Title: Beyond the Standard Model Physics and the LHC (Lecture 1)

Date: Mar 29, 2010 11:00 AM

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Abstract: These three lectures cover several ideas of physics beyond the Standard Model. My focus is on ideas that give a natural stabilization solution to the electroweak scale, which is mysteriously light compared to the gravitational Planck scale. These ideas include supersymmetric field theories, extra dimensions, and Higgs boson physics. I shall describe what I think are the "best bets" among these approaches, and more importantly the ways they can be discerned by experiment. Special emphasis will be on theories that can be confirmed at the Large Hadron Collider (LHC) that is just now starting.

SM Higgs

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\, G^{+} \\ v + h + i G^{0} \end{pmatrix}$$

SU(2) doublet $Y = 1/2$.

$$G^{0}, G^{\pm} \longrightarrow Z^{0}_{L}, W^{\pm}_{L}$$

$$v = 246 \text{ GeV}$$

$$D_\mu \Phi = \Big(\partial_\mu + i g \underbrace{\frac{\tau^a}{2} W^a_\mu}_{\text{SU(2) bosons}} + i g' \underbrace{\frac{Y}{2} B_\mu}_{\text{hypercharge boson}}\Big) \Phi$$

$$\langle |D_\mu \Phi|^2 \rangle \longrightarrow \mathcal{L}_{bos} = \left(m_W^2 W^{+}_{\mu} W^{-\mu} + \frac{m_Z^2}{2} Z_\mu Z^\mu \right) \times \left(1 + \frac{h}{v}\right)^2$$

where $m_W^2 = \frac{1}{2} g^2 v^2$, $m_Z^2 = \frac{1}{4}(g^2 + g'^2) v^2$

Fermions

$$\Delta \mathcal{L} = y_b Q^\dagger \Phi b_R + \text{c.c.}$$

$$\Longrightarrow m_b \left(b_L^\dagger b_R + \text{c.c.}\right)\left(1 + \frac{h}{v}\right) \text{ where } m_b = \frac{y_b v}{\sqrt{2}}$$

SM Higgs

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\, G^{\pm} \\ v + h + i G^0 \end{pmatrix}$$

$D_\mu \Phi$

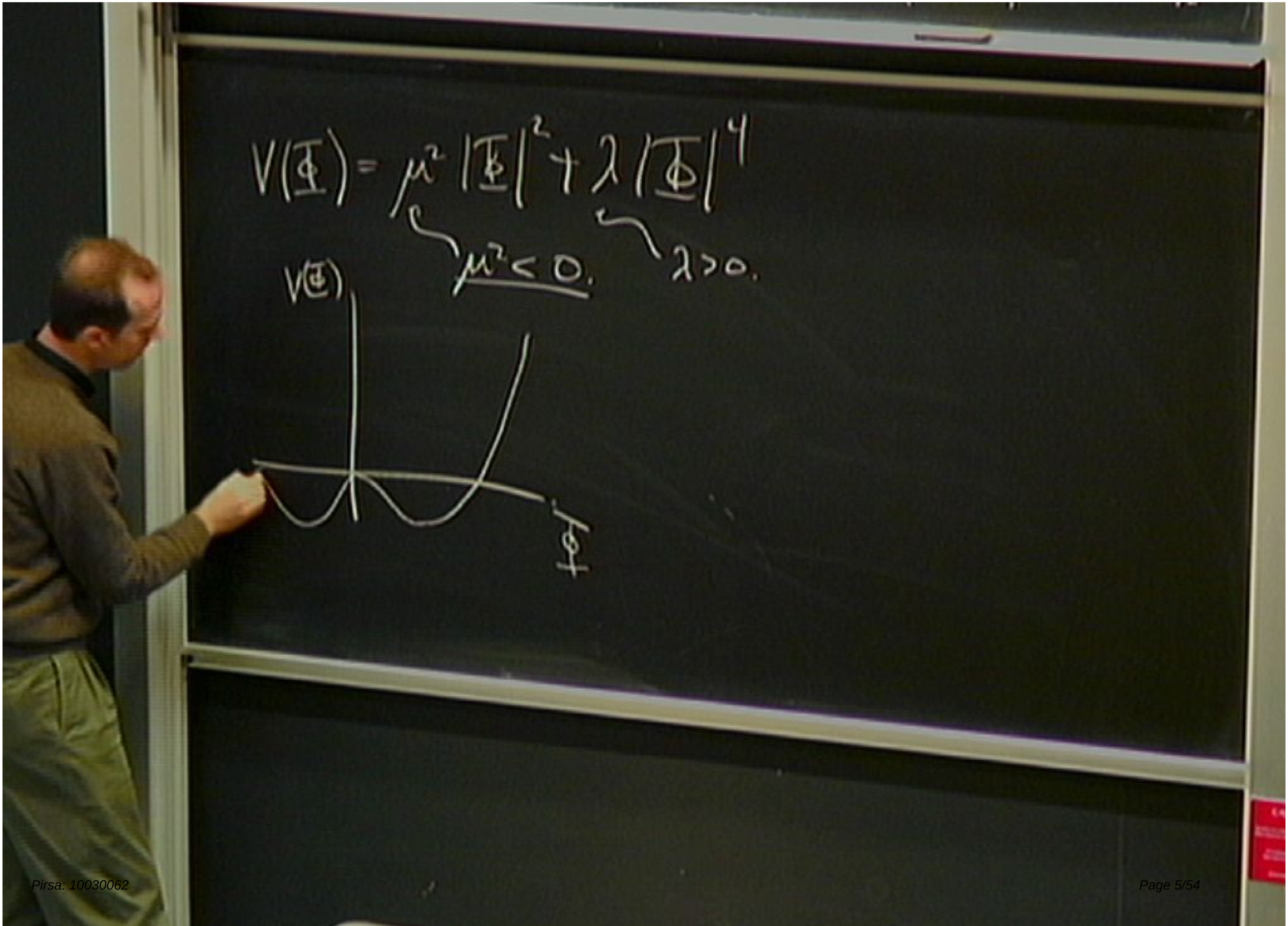
$\langle |D_\mu \Phi|^2 \rangle$

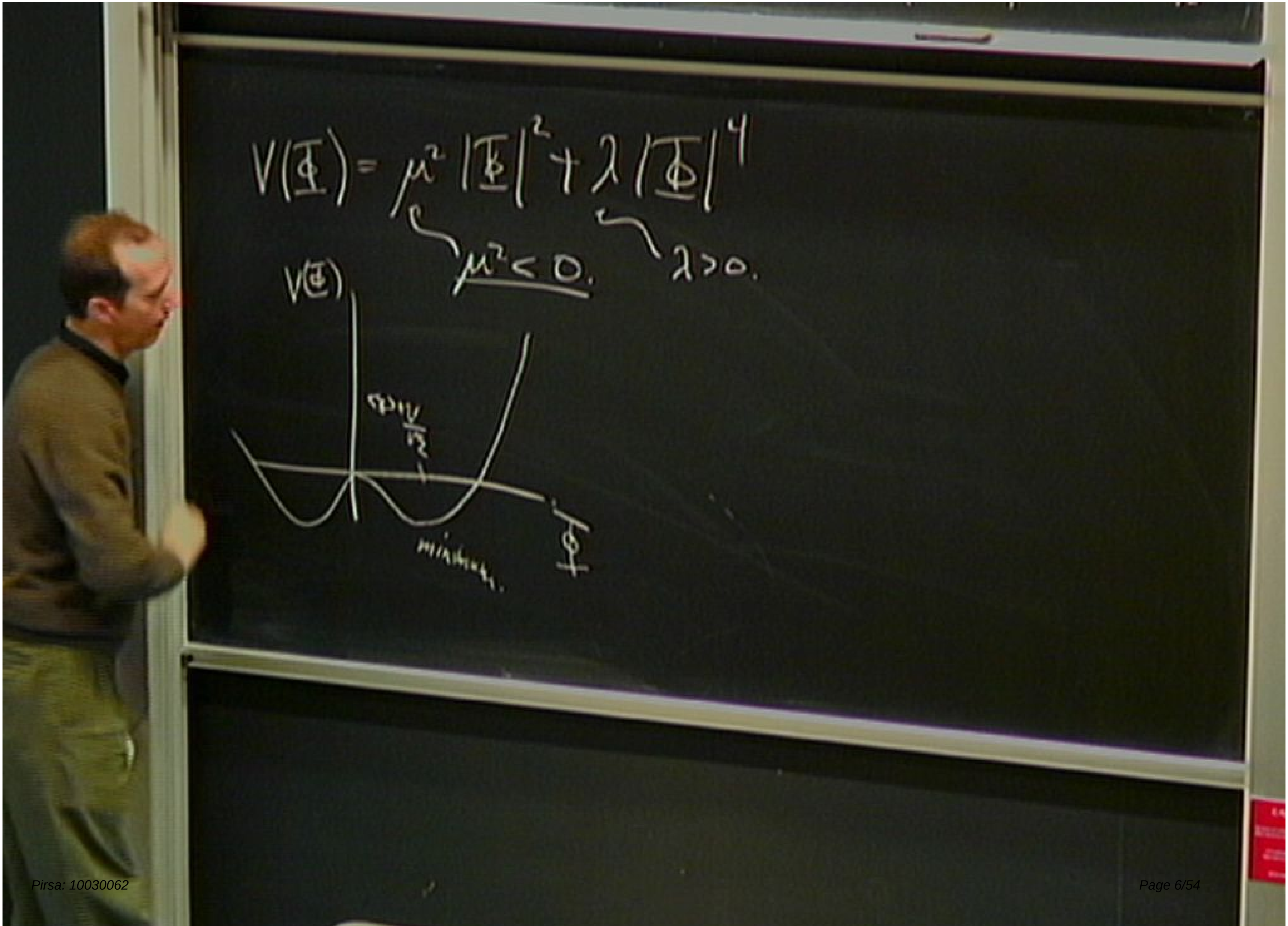
SU(2) doublet $Y = 1/2$.

$G^0, G^{\pm} \to Z^0, W^{\pm}$

$$V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4$$

$$\mu^2 < 0.$$

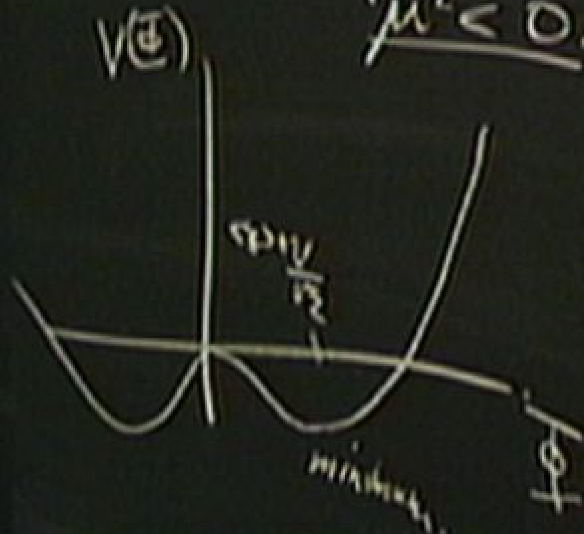

$V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4$
$\mu^2 < 0.$
$\lambda > 0.$
$V(\Phi)$
Φ



$V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4$
$\mu^2 < 0.$
$\lambda > 0.$
$V(\Phi)$
$\frac{v}{\sqrt{2}}$
minimum.
Φ

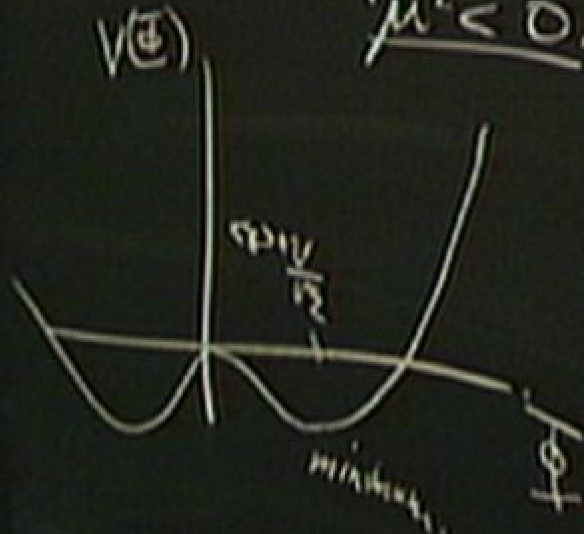
$$V(\Phi) = \underbrace{\mu^2}_{\mu^2 < 0} |\Phi|^2 + \underbrace{\lambda}_{\lambda > 0} |\Phi|^4 \qquad v = \sqrt{\frac{-\mu^2}{\lambda}} = 246 \text{ GeV.}$$

$$m_h^2 = 2\lambda v^2$$



$$V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4$$

$\mu^2 < 0$. $\lambda > 0$.



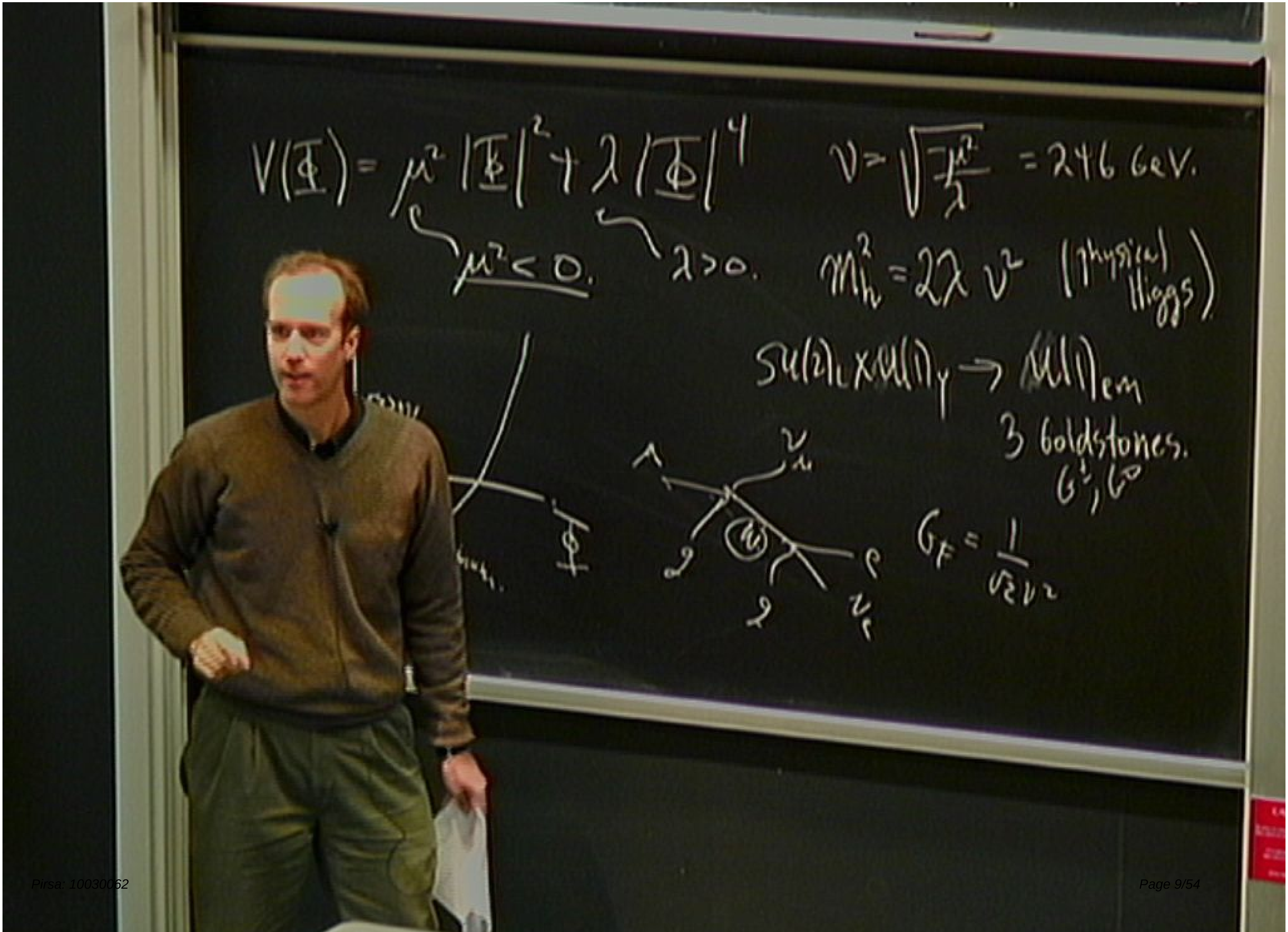
$$v = \sqrt{\frac{-\mu^2}{\lambda}} = 246 \text{ GeV.}$$

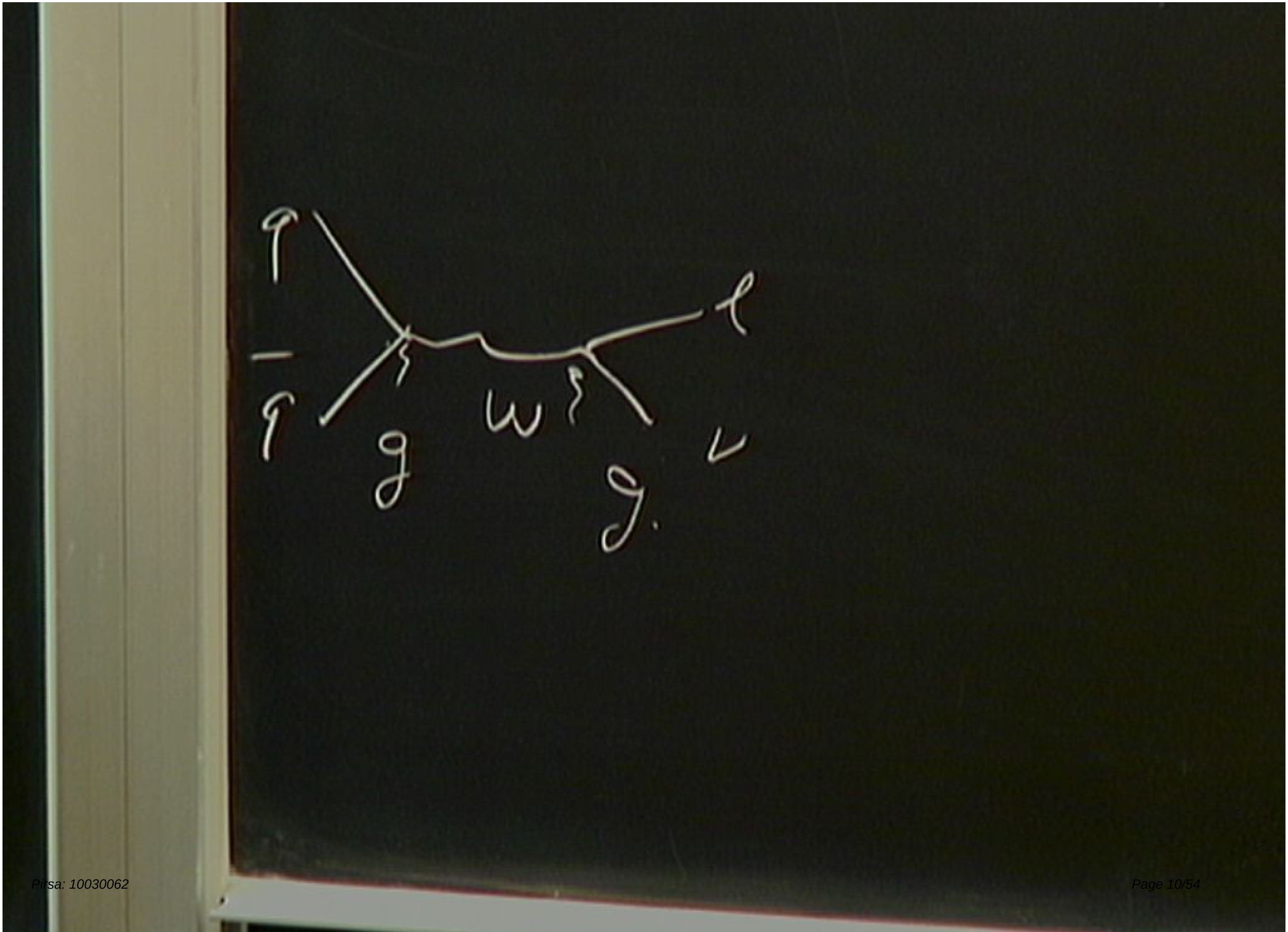
$$m_h^2 = 2\lambda v^2 \quad \text{(physical Higgs)}$$

