SUPERSYMMETRY AND THE HIGGS:LECTURE 1

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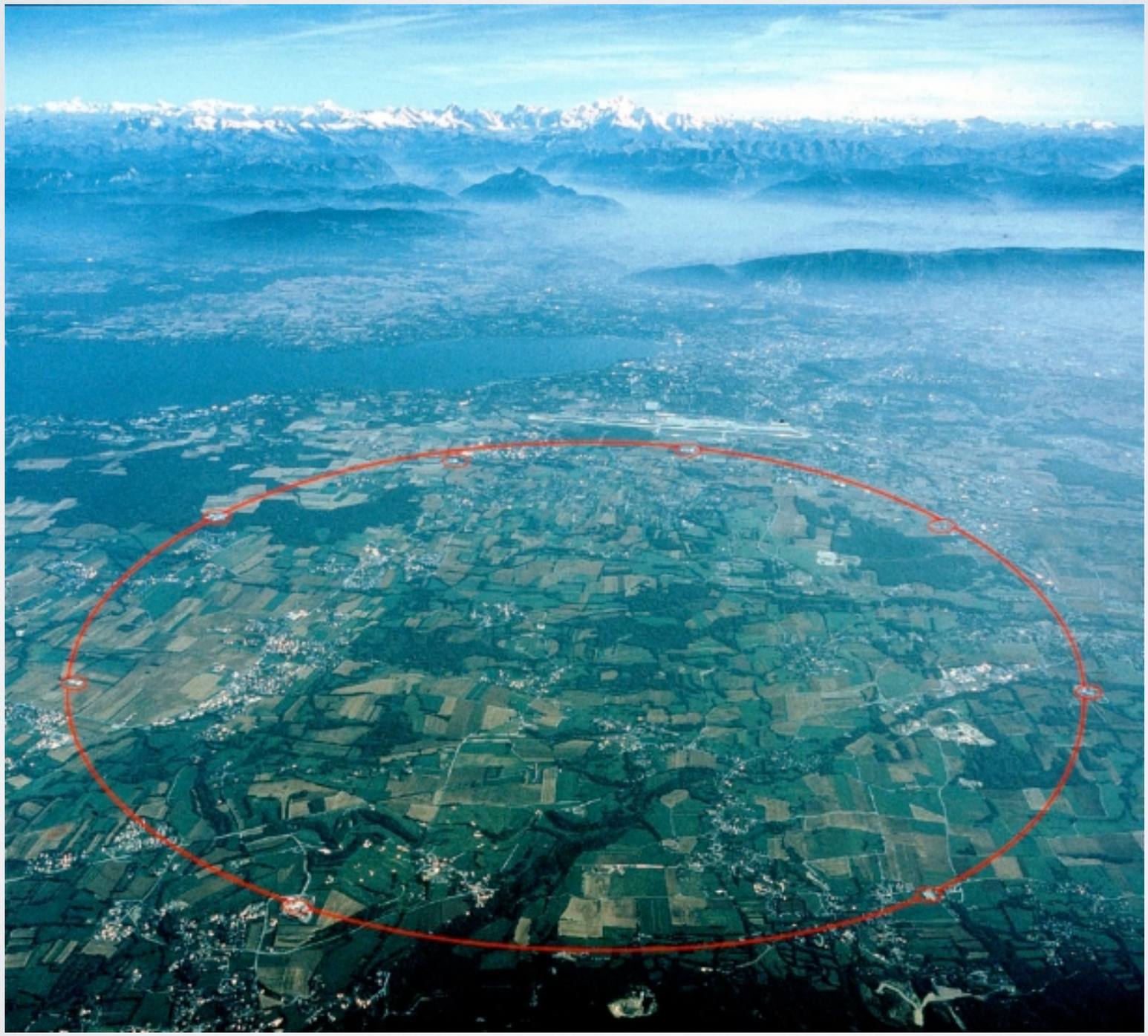
OUTLINE OF LECTURES

- EWSB, the Higgs, and the Hierarchy Problem
- Solutions and **non**-solutions of the Hierarchy Problem
- Supersymmetry
- Supersymmetry and the Higgs
- Where are we and where do we go from here?

WHAT WAS/IS THE GOAL OF THE LHC?



TO FIND THE MECHANISM THAT CAUSES EWSB

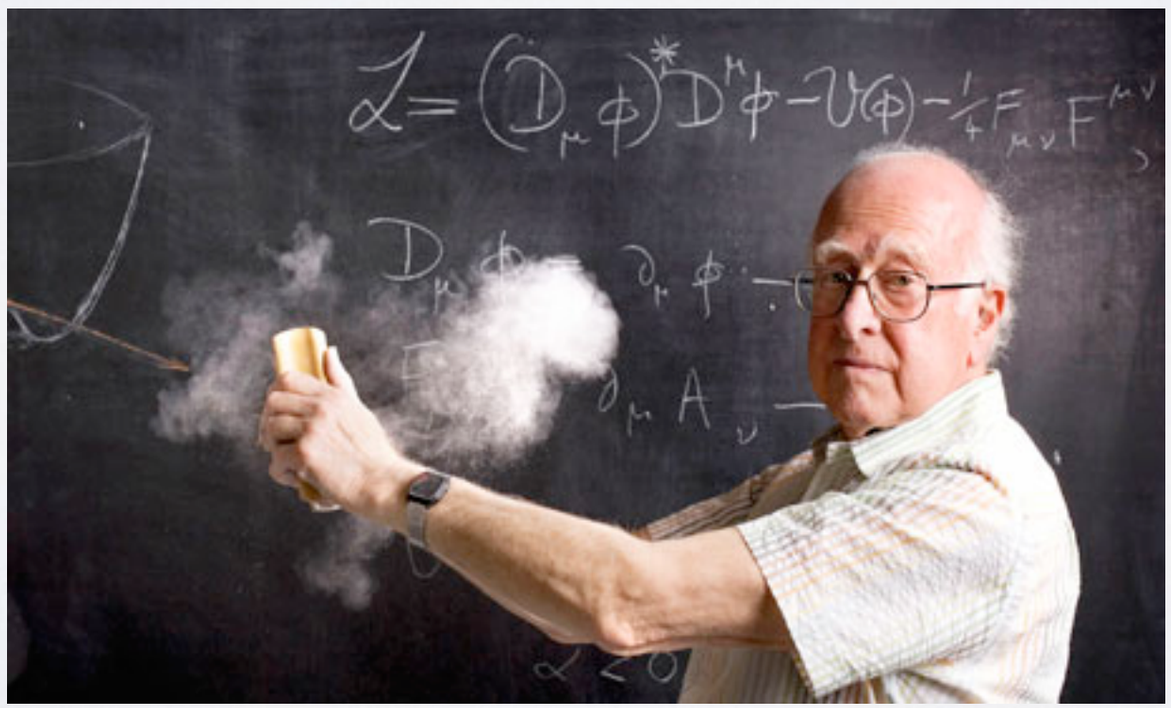
$$SU(3) \times SU(2) \times U(1)$$

$$\downarrow$$

$$SU(3) \times U(1)_{\mathrm{EM}}$$

Necessary because of W,Z masses and we knew the scale ahead of time

How do we accomplish this?



