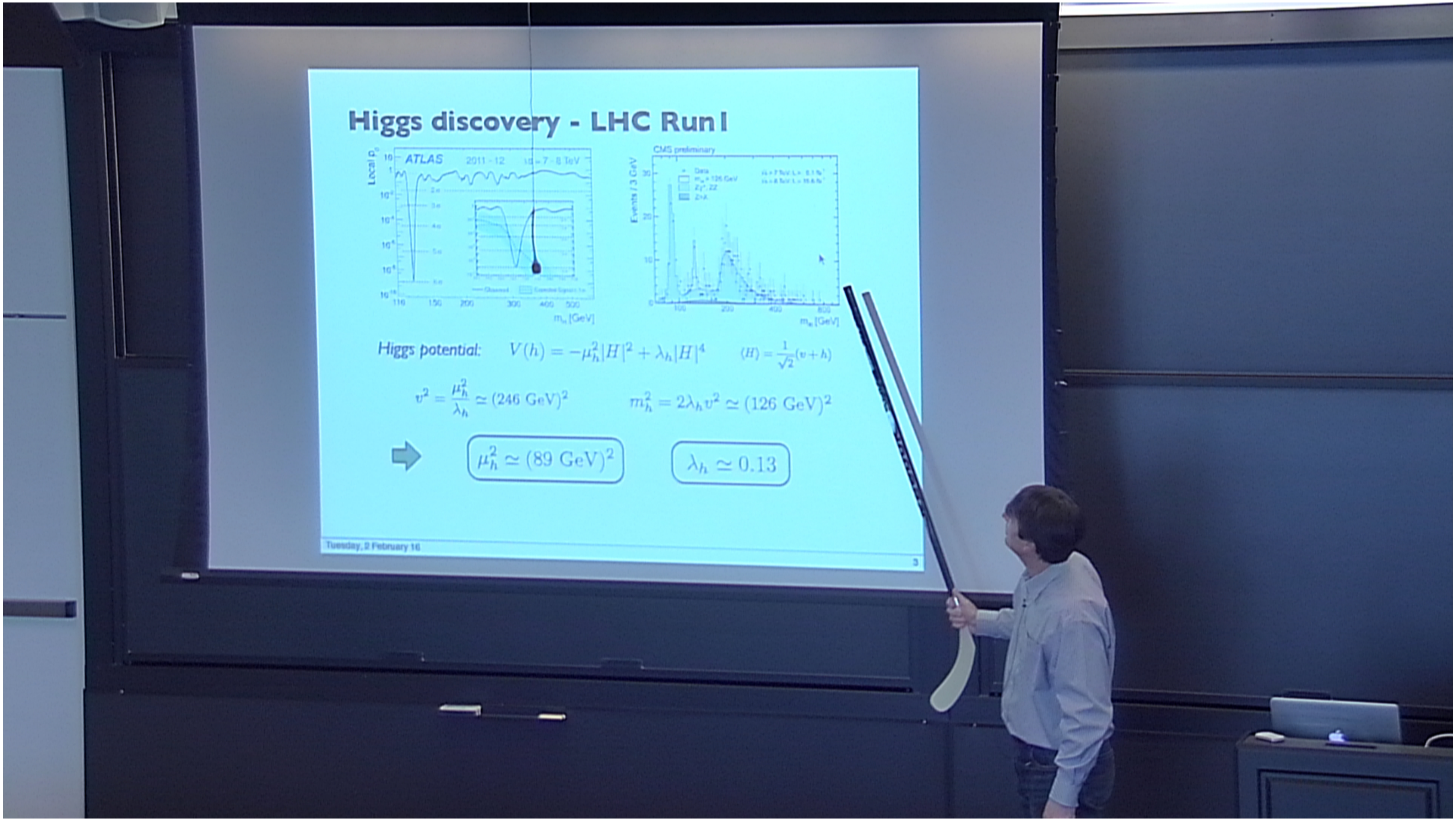
Title: The Unnatural (or Split) Composite Higgs

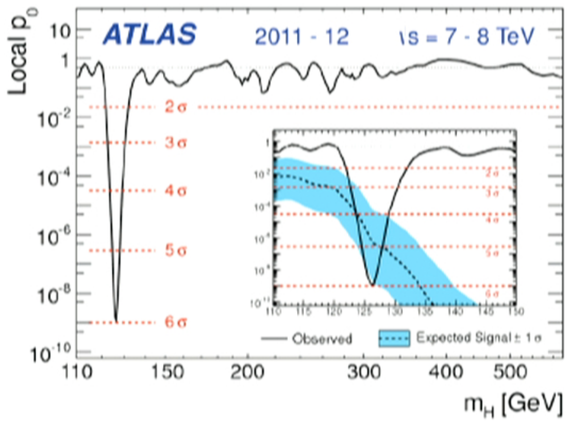
Date: Feb 02, 2016 01:00 PM

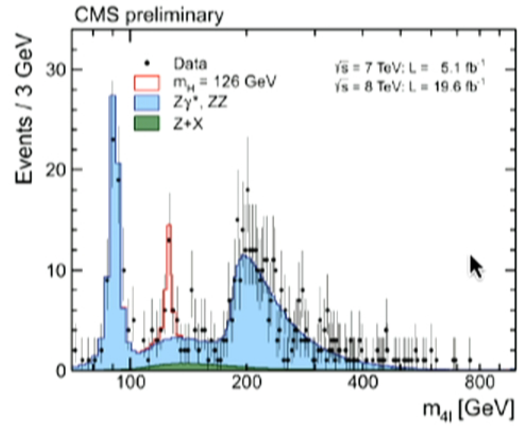
URL: http://pirsa.org/16020052

Abstract: <p>A simple way to trivially satisfy precision-electroweak and flavor constraints in composite Higgs models is to require a large global symmetry breaking scale, f > 10 TeV. This leads to a tuning of order 10^-4 to obtain the observed Higgs mass, but gives rise to a 'split' spectrum where the strong-sector resonances with masses greater than 10 TeV are separated from the pseudo Nambu-Goldstone bosons, which remain near the electroweak scale. To preserve gauge-coupling unification (due to a composite top quark), the symmetry breaking scale satisfies an upper bound f < 100-1000 TeV, which implies that the resonances are not arbitrarily heavy and may be accessible at future colliders. Furthermore, by identifying dark matter with a pseudo Nambu-Goldstone boson, the smallest coset space containing a stable, scalar singlet and an unbroken SU(5) symmetry is SU(7) / SU(6) x U(1). Interestingly, this coset space also contains a metastable color-triplet pseudo Nambu-Goldstone boson that can decay via a displaced vertex when produced at colliders, leading to a distinctive signal of unnaturalness.</p>


Higgs discovery - LHC Run I
ATLAS
2011 - 12
CMS preliminary
Higgs potential: $V(h) = -\mu_h^2|H|^2 + \lambda_h|H|^4$ $\langle H\rangle = \frac{1}{\sqrt{2}}(v+h)$
$v^2 = \frac{\mu_h^2}{\lambda_h} \simeq (246\ \mathrm{GeV})^2$
$m_h^2 = 2\lambda_h v^2 \simeq (126\ \mathrm{GeV})^2$
$\mu_h^2 \simeq (89\ \mathrm{GeV})^2$
$\lambda_h \simeq 0.13$
Tuesday, 2 February 16
3