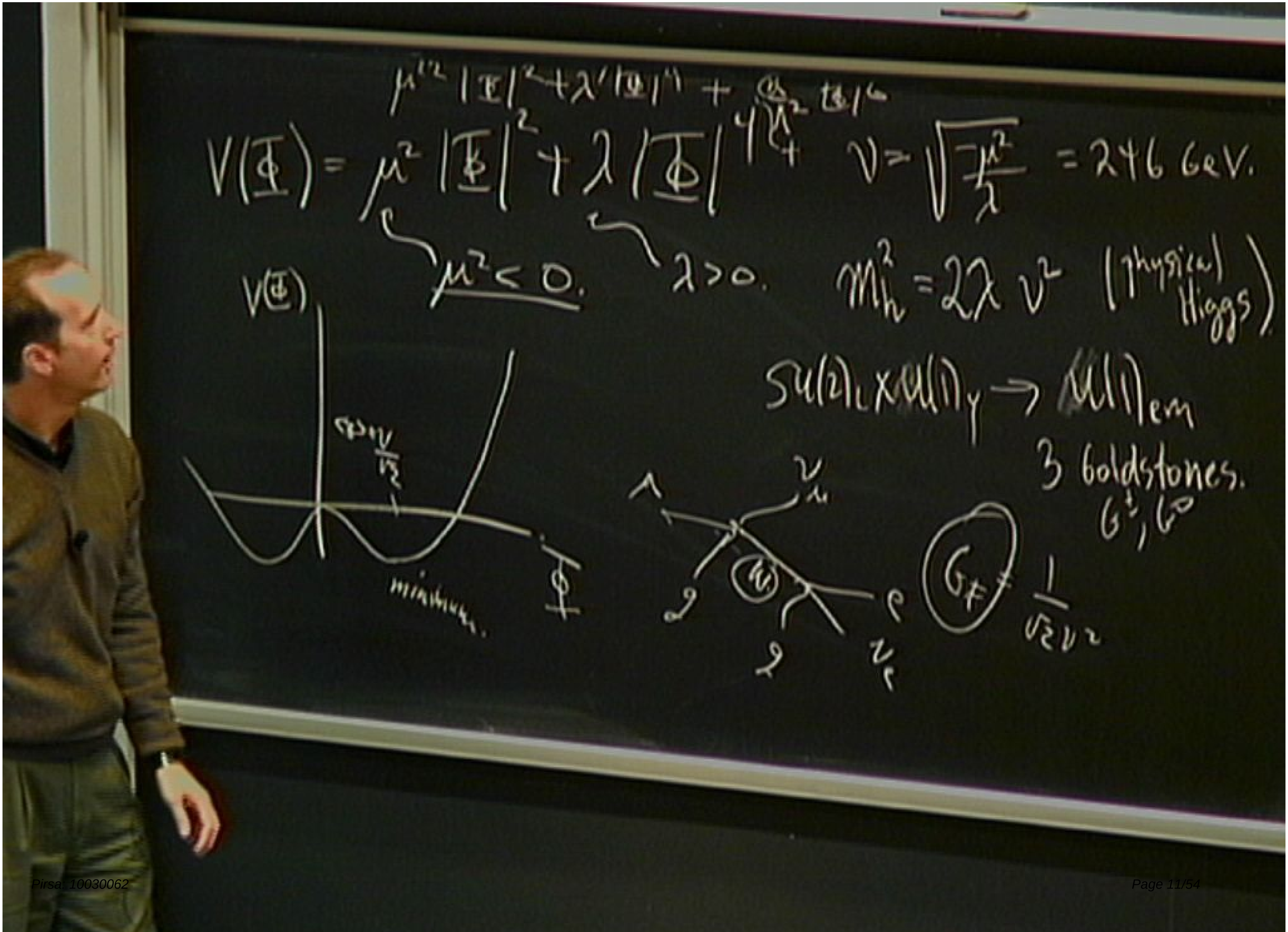
$$SU(2)_L \times U(1)_Y \to U(1)_{em}$$

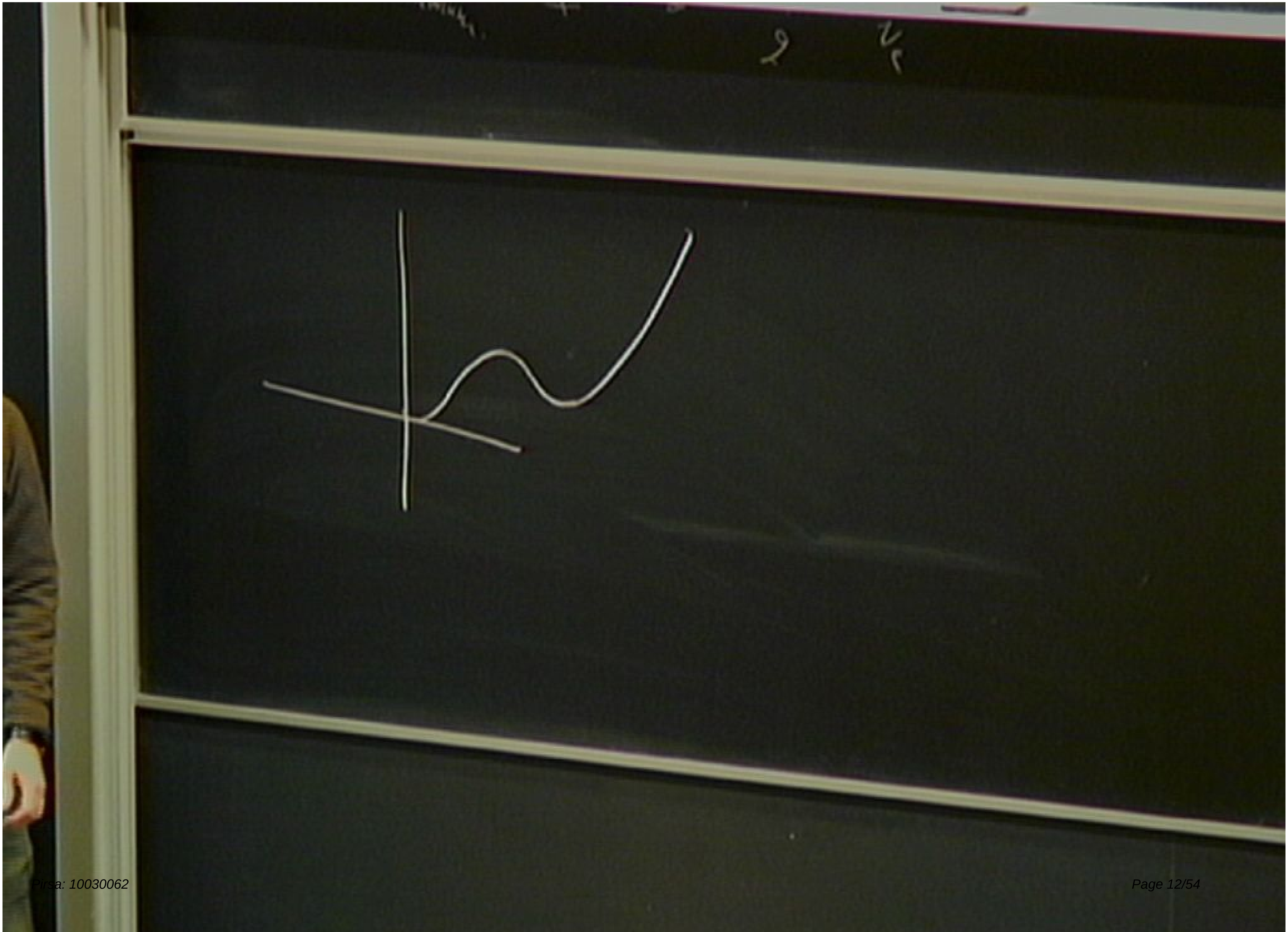
3 Goldstones.

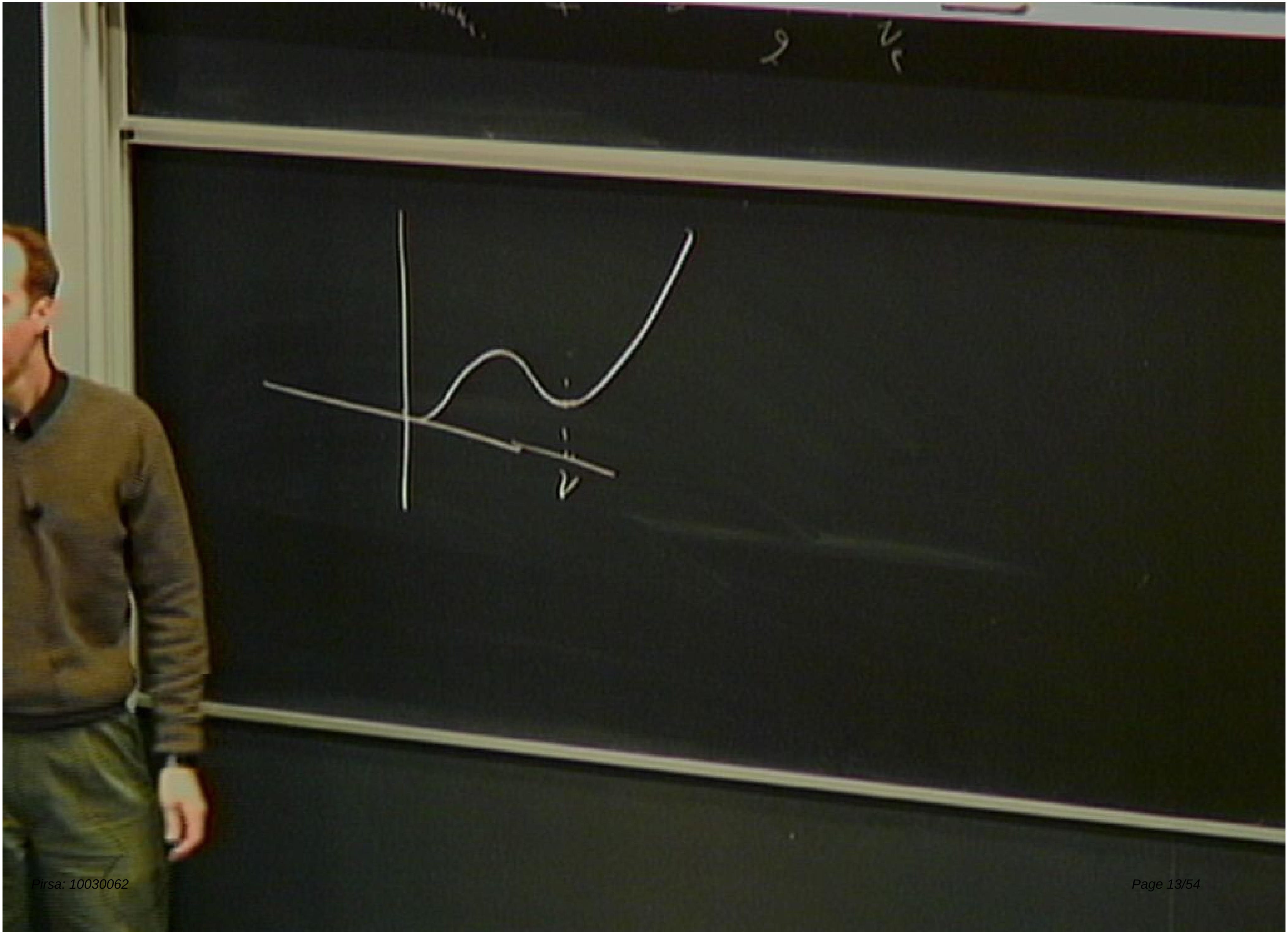
$G^\pm, G^0$

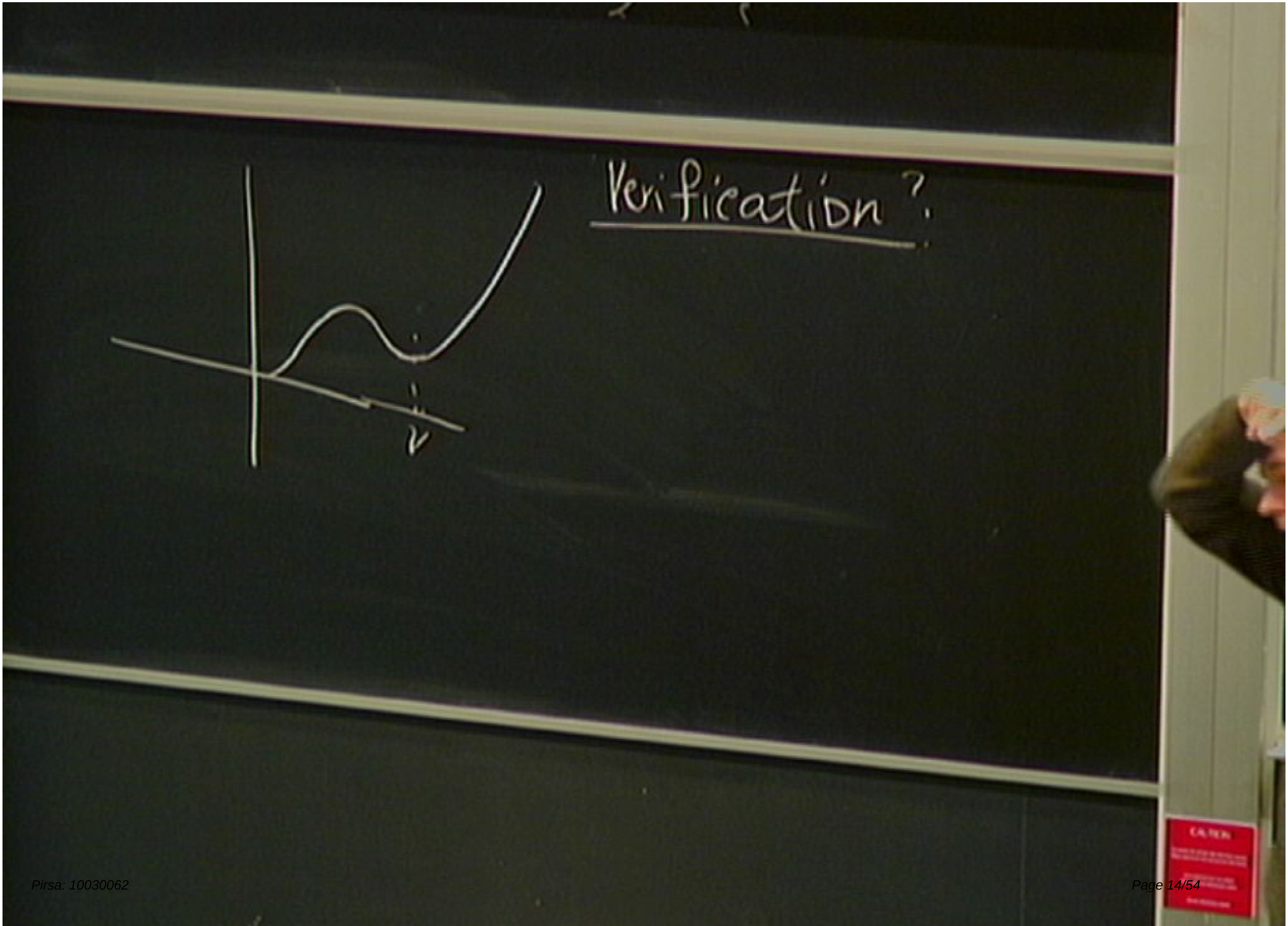

V(Φ) = μ² |Φ|² + λ |Φ|⁴
μ² < 0.
λ > 0.
v = √(−μ²/λ) = 246 GeV.
m_h² = 2λ v² (physical Higgs)
SU(2)_L × U(1)_Y → U(1)_em
3 Goldstones.
G^±, G^0
G_F = 1/(√2 v²)

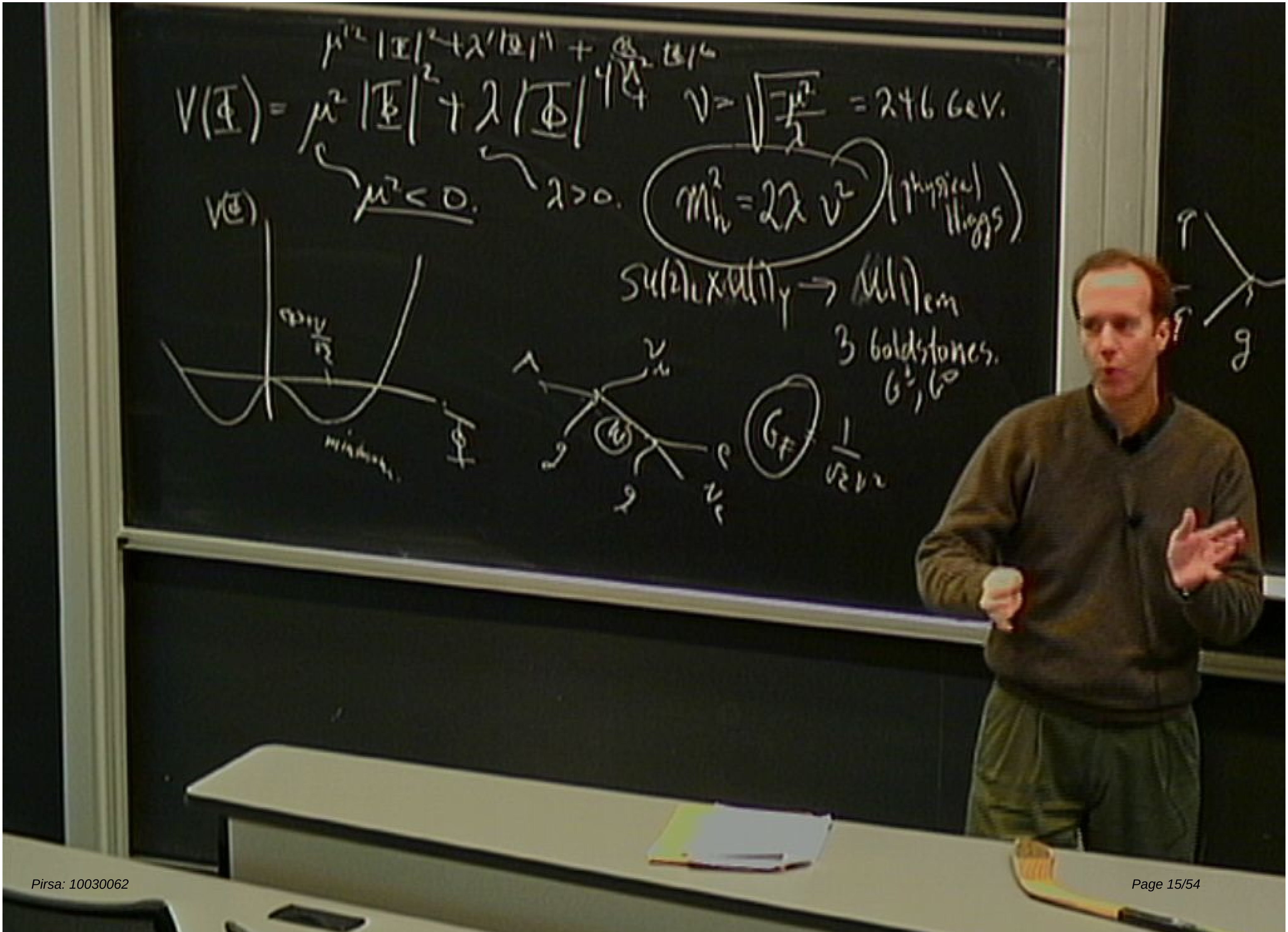

q
q̄
g
W
g
ℓ
ν

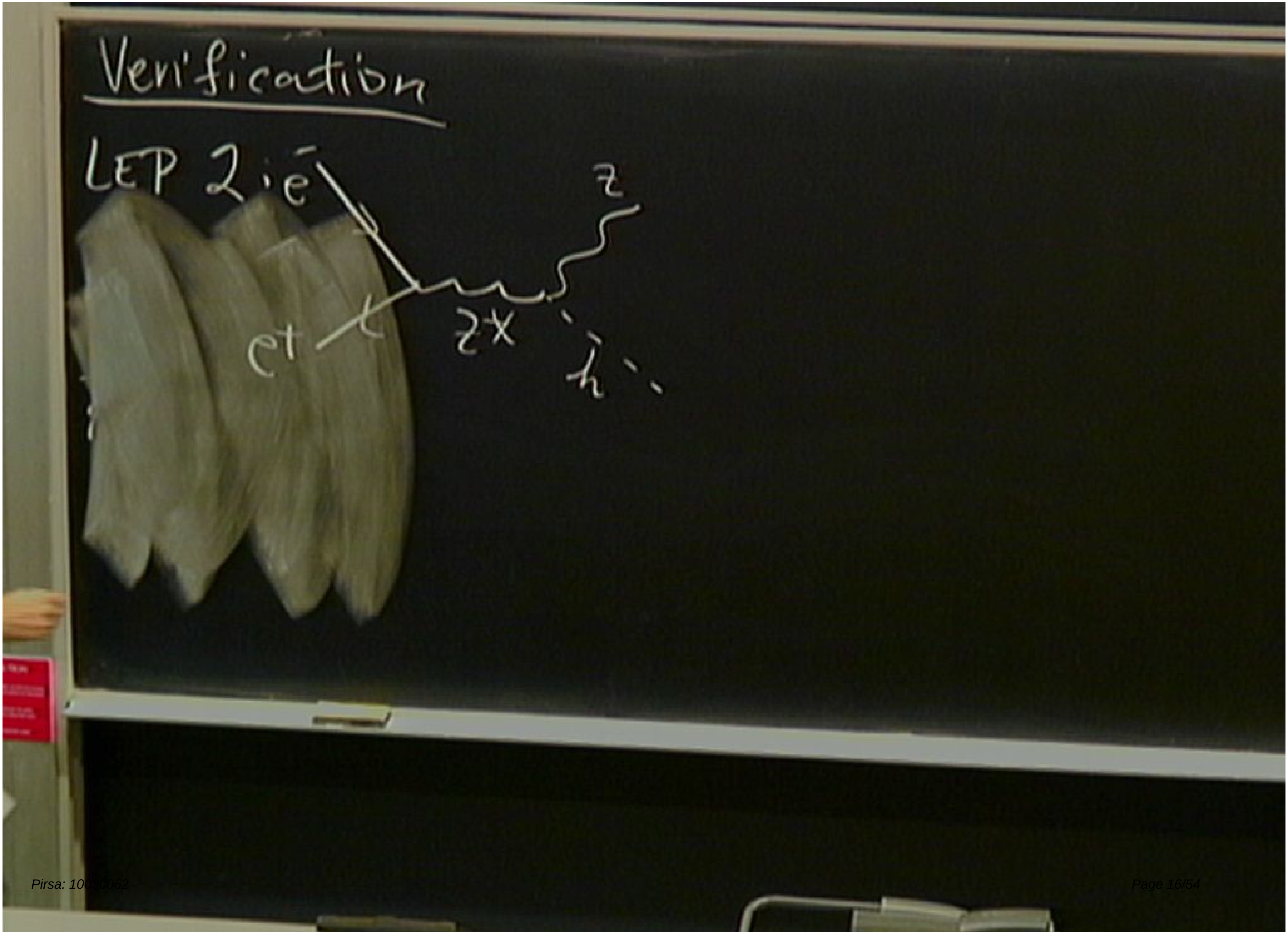

$\mu'^2 |\Phi|^2 + \lambda' |\Phi|^4 + \frac{c_6}{\Lambda^2} |\Phi|^6$
$V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4$
$v = \sqrt{\frac{-\mu^2}{\lambda}} = 246$ GeV.
$\mu^2 < 0.$
$\lambda > 0.$
$m_h^2 = 2\lambda v^2$ (physical Higgs)
$V(\Phi)$
$v/\sqrt{2}$
minimum
Φ
$SU(2)_L \times U(1)_Y \to U(1)_{em}$
3 Goldstones.
$G^{\pm}, G^0$
ν_μ
ν_e
$G_F = \frac{1}{\sqrt{2} v^2}$

