Physics Beyond the Standard Model: An Introduction

3 Lectures Given at the 2006 CERN/Fermilab Hadronic Collider School

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What these lectures are:

- Cursory overview of many models
- Detailed look at none
- Hadron collider high-energy physics implications only (no b-physics, no neutrino physics, no cosmology)

- Suitable only as a stepping stone for further reading
- Aimed mainly at experimentalists but probably useful for theorists too
- A personal view – not to be taken as an authoritative tour!
- But I don't have a favorite theory, so an agnostic view
- Warning: Idiosyncractic and provocative viewpoints ahead

A Theorist's Worldview

- **Heaven**
  - The essential properties of the universe are simple and logical, and within our grasp.
  - All particles are well-motivated by basic principles
  - All dynamical mechanisms are minimal and elegant
  - With enough intelligent reasoning and a few more hints, theorists can soon deduce the structure of the laws of nature
- **Hell**
  - The essential properties of the universe are complex and we have not yet even begun to understand their logic, if any.
  - Some particles are just there; they are not motivated by any theoretical requirement.
  - Most dynamical mechanisms are non-minimal and baroque
  - Theorists are far from determining the principles, if any, that govern the laws of nature, and therefore far from guessing what they are.

An Experimentalist's Worldview

- **Hell**
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  - Theorists are far from determining the principles, if any, that govern the laws of nature, and therefore far from guessing what they are.

A middle path

- I will begin with the Higgs sector as a place to go fishing
- Then I will discuss theorists' models based on trying to solve the supposed hierarchy problem
- Then I will talk about consequences of global symmetries in a general way, without reference to a model
- If time permits I'll talk about fishing for less theorist-motivated particles and the wide variety of weird things we need to keep our eyes open for
  - *especially since they can completely change standard signals of minimal motivated models!!!!*

One unmotivated particle can ruin your whole day.

(or make you famous.)

Higgs Physics

- The Higgs sector is an good place to start our exploration
- Even a standard Higgs itself will be new
- But even a single Higgs boson, as predicted by the standard model, may not be standard
- Many more scalar particles may be present
- We'll see the Higgs sector is an excellent probe of a range of new phenomena

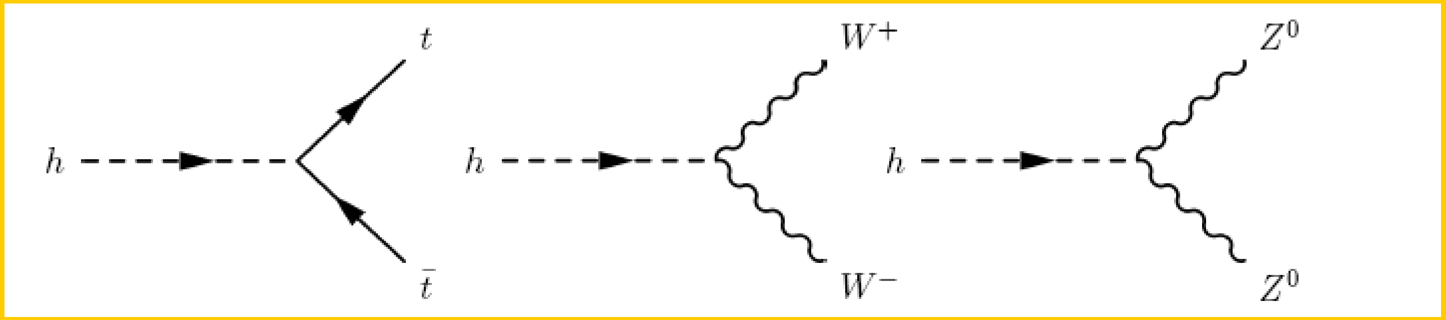
- *Higgs Hunter's Guide for basics*
- *Lots of review articles , for instance:*
  - **The Anatomy of electro-weak symmetry breaking,** by Abdelhak Djouadi
    - **I: The** Higgs **boson in the standard model. hep-ph/0503172**
    - **II. The** Higgs **bosons in the minimal supersymmetric model. hep-ph/0503173**

680 pages!!

Higgs Boson Couplings

- Crudely: Higgs is responsible for mass:
- Therefore it couples to a particle with a strength proportional to its mass, so heavier particles are more likely to appear in Higgs decays
- *Not quite true: strong QCD interactions can shift masses*
- *Not quite true: quantum Higgs interacts with photons, gluons*
- *NOTE : Higgs is not related to gravity!*
    - $E^2 - p^2c^2 = (mc^2)^2$ *Note E is only equal to* mc^2 *for particles at rest!!!*
    - *Gravity couples to ENERGY-MOMENTUM in Einstein's theory.*
    - *Remember classical gravity couples to photons!!! (it bends light…!)*
- *Higgs provides mass, yes, and affects relation between energy and momentum, but not responsible for gravitational effects, and does not provide all mass to all particles.*

Higgs Boson Decays



- If the Higgs boson is heavy enough it does prefer to decay to heavy particles
- Easiest decay to see is *ZZ* where both *Z* bosons decay leptonically; *WW* challenging, *tt* may be too rare
- Its decays to lighter particles will be difficult to observe; the heavier the Higgs, the worse it gets, because Br($h \rightarrow ZZ$) increases with m_h.

More Higgs Decays

- A light Higgs must decay to lighter particles, and small couplings imply a small width.

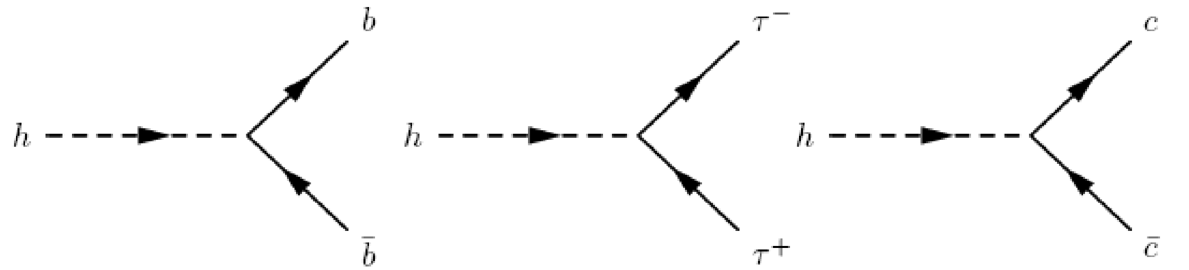


Figure 2: Small Higgs decay modes

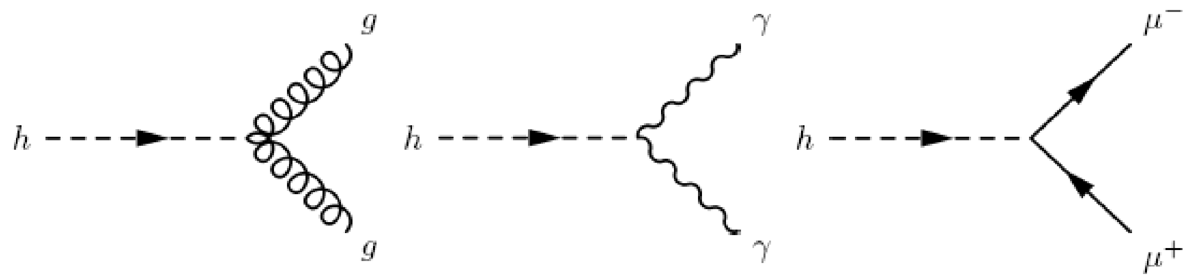


Figure 3: Some tiny Higgs decay modes

Higgs coupling to W bosons

- *W* boson mass comes from Higgs boson kinetic term:

