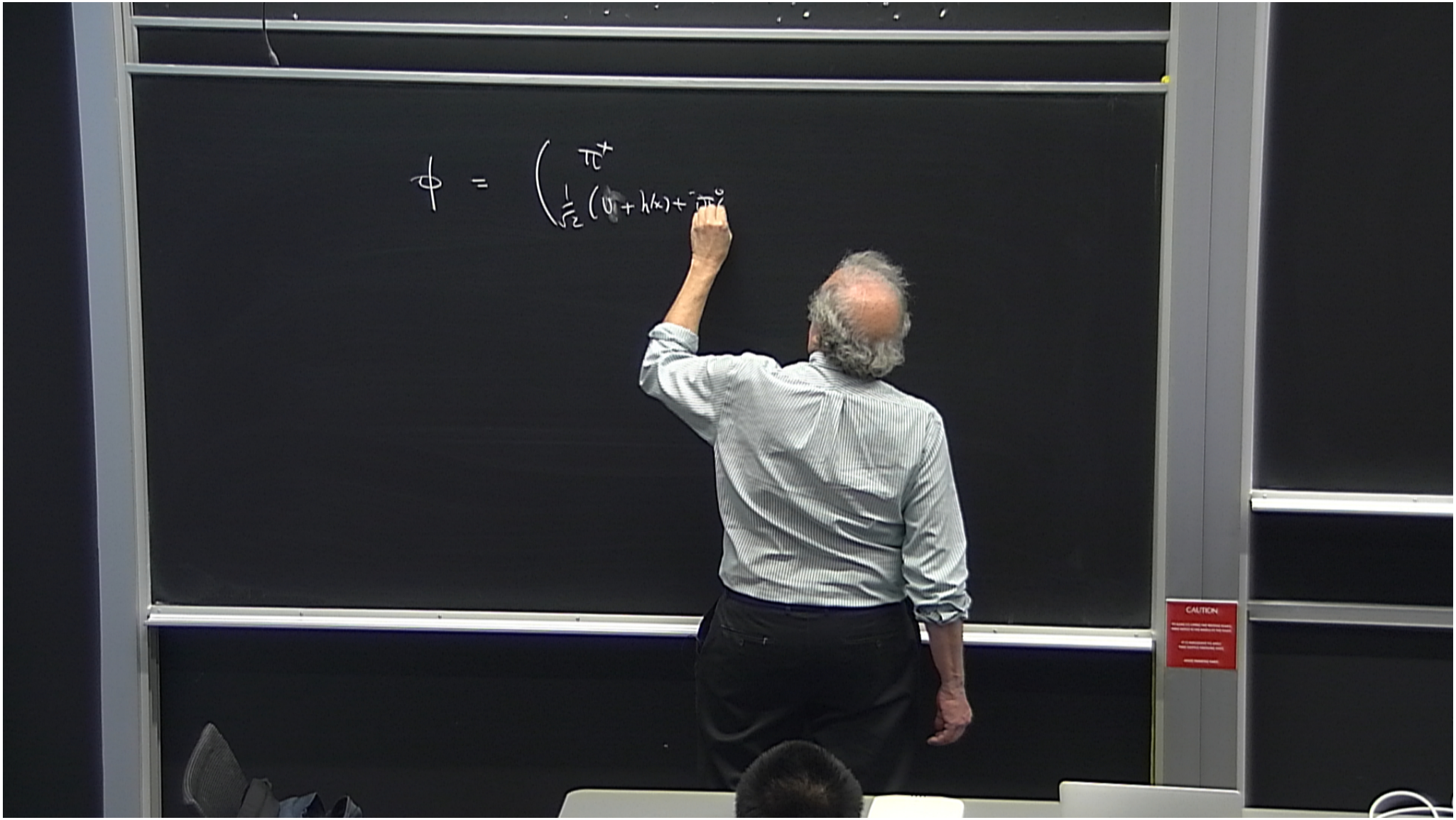

Collider Physics
Higgs Boson

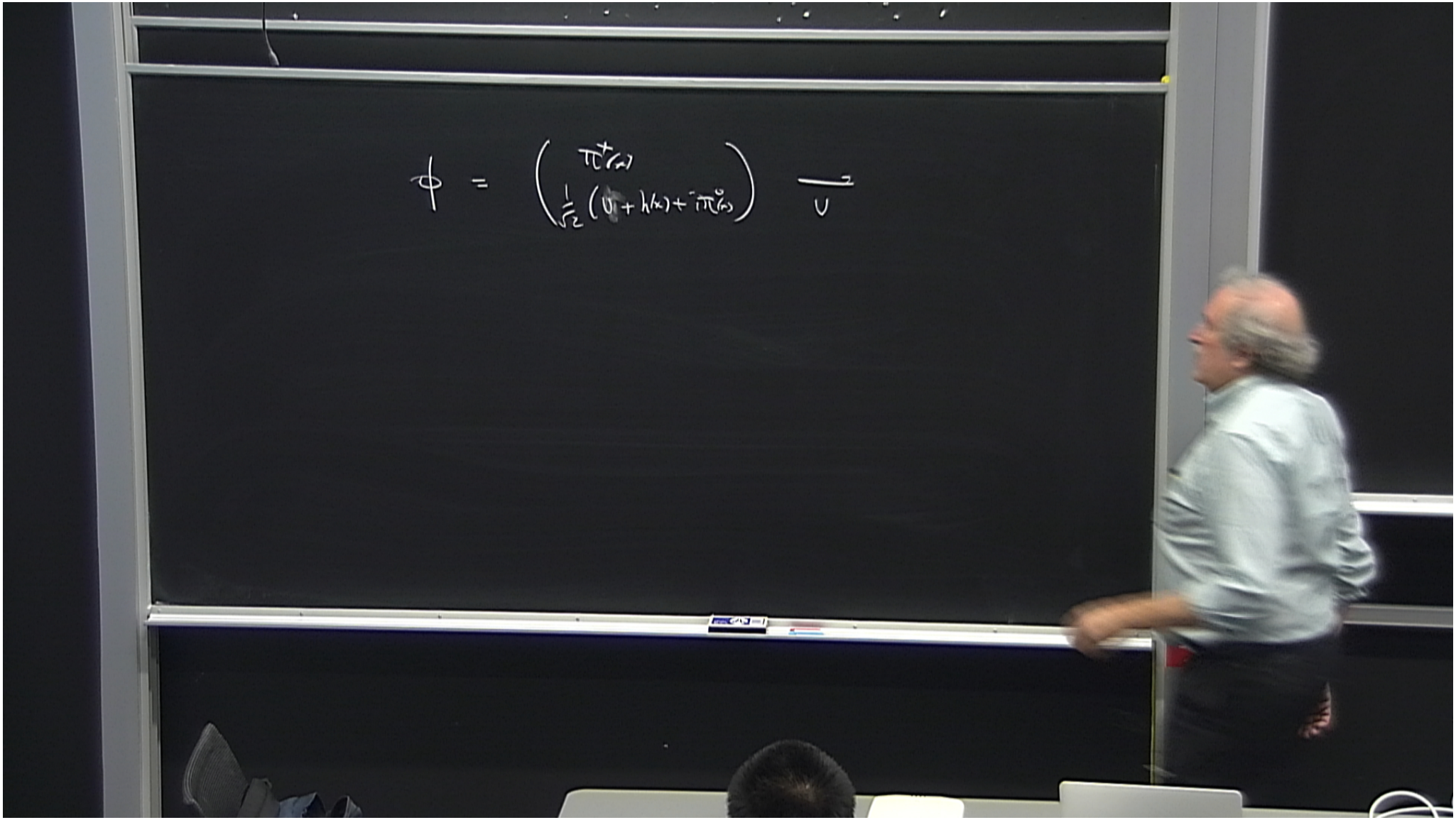
Collider Physics

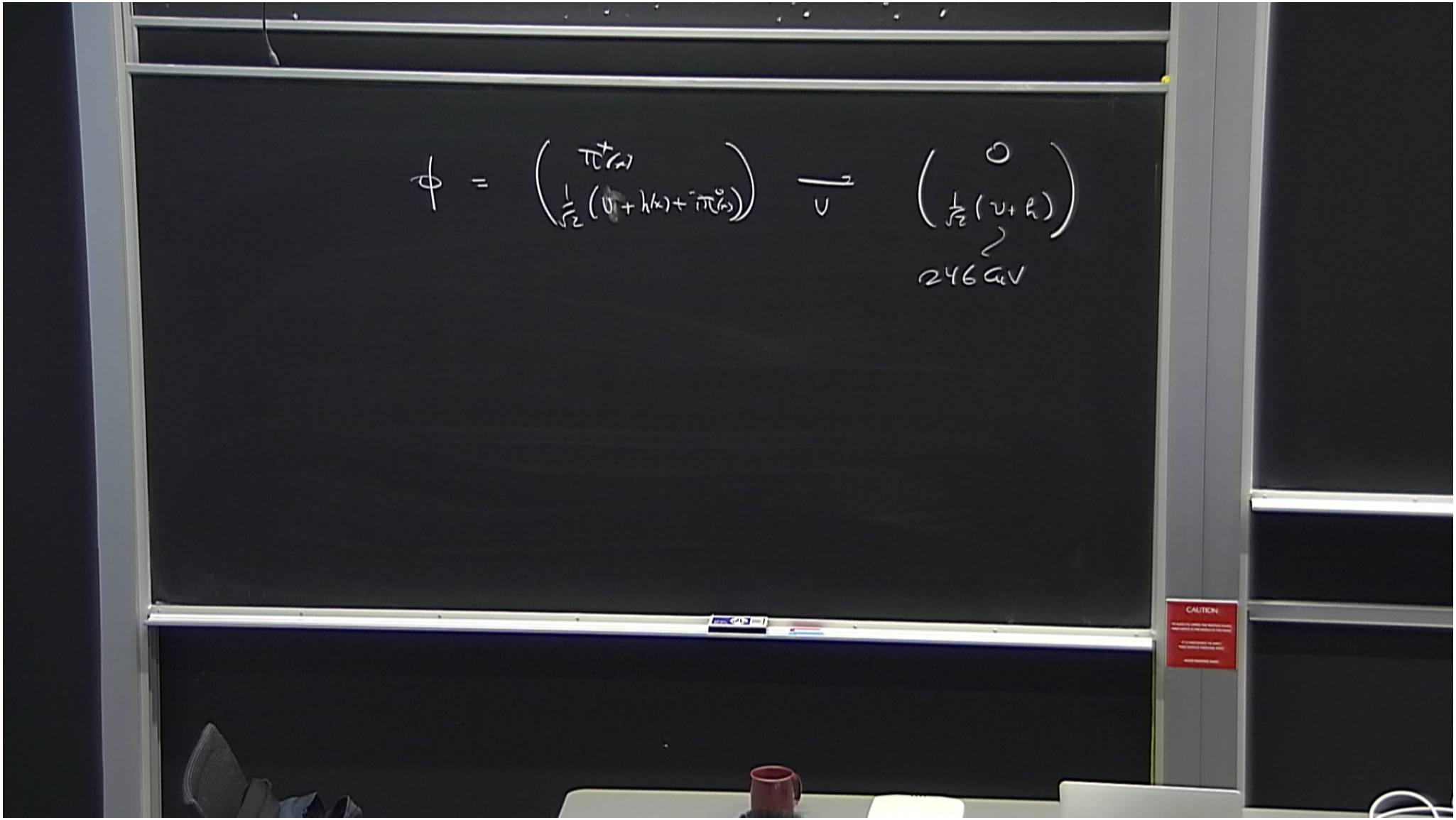
figures for lecture 6

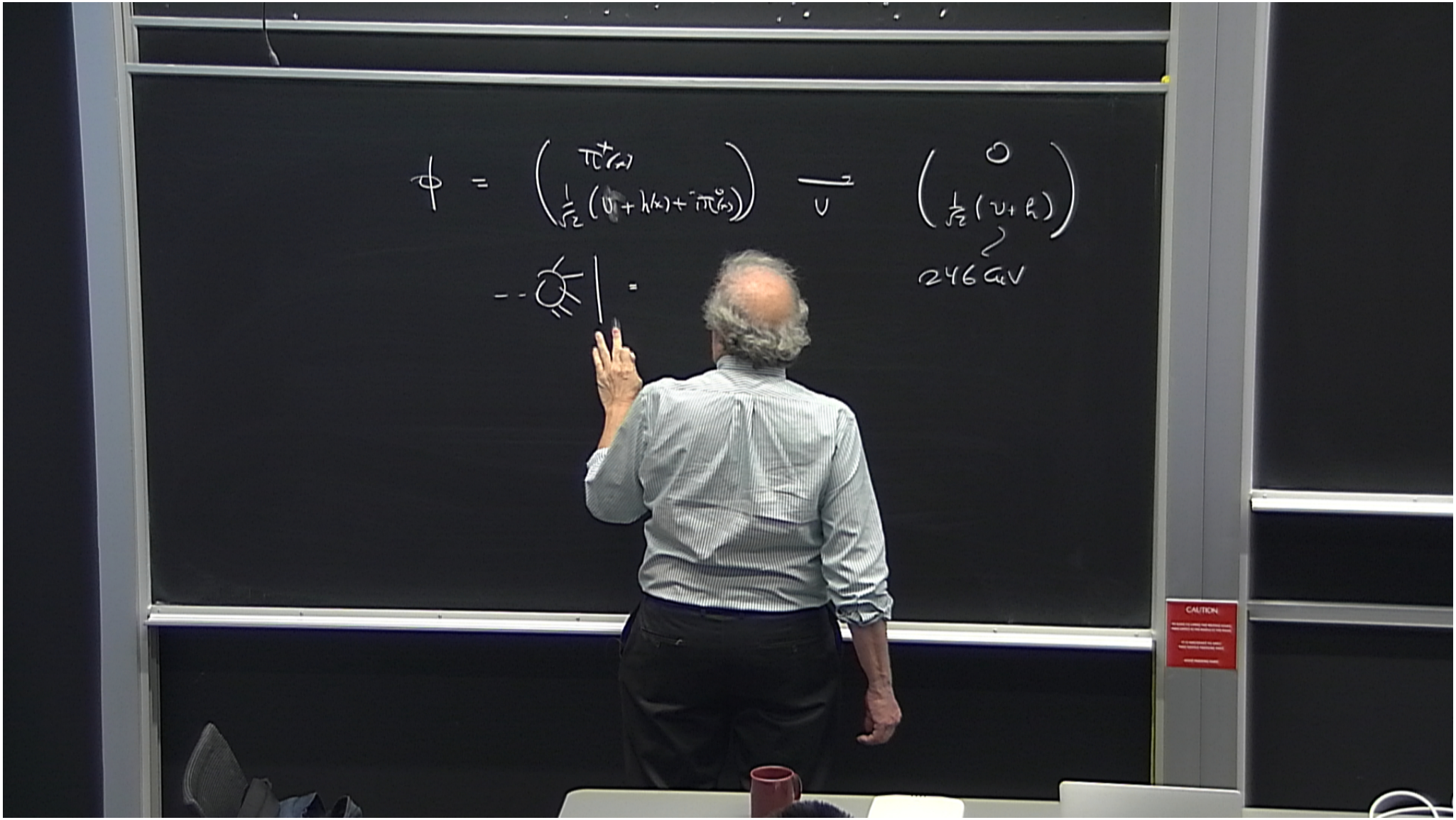
Higgs Boson

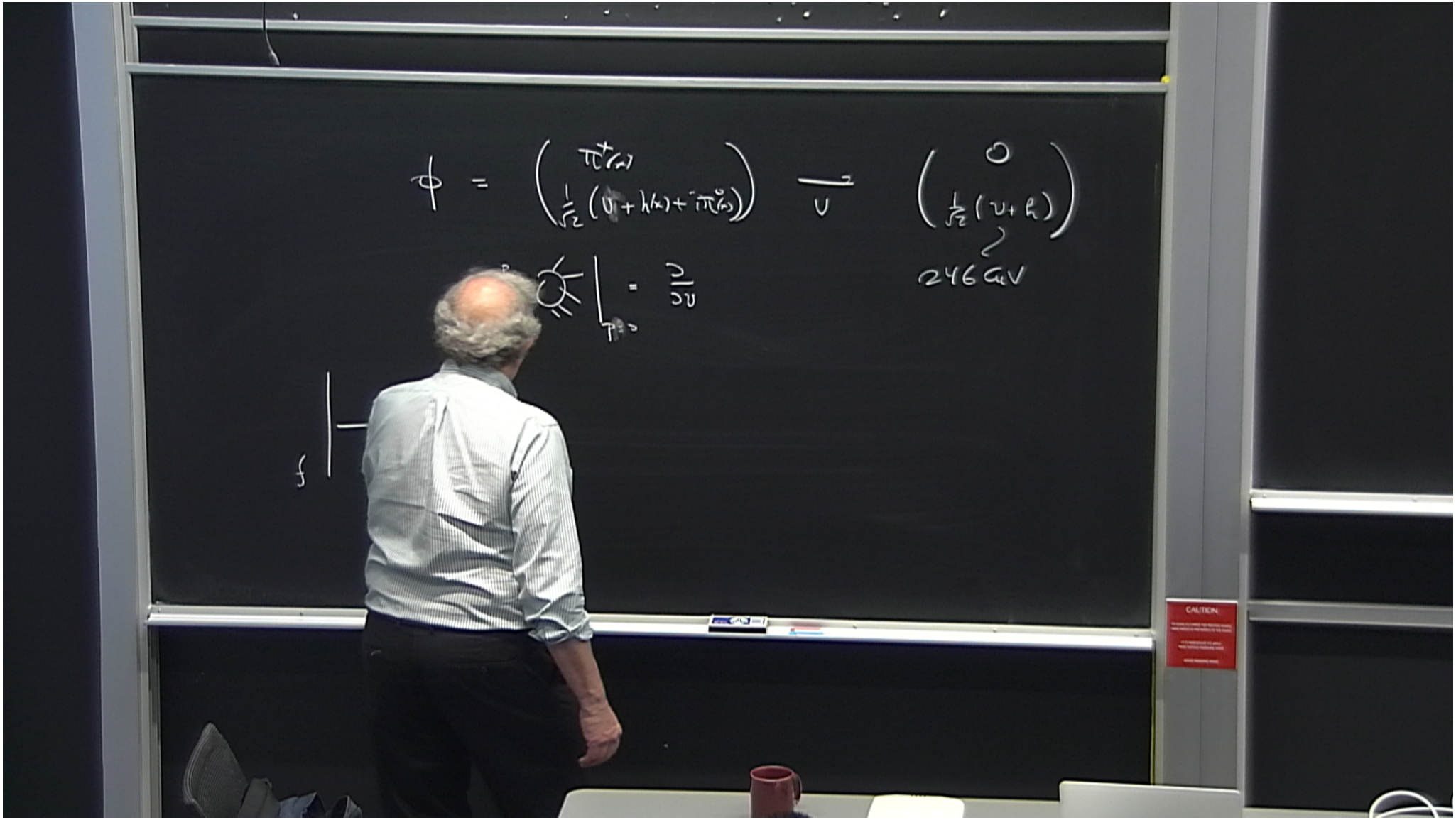
Michael Peskin
TRISEP School 2015

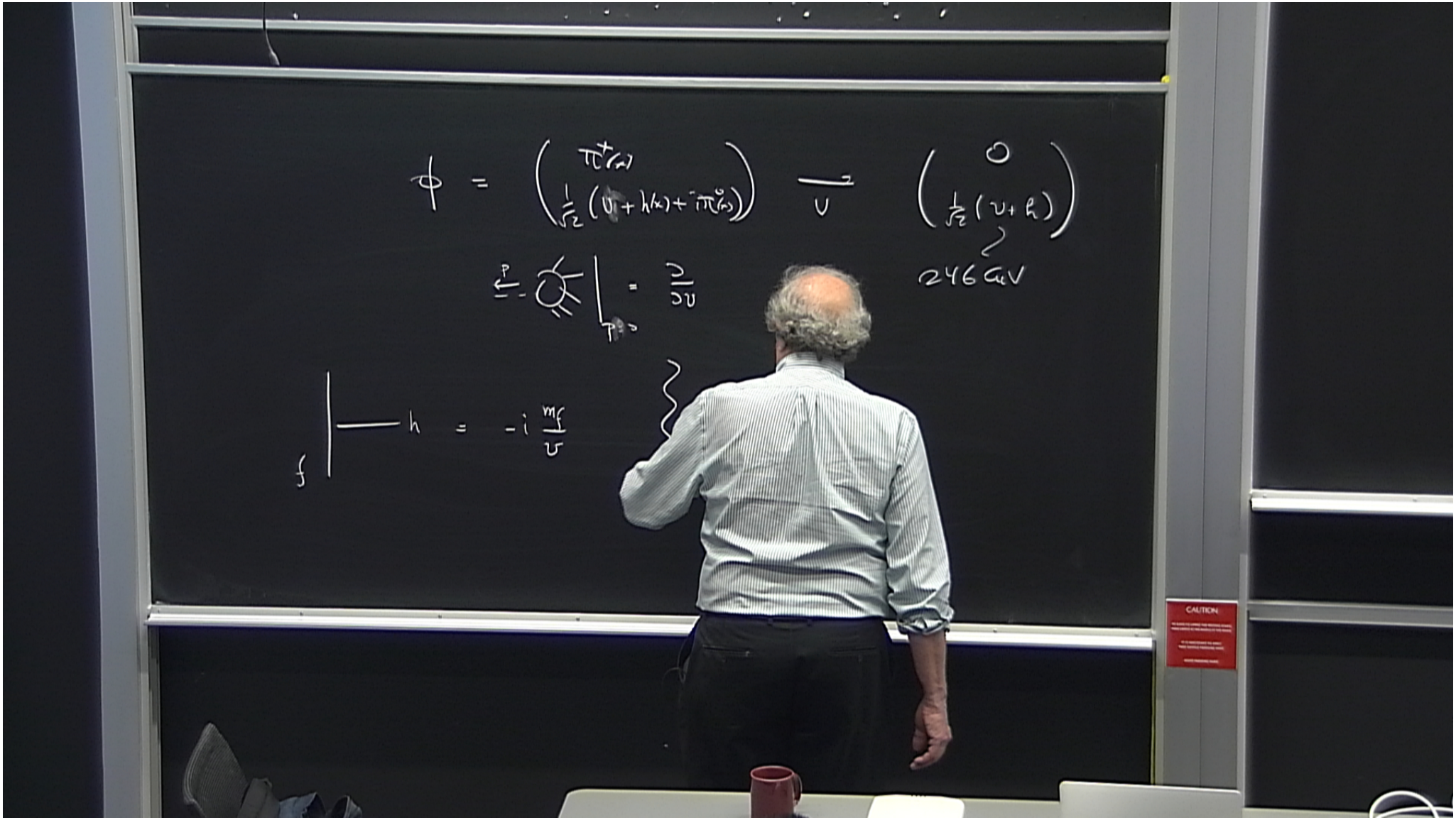

$\phi = \begin{pmatrix} \pi^+ \\ \frac{1}{\sqrt{2}}(v + h(x) + i\pi^0) \end{pmatrix}$
CAUTION

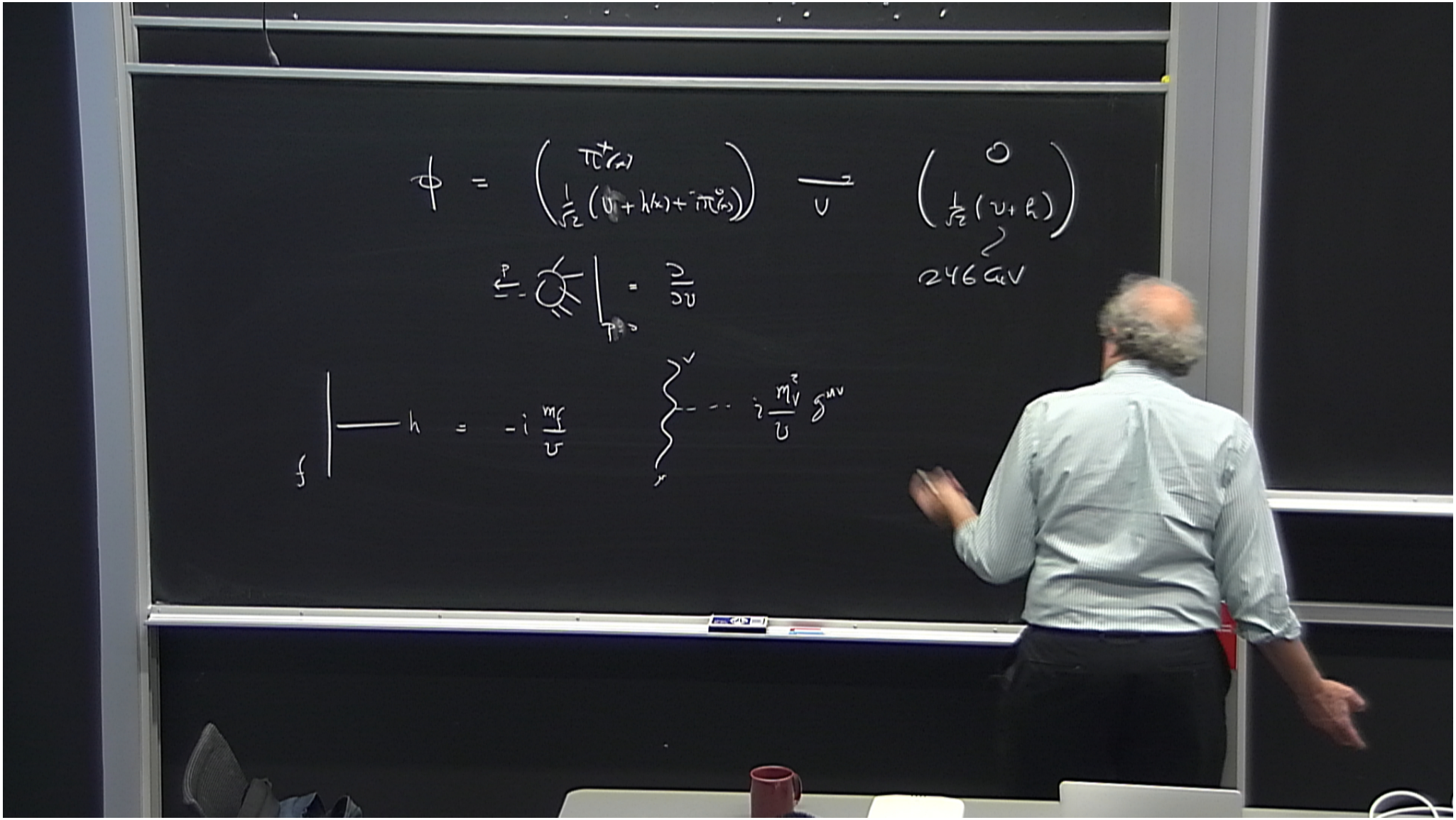

$\phi = \begin{pmatrix} \pi^+(x) \\ \frac{1}{\sqrt{2}}(v + h(x) + i\pi^0(x)) \end{pmatrix}$ $\frac{2}{v}$

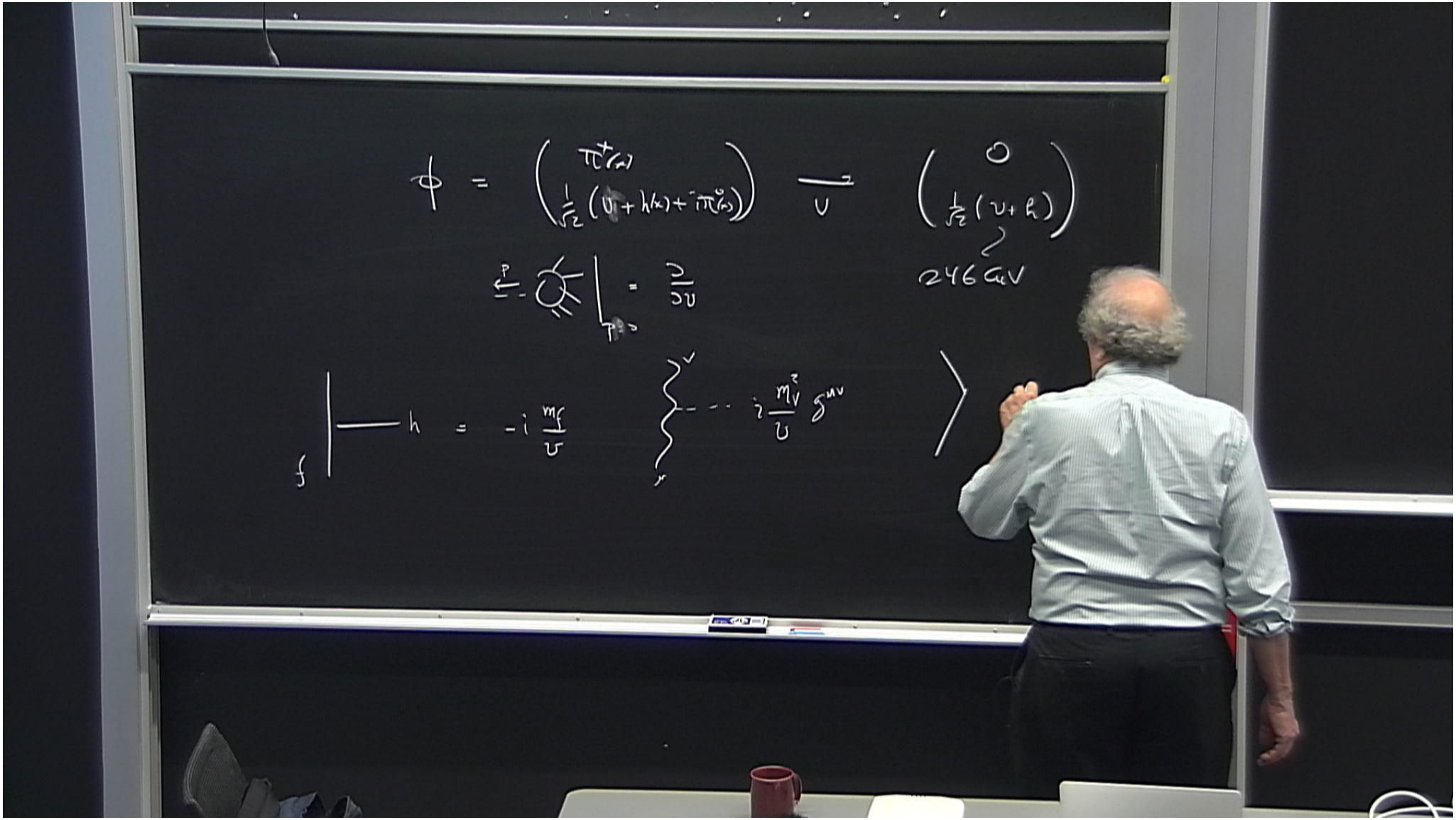

$\phi = \begin{pmatrix} \pi^+(x) \\ \frac{1}{\sqrt{2}}(v + h(x) + i\pi^0(x)) \end{pmatrix} \xrightarrow{v} \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+h) \end{pmatrix}$
246 GeV
CAUTION

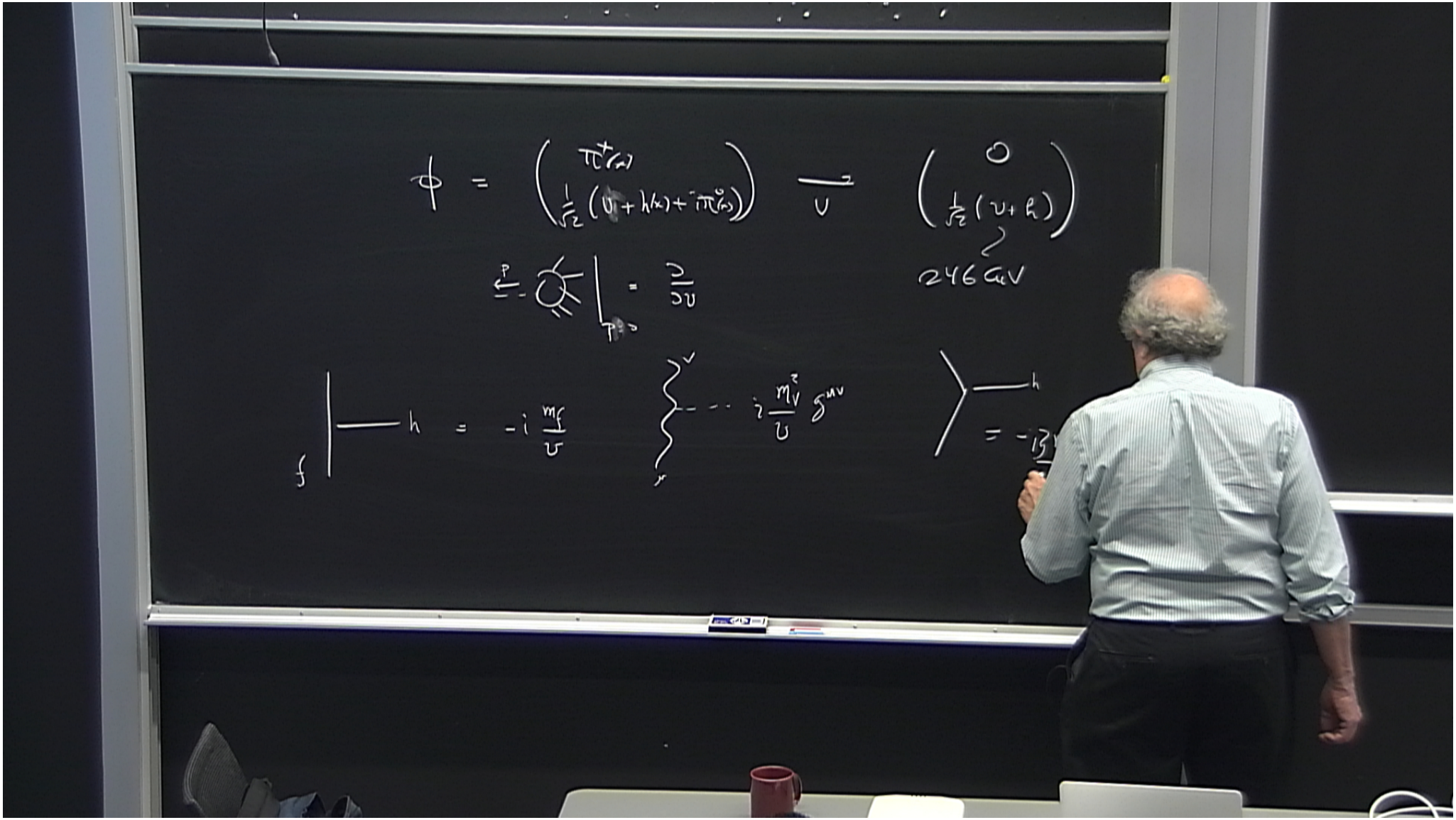

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246 GeV
CAUTION

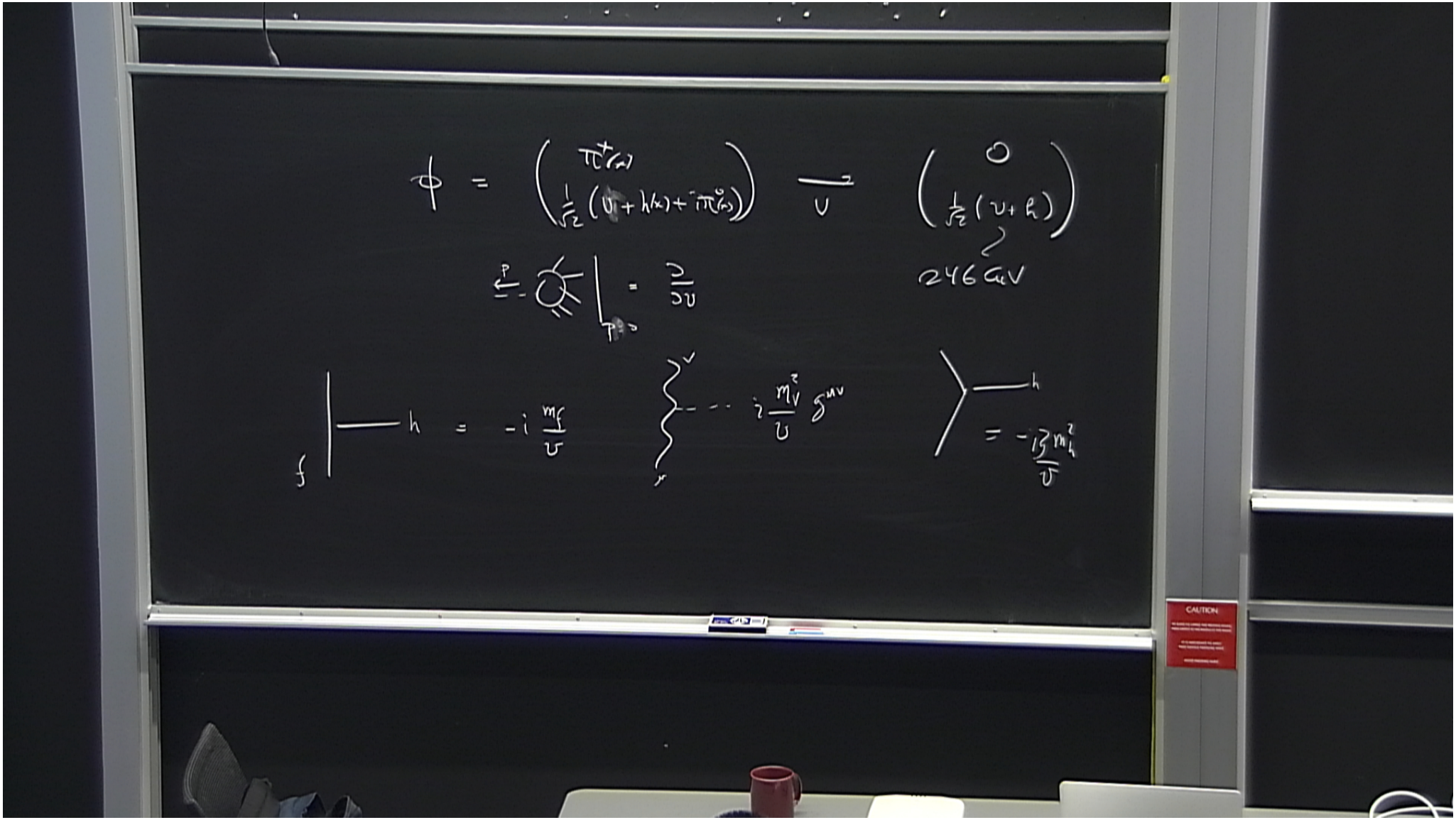

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246 GeV
$= \frac{2}{\partial v}$
CAUTION

