Title: The Higgs Boson and speculative particle physics

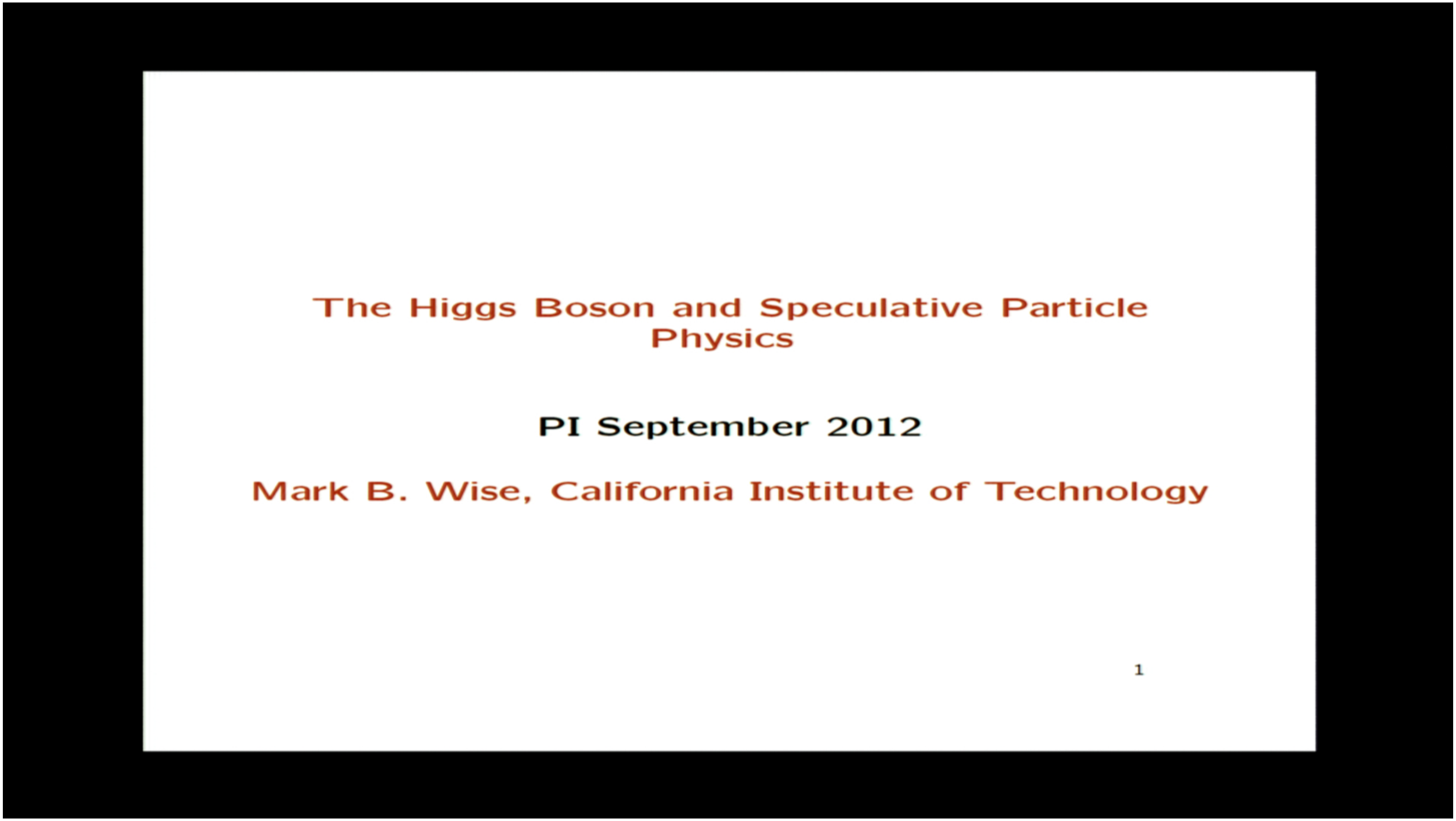
Date: Sep 19, 2012 02:00 PM

URL: http://pirsa.org/12090065

Abstract: The crucial role that the Higgs boson plays in the standard model for strong weak and electromagnetic interactions is reviewed.

Recently a resonance with properties consistent with those expected for the Higgs boson has been discovered at the large hadron collider (LHC).

This discovery
constrains speculations about new physics beyond what is in the standard model. The motivation for such new physics, at roughly the energy scale probed by LHC experiments, and the nature of the constraints imposed by the recent LHC results are discussed.



The Higgs Boson and Speculative Particle Physics

PI September 2012

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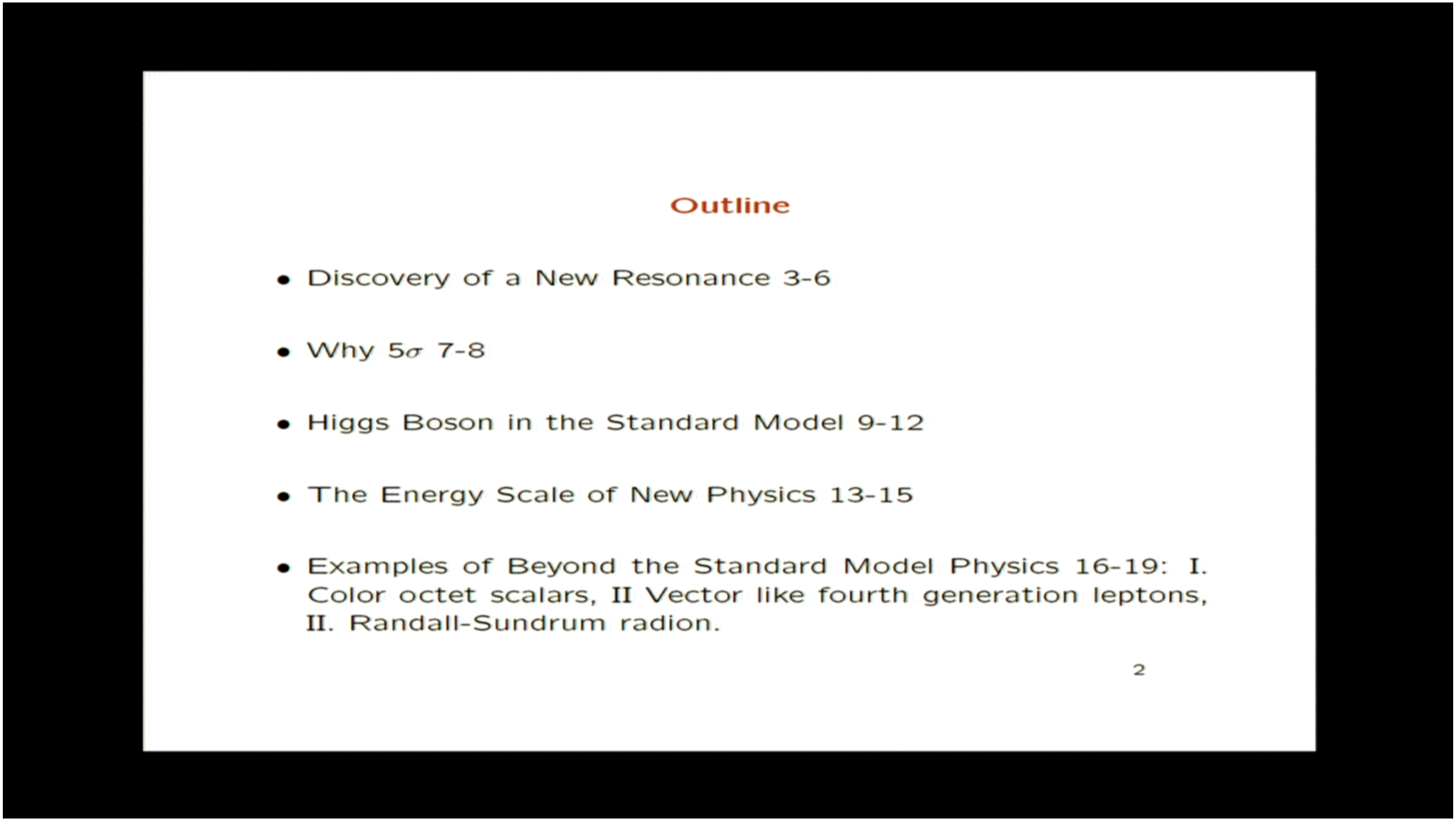