GAUGE BOSON MASSES

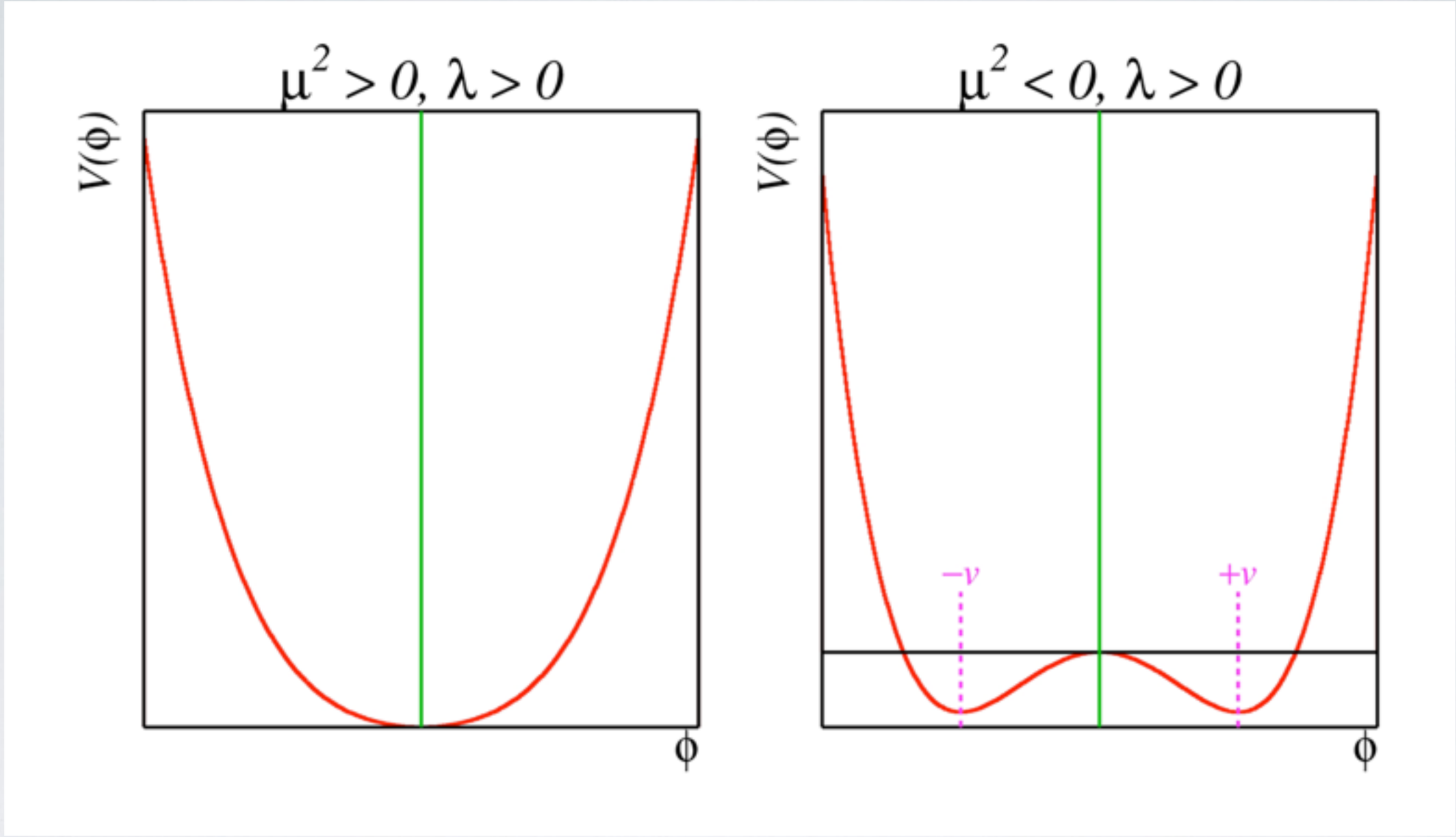
- Want $\sim M^2 W_\mu W^\mu$
- This breaks gauge invariance... bad!
- We do this in a gauge invariant way with our favorite field...