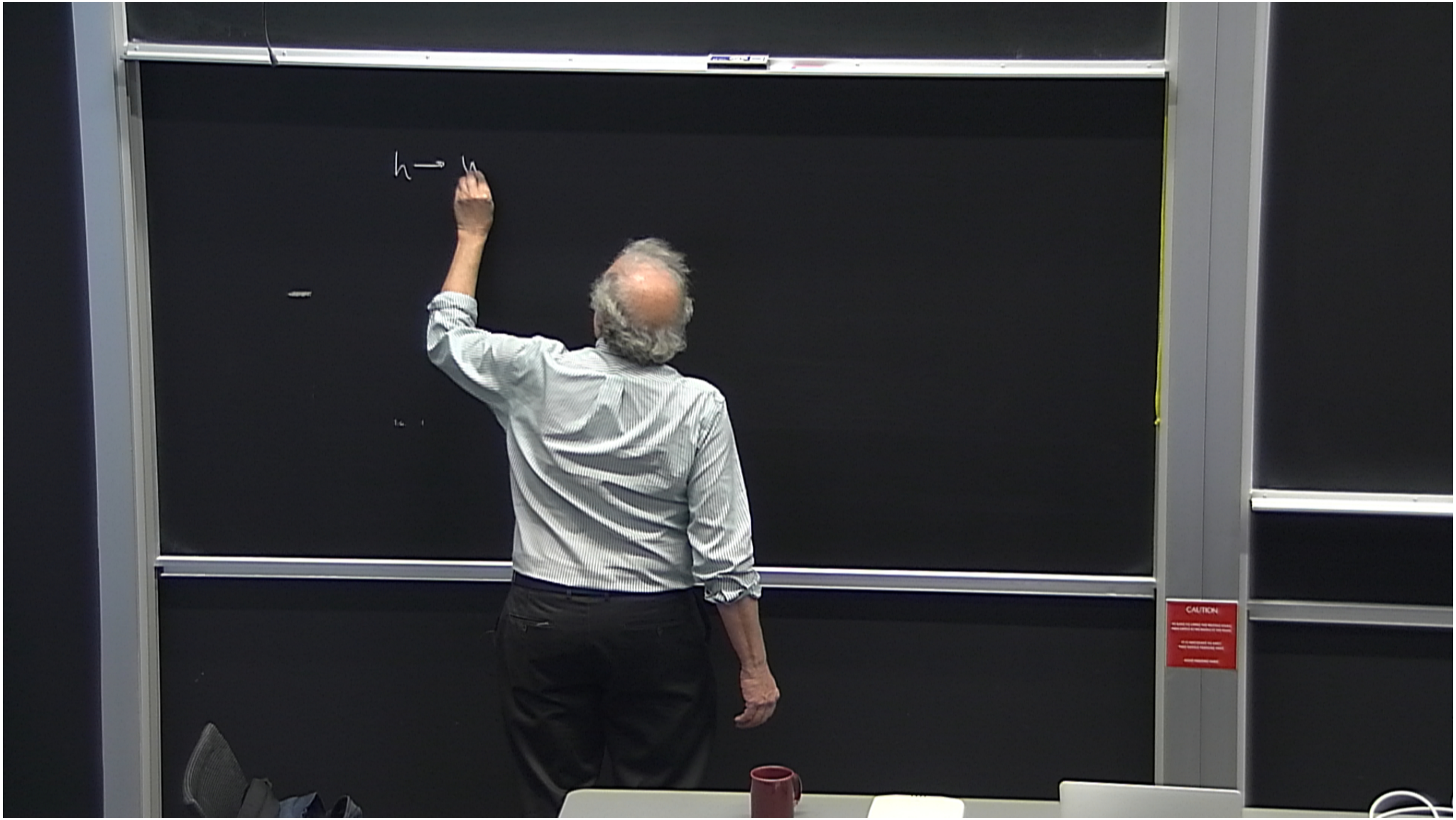

$\phi = \begin{pmatrix} \pi^+(x) \\ \frac{1}{\sqrt{2}}(v + h(x) + i\pi^0(x)) \end{pmatrix} \xrightarrow{} \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v + h) \end{pmatrix}$
246 GeV
$= \frac{2}{v}$
$= -i\frac{m_f}{v}$
CAUTION

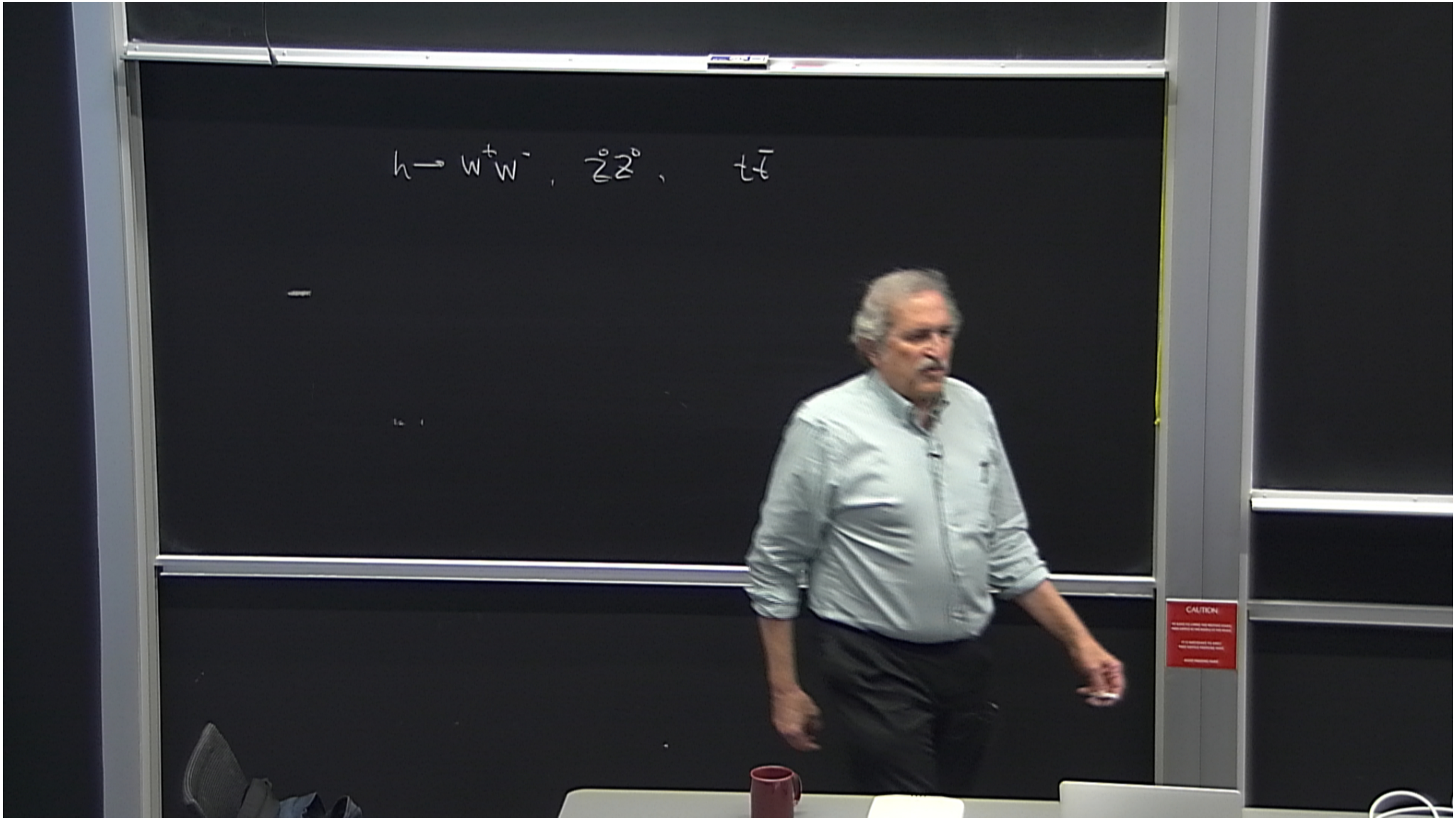

246 GeV

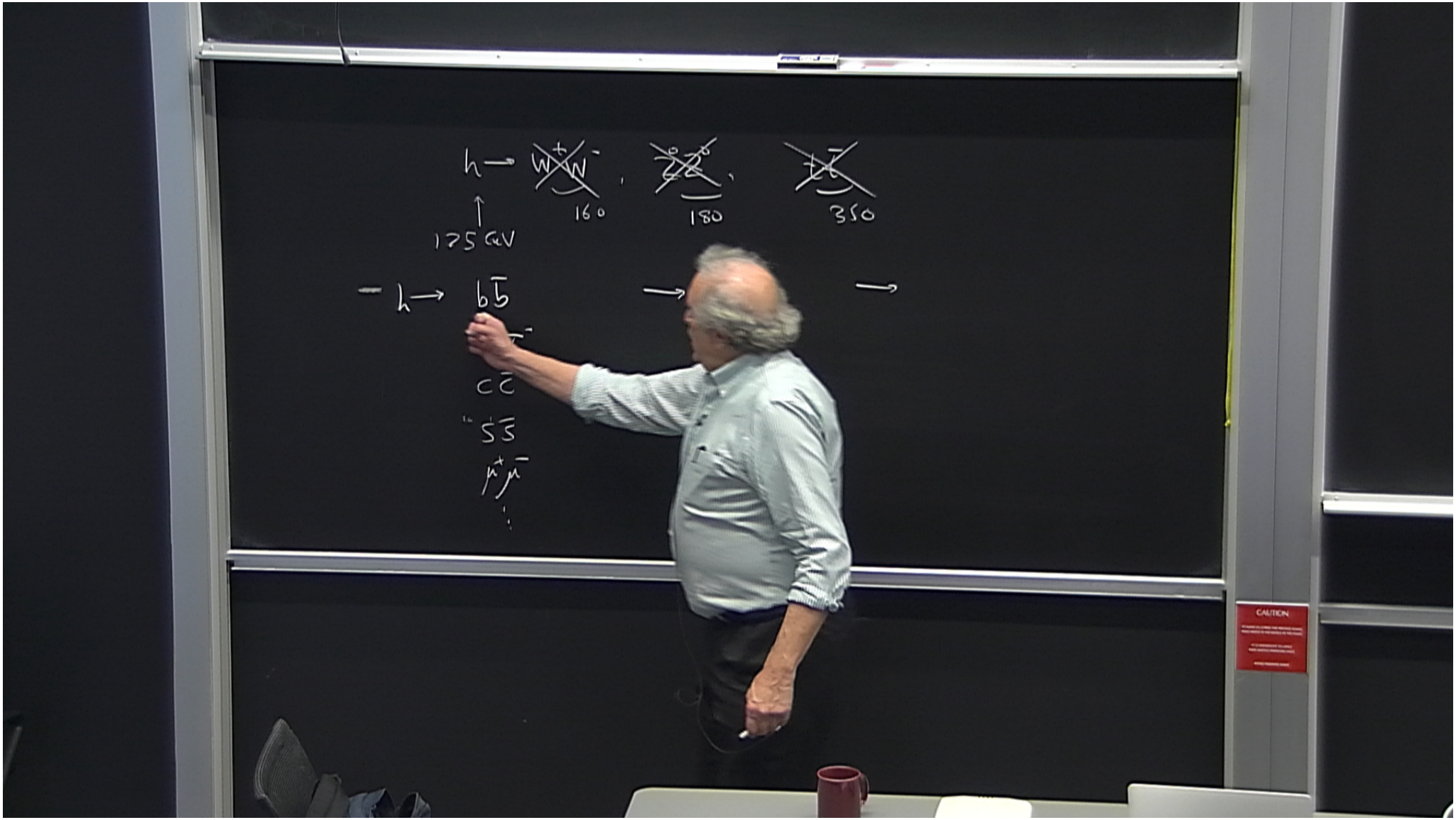

246 GeV

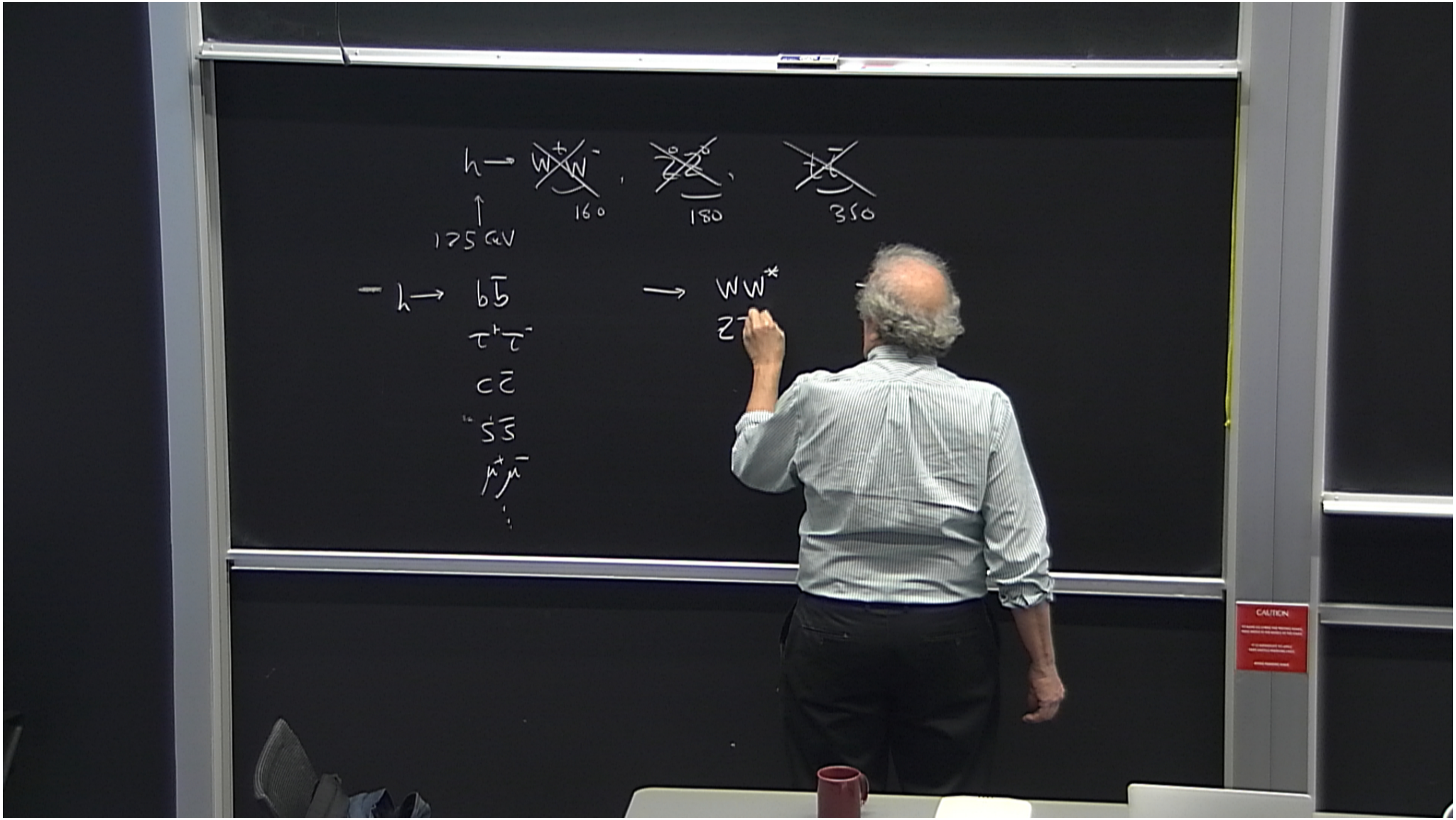

$\phi = \begin{pmatrix} \pi^+(x) \\ \frac{1}{\sqrt{2}}(v + h(x) + i\pi^0(x)) \end{pmatrix} \xrightarrow{\quad v \quad} \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v + h) \end{pmatrix}$
246 GeV
$= \frac{2}{v}$
$= -i\frac{m_f}{v}$
$= i\frac{2m_V^2}{v} g^{\mu\nu}$

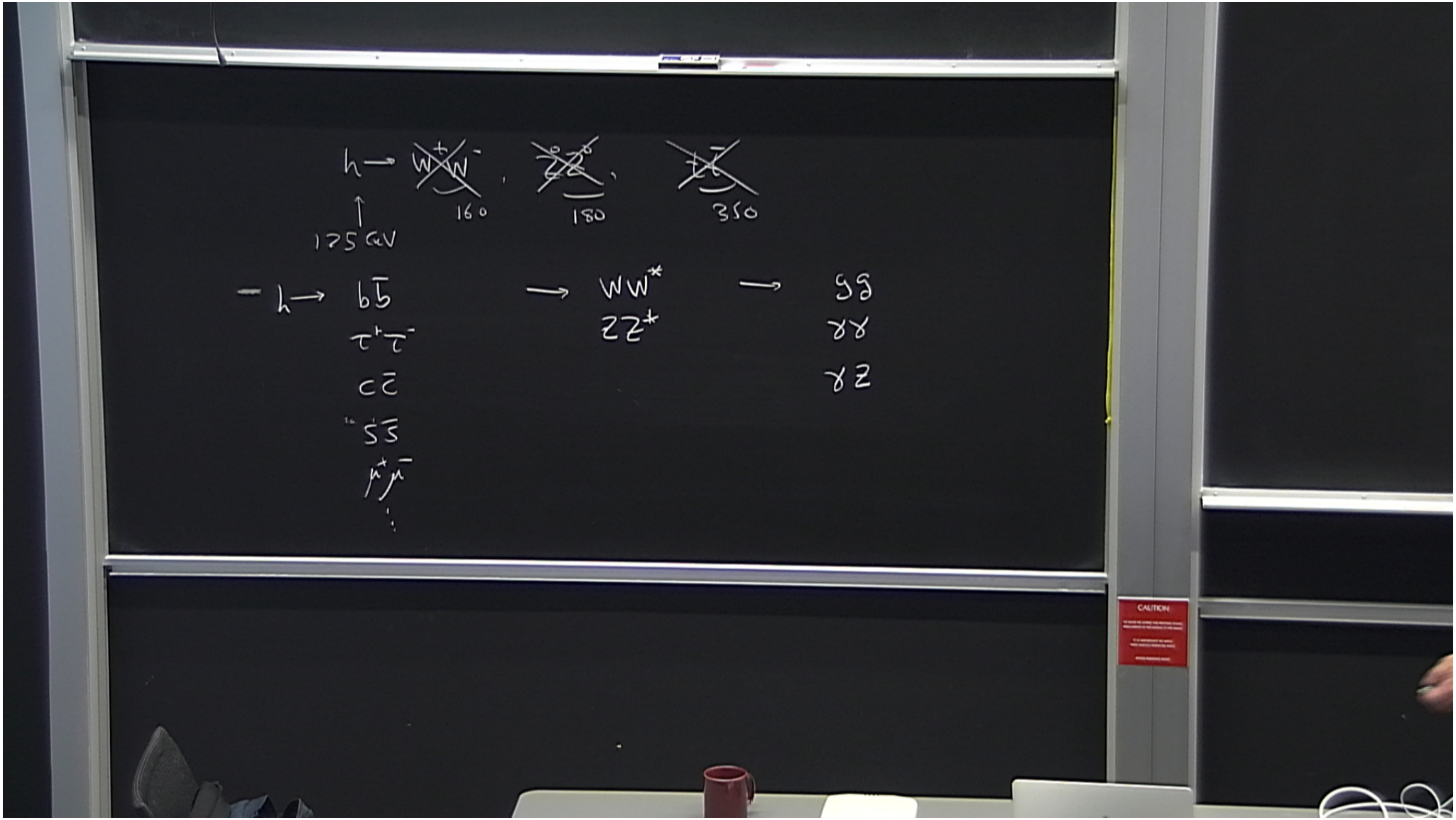

$\phi = \begin{pmatrix} \pi^+(x) \\ \frac{1}{\sqrt{2}}(v + h(x) + i\pi^0(x)) \end{pmatrix} \xrightarrow{} \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+h) \end{pmatrix}$
246 GeV
$= \frac{2}{v}$
$= -i\frac{m_f}{v}$
$= i\frac{m_V^2}{v} g^{\mu\nu}$
$= -i\frac{3m_h^2}{v}$
CAUTION

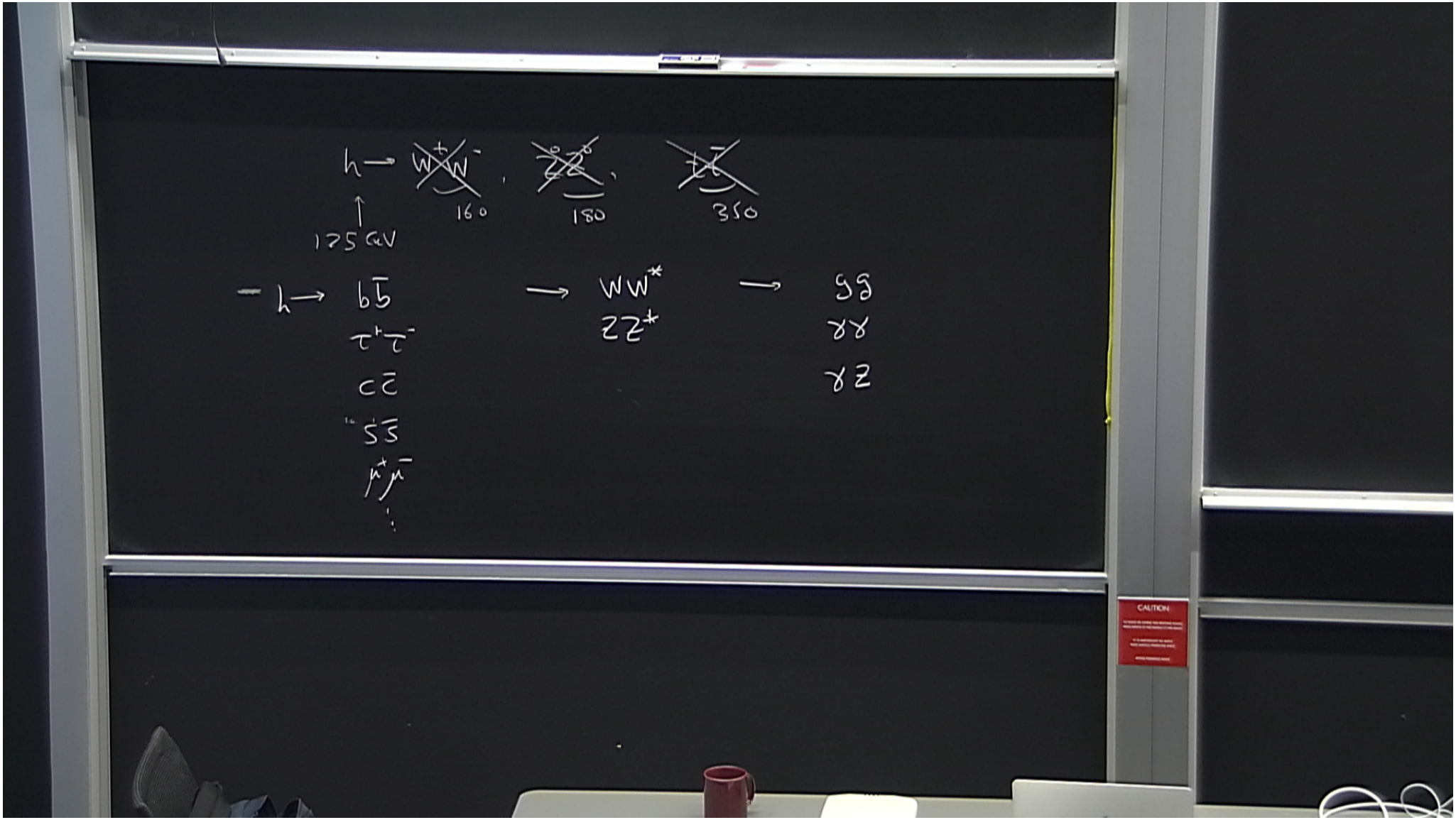

CAUTION

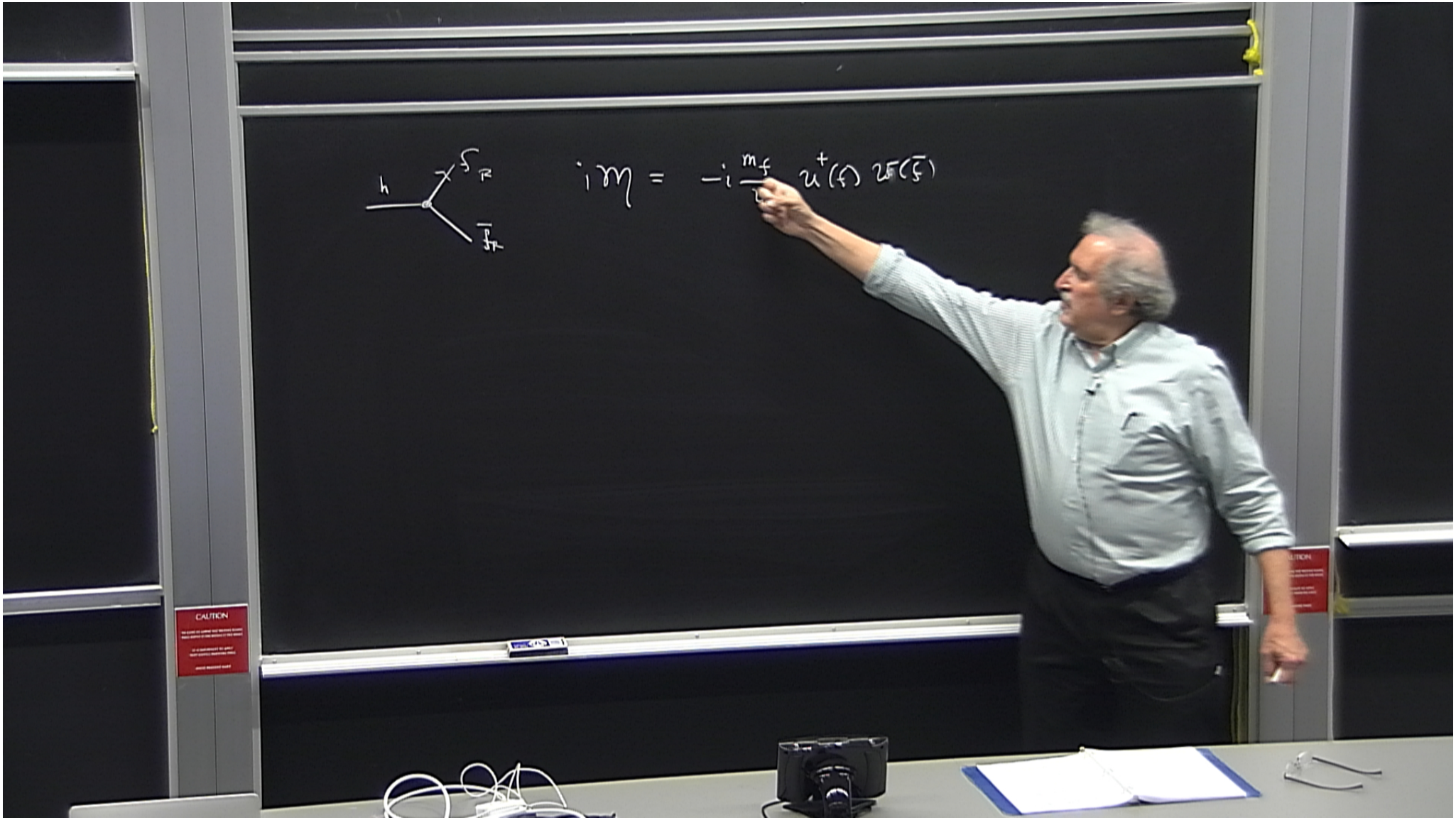

h → W⁺W⁻ , ZZ , tt̄
CAUTION

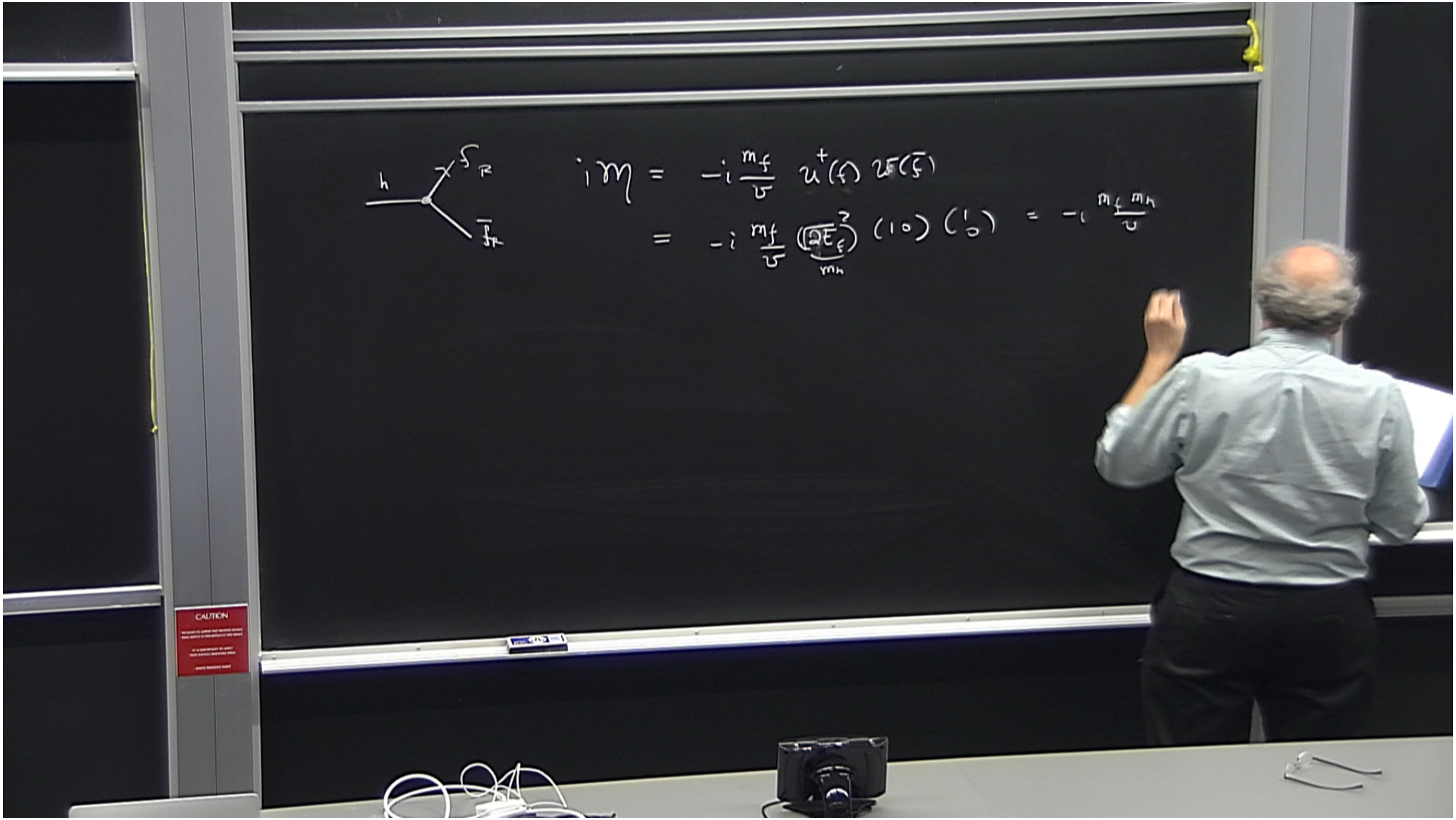

h → W⁺W⁻ , ZZ , tt̄
160
180
350
175 GeV
h → bb̄
cc̄
ss̄
μ⁺μ⁻
CAUTION

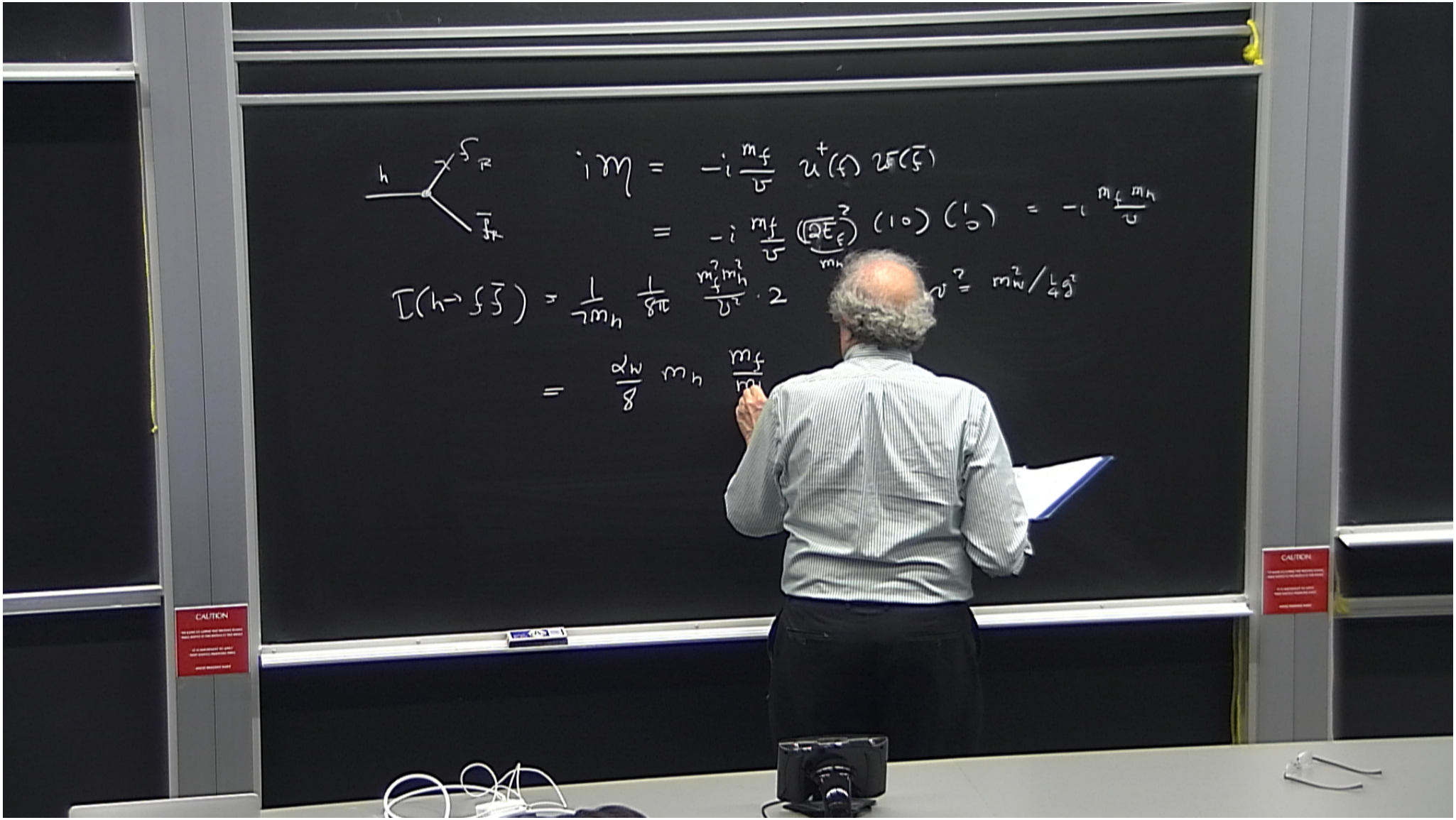

h → W⁺W⁻ , ZZ , tt̄
160
180
350
125 GeV
h → bb̄
τ⁺τ⁻
cc̄
ss̄
μ⁺μ⁻
WW*
ZZ*
CAUTION