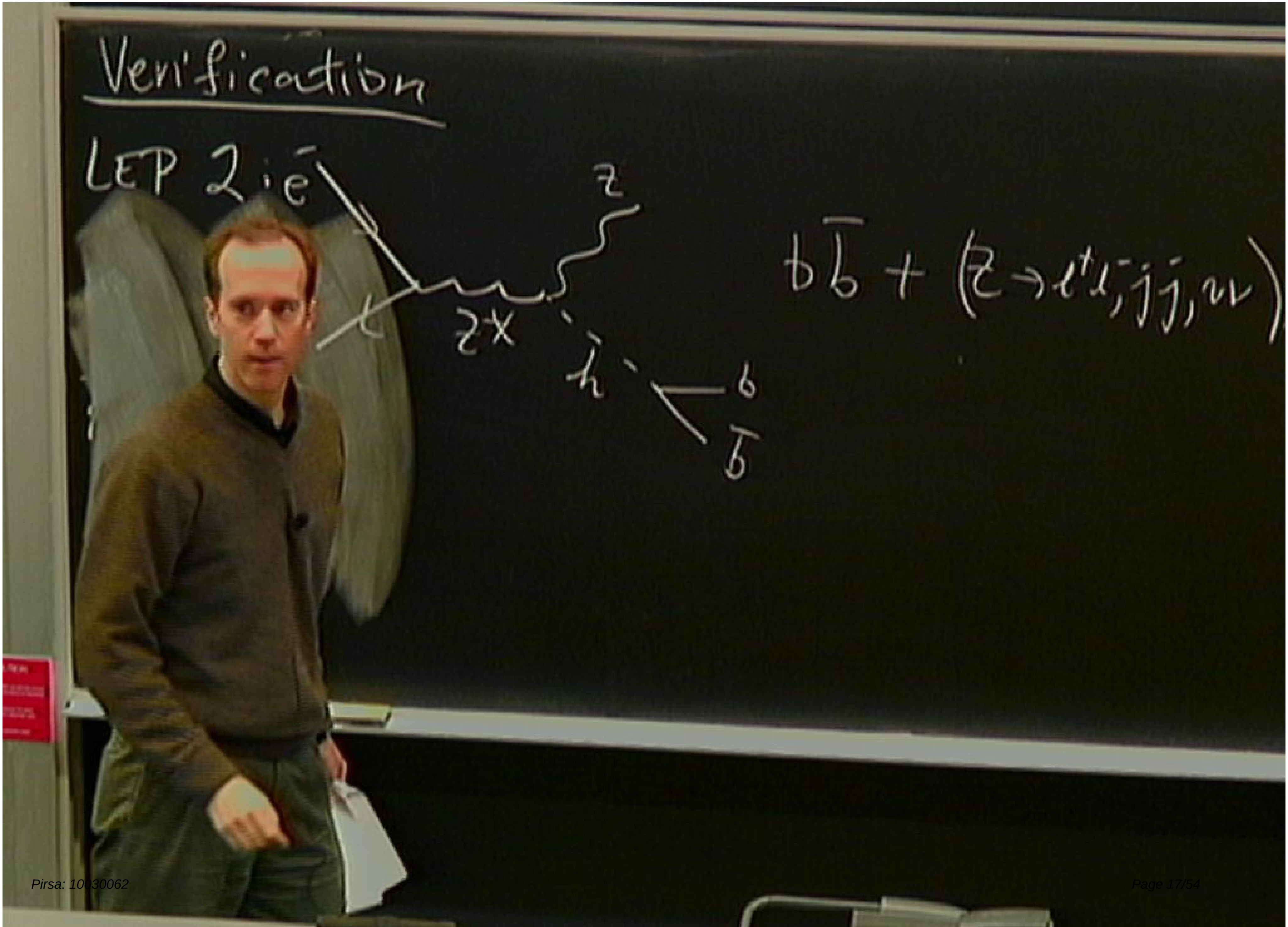


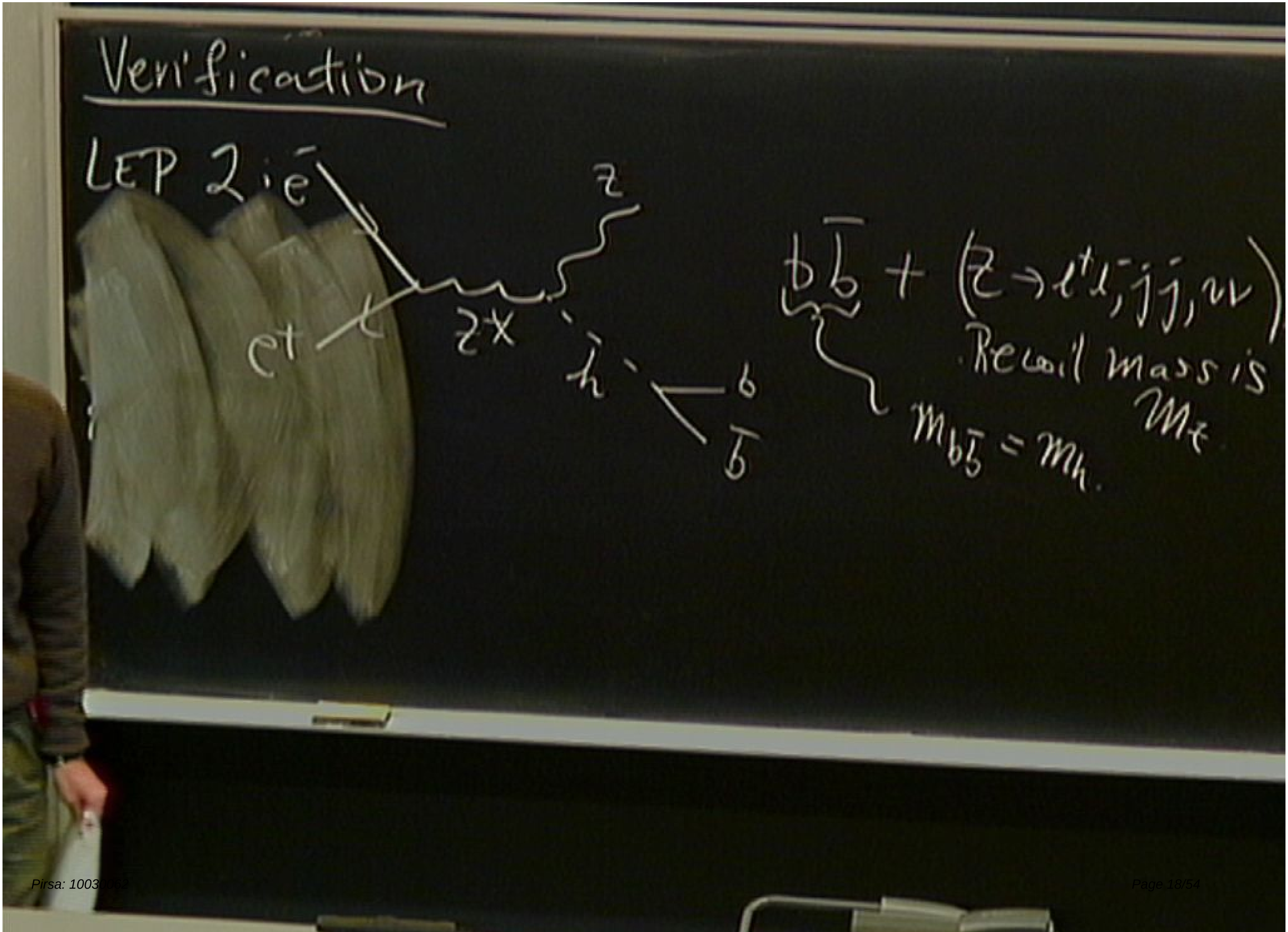

v

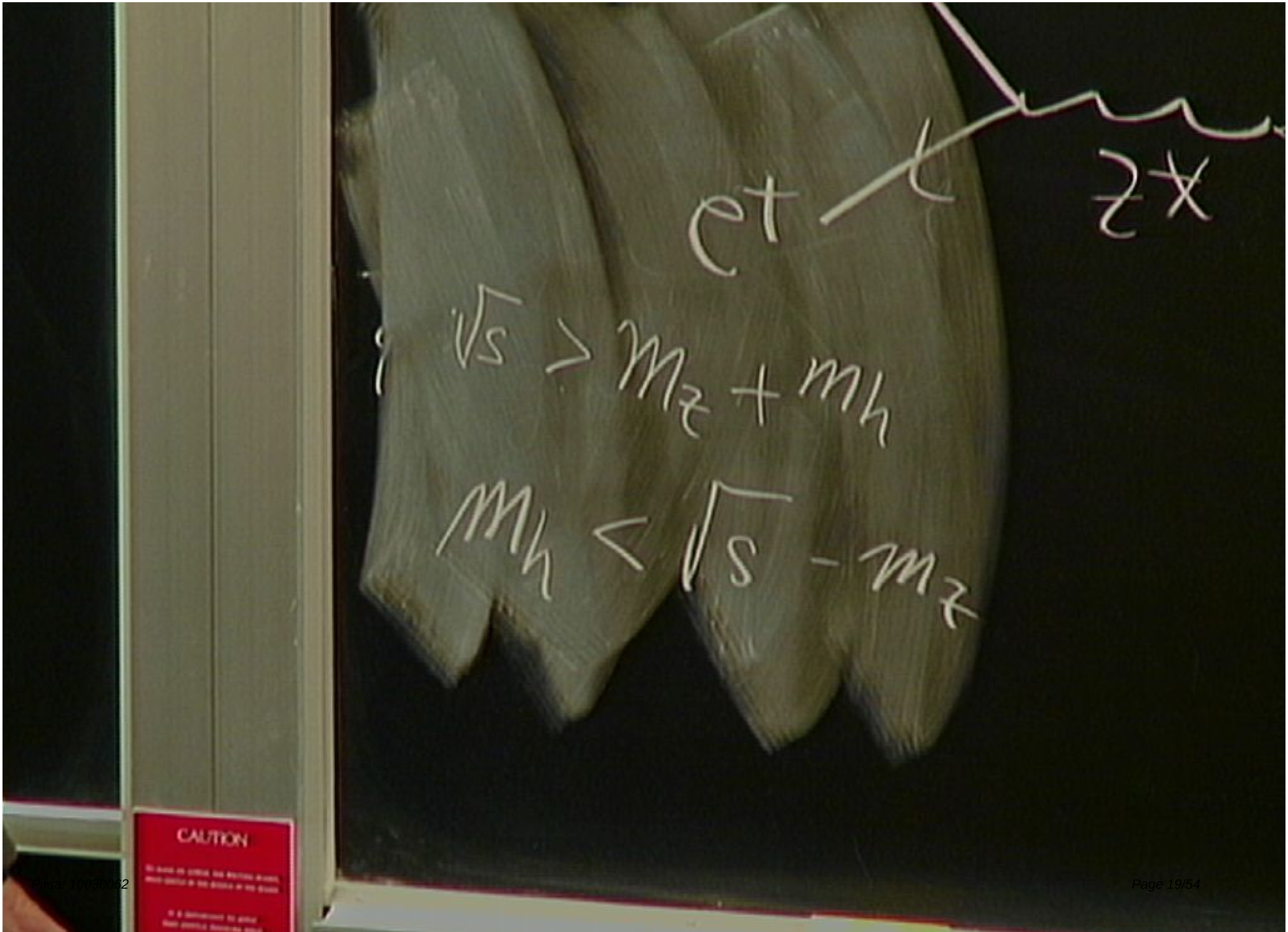

Verification ?
v

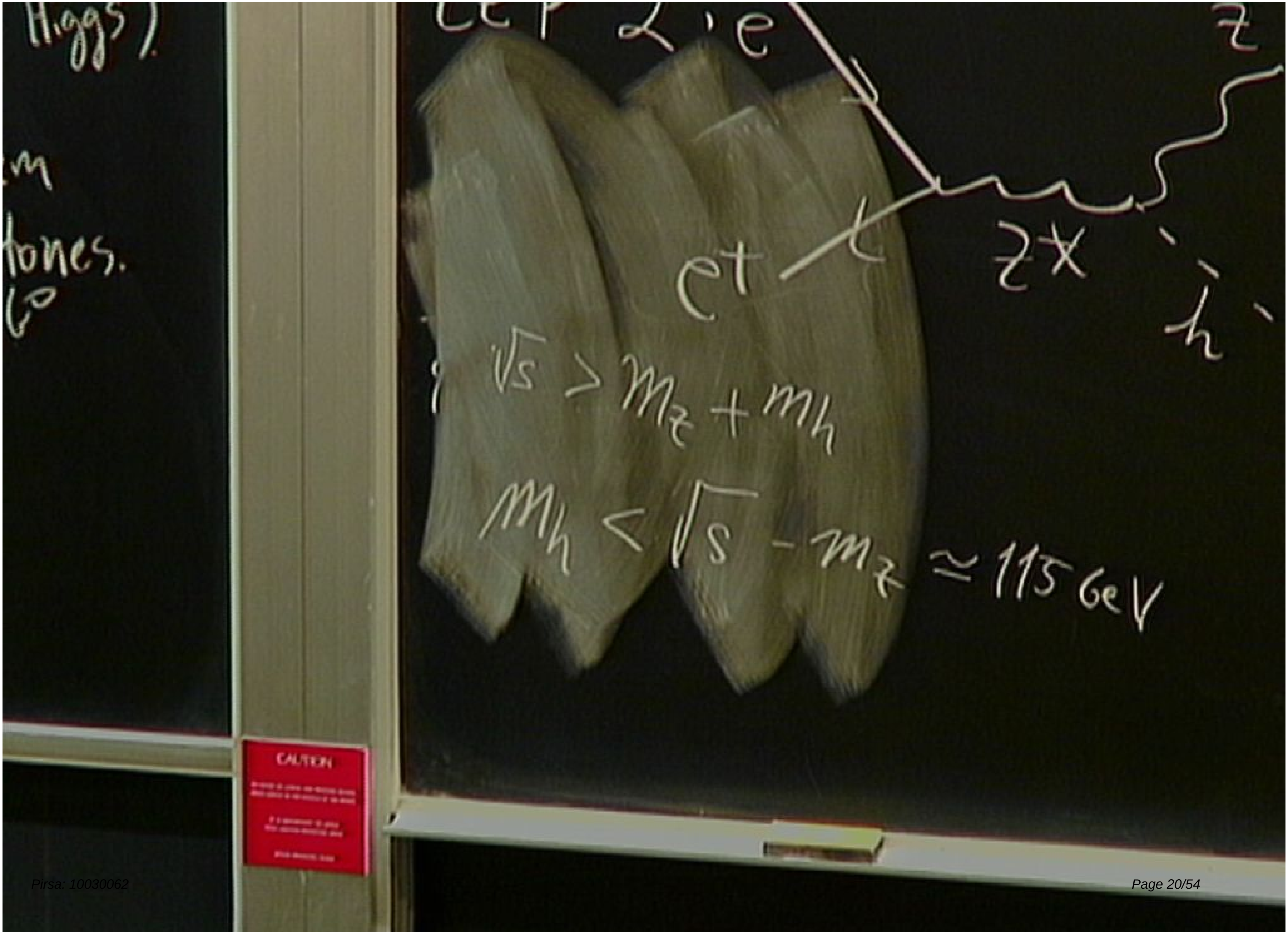

V(Φ) = μ² |Φ|² + λ |Φ|⁴
v = √(−μ²/λ) = 246 GeV.
μ² < 0.
λ > 0.
m_h² = 2λ v²
(physical Higgs)
SU(2)_L × U(1)_Y → U(1)_em
3 Goldstones.
minimum
G_F ~ 1/(√2 v²)


Verification
LEP 2
e⁻
e⁺
Z
Z*
h


Verification
LEP 2 i.e.
Z
Z*
h
b
b̄
bb̄ + (Z → l⁺l⁻, jj, νν)

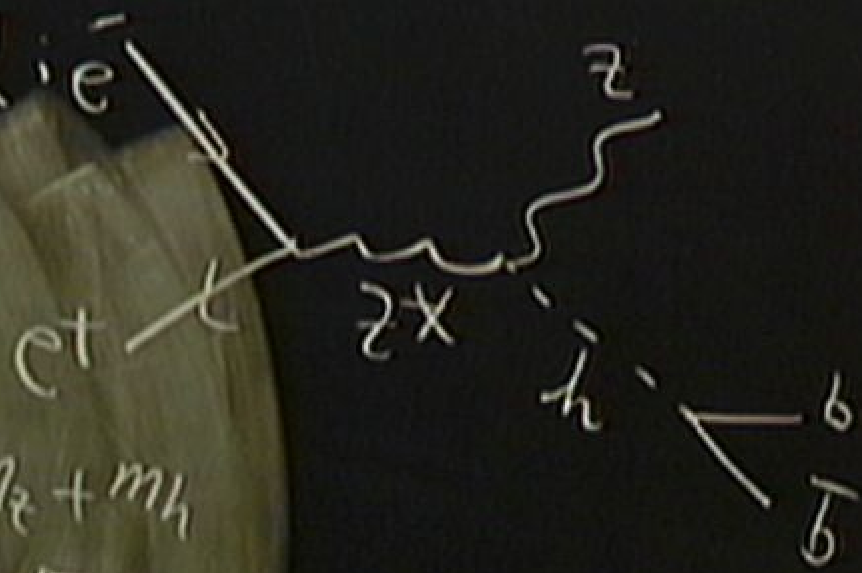

Verification
LEP 2 : e^-
Z
e^+
Z^*
h
b
$\bar{b}$
$\underbrace{b\bar{b}}_{m_{b\bar{b}} = m_h} + (Z \to l^+l^-, jj, \nu\nu)$
Recoil mass is m_Z
$m_{b\bar{b}} = m_h$


e^+
Z^*
$\sqrt{s} > m_Z + m_h$
$m_h < \sqrt{s} - m_Z$
CAUTION


Higgs).
tones.
e^+
Z^*
h
$\sqrt{s} > m_Z + m_h$
$m_h < \sqrt{s} - m_Z \approx 115$ GeV
CAUTION

Verification

LEP 2:



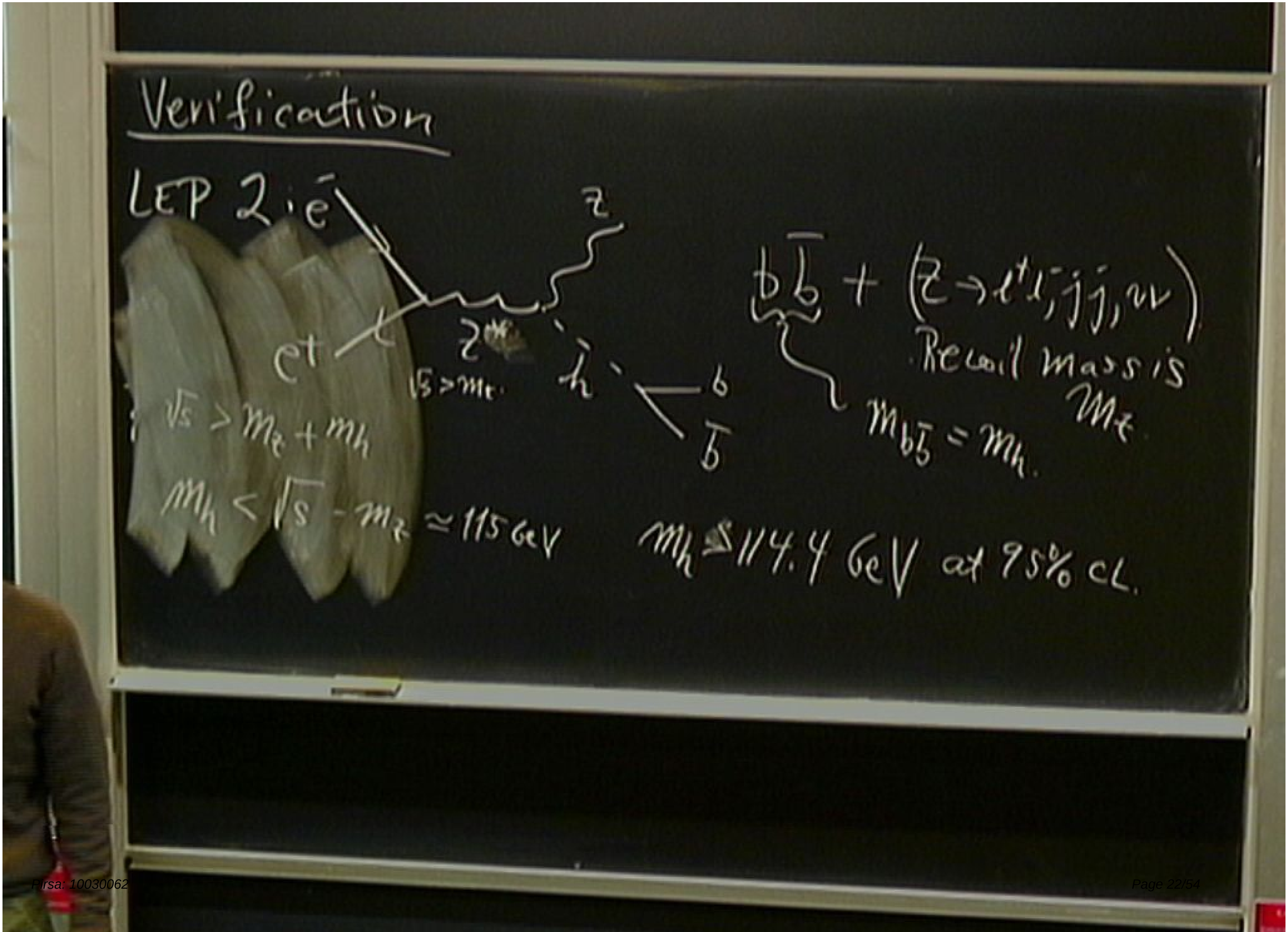
$\sqrt{s} > m_Z + m_h$

$m_h < \sqrt{s} - m_Z \simeq 115$ GeV

$\underbrace{b\bar{b}}_{m_{b\bar{b}} = m_h} + (Z \to \ell^+\ell^-, jj, \nu\nu)$

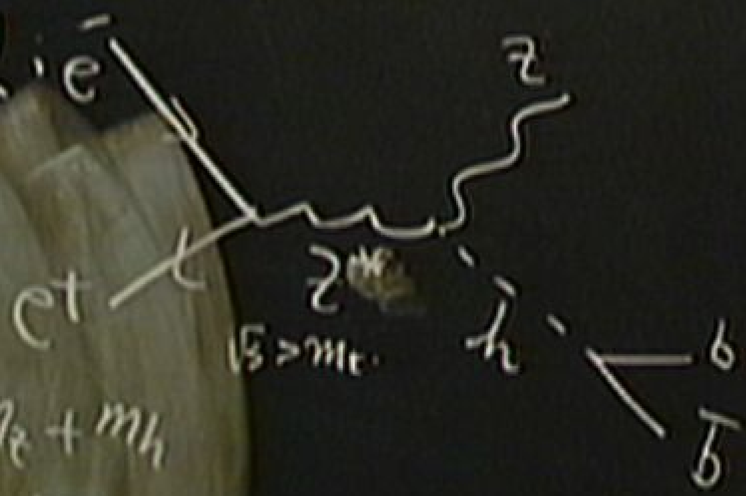
Recoil mass is m_Z

$m_h \geq 114.4$ GeV at 95% CL.


Verification
LEP 2: e^-
Z
e^+
Z^*
h
b
$\bar{b}$
$\sqrt{s} > m_Z$
$\sqrt{s} > m_Z + m_h$
$m_h < \sqrt{s} - m_Z \simeq 115$ GeV
$b\bar{b} + (Z \to \ell^+\ell^-, jj, \nu\nu)$
Recoil mass is m_Z
$m_{b\bar{b}} = m_h$
$m_h \gtrsim 114.4$ GeV at 95% CL.

Verification

LEP 2:



$\underbrace{b\bar{b}}_{m_{b\bar{b}} = m_h} + (Z \to \ell^+\ell^-, jj, \nu\nu)$

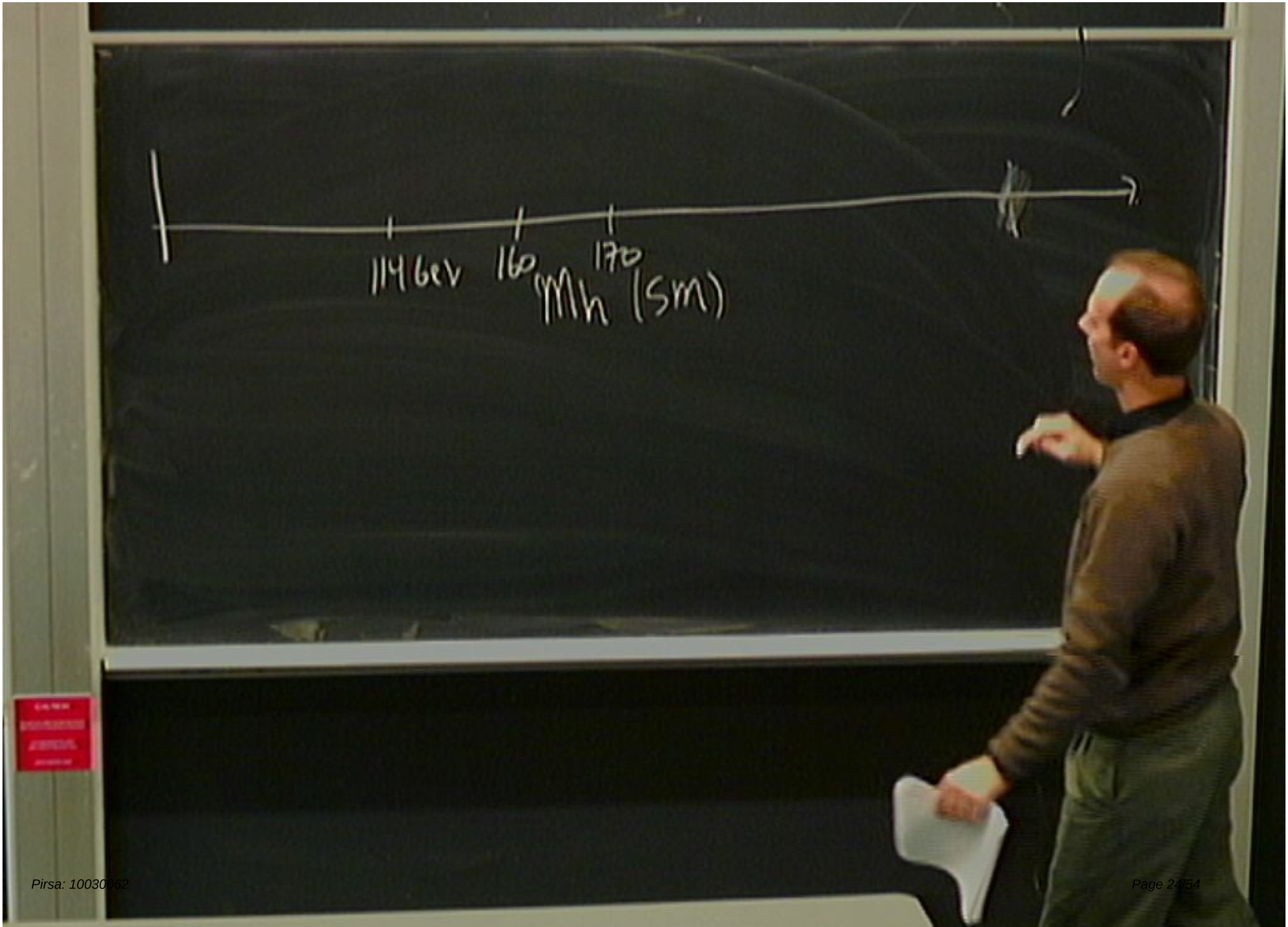
Recoil mass is m_Z

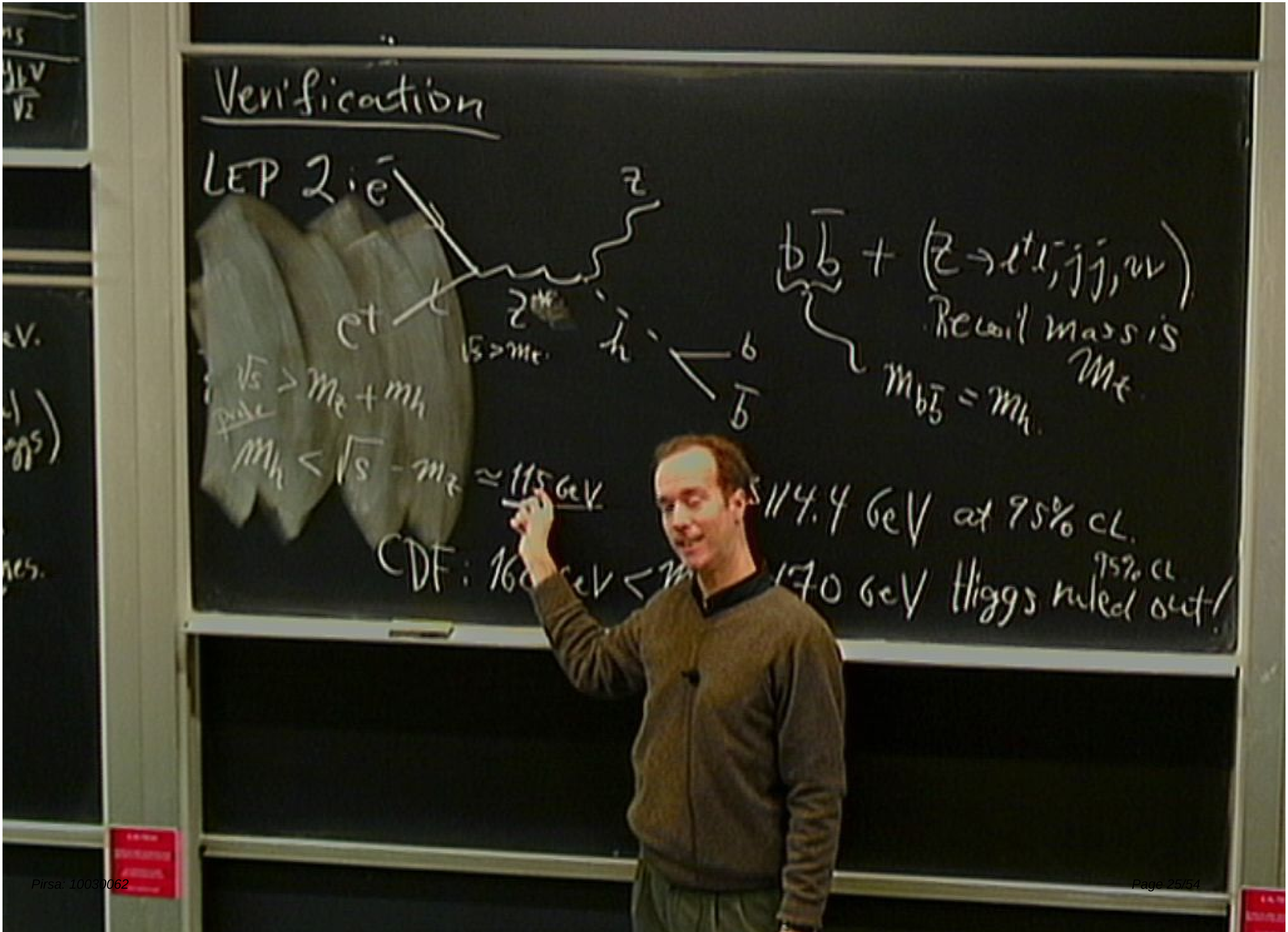
$\sqrt{s} > m_Z + m_h$

$m_h < \sqrt{s} - m_Z \simeq 115$ GeV

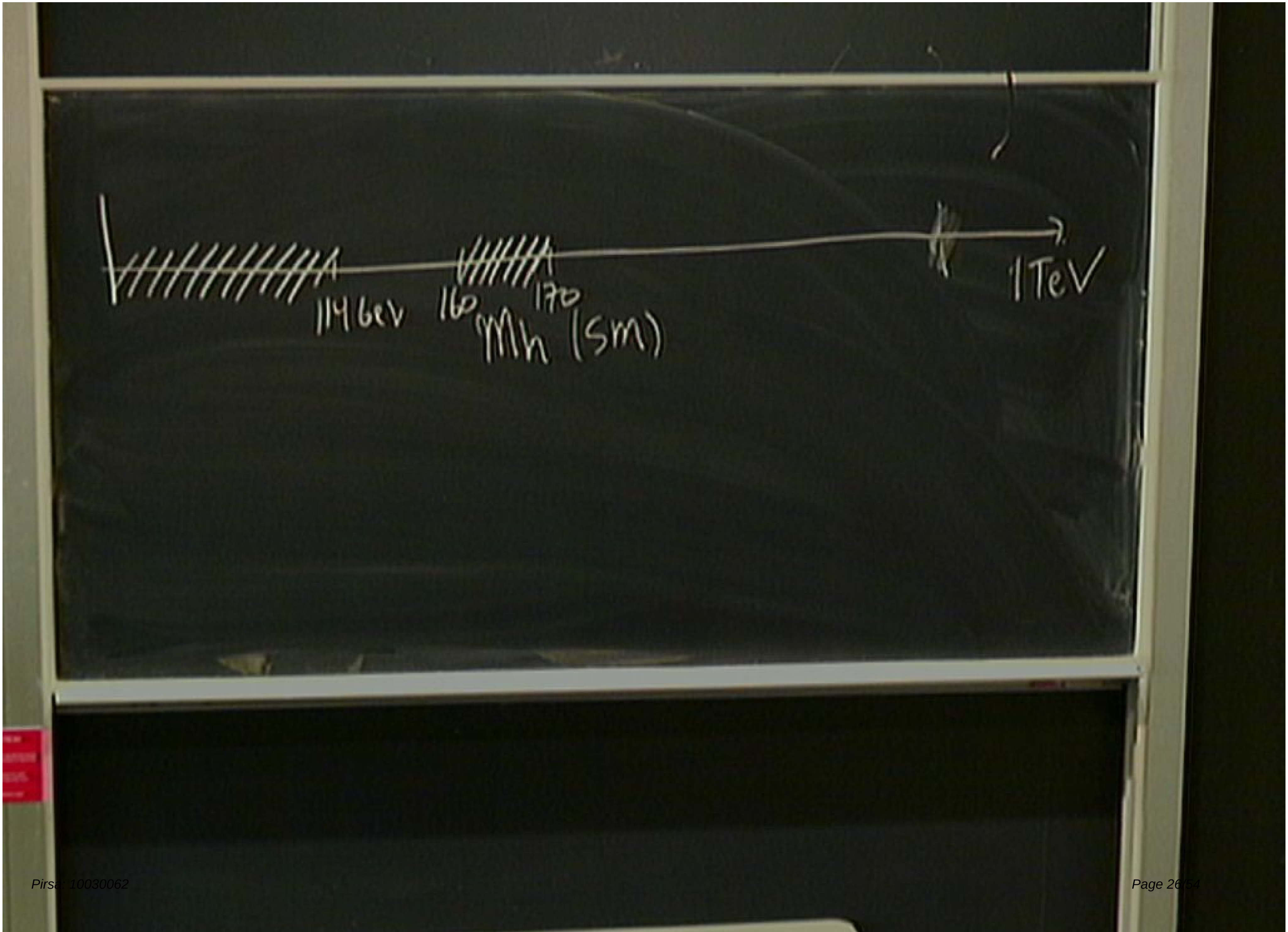
$m_h \gtrsim 114.4$ GeV at 95% CL.

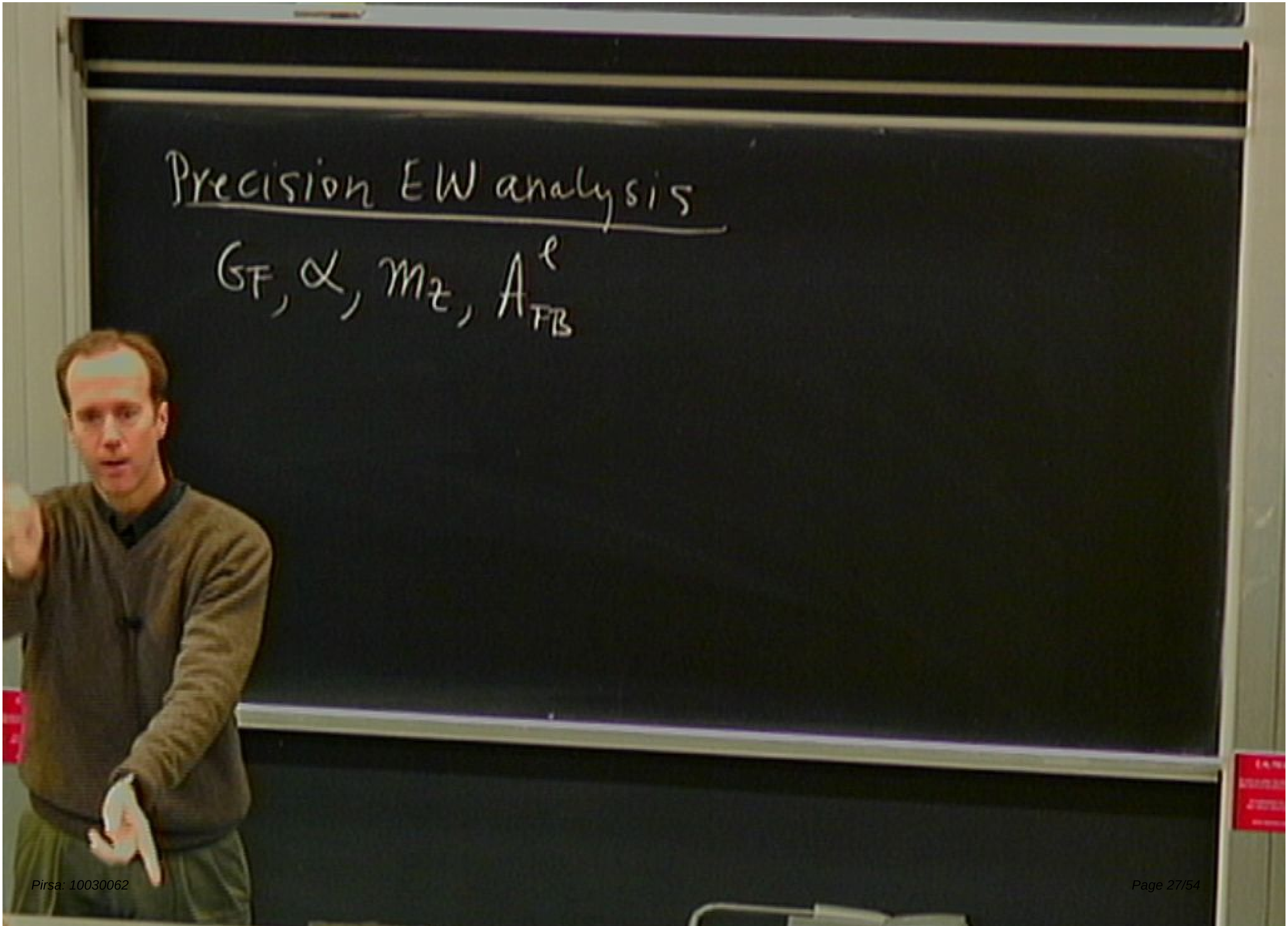
CDF: 160 GeV $< m_h <$ 170 GeV Higgs ruled out!