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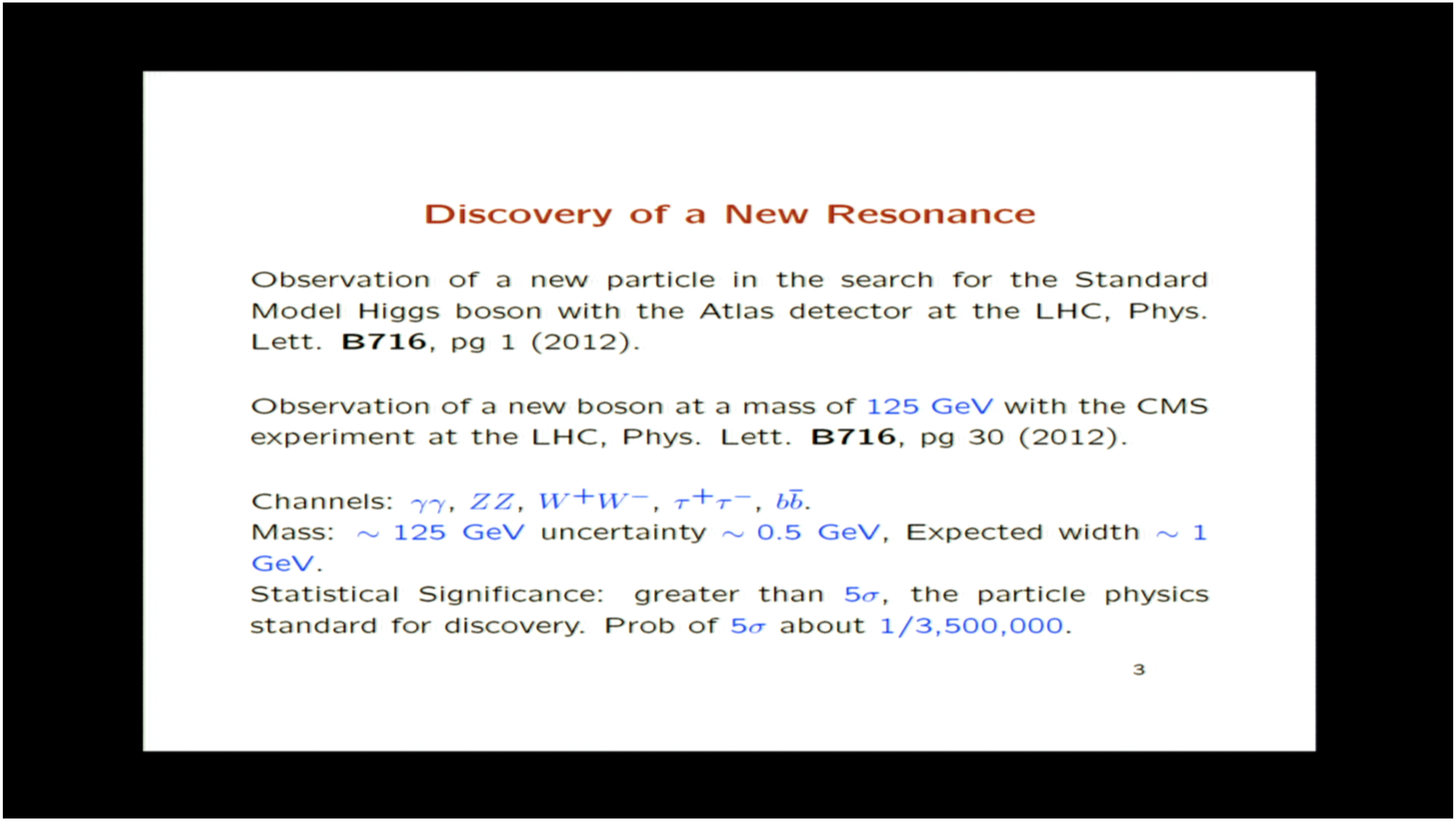
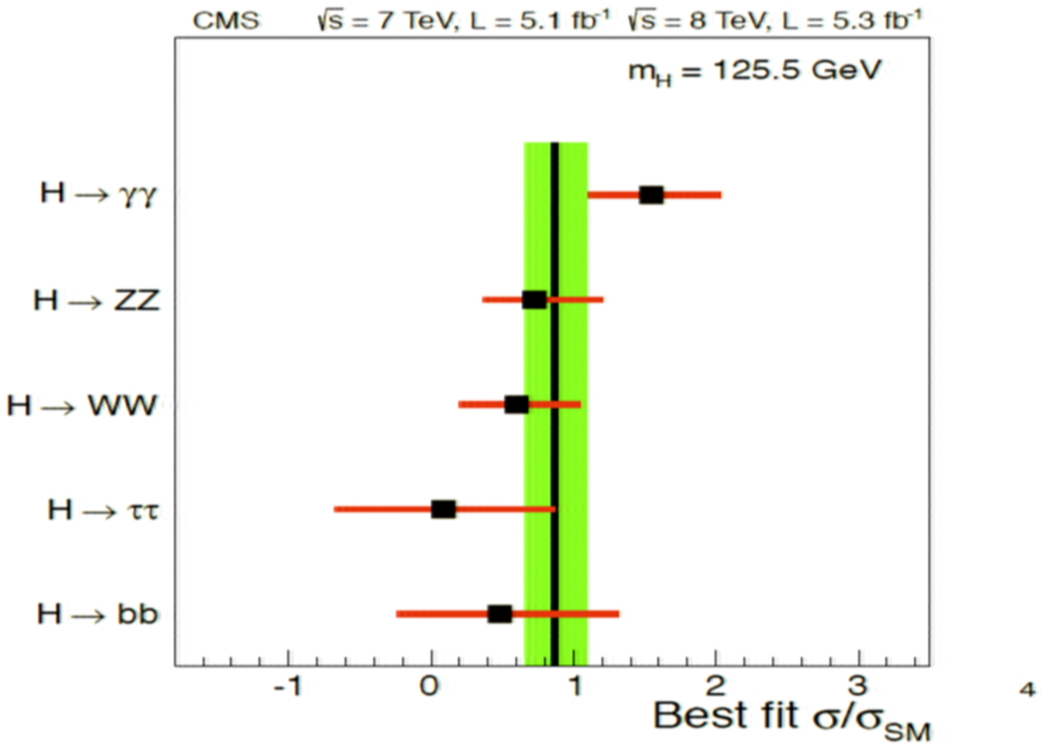