Higgs discovery - LHC Run I





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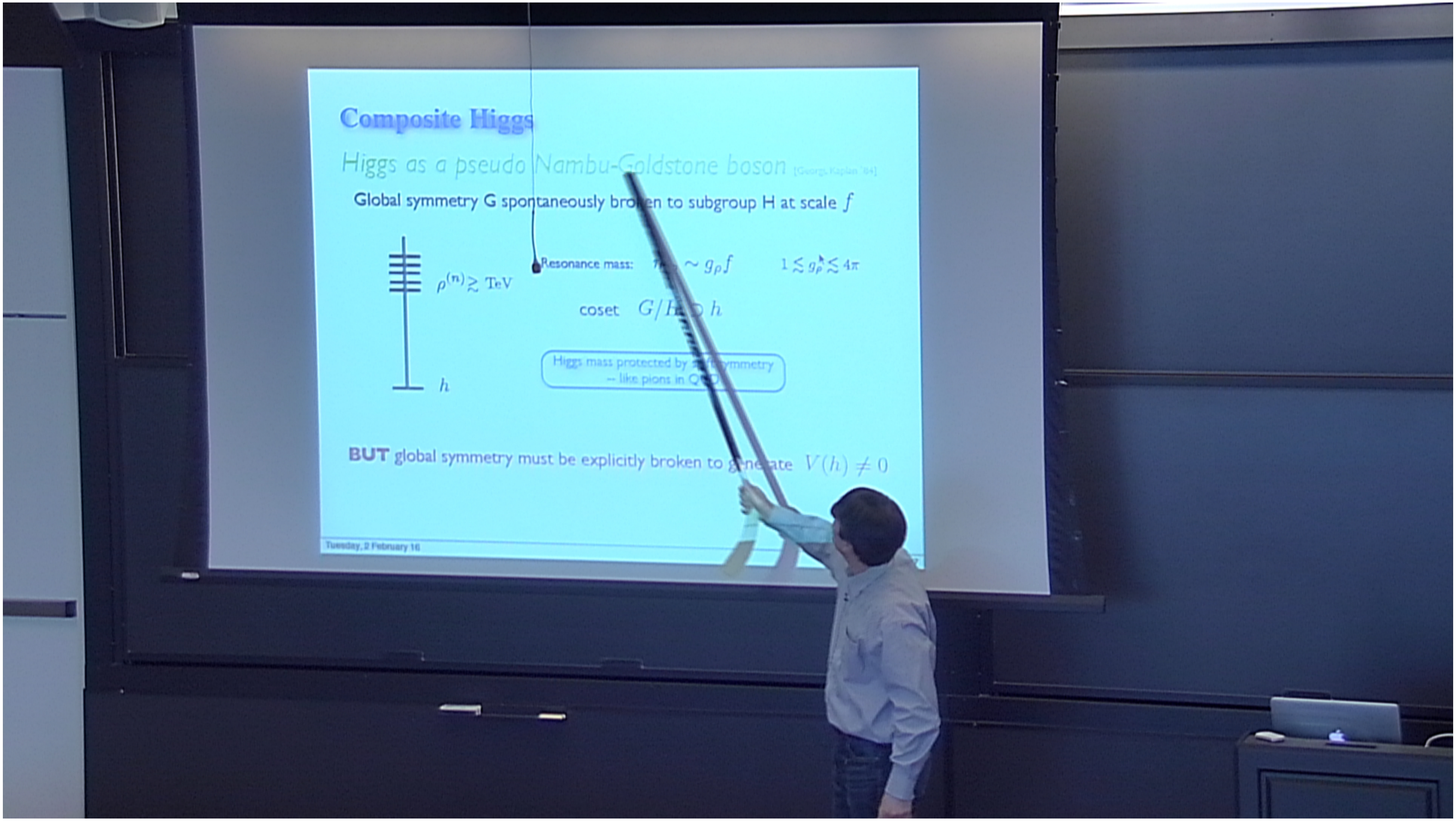
What is the nature of the Higgs boson?

HIGGS BOSON
- Elementary? → Standard Model/ Supersymmetry
- **OR**
- Composite? → New strong dynamics

Understanding why $m_h \ll M_p$ can help address shortcomings in the SM



Composite Higgs
Higgs as a pseudo Nambu-Goldstone boson [Georgi, Kaplan '84]
Global symmetry G spontaneously broken to subgroup H at scale f
Resonance mass:
$\sim g_\rho f$
$1 \lesssim g_\rho \lesssim 4\pi$
$\rho^{(n)} \gtrsim$ TeV
coset
h
BUT global symmetry must be explicitly broken to generate $V(h) \neq 0$
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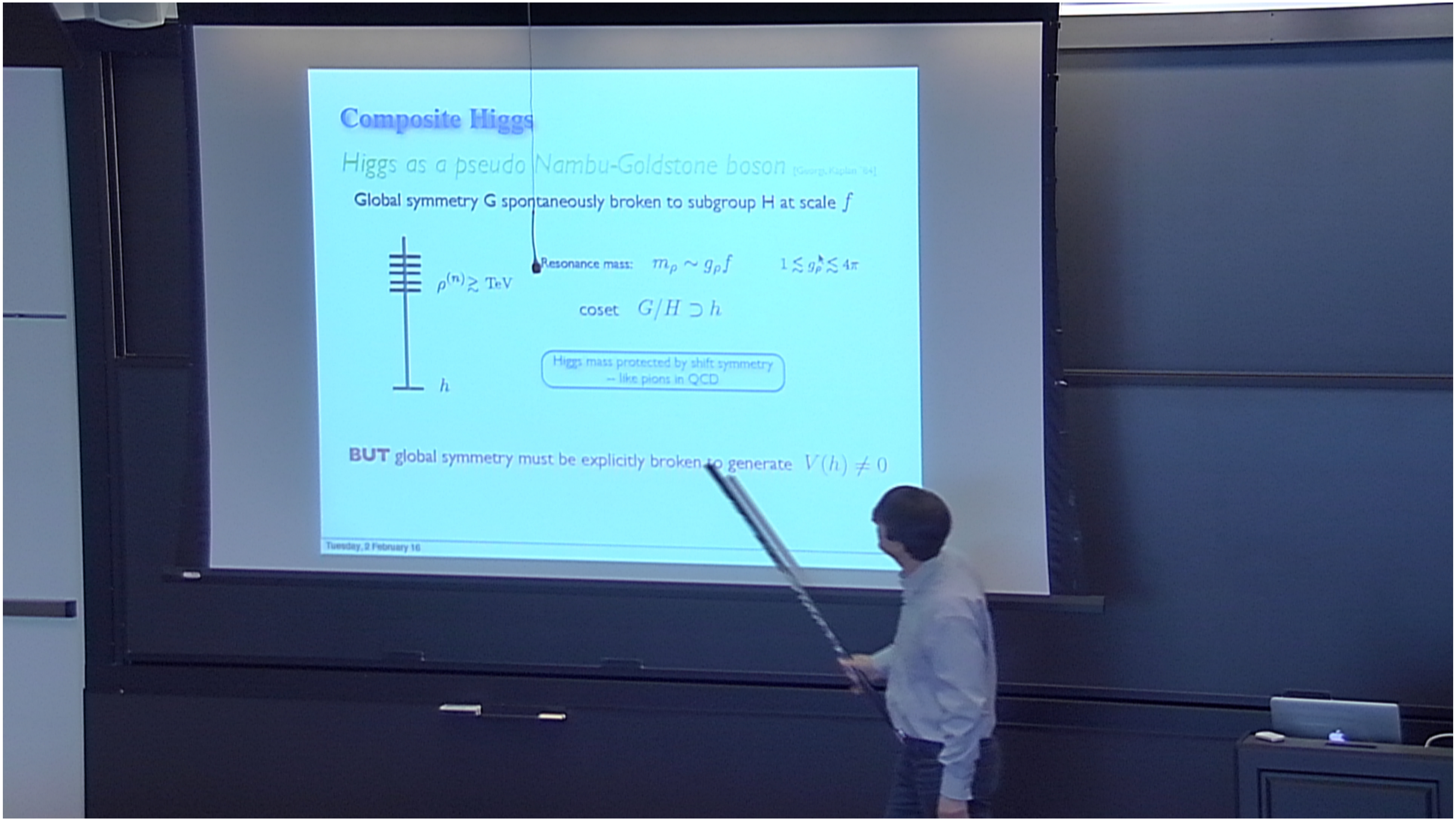