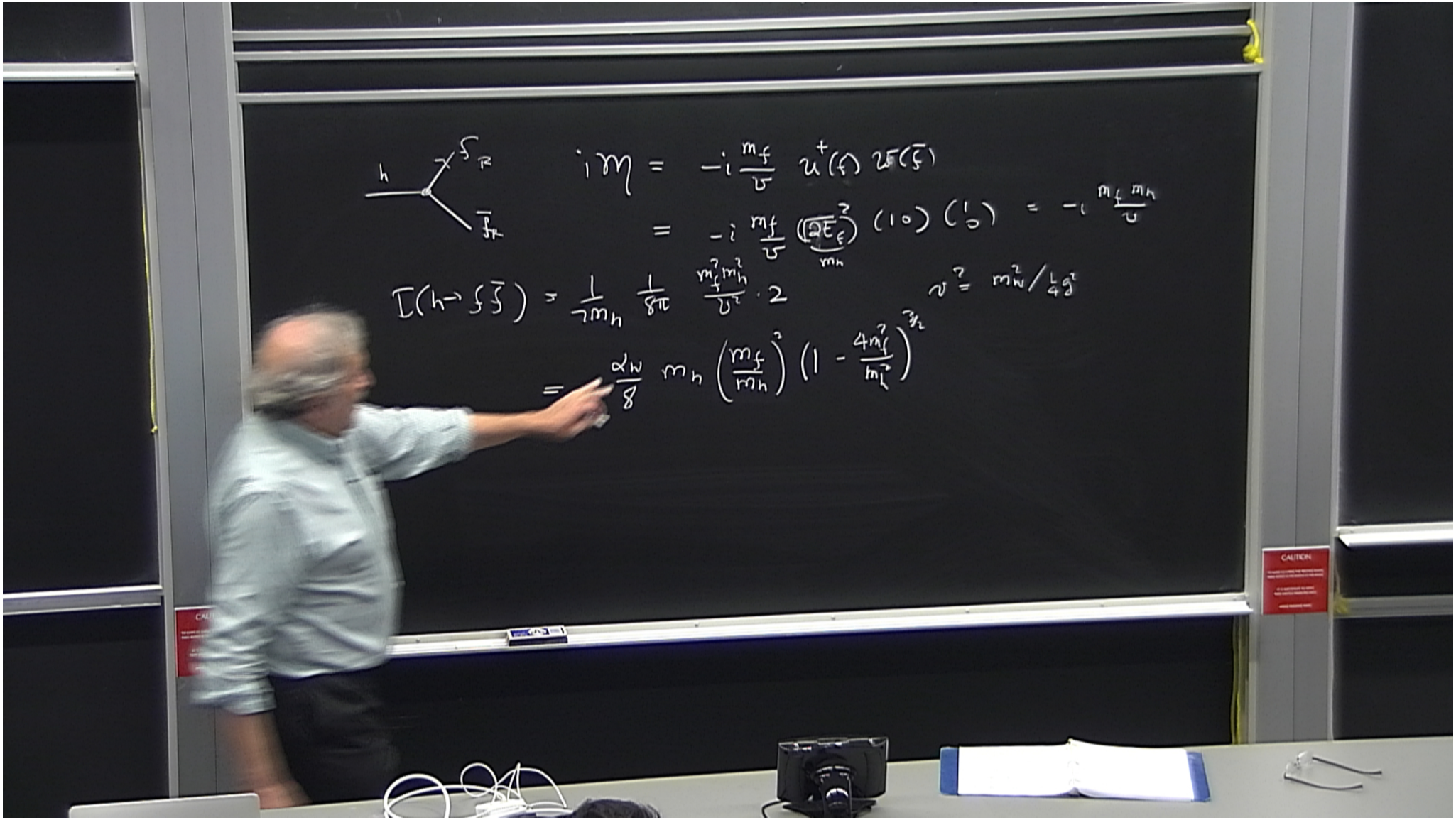

h → W⁺W⁻ , ZZ , tt̄
160
180
350
125 GeV
h → bb̄
τ⁺τ⁻
cc̄
ss̄
μ⁺μ⁻
→ WW*
ZZ*
→ gg
γγ
Zγ
CAUTION

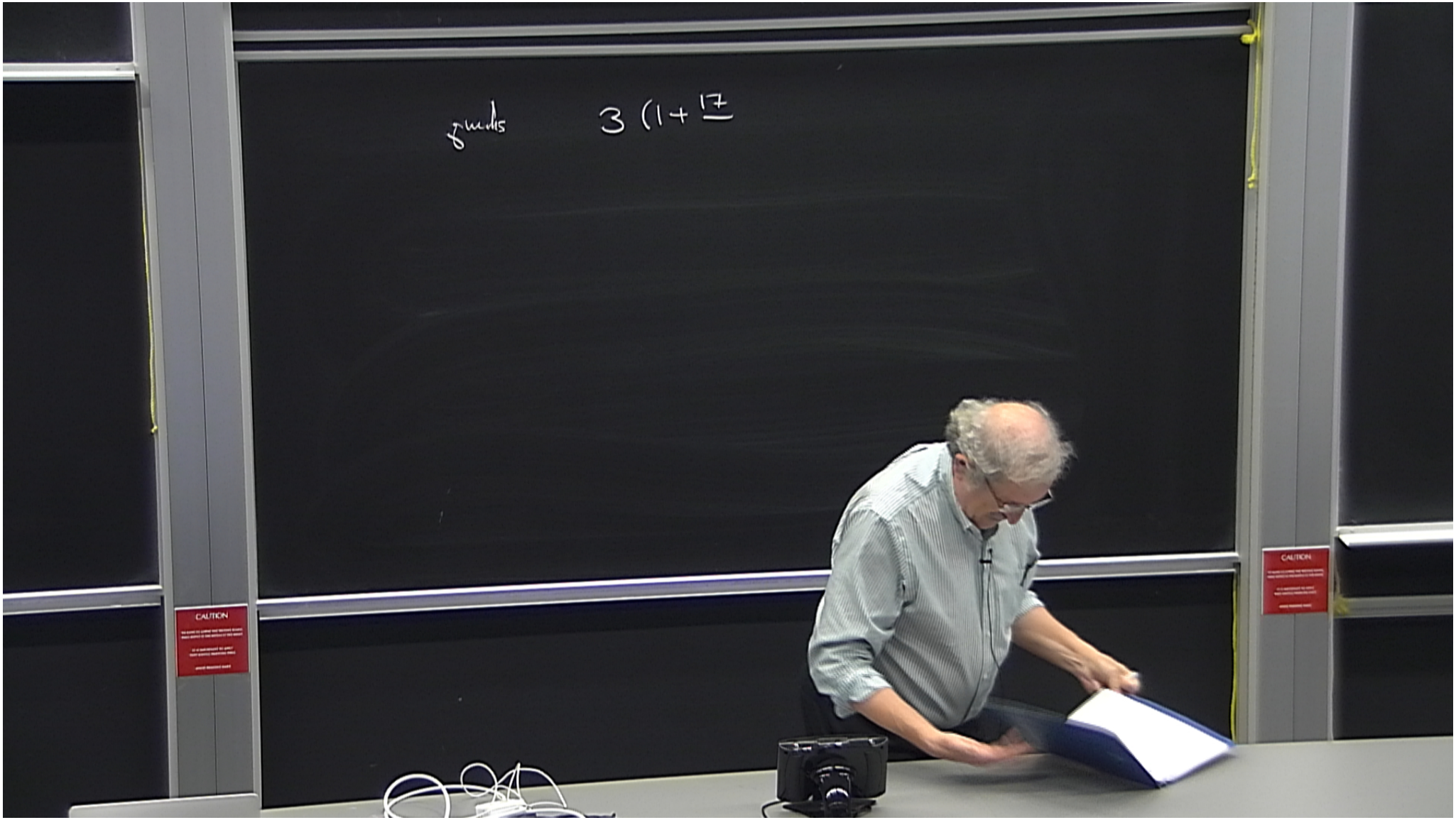

h → W⁺W⁻ , ZZ , tt̄
160
180
350
125 GeV
h → bb̄
τ⁺τ⁻
cc̄
ss̄
μ⁺μ⁻
→ WW*
ZZ*
→ gg
γγ
Zγ
CAUTION

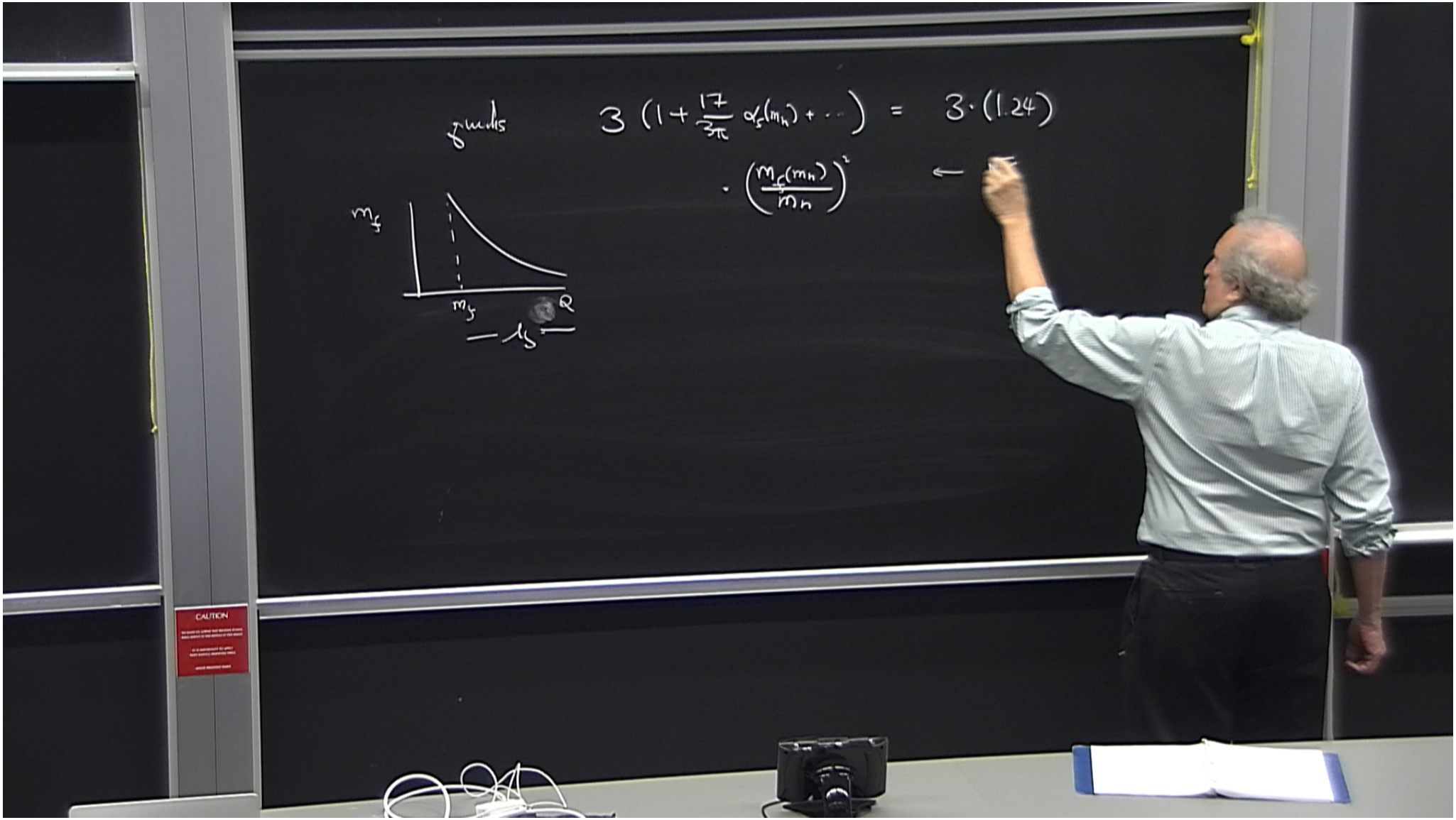

h
$\bar{f}_2$
$i\mathcal{M} = -i\frac{m_f}{v}\,\bar{u}^+(f_1)\,v(\bar{f}_2)$
CAUTION

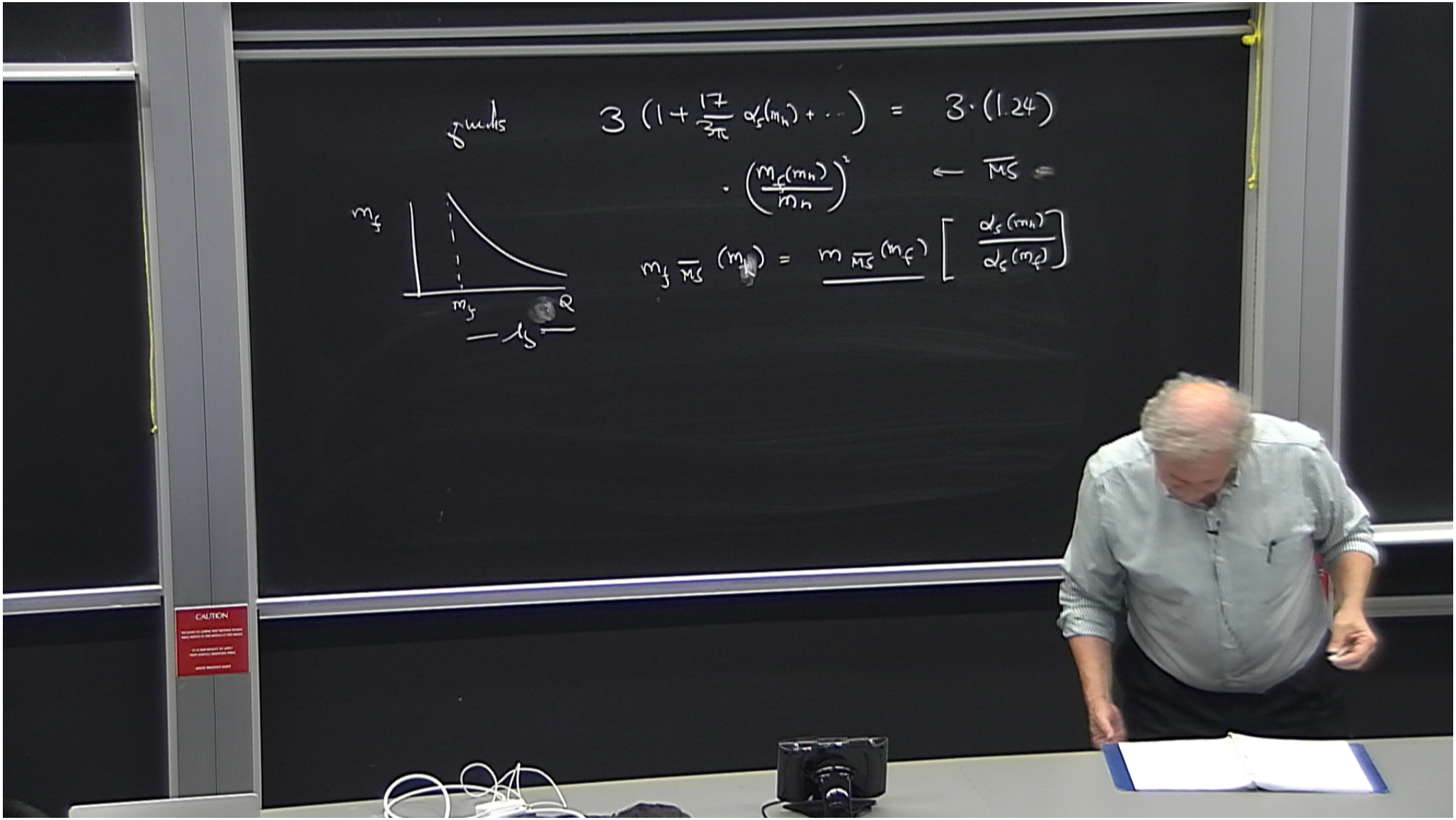

h
$\bar{f}_R$
f_L
$i\mathcal{M} = -i\frac{m_f}{v} u^+(\vec{p}_1) v(\vec{p}_2)$
$= -i\frac{m_f}{v}\left(\frac{2E_f}{m_h}\right)(10)\begin{pmatrix}0\\1\end{pmatrix} = -i\frac{m_f m_h}{v}$
CAUTION

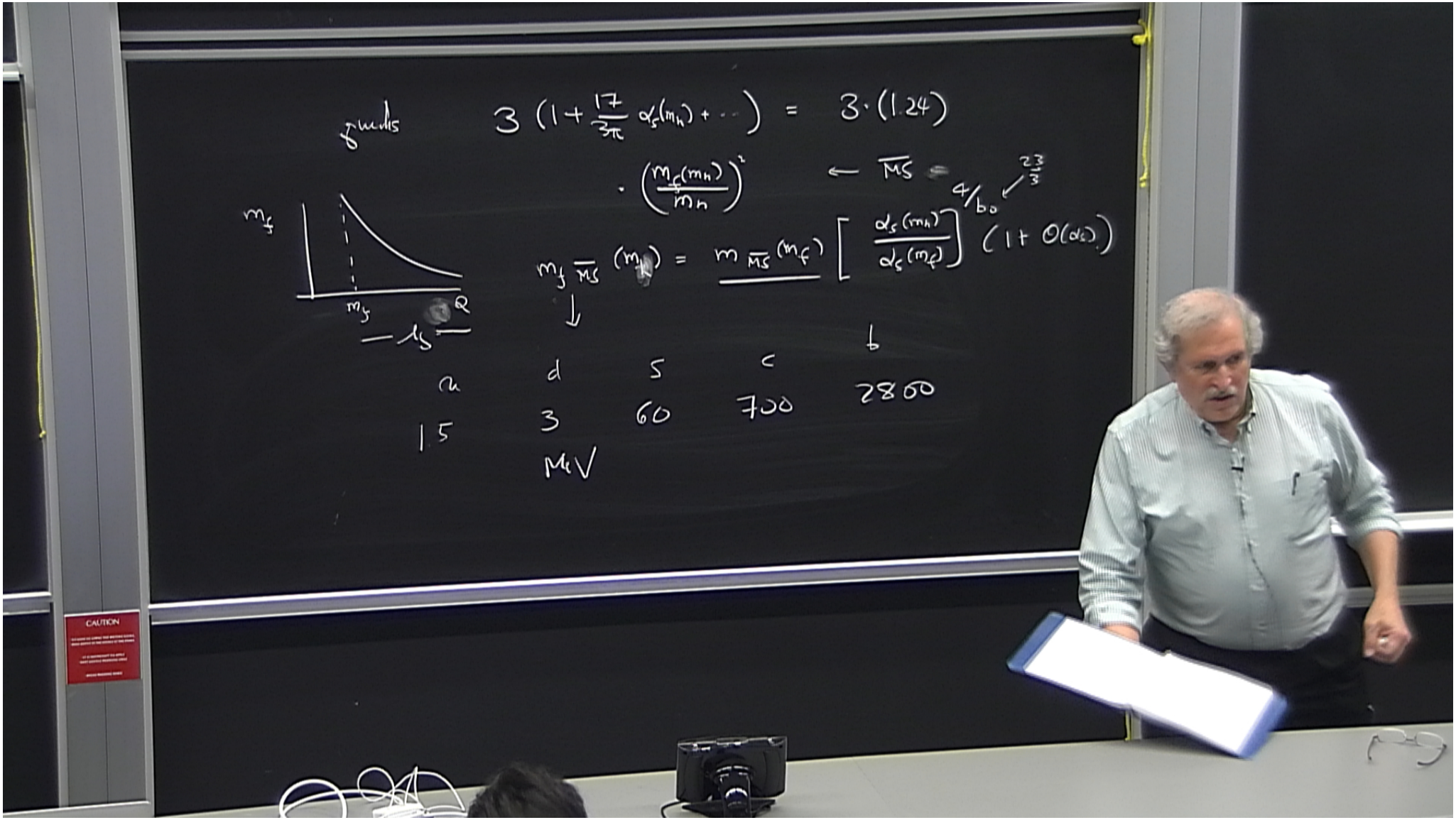

h
χ_R
$\bar{\chi}_L$
$i\mathcal{M} = -i\frac{m_f}{v}\, u^+(f)\, v_R(\bar{f})$
$= -i\frac{m_f}{v}\,(\sqrt{2}E_f)\,(10)\begin{pmatrix}1\\0\end{pmatrix} = -i\frac{m_f}{v}\,m_h$
$\Gamma(h\to f\bar{f}) = \frac{1}{m_h}\frac{1}{8\pi}\frac{m_f^2 m_h^2}{v^2}\cdot 2$
$v^2 = m_W^2/\frac{1}{4}g^2$
$= \frac{\alpha_W}{8}\, m_h\, \frac{m_f}{m_W}$
CAUTION
CAUTION

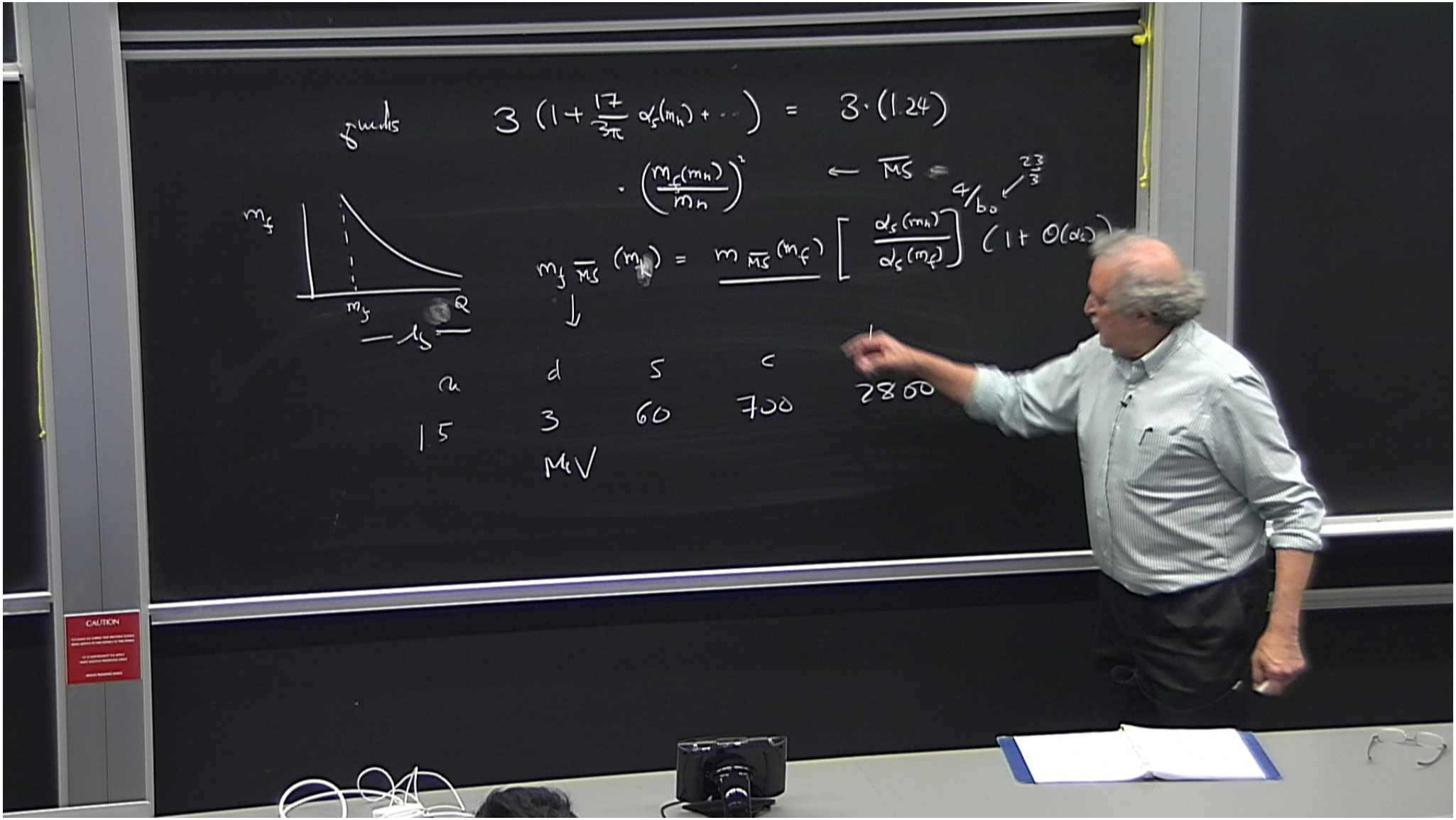

$i\mathcal{M} = -i\frac{m_f}{v}\,u^+(f)\,v(\bar{f})$
$= -i\frac{m_f}{v}\,(\sqrt{2}E_f)\,(1\,0)\,\begin{pmatrix}0\\1\end{pmatrix} = -i\frac{m_f m_h}{v}$
$\Gamma(h\to f\bar{f}) = \frac{1}{16\pi m_h}\,\frac{1}{8\pi}\,\frac{m_f^2 m_h^2}{v^2}\cdot 2$
$= \frac{\alpha_W}{8}\,m_h\left(\frac{m_f}{m_W}\right)^2\left(1-\frac{4m_f^2}{m_h^2}\right)^{3/2}$
$v^2 = m_W^2/\frac{1}{4}g^2$

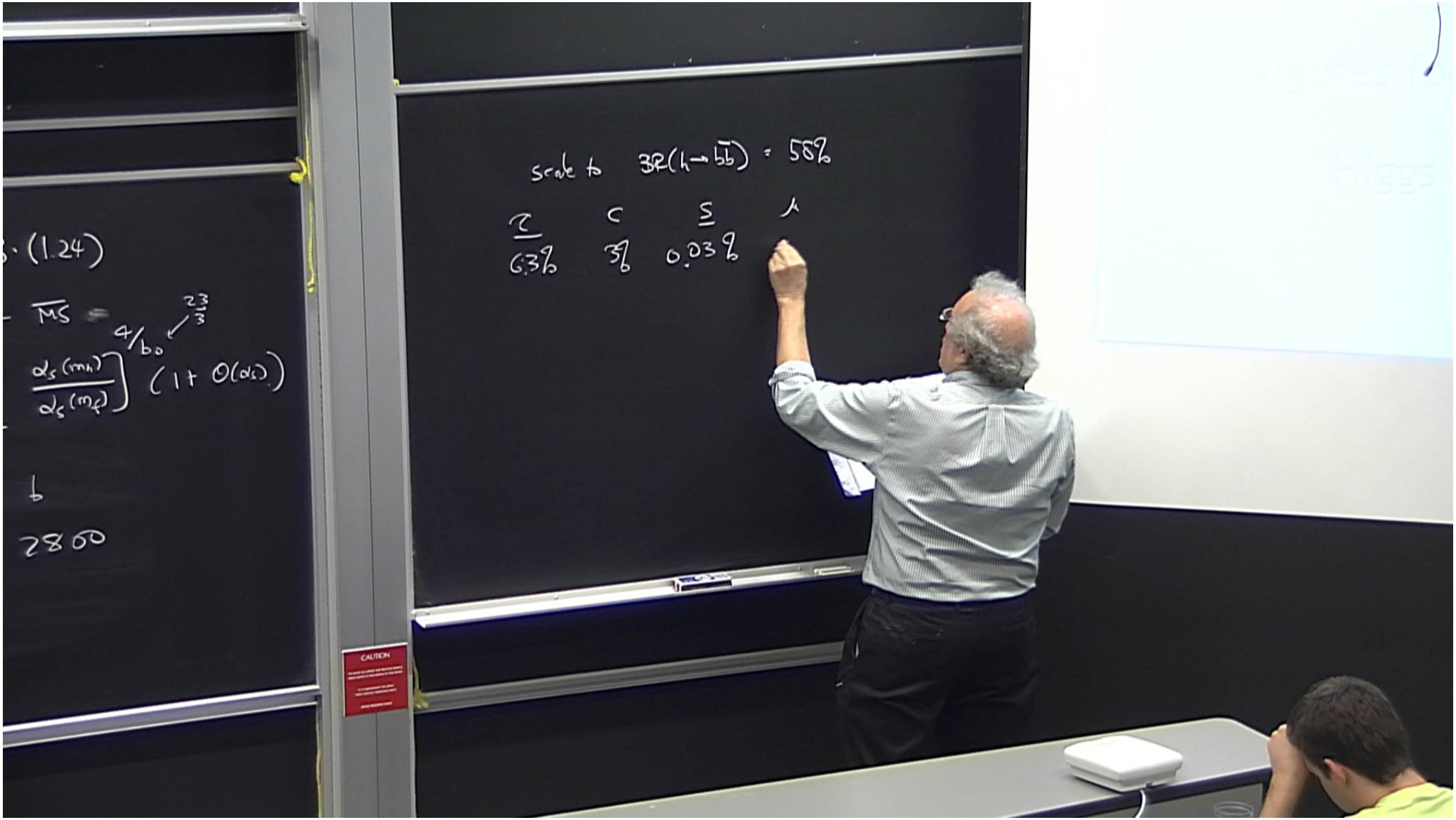

3 (1+ 17

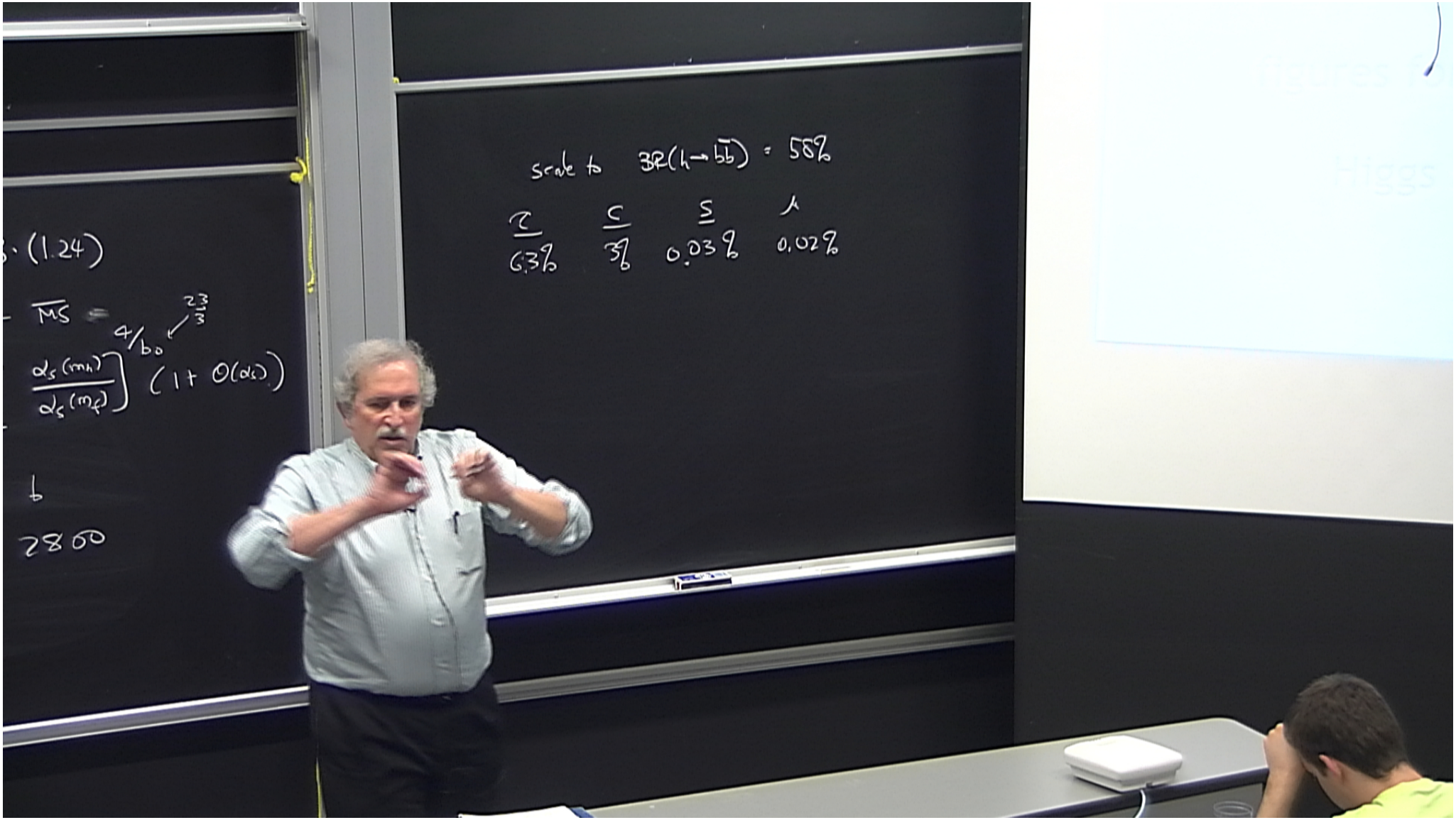

gluons
$3\left(1+\frac{17}{3\pi}\alpha_s(m_h)+\cdots\right) = 3\cdot(1.24)$
$\cdot\left(\frac{m_s(m_h)}{m_h}\right)^2$
m_s
m_s
R
-1_S-
CAUTION

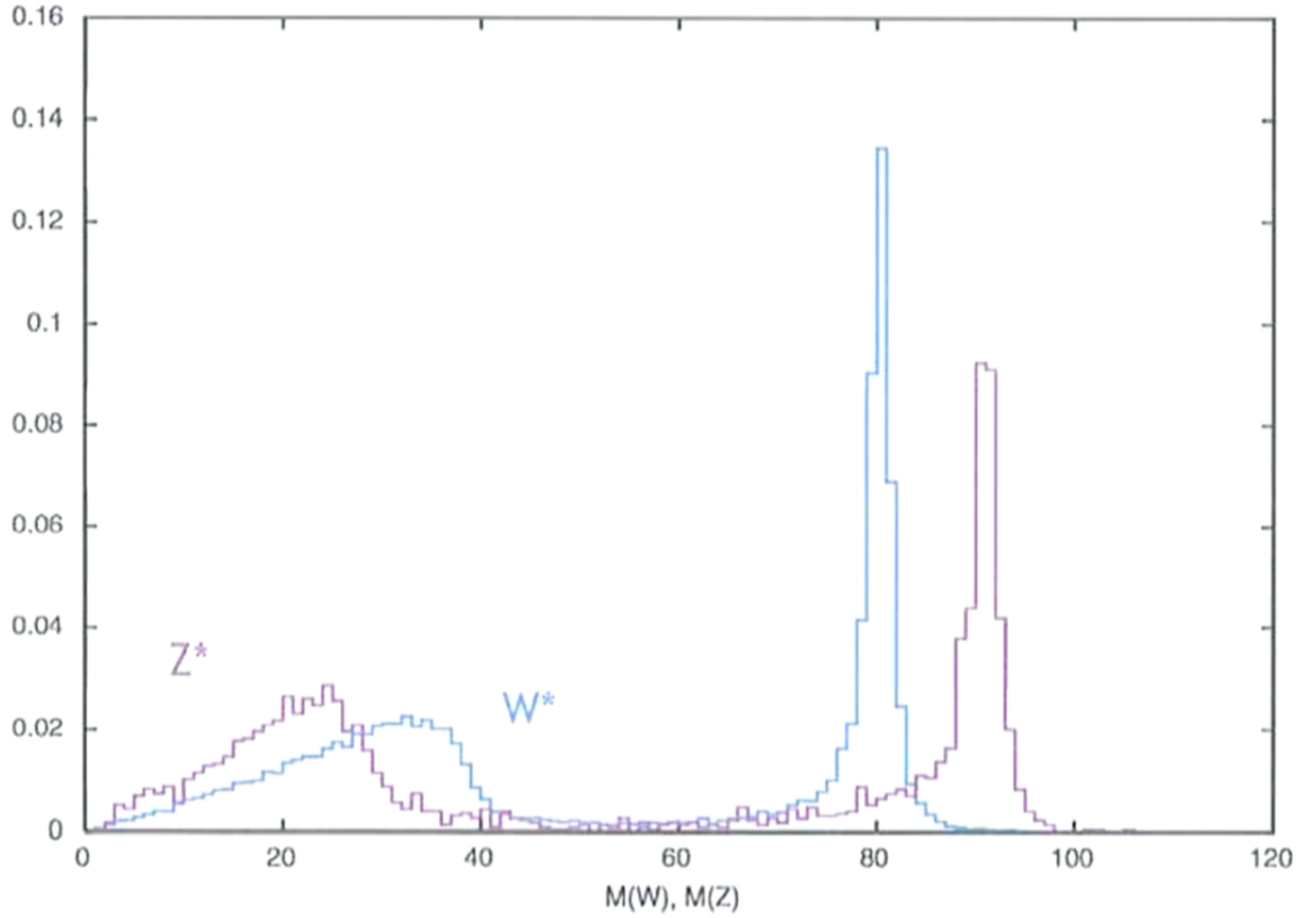

g_{quarks}
$3\left(1+\frac{17}{3\pi}\alpha_s(m_h)+\cdots\right) = 3\cdot(1.24)$
$\cdot\left(\frac{m_c(m_h)}{m_h}\right)^2$ ← $\overline{MS}$
m_f
m_f
R
$m_{f\,\overline{MS}}(m_h) = \frac{m_{\overline{MS}}(m_f)}{}\left[\frac{\alpha_s(m_h)}{\alpha_s(m_f)}\right.$
CAUTION