I use g_2, g_1, not g, g', for SU(2) x U(1) gauge couplings

$$H = \begin{bmatrix} H^+ \\ H^0 \end{bmatrix} = \begin{bmatrix} h_1 + ih_2 \\ h_0 + ih_3 \end{bmatrix}$$

$$\begin{aligned} |D_\mu H|^2 &= |\partial_\mu H^+ + i\frac{g_2}{\sqrt{2}} W^+ H^0 + \ldots|^2 \\ &= \partial_\mu H^+ \partial^\mu H^- + i\frac{g_2}{\sqrt{2}} H^0 W^+ \partial_\mu H^- - i\frac{g_2}{\sqrt{2}} H^{0*} W^- \partial_\mu H^+ + \frac{1}{2} g_2^2 W^+ W^- |H^0|^2 + \end{aligned}$$

$H^0=(v+h)/\sqrt{2}$

$$\to i\frac{g_2}{2}(v+h) W^+ \partial_\mu H^- - i\frac{g_2}{2}(v+h) W^- \partial_\mu H^+ + \frac{1}{4} g_2^2 W^+ W^- (v^2 + 2vh + h^2) + \ldots$$

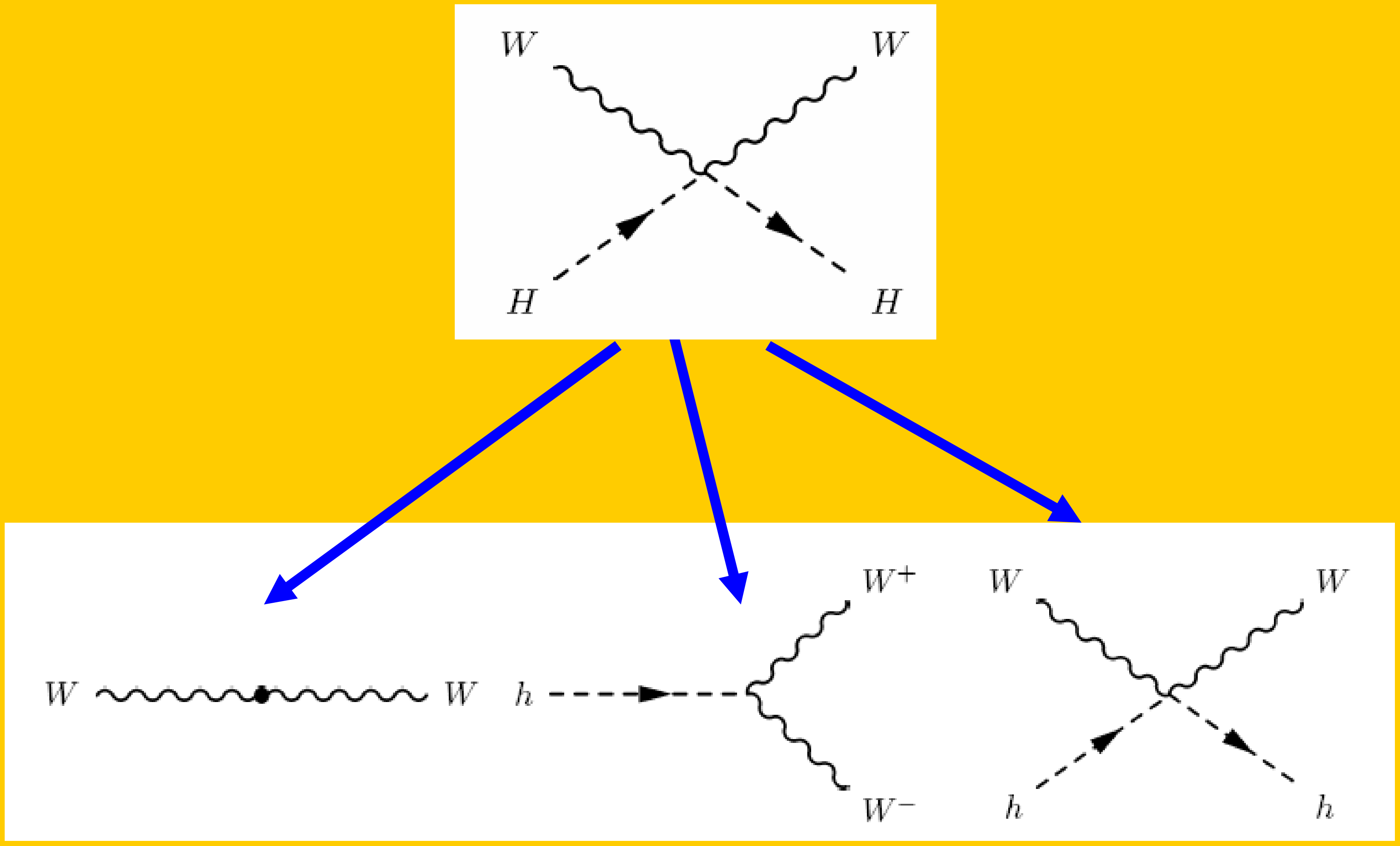
W^+ absorbs *H^+*

W mass

h W W coupling

Note that the h W W coupling requires non-zero vev!

In diagrams ---



Higgs coupling to fermions

$$y_b[\bar{t}H^+ + \bar{b}H^0]b$$

- Yukawa coupling between (*t,b*) and *H* leads to a bottom quark mass $m_b = y_b\, v/\sqrt{2}$
- The $h\, b\, \bar{b}$ coupling does ***not*** require nonzero *v; its presence does not test the Higgs mechanism, since other scalars could also couple to* $b\, \bar{b}$
- The H^+ is absorbed into W^+, so the first term leaves no trace

(except for the fact that the longitudinal W^+ has a surprisingly large coupling to the top quark, explaining the latter's large width.)