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$\rho^{(n)} \gtrsim$ TeV
coset $G/H \supset h$
Higgs mass protected by shift symmetry
-- like pions in QCD
h
BUT global symmetry must be explicitly broken to generate $V(h) \neq 0$
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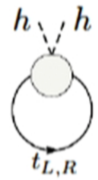
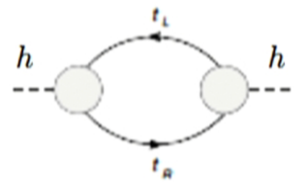
Global symmetry broken by mixing with elementary sector

[Contino, Nomura, Pomarol `03; Agashe, Contino, Pomarol `04]

SM matter and gauge fields Ψ_i, A_μ - - - $\mathcal{L}_{mix} = \lambda_{L,R}\bar{\Psi}_{L,R}\mathcal{O}_\Psi + g_V A^\mu J_\mu$ - - - strongly-coupled Higgs sector $\mathcal{O}_i$

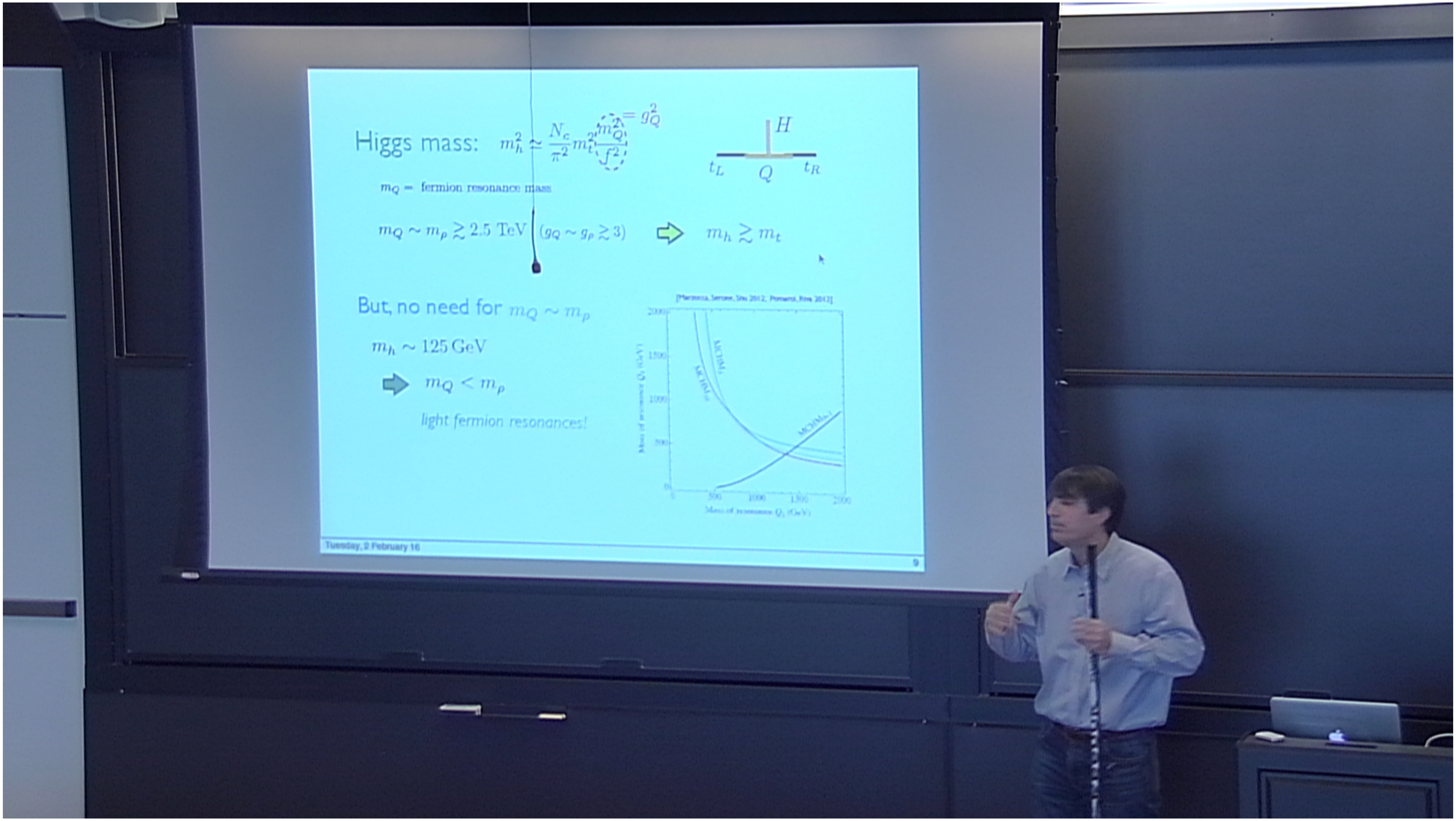
Higgs potential:





$V(h) = -\mu_h^2|H|^2 + \lambda_h|H|^4$ where $\mu_h^2 \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2 f^2$ $\lambda_h \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2$

EWSB $\left(\langle H\rangle = \frac{v}{\sqrt{2}}\right)$ $v^2 = \frac{\mu_h^2}{\lambda_h}$ ➡ **Prefers:** $f \sim v$