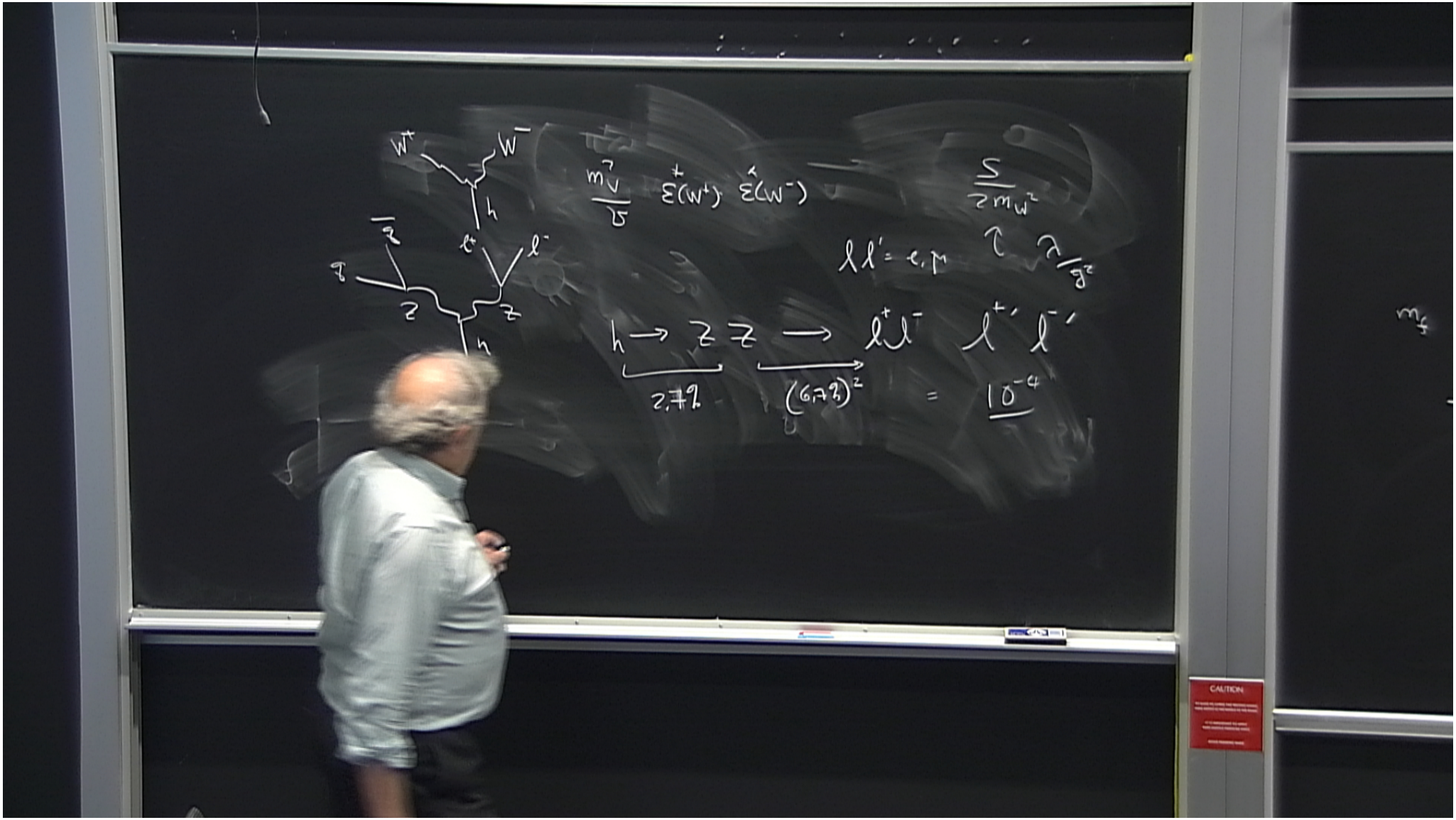

$3\left(1+\frac{17}{3\pi}\alpha_s(m_h)+\cdots\right) = 3\cdot(1.24)$
$\cdot\left(\frac{m_c(m_h)}{m_h}\right)^2$ ← $\overline{MS}$
$4/b_0$ $\frac{23}{3}$
m_f
m_f
R
$m_f\ \overline{MS}\ (m_f) = m\ \overline{MS}\ (m_f)\left[\frac{\alpha_s(m_h)}{\alpha_s(m_f)}\right](1+O(\alpha_s))$
u d s c b
1.5 3 60 700 2800
MeV
CAUTION

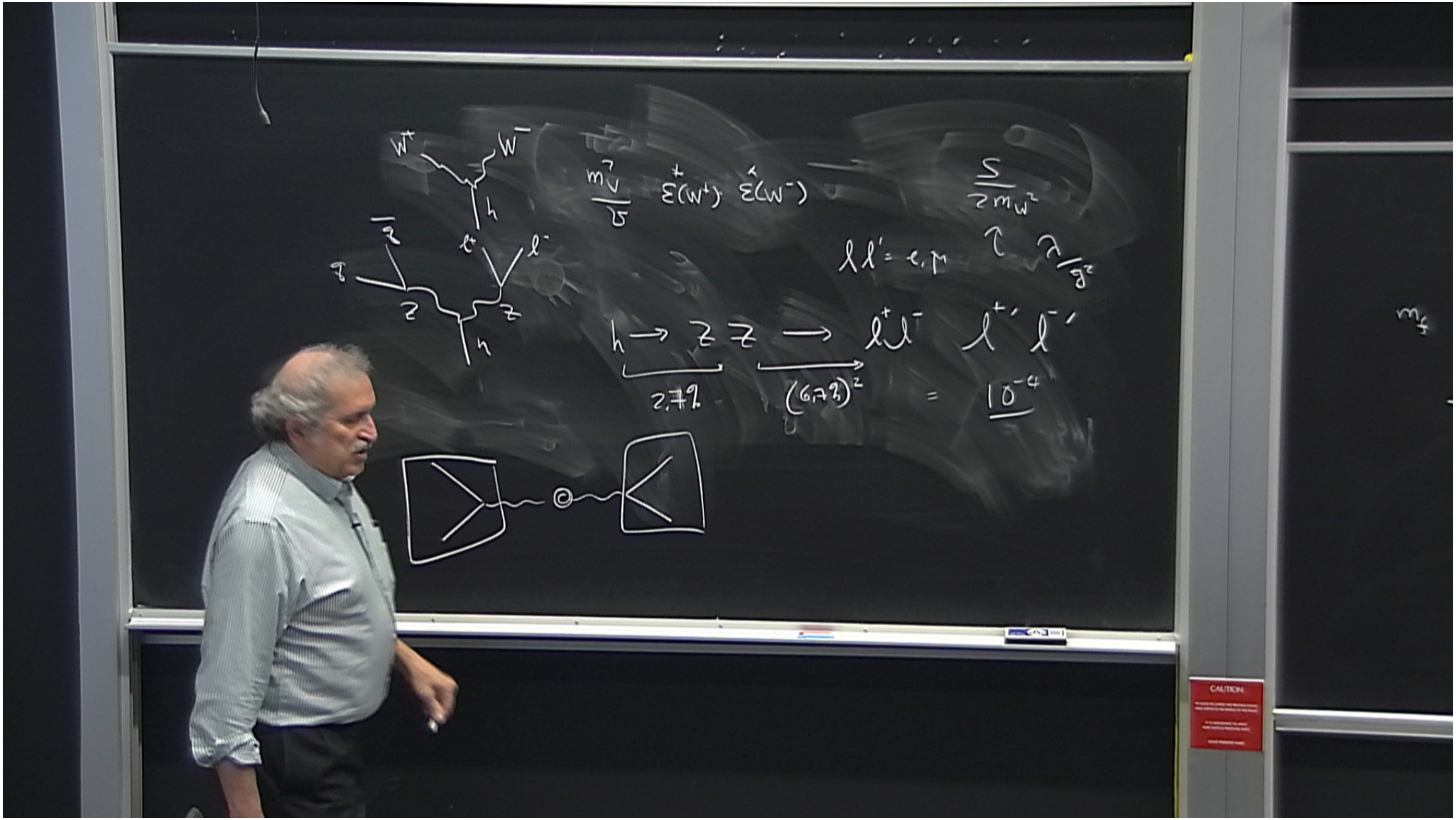

$3\left(1+\frac{17}{3\pi}\alpha_s(m_h)+\cdots\right) = 3\cdot(1.24)$
$\cdot\left(\frac{m_c(m_h)}{m_h}\right)^2$ ← $\overline{MS}$
$4/b_0$ $\frac{23}{3}$
m_f
m_f
R
$m_f \overline{MS}(m_f) = m_{\overline{MS}}(m_f)\left[\frac{\alpha_s(m_h)}{\alpha_s(m_f)}\right]$ $(1+O(\alpha_s))$
u d s c
1.5 3 60 700 2800
MeV

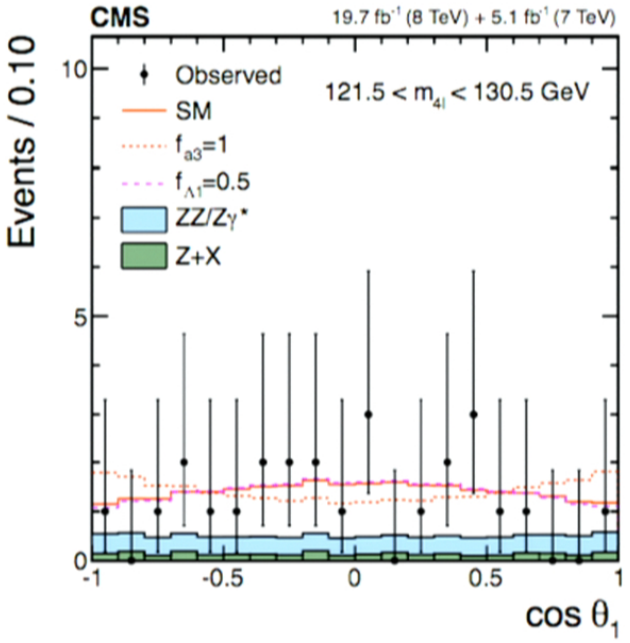

scale to BR(h→bb̄) = 58%
τ c s
6.3% 3% 0.03%
(1.24)
MS
4/b0
23/3
(1 + O(αs))
b
2800
CAUTION


scale to BR(h→bb̄) = 58%
τ 6.3%
c 3%
s 0.03%
μ 0.02%
(1.24)
MS
4/b0
23/3
(1 + O(α
2800
Higgs

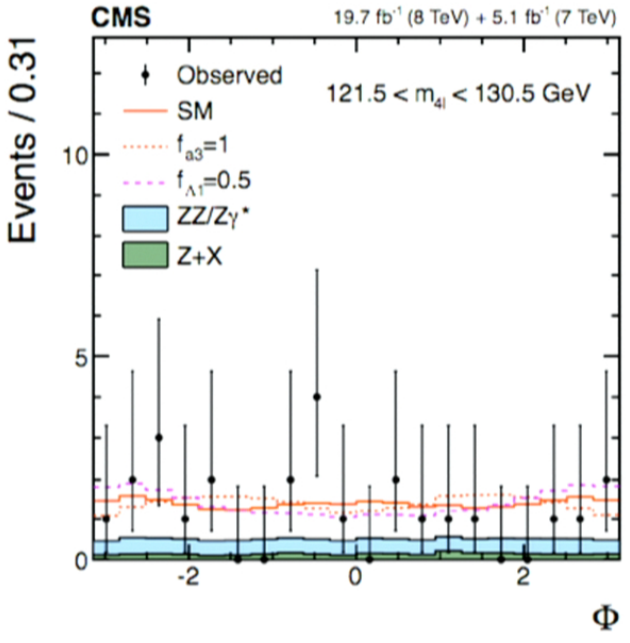

0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
20
40
60
80
100
120
M(W), M(Z)
Z*
W*


W+
W−
h
t
t̄
l−
q
q̄
Z
Z
h
$\frac{m_V^2}{v}$ $\varepsilon^*(W^+)$ $\varepsilon^*(W^-)$
$\frac{s}{2m_W^2}$
$ll' = e,\mu$
τ τ/δ^2
$h \to ZZ \to l^+l^-$ $l^{+\prime}l^{-\prime}$
2.7%
$(6.73)^2$
$= 10^{-4}$
m_t
CAUTION

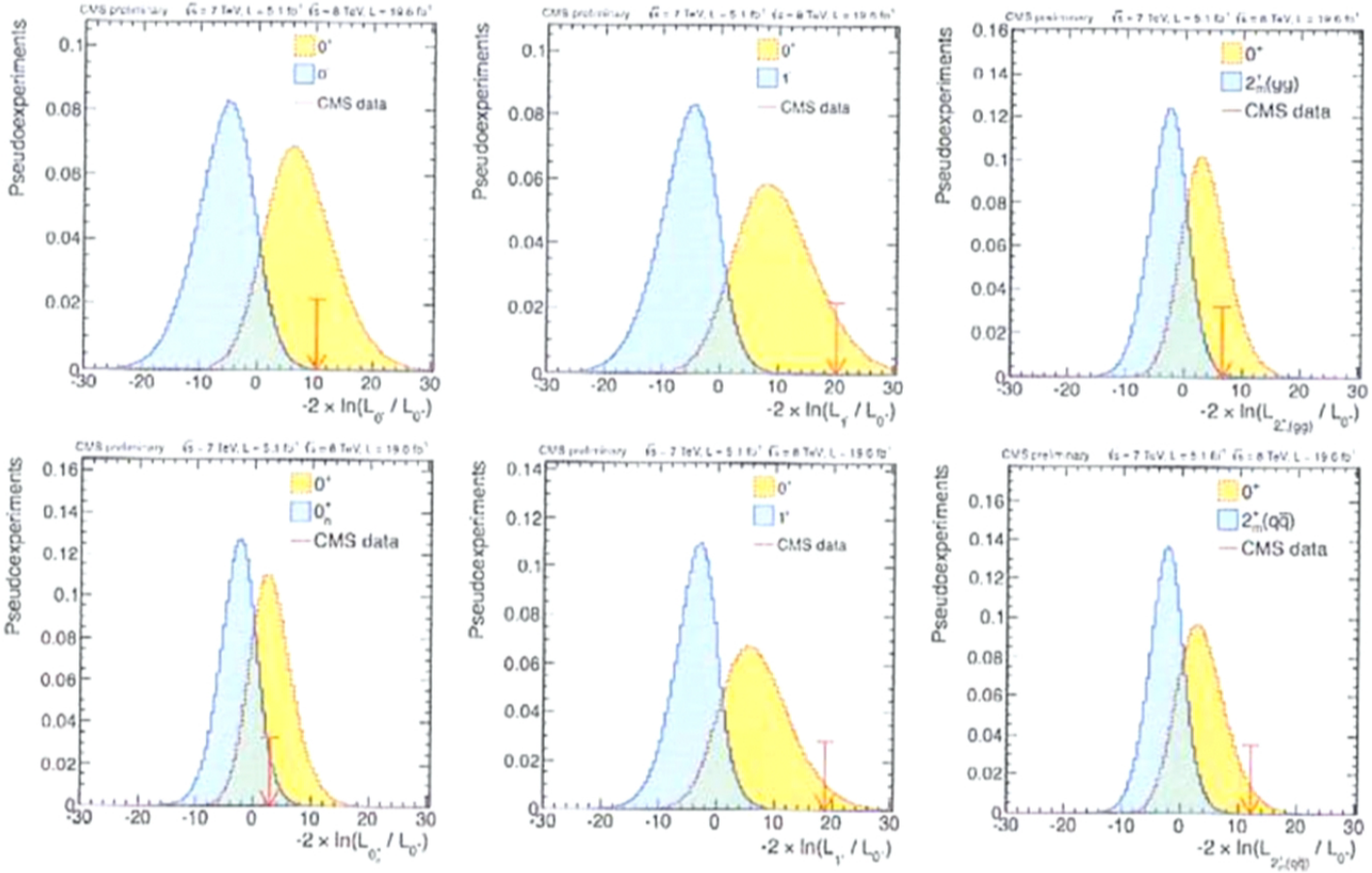

W+
W−
h
q̄
q
t*
l−
Z
Z
h
$\frac{m_V^2}{v}$ $\varepsilon^*(W^+)$ $\varepsilon^*(W^-)$
$\frac{s}{2m_W^2}$
$ll' = e, \mu$
τ τ/β^2
$h \to ZZ \to l\bar{l}$ $l^+ l^-$
2.7%
$(6.7\%)^2$
$= 10^{-4}$
m_t
CAUTION



preference for Z to be longitudinally polarized

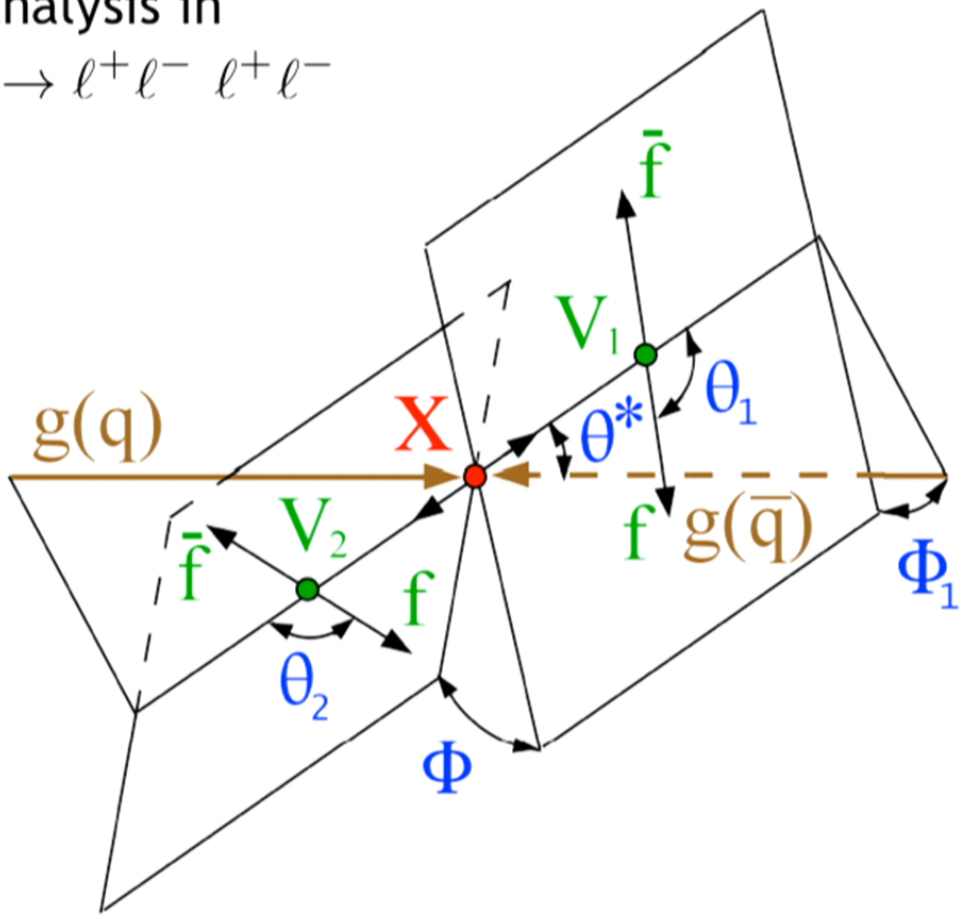


preference for Z decay planes to be parallel

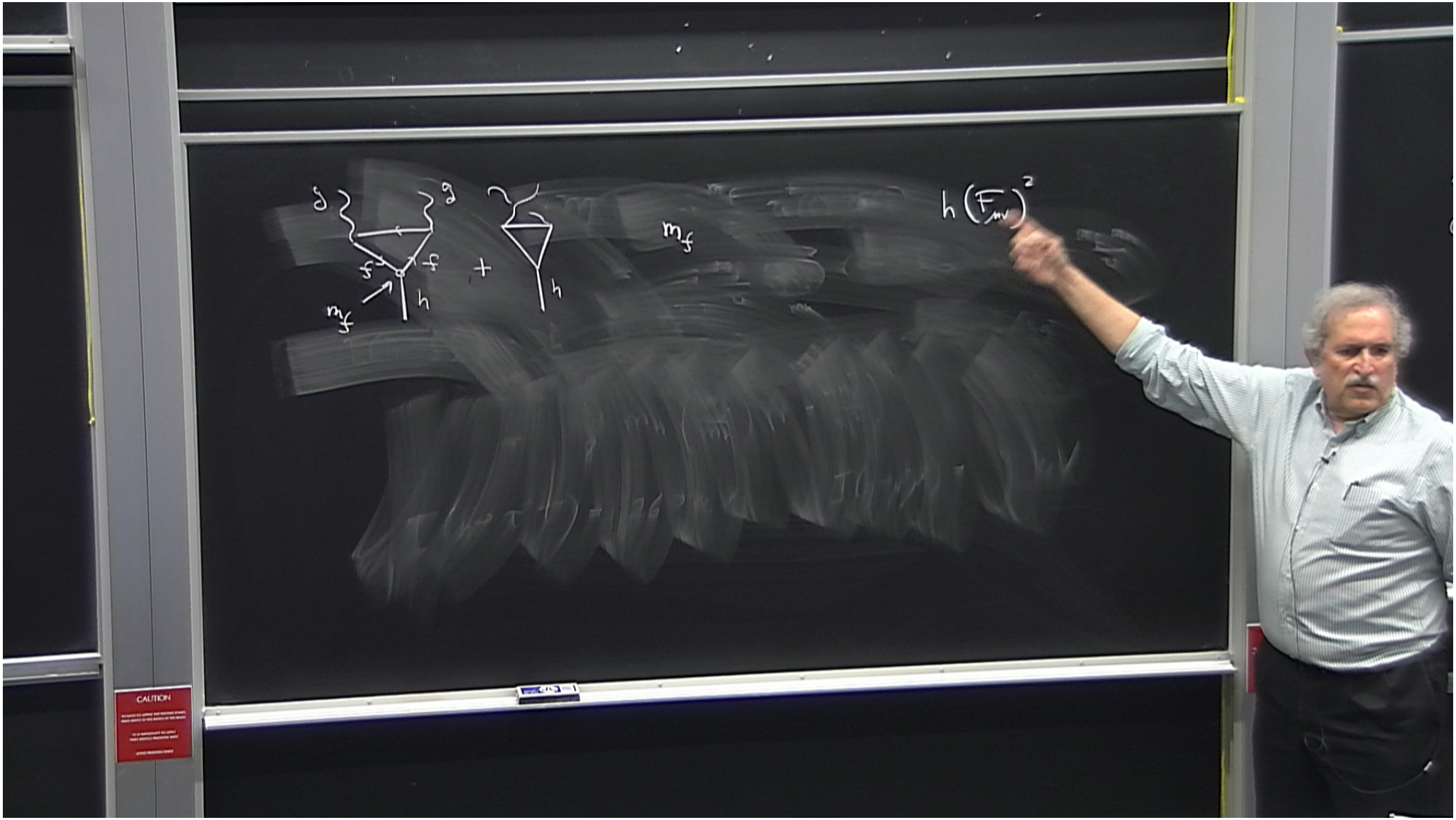

Pseudoexperiments
0⁺
0⁻
CMS data
-2 × ln(L0⁻ / L0⁺)
0⁺
1⁻
CMS data
-2 × ln(L1⁻ / L0⁺)
0⁺
2⁺m(gg)
CMS data
-2 × ln(L2⁺m(gg) / L0⁺)
0⁺
0⁻h
CMS data
-2 × ln(L0⁻h / L0⁺)
0⁺
1⁻
CMS data
-2 × ln(L1⁻ / L0⁺)
0⁺
2⁺m(qq̄)
CMS data
-2 × ln(L2⁺m(qq̄) / L0⁺)

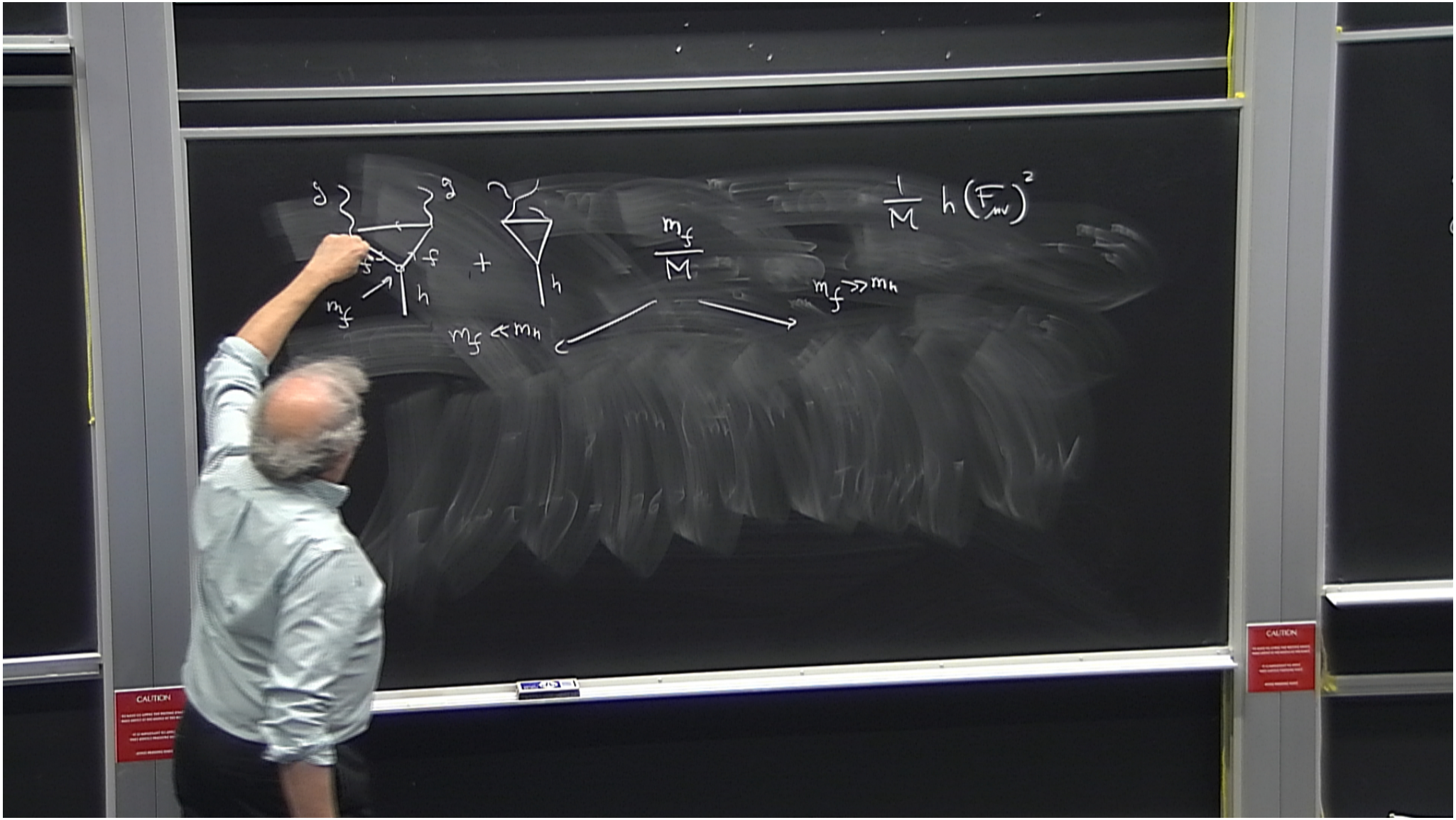
variables for the CMS spin analysis in

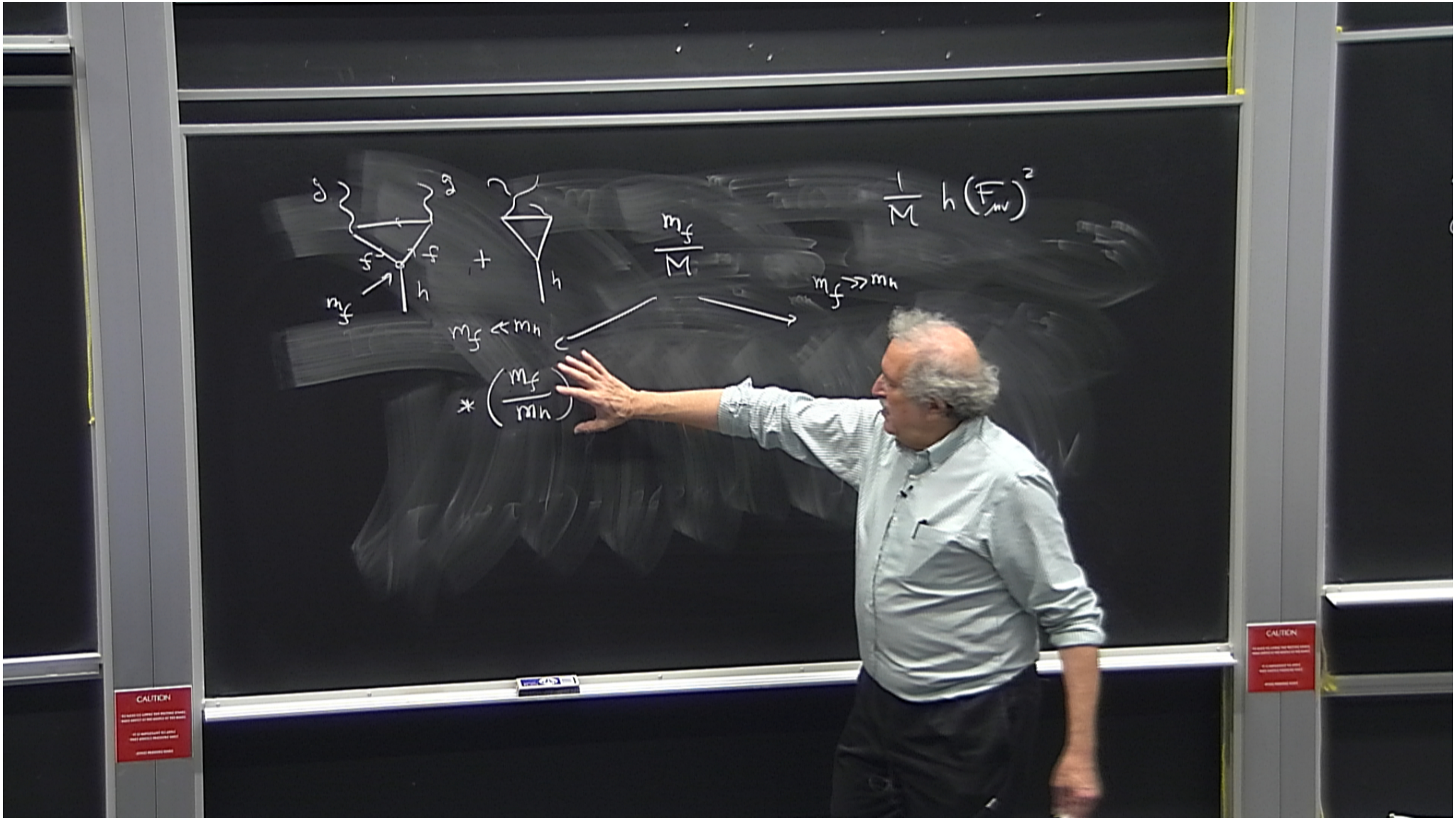
$h \to ZZ^* \to \ell^+\ell^- \ \ell^+\ell^-$