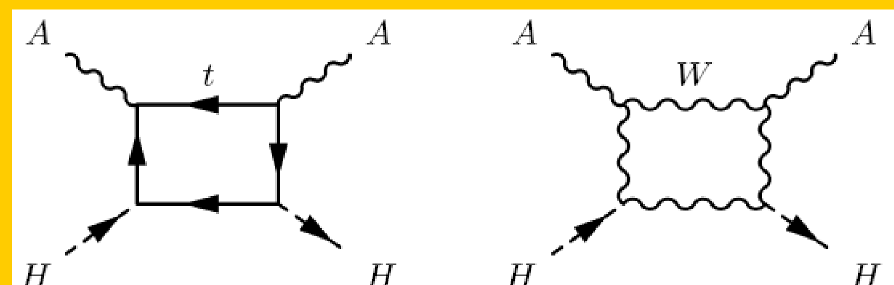
Higgs coupling to photons

- At classical level, photon = combination of SU(2) and U(1) bosons absent from Higgs kinetic term
- Quantum effects can change normalization of Higgs boson, value of gauge couplings
- But no matter what, always one combination of SU(2) and U(1) bosons which is absent from Higgs kinetic term --- CHECK THIS YOURSELF!

- *This combination is massless, and, by definition, is the physical photon*

Higgs coupling to photons

- This coupling is a one-loop effect
- Not $e^2\, H\, H\, A_\mu A^\mu$ (here A^μ is the photon potential) which can't be generated by *any* quantum corrections!
- Instead $\zeta\, H\, H\, F_{\mu\nu} F^{\mu\nu}$ (here $F_{\mu\nu}$ is field strength)
- Dominated by W boson loop, top quark loop



So instead of

$(ev)^2\, A_\mu\, A^\mu$ and $(ev)\, h\, A_\mu\, A^\mu$,

get

$(\zeta v^2)\, F_{\mu\nu}\, F^{\mu\nu}$ and $(\zeta v)\, h\, F_{\mu\nu}\, F^{\mu\nu}$

Photon mass term

Small shift in gauge coupling

W t

$$\zeta \approx [redacted] \frac{e^2}{16\pi^2 v^2}\left[7 - \frac{16}{9}\right]$$

Sensitive to new physics!

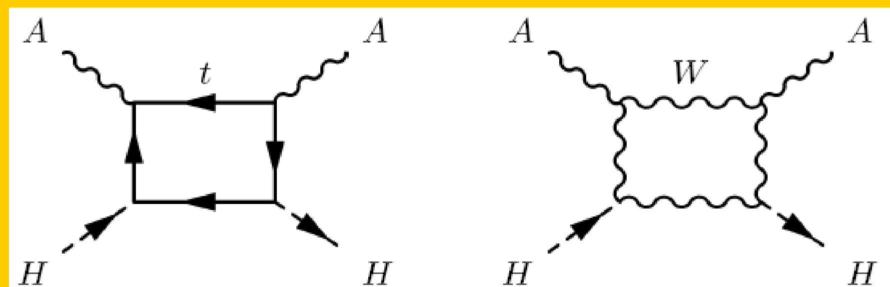
Why don't y_t , m_t appear?

Numerator y_t^2 , Denominator $1/m_t^2$

Thus $\zeta \sim 1/v^2$, $h\,F\,F$ coupling $\sim 1/v$

independent of m_t!

(for light quarks, small)



- Br ($h \to \gamma\gamma$) $\sim \zeta^2 \sim 10^{-3}$

  (light higgs only! Competes with $h \to bb$)

  Not measurable for heavy Higgs

$\zeta \approx$ [redacted] $\frac{e^2}{16\pi^2 v^2}\left[7 - \frac{16}{9}\right]$

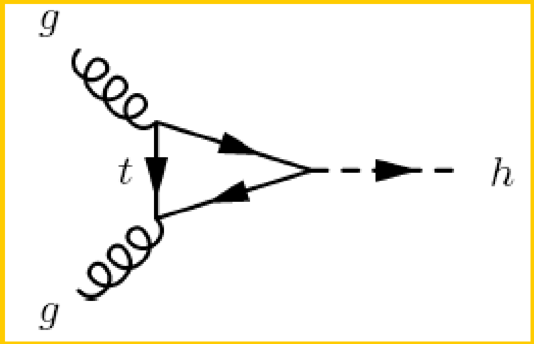
- Heavy Fourth Generation:

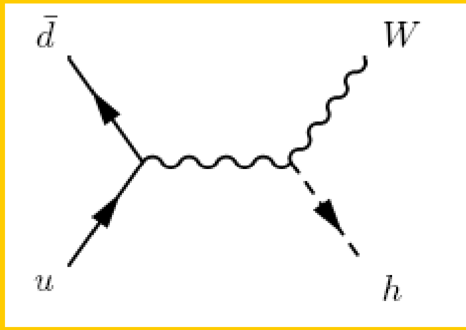
$\zeta \sim 7 - 16/9 - 16/9 - 4/9 - 1/3$

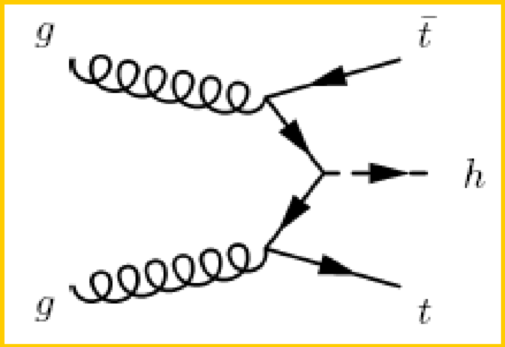
W $\quad t$ $\quad t'$ $\quad b'$ $\quad \tau'$

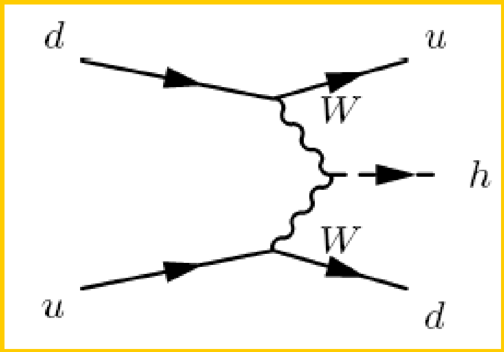
Most models modify this coupling!

How is the Higgs produced?