$$(D^\mu \phi)^2 \supset \phi^2 W_\mu W^\mu$$

Gauge Invariant

Looks like a mass if ϕ has a VEV

HIGGS POTENTIAL

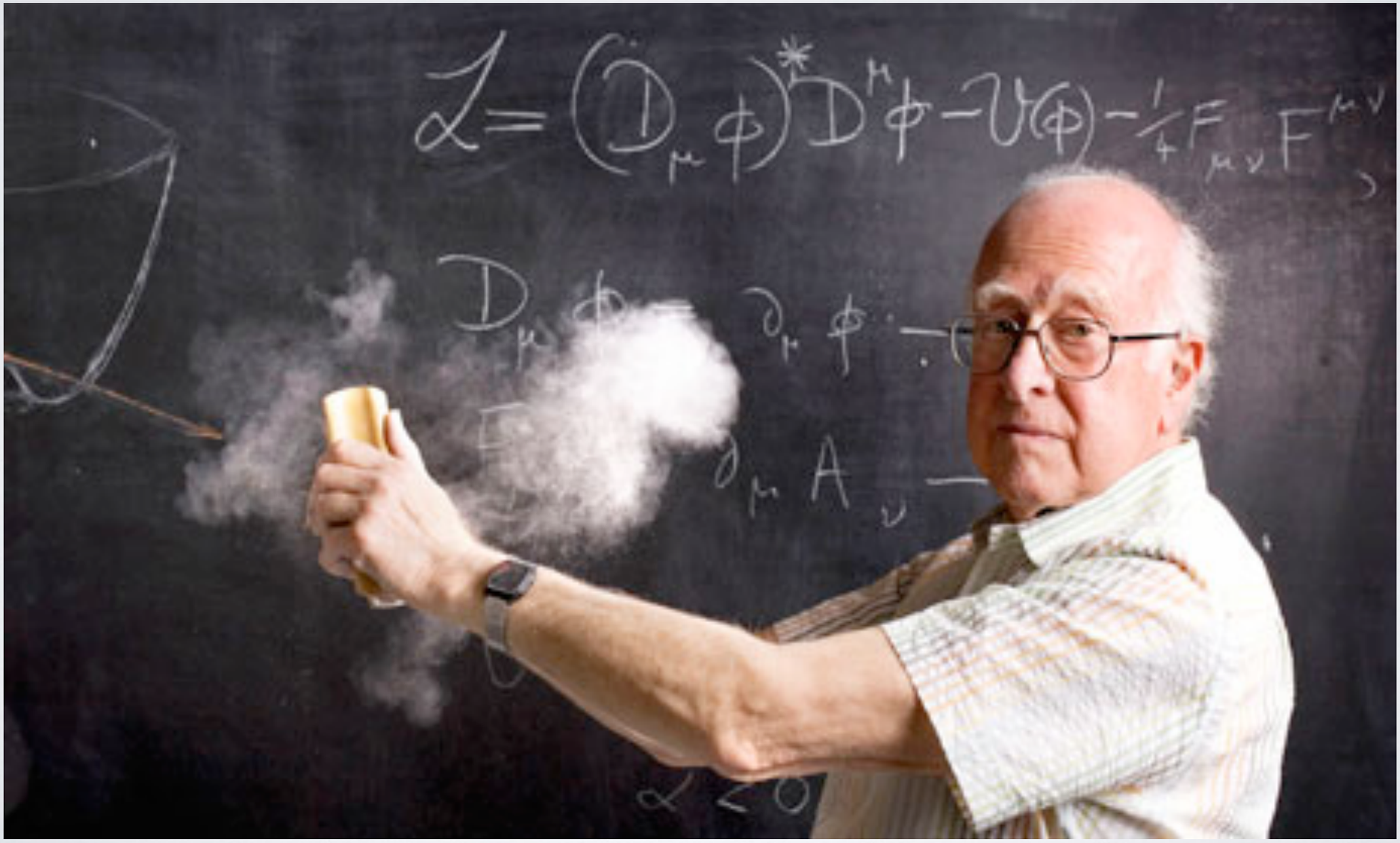


$$V(\phi) \sim \mu^2\phi^2 + \lambda\phi^4$$

$$\langle\phi\rangle \equiv v \sim \sqrt{\frac{\mu^2}{\lambda}} \qquad\qquad m_h \sim \mu$$

COMPLETELY ARBITRARY, but it works better than it should, it just doesn't predict the mass (or VEV)…

SO WASN'T THE LHC JUST FINDING THE MASS OF THE HIGGS?



IT DIDN'T HAVE TO BE A HIGGS!

EWSB occurs in the SM ***without*** a Higgs!

GB MASSES AND LONGITUDINAL MODES

$$2 \neq 3$$

- Higgs not only gives a mass to the W,Z but also provides extra needed degrees of freedom
- Can describe the other "modes" using a linear/non-linear sigma model description
- Let's look at a Global U(1) with a complex scalar Higgs example:

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$$\mathcal{L}_\Phi = |\partial\Phi|^2 - V(|\Phi|) \qquad V(\Phi) = -M^2|\Phi|^2 + \tfrac{1}{2}\lambda|\Phi|^4$$

$\langle\Phi\rangle = 0$ Unstable

$\langle\Phi\rangle = v/\sqrt{2}$ Actual Minima

$$\frac{v}{\sqrt{2}} = \frac{M}{\sqrt{\lambda}}$$

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$$\Phi = \frac{1}{\sqrt{2}}(v + h(x))\exp(i\phi(x)/f)$$

Expand around our true vacuum

$$\frac{v}{\sqrt{2}} = \frac{M}{\sqrt{\lambda}}$$

"Decay" constant

GB MASSES AND LONGITUDINAL MODES

- Expand in our parametrization for small oscillations

$$V(\Phi) = -M^2|\Phi|^2 + \tfrac{1}{2}\lambda|\Phi|^4$$

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$$\begin{aligned}\mathcal{L}_\Phi &= \tfrac{1}{2}(\partial h)^2 - M^2h^2 - \sqrt{\frac{\lambda}{2}}Mh^3 - \frac{1}{8}\lambda h^4 \\ &\quad + \frac{v^2}{2f^2}(\partial\phi)^2 + \frac{1}{2f^2}h^2(\partial\phi)^2 + \frac{\sqrt{2}M}{\lambda f^2}h(\partial\phi)^2\end{aligned}$$

h massive

ϕ massless GB, only derivative coupled
because of shift symmetry $\phi \to \phi + C$

GB MASSES AND LONGITUDINAL MODES

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f=v to give
canonical normalization

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f=v to give canonical normalization

Non-linear Sigma Model Limit

Keep fixed $v^2 = \dfrac{2M^2}{\lambda}$

Take $M, \lambda \to \infty$

Decouple h

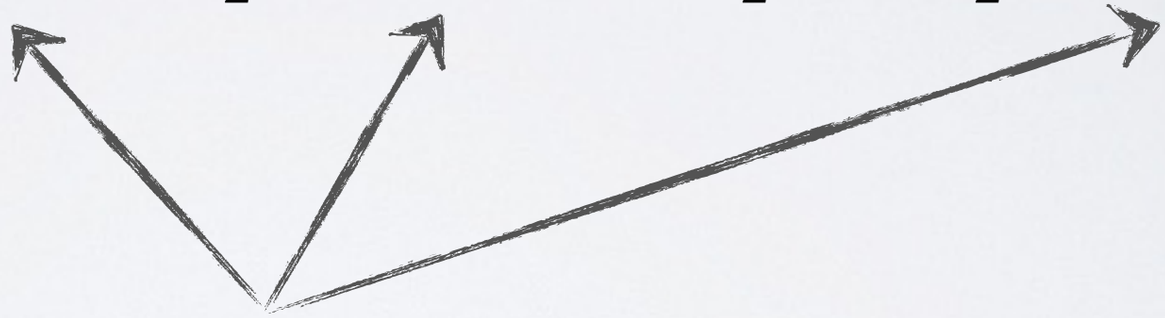
$$\Phi = (f/\sqrt{2}) \exp(i\phi/f)$$

GB MASSES AND LONGITUDINAL MODES

Can do the same exercise for SM Higgs Potential

$$\phi = \exp(i\pi^a \tau^a / v_0) \begin{pmatrix} v_0/\sqrt{2} + h_0/\sqrt{2} \\ 0 \end{pmatrix}$$

$$D_\mu \phi^\dagger D^\mu \phi \rightarrow \frac{g_2}{2} v_0 W_\mu^+ \partial^\mu \pi^- + \frac{g_2}{2} v_0 W_\mu^- \partial^\mu \pi^+ + v_0 (\frac{g_2}{2} W_\mu^0 + \frac{g_1}{2} B_\mu) \partial^\mu \pi^0 + ...$$



Goldstone Boson "pion" modes

EWSB OCCURS IN QCD!!