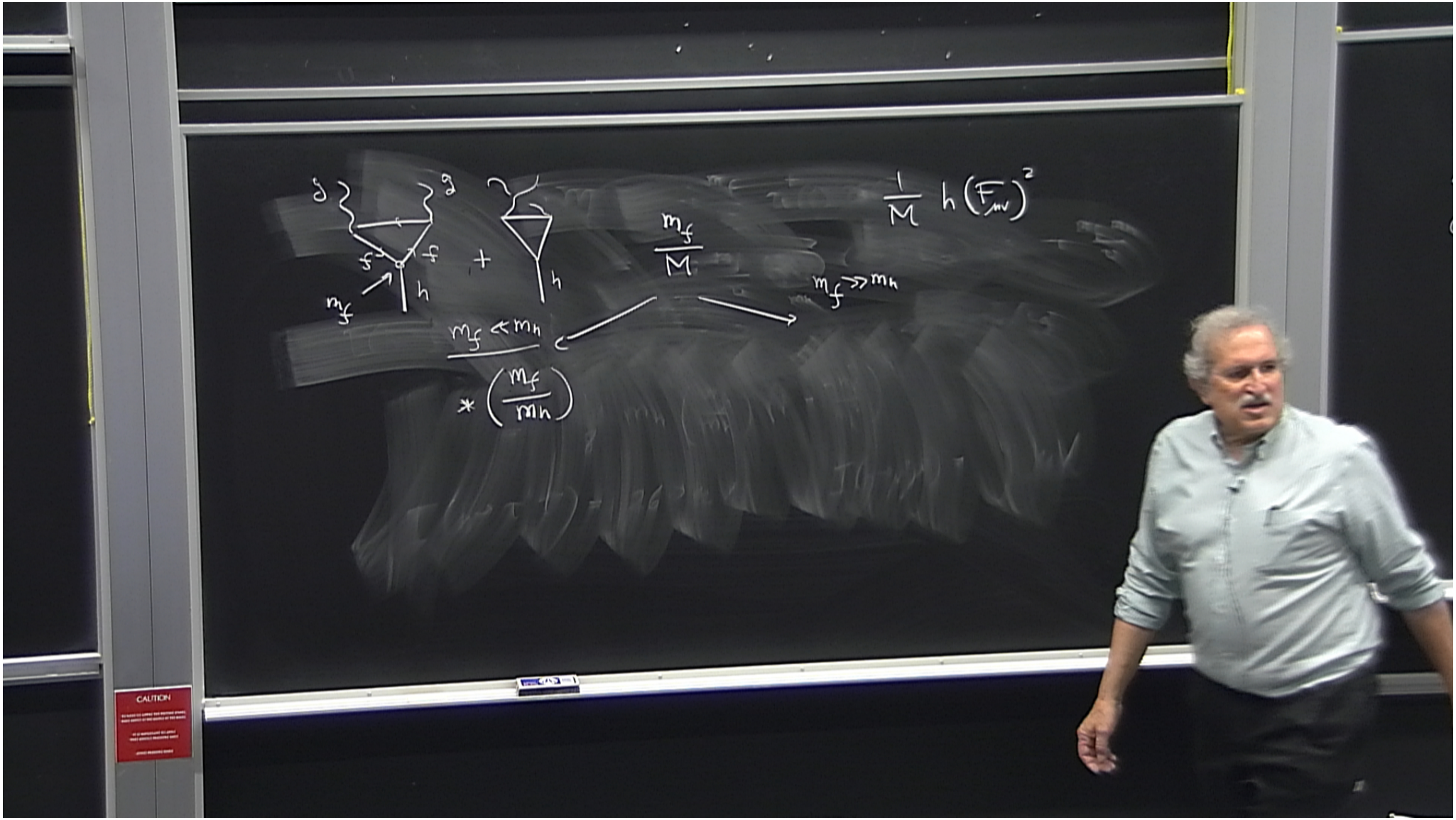


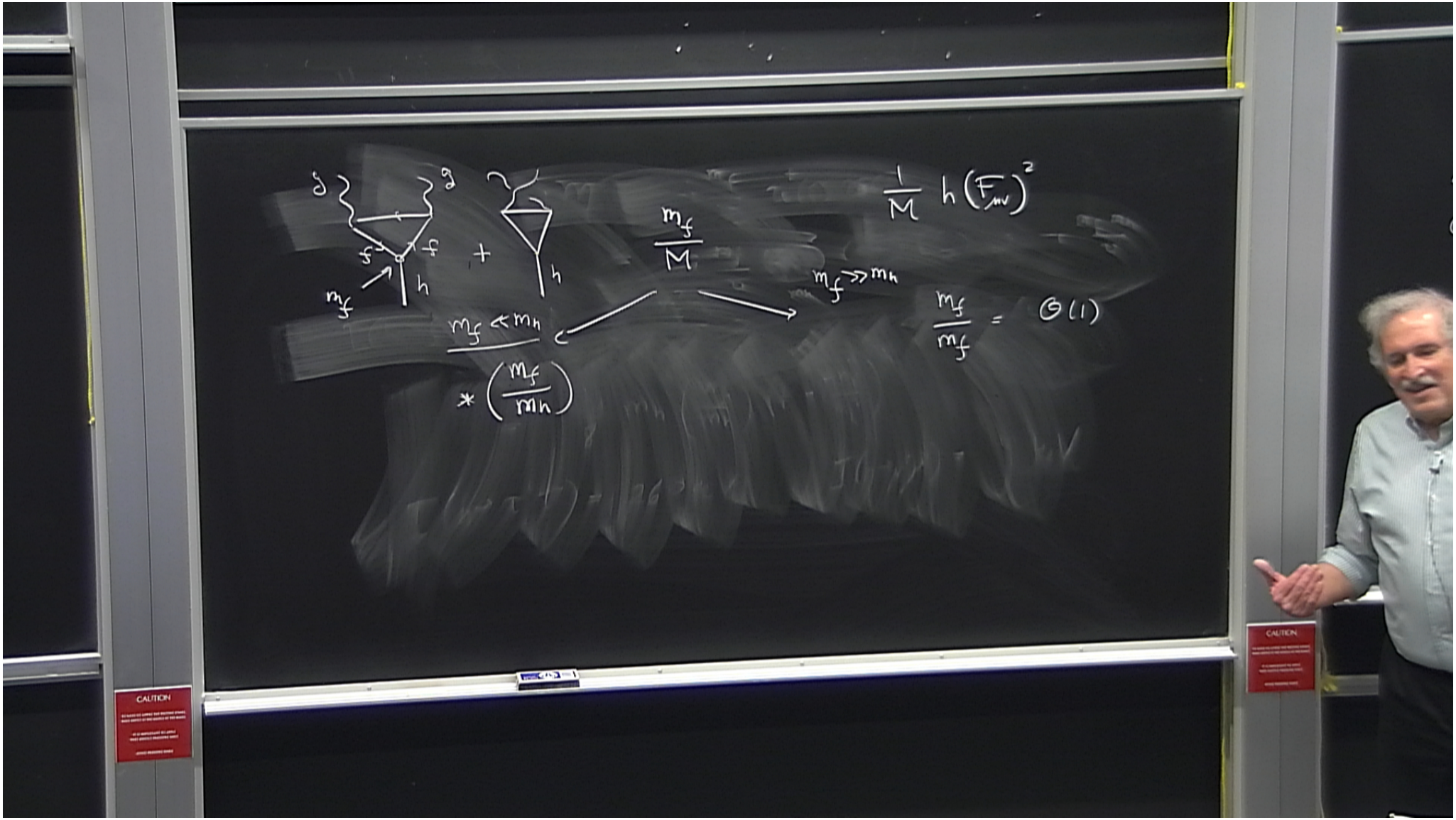

CAUTION
CAUTION

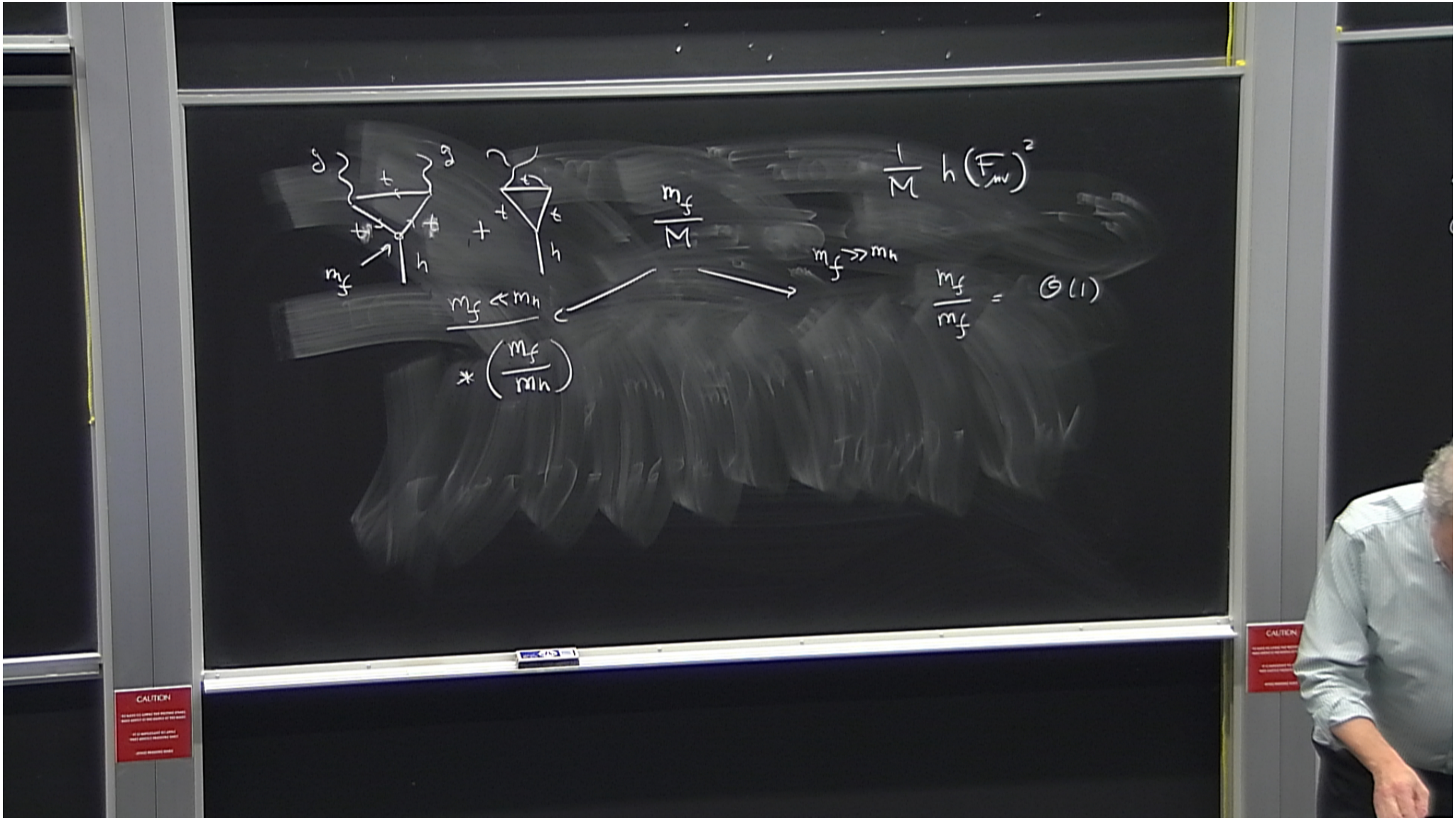

g
g
f
f
m_f
h
+
h
m_f
$h\left(\frac{F_{\mu\nu}}{}\right)^2$

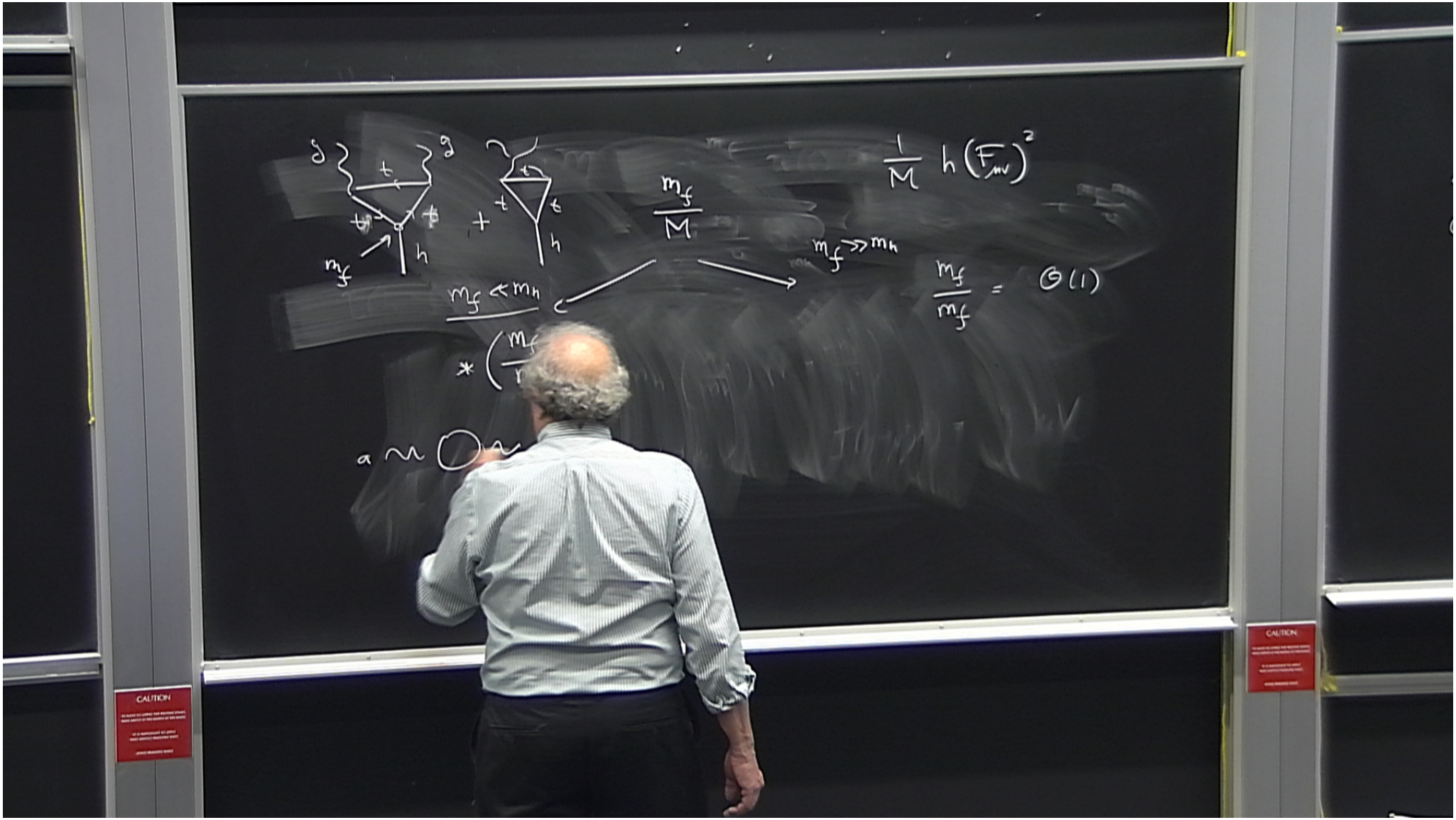

g
g
f
f
h
h
+
m_f
$\frac{m_f}{M}$
$m_f \ll m_h$
$m_f \gg m_h$
$\frac{1}{M} h (F_{\mu\nu})^2$

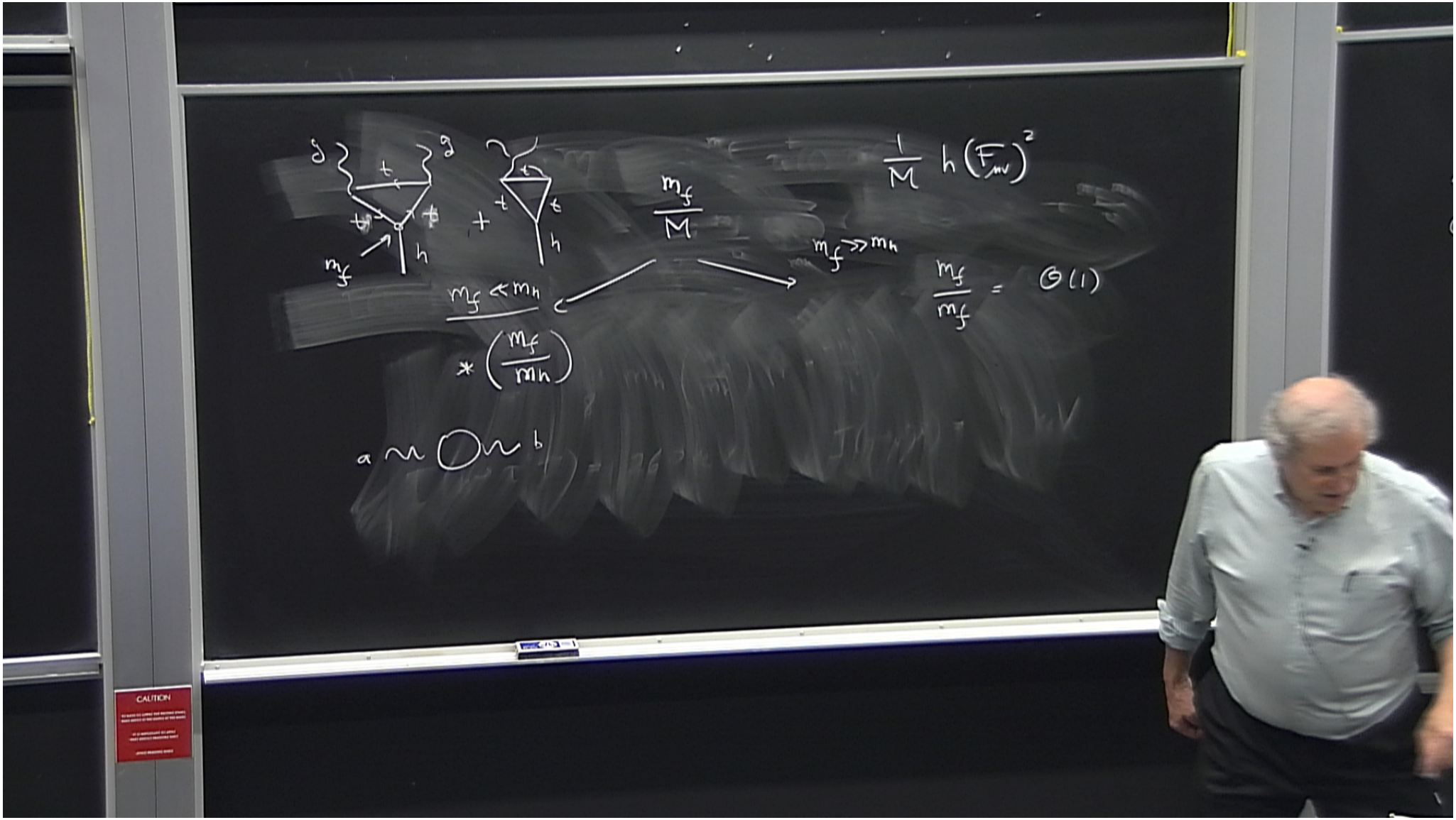

$\frac{1}{M} h (F_{\mu\nu})^2$
$\frac{m_f}{M}$
$m_f \gg m_h$
$m_f \ll m_h$
$* \left(\frac{m_f}{m_h}\right)$
CAUTION
CAUTION

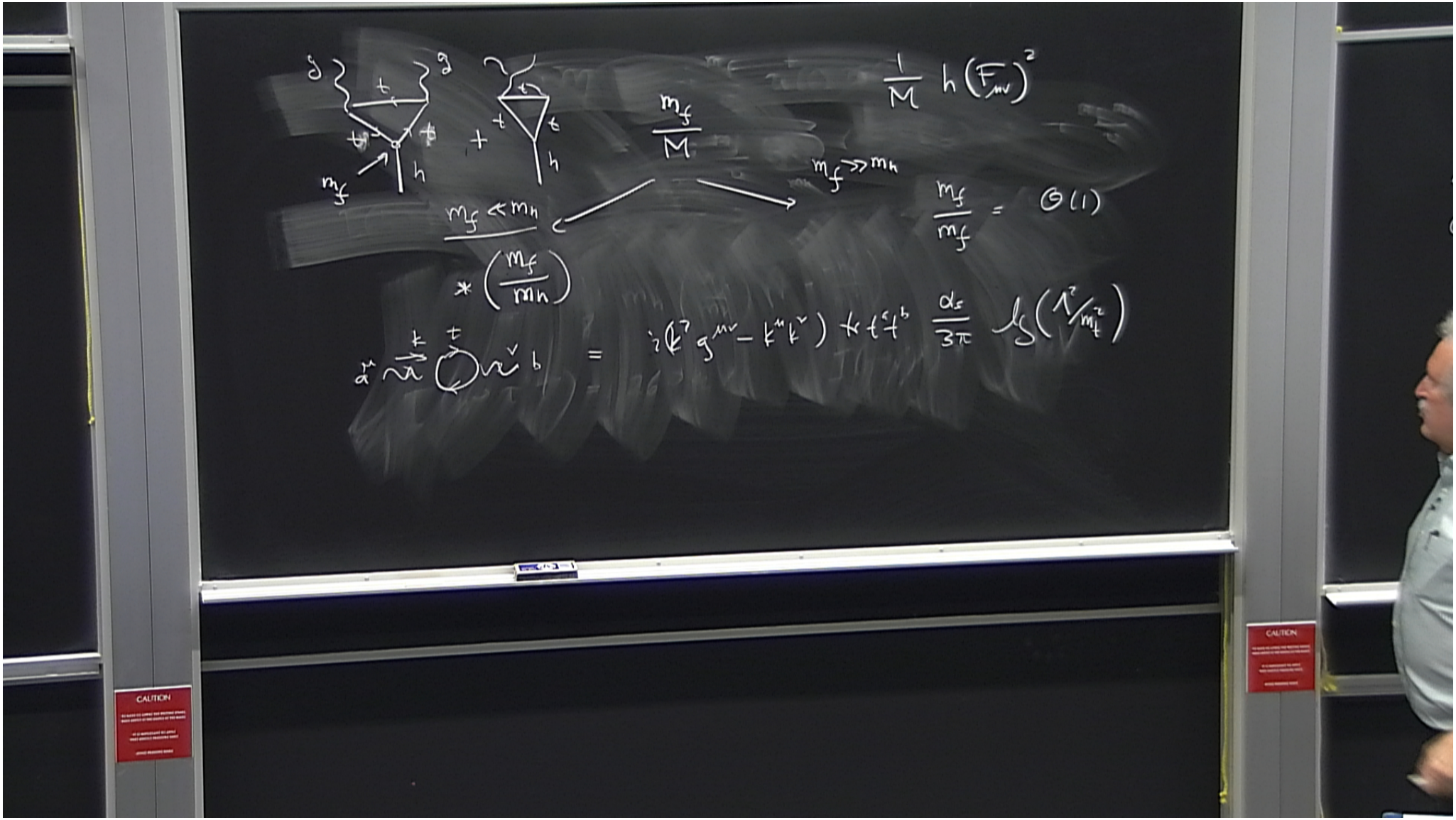

$\frac{m_f}{M}$
$\frac{1}{M}\, h\,(F_{\mu\nu})^2$
$m_f \gg m_h$
$m_f \ll m_h$
$* \left(\frac{m_f}{m_h}\right)$

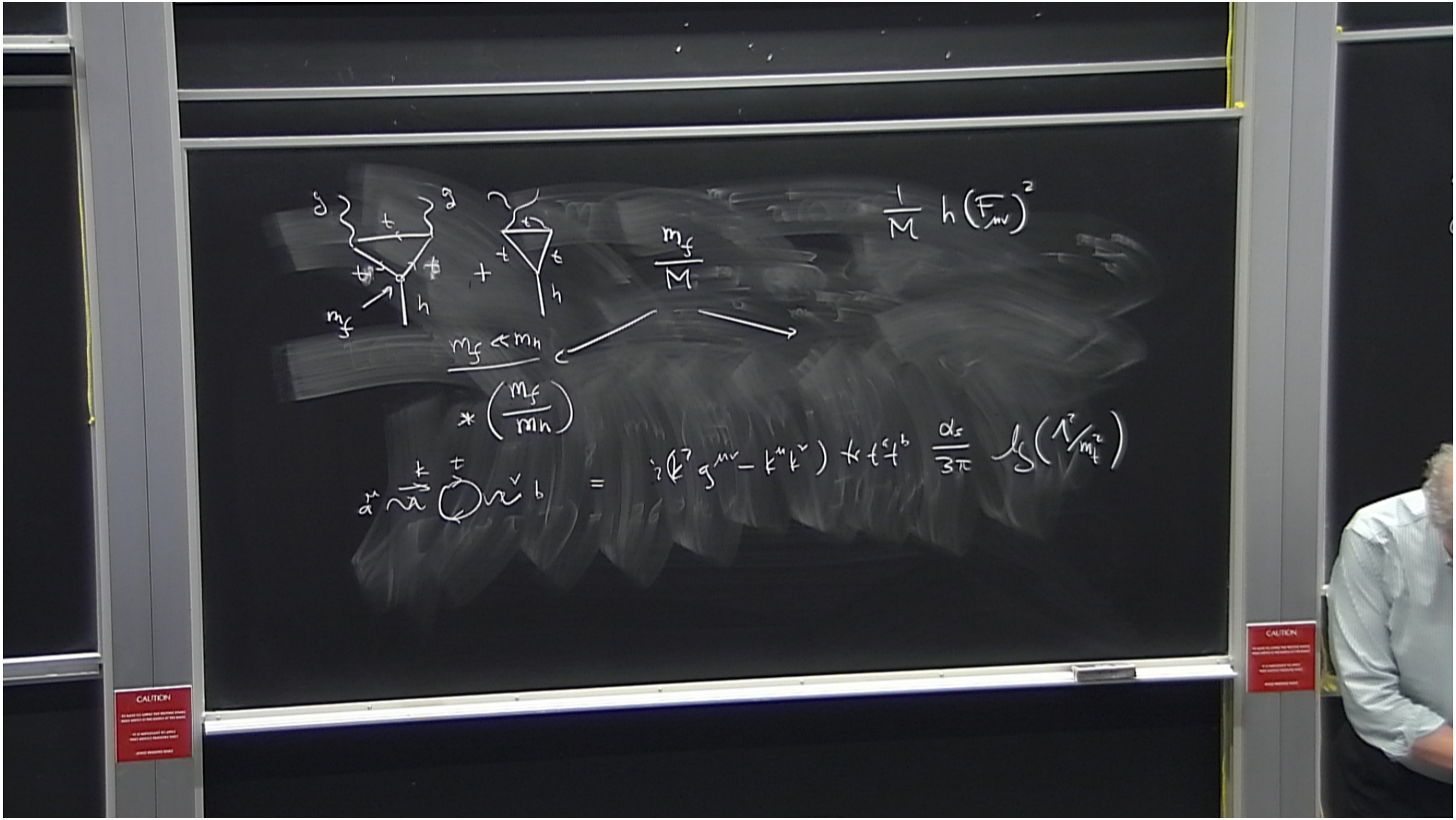

g
g
f
f
h
h
m_f
+
$\frac{m_f}{M}$
$\frac{1}{M}\, h\,(F_{\mu\nu})^2$
$m_f \gg m_h$
$\frac{m_f}{m_f} = O(1)$
$m_f \ll m_h$
$* \left(\frac{m_f}{m_h}\right)$
CAUTION
CAUTION

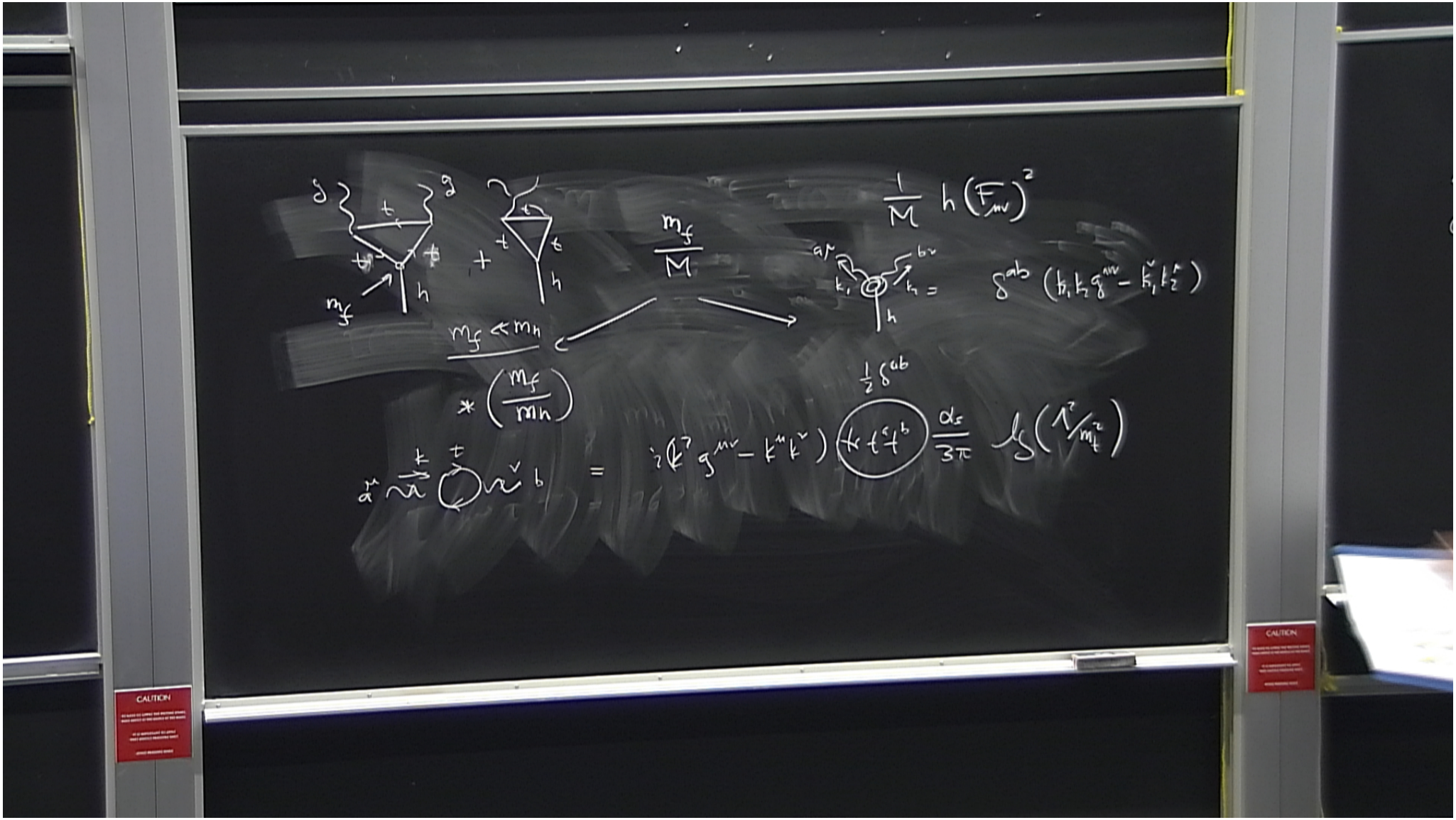

$\frac{m_f}{M}$
$\frac{1}{M} h (F_{mv})^2$
$m_f \gg m_h$
$\frac{m_f}{m_f} = O(1)$
$m_f \ll m_h$
$* \left(\frac{m_f}{m_h}\right)$
CAUTION

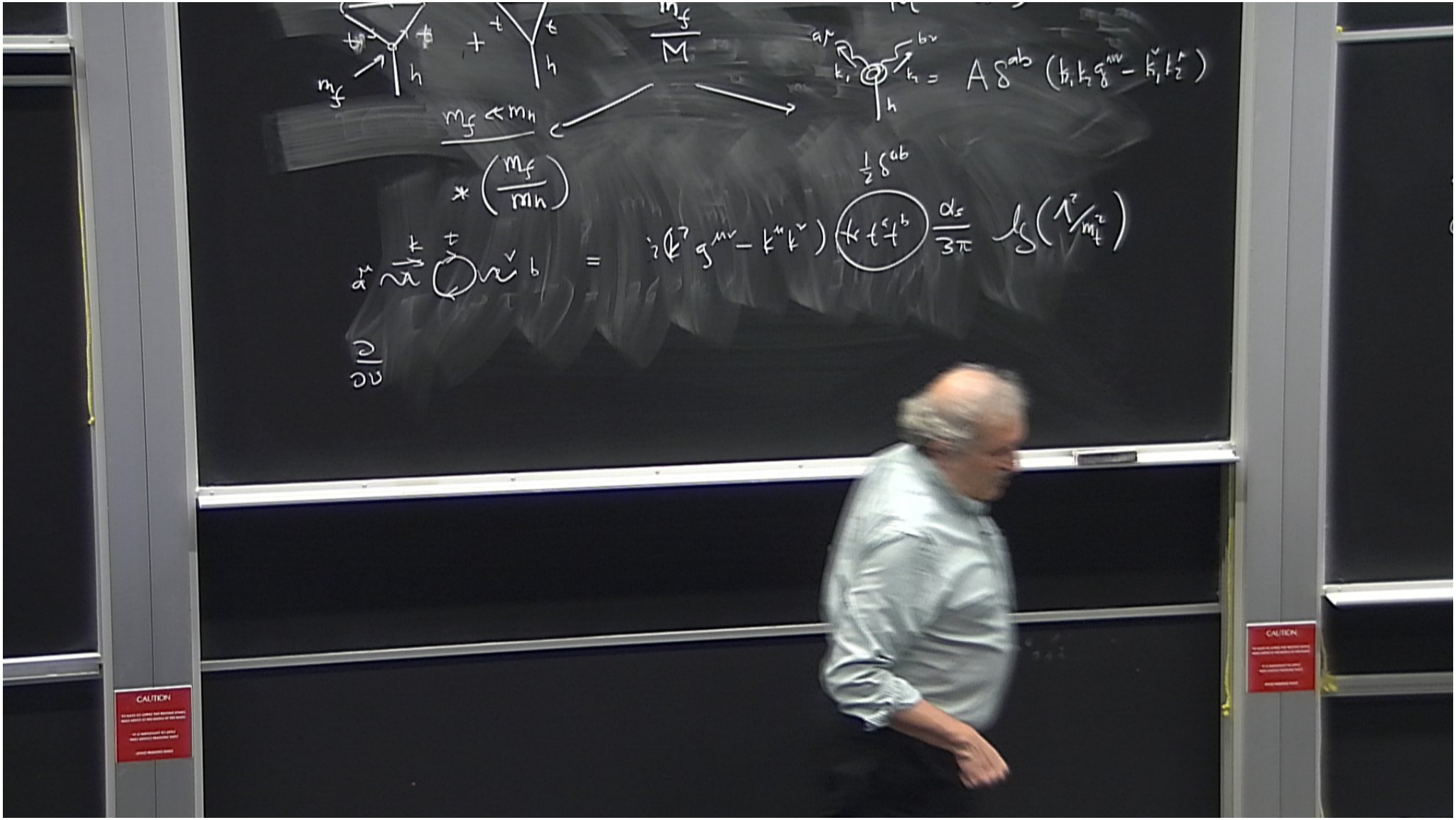

g
g
t
t
t
t
t
t
h
h
m_f
$\frac{m_f}{M}$
$\frac{1}{M} h (F_{\mu\nu})^2$
$m_f \gg m_h$
$m_f \ll m_h$
$\frac{m_f}{m_f} = O(1)$
$a \sim$

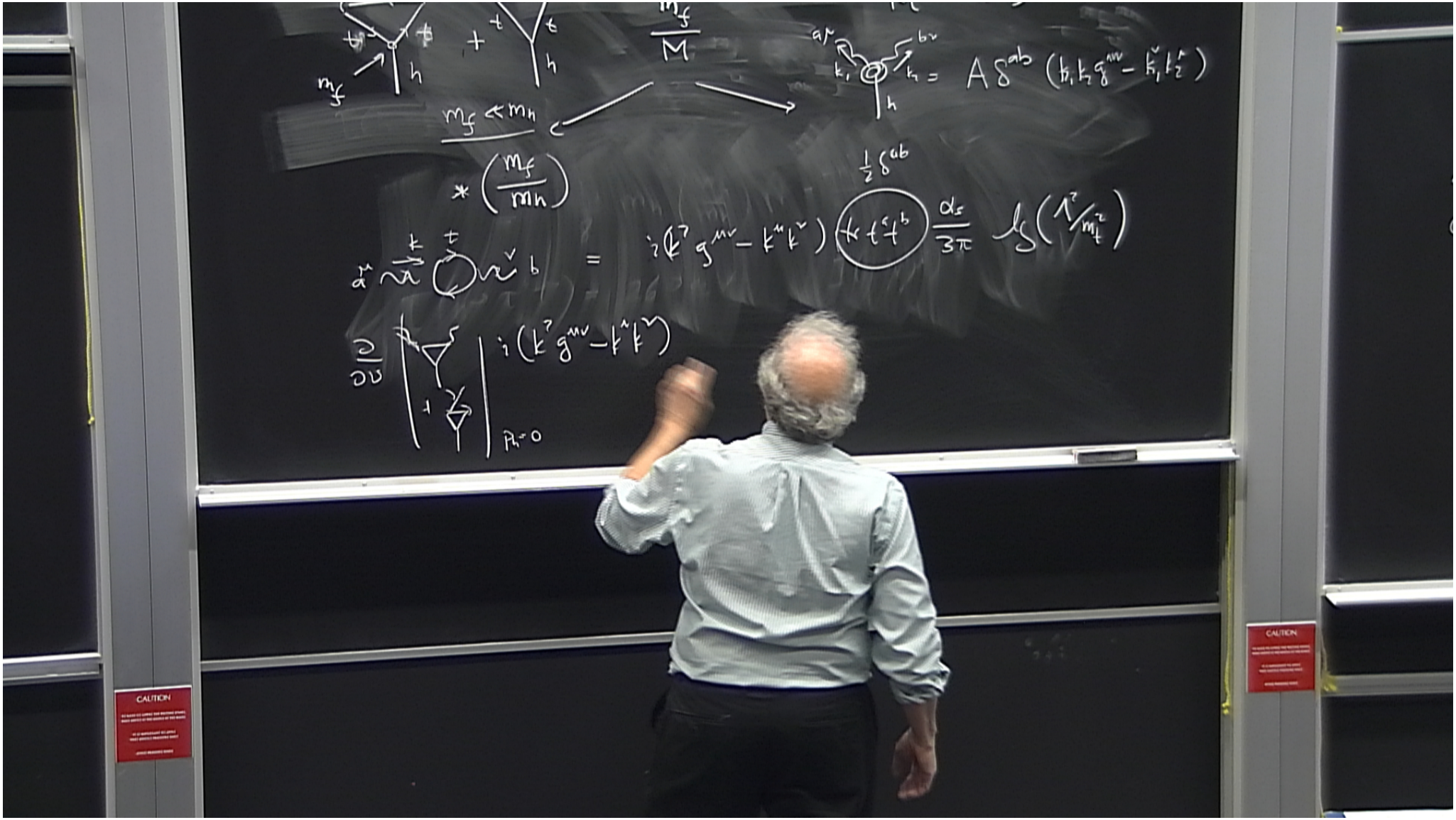

g
g
t
t
t
t
t
h
h
m_f
+
+
$\frac{m_f}{M}$
$m_f \ll m_h$
$* \left(\frac{m_f}{m_h}\right)$
$m_f \gg m_h$
$\frac{1}{M} h (F_{\mu\nu})^2$
$\frac{m_f}{m_f} = O(1)$
a
b
CAUTION