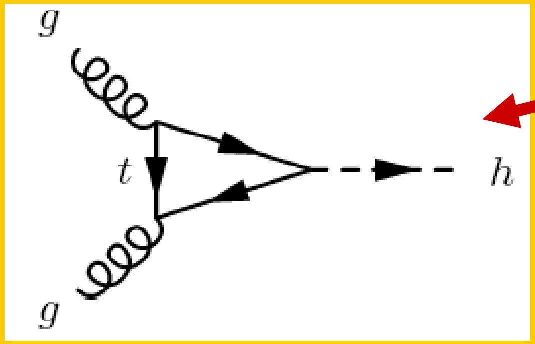


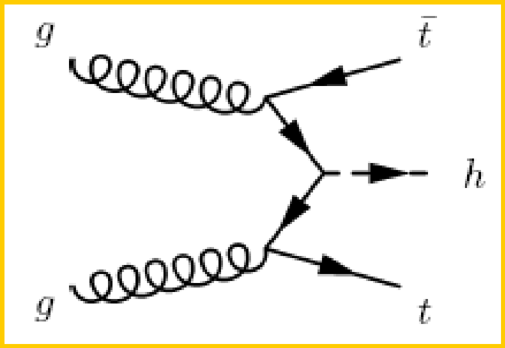






How is the Higgs produced?

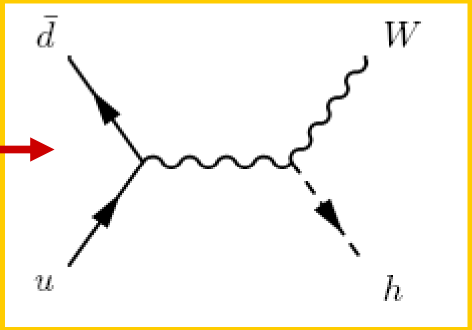


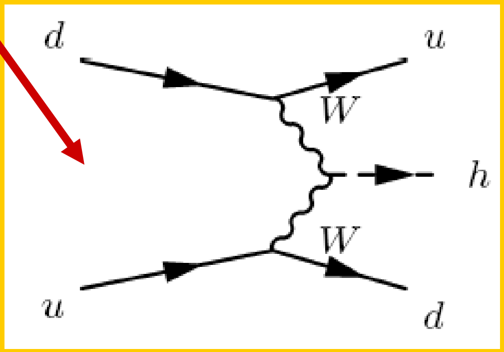


- The dominant Higgs production mode is a loop effect!
- Just as sensitive to new physics as the photon loop!
- Unlike photon loop, sensitive only to colored particles coupling to *h***;** thus *gg* → *h* , *h* → γγ provide independent information
- Fourth generation *t', b'* increases production rate by 9!

How is the Higgs produced?

- These modes test the *hWW* vertex
- Unlike the decay branching fraction, these cross-sections directly measure the size of this coupling
- They therefore test that the candidate Higgs boson is really the one that gives the W and Z their masses.





Modifying the Higgs Sector

- The Higgs boson is very sensitive to the presence of additional scalar particles
- *More scalars can generate mixing of eigenstates, new decay channels, new production mechanisms.*

- Let's consider adding a single real scalar *S* to the standard model
- *S* carries no charges and couples to nothing except the Higgs, through the potential

$$V(H,S) = -\mu^2|H|^2 + \lambda|H|^4 + \eta S^2 H^2 + m_s^2 S^2 + \kappa S^4$$

If <*S*> = 0, an Invisible Decay

$$V(H,S) = -\mu^2|H|^2 + \lambda|H|^4 + \eta S^2 H^2 + m_s^2 S^2 + \kappa S^4$$

If, at the minimum of *V(H,S)*, $\langle H\rangle = v/\sqrt{2}$, $\langle S\rangle = 0$,

then $S^2H^2 \rightarrow (v+h)^2 S^2 = v^2\, S^2 + 2v\, hSS + hhSS$

a shift in mass for S and a cubic coupling

This allows $h \rightarrow SS$ (if $m_h > 2\, m_S$) with a width ~ $\eta^2 v^2 / m_h$.

This can easily exceed decays to bottom quarks, with width ~ $y_b^{\,2}\, m_h$!

So Br($h \rightarrow SS$) could be substantial, even ~1 for a light Higgs boson, depending on η.

But S is stable. There is an $S \rightarrow -S$ symmetry. So this decay is ***invisible***.

Therefore a light Higgs could be essentially invisible!

(its existence might be inferred in VBF or diffractive Higgs production, with difficulty.)

Remember what I said?

- ***This is an example of one additional, not particularly well-motivated particle ruining your whole day***

- And it's not even that unmotivated – it is a simple dark matter candidate.

- At least we know about this one.

- *It's the particles we haven't thought much about that could really hurt us. Keep your eyes open.*

- Be Careful of Cultural Bias: the culture of theorists always prefers minimal models. Non-minimal models can't be published and are always greeted with derision; only tenured faculty can work on them, and few do.
- **Nature may not share this bias.**

Finding an Invisible Higgs?

<u>For further reading:</u>

One of a number of papers on invisible Higgs, classic but somewhat out of date

- **Observing an invisible Higgs boson** Authors: O.J.P.Eboli, D.Zeppenfeld **hep-ph/0009158**

  Given its weak coupling to bottom quarks and tau leptons, the Higgs boson may predominantly decay into invisible particles like gravitinos, neutralinos, or gravitons. We consider the manifestation of such an invisibly decaying Higgs boson in weak boson fusion at the CERN LHC. Distinctive kinematic distributions of the two quark jets of the signal as compared to Zjj and Wjj backgrounds allow to restrict the Higgs branching ratio to 'invisible' final states to some 13% with 10fb^{-1} of data, provided events with two energetic forward jets of high dijet invariant mass and with substantial missing transverse momentum can be triggered efficiently. It is also possible to discover these particles with masses up to 480 GeV in weak boson fusion, at the 5 sigma level, provided their invisible branching ratio is close to 100%.

Or look up “Diffractive Higgs Production” on Google:

this means ***proton proton → proton proton higgs***

If $\langle S \rangle \neq 0$, a second 'Higgs'

$$V(H,S) = -\mu^2|H|^2 + \lambda|H|^4 + \eta S^2 H^2 + m_s^2 S^2 + \kappa S^4$$

If, at the minimum of *V(H,S)*, $\langle H \rangle = v/\sqrt{2}$, $\langle S \rangle = w/\sqrt{2}$, $S = (w+s)/\sqrt{2}$,

then $S^2H^2 \rightarrow (v+h)^2(w+s)^2 = v^2\, s^2 + w^2\, h^2 + 4vw\, hs + 2v\, hss + 2w\, hhs + hhss$

we get new mass terms, new cubic couplings, new quartic couplings

(Note I cheated slightly here; need to self-consistently find minimum)

The first two terms shift the masses; the third allows *h* and *s* to ***mix***!