Confinement and Chiral Symmetry Breaking causes EWSB as well!

$$\langle \bar{Q}_l q_R \rangle \sim \Lambda_{QCD}^3$$

Color invariant, but not SU(2)!

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What about W,Z masses??

$\bar{Q}\gamma^\mu D_\mu Q$ This doesn't look like a gauge boson mass term?

Go back to our "Goldstone" parametrization

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these terms are contained in the

ACTUAL QCD Pion chiral Lagrangian

$$\bar{Q} \gamma^\mu D_\mu Q \longrightarrow \frac{f^2}{4} (D^\mu U)^\dagger (D_\mu U)$$

Longitudinal mode of W,Z come from pions!

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Longitudinal mode of W,Z come from pions!

$$m_V(QCD) \sim \frac{f_\pi}{v} m_V$$

$$m_W, m_Z \sim 30\,\mathrm{MeV}$$

So close!...

STRONG DYNAMICS EWSB

- Nature could have worked this way just with a new confining scale

- For instance redo QCD at higher scales - Technicolor

- Nature has broke symmetries this way before, superconductors, QCD

- The devil is in the details - Extended Technicolor, Randall-Sundrum Models (AdS/CFT)

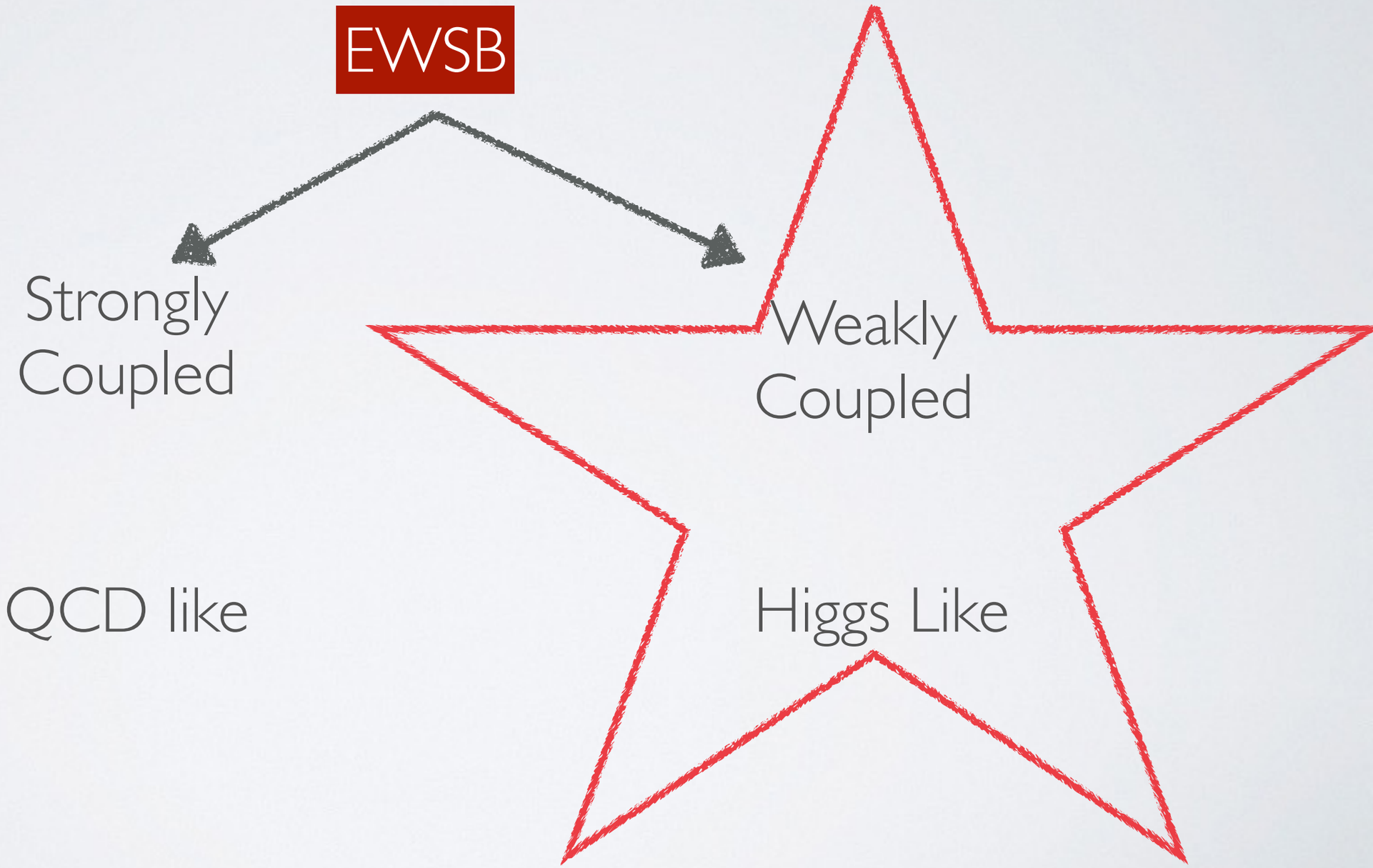
SO IT COULD HAVE BEEN ONE OF TWO POSSIBILITIES

QCD like

Higgs Like

BUT…

SO IT COULD HAVE BEEN ONE OF TWO POSSIBILITIES



IS THIS THE END? DO WE KNOW ALL WE NEED TO KNOW ABOUT PARTICLE PHYSICS?