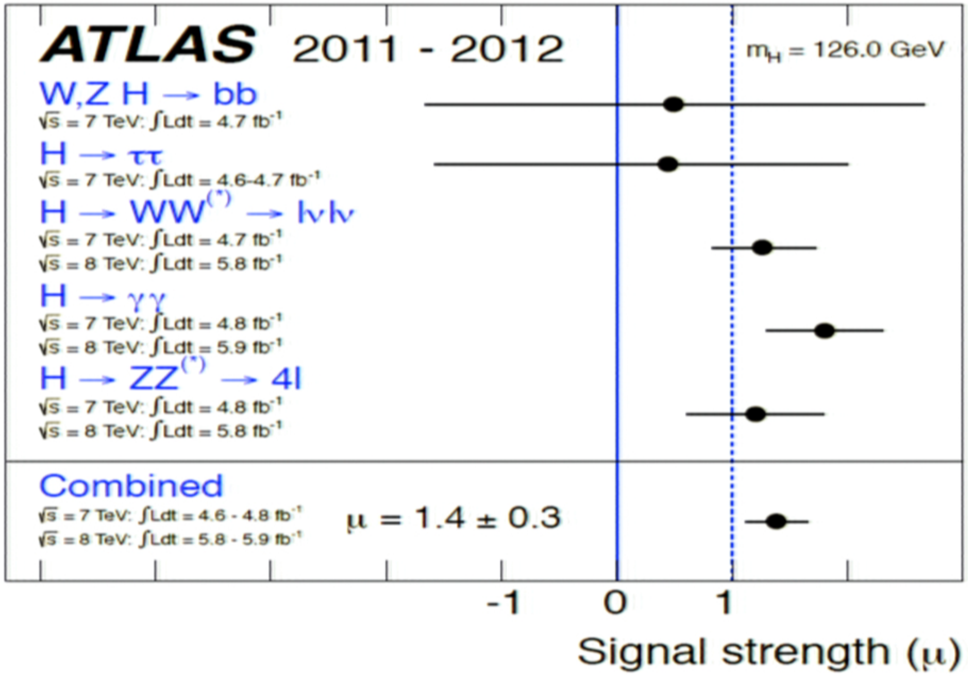
Discovery of a New Resonance

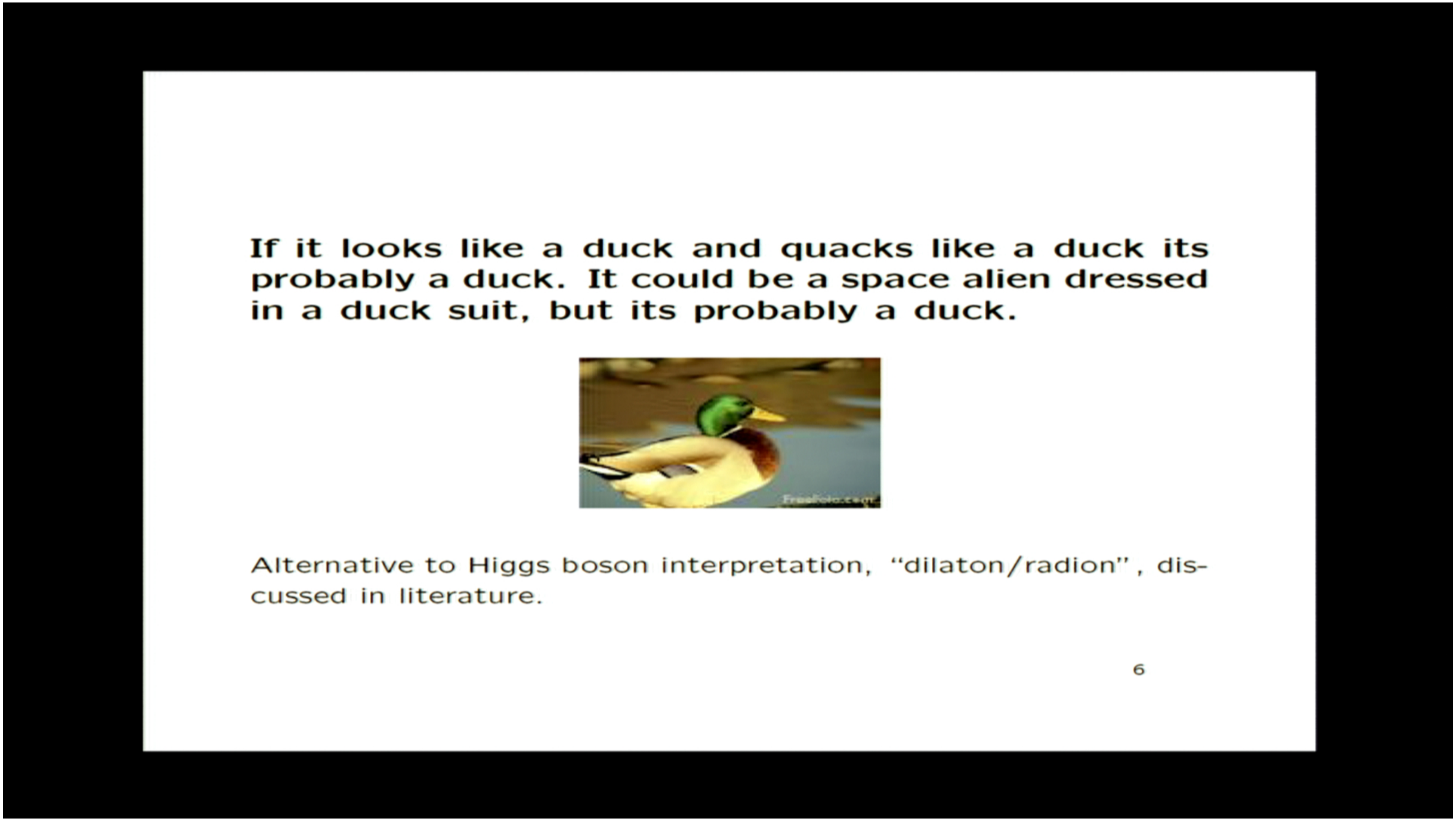
Observation of a new particle in the search for the Standard Model Higgs boson with the Atlas detector at the LHC, Phys. Lett. **B716**, pg 1 (2012).

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. **B716**, pg 30 (2012).

Channels: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, $b\bar{b}$.
Mass: $\sim$ 125 GeV uncertainty $\sim$ 0.5 GeV, Expected width $\sim$ 1 GeV.
Statistical Significance: greater than 5σ, the particle physics standard for discovery. Prob of 5σ about 1/3,500,000.

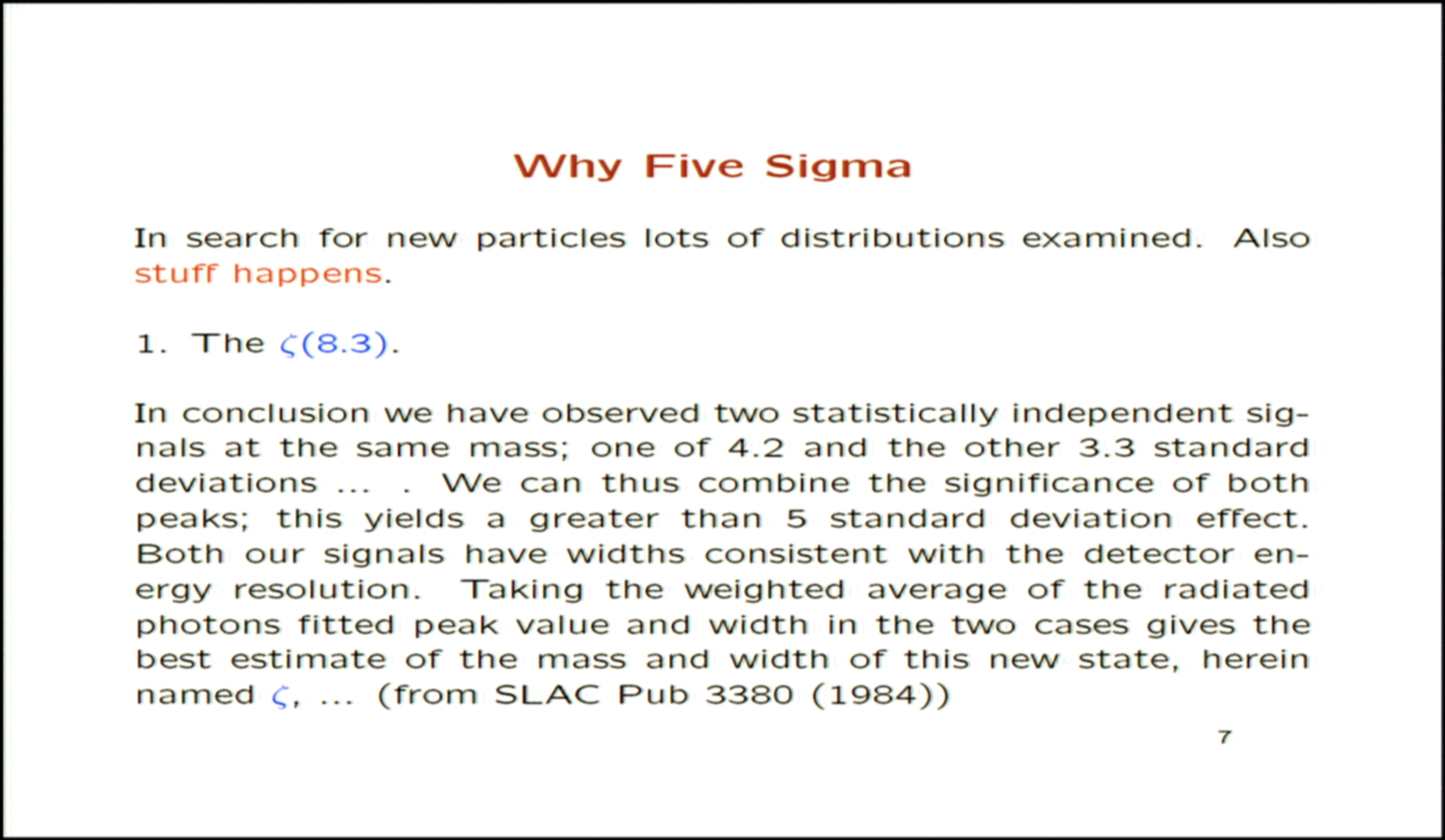

CMS
$\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1} $\sqrt{s}$ = 8 TeV, L = 5.3 fb^{-1}
m_H = 125.5 GeV
$H \rightarrow \gamma\gamma$
$H \rightarrow ZZ$
$H \rightarrow WW$
$H \rightarrow \tau\tau$
$H \rightarrow bb$
-1
0
1
2
3
4
Best fit σ/σ_{SM}


ATLAS 2011 - 2012
$m_H = 126.0$ GeV
W,Z H → bb
$\sqrt{s} = 7$ TeV: $\int Ldt = 4.7$ fb^{-1}
H → ττ
$\sqrt{s} = 7$ TeV: $\int Ldt = 4.6$-4.7 fb^{-1}
H → WW$^{(*)}$ → lνlν
$\sqrt{s} = 7$ TeV: $\int Ldt = 4.7$ fb^{-1}
$\sqrt{s} = 8$ TeV: $\int Ldt = 5.8$ fb^{-1}
H → γγ
$\sqrt{s} = 7$ TeV: $\int Ldt = 4.8$ fb^{-1}
$\sqrt{s} = 8$ TeV: $\int Ldt = 5.9$ fb^{-1}
H → ZZ$^{(*)}$ → 4l
$\sqrt{s} = 7$ TeV: $\int Ldt = 4.8$ fb^{-1}
$\sqrt{s} = 8$ TeV: $\int Ldt = 5.8$ fb^{-1}
Combined
$\sqrt{s} = 7$ TeV: $\int Ldt = 4.6$ - 4.8 fb^{-1}
$\sqrt{s} = 8$ TeV: $\int Ldt = 5.8$ - 5.9 fb^{-1}
μ = 1.4 ± 0.3
-1
0
1
Signal strength (μ)



If it looks like a duck and quacks like a duck its probably a duck. It could be a space alien dressed in a duck suit, but its probably a duck.

Alternative to Higgs boson interpretation, "dilaton/radion", discussed in literature.