Thus we have two eigenstates with masses m_1, m_2

$$\phi_1 = h\cos\gamma + s\sin\gamma\ ;\ \phi_2 = s\cos\gamma - h\sin\gamma$$

Both eigenstates couple to *WW, ZZ, bb, gg*, γγ, through their *h* component; for instance,

$$hgg = \cos\gamma\ \phi_1 gg - \sin\gamma\ \phi_2 gg$$

If <*S*> not 0, a second Higgs?

$$V(H,S) = -\mu^2|H|^2 + \lambda|H|^4 + \eta S^2 H^2 + m_s^2 S^2 + \kappa S^4$$

$$\phi_1 = h\cos\gamma + s\sin\gamma \; ; \phi_2 = s\cos\gamma - h\sin\gamma$$

So there are two scalar particles that can be produced in *gg* collisions

And both decay to usual Higgs final states, via their *h* component --- thus

ϕ_1 has same branching fractions as an SM Higgs boson of mass m_1
ϕ_2 has same branching fractions as an SM Higgs boson of mass m_2

So there are two Higgs-like states to find, each with a reduced production cross section, each standard-model-like in its branching fractions.

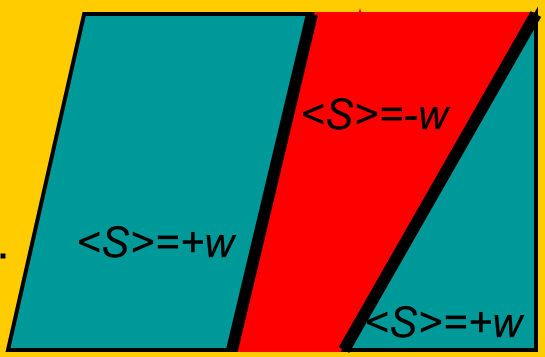
EXCEPTION: if $m_1 > 2\,m_2$, then a new decay channel opens up:

$\phi_1 \rightarrow \phi_2\,\phi_2 \rightarrow$ $(bb)(bb)$, $(bb)(\tau^+\tau^-)$, $(\tau^+\tau^-)(\tau^+\tau^-)$

These exotic final states can occur in many models; recent heightened interest, since a light Higgs with these decay channels can escape LEP bounds.

An aside – and some advice

The previous model spontaneously breaks the S ←→ -S symmetry; predicts domain walls produced in the early universe, which would totally dominate the energy density of the universe today.



BUT this is true in ***standard cosmology***!

- Reheating to low temperatures? They never form.
- Late inflation? They are diluted.

All cosmological constraints have loopholes!!

- In general, I suggest you listen politely to a theorist giving you a list of cosmological constraints, but ignore the constraints when doing collider analyses!
- *If you assume these constraints, you eliminate the possibility of testing standard cosmology using collider data – and you might miss a discovery!*

Two complex Higgs doublets?

- This is a classic; arises in supersymmetry, little Higgs, elsewhere
- Two Higgs doublets H_1, H_2 just like standard model doublet
- Most general scalar potential $V(H_1,H_2)$ (restriction of CP conservation often imposed; see Higgs Hunter's Guide)
- To understand, first consider case where $\langle H_2 \rangle = 0$. Then H_1 acts just like SM Higgs, with vev v, and H_2 is an extra multiplet of scalars:

H^+ (and its conjugate H^-) and $H^0 + i\,A^0$

CP even (arrow to H^0) *CP odd* (arrow to A^0)

Two complex Higgs doublets?

- Now consider case $\langle H_1 \rangle = v_1/\sqrt{2}$, $\langle H_2 \rangle = v_2/\sqrt{2}$, $v_1^2 + v_2^2 = v^2$

- Linear combination of H_1^+ and H_2^+ are absorbed into W^+
- Other linear combination becomes a physical charged scalar H^+

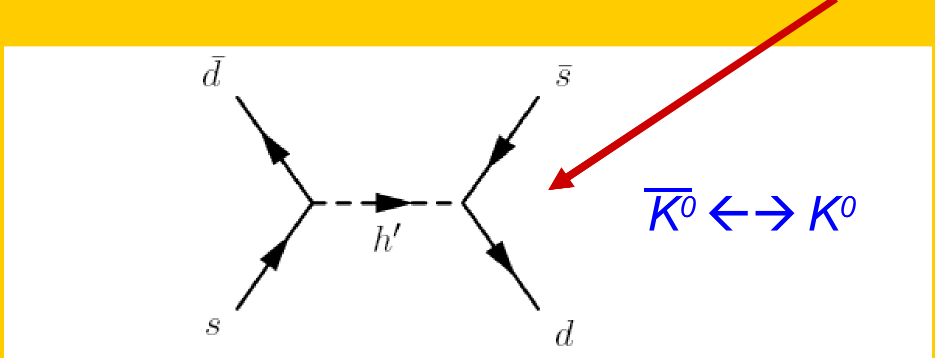
- Linear combination of A_1^0 and A_2^0 are absorbed into Z
- Other linear combination becomes a physical CP-odd scalar A^0

- Two CP-even scalars h^0 , H^0 , linear combinations of H_1^0 and H_2^0
  (by convention h^0 is the lighter of the two eigenstates)
  similar to the H/S model considered above (but with new fermion couplings)

- Typical Spectra:
  - h^0 light, similar to SM higgs; H^0 A^0 H^+ H^- heavy, near-degenerate
  - h^0 light, A^0 light, H^+ H^- medium, H^0 heavy; very non-SM regime
  - Many other possibilities though.

Couplings to fermions

- We cannot freely add couplings of all fermions to both Higgs bosons.
- Two Yukawa coupling matrices for (say) down quarks would be needed: y_{d1} ,y_{d2} 3x3 matrices that couple H_1 and H_2 to the down quarks.
- Only one of each pair of Yukawa matrices can be diagonalized at a time; other would have off-diagonal terms
  - For instance, if we diagonalize the matrix y_{d1} by rotating d_L s_L b_L and d_R s_R b_R , then y_{d2} will in general not be diagonal
  - And vice versa…
  - *Flavor-Changing Neutral Currents* will result, affecting K-meson mixing, etc.



Multiple Higgses can generate flavor-changing processes.

Couplings to fermions

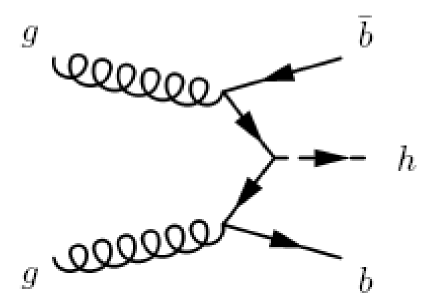
Thus only one Higgs can couple to each class of fermions --- e.g.