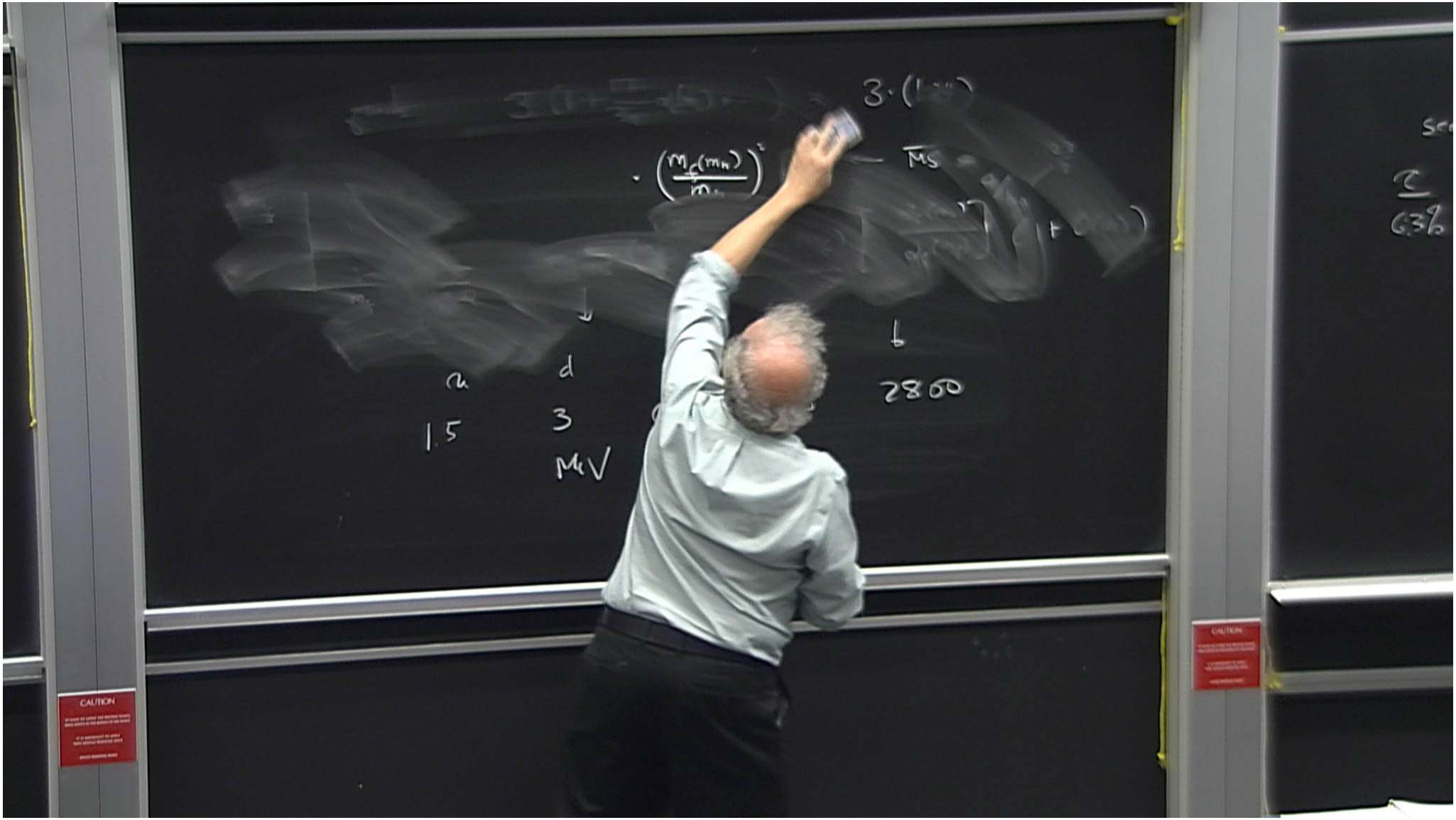

$\frac{1}{M} h (F_{\mu\nu})^2$
$\frac{m_f}{M}$
$m_f \gg m_h$
$\frac{m_f}{m_f} = \mathcal{O}(1)$
$m_f \ll m_h$
$* \left(\frac{m_f}{m_h}\right)$
$= i(k^2 g^{\mu\nu} - k^\mu k^\nu) * t^a t^b \frac{\alpha_s}{3\pi} \log\left(\Lambda^2/m_t^2\right)$

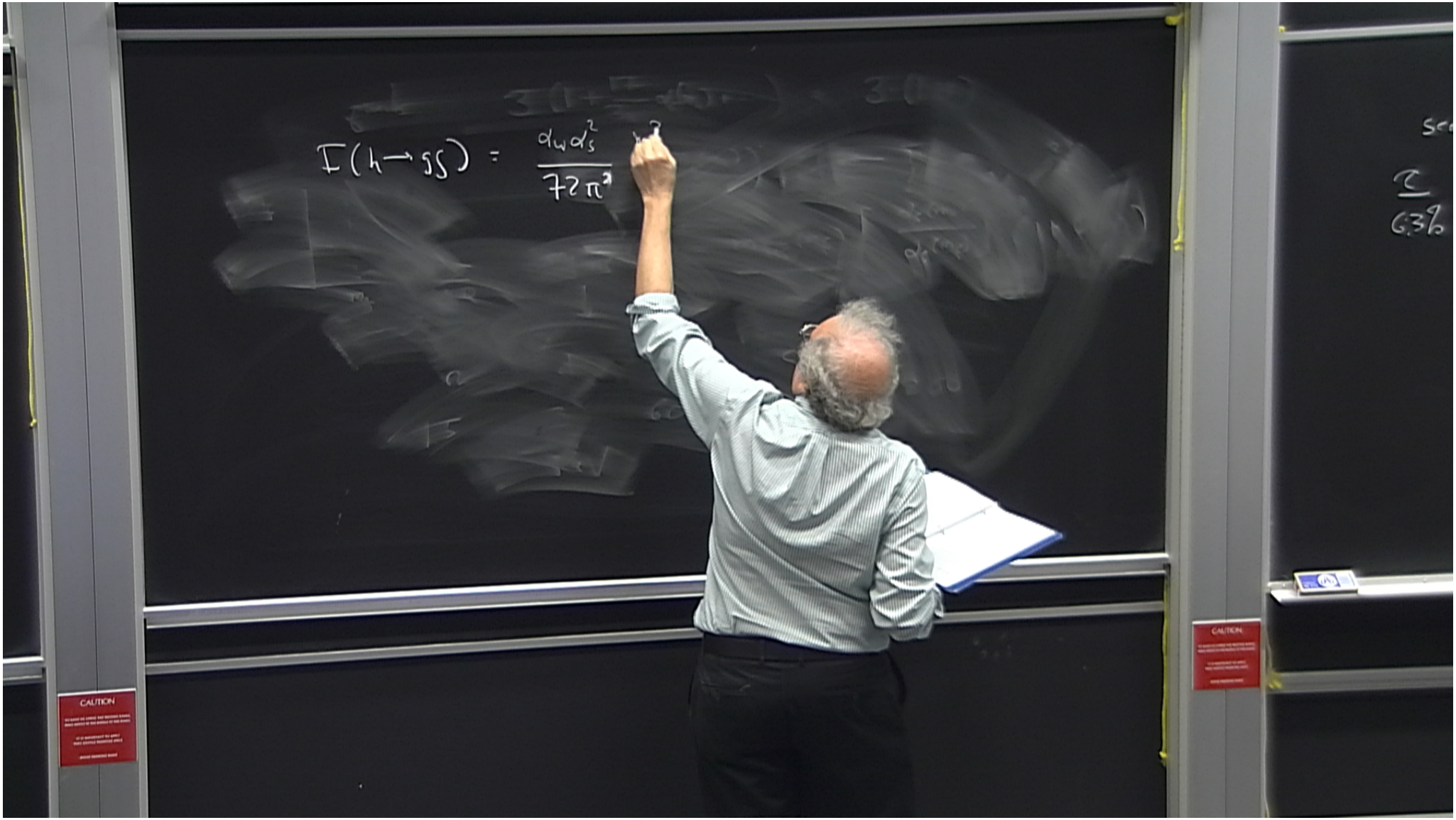

g
g
t
t
t
h
m_f
+
t
t
h
$\frac{m_f}{M}$
$\frac{1}{M} h (F_{\mu\nu})^2$
$m_f \ll m_h$
$* \left(\frac{m_f}{m_h}\right)$
$= i(k^2 g^{\mu\nu} - k^\mu k^\nu) \delta^{ab} \frac{\alpha_s}{3\pi} f_3\left(\frac{\Lambda^2}{m_t^2}\right)$

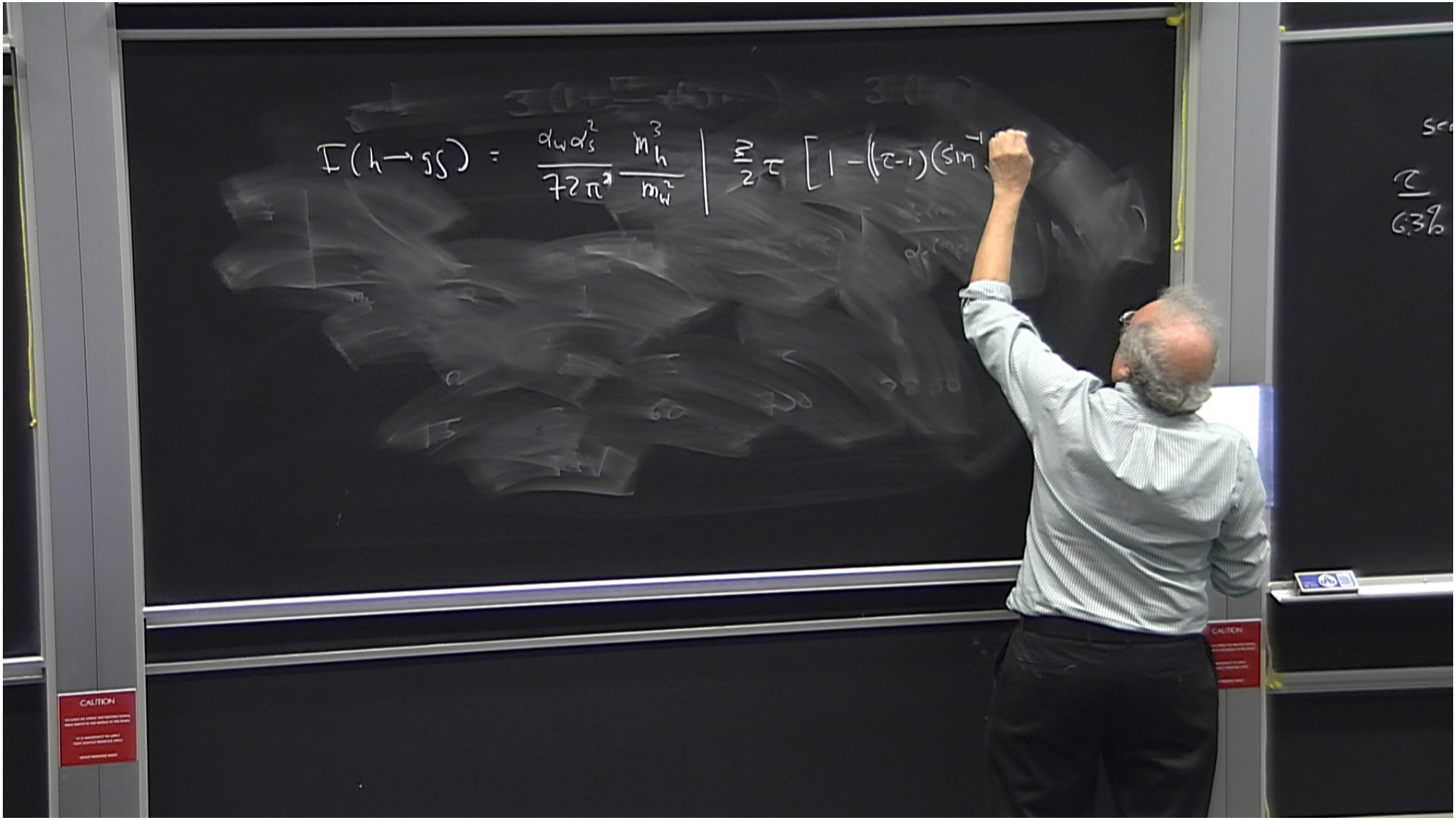

$\frac{m_f}{M}$
$\frac{1}{M} h (F_{\mu\nu})^2$
$m_f \ll m_h$
$* \left(\frac{m_f}{m_h}\right)$
$\frac{1}{2} \delta^{ab}$
$= i(k^2 g^{\mu\nu} - k^\mu k^\nu)$
$\frac{\alpha_s}{3\pi}$
$f_3\left(\frac{1^2}{m_t^2}\right)$

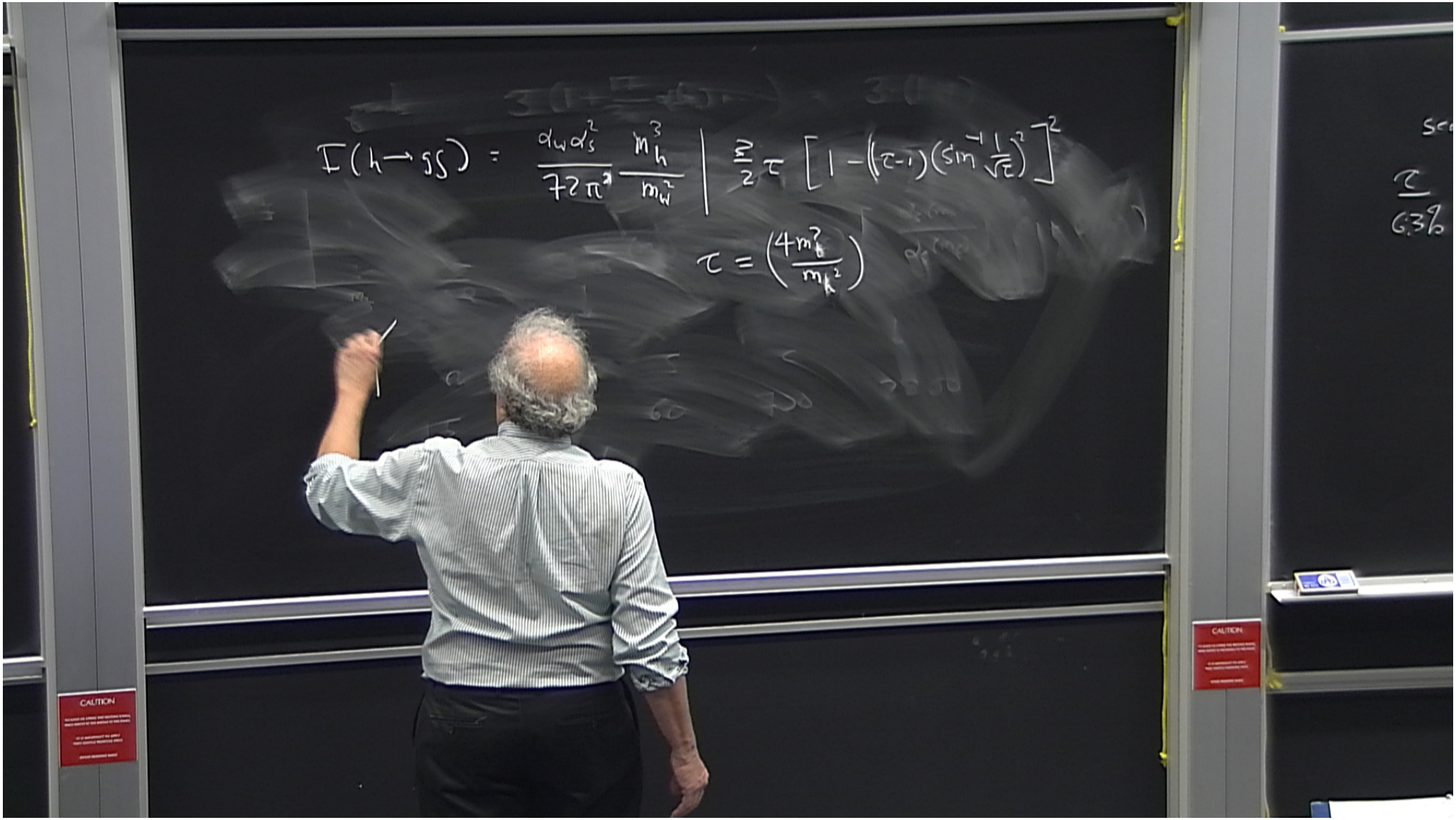

$\frac{m_f}{M}$
$m_f \ll m_h$
$* \left(\frac{m_f}{m_h}\right)$
$= A\delta^{ab}(k_1 k_2 g^{\mu\nu} - k_1^\nu k_2^\mu)$
$\frac{1}{2}\delta^{ab}$
$= i(k^2 g^{\mu\nu} - k^\mu k^\nu)$
$\frac{\alpha_s}{3\pi}$
$f_3\left(\frac{\Lambda^2}{m_t^2}\right)$
$\frac{\partial c}{\partial v}$
CAUTION
CAUTION


$\frac{m_f}{M}$
$m_f \ll m_h$
$* \left(\frac{m_f}{m_h}\right)$
$A\delta^{ab}(k_1 k_2 g^{\mu\nu} - k_1^\nu k_2^\mu)$
$\frac{1}{2}\delta^{ab}$
$i(k^2 g^{\mu\nu} - k^\mu k^\nu)$
$k=0$
CAUTION
CAUTION


3.(
$\left(\frac{m_c(m_n)}{m_\cdot}\right)^2$
MS
d
1.5
3
MeV
b
2800
CAUTION


$\Gamma(h \to gg) = \frac{\alpha_w \alpha_s^2}{72\pi^3}$
CAUTION
CAUTION


$\Gamma(h \to gg) = \frac{\alpha_w \alpha_s^2}{72\pi^3} \frac{m_h^3}{m_W^2} \left| \frac{3}{2}\tau \left[1 - (\tau - 1)(\sin^{-1}$
τ
63%
CAUTION
CAUTION


$\Gamma(h \to gg) = \frac{\alpha_w \alpha_s^2}{72\pi^3} \frac{m_h^3}{m_W^2} \left| \frac{3}{2}\tau \left[1 - (\tau - 1)\left(\sin^{-1}\frac{1}{\sqrt{\tau}}\right)^2 \right]^2 \right.$
$\tau = \left(\frac{4m_b^2}{m_h^2}\right)$
CAUTION
CAUTION

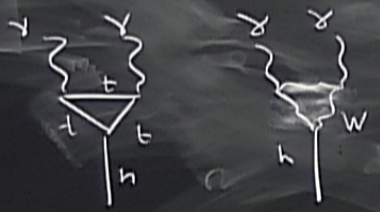
$$\Gamma(h \to gg) = \frac{\alpha_w \alpha_s^2}{72\pi^3} \frac{m_h^3}{m_W^2} \left| \frac{3}{2}\tau \left[1 - (\tau - 1)\left(\sin^{-1}\frac{1}{\sqrt{\tau}}\right)^2 \right]^2 \right.$$

$$\tau = \left(\frac{4m_t^2}{m_h^2}\right)$$



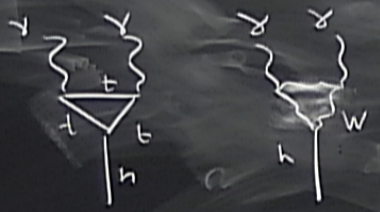
$$\Gamma(h \to gg) = \frac{\alpha_W \alpha_s^2}{72\pi^3} \frac{m_h^3}{m_W^2} \left| \frac{3}{2}\tau \left[1 - (\tau - 1)\left(\sin^{-1}\frac{1}{\sqrt{\tau}}\right)^2 \right]^2 \right.$$

$$\tau = \left(\frac{4m_t^2}{m_h^2}\right)$$

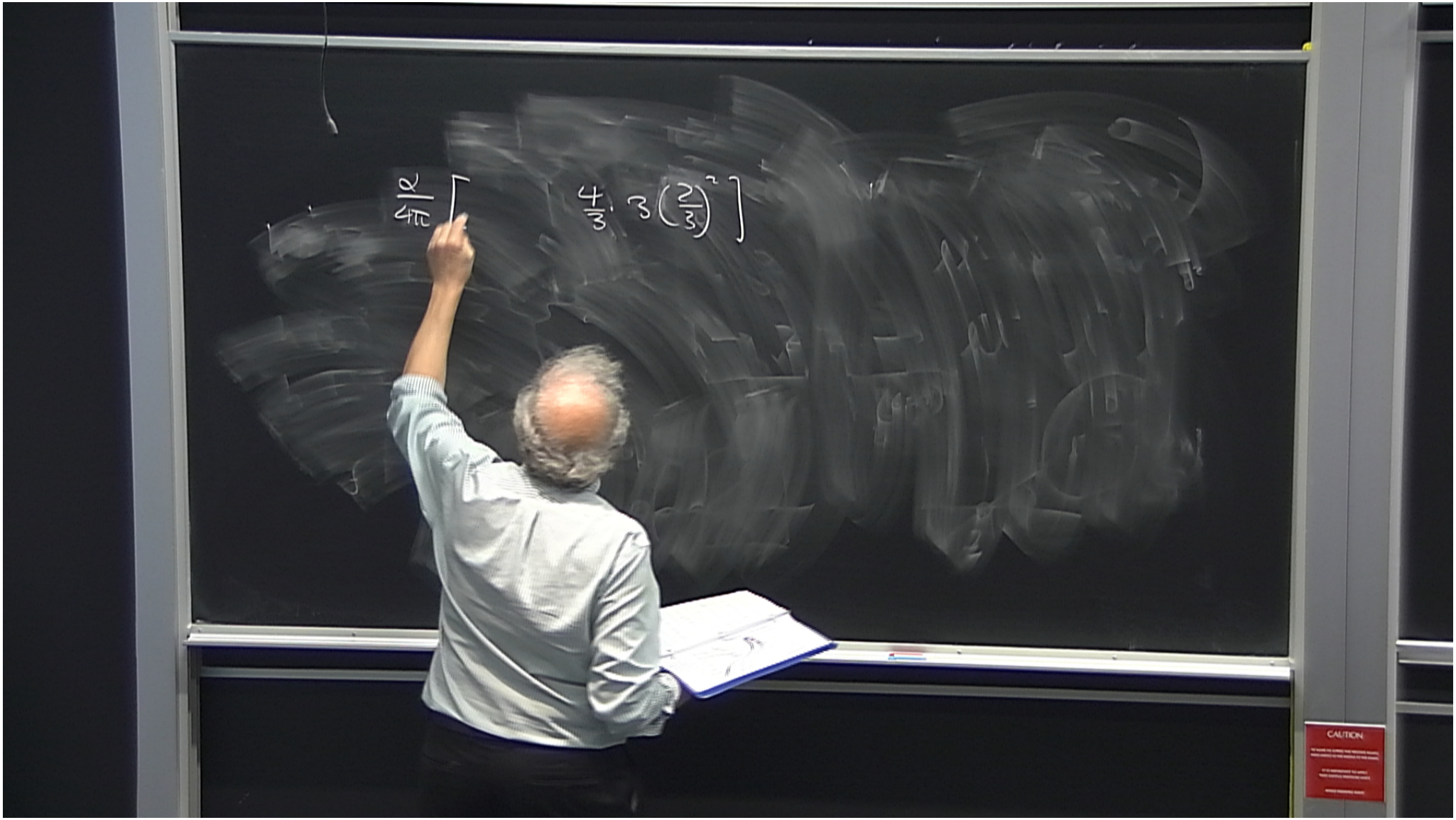


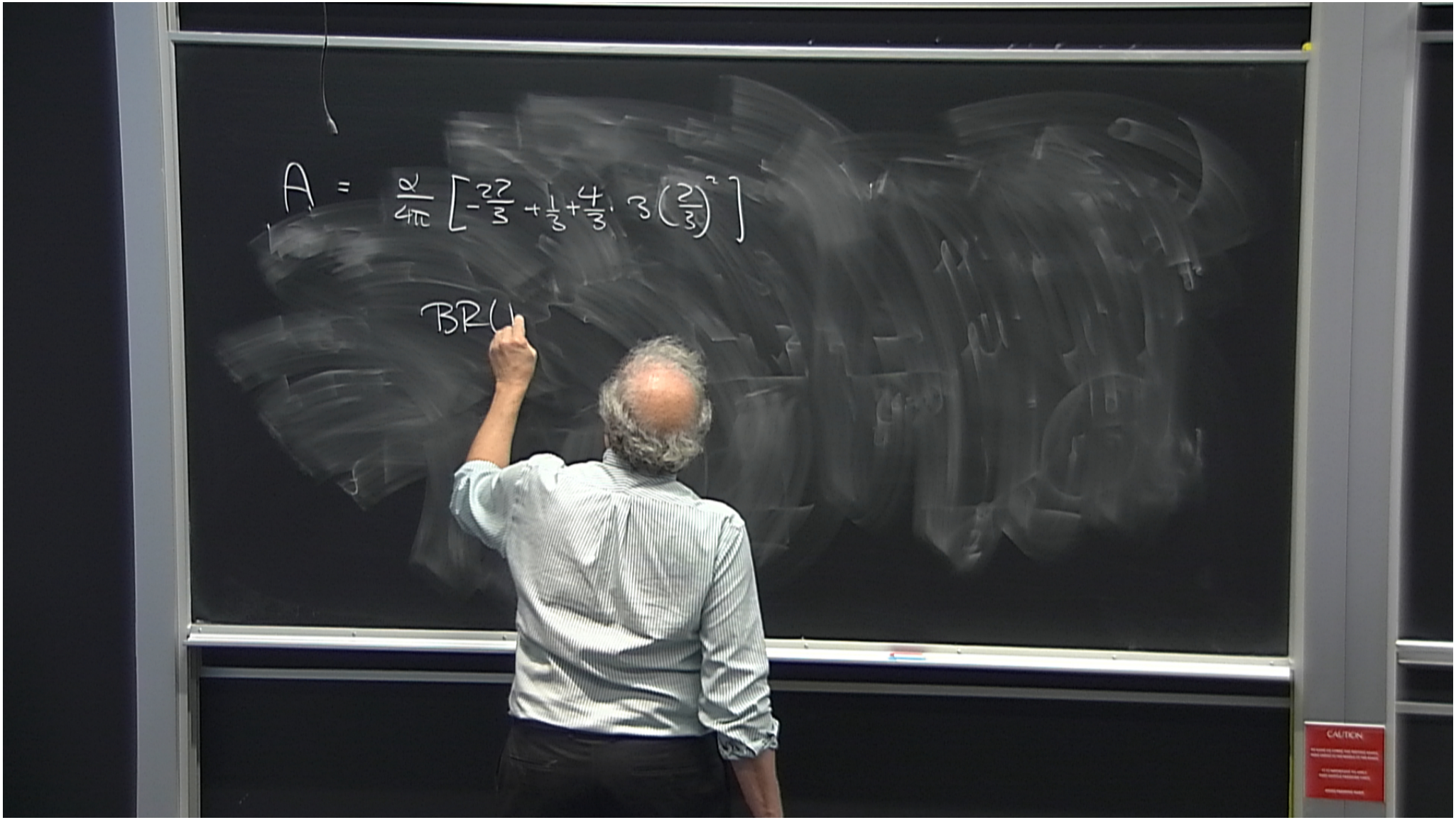
$$\Gamma(h \to gg) = \frac{\alpha_W \alpha_s^2}{72\pi^3} \frac{m_h^3}{m_W^2} \left| \frac{3}{2}\tau \left[1 - (\tau - 1)\left(\sin^{-1}\frac{1}{\sqrt{\tau}}\right)^2 \right] \right|^2$$

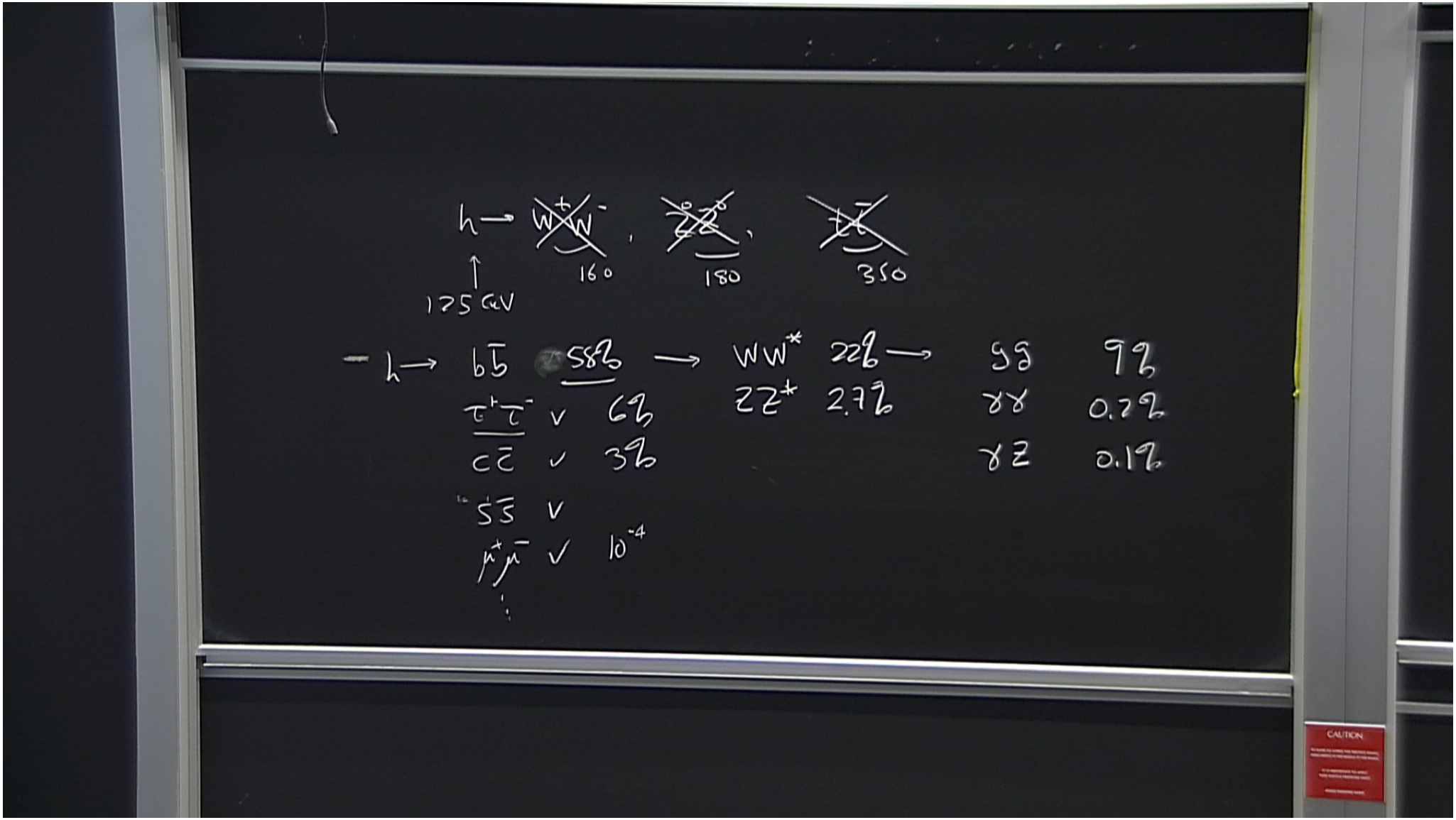
$$\tau = \left(\frac{4m_t^2}{m_h^2}\right)$$

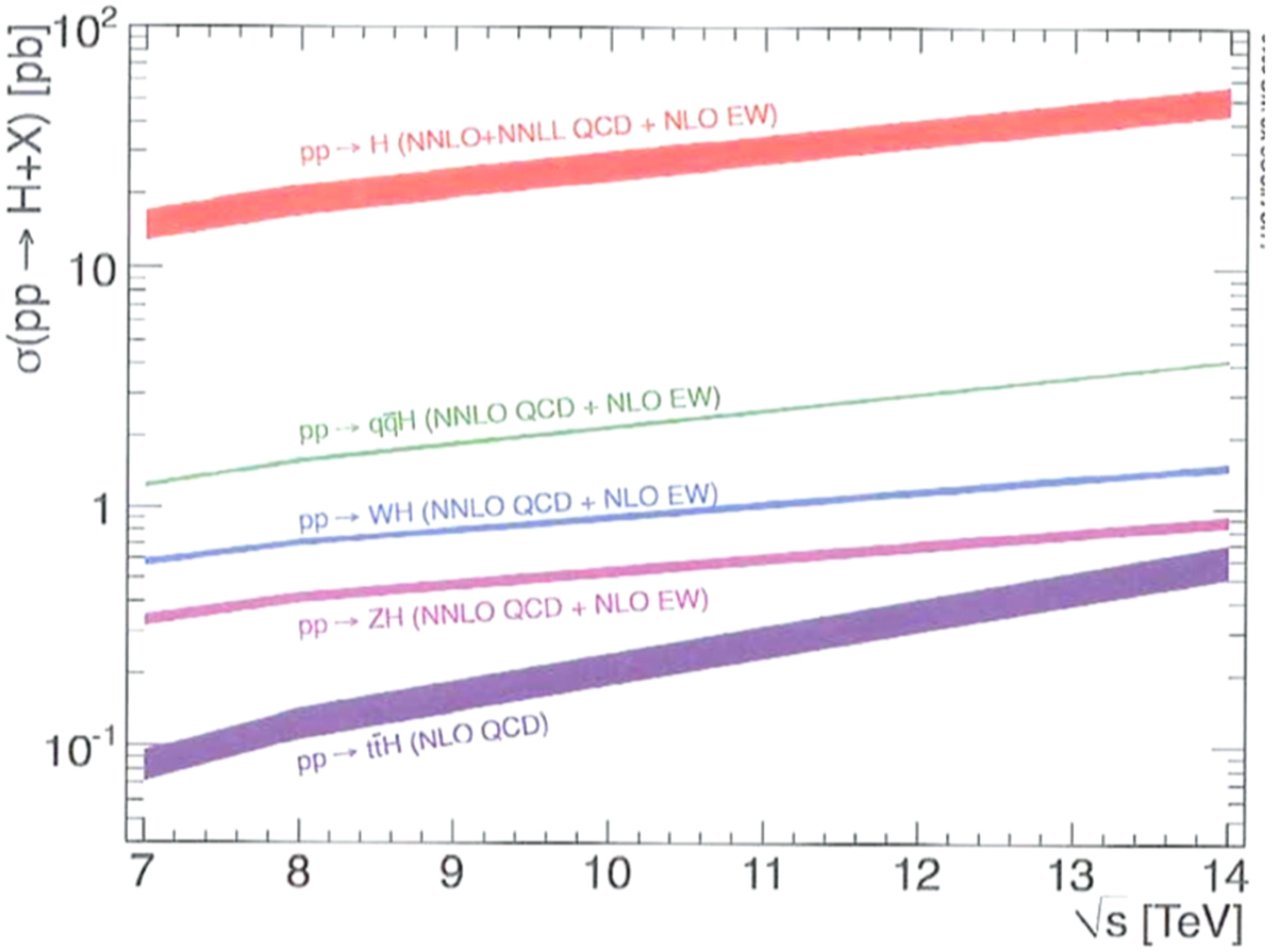


$$\gamma \sim\!\!\sim \bigcirc\!\!\!\!\!\!\sim \gamma = i\left(k^2 g^{\mu\nu} - k^\mu k^\nu\right) \frac{3Q_f^2 \alpha}{3\pi} \; 1/m_t^2$$