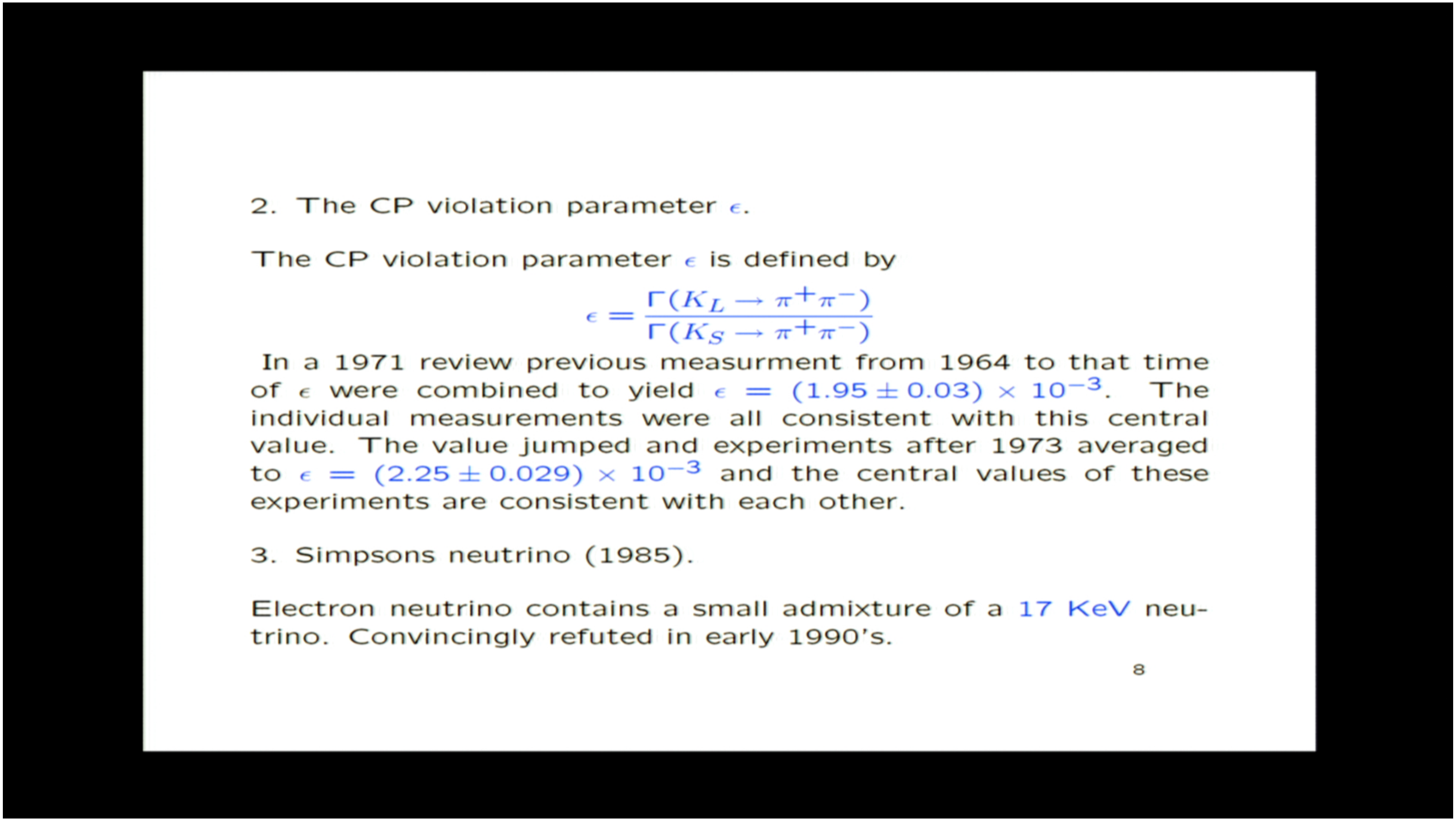


Why Five Sigma

In search for new particles lots of distributions examined. Also stuff happens.

1. The $\zeta(8.3)$.

In conclusion we have observed two statistically independent signals at the same mass; one of 4.2 and the other 3.3 standard deviations ... . We can thus combine the significance of both peaks; this yields a greater than 5 standard deviation effect. Both our signals have widths consistent with the detector energy resolution. Taking the weighted average of the radiated photons fitted peak value and width in the two cases gives the best estimate of the mass and width of this new state, herein named ζ, ... (from SLAC Pub 3380 (1984))



2. The CP violation parameter ϵ.

The CP violation parameter ϵ is defined by

$$\epsilon = \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)}$$

In a 1971 review previous measurment from 1964 to that time of ϵ were combined to yield $\epsilon = (1.95 \pm 0.03) \times 10^{-3}$. The individual measurements were all consistent with this central value. The value jumped and experiments after 1973 averaged to $\epsilon = (2.25 \pm 0.029) \times 10^{-3}$ and the central values of these experiments are consistent with each other.

3. Simpsons neutrino (1985).

Electron neutrino contains a small admixture of a 17 KeV neutrino. Convincingly refuted in early 1990's.

The Higgs Boson in the Standard Model

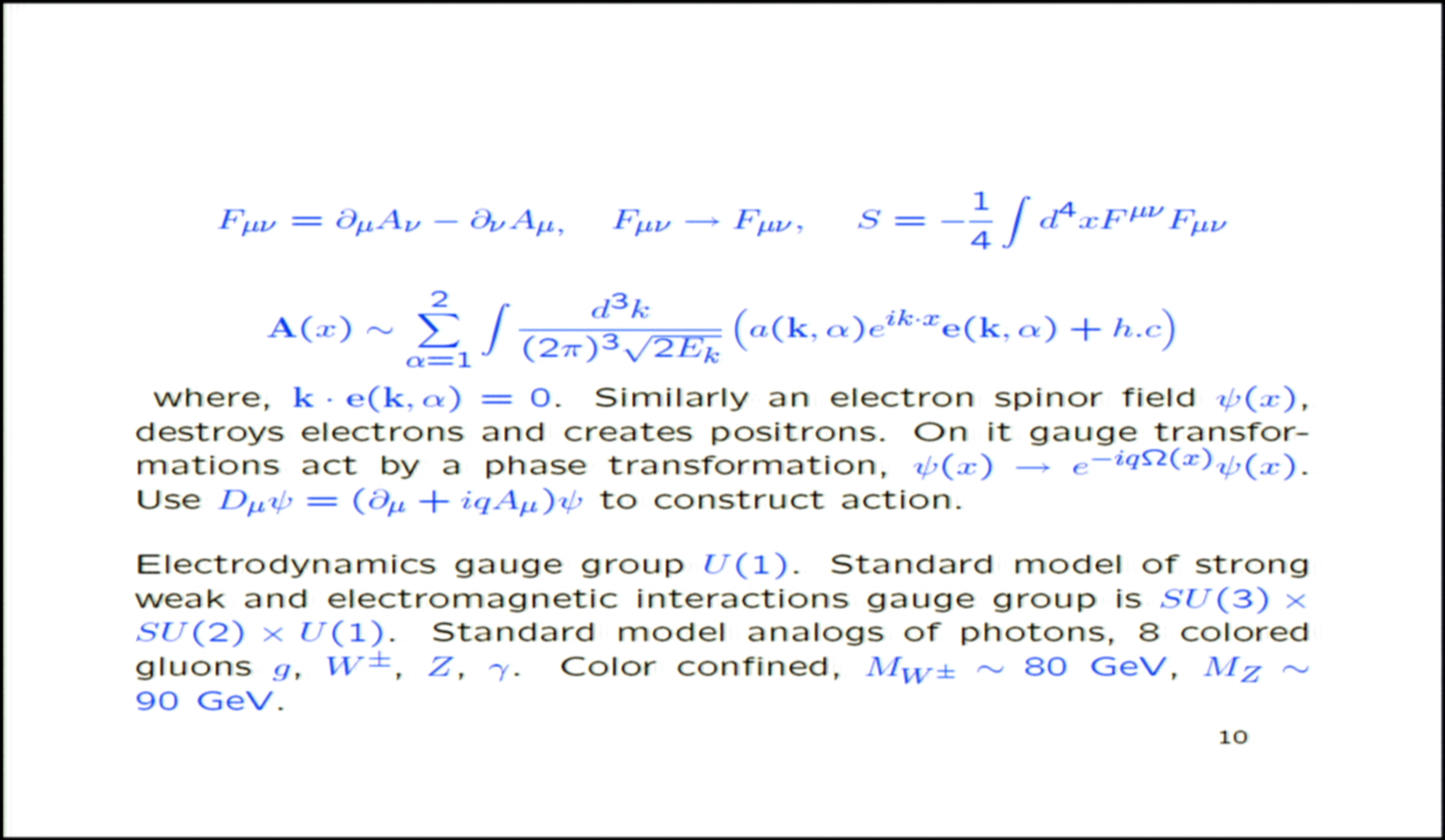
Standard model is a generalization of electrodynamics of electrons and photons. Often we will use perturbation theory. Beyond leading order it contains sums over states that are eignstates of the unperturbed Hamiltonian. For us the unperturbed Hamiltonian is one that describes free non interacting particles. Put system in box and states labelled by quantum number

$$p_j = \frac{2\pi n_j}{L} \sum_{n_1,n_2,n_3} \rightarrow L^3 \int \frac{d^3p}{(2\pi)^3}$$

Electromagnetism based on principle of gauge invariance. Photon field

$$A_\mu \rightarrow A_\mu + \partial_\mu \Omega(x).$$

No mass term $\int d^4x(1/2)A_\mu A^\mu$ in action because of gauge invariance.