- H_1 gives masses to fermions, H_2 does not couple to them
- H_1 couples to quarks, H_2 to leptons
- H_2 couples to up type quarks, neutrinos, while
  H_1 couples to down-type quarks, charged leptons (supersymmetry)

You can read all about this in the Higgs Hunter's Guide

Third case:

- Since top quark is heavy, its coupling is large: $m_t = y_t\, v_2 / \sqrt{2} \sim v$
- Bottom quark is lighter, but $m_b = y_b\, v_1 / \sqrt{2} << v$
  - so perhaps $y_b << y_t$ as in SM
  - or perhaps $v_1 << v_2$ (***i.e.,*** $\tan\beta = v_2/v_1 >> 1$) in which case
    y_b may not be small!
  - This can change branching fractions and enhance $gg \rightarrow b\, h\, b$



Some phenomenogical details

- ***Loop corrections to tree-level relations, especially masses, tend to be large! Do not use tree-level formulas without checking size of loop corrections!!!***

- The h^0, H^0 decay through the same modes as the ordinary Higgs boson, but with couplings affected by mixing angles.

- The A^0, H^+ do not have classical (tree-level) couplings to *WW, ZZ, WZ*!
  - Therefore they are not produced in associated WA^0, WH^+, or in VBF; $gg \to A^0$ ok ; H^+ hard to produce except in pairs or decays of heavy objects.
  - For same reason, preferentially decay to fermions: $A^0 \to b\bar{b}$, $\tau^+\tau^-$, $H^+ \to \tau^+\nu$, even when heavy! May be very hard to observe.

- The h^0 *(if light)*, A^0, H^+ usually have small widths in minimal models
  - *Exotic rare (or not-so-rare) decays are commonly present in nonminimal models*
  - *These are potential discovery channels!! may reveal Higgs bosons more easily than usually-considered decay modes*.

Summary

It is vital, when a Higgs boson candidate is found, to

- Measure all its production modes and decay modes with the highest possible precision
- Not assume it is standard even if its visible branching fractions appear standard
- Search for other scalar resonances
- Search for invisible and exotic visible decay modes
- Exotic decays may be the best way to find the Higgs boson!!

It will take a long time and a lot of work to verify that the Higgs boson is truly standard; and the first deviations from the standard model may be found as its properties are explored.

The hierarchy ``problem''

Sally Dawson mentioned several different issues: don't confuse them!

- Unitarity of perturbative WW scattering: *Rigorous!*
  either the SM Higgs is below ~ 800 GeV or there must be new physics at the TeV scale.
- Triviality and stability: *A bit less rigorous.*
  Unless the SM Higgs boson lies between 100 and 200 GeV, must be new physics below Planck scale.
- Hierarchy problem ("quadratic divergences" or "high-energy sensitivity"): *Powerful, but dangerous.*
  the SM with a small vev and a light Higgs is extremely ugly and ridiculously sensitive to little adjustments, so there must be new physics at the TeV scale.

Claim: it is a problem that the weak and gravitational scales are so different:

$v / M_{pl} \sim 10^{-16}$ (a free parameter in the standard model coupled to gravity)

To understand the problem, compare to some quantities that don't have one.

- Is it a problem that $\alpha_{\text{hypercharge}} << 1$? *No.*
- Is it a problem that $m_e << M_{pl}$? *No.*
- Is it a problem that $m_h << M_{pl}$? *YES*. (or at least, maybe)

Quantum effects

- A quantum field theory is typically (but not always) defined by some fields and a Lagrangian that describes their interactions

- But quantum effects may cause physical properties of particles described by the theory to be very different from those appearing in the classical Lagrangian --- even the particles themselves may be different.
  - the proton does not even appear in the Lagrangian
  - the electron mass we measure is not the electron mass we put into the Lagrangian; we measure the fully *quantum-corrected* mass.
- *What electron mass **should** we put in the Lagrangian?*
- *More precisely, what electron-Higgs Yukawa coupling y_e **should** we put in our Lagrangian?*

- **Answer: Choose y_e in Lagrangian** (which I'll call y_e^0) **so that the physical m_e matches with data.**

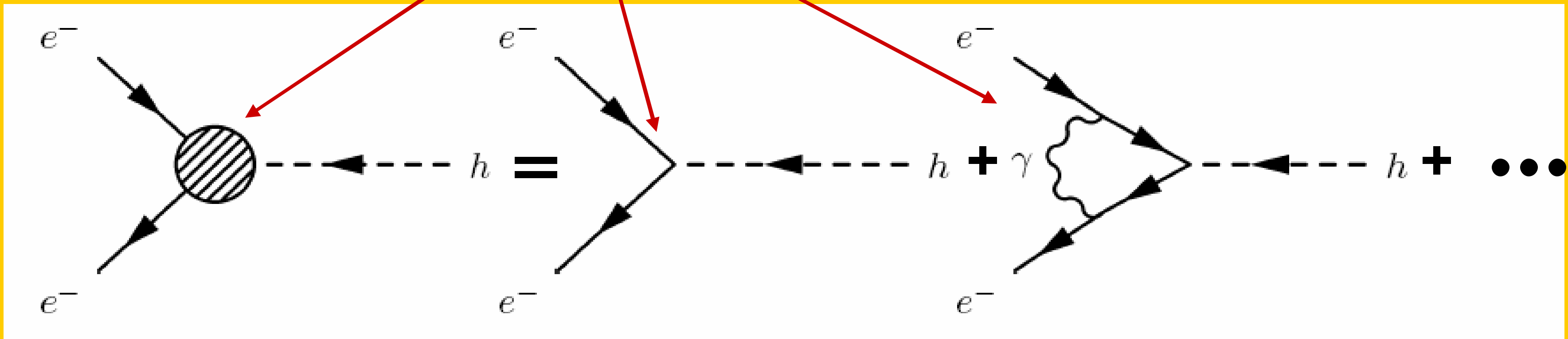
Effective Field Theory

- *More precisely, what electron-Higgs Yukawa coupling y_e **should** we put in our Lagrangian?*
- **Answer: Choose y_e in Lagrangian** (which I'll call y_e^0) **so that the physical m_e matches with data.**

- All realistic quantum theories (including the SM) are "**effective theories**"
  - Valid below some finite energy scale M (and at distances longer than $1 / M$).
  - Any $M < M_{new}$, where M_{new} is a scale where new particles, new interactions, or other new physics becomes important, can be used.
  - In the SM, M_{new} presumably could not be larger than M_{pl}, so we are only interested in the SM defined at $M < M_{pl}$
- We define the SM Lagrangian valid at and below M, and choose $y_e^0(M)$
- For a different M, a different Lagrangian, with a different $y_e^0(M)$, is required to get physical m_e to come out right.