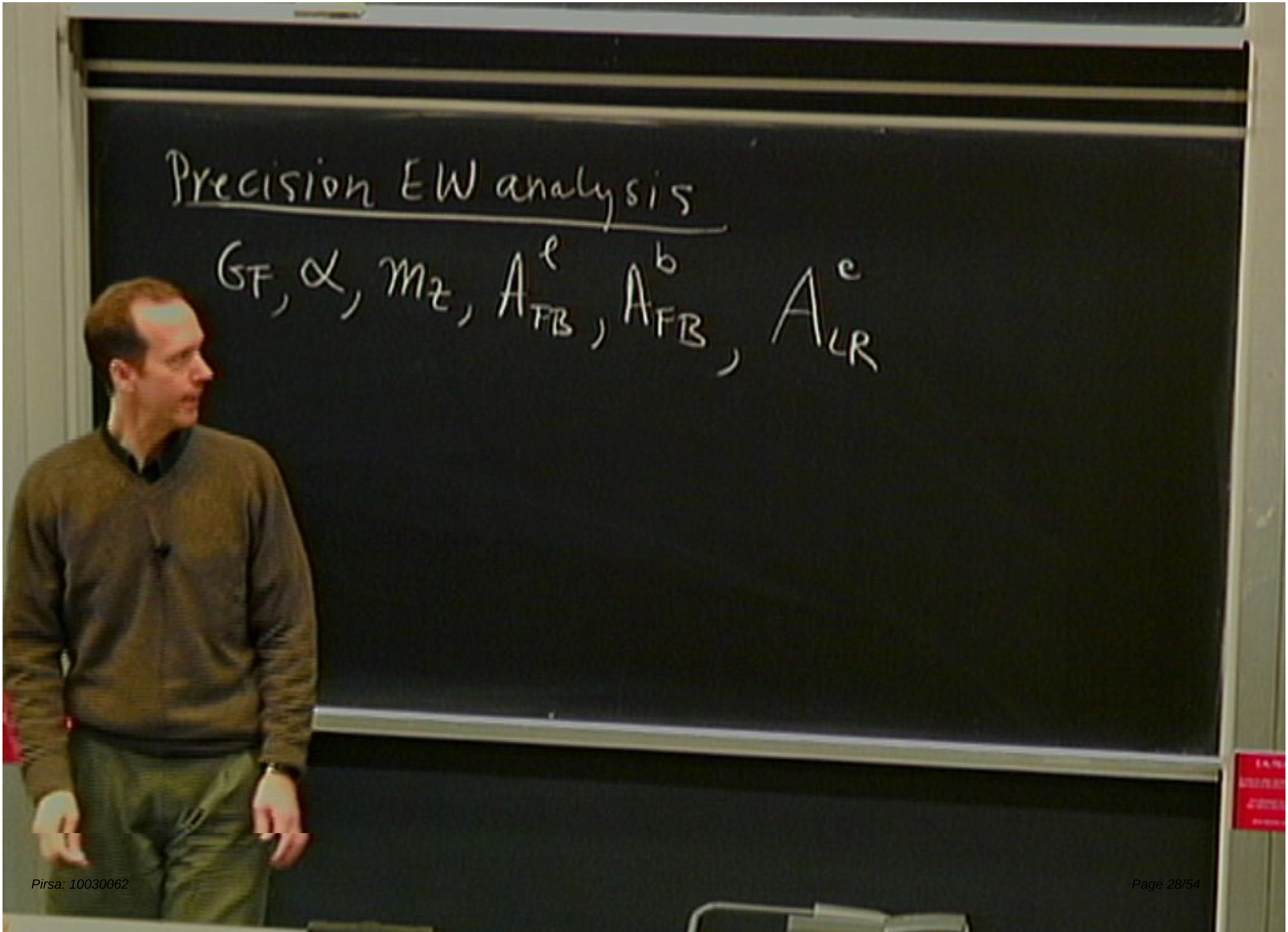

114 GeV
160
170
mh (SM)

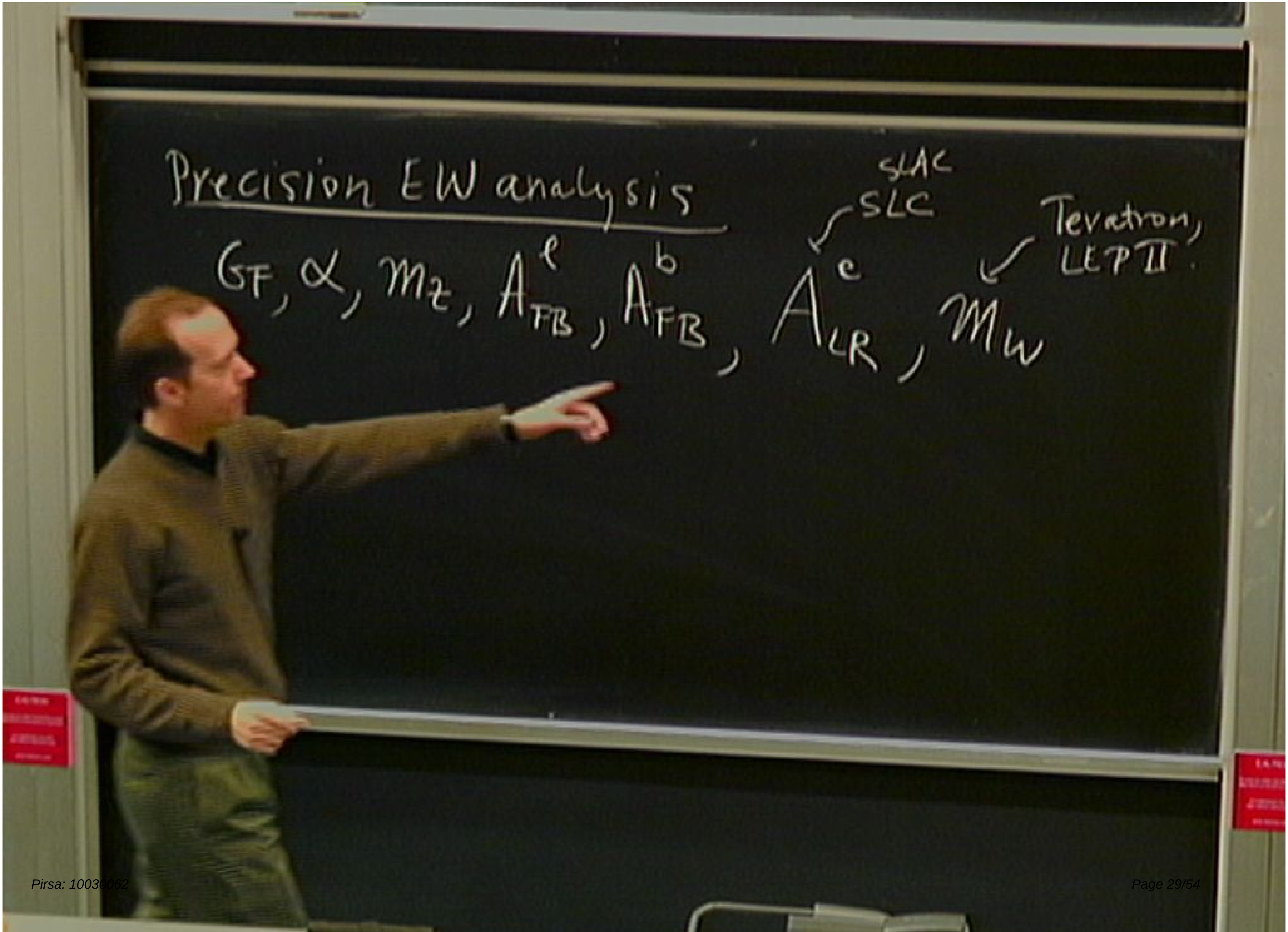


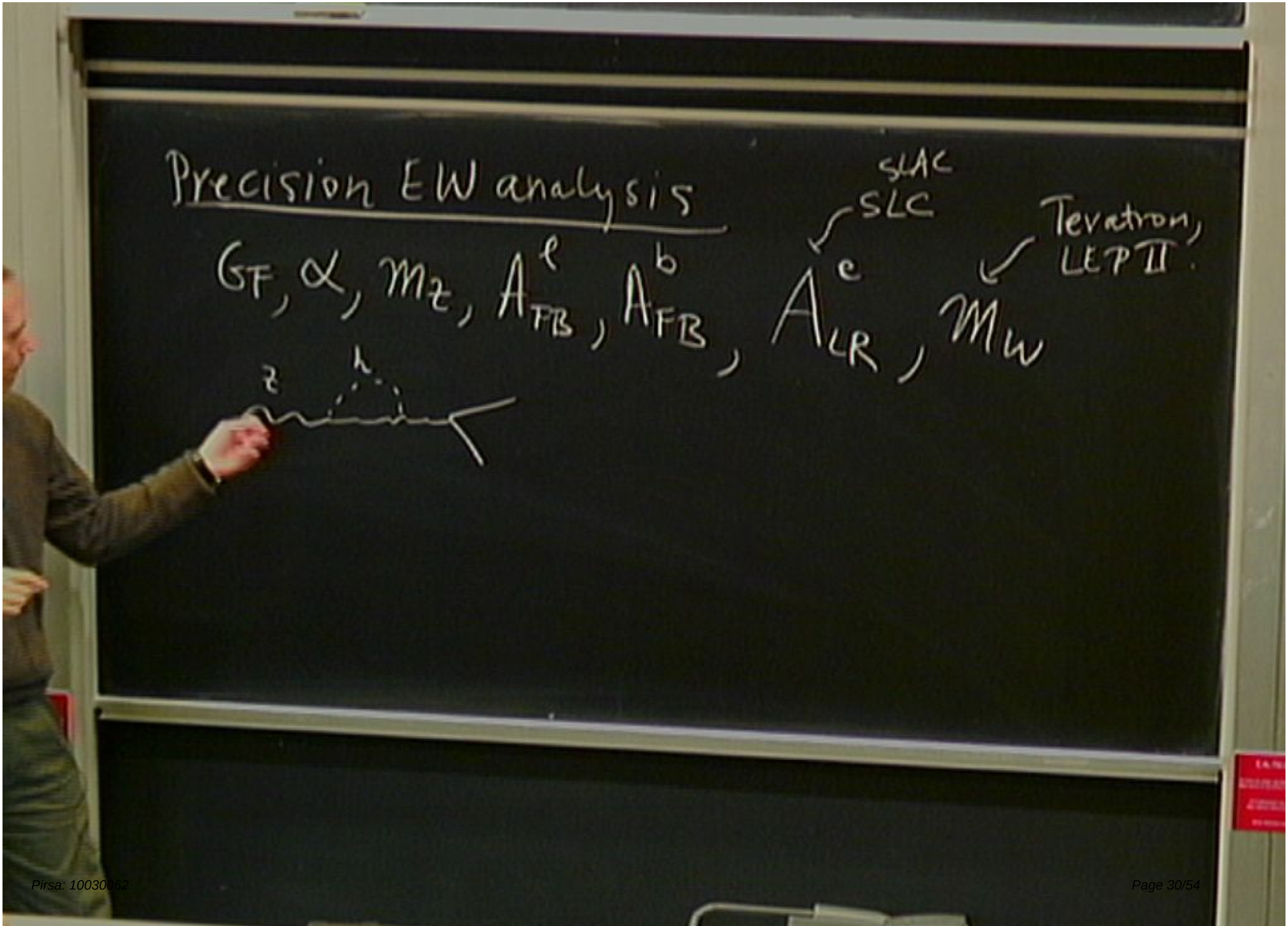
Verification
LEP 2: e⁻ e⁺ → Z* → Z h
√s > m_Z
√s > m_Z + m_h
m_h < √s − m_Z ≃ 115 GeV
b b̄ + (Z → ℓ⁺ℓ⁻, jj, νν̄)
Recoil mass is m_Z
m_bb̄ = m_h
≲ 114.4 GeV at 95% CL
CDF: 160 GeV < m_h < 170 GeV Higgs ruled out!
95% CL


114GeV
160
170
mh (SM)
1TeV


Precision EW analysis
G_F, α, m_Z, A_{FB}^{ℓ}


Precision EW analysis
$G_F, \alpha, m_Z, A_{FB}^{\ell}, A_{FB}^{b}, A_{LR}^{e}$


Precision EW analysis
SLAC
SLC
Tevatron,
LEP II
G_F, α, m_Z, A_{FB}^{ℓ}, A_{FB}^{b}, A_{LR}^{e}, m_W

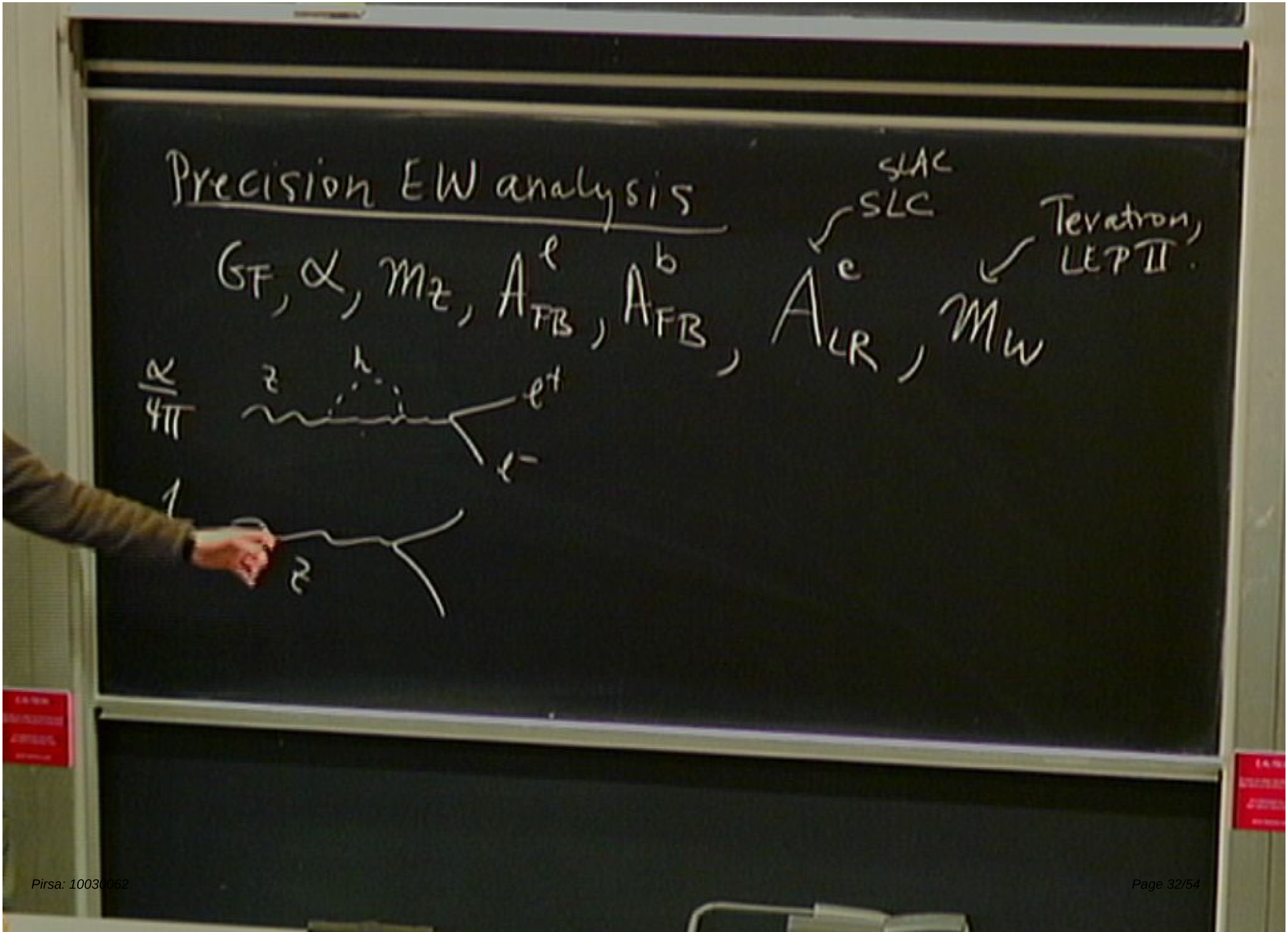

Precision EW analysis
SLAC
SLC
Tevatron,
LEP II
G_F, α, m_Z, A_{FB}^{ℓ}, A_{FB}^{b}, A_{LR}^{e}, m_W
Z
h

<u>Precision EW analysis</u>

SLAC SLC

Tevatron, LEP II

$$G_F,\ \alpha,\ m_Z,\ A_{FB}^{\ell},\ A_{FB}^{b},\ A_{LR}^{e},\ m_W$$


Precision EW analysis
SLAC
SLC
Tevatron, LEP II
G_F, α, m_Z, A^{ℓ}_{FB}, A^{b}_{FB}, A^{e}_{LR}, m_W
$\frac{\alpha}{4\pi}$
Z
h
ℓ^+
ℓ^-
1
Z

Precision EW analysis

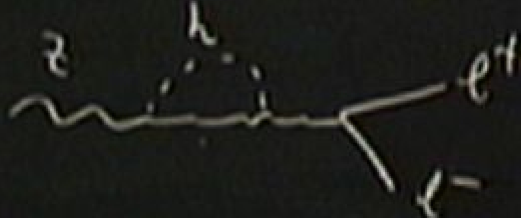
SLAC

SLC

Tevatron, LEP II

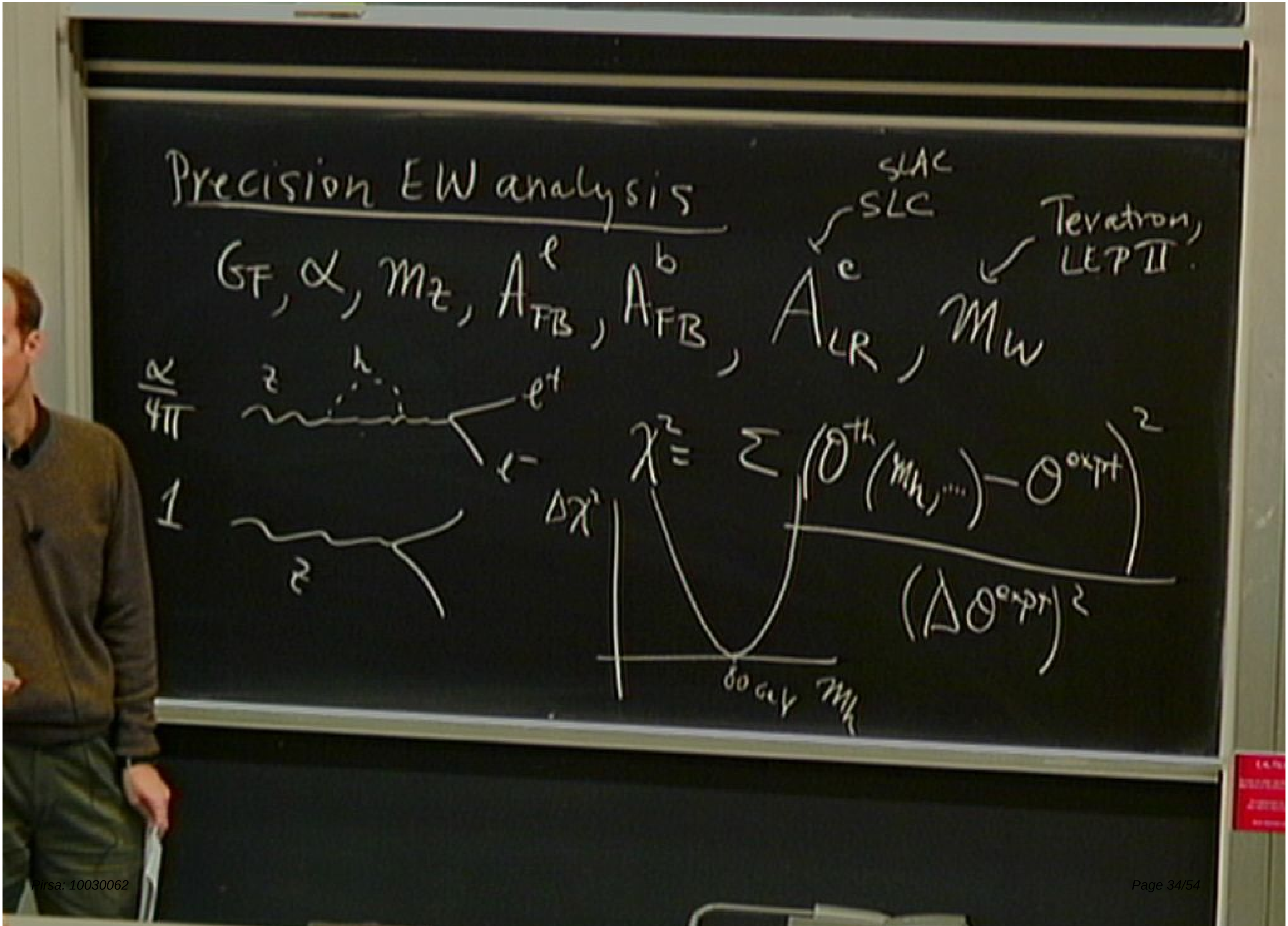
$$G_F,\ \alpha,\ m_Z,\ A_{FB}^{\ell},\ A_{FB}^{b},\ A_{LR}^{e},\ m_W,$$