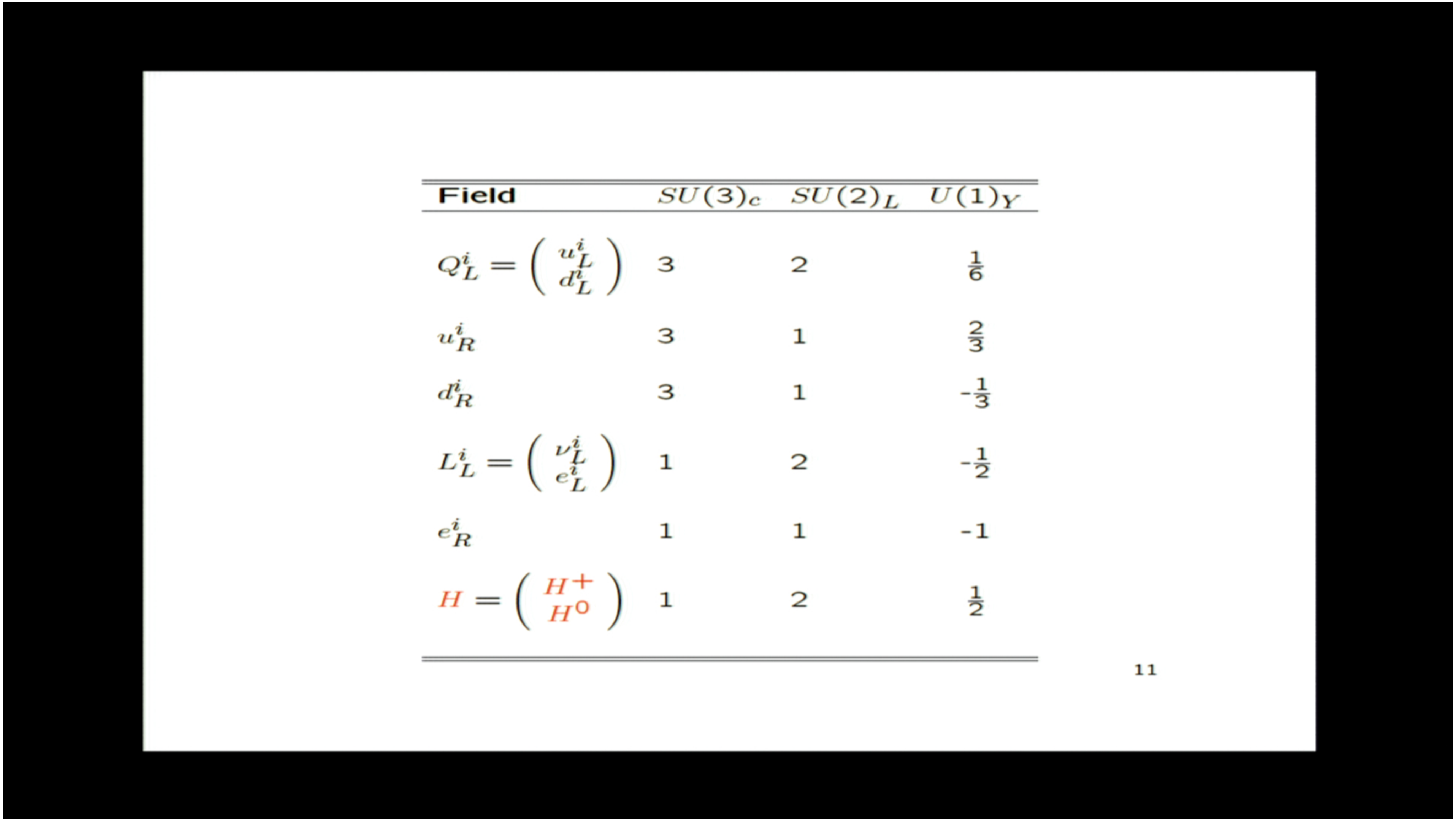


$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad F_{\mu\nu} \to F_{\mu\nu}, \quad S = -\frac{1}{4}\int d^4x F^{\mu\nu} F_{\mu\nu}$$

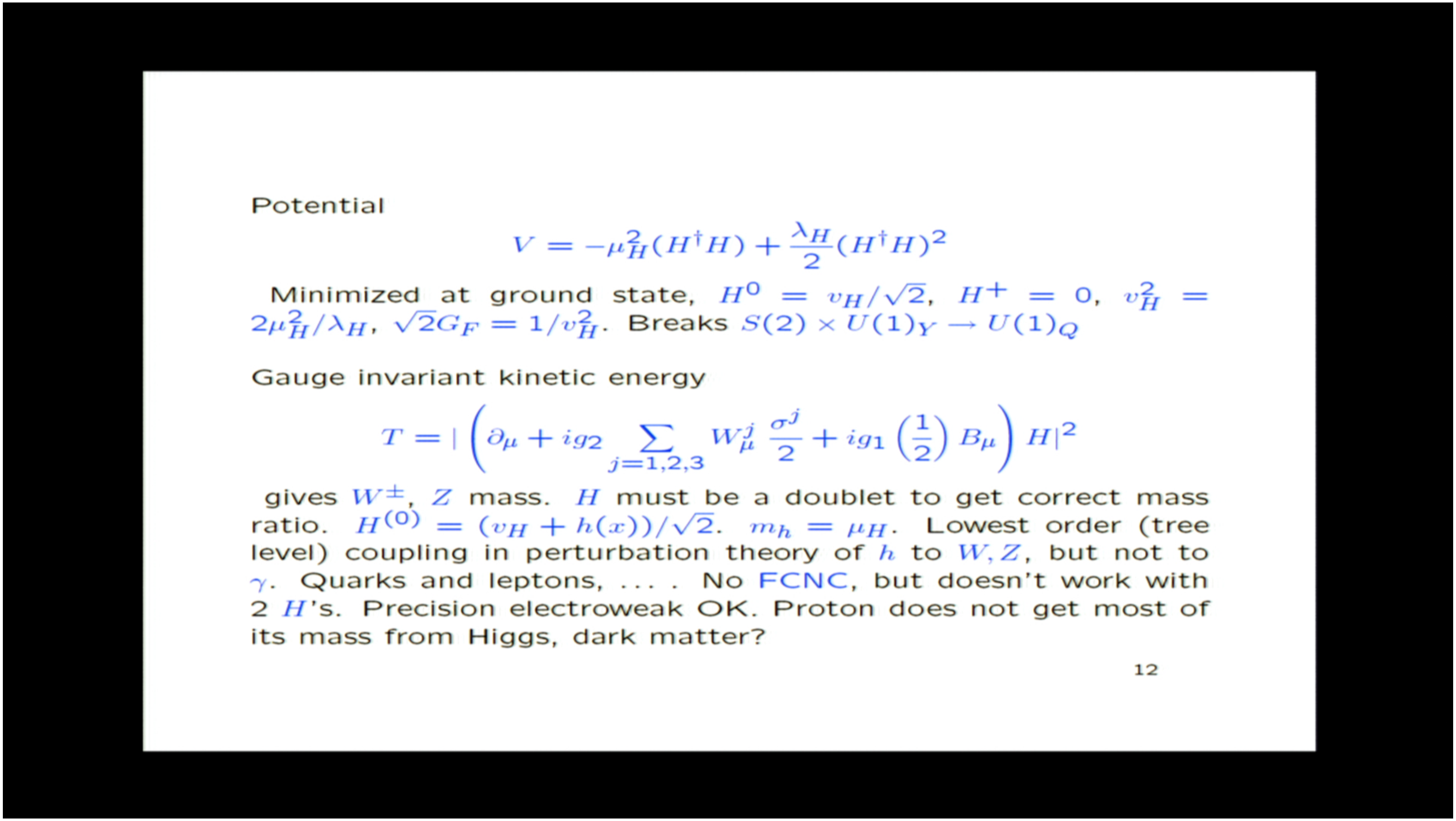
$$\mathbf{A}(x) \sim \sum_{\alpha=1}^{2} \int \frac{d^3k}{(2\pi)^3\sqrt{2E_k}} \left(a(\mathbf{k},\alpha)e^{ik\cdot x}\mathbf{e}(\mathbf{k},\alpha) + h.c\right)$$

where, $\mathbf{k}\cdot\mathbf{e}(\mathbf{k},\alpha) = 0$. Similarly an electron spinor field $\psi(x)$, destroys electrons and creates positrons. On it gauge transformations act by a phase transformation, $\psi(x) \to e^{-iq\Omega(x)}\psi(x)$. Use $D_\mu\psi = (\partial_\mu + iqA_\mu)\psi$ to construct action.

Electrodynamics gauge group $U(1)$. Standard model of strong weak and electromagnetic interactions gauge group is $SU(3) \times SU(2) \times U(1)$. Standard model analogs of photons, 8 colored gluons g, $W^{\pm}$, Z, γ. Color confined, $M_{W^\pm} \sim 80$ GeV, $M_Z \sim 90$ GeV.



Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
$Q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$	3	2	$\frac{1}{6}$
u_R^i	3	1	$\frac{2}{3}$
d_R^i	3	1	$-\frac{1}{3}$
$L_L^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$	1	2	$-\frac{1}{2}$
e_R^i	1	1	-1
$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$	1	2	$\frac{1}{2}$