Corrected electron mass

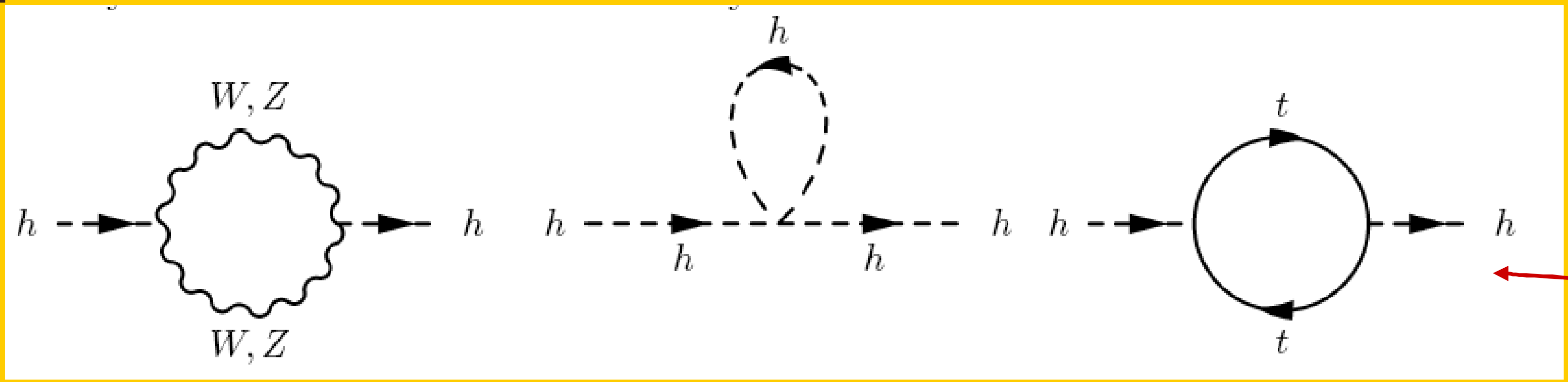
- The physical electron-Higgs Yukawa coupling is not the coupling in the Lagrangian; $y_e = y_e^0 + \delta y_e$



- Multiplicative renormalization! $\delta y_e \sim y_e \alpha \ln M/m_e$
  - If $y_e^0 = 0$ then $y_e = 0$ (chiral symmetry)
  - If y_e^0 is small in Lagrangian, the physical y_e is small (though it differs by a factor of order $\alpha \ln M/m_e$)
- Big correction if $\alpha \ln M/m_e$ is big; for quarks, QCD corrections are even larger, $\alpha_s \ln M/m_q$, commonly of order 3 or so –

But that's nothing compared to…

Corrected Higgs mass



- The physical Higgs mass-squared m_h^2 is not the mass-squared in the Lagrangian;

$$m_h^2 = (m_h^2)_0 + \delta m_h^2$$

- *Additive* renormalization! $\delta m_h^2 = m_h^2 - (m_h^2)_0 \sim (y_t^2 / 16\,\pi^2)M^2$
  - If $(m_h^2)_0 = 0$ in Lagrangian, physical $m_h^2 \sim M^2$ (no symmetry)
- To get small physical m_h^2 **always requires $(m_h^2)_0 \sim M^2$**

(Recall: to get the physical y_e to be small only requires $(y_e)_0$ small)

Fine Tuning and the SM

Suppose $M = M_{GUT} \sim 10^{16}$ GeV and physical $m_h = (145 \text{ GeV})$

- Then we may need, say, $(m_h{}^2)_0 = (42{,}283{,}842{,}355{,}123{,}822 \text{ GeV})^2$
- But suppose the divine scribe accidentally wrote
  $(m_h{}^2)_0 = (42{,}283{,}842{,}355{,}133{,}822 \text{ GeV})^2$

whoops!

Then the physical m_h would be ~ (10^{11} GeV) – *Ouch!*

- Must *fine-tune* $(m_h{}^2)_0$ in the SM Lagrangian at the scale M to an extreme level to make the physical $m_h{}^2$ small, if M >> 1 TeV, so either
  - **The SM is correct at *M* >> 1 TeV and there is *extreme fine-tuning*, or**
  - **The SM is corrected by *new physics* around 1 TeV.**

Couldn't we raise $m_h{}^2$ large and still have a small v?

Not within the SM!

The unitarity argument then rigorously implies new physics at a TeV.

So this is a "problem"

- ***Emotionally, theorists are uncomfortable with this situation***

- This discomfort may or may not be justified
  - The argument almost requires nature to act like a theorist, with a need to carefully write down a Lagrangian – is this how nature does it?
  - The small but nonzero cosmological constant (which should be ~ M^4) enhances the worry that maybe this is all wrong.
- *Still, this type of argument does work elsewhere in particle physics, and in other applications of quantum field theory, so it should not be sneered at.*

- We are left with a certain ambiguity

  - Maybe fine-tuning is an illusion --- incorrect understanding of theory
  - Maybe fine-tuning is true but achieved through an as-yet unknown mechanism
  - Maybe fine-tuning is a consequence of observers being possible only in weird corners of the universe that have small Higgs vev and mass
  - Or maybe the standard model really is invalid above 1 TeV

Theories to resolve hierarchy

Despite the worry that maybe we have it all wrong, I must still bow to the 25 years of theory that have been predicated on the idea that the standard model must be changed at or around 1 TeV

I will briefly touch on the principles behind

- Technicolor
- Extra Dimensions
- Little Higgs Models
- Supersymmetry

and say a few words about their phenomenology

Learning from QCD

- If $v / M_{pl} << 1$ is a "problem",

  why isn't $\Lambda_{QCD} / M_{pl} << 1$ a "problem"?

$$\Lambda_{QCD} \sim M e^{-2\pi / b\alpha_s(M)}$$

One-loop beta function coefficient

~ 5 in QCD

- Λ_{QCD} doesn't appear in Lagrangian
- What appears is α_s, but unless $\alpha_s(M) \sim 1$, $\Lambda_{QCD} << M$
- Thus it is *easy* to obtain $\Lambda_{QCD} << M$!
- This is the *opposite* of the situation with m_h
- *Can we get a composite Higgs boson created through new strong forces?*

Abelian Higgs

Abelian Higgs model: U(1) global symmetry or gauge ‘symmetry’

- Complex scalar ϕ, potential V($|\phi|$)
- Minimum at $\phi = v\, e^{i\alpha}$ (any angle α)
- This breaks the U(1), since under U(1) rotation α would shift.