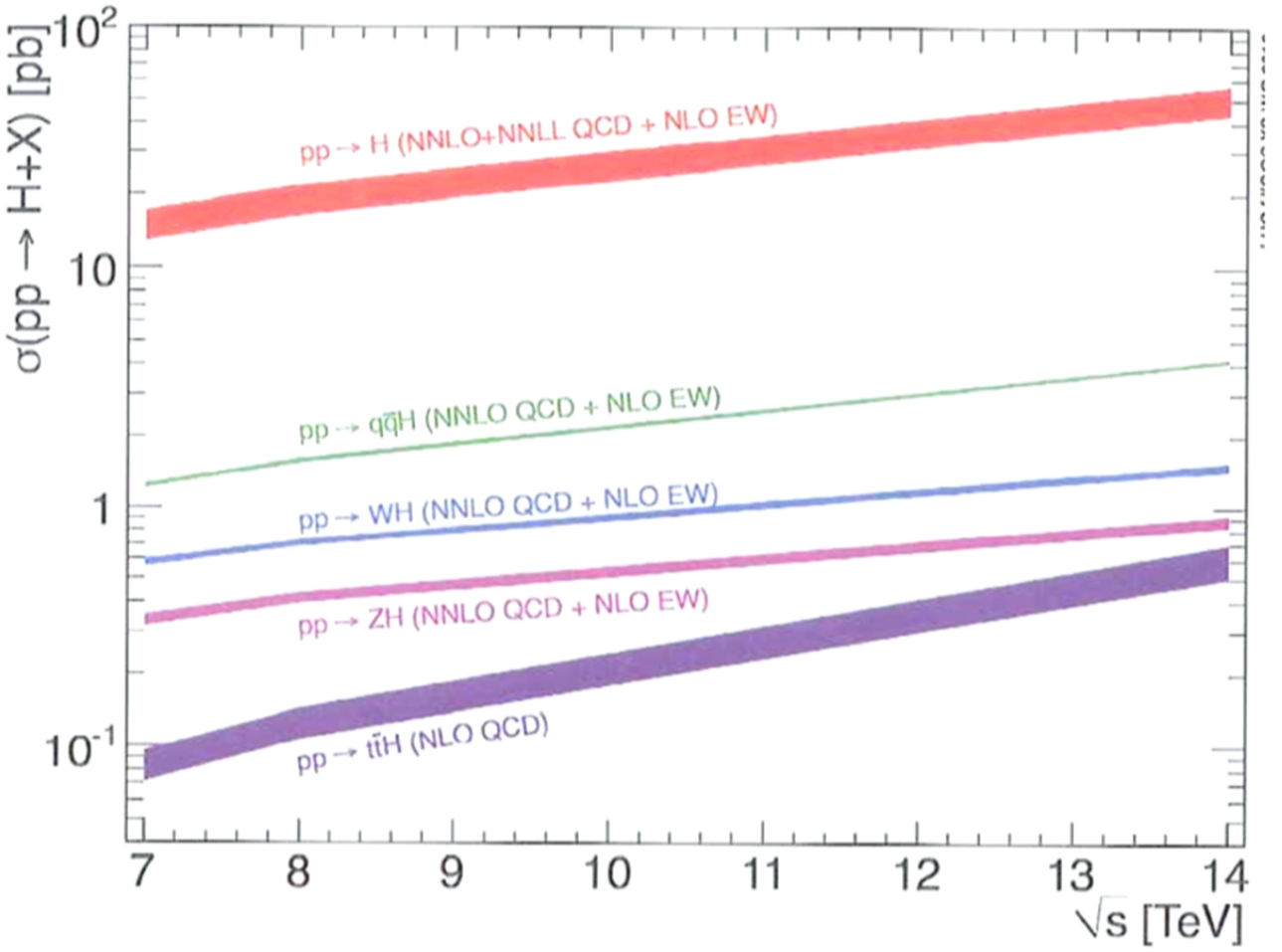

$\frac{\alpha}{4\pi}\left[\right.$
$\frac{4}{3}\cdot 3\left(\frac{2}{3}\right)^2\left.\right]$
CAUTION


A = α/4π [-22/3 + 1/3 + 4/3 · 3(2/3)²]
BR(

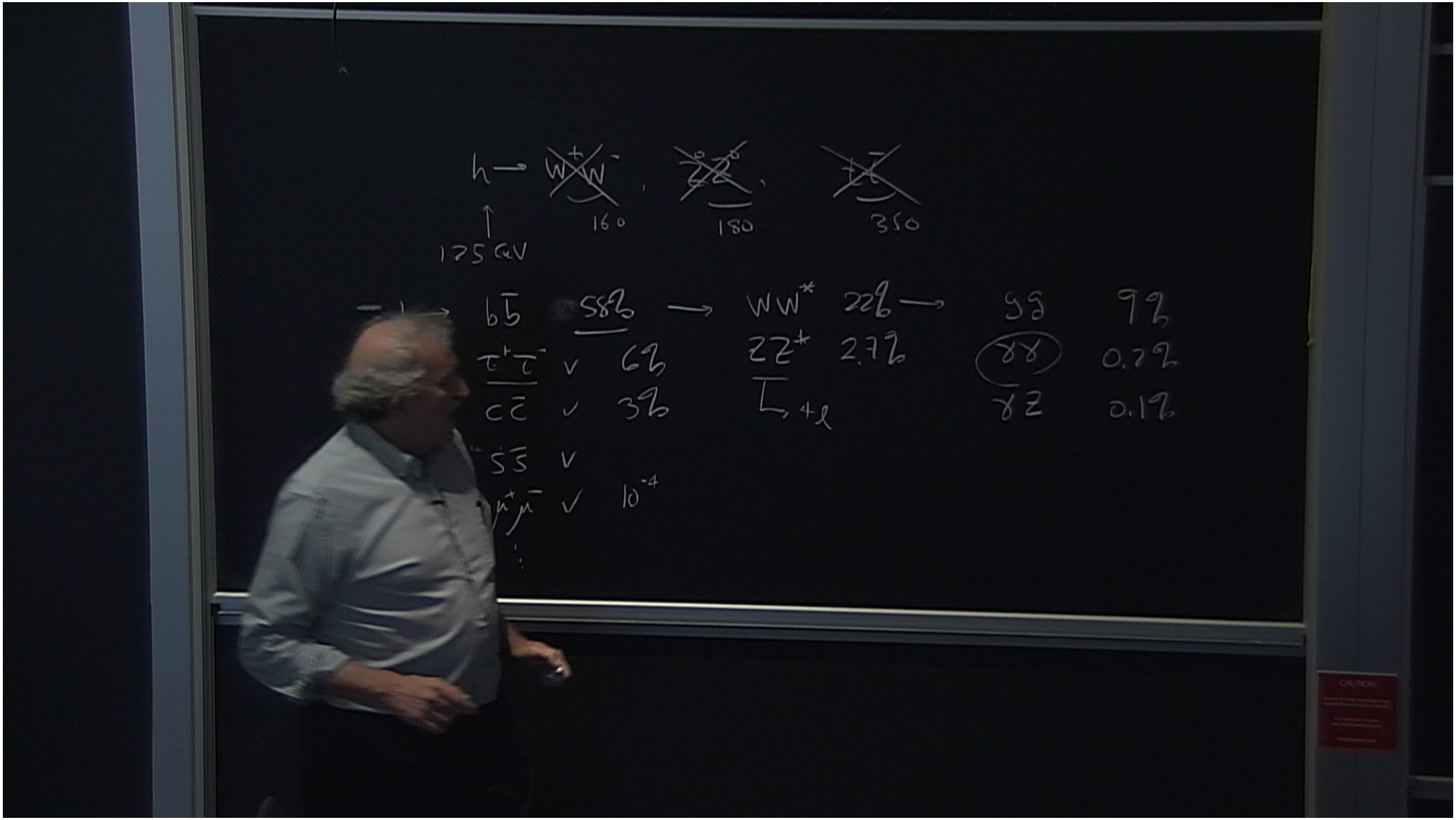

h → W+W- , ZZ , tt̄
160
180
350
125 GeV
h → bb̄ 58% → WW* 22% → gg 9%
ττ̄ 6%
cc̄ 3%
ss̄
μ+μ- 10^-4
ZZ* 2.7%
γγ 0.2%
γZ 0.1%
CAUTION

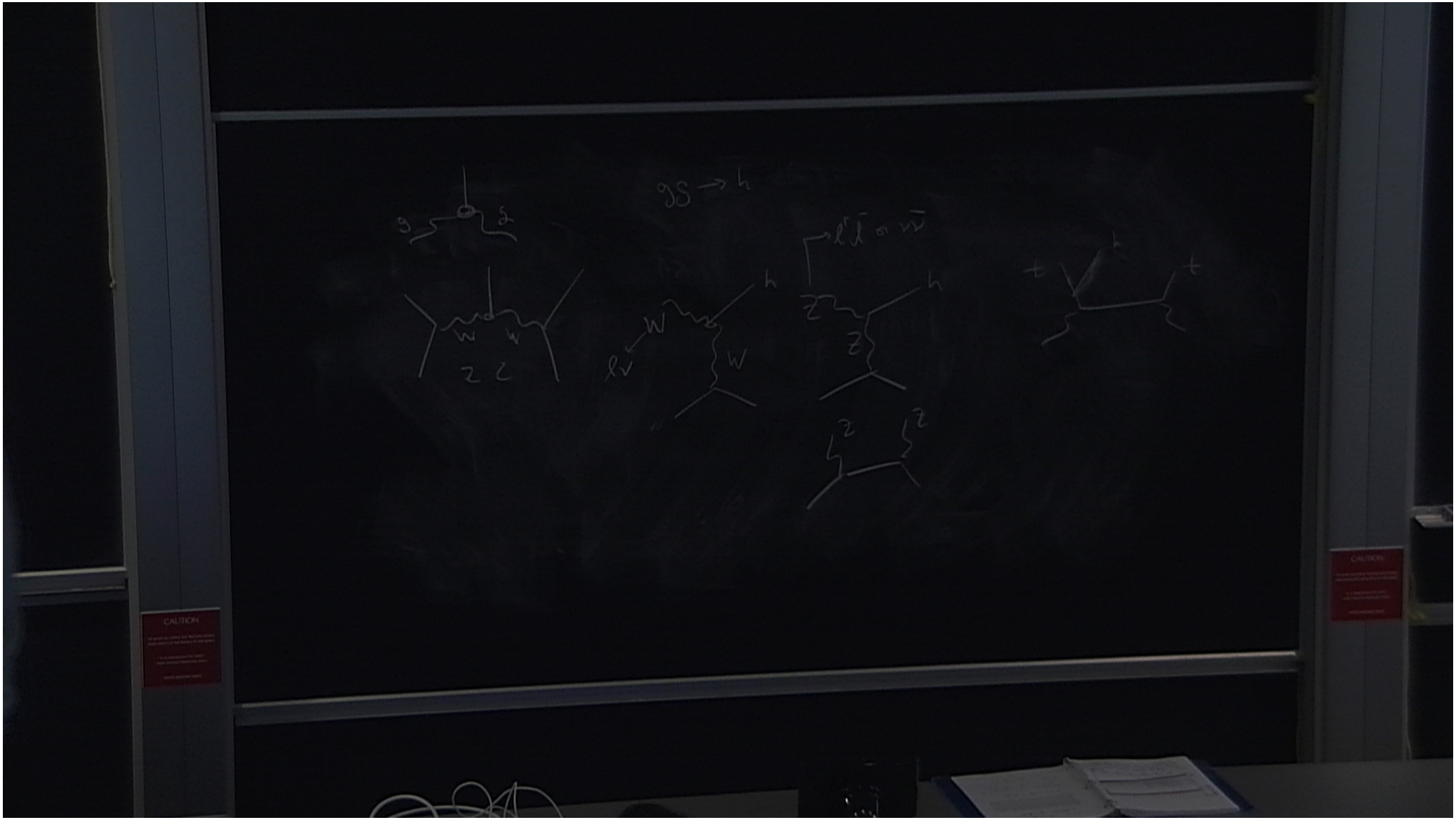


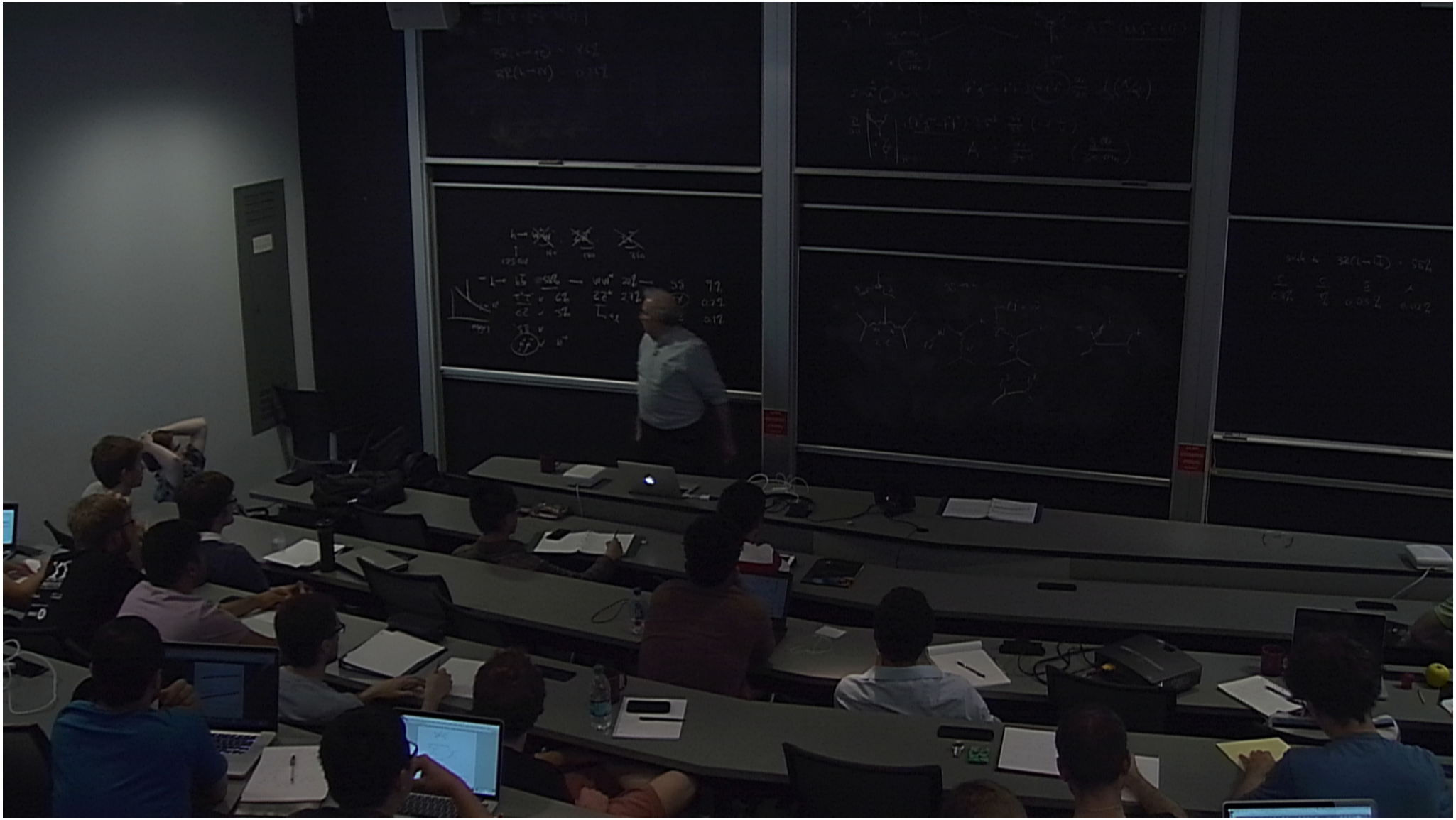
LHC Higgs Cross Section Working Group

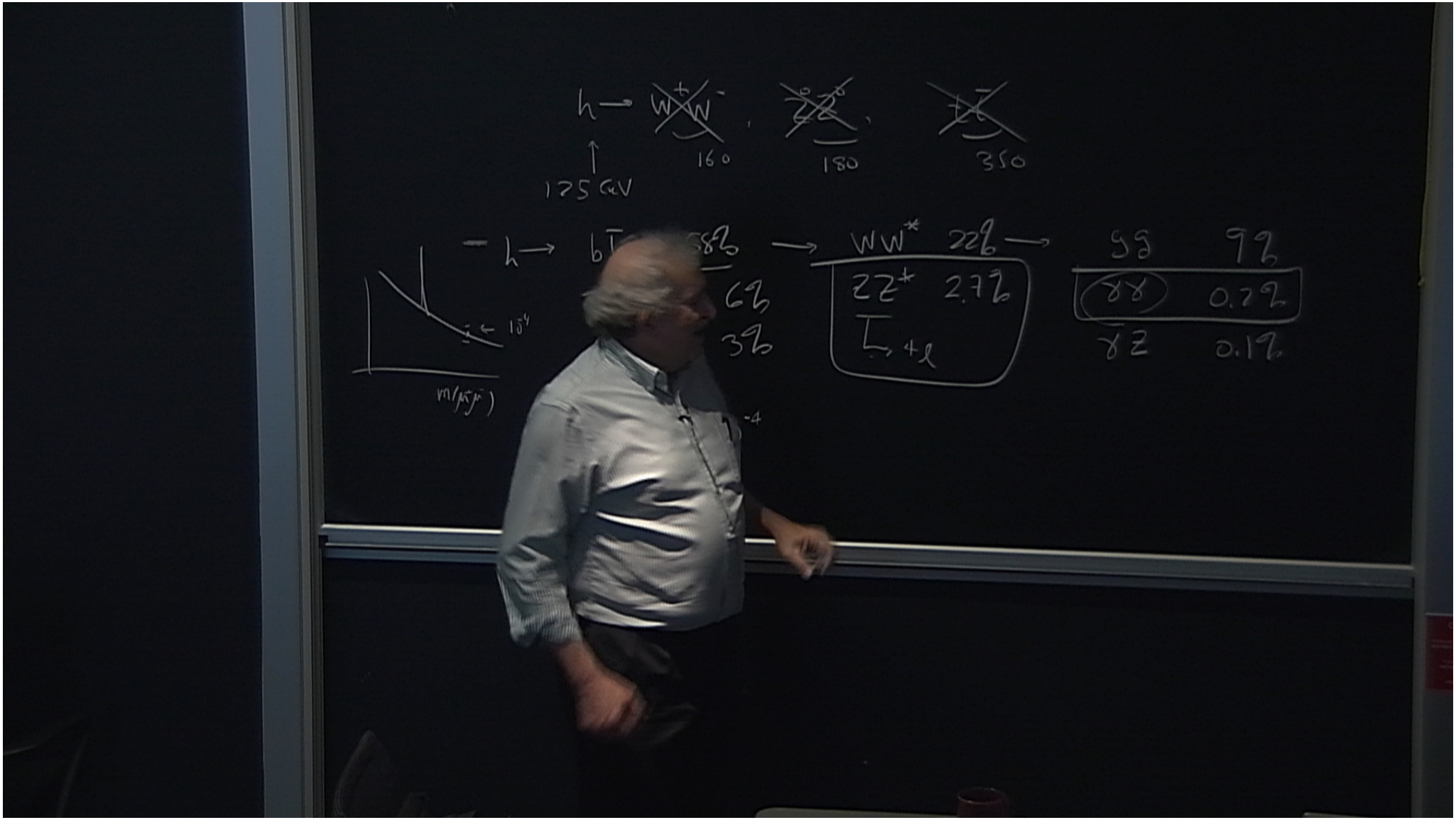


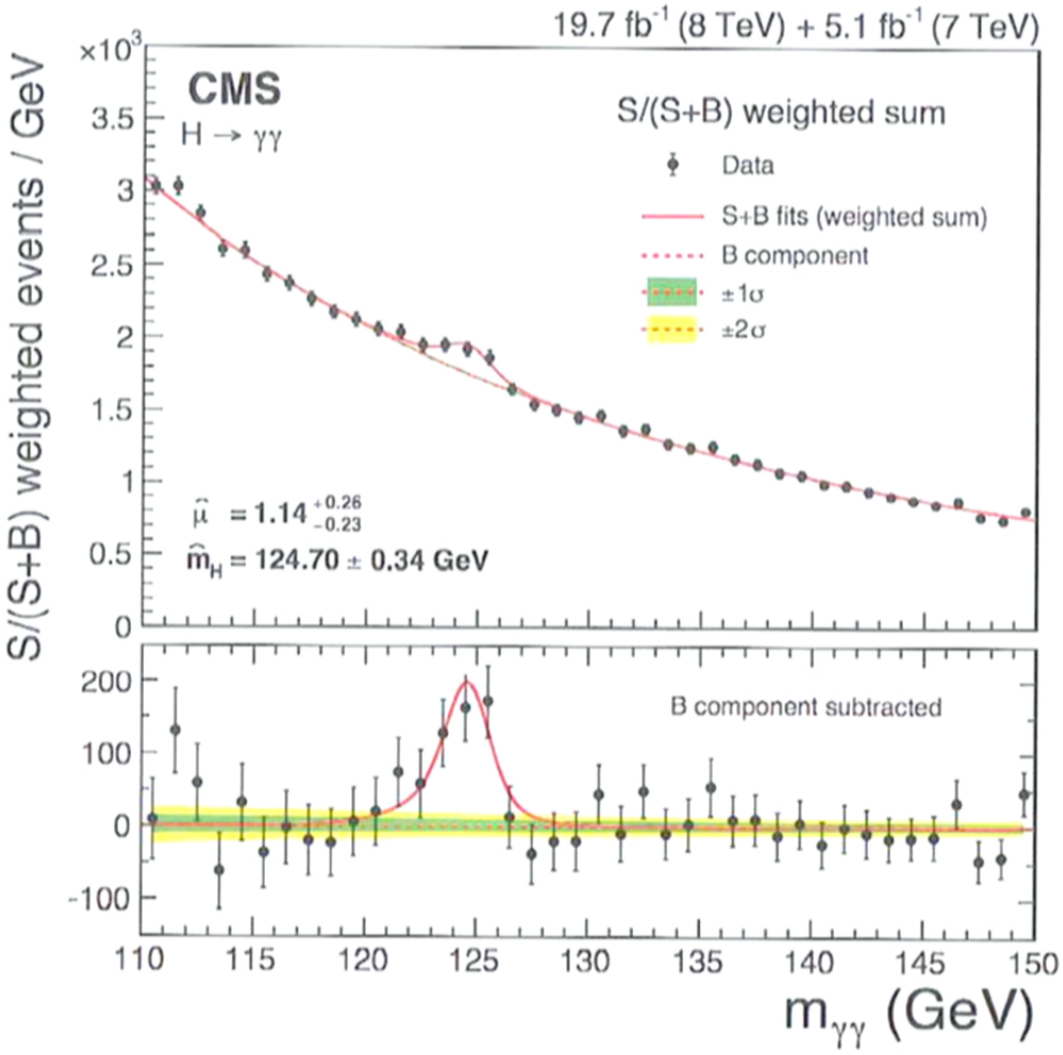
LHC Higgs Cross Section Working Group

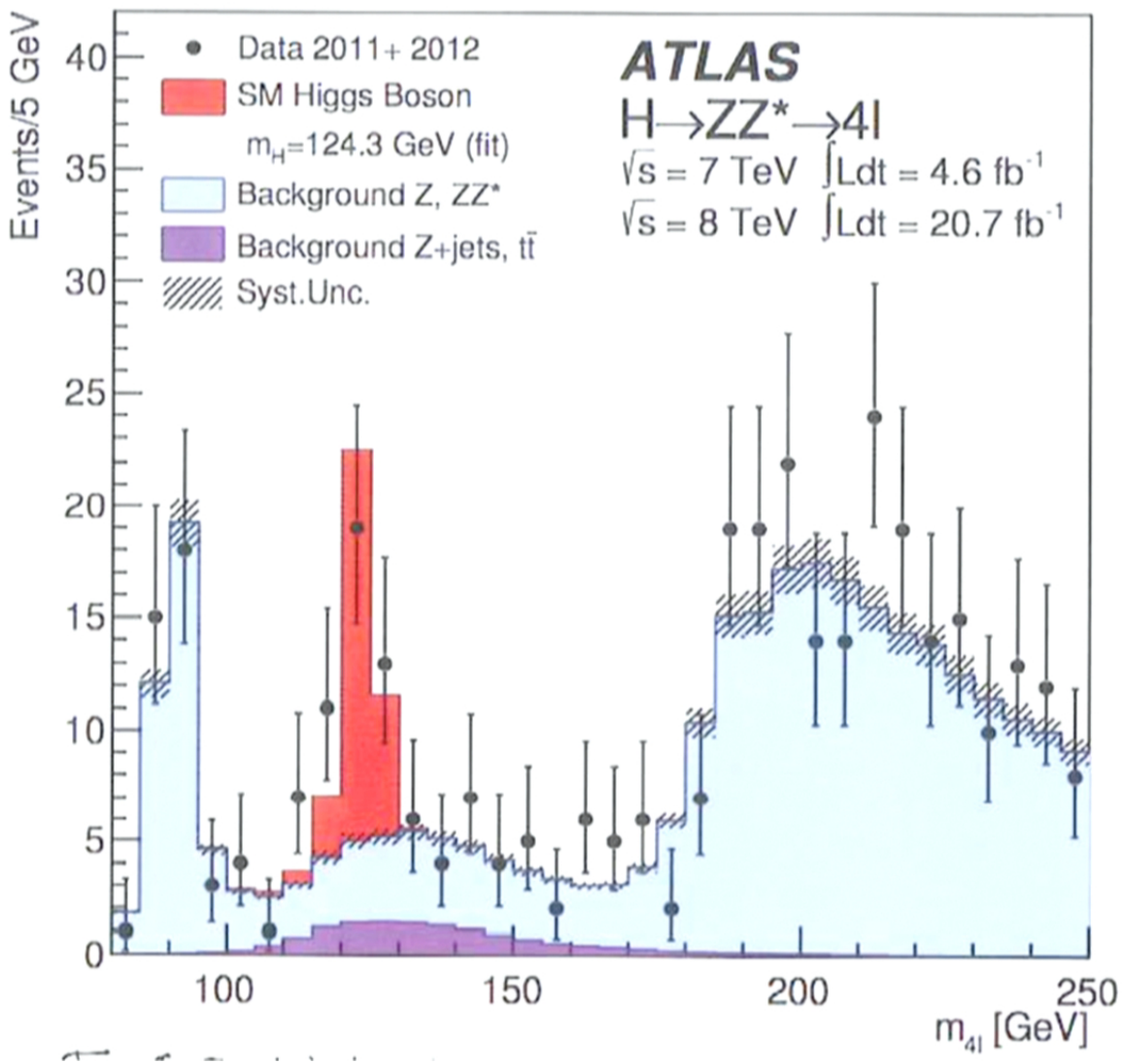

h → W⁺W⁻ , ZZ , tt̄
160
180
350
125 GeV
bb̄ 58% → WW* 22% → gg 9%
τ⁺τ⁻ ν 6% ZZ* 2.7% γγ 0.2%
cc̄ ν 3% l, +l γZ 0.1%
ss̄ ν
μ⁺μ⁻ ν 10⁻⁴


gs → h
g
g
W
W
Z
Z
h
W
W
h
Z
Z
Z
Z
t
t
h

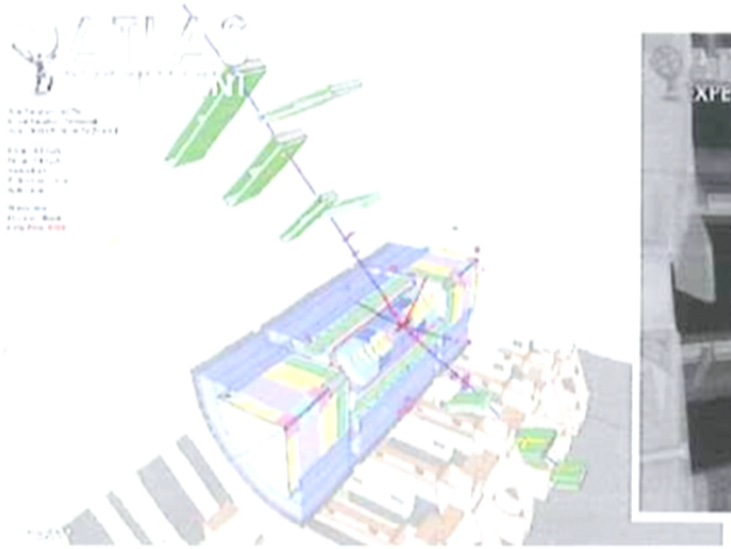


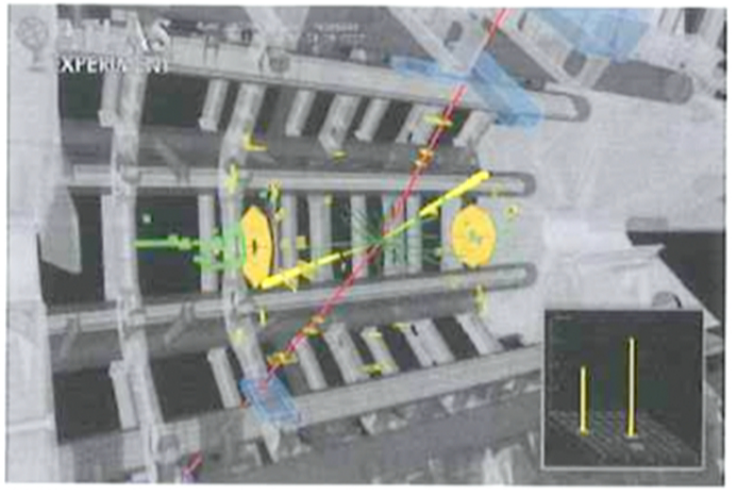

h → W⁺W⁻ , ZZ , tt̄
160
180
350
175 GeV
h → bb̄ ττ → WW* 2ν2b →
gg gg
ZZ* 2.7%
ττ 6%
bb̄ 3%
γγ 0.2%
γZ 0.1%
m(μ⁺μ⁻)

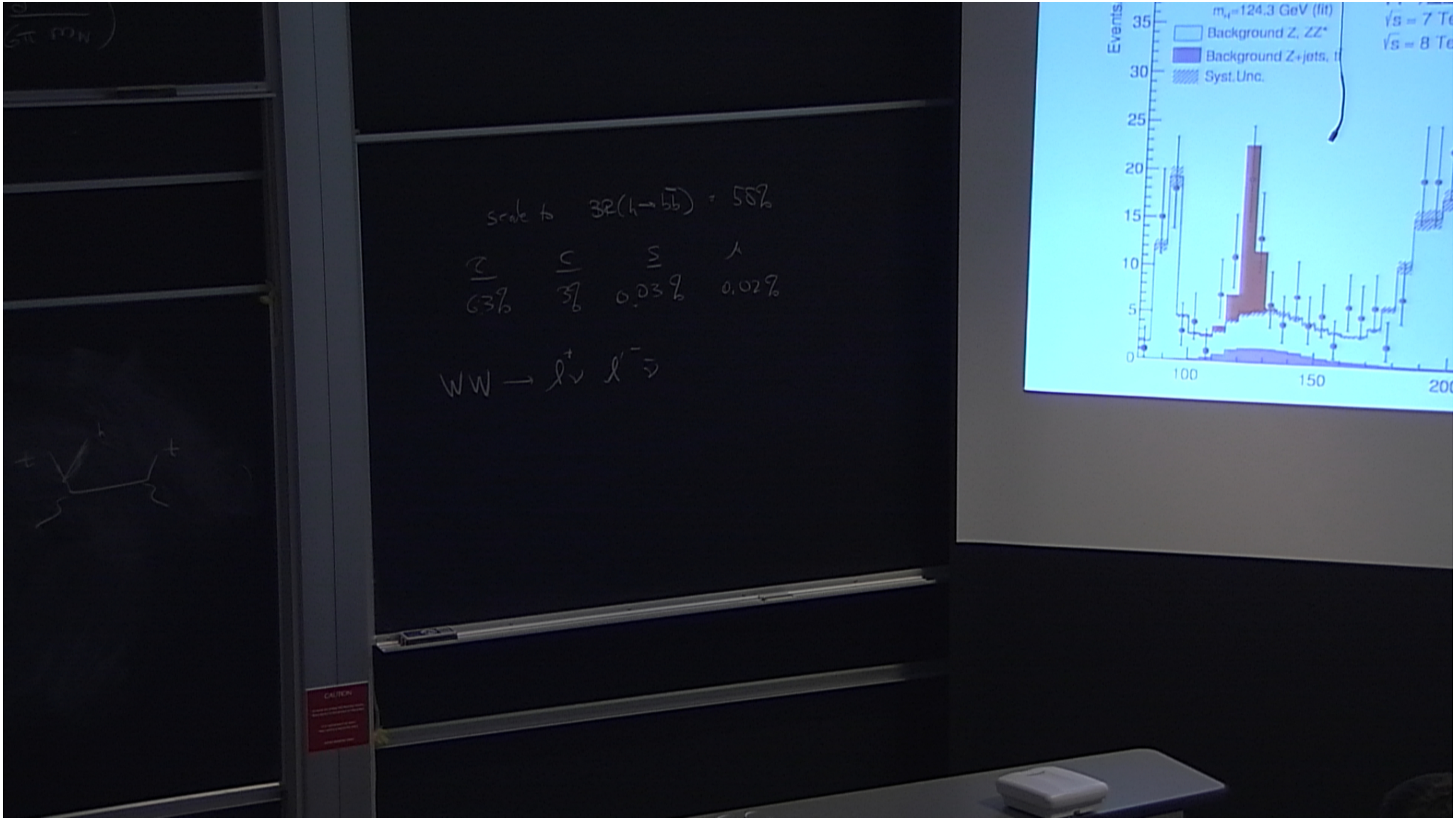

19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
CMS
H → γγ
S/(S+B) weighted sum
Data
S+B fits (weighted sum)
B component
±1σ
±2σ
μ̂ = 1.14 +0.26 −0.23
m̂H = 124.70 ± 0.34 GeV
B component subtracted
S/(S+B) weighted events / GeV
×10³
mγγ (GeV)

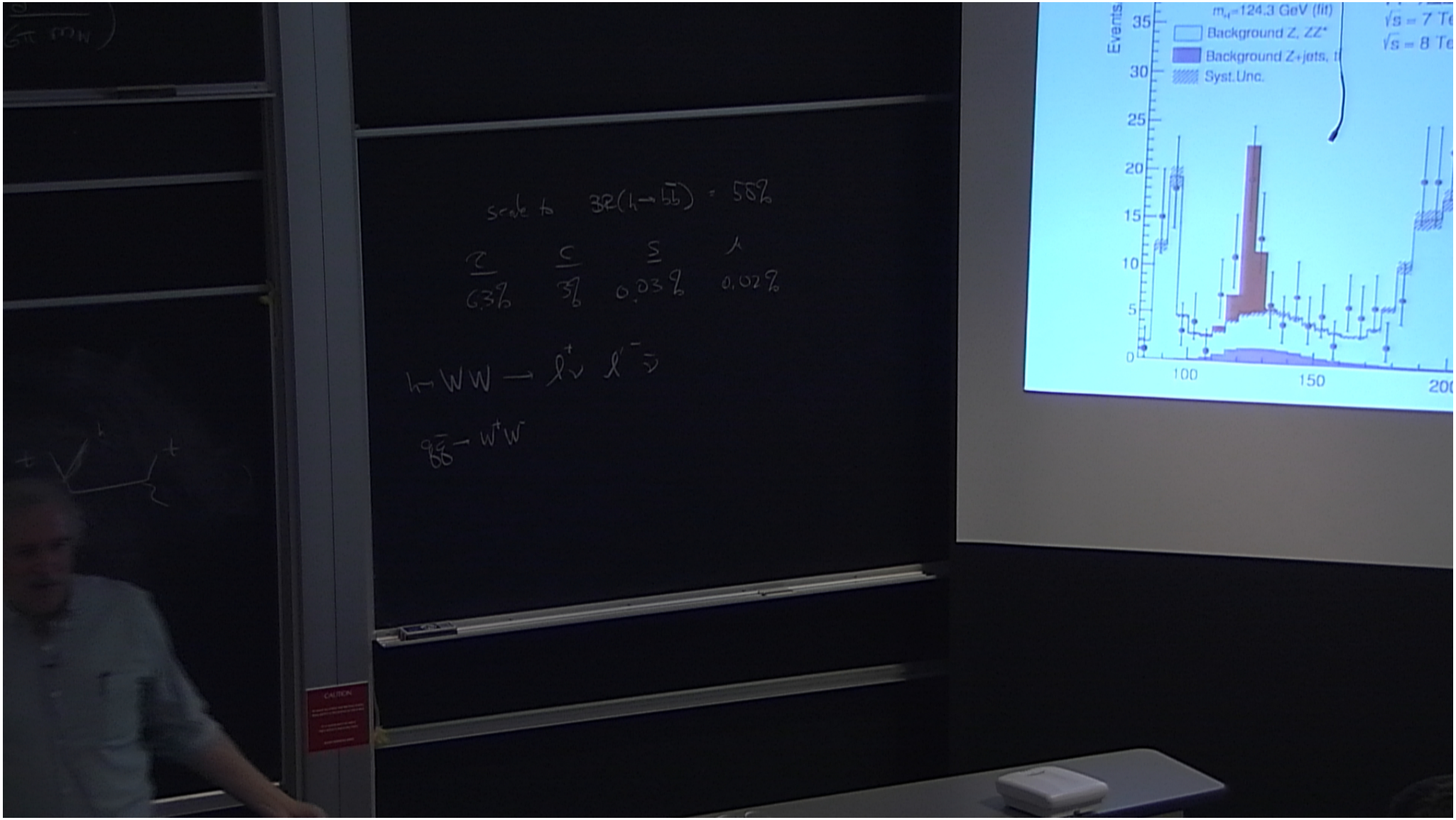

ATLAS
H→ZZ*→4l
√s = 7 TeV ∫Ldt = 4.6 fb-1
√s = 8 TeV ∫Ldt = 20.7 fb-1
Data 2011+ 2012
SM Higgs Boson
mH=124.3 GeV (fit)
Background Z, ZZ*
Background Z+jets, tt̄
Syst.Unc.
Events/5 GeV
m4l [GeV]