- Of course not…

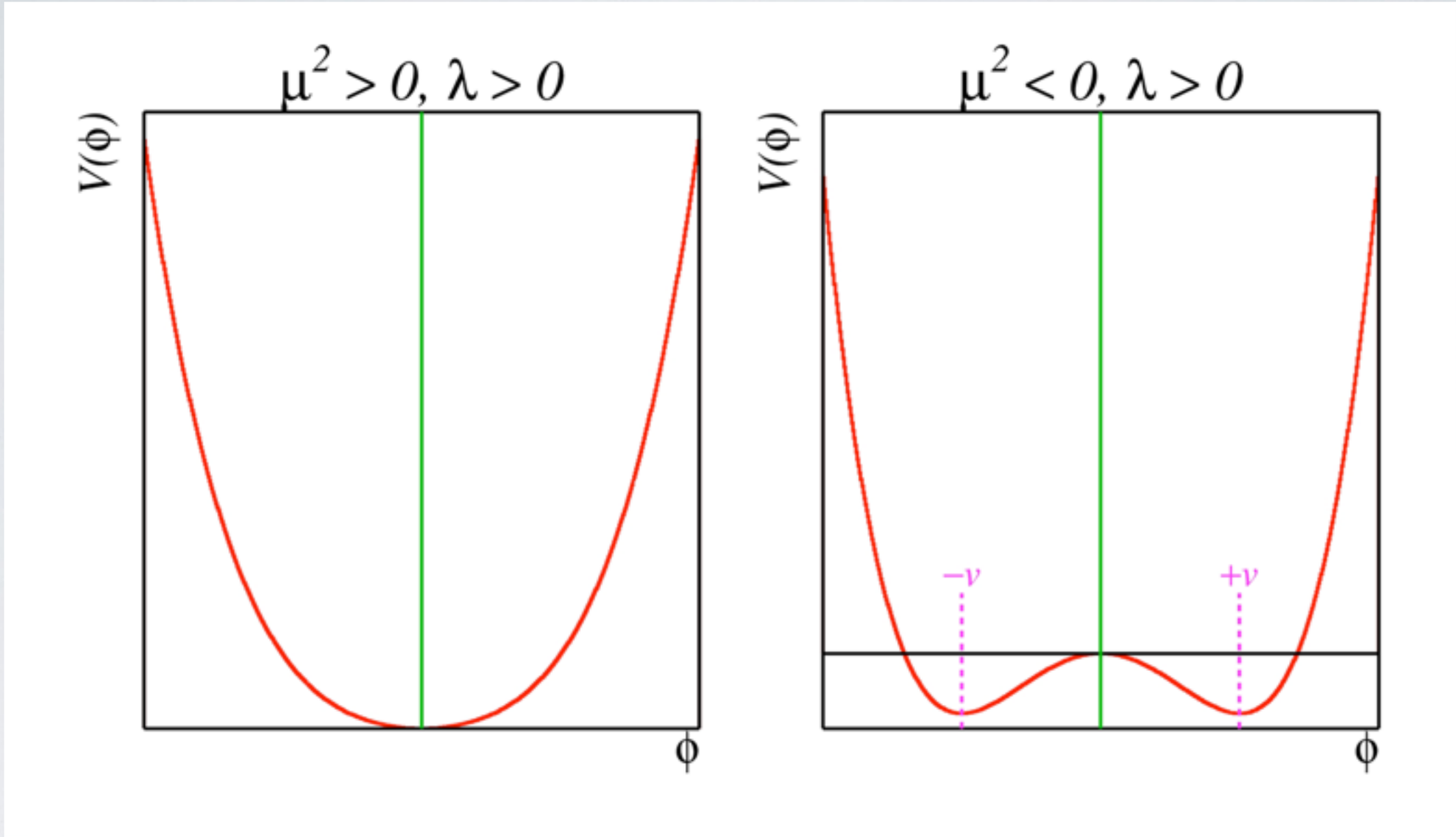
- Many unanswered questions
    - Dark Matter, Baryogenenesis, Flavor, Inflation, Dark Energy, etc.

- BUT… now that we found the Higgs there's a direct problem staring us down: the Hierarchy Problem

THE HIGGS SEEMS SO SIMPLE WHY DO PEOPLE LIKE ALTERNATIVES?

- Arbitrary and doesn't explain anything
- We've seen spontaneous symmetry breaking in other systems done the same way over and over, the Higgs is ***new***
- The Higgs is a really weird object in QFT

HIGGS POTENTIAL



$$V(\phi) \sim \mu^2\phi^2 + \lambda\phi^4$$

$$\langle\phi\rangle \equiv v \sim \sqrt{\frac{\mu^2}{\lambda}} \qquad m_h \sim \mu$$

Does this potential make sense quantum mechanically?