Higgs mass: $m_h^2 \simeq \frac{N_c}{\pi^2} m_t^2 \frac{m_Q^2}{f^2}$ $= g_Q^2$
H
t_L Q t_R
m_Q = fermion resonance mass
$m_Q \sim m_\rho \gtrsim 2.5$ TeV $(g_Q \sim g_\rho \gtrsim 3)$
$m_h \gtrsim m_t$
But, no need for $m_Q \sim m_\rho$
$m_h \sim 125\,\mathrm{GeV}$
$m_Q < m_\rho$
light fermion resonances!
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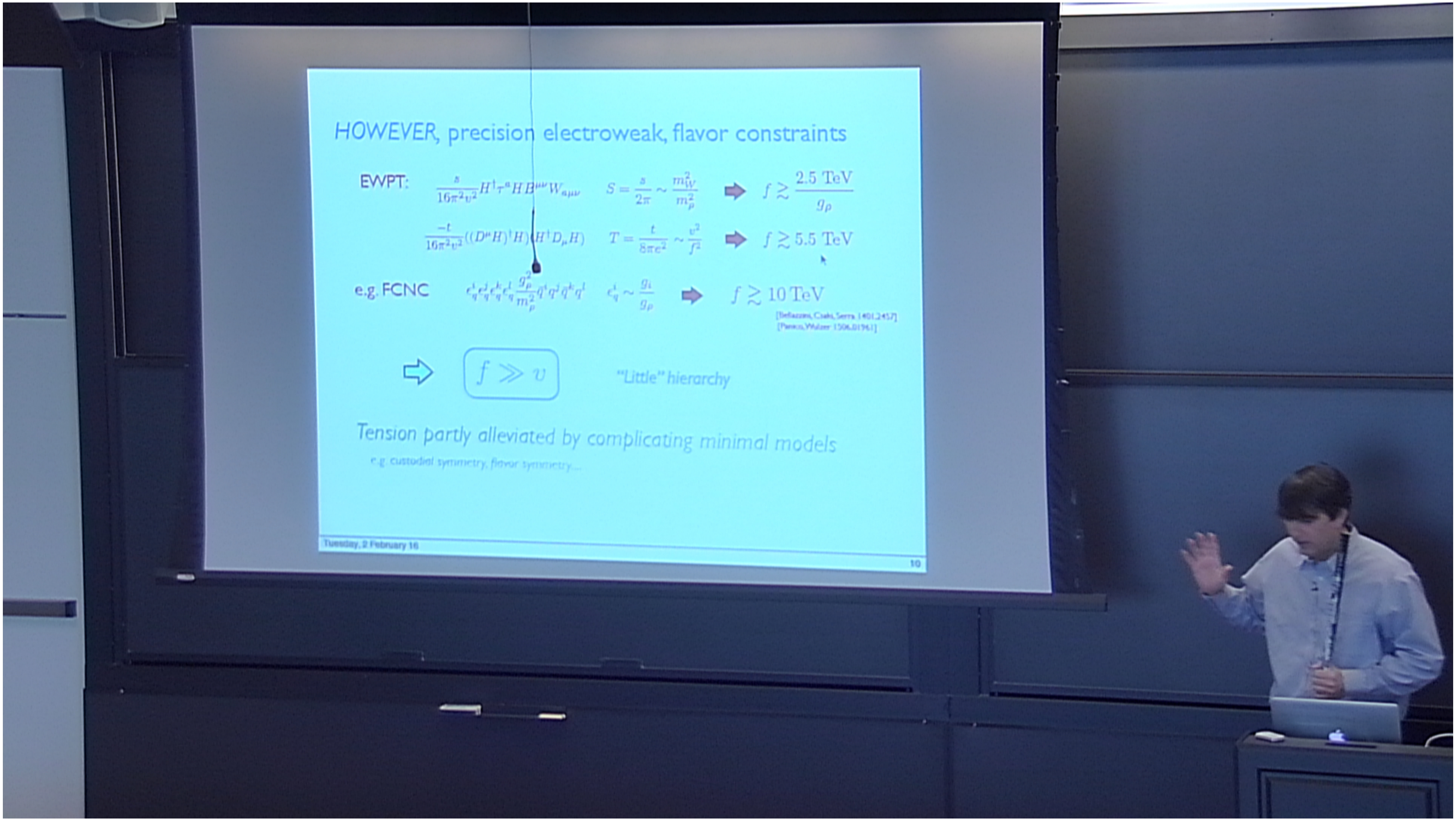
9