Potential

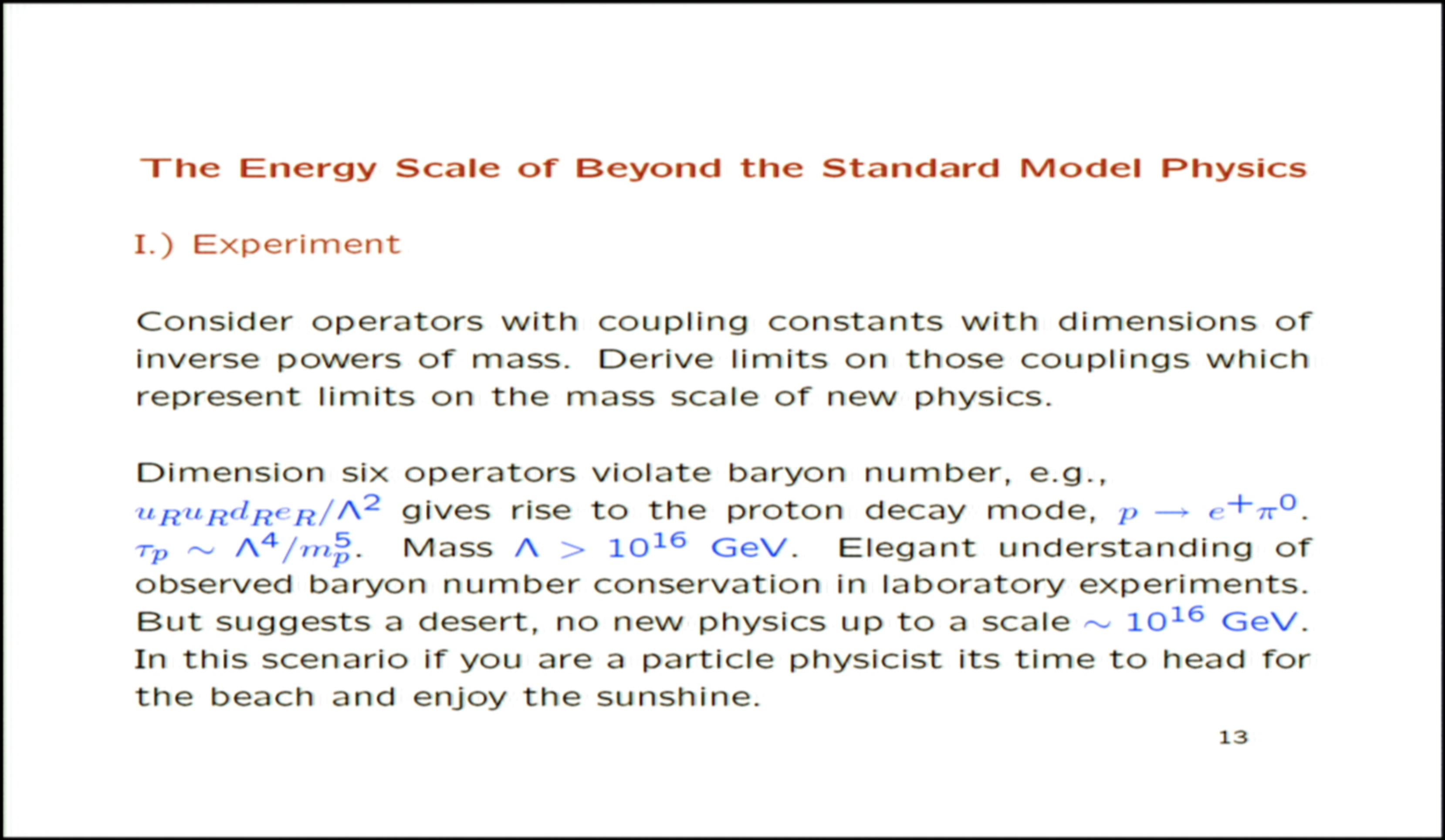
$$V = -\mu_H^2(H^\dagger H) + \frac{\lambda_H}{2}(H^\dagger H)^2$$

Minimized at ground state, $H^0 = v_H/\sqrt{2}$, $H^+ = 0$, $v_H^2 = 2\mu_H^2/\lambda_H$, $\sqrt{2}G_F = 1/v_H^2$. Breaks $S(2) \times U(1)_Y \rightarrow U(1)_Q$

Gauge invariant kinetic energy

$$T = |\left(\partial_\mu + ig_2 \sum_{j=1,2,3} W_\mu^j \frac{\sigma^j}{2} + ig_1 \left(\frac{1}{2}\right) B_\mu\right) H|^2$$

gives $W^\pm$, Z mass. H must be a doublet to get correct mass ratio. $H^{(0)} = (v_H + h(x))/\sqrt{2}$. $m_h = \mu_H$. Lowest order (tree level) coupling in perturbation theory of h to W, Z, but not to γ. Quarks and leptons, ... No FCNC, but doesn't work with 2 H's. Precision electroweak OK. Proton does not get most of its mass from Higgs, dark matter?



The Energy Scale of Beyond the Standard Model Physics

I.) Experiment

Consider operators with coupling constants with dimensions of inverse powers of mass. Derive limits on those couplings which represent limits on the mass scale of new physics.

Dimension six operators violate baryon number, e.g., $u_R u_R d_R e_R / \Lambda^2$ gives rise to the proton decay mode, $p \longrightarrow e^+ \pi^0$. $\tau_p \sim \Lambda^4 / m_p^5$. Mass $\Lambda > 10^{16}$ GeV. Elegant understanding of observed baryon number conservation in laboratory experiments. But suggests a desert, no new physics up to a scale $\sim 10^{16}$ GeV. In this scenario if you are a particle physicist its time to head for the beach and enjoy the sunshine.

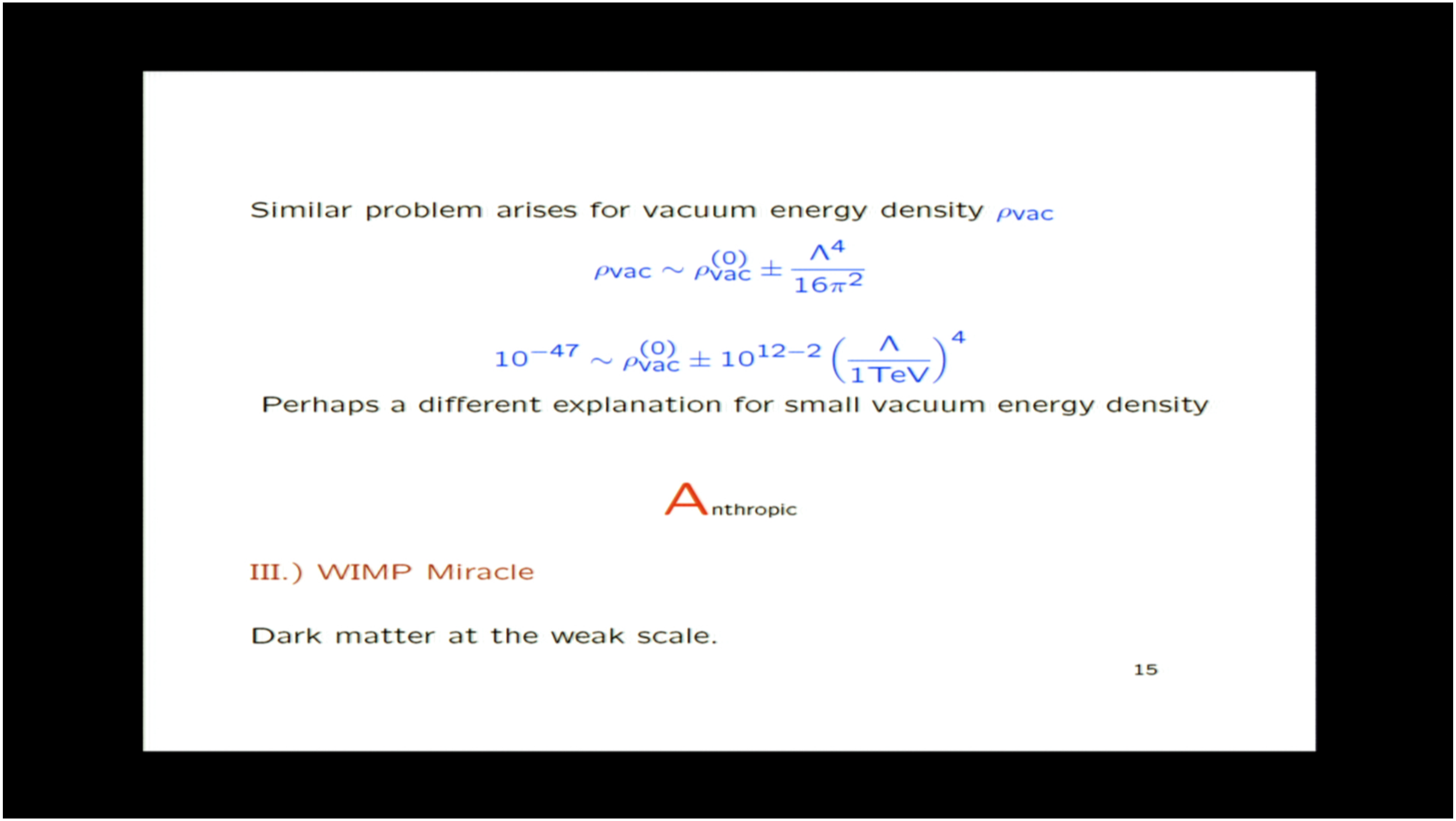
II.) The Hierarchy Puzzle

Calculate the contribution to the Higgs mass in perturbation theory. Focus on contribution of intermediate $\bar{t}t$ states and cut of sum over intermediate states (*i.e.* the momentum integral) at a momentum scale scale Λ

$$m_h^2 \sim m_h^{(0)2} \pm g_t^2 \frac{\Lambda^2}{16\pi^2},$$

$$100^2 \sim m_h^{(0)2} \pm 10^{6-2} \left(\frac{\Lambda}{1\text{TeV}} \right)^2$$

Expected scale of new physics $1\text{TeV} = 10^3\text{GeV}$. SUSY. $\Lambda =$ 10 TeV then ~ 1% fine tuning. Note, $m_Z m_t / m_h^2 = 1.0022 \pm 0.01$.