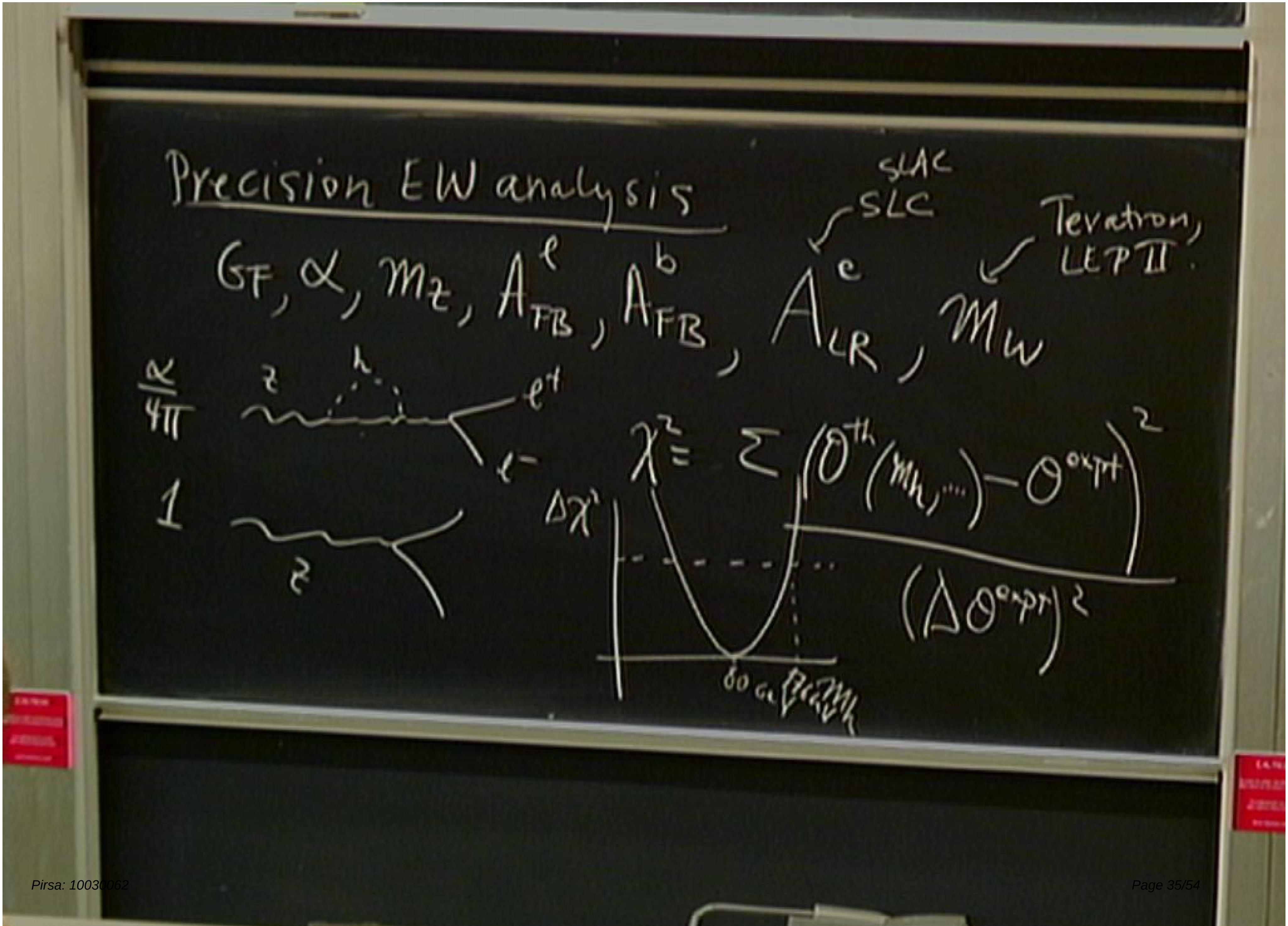
$\frac{\alpha}{4\pi}$

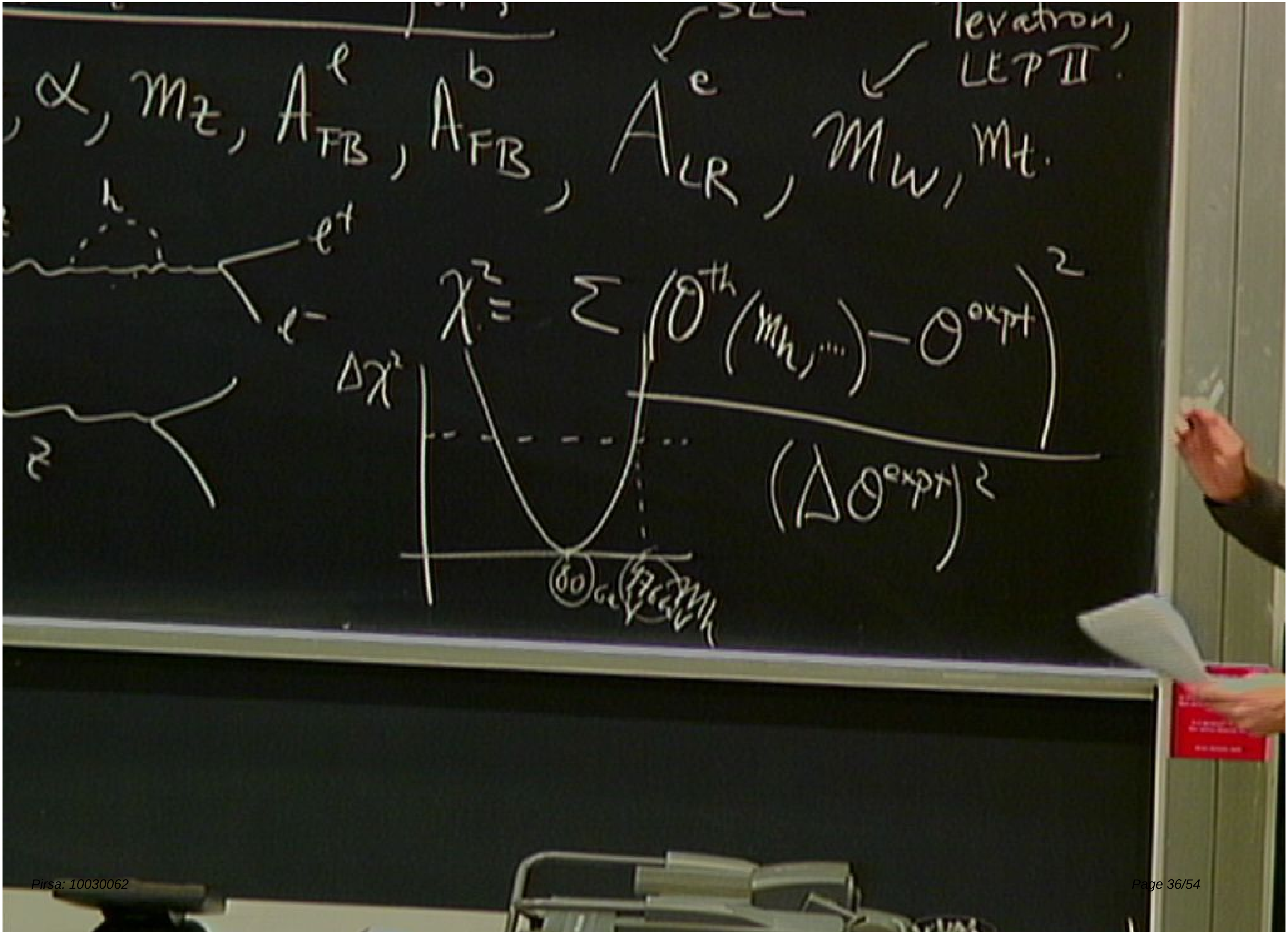


1

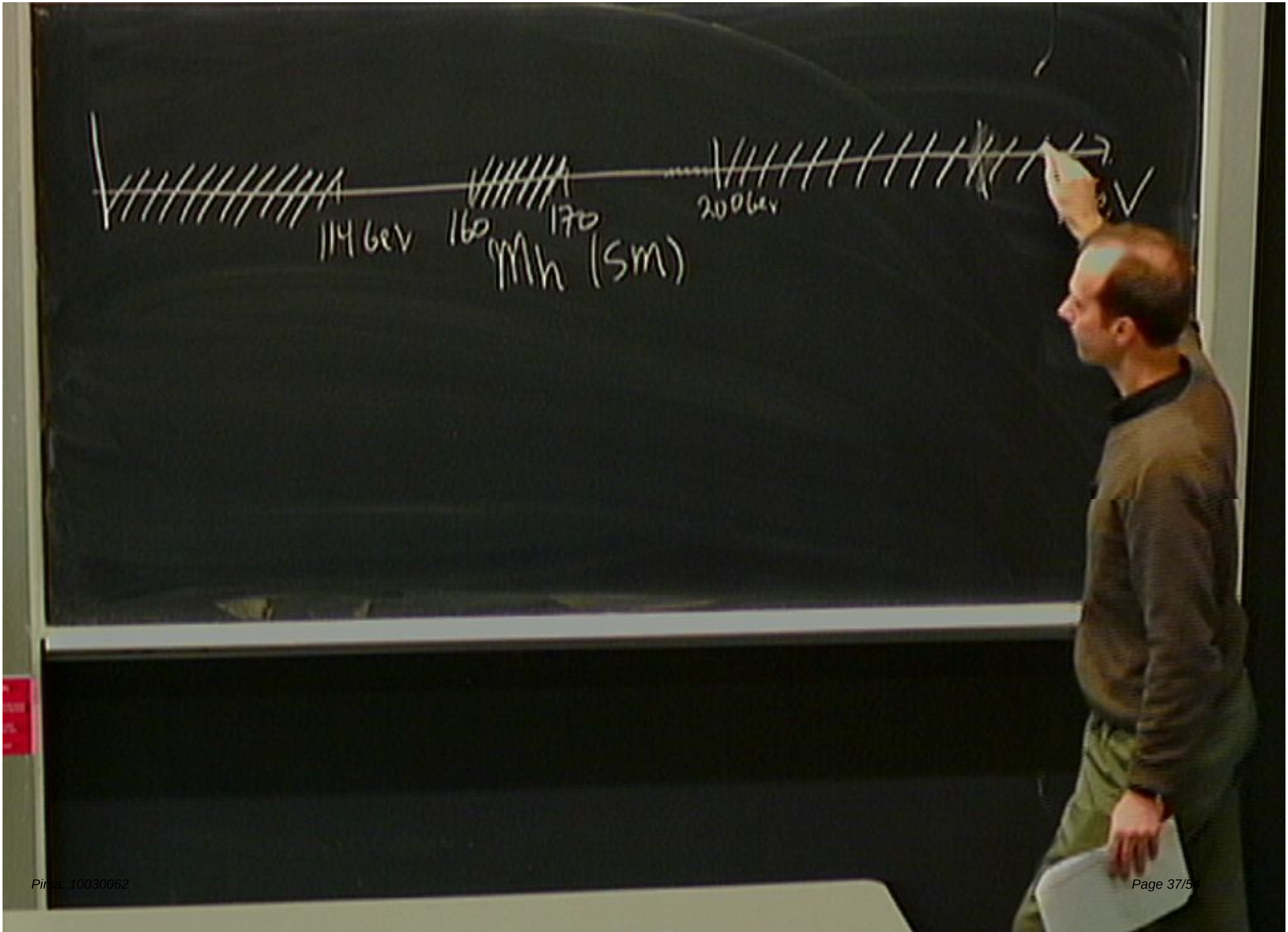
$$\chi^2 = \sum \frac{\left(\mathcal{O}^{th}(m_h, \ldots) - \mathcal{O}^{expt}\right)^2}{\left(\Delta \mathcal{O}^{expt}\right)^2}$$

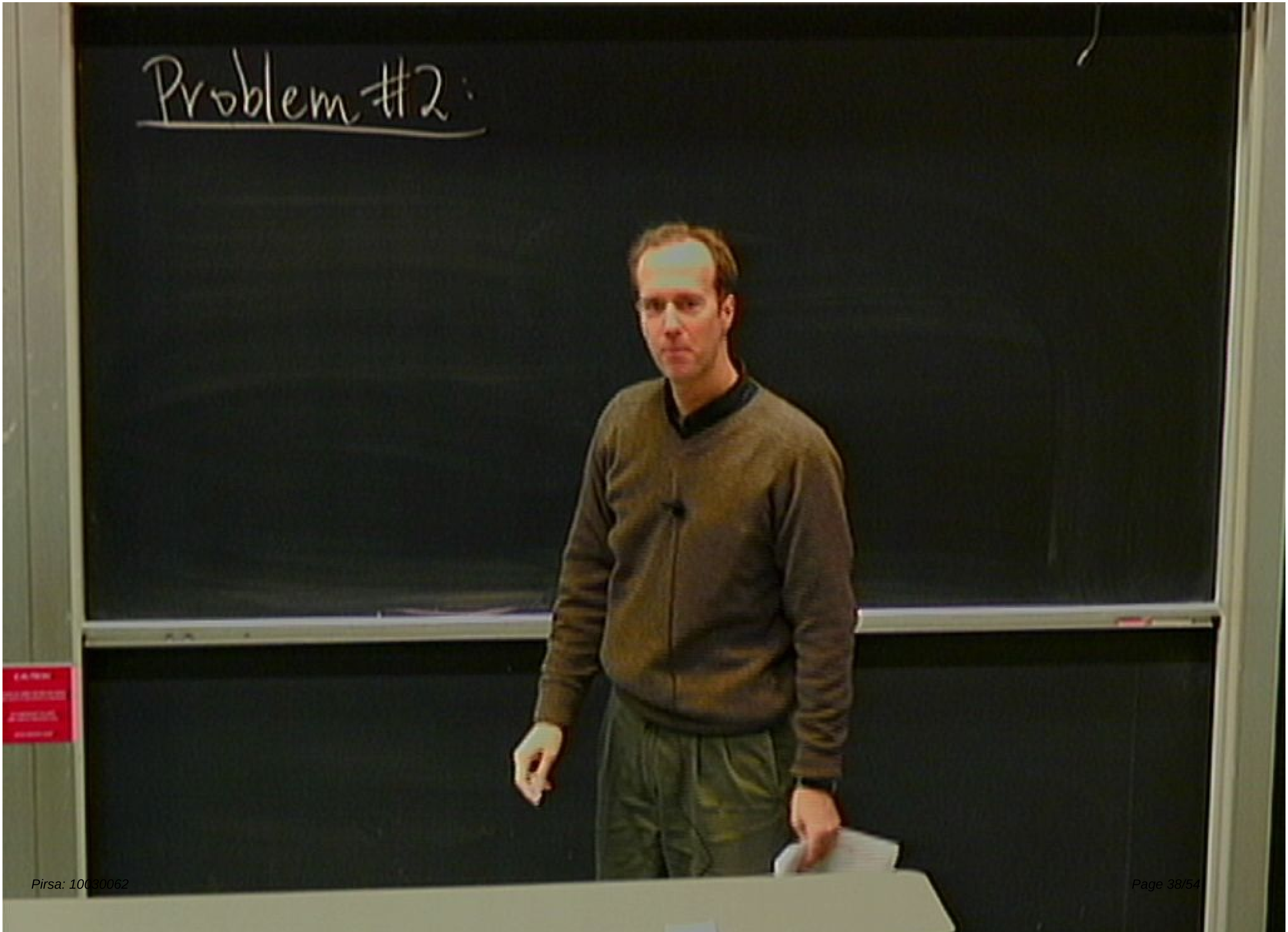

Precision EW analysis
SLAC
SLC
Tevatron, LEP II
$G_F, \alpha, m_Z, A^{\ell}_{FB}, A^{b}_{FB}, A^{e}_{LR}, m_W$
$\frac{\alpha}{4\pi}$
Z
h
e^+
e^-
1
Z
$\chi^2 = \sum \left(\frac{\theta^{th}(m_h, \ldots) - \theta^{expt}}{(\Delta\theta^{expt})^2} \right)^2$
$\Delta\chi^2$
80 GeV
m_h


Precision EW analysis
SLAC
SLC
Tevatron, LEP II
G_F, α, m_Z, A^ℓ_FB, A^b_FB, A^e_LR, m_W
α/4π
Z
h
ℓ+
ℓ−
1
Z
χ² = Σ (O^th(m_h, ...) − O^expt)² / (ΔO^expt)²
Δχ²
80 GeV



SLC
levatron,
LEP II
$\alpha, m_Z, A^{\ell}_{FB}, A^{b}_{FB}, A^{e}_{LR}, m_W, m_t.$
e^+
e^-
h
Z
$\chi^2 = \Sigma \frac{\left(O^{th}(m_h, \ldots) - O^{expt}\right)^2}{(\Delta O^{expt})^2}$
$\Delta\chi^2$
80 GeV
m_h


114 GeV
160
170
200 GeV
Mh (SM)


Problem #2:

Problem #2:

Nobody believes it!

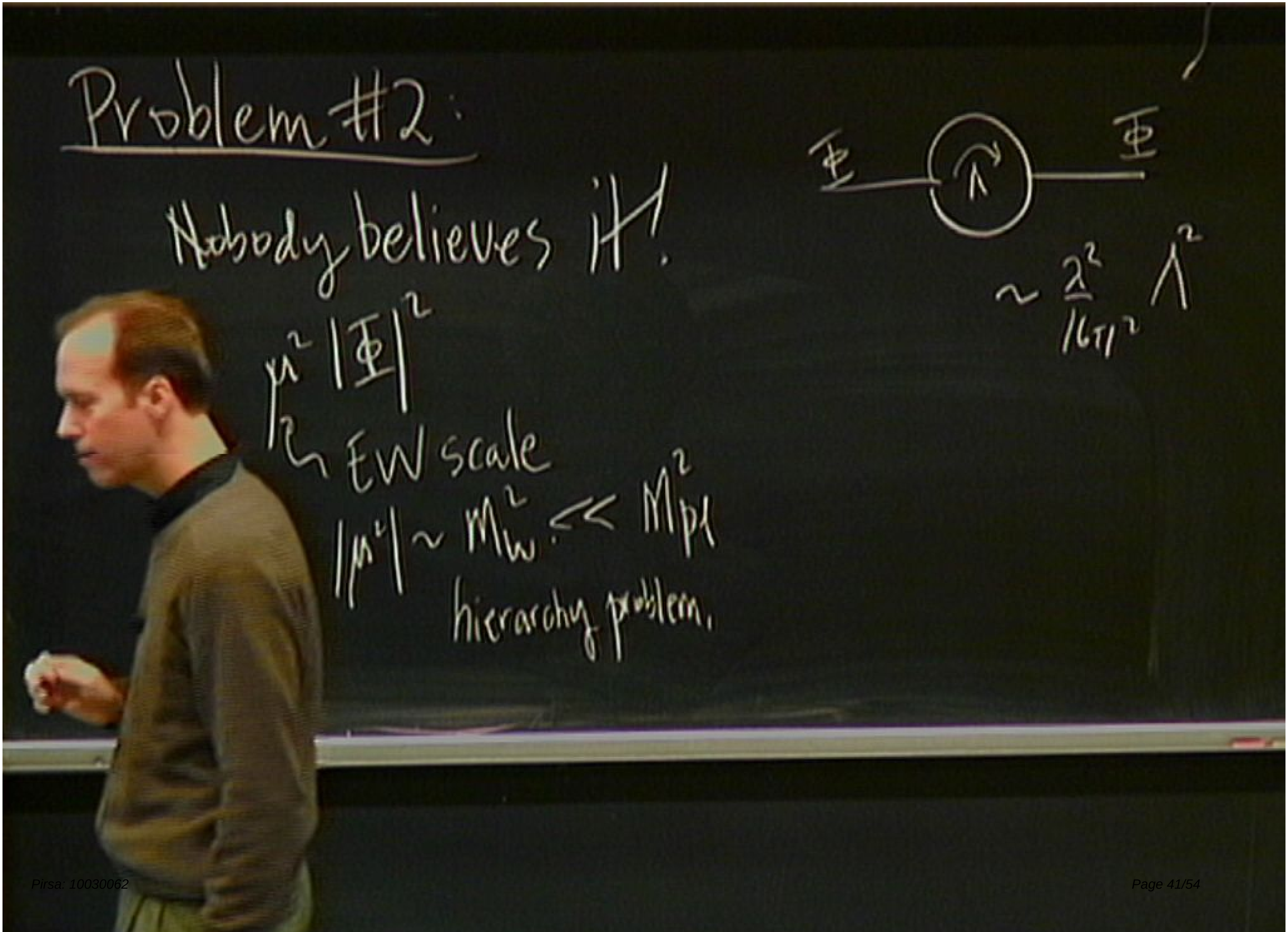
Problem #2:

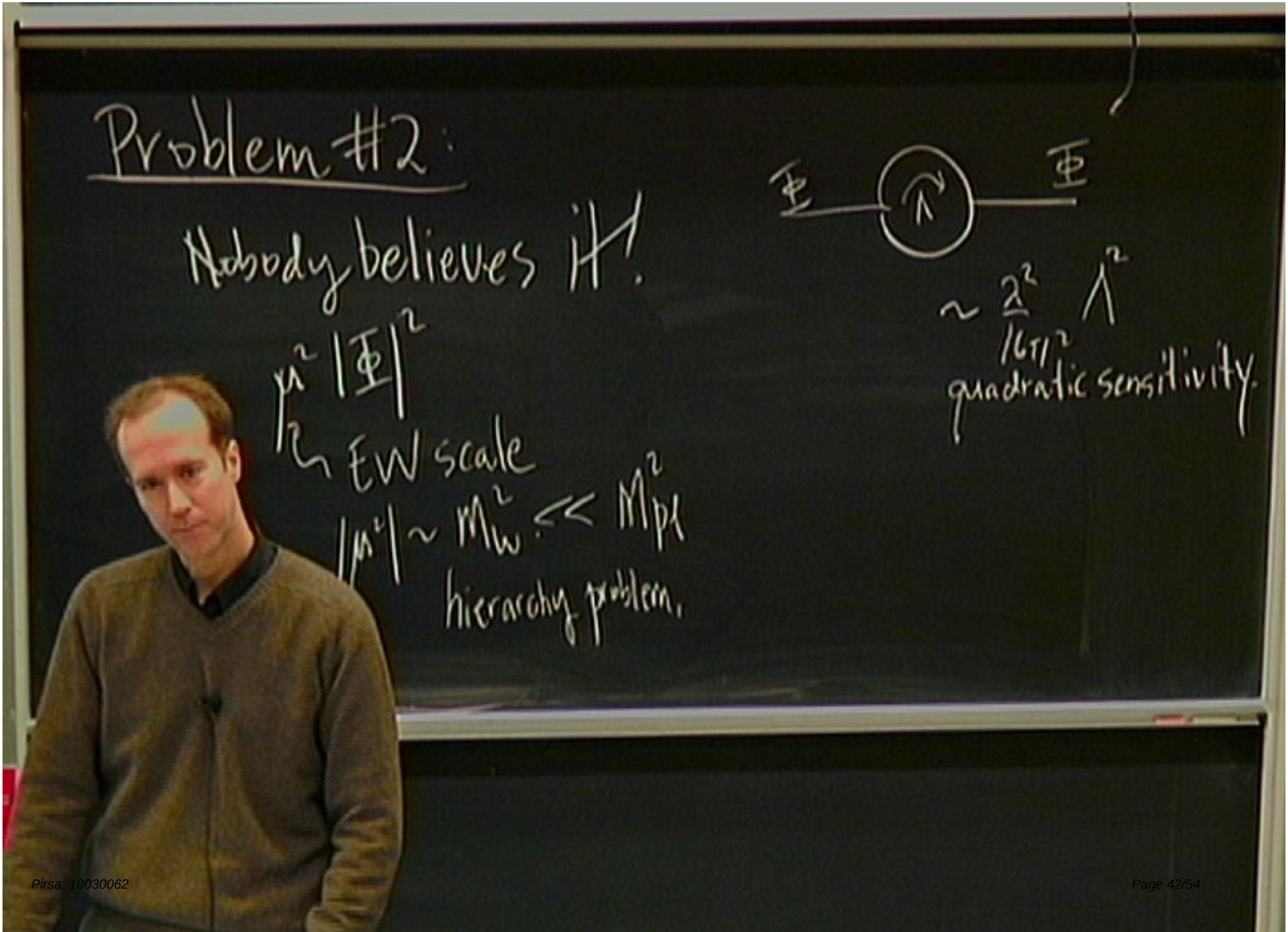
Nobody believes it!