HOWEVER, precision electroweak, flavor constraints
EWPT:
$\frac{s}{16\pi^2 v^2} H^\dagger \tau^a H B^{\mu\nu} W_{a\mu\nu}$
$S = \frac{s}{2\pi} \sim \frac{m_W^2}{m_\rho^2}$
$f \gtrsim \frac{2.5\ \mathrm{TeV}}{g_\rho}$
$\frac{-t}{16\pi^2 v^2}((D^\mu H)^\dagger H)(H^\dagger D_\mu H)$
$T = \frac{t}{8\pi e^2} \sim \frac{v^2}{f^2}$
$f \gtrsim 5.5\ \mathrm{TeV}$
e.g. FCNC
$\epsilon_q^i \epsilon_q^j \epsilon_q^k \epsilon_q^l \frac{g_\rho^2}{m_\rho^2} q^i q^j q^k q^l$
$\epsilon_q^i \sim \frac{g_i}{g_\rho}$
$f \gtrsim 10\ \mathrm{TeV}$
$f \gg v$
"Little" hierarchy
Tension partly alleviated by complicating minimal models
e.g. custodial symmetry, flavor symmetry...
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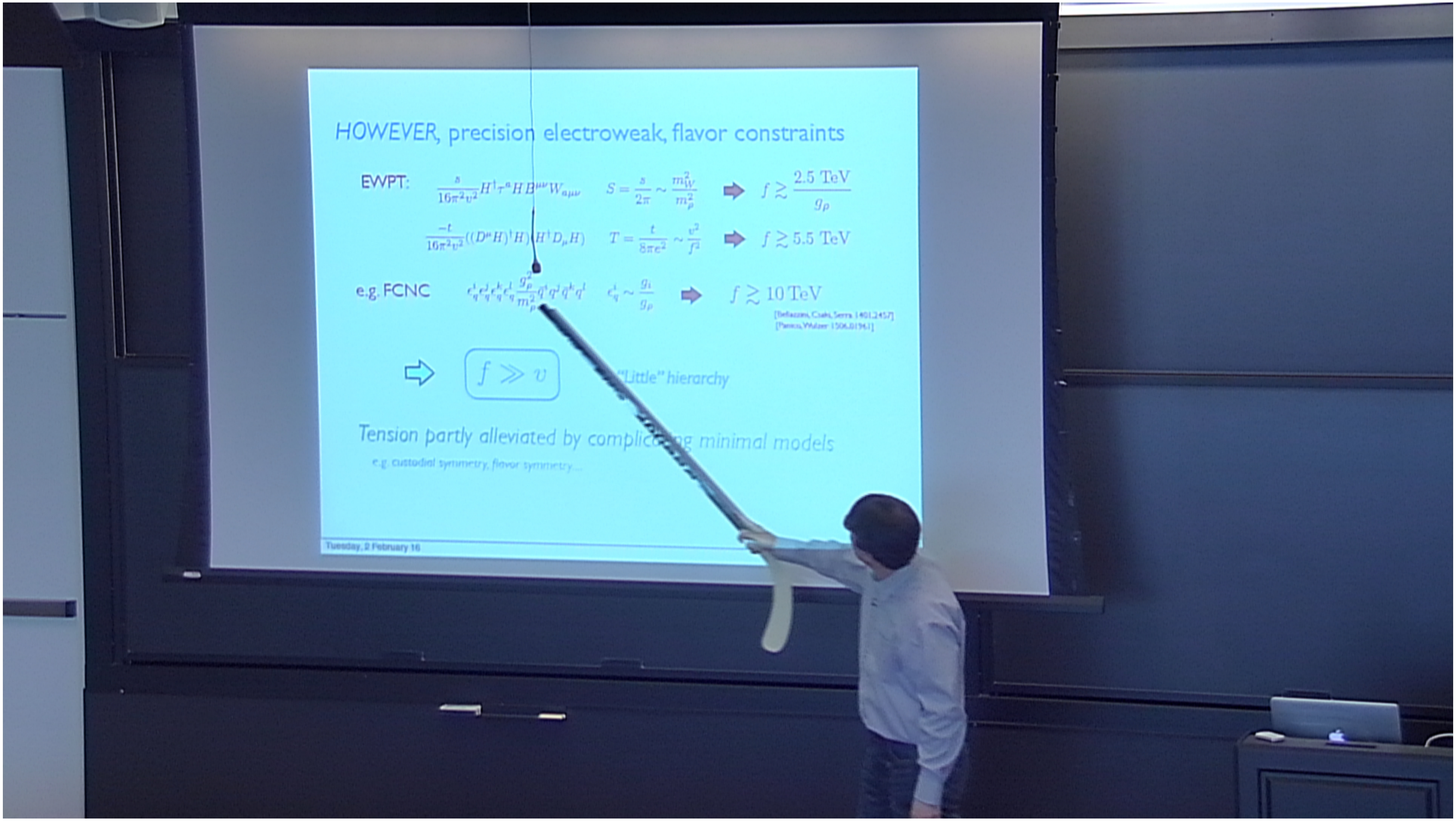
10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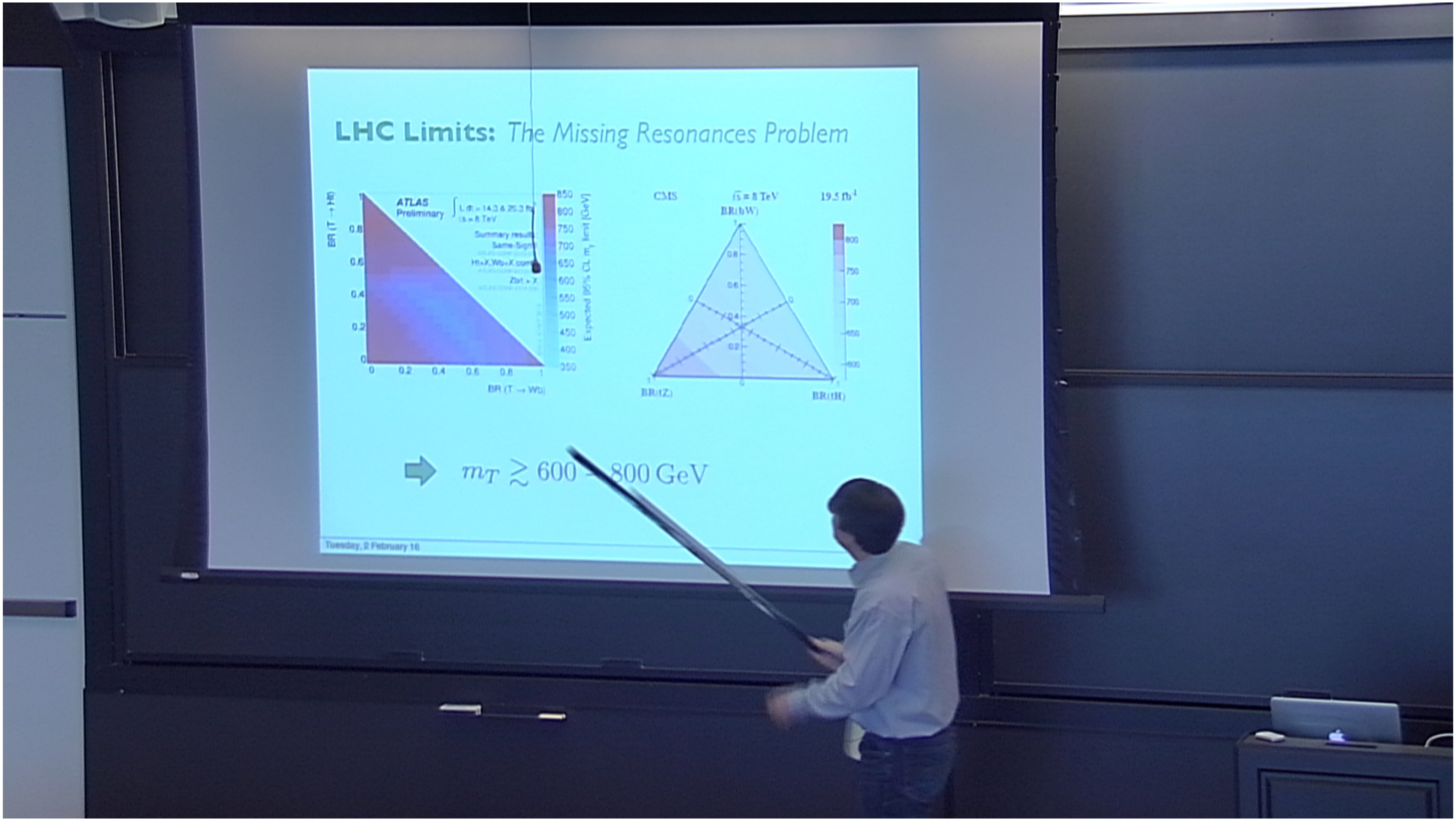
LHC Limits: The Missing Resonances Problem
ATLAS
Preliminary
Summary results
BR (T → Wb)
CMS
√s = 8 TeV
19.5 fb⁻¹
BR(bW)
BR(tZ)
BR(tH)
$m_T \gtrsim 600 - 800\,\mathrm{GeV}$
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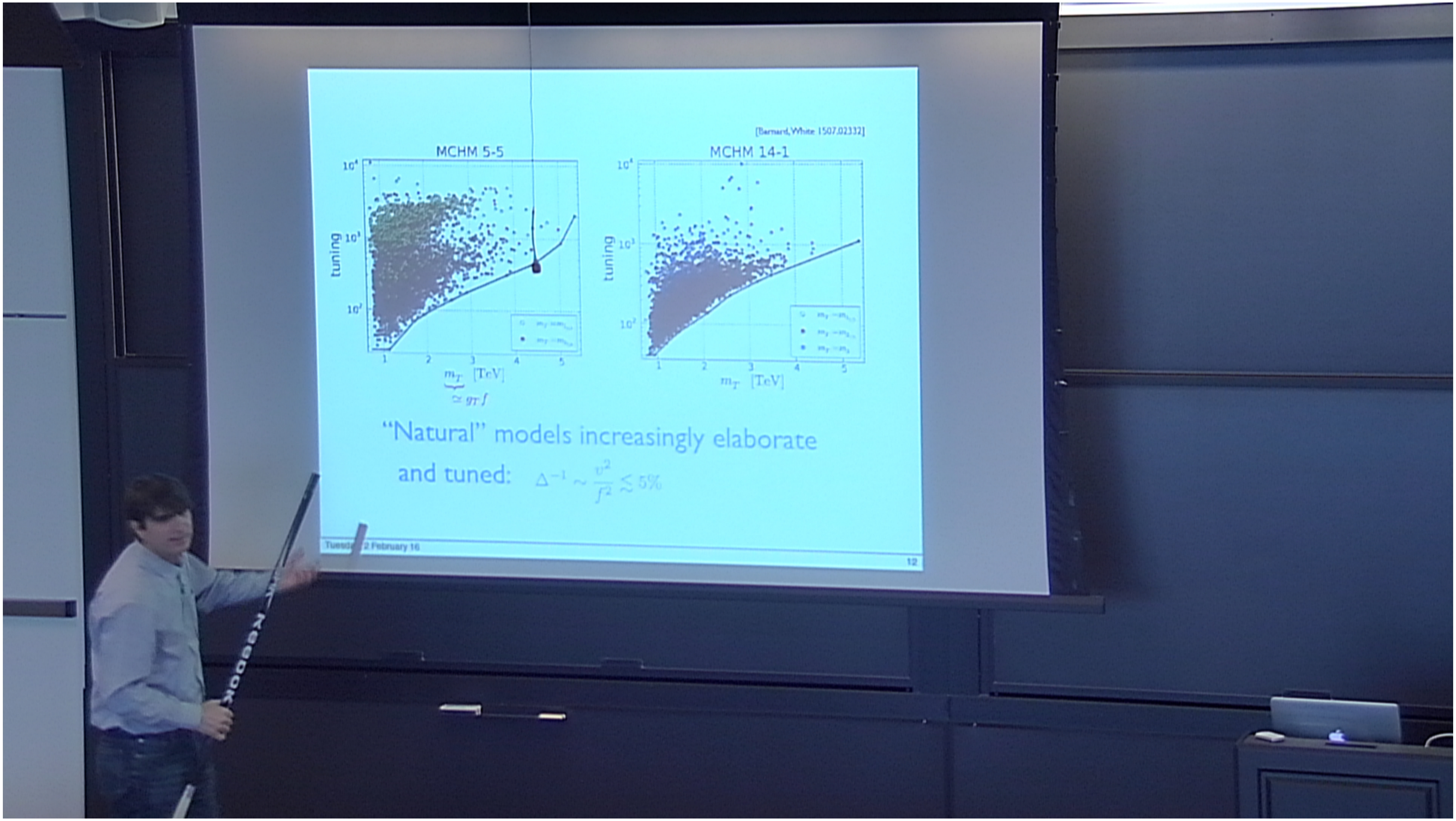