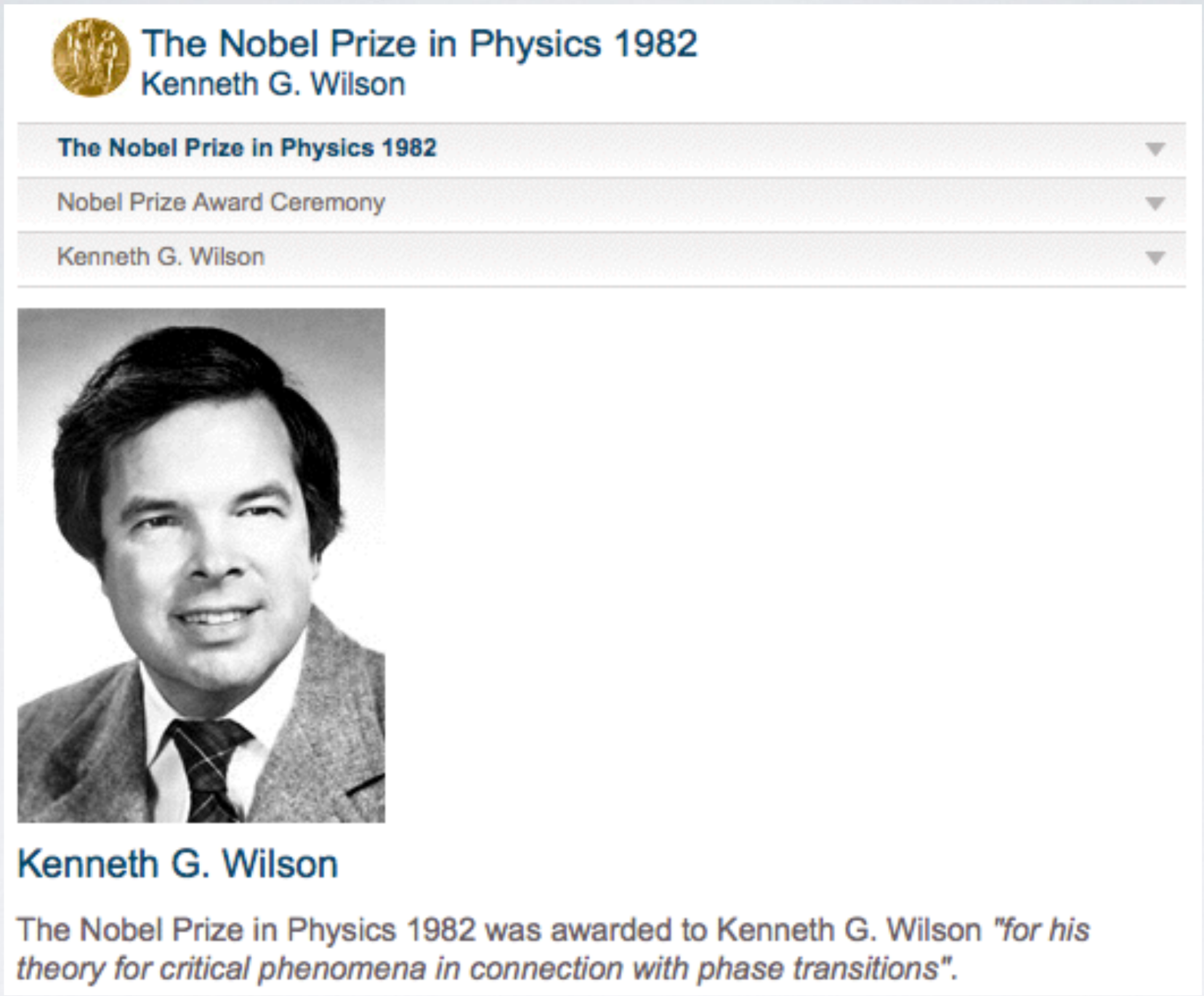
… OF COURSE??

The Nobel Prize in Physics 1999

Gerardus 't Hooft, Martinus J.G. Veltman

The Nobel Prize in Physics 1999 was awarded jointly to Gerardus 't Hooft and Martinus J.G. Veltman *"for elucidating the quantum structure of electroweak interactions in physics"*

BUT WAIT...



Lots of smart people have thought about how QFTs work

QUANTUM CORRECTIONS

- SM *is* renormalizable, but how you ***understand*** renormalization matters

- Wilsonian Effective Field Theory (EFT)

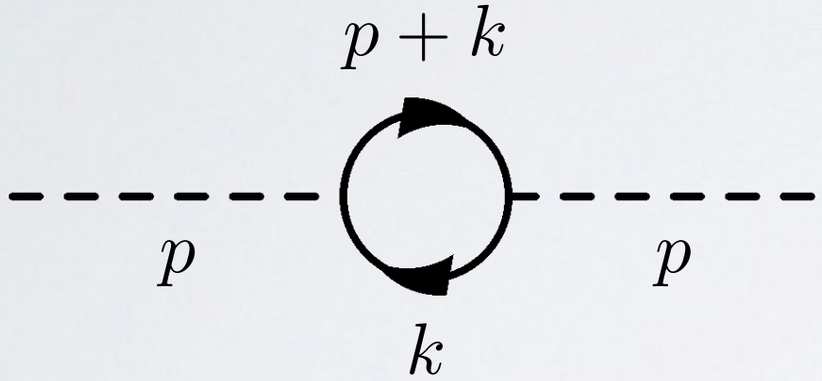
    - Many great examples, and you already had 2 lectures on this

- View SM as EFT valid until scale Λ

Naively this means that instead of integrating all quantum loops over all momenta they are cutoff at Λ

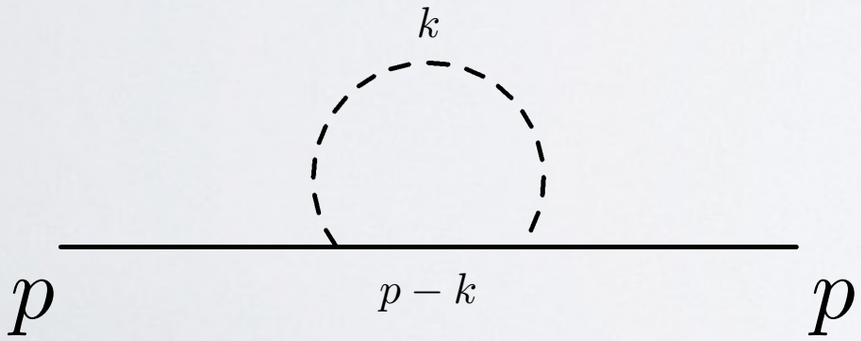
QUANTUM CORRECTIONS TO MASSES IN QFT

Scalar masses



$$\delta m^2 \sim \int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2} \sim \Lambda^2$$

Fermion masses



$$\delta M \sim \int \frac{d^4k}{(2\pi)^4}\frac{1}{k^4} \sim M\log\Lambda$$

TECHNICAL NATURALNESS

- Why is the scalar mass shift quadratic and independent of the mass while the fermion correction is proportional to it's own mass??

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SYMMETRY

TECHNICAL NATURALNESS

$$\bar{\psi}\not{D}\psi + m_e\bar{\psi}\psi = \bar{\psi}_R\not{D}\psi_R + \bar{\psi}_L\not{D}\psi_L + m_e\bar{\psi}_L\psi_R + m_e\bar{\psi}_R\psi_L$$

Fermions without mass terms have a Chiral Symmetry

RH and LH fields can be rotated separately

Fermion mass terms **BREAK** this symmetry

When $m_e = 0$ the symmetry is **exact**

The fermion stays massless to all loop orders

TECHNICAL NATURALNESS

- Fermions and Gauge Bosons Masses have extra symmetry protection from Chiral and Gauge Symmetries

- Scalars generically have no such symmetry!