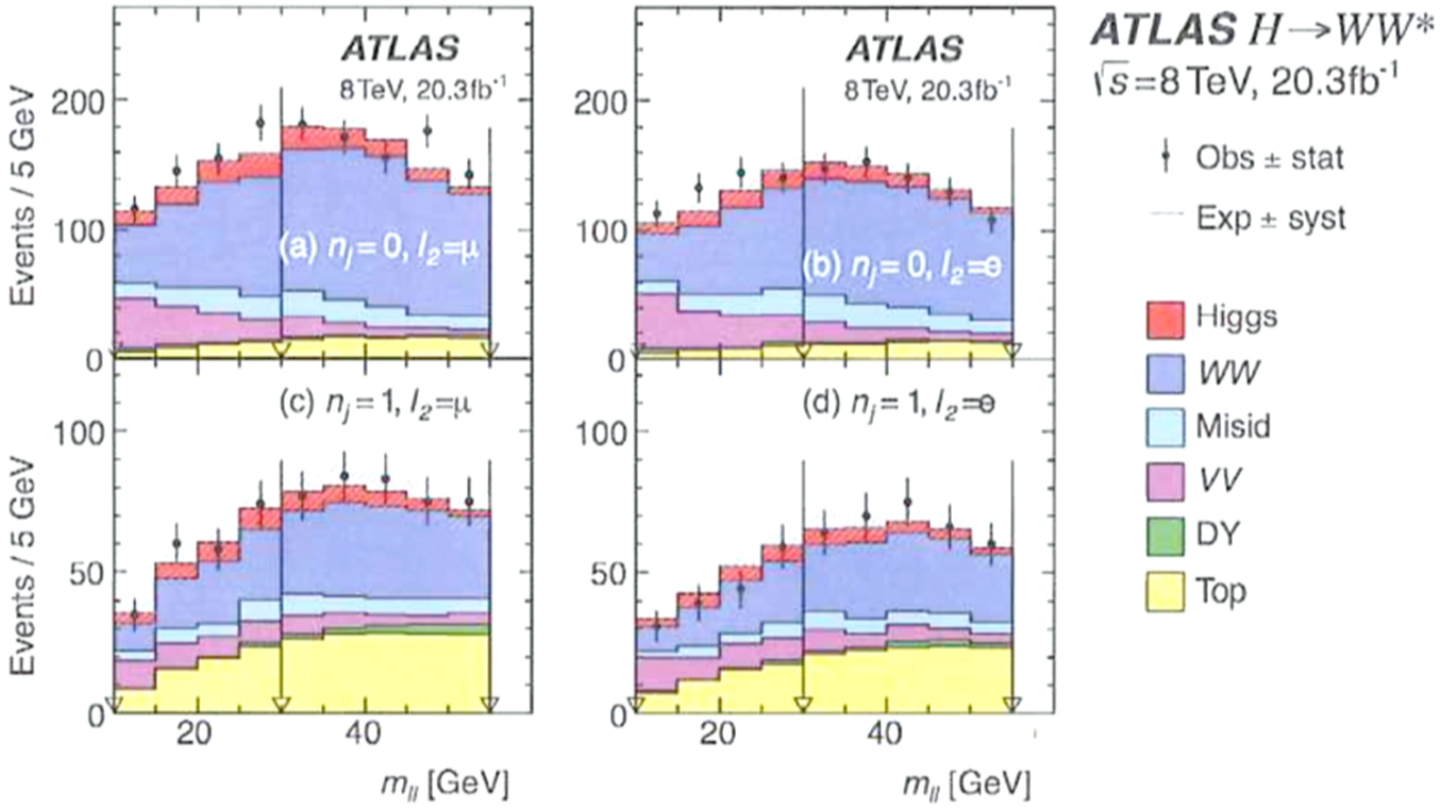
$$h^0 \to Z^0 Z^0 \to \mu^+ \mu^- e^+ e^-$$

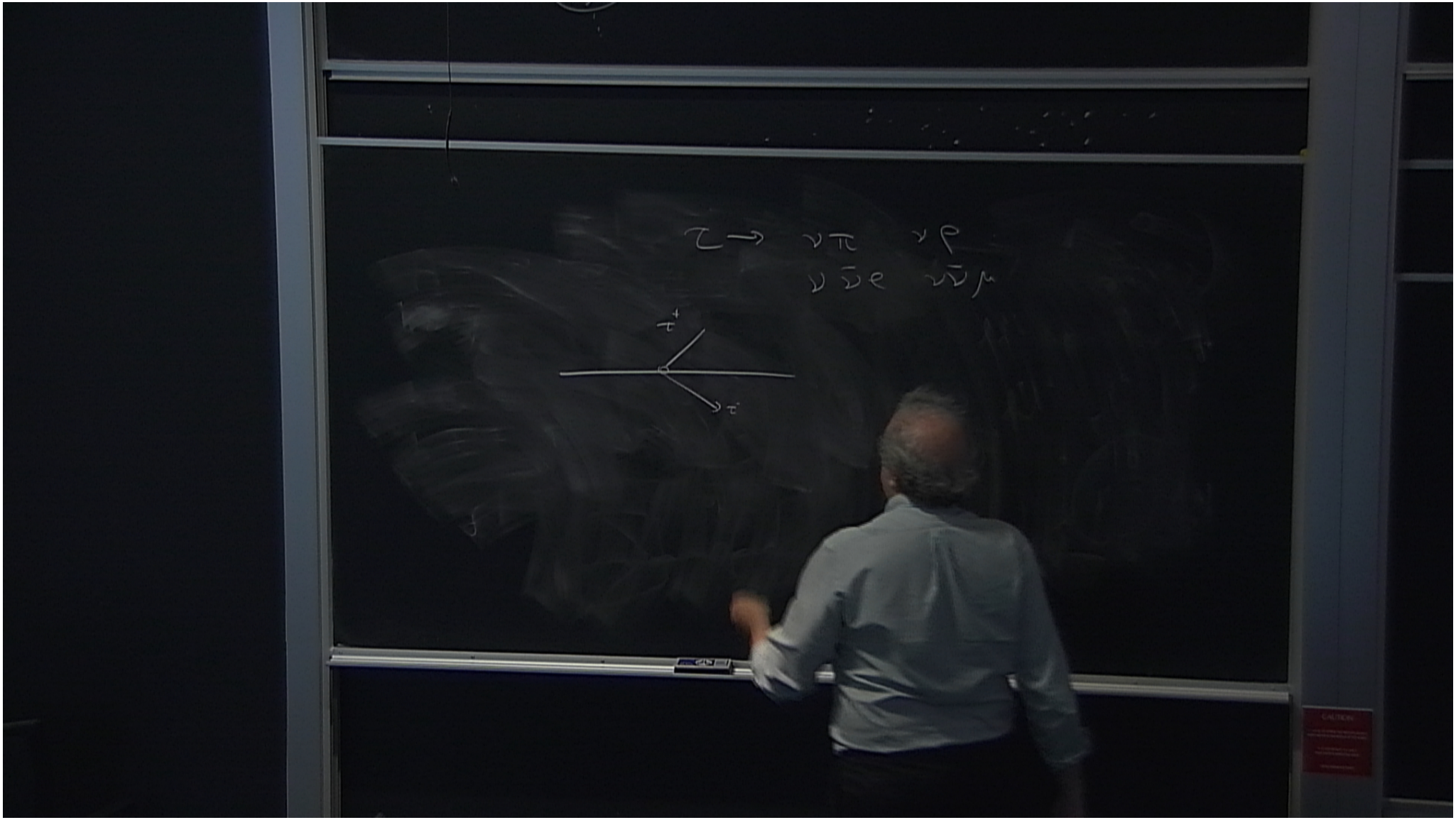


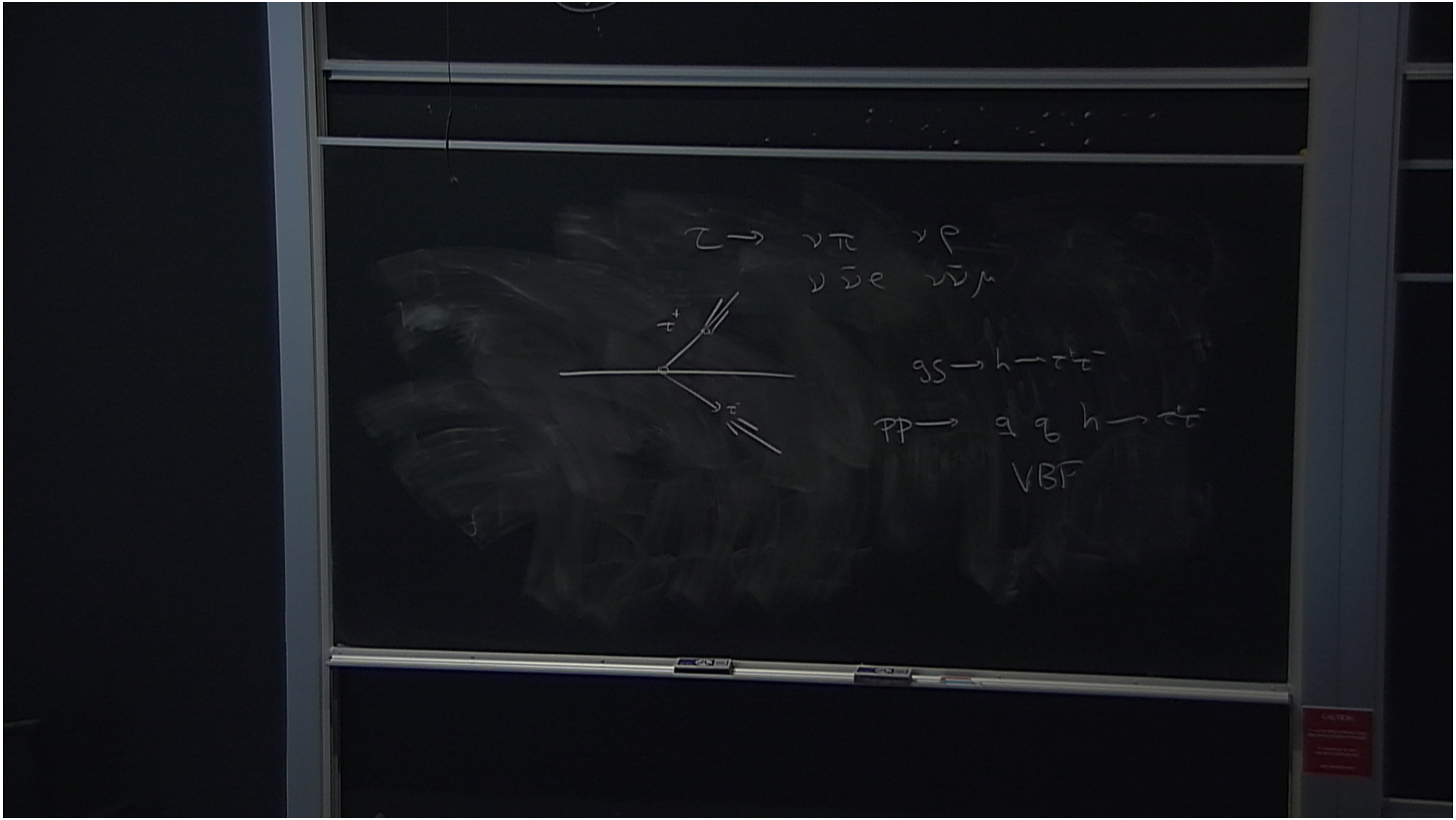


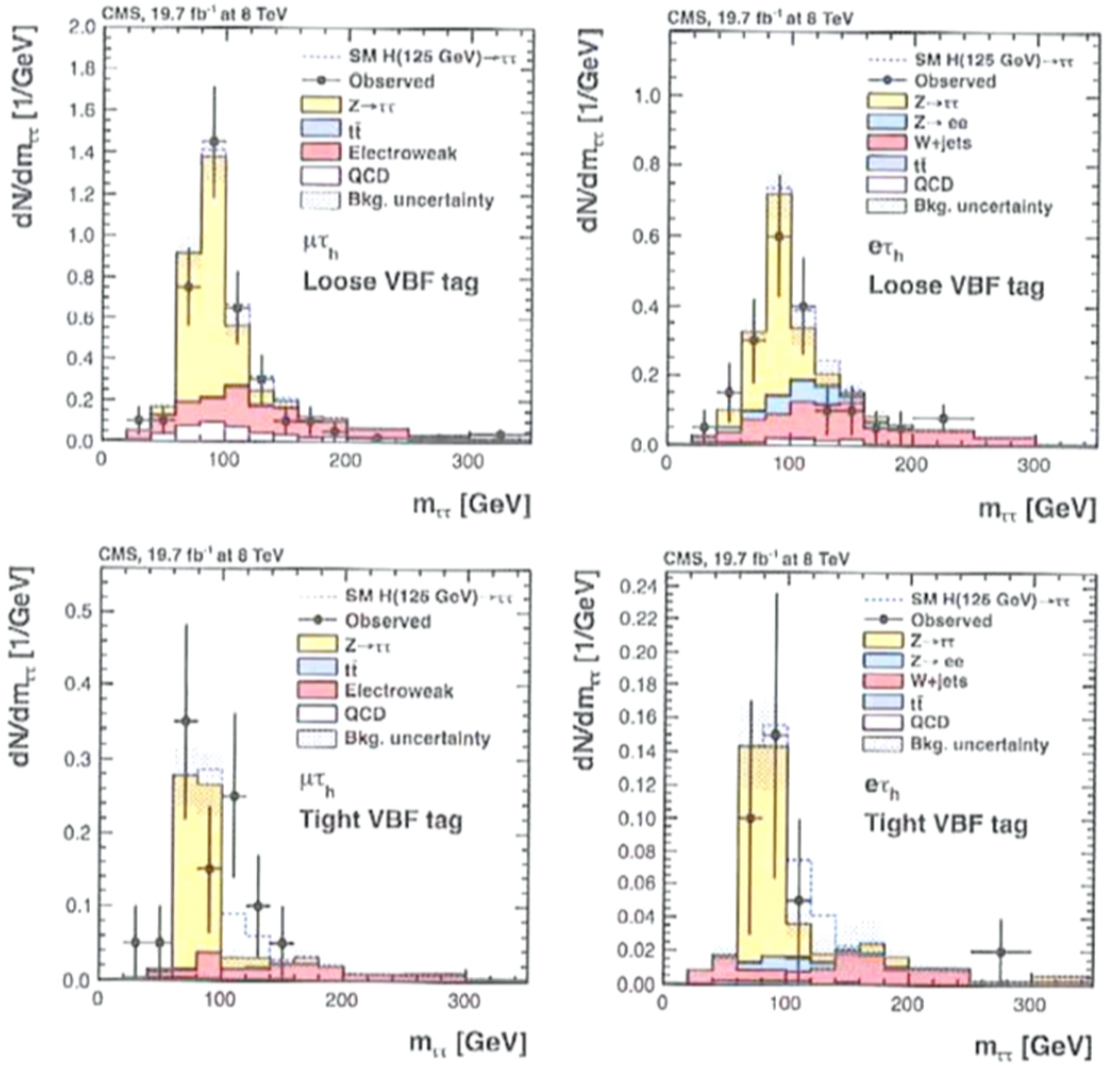

scale to BR(t→bb) = 58%
b
63%
c
3%
s
0.03%
u
0.02%
WW → l⁺ν l⁻ν̄
m_H=124.3 GeV (fit)
Background Z, ZZ*
Background Z+jets, tt̄
Syst.Unc.
√s = 7 Te
√s = 8 Te
Events
35
30
25
20
15
10
5
0
100
150
200

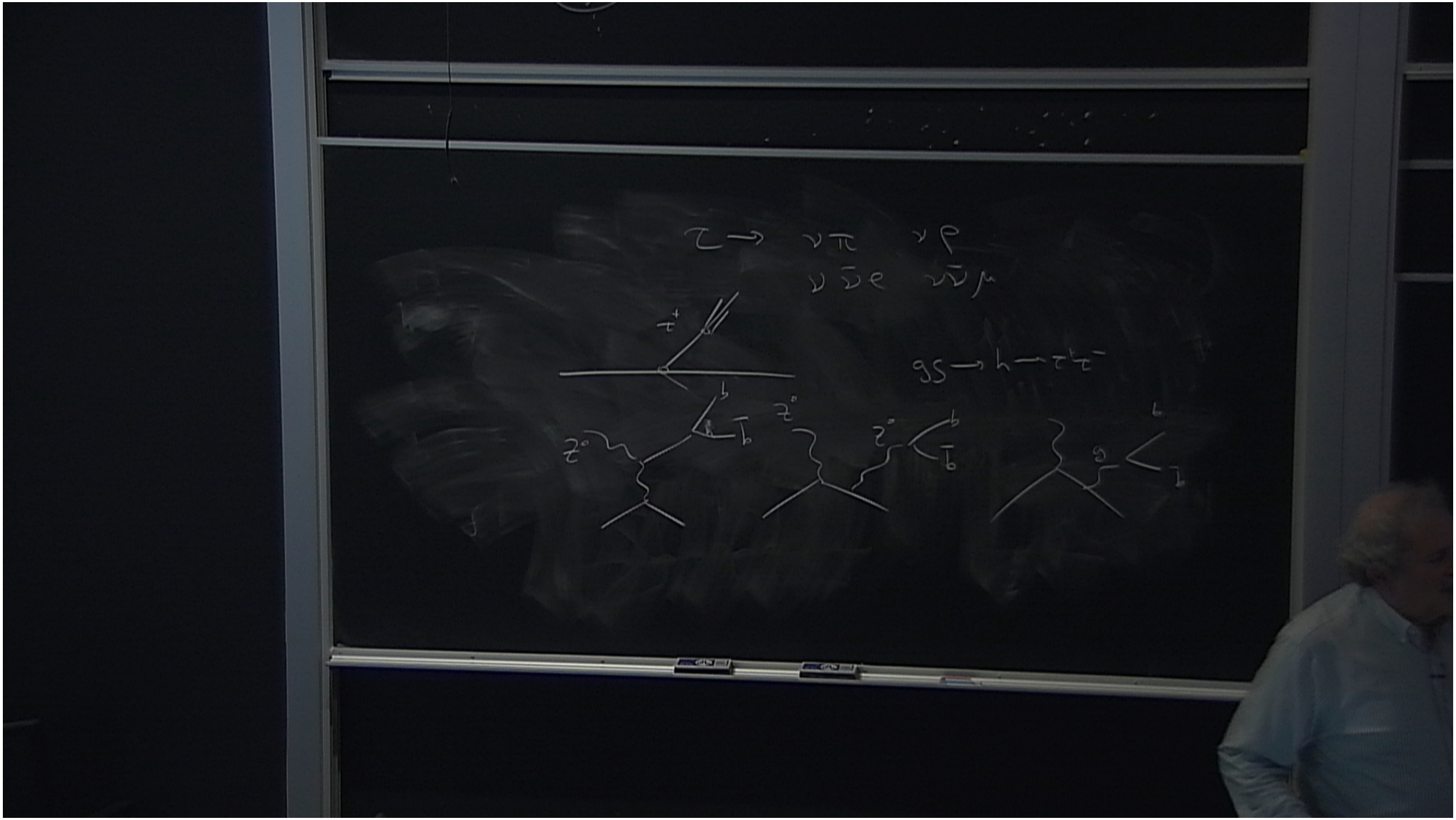

Events
35
30
25
20
15
10
5
0
100
150
200
m_H=124.3 GeV (fit)
Background Z, ZZ*
Background Z+jets, t
Syst.Unc.
$\sqrt{s}$ = 7 Te
$\sqrt{s}$ = 8 Te
scale to $3Z(h \to b\bar{b}) = 58\%$
τ 6.3%
c 3%
s 0.03%
λ 0.02%
$h \to WW \to l^+\nu\, l^-\bar{\nu}$
$q\bar{q} \to W^+W^-$

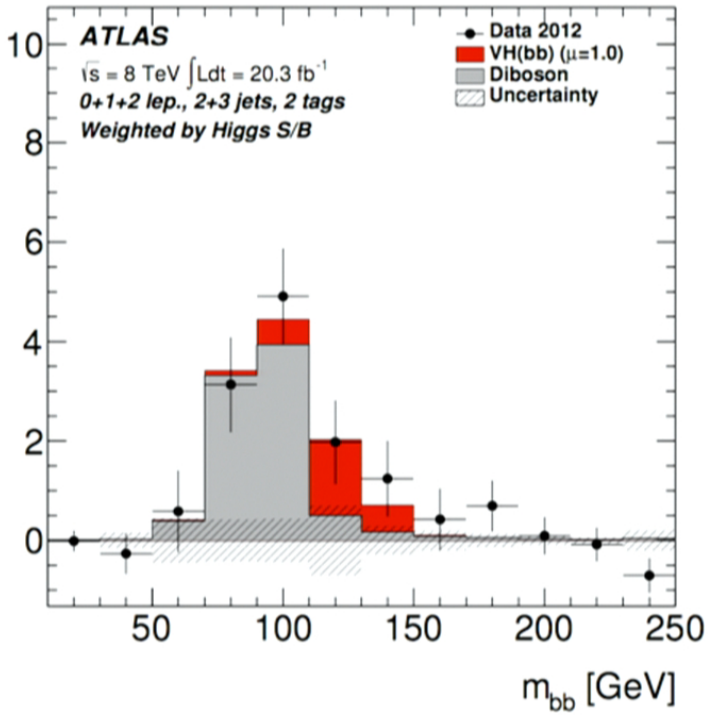

ATLAS
8 TeV, 20.3fb-1
(a) nj = 0, l2 = μ
(b) nj = 0, l2 = e
(c) nj = 1, l2 = μ
(d) nj = 1, l2 = e
Events / 5 GeV
mll [GeV]
ATLAS H → WW*
√s = 8 TeV, 20.3fb-1
Obs ± stat
Exp ± syst
Higgs
WW
Misid
VV
DY
Top

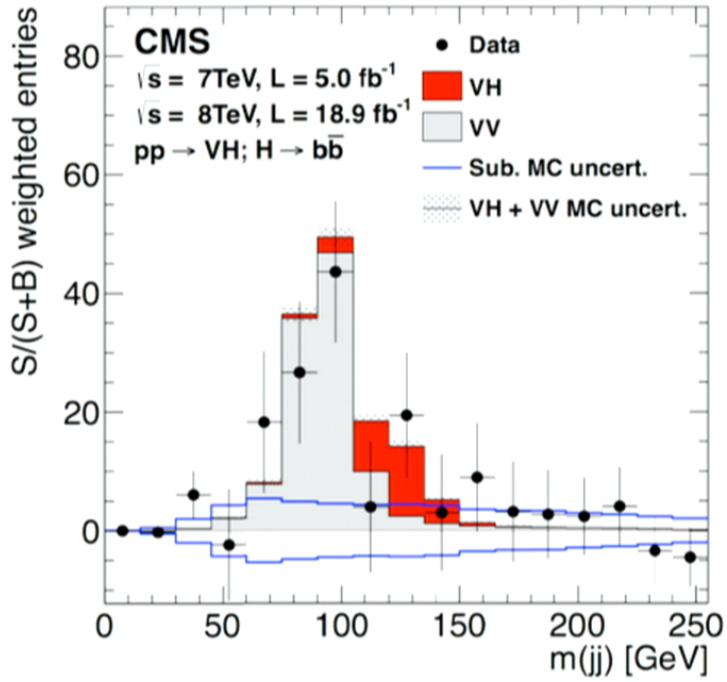

τ → ν π ν
ν e ν μ
τ⁺
τ⁻

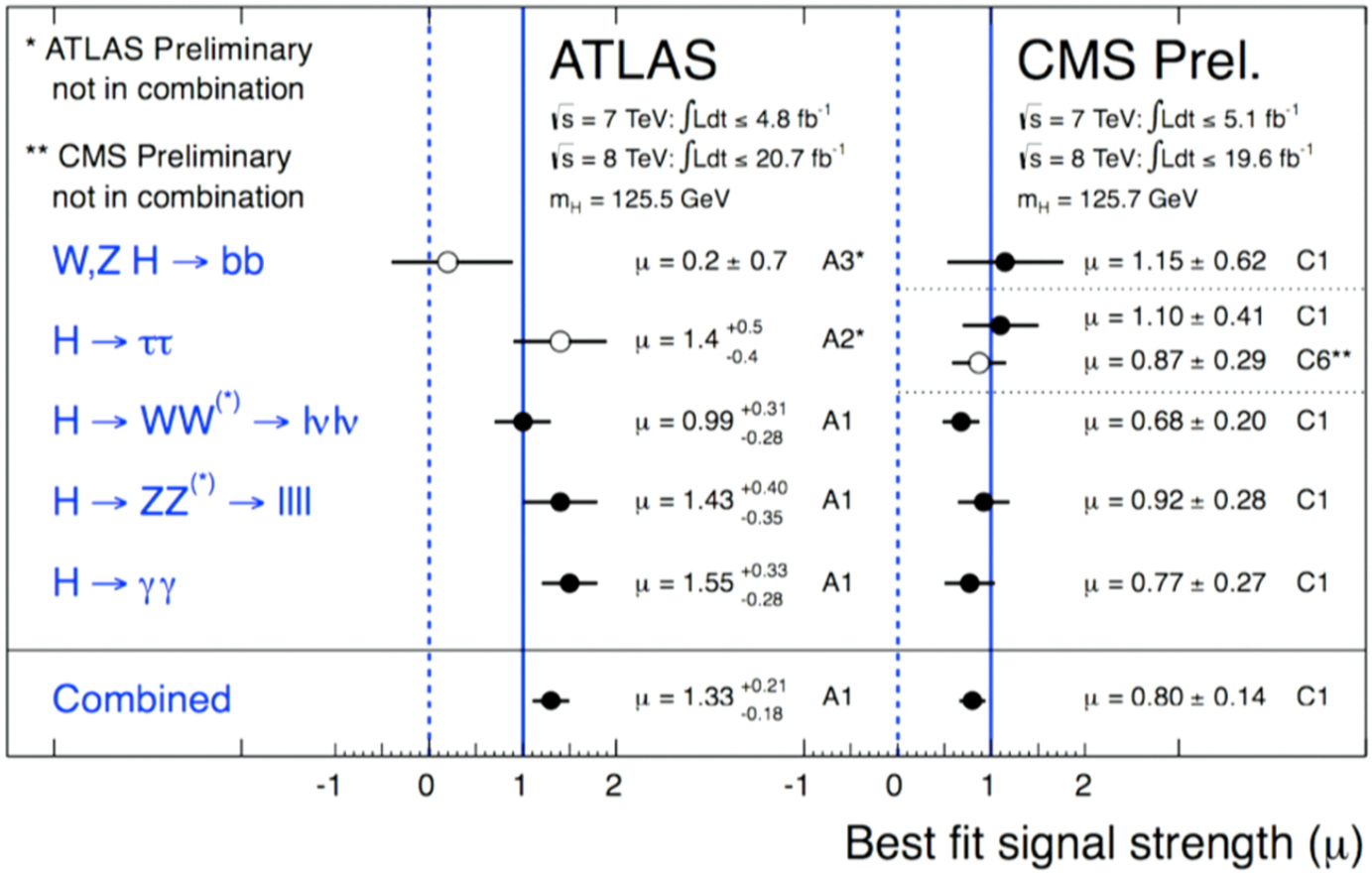

τ → ν π ν ρ
ν ν̄e ν ν̄μ
τ⁺
τ⁻
gg → h → ττ
pp → q q h → ττ
VBF


CMS, 19.7 fb⁻¹ at 8 TeV
SM H(125 GeV)→ττ
Observed
Z→ττ
tt̄
Electroweak
QCD
Bkg. uncertainty
μτh
Loose VBF tag
dN/dmττ [1/GeV]
mττ [GeV]
CMS, 19.7 fb⁻¹ at 8 TeV
SM H(125 GeV)→ττ
Observed
Z→ττ
Z→ ee
W+jets
tt̄
QCD
Bkg. uncertainty
eτh
Loose VBF tag
dN/dmττ [1/GeV]
mττ [GeV]
CMS, 19.7 fb⁻¹ at 8 TeV
SM H(125 GeV)→ττ
Observed
Z→ττ
tt̄
Electroweak
QCD
Bkg. uncertainty
μτh
Tight VBF tag
dN/dmττ [1/GeV]
mττ [GeV]
CMS, 19.7 fb⁻¹ at 8 TeV
SM H(125 GeV)→ττ
Observed
Z→ττ
Z→ ee
W+jets
tt̄
QCD
Bkg. uncertainty
eτh
Tight VBF tag
dN/dmττ [1/GeV]
mττ [GeV]

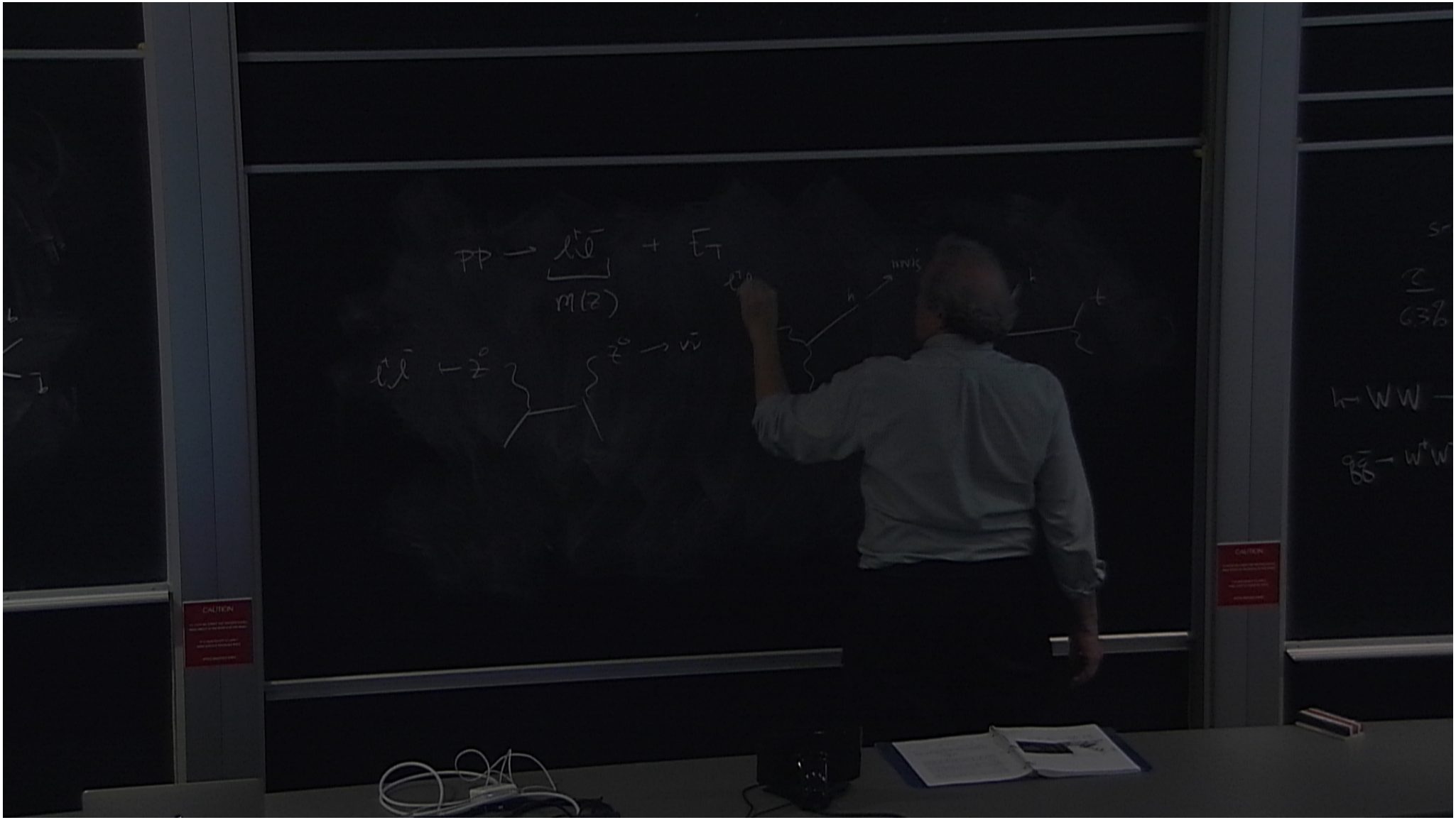

τ → ντ π ντ ρ
νν̄e νν̄μ
gg → h → ττ̄
τ+
b
b̄
Z0
Z0
Z0
b
b̄
b
b̄

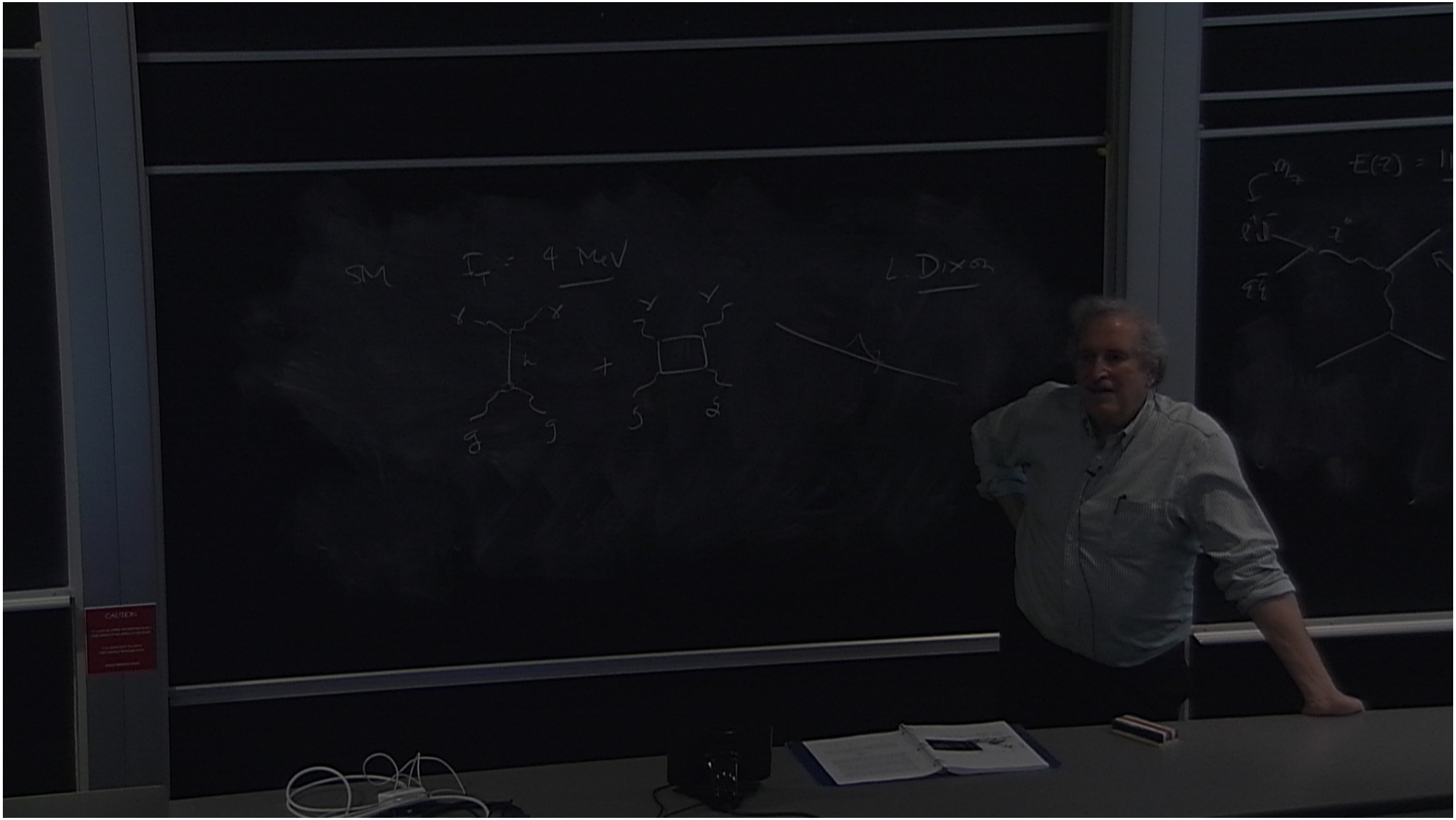

ATLAS
√s = 8 TeV ∫Ldt = 20.3 fb-1
0+1+2 lep., 2+3 jets, 2 tags
Weighted by Higgs S/B
Data 2012
VH(bb) (μ=1.0)
Diboson
Uncertainty
m_bb [GeV]


CMS
√s = 7TeV, L = 5.0 fb-1
√s = 8TeV, L = 18.9 fb-1
pp → VH; H → bb̄
Data
VH
VV
Sub. MC uncert.
VH + VV MC uncert.
S/(S+B) weighted entries
m(jj) [GeV]



PDG summary 2014


pp → ll̄ + E_T
M(Z)
ll̄ → Z⁰
Z⁰ → νν̄
h → WW
qq̄ → W⁺W⁻


SM
$E_T = 4$ MeV
L. Dixon