[Barnard, White 1507.02332]
MCHM 5-5
MCHM 14-1
tuning
m_T [TeV]
$\simeq g_T f$
“Natural” models increasingly elaborate
and tuned: $\Delta^{-1} \sim \frac{v^2}{f^2} \lesssim 5\%$
2 February 16
12

Simple solution:

Assume $f \gtrsim 10\,\mathrm{TeV}$ *-- no need for custodial or flavor symmetries!*

Tuned Higgs potential

$$V \sim c_2 f^2 |H|^2 + c_4 |H|^4$$

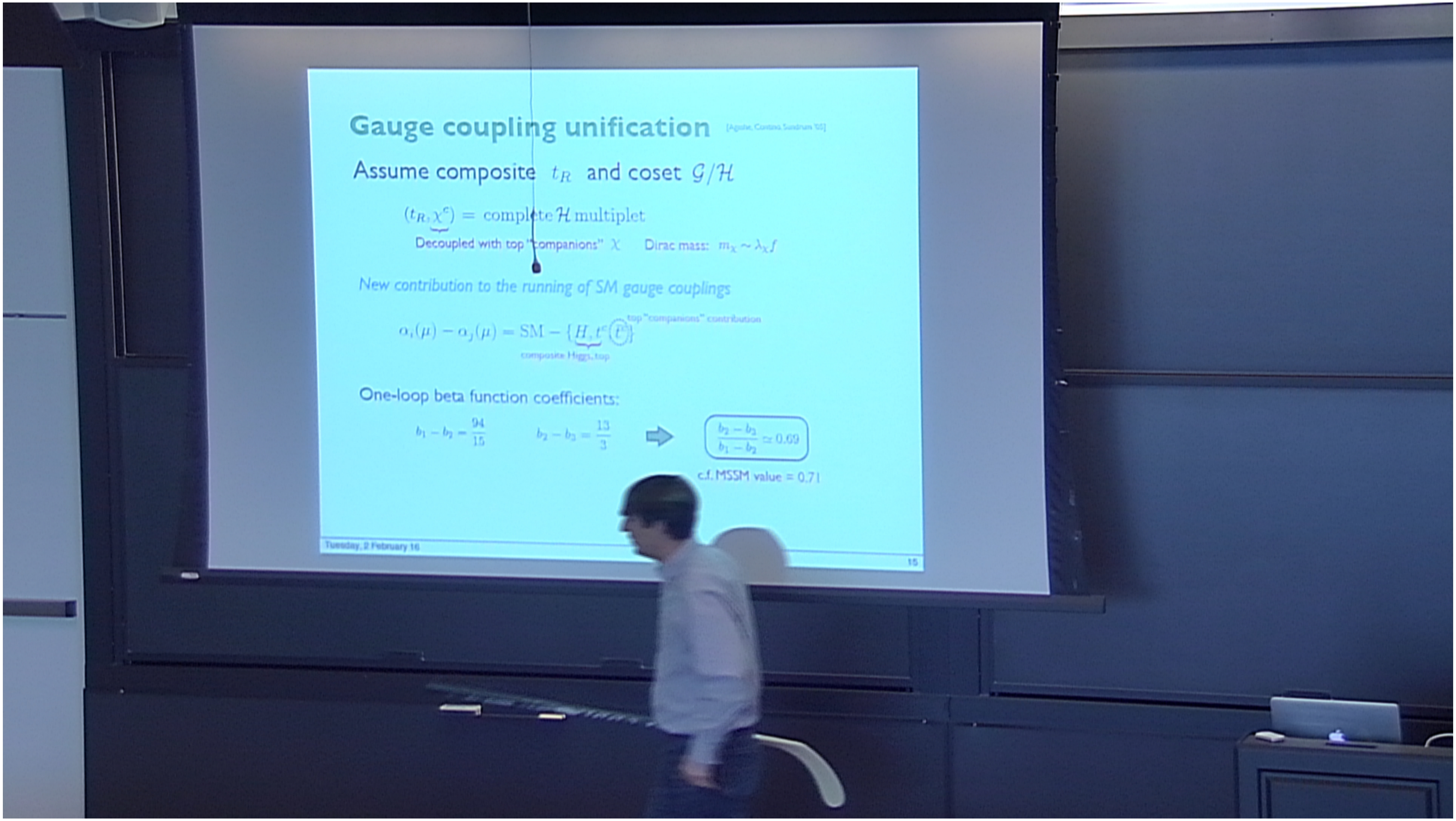
tuning $\frac{v^2}{f^2} \lesssim 10^{-4}$

This compares to $\sim 10^{-28}$ in SM!

e.g. QCD - sensitivity in neutron, proton mass $\frac{m_{u,d}}{m_{nucleon}} \sim 10^{-3}$

Is there a motivated upper bound for f ?

Yes! 