  - i.e. when setting the scalar mass to zero there is no enhanced symmetry

QUANTUM CORRECTIONS TO HIGGS

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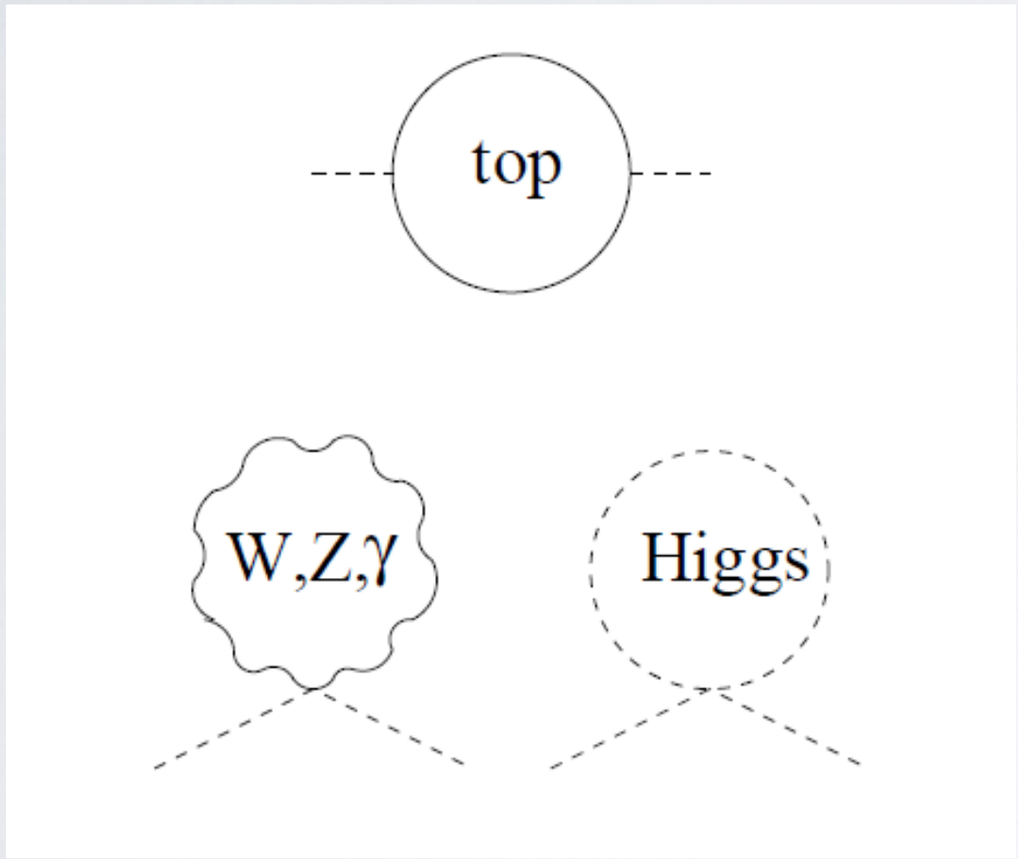


$$\longrightarrow \quad m_h^2 \sim m_0^2 + \Lambda^2$$

HIERARCHY PROBLEM

- EFT+Higgs Mechanism = ***Trouble***...

$$V(\phi) \sim \mu^2\phi^2 + \lambda\phi^4$$

$$\langle\phi\rangle \equiv v \sim \sqrt{\frac{\mu^2}{\lambda}} \qquad m_h \sim \mu$$

$$\mu^2 \sim \mu_0^2 + \Lambda^2$$

$$v \sim \Lambda$$

$$v \sim 10^2\,\mathrm{GeV} \qquad \Lambda \sim M_{pl} \sim 10^{18}\,\mathrm{GeV}$$

YIKES!

HIERARCHY PROBLEM

- SM is correct and we just have to tune to a part in 10^32
  - .00000000000000000000000000000001 **FINE TUNING**

OR

- New physics needs to show up at the TeV scale! In particular we need a **mechanism/symmetry**

THIS IS WHY PEOPLE LIKED STRONG DYNAMICS FOR EWSB!

- Why don't you hear about this problem with QCD?

$$\Lambda_{QCD} \ll v \qquad\qquad M_{pl}$$

Λ_{QCD} is a dynamically generated scale via strong dynamics

Start with a coupling order .1-.01 at high scale log running to low scale, there is no large tuning needed!

IS THIS ALL MISLEADING?

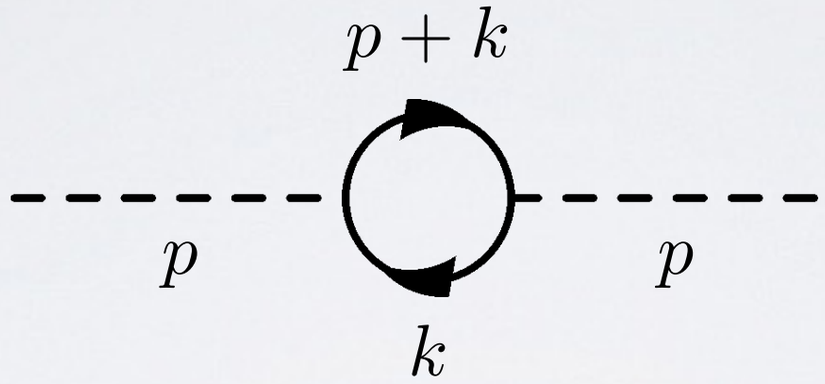
- We just cutoff a 4d integral and found a bad divergence, isn't the SM renormalizable? YES

- Can't I just use dim reg and avoid all quadratic divergences? YES

- What's the point then?

EFFECTIVE THEORY MAKES SENSE

- Dim reg in $d = 4 - \epsilon$ gives $\frac{1}{\epsilon}$ poles



- If there is some new heavy scale we still see it

$$\delta m^2 \sim \frac{1}{\epsilon} + M^2$$

Integrating out a heavy fermion of mass M would set an EFT cutoff

$$\Lambda \sim M$$

$$\delta m^2 \sim M^2 \sim \Lambda^2$$

THERE'S NO WAY AROUND THE HIERARCHY PROBLEM…

- UNLESS there are NO new mass scales in the universe… We already know there is the Planck scale

- IF you massively modify gravity… what if conformal symmetry was spontaneously broken and that's the symmetry that protected the Higgs? Beautiful WRONG idea *without* new physics at low scale…

HIERARCHY PROBLEM

- It is a problem, and not an artifact of how we do renormalization
- Three "reasonable" options (so far)
  - Fine Tuned Universe - Anthropic Principle?
  - Strong Dynamics - Ruled out
  - Weakly coupled Higgs like object with some symmetry protecting its mass

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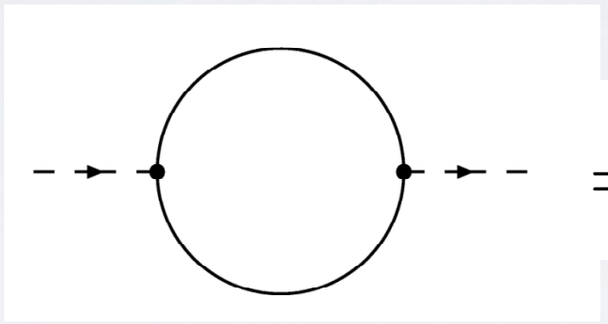
WHAT IS THE SYMMETRY AND WHERE IS THE NEW PHYSICS?

v $\Lambda \sim \mathrm{TeV}?$ $\Lambda \sim M_P?$

Top loop



$$= \frac{3y_t^2}{8\pi^2}\Lambda^2$$

How tuned is acceptable??