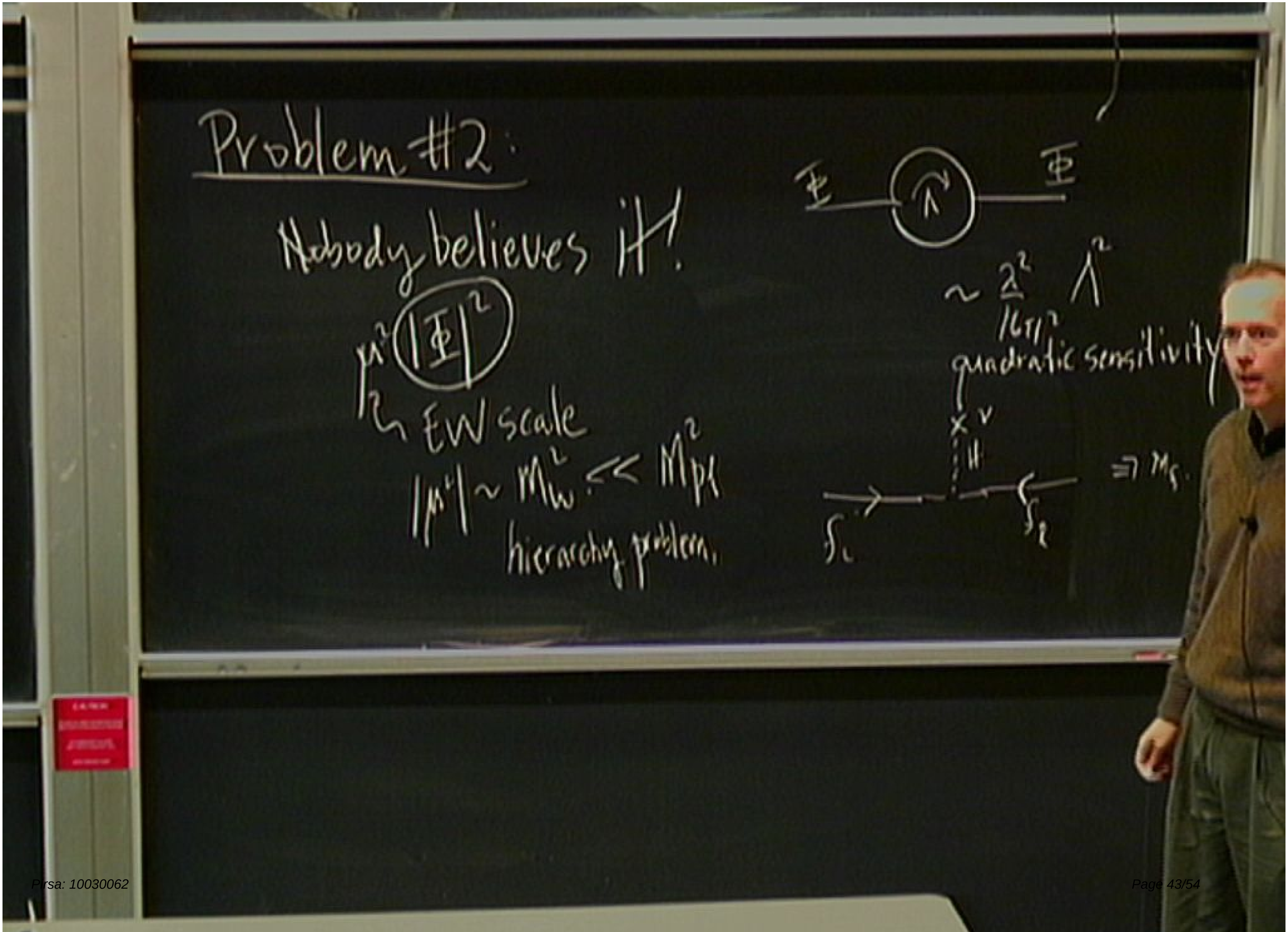
$$\mu^2 |\Phi|^2$$

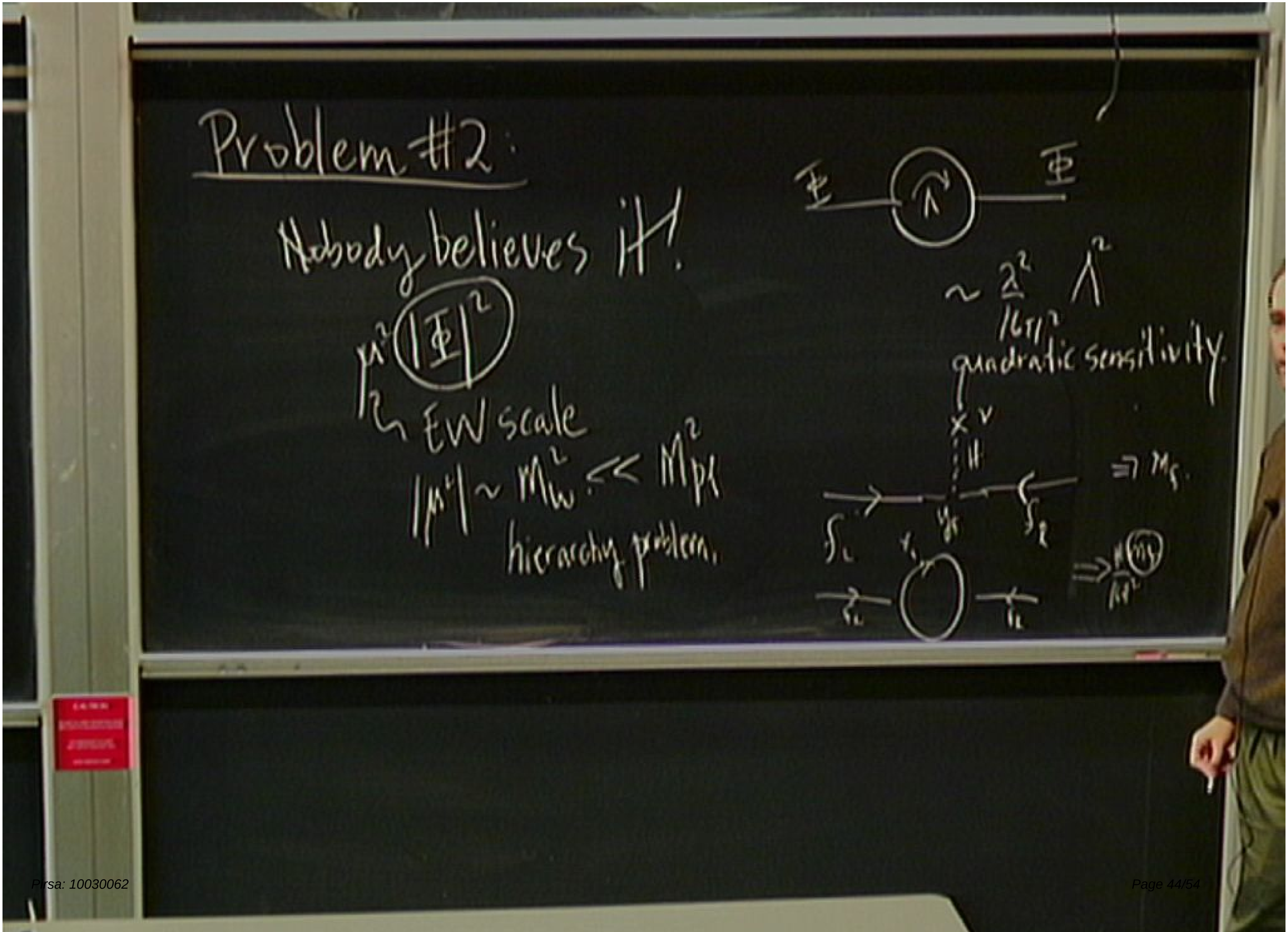
EW scale

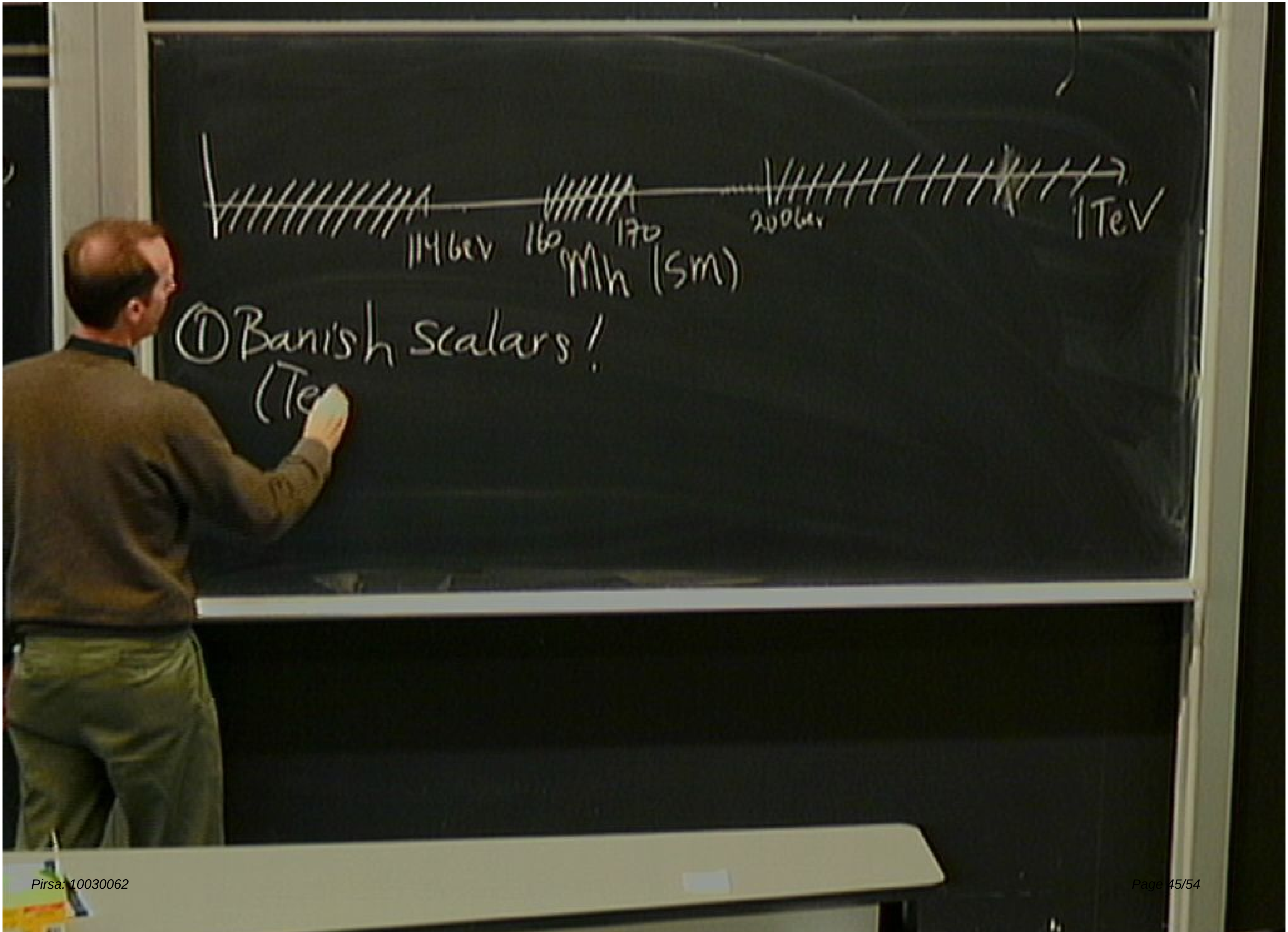
$$|\mu^2| \sim m_W^2.$$

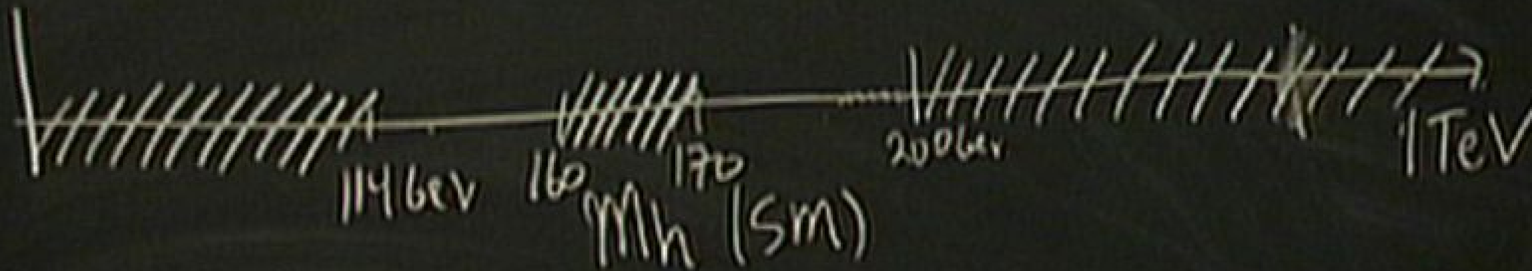

Problem #2:
Nobody believes it!
$\mu^2 |\Phi|^2$
EW scale
$|\mu^2| \sim M_W^2 << M_{Pl}^2$
hierarchy problem.
Φ
Λ
Φ
$\sim \frac{\lambda^2}{16\pi^2} \Lambda^2$


Problem #2:
Nobody believes it!
$\mu^2 |\Phi|^2$
EW scale
$|\mu^2| \sim M_W^2 << M_{Pl}^2$
hierarchy problem.
Φ
Λ
Φ
$\sim \frac{\lambda^2}{16\pi^2} \Lambda^2$
quadratic sensitivity.

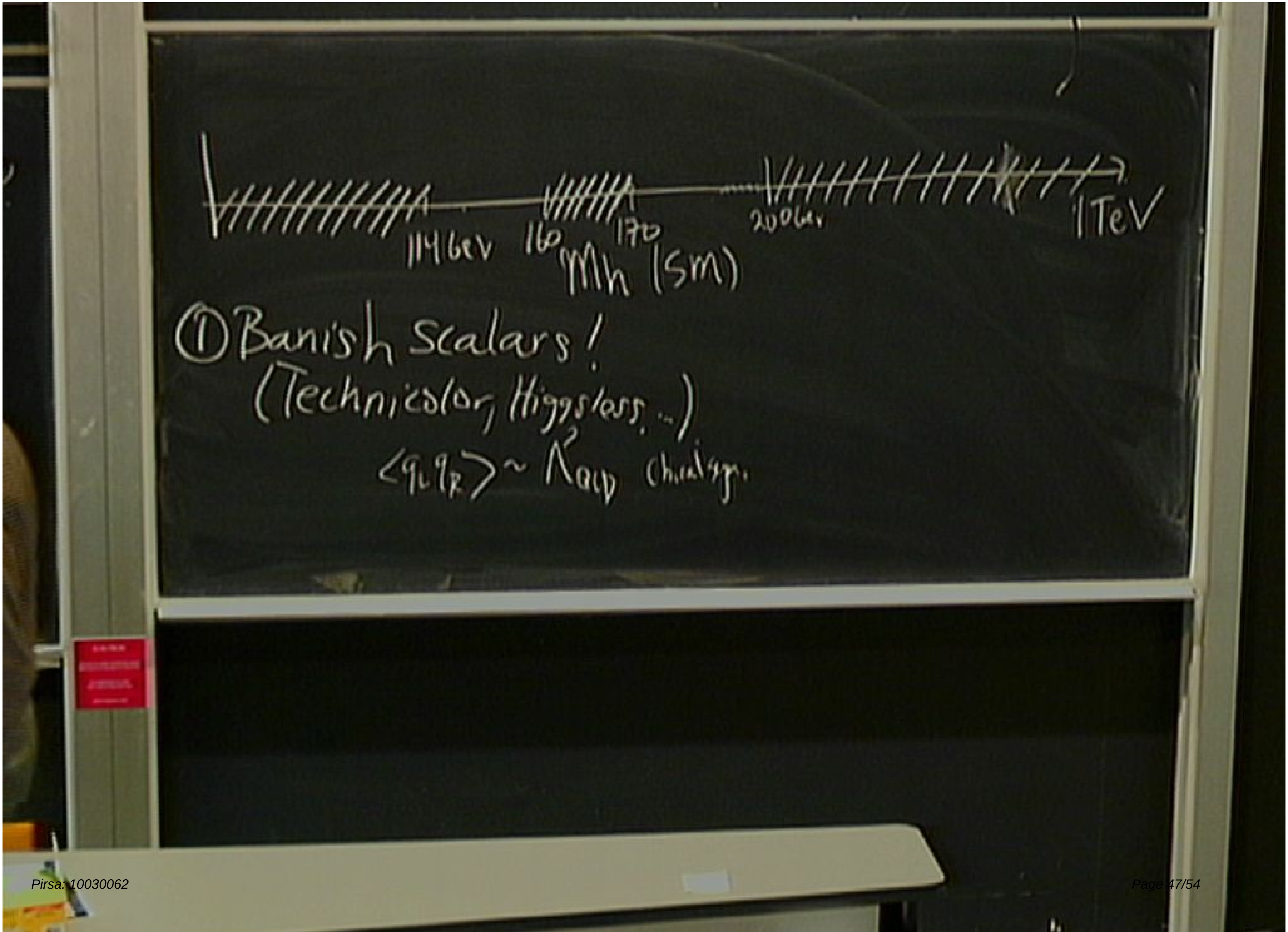

Problem #2:
Nobody believes it!
μ² |Φ|²
~ EW scale
|μ²| ~ M_W² << M_Pl²
hierarchy problem.
Φ Λ Φ
~ λ²/16π² Λ²
quadratic sensitivity
× v
H
f₁ f₂
⇒ m_f.