Similar problem arises for vacuum energy density $\rho_{\rm vac}$

$$\rho_{\rm vac} \sim \rho_{\rm vac}^{(0)} \pm \frac{\Lambda^4}{16\pi^2}$$

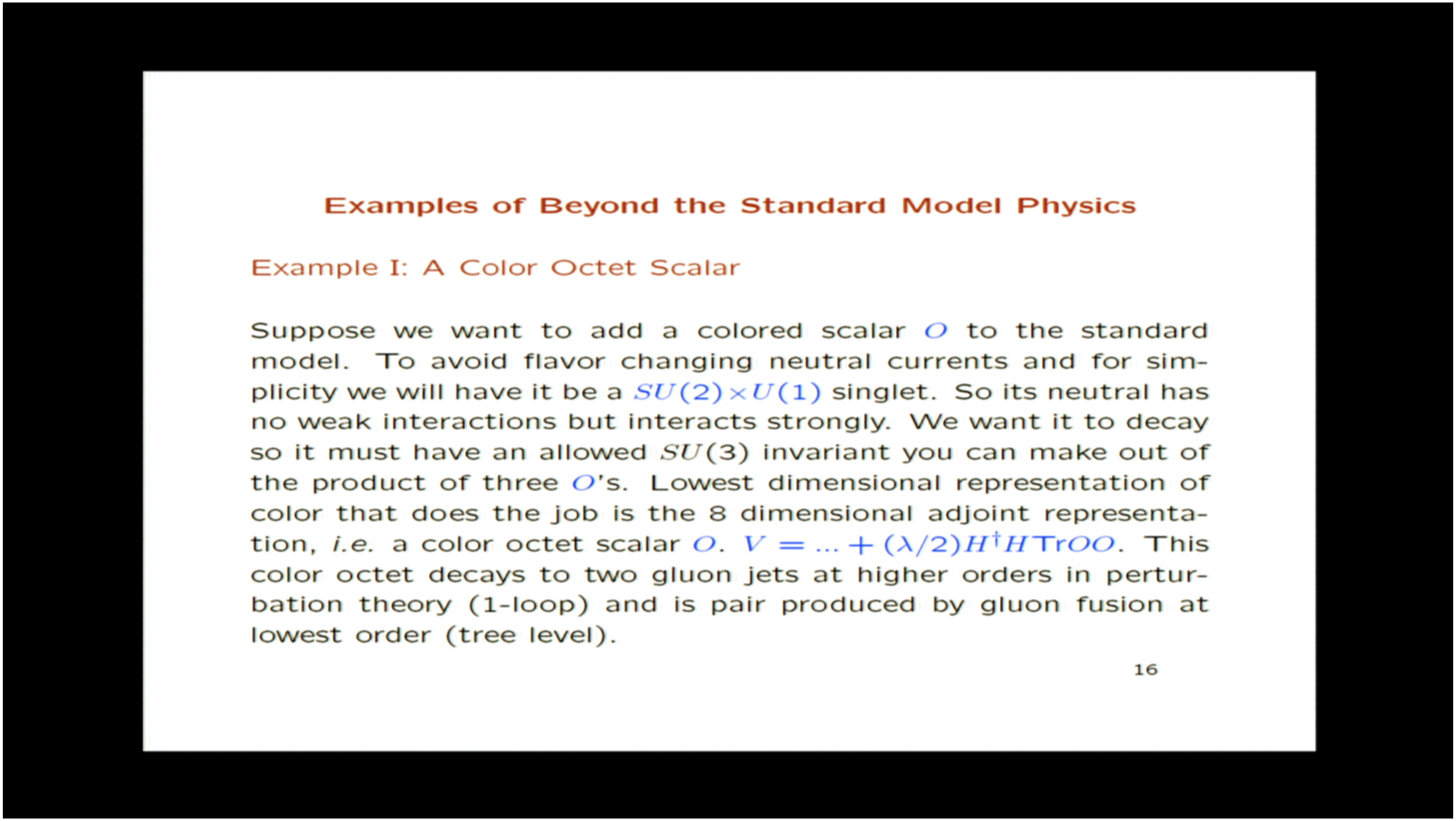
$$10^{-47} \sim \rho_{\rm vac}^{(0)} \pm 10^{12-2}\left(\frac{\Lambda}{1\,{\rm TeV}}\right)^4$$

Perhaps a different explanation for small vacuum energy density

Anthropic

III.) WIMP Miracle

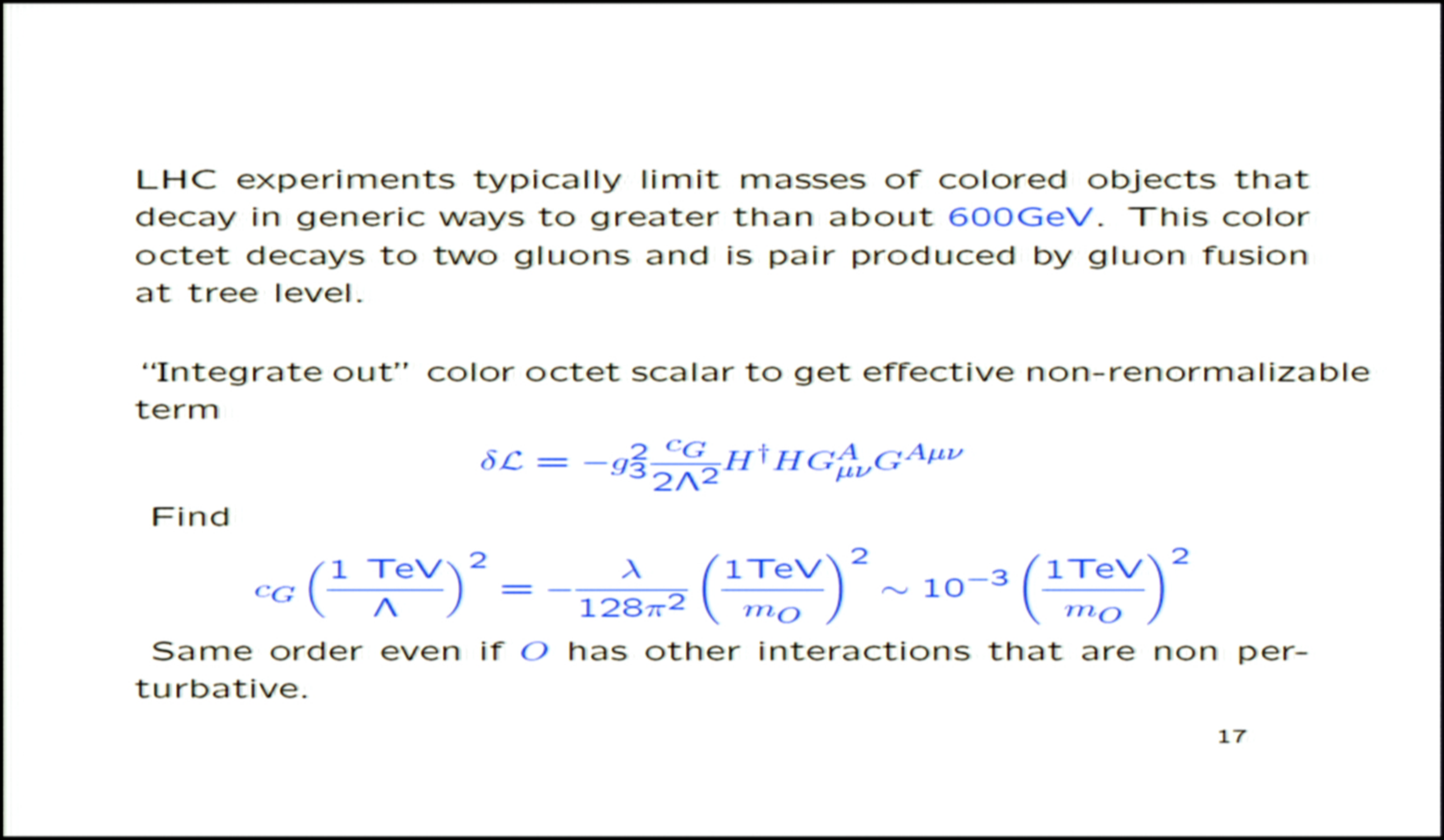
Dark matter at the weak scale.



Examples of Beyond the Standard Model Physics

Example I: A Color Octet Scalar

Suppose we want to add a colored scalar O to the standard model. To avoid flavor changing neutral currents and for simplicity we will have it be a $SU(2)\times U(1)$ singlet. So its neutral has no weak interactions but interacts strongly. We want it to decay so it must have an allowed $SU(3)$ invariant you can make out of the product of three O's. Lowest dimensional representation of color that does the job is the 8 dimensional adjoint representation, *i.e.* a color octet scalar O. $V = ... + (\lambda/2) H^\dagger H \mathrm{Tr} OO$. This color octet decays to two gluon jets at higher orders in perturbation theory (1-loop) and is pair produced by gluon fusion at lowest order (tree level).



LHC experiments typically limit masses of colored objects that decay in generic ways to greater than about 600GeV. This color octet decays to two gluons and is pair produced by gluon fusion at tree level.