Gauge coupling unification
Assume composite t_R and coset $\mathcal{G}/\mathcal{H}$
$(t_R, \chi^c) =$ complete $\mathcal{H}$ multiplet
Decoupled with top "companions" χ
Dirac mass: $m_\chi \sim \lambda_\chi f$
New contribution to the running of SM gauge couplings
$\alpha_i(\mu) - \alpha_j(\mu) = \mathrm{SM} - \{H, t^c, t^c\}$
top "companions" contribution
composite Higgs, top
One-loop beta function coefficients:
$b_1 - b_2 = \frac{94}{15}$
$b_2 - b_3 = \frac{13}{3}$
$\frac{b_2 - b_3}{b_1 - b_2} \simeq 0.69$
c.f. MSSM value = 0.71
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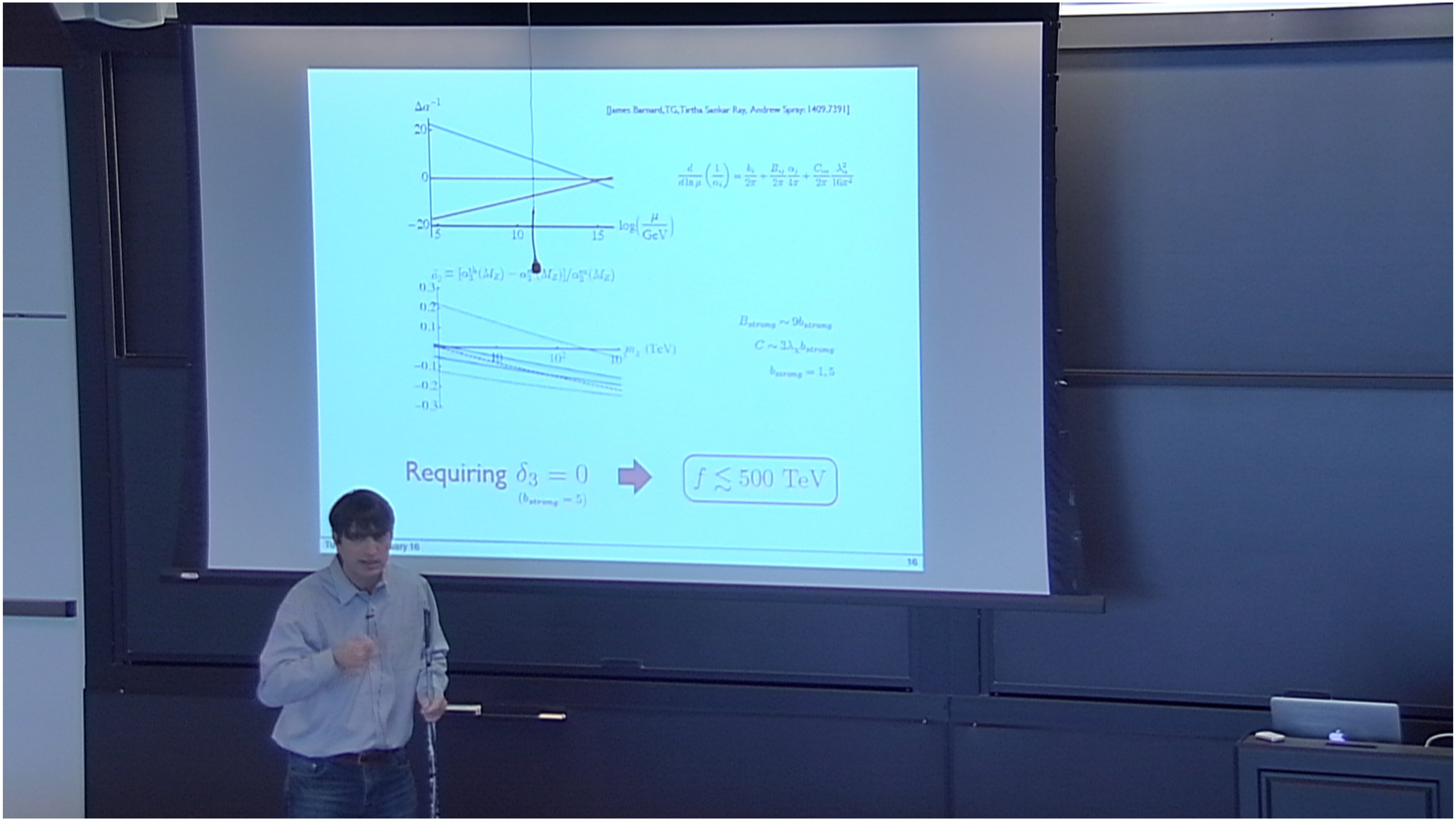
15



[James Barnard, TG, Tirtha Sankar Ray, Andrew Spray: 1409.7391]
$\frac{d}{d\ln\mu}\left(\frac{1}{\alpha_i}\right) = -\frac{b_i}{2\pi} + \frac{B_{ij}}{2\pi}\frac{\alpha_j}{4\pi} + \frac{C_{ia}}{2\pi}\frac{\lambda_a^2}{16\pi^2}$
$\Delta\alpha^{-1}$
$\log\left(\frac{\mu}{\text{GeV}}\right)$
m_χ (TeV)
$B_{strong} \sim 9 b_{strong}$
$C \sim 3\lambda_\chi b_{strong}$
$b_{strong} = 1, 5$
Requiring $\delta_3 = 0$
$(b_{strong} = 5)$
$f \lesssim 500$ TeV
16

Effective Lagrangian

Integrate out strong sector

$$
\begin{aligned}
\mathcal{L}_{\text{eff}} \supset\ & (\bar{\tilde{q}}^c, \bar{\tilde{e}})_{i_4 i_2} \not{p} (\tilde{q}^c, \tilde{e})^{j_4 j_2} \left[\Pi^{\chi\chi} (\lambda_\chi^{\mathbf{10}*})^{i_4 i_2}_{IJK} (\lambda_\chi^{\mathbf{10}})^{IJL}_{j_4 j_2} \right] \Sigma^K_L \\
& + (\bar{\tilde{q}}^c, \bar{\tilde{e}})_{i_4 i_2} \not{p} (\tilde{d}^c, \tilde{l})^{j_5} \left[\Pi^{\chi\chi} (\lambda_\chi^{\mathbf{10}*})^{i_4 i_2}_{IJK} (\lambda_\chi^{\mathbf{5}})^{IJL}_{j_5} \right] \Sigma^K_L + \text{h.c.} \\
& + (\bar{\tilde{d}}^c, \bar{\tilde{l}})_{i_5} \not{p} (\tilde{d}^c, \tilde{l})^{j_5} \left[\Pi^{\chi\chi} (\lambda_\chi^{\mathbf{5}*})^{i_5}_{IJK} (\lambda_\chi^{\mathbf{5}})^{IJL}_{j_5} \right] \Sigma^K_L \\
& + \bar{q}^{i_3 i_2} \not{p} q_{j_3 j_2} \left[\Pi^{tt} (\lambda_t^*)_{i_3 i_2, IJK} (\lambda_t)^{j_3 j_2, IJL} + \Pi^{bb} (\lambda_b^*)^{IJL}_{i_3 i_2} (\lambda_b)^{j_3 j_2}_{IJK} \right] \Sigma^K_L \\
& + \bar{b}^c_{i_3} \not{p} b^{c j_3} \left[\Pi^{b^c b^c} (\lambda_{b^c}{}^*)^{i_3}_{IJK} (\lambda_{b^c})^{IJL}_{j_3} \right] \Sigma^K_L \\
& + (\bar{\tilde{q}}^c, \bar{\tilde{e}})_{i_4 i_2} \not{p} q_{j_3 j_2} \left[\Pi^{\chi t} (\lambda_\chi^{\mathbf{10}*})^{i_4 i_2}_{IJK} (\lambda_t)^{j_3 j_2, IJL} \right] \Sigma^K_L + \text{h.c.} \\
& + (\bar{\tilde{d}}^c, \bar{\tilde{l}})_{i_5} \not{p} q_{j_3 j_2} \left[\Pi^{\chi t} (\lambda_\chi^{\mathbf{5}*})^{i_5}_{IJK} (\lambda_t)^{j_3 j_2, IJL} \right] \Sigma^K_L + \text{h.c.} \\
& + q_{i_3 i_2} b^{c j_3} \left[M^{b b^c} (\lambda_b)^{i_3 i_2}_{IJK} (\lambda_{b^c})^{IJL}_{j_3} \right] \Sigma^K_L + \text{h.c.}
\end{aligned}
$$