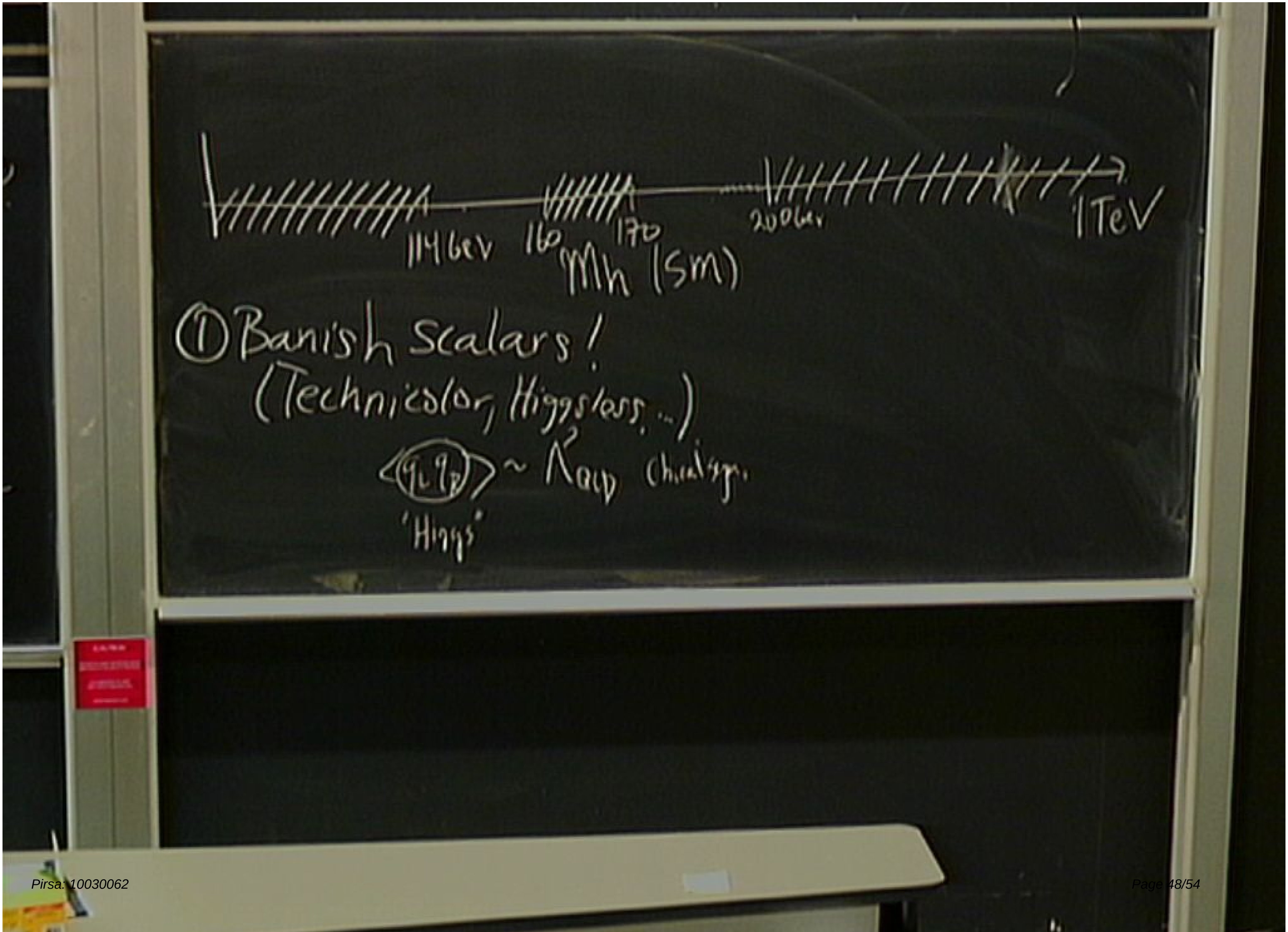

Problem #2:
Nobody believes it!
$\mu^2 |\Phi|^2$
EW scale
$|\mu^2| \sim M_W^2 << M_{Pl}^2$
hierarchy problem.
Φ
Λ
Φ
$\sim \frac{\lambda^2}{16\pi^2} \Lambda^2$
quadratic sensitivity.
$\times\ v$
H
y_f
f_L
f_R
$\Rightarrow m_f$
$\Rightarrow \frac{y_f m_f}{16\pi^2}$

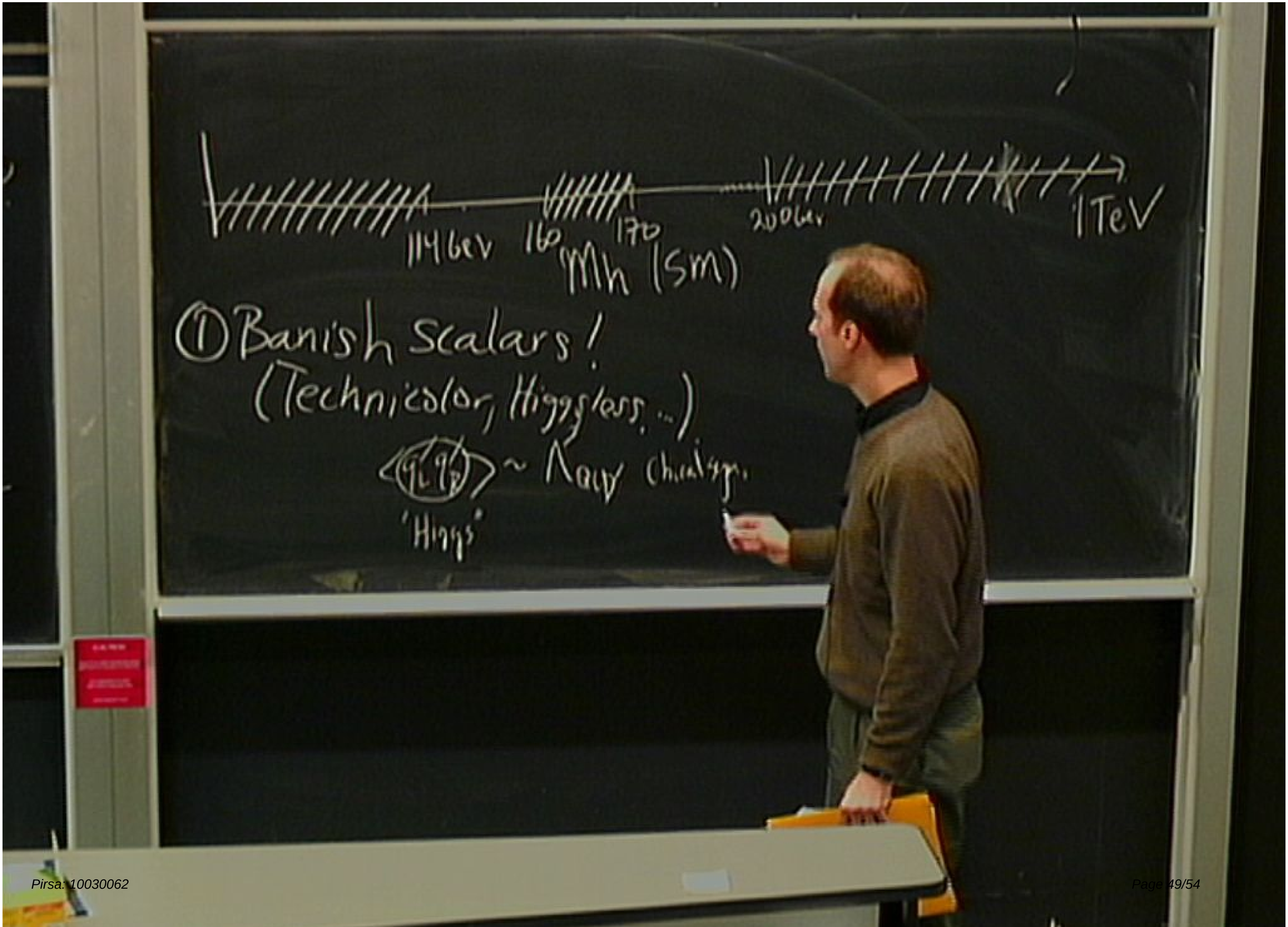

114 GeV
160
170
200 GeV
1 TeV
mh (SM)
1 Banish scalars!
(Te

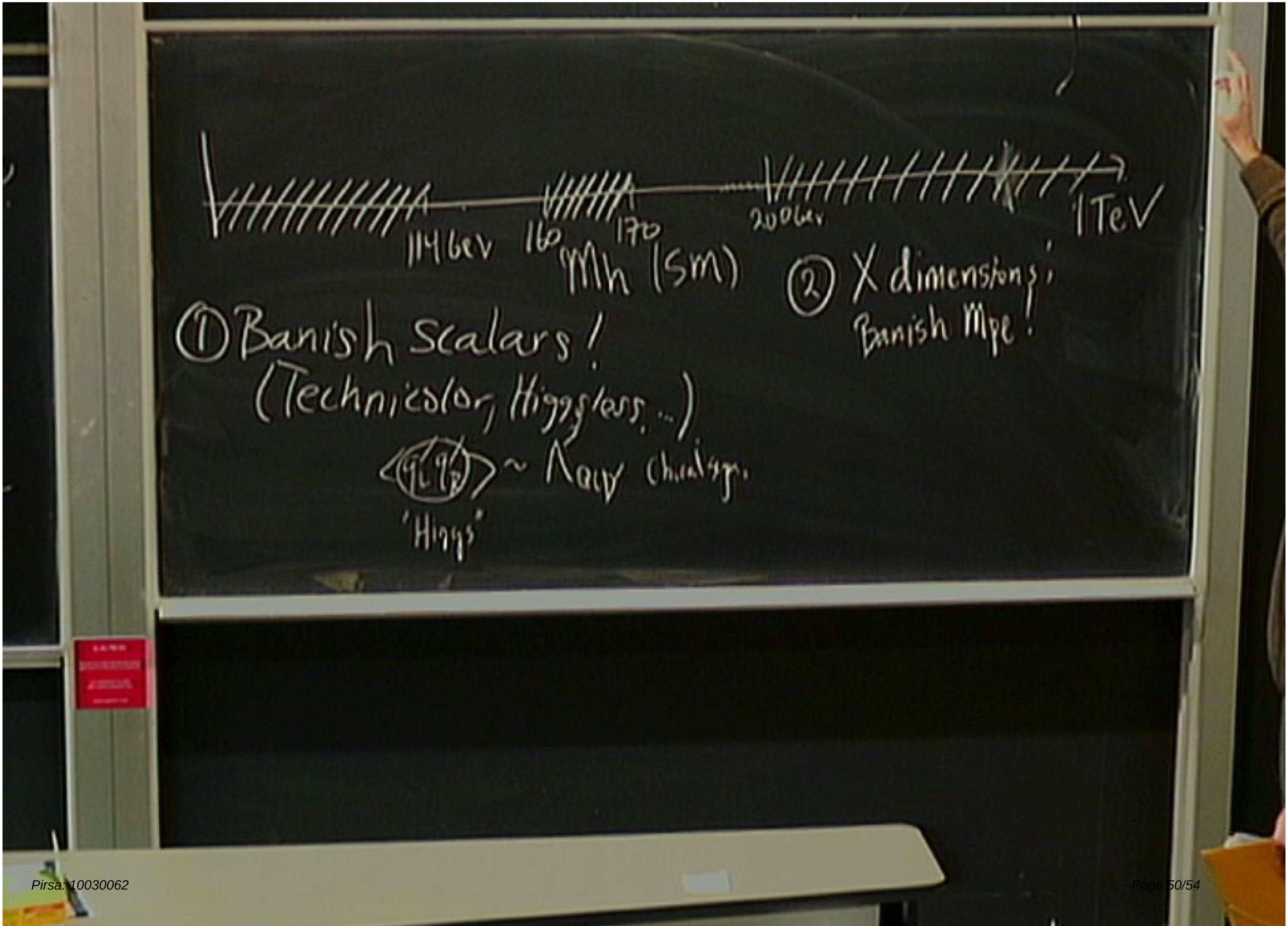


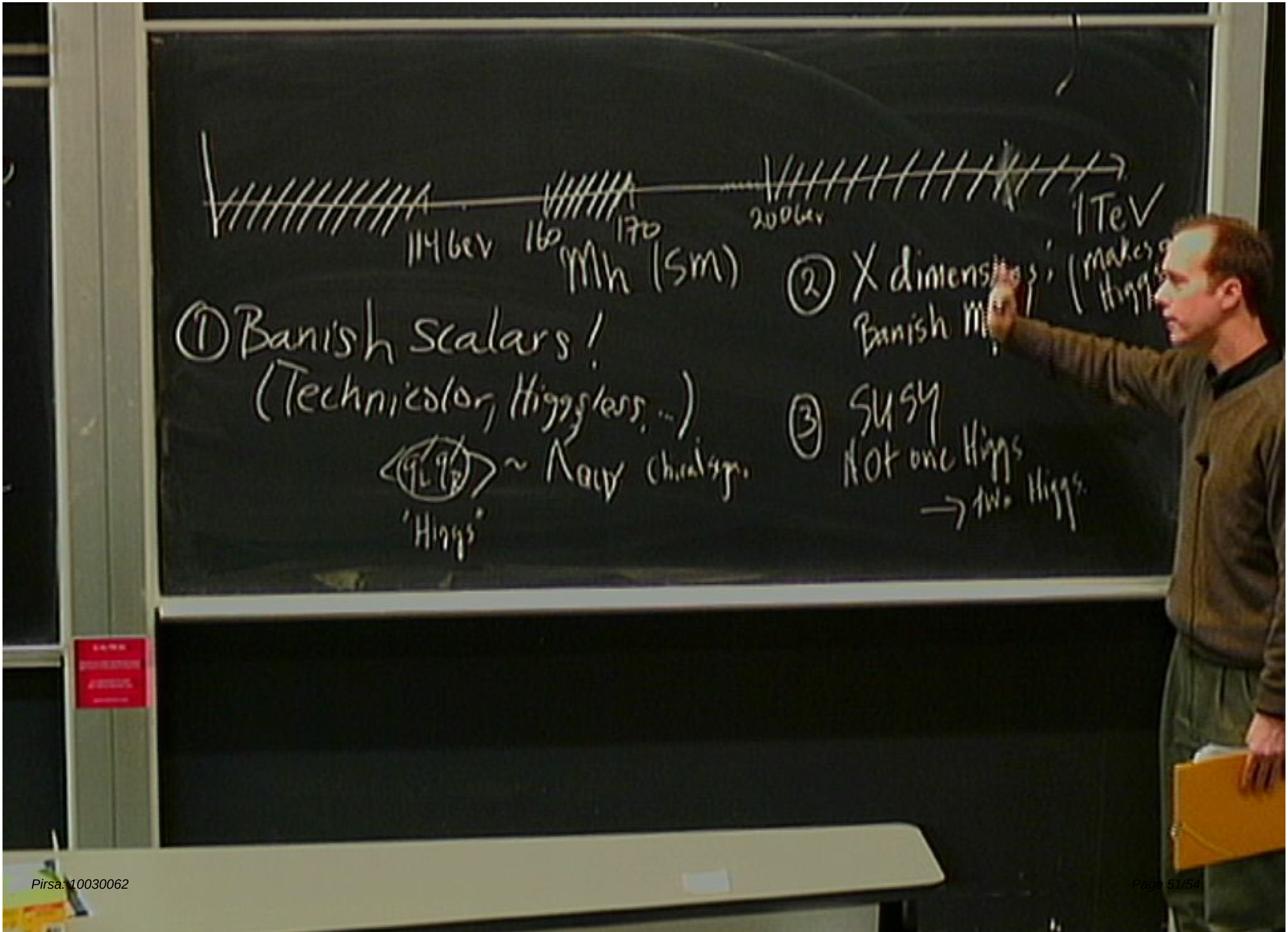
① Banish scalars!
(Technicolor, Higgsless, ...)

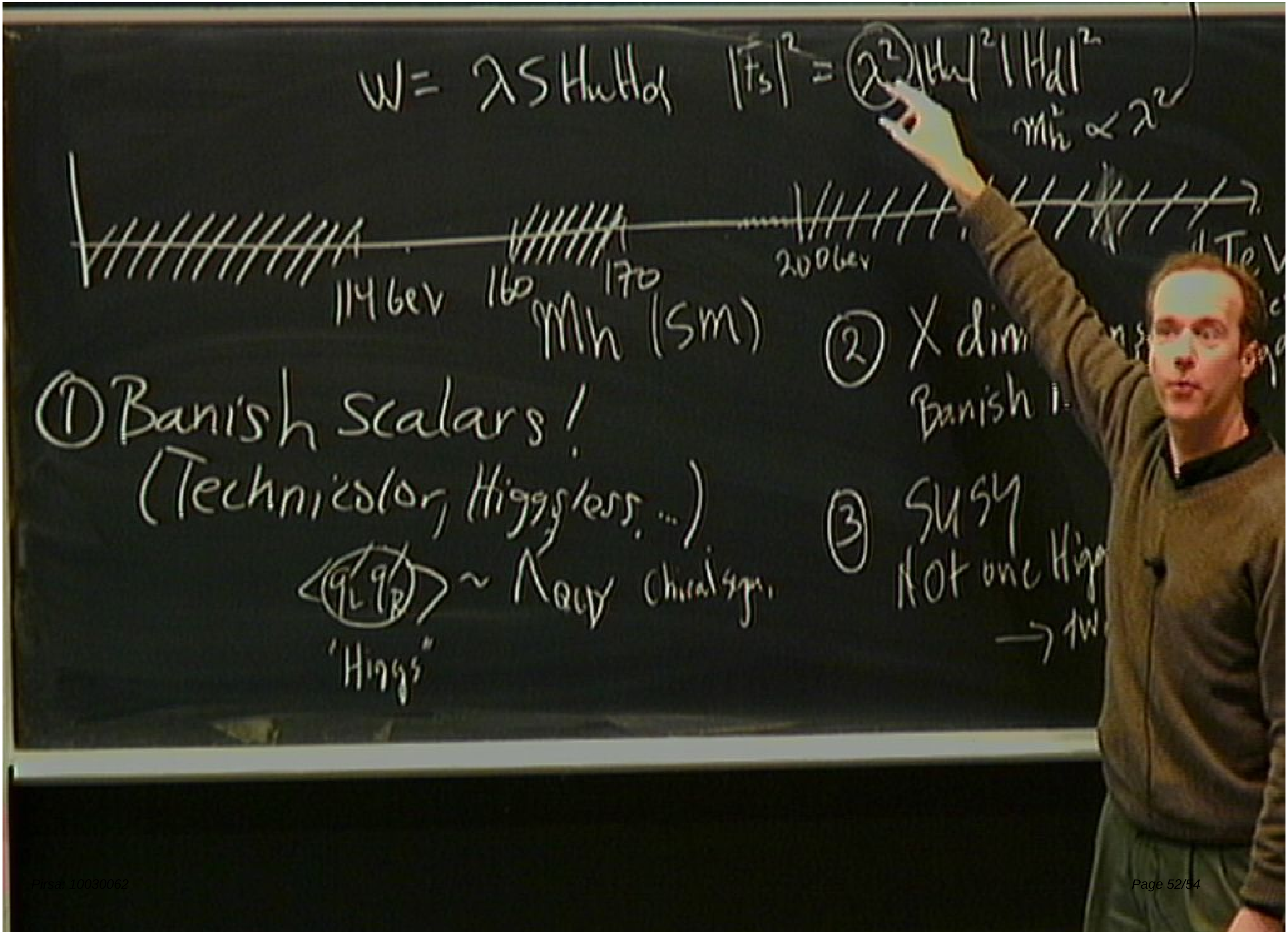

114 GeV
160
170
200 GeV
1 TeV
mh (SM)
① Banish scalars!
(Technicolor, Higgsless, ...)
⟨qL qR⟩ ~ ΛQCD³


114 GeV
160
170
200 GeV
1 TeV
m_h (SM)
① Banish scalars!
(Technicolor, Higgsless, ...)
$\langle q_L q_R \rangle \sim \Lambda_{QCD}$ chiral sym.
'Higgs'


114 GeV
160
170
200 GeV
1 TeV
m_h (SM)
① Banish scalars!
(Technicolor, Higgsless, ...)
$\langle q_L \bar{q}_R \rangle \sim \Lambda_{QCD}$ chiral sym.
'Higgs'

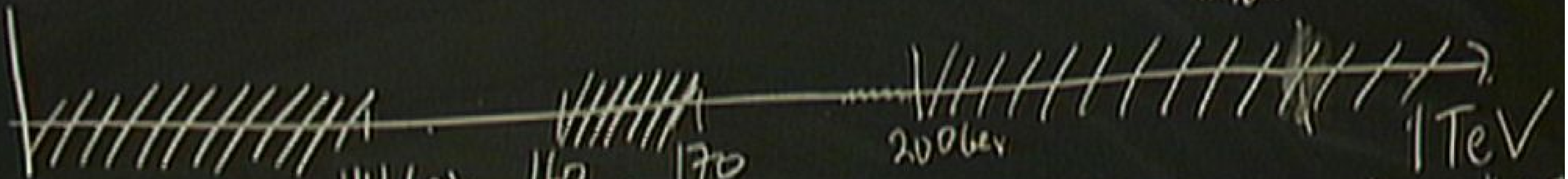

114 GeV
160
170
200 GeV
1 TeV
mh (SM)
① Banish scalars!
(Technicolor, Higgsless, ...)
~ ΛQCD chiral sym.
'Higgs'
② X dimensions:
Banish Mpl!


114 GeV
160
170
200 GeV
1 TeV
Mh (SM)
① Banish scalars!
(Technicolor, Higgsless, ...)
'Higgs'
② X dimensions
Banish
③ SUSY
Not one Higgs
→ two Higgs


W = λSHuHd
|Fs|² = λ²|Hu|²|Hd|²
mh² ∝ λ²
114 GeV
160
170
200 GeV
1 TeV
Mh (SM)
① Banish scalars!
(Technicolor, Higgsless, ...)
⟨qL qR⟩ ~ ΛQCD
'Higgs'
② X dim
Banish
③ SUSY
Not one Hig

$W = \lambda S H_u H_d \quad |F_S|^2 = \lambda^2 |H_u|^2 |H_d|^2$

$m_h^2 \propto \lambda^2$



m_h (SM)

① Banish scalars!

(Technicolor, Higgsless, ...)

$\langle q_L q_R \rangle \sim \Lambda_{QCD}$ chiral sym.

"Higgs"

② X dimensions; (makes o... Higgs...)

Banish M_{Pl}!

③ SUSY

Not one Higgs

→ two Higgs.

$W = \lambda S H_u H_d \qquad |F_S|^2 = \lambda^2 |H_u|^2 |H_d|^2$

$m_h^2 \propto \lambda^2$

114 GeV 160 170 200 GeV 1 TeV

M_h (SM)

...n Scalars!

...icolor, Higgsless, ...)

$\langle q_L q_R \rangle \sim \Lambda_{QCD}$ chiral sym.

"Higgs"

(2) X dimensions; (makes only Higgs ok!)

Banish M_{pl}!

(3) SUSY

Not one Higgs

$\longrightarrow$ Two Higgs.