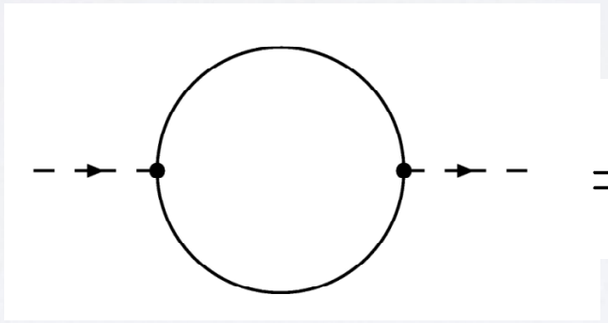
Beauty is in the eye of the beholder

WHAT IS THE SYMMETRY AND WHERE IS THE NEW PHYSICS?

v $\Lambda \sim \mathrm{TeV}?$ $\sim 100\,\mathrm{TeV}$ $\Lambda \sim M_P?$

Natural Mesotuning? Fine-Tuned Anthropic

Top loop



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IT ISN'T JUST WHERE THE CUTOFF IS…

- If you numerically cancelled the top contribution to the quadratic divergence of the Higgs at a given scale, without a symmetry it will be regenerated!!

- We need to construct a symmetry that preserves this cancellation

A NATURAL UNIVERSE

UV completion of SM
~ TeV scale

What is this?

v Standard Model

The LHC is probing this scale already and in case you haven't heard it hasn't found anything other than the Higgs!

WHAT DOES A NATURAL UNIVERSE LOOK LIKE?

To come up with a symmetry AND satisfy all experimental constraints do we have to build models that look like…

WHAT DOES A NATURAL UNIVERSE LOOK LIKE?

WHAT DOES A NATURAL UNIVERSE LOOK LIKE?

When really the universe looks like this, and we're not that special?

WE DON'T KNOW FOR SURE…

- We also don't even *know* how to ever say for sure unless we build a Planck scale collider…

- All we can do is try to come up with all the mechanisms that could protect the Higgs mass and look for them

- Physics is an experimentally driven science!

NATURAL MODELS/HOW TO PROTECT THE HIGGS MASS?

In a weakly coupled theory, despite 30+ years of smart theorists working hard, we have two ideas...

The Higgs is a pseudo-Goldstone boson

Our universe has new quantum dimensions... Supersymmetry

VERY different mechanism and not on the same footing…

HIGGS AS A PSEUDO GOLDSTONE BOSON (PGB)

- Symmetry to make "Higgs" light
- What if Higgs were a Goldstone boson itself??

For example enlarge EW gauge group to SU(3)

$$SU(3) \to SU(2)$$

Introduce a complex scalar triplet of SU(3) that gets a VEV

$$\Phi = e^{i\theta/f} \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix}$$

HIGGS AS A PSEUDO GOLDSTONE BOSON (PGB)

$$SU(3) \to SU(2) \qquad \Phi = e^{i\theta/f} \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix}$$

$$\theta = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & h \\ 0 & 0 & \\ h^\dagger & & 0 \end{pmatrix} + \frac{\eta}{4} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

Goldstone Bosons

h is a doublet under SU(2)!

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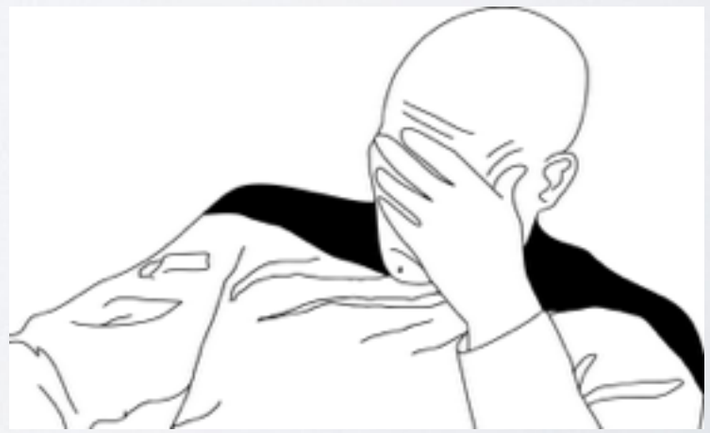
Goldstone Bosons

h is a doublet under SU(2)!

h only has derivative interactions



HIGGS AS A PSEUDO GOLDSTONE BOSON (PGB)

- Symmetry to make "Higgs" light
- What if Higgs were a Goldstone boson??
  - ONLY DERIVATIVE COUPLINGS!
- Introduce NON-derivative couplings by hand to get the things we know and love...
- **Ruins the whole point!**

LITTLE HIGGS

- After many decades, theorists became more clever and came up with a way to "double" protect the PGB so quadratic divergences were canceled at one loop

$$\mathcal{L} = \mathcal{L}_0 + \epsilon_1 \mathcal{L}_1 + \epsilon_2 \mathcal{L}_2$$

Each term preserves extra symmetry by itself, but collectively the symmetry is broken

LITTLE HIGGS

- After many decades, theorists became more clever and came up with a way to "double" protect the PGB so quadratic divergences were canceled at one loop

- Typical structure of theory: ——— $\Lambda \sim 4\pi f$

$$\delta m_h^2 \sim f^2$$

——— $f \sim \text{TeV}$

There are other PGB theories, e.g. Twin Higgs, but they all rely on the same shift symmetry mechanism

HIERARCHY PROBLEM MINI-REVIEW

- Just tune the SM and ignore the problem
- End physics at a TeV (Large Extra Dimensions)
- Technicolor/Strong Dynamics
  - Randall-Sundrum Models
- PGB Models
- Supersymmetry - Tomorrow