where $\Sigma = w^\dagger w$ = adjoint spurion (contains D,T and S)

Π, M^{bb^c} = momentum dependent form factors

Obtain:

$$V(|D|) = -\frac{\alpha}{f^2}|D|^2 + \frac{\beta}{f^4}|D|^4$$

HIGGS POTENTIAL

must be tuned

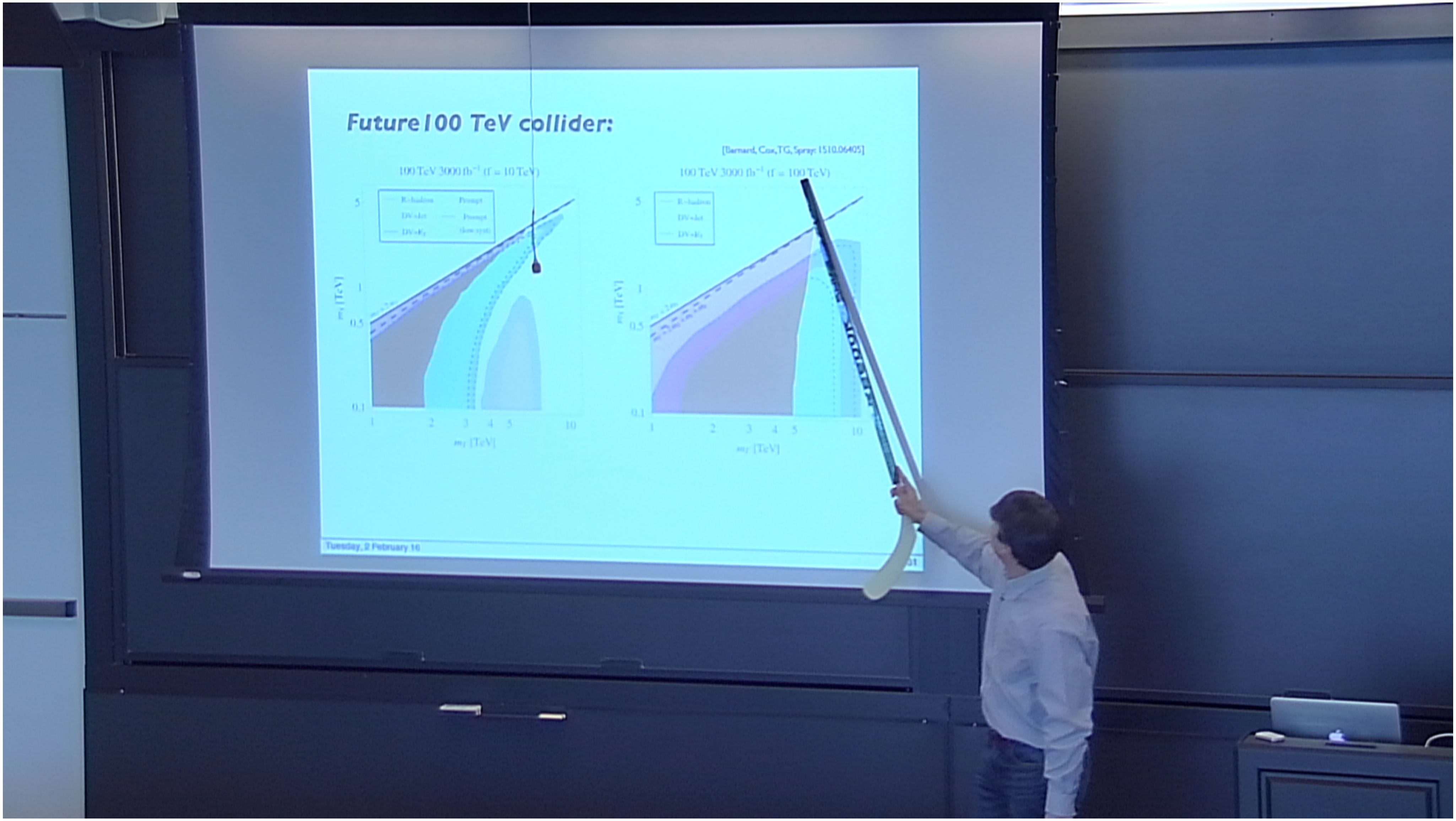
Electroweak VEV: $v = f\sqrt{\frac{\alpha}{\beta}}$

W-boson mass

Higgs mass: $m_h^2 = \frac{2\beta v^2}{f^4} = \frac{3c_2^\Lambda g_\rho^2}{8\pi^2} M_W^2$

Requires: $c_2^A \sim \frac{64}{g_\rho^2} \sim 0.5 - 4$

where
$$\alpha = \frac{g_\rho^2}{16\pi^2} f^4 \left(\frac{14}{3} c_1^\chi |\lambda_\chi|^2 - 2c_1^t |\lambda_t|^2 - 2c_1^b |\lambda_b|^2 + 2c_1^{b^c} |\lambda_{b^c}|^2 - \frac{9}{4} c_1^\Lambda g_2^2 \right)$$
$$\beta = \frac{g_\rho^2}{16\pi^2} f^4 \left(\frac{3}{4} c_2^\Lambda g_2^2 \right).$$


Future100 TeV collider:
[Barnard, Cox, TG, Spray: 1510.06405]
100 TeV 3000 fb⁻¹ (f = 10 TeV)
R-hadron
Prompt
DV+Jet
Prompt
DV+$\not{E}_T$
(low syst)
m_χ [TeV]
$m_{\tilde{t}}$ [TeV]
100 TeV 3000 fb⁻¹ (f = 100 TeV)
R-hadron
DV+Jet
DV+$\not{E}_T$
m_χ [TeV]
$m_{\tilde{t}}$ [TeV]
Tuesday, 2 February 16

Summary

- $f \gtrsim 10$ TeV simply eliminates all precision electroweak and flavor constraints
  - — *Higgs potential is tuned at 10^{-4} level*
  - — *"Unnatural" or "split" composite Higgs*
- SU(7)/SU(6)xU(1) minimal model
  - — *Improves gauge coupling unification*
  - — *Explains fermion mass hierarchy*
- Higgs partners: S = dark matter, T= color triplet
- Long-lived T decays = sign of unnaturalness!