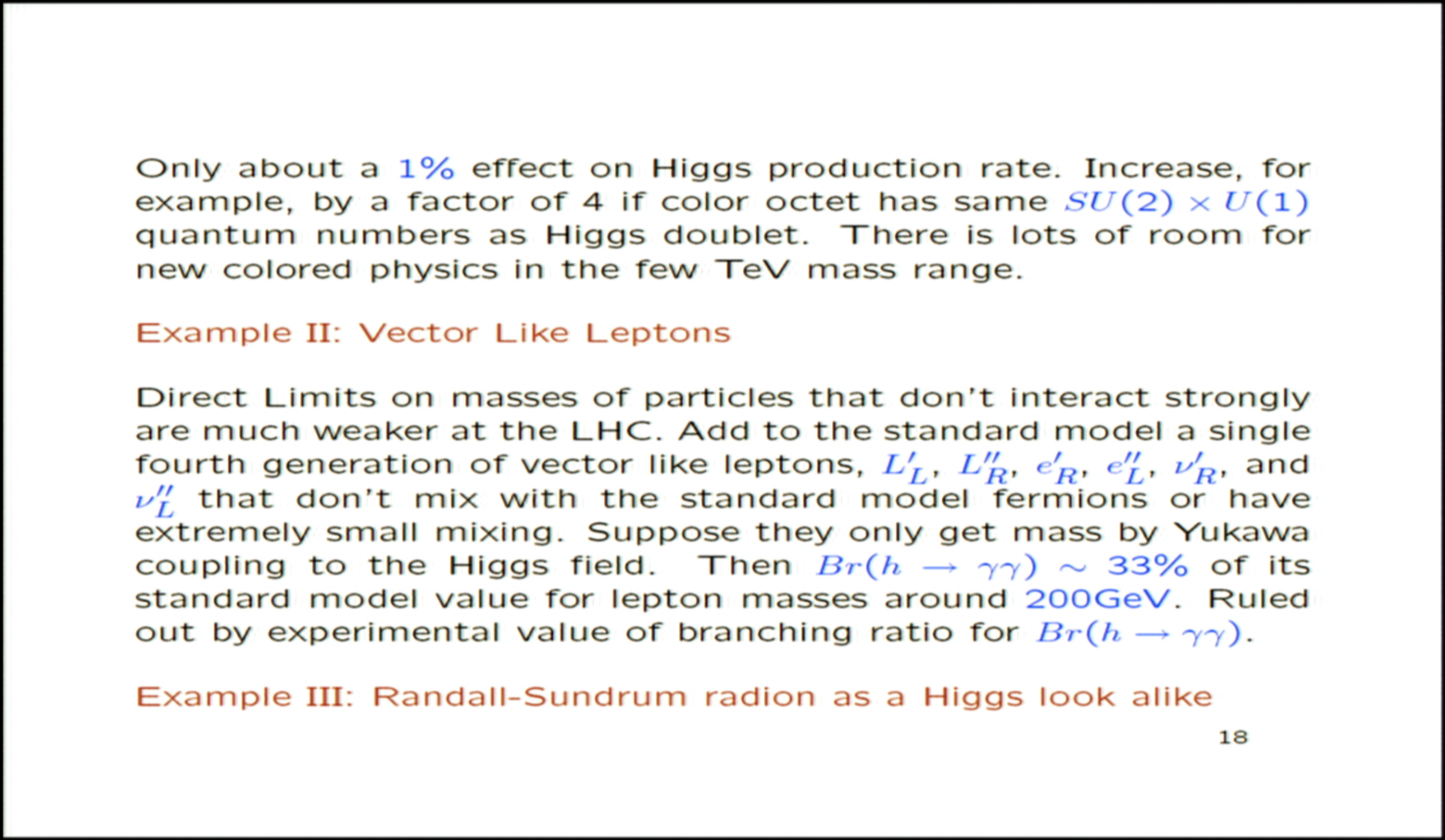
"Integrate out" color octet scalar to get effective non-renormalizable term

$$\delta\mathcal{L} = -g_3^2 \frac{c_G}{2\Lambda^2} H^\dagger H G^A_{\mu\nu} G^{A\mu\nu}$$

Find

$$c_G \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2 = -\frac{\lambda}{128\pi^2}\left(\frac{1\text{TeV}}{m_O}\right)^2 \sim 10^{-3}\left(\frac{1\text{TeV}}{m_O}\right)^2$$

Same order even if O has other interactions that are non perturbative.

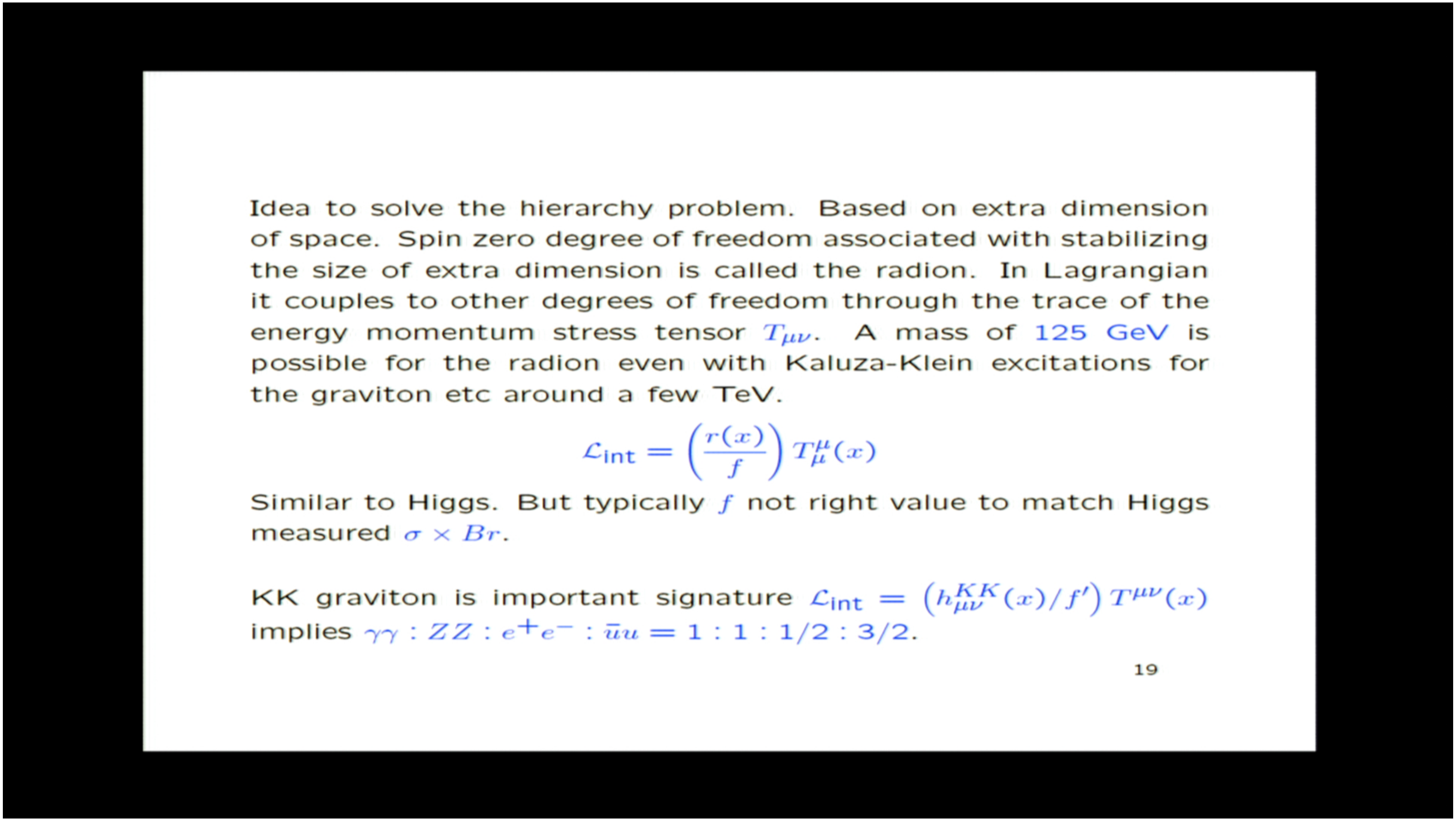


Only about a 1% effect on Higgs production rate. Increase, for example, by a factor of 4 if color octet has same $SU(2) \times U(1)$ quantum numbers as Higgs doublet. There is lots of room for new colored physics in the few TeV mass range.

Example II: Vector Like Leptons

Direct Limits on masses of particles that don't interact strongly are much weaker at the LHC. Add to the standard model a single fourth generation of vector like leptons, L'_L, L''_R, e'_R, e''_L, ν'_R, and ν''_L that don't mix with the standard model fermions or have extremely small mixing. Suppose they only get mass by Yukawa coupling to the Higgs field. Then $Br(h \to \gamma\gamma) \sim 33\%$ of its standard model value for lepton masses around 200GeV. Ruled out by experimental value of branching ratio for $Br(h \to \gamma\gamma)$.

Example III: Randall-Sundrum radion as a Higgs look alike



Idea to solve the hierarchy problem. Based on extra dimension of space. Spin zero degree of freedom associated with stabilizing the size of extra dimension is called the radion. In Lagrangian it couples to other degrees of freedom through the trace of the energy momentum stress tensor $T_{\mu\nu}$. A mass of 125 GeV is possible for the radion even with Kaluza-Klein excitations for the graviton etc around a few TeV.

$$\mathcal{L}_{\text{int}} = \left(\frac{r(x)}{f}\right) T^{\mu}_{\mu}(x)$$

Similar to Higgs. But typically f not right value to match Higgs measured $\sigma \times Br$.

KK graviton is important signature $\mathcal{L}_{\text{int}} = \left(h^{KK}_{\mu\nu}(x)/f'\right) T^{\mu\nu}(x)$ implies $\gamma\gamma : ZZ : e^{+}e^{-} : \bar{u}u = 1 : 1 : 1/2 : 3/2$.