- If U(1) symmetry is *global*, fluctuations of α are a massless particle
- If U(1) symmetry is *gauged*, fluctuations of α are absorbed by photon, which becomes massive

- In either case, fluctuations of $|\phi|$ around *v*, the “Higgs boson”, are a physical massive particle

Standard Higgs

Standard Higgs model SU(2) x U(1) global symmetry or gauge 'symmetry'

- Complex doublet scalar ϕ, potential V($|\phi^\dagger\phi|$)
- Minimum at $\phi = (v \sin\theta\, e^{i\alpha}, v \cos\theta\, e^{i\beta})$ (any angle α, β, θ)
- This breaks the U(1), since under U(1) rotation α, β would shift.
- This breaks the SU(2), since under SU(2) rotation α, β, θ would shift.
- But a diagonal U(1) is unbroken: to see this, first rotate vev to

$$\phi = (0, v)$$

Then clearly the following rotation leaves the vev $<\phi>$ unchanged.

first rotate by SU(2): $(\phi^+, \phi^0) \rightarrow (e^{i\eta}\,\phi^+, e^{-i\eta}\,\phi^0)$

then rotate by U(1): $(\phi^+, \phi^0) \rightarrow (e^{i\eta}\,\phi^+, e^{i\eta}\,\phi^0)$

which altogether is $(\phi^+, \phi^0) \rightarrow (e^{2i\eta}\,\phi^+, \phi^0)$

- If SU(2) x U(1) symmetry is *global*, fluctuations of α, β, θ are massless – three pions
- If SU(2) x U(1) symmetry is *gauged*, fluctuations of α, β, θ are absorbed by three of the four gauge bosons, which become massive *W,Z,* and a massless photon remains.
- In either case, fluctuations of $|\phi|$ around *v*, the "Higgs boson", are a physical massive particle

Chiral Symmetry Breaking

In QCD, and technicolor, these ideas are generalized; the field ϕ is composite,and its vev is generated by complicated quantum effects.

- In QCD with N_f massless quarks, the theory has a $SU(N_f)_L \times SU(N_f)_R$ chiral symmetry
- This chiral symmetry is spontaneously broken at low energy because of strong nonperturbative dynamics
- A *composite* operator, a quark-antiquark bilinear $\phi = \overline{q}_i q_j$, an $N_f \times N_f$ matrix scalar

  for two flavors $\phi = \begin{bmatrix} \bar{u}u & \bar{u}d \\ \bar{d}u & \bar{d}d \end{bmatrix}$

  develops a vev proportional to the unit matrix
- It thereby breaks the $SU(N_f)_L \times SU(N_f)_R$ chiral symmetry to the diagonal $SU(N_f)_{L+R}$, generating $N_f^2 - 1$ massless Goldstone bosons.
- Real QCD has quarks with small masses, $m_u, m_d << m_s < \Lambda_{QCD}$, but the fact that
  - $2^2 - 1 = 3$ particles must be massless when $m_u, m_d \rightarrow 0$, and
  - $3^2 - 1 = 8$ particles must be massless when $m_u, m_d, m_s \rightarrow 0$

  ensures that the πs, Ks, η are all light, with the πs the lightest of all.

QCD-based Higgs-like Model

N_f = 2 QCD model: *SU(2)$_L$ x SU(2)$_R$* global symmetry or gauge 'symmetry'

- 2 x 2 matrix scalar $\phi = \begin{bmatrix} \bar{u}u & \bar{u}d \\ \bar{d}u & \bar{d}d \end{bmatrix}$
- Potential V($|\phi^\dagger\phi|$), with minimum at $<\phi>$ = *v* **M** which we can always rotate to $<\phi>$ = *v* **1** (unit matrix)
- Since $<\phi>$ = *v* **1** → *v* **U$_L$ 1 U$_R$** under *SU(2)$_L$ x SU(2)$_R$*
  this vev preserves the *diagonal* subgroup *SU(2)$_{L+R}$* , with rotations **U$_R$ = U$_L^{-1}$**
- If *SU(2) x SU(2)* symmetry is *global*, fluctuations of **U$_R$** = **U$_L$** , broken combination of the SU(2)'s, are massless particles – three massless GBs
- If *SU(2) x* ***U(1)*** symmetry is *gauged*, fluctuations **U$_R$** = **U$_L$** are absorbed by three of the four gauge bosons, which become massive *W,Z,* and a massless photon remains. *Nothing remains of the rest of SU(2)$_R$; it is not a symmetry.*
- If ***SU(2)$_{L+R}$*** is *gauged*, vev does **not** break it, so the *gauge bosons are massless*. However, n*othing remains of the rest of SU(2)$_L$ x SU(2)$_R$;* there is no broken global symmetry. The fluctuations **U$_R$** = **U$_L$** are *massive pseudo-GBs*, with masses generated at one loop by the gauge bosons.
- In all cases, fluctuations of $|\phi|$ around *v*, the "Higgs boson", are a physical massive particle, known in QCD as the σ or the $f_{0,}$; (very wide in QCD because $\sigma \to \pi\,\pi$ very rapidly.)

QCD-based Higgs-like Mo

If the quarks aren't quite massless, the $SU(2)_L$ x $SU(2)_R$ *symmetry isn't exact, and the pions aren't quite massless either*

N_f = 2 QCD model: $SU(2)_L \times SU(2)_R$ global symmetry or gauge 'symmetr

- 2 x 2 matrix scalar $\phi = \begin{bmatrix} \bar{u}u & \bar{u}d \\ \bar{d}u & \bar{d}d \end{bmatrix}$
- Potential V($|\phi^\dagger\phi|$), with minimum at $\langle\phi\rangle = v\,\mathbf{M}$ which we can always rotate to $\langle\phi\rangle = v\,\mathbf{1}$ (unit matrix)
- Since $\langle\phi\rangle = v\,\mathbf{1} \rightarrow v\,\mathbf{U_L}\,\mathbf{1}\,\mathbf{U_R}$ under $SU(2)_L \times SU(2)_R$
  this vev preserves the *diagonal* subgroup $SU(2)_{L+R}$, with rotations $\mathbf{U_R} = \mathbf{U_L}^{-1}$
- If *SU(2) x SU(2)* symmetry is *global*, fluctuations of $\mathbf{U_R} = \mathbf{U_L}$, broken combination of the SU(2)'s, are massless particles – <u>three massless GBs</u>
- If *SU(2) x* ***U(1)*** symmetry is *gauged*, fluctuations $\mathbf{U_R} = \mathbf{U_L}$ are absorbed by three of the four gauge bosons, which become <u>massive *W,Z*, and a massless photon</u> remains. *Nothing remains of the rest of* $SU(2)_R$ *; it is not a symmetry.*

<u>What if there were no Higgs vev in the real world?</u>
- the up and down quarks would have been massless;
- SU(2) x SU(2) would have been exact, with SU(2)xU(1) gauged;
- the QCD vev would have broken electroweak SU(2)xU(1) → U(1) in the standard way;
- the W and Z bosons would have eaten the pions and would have had mass of tens of ***MeV****;*
- and the σ ***would*** *have been the Higgs boson!*

- In all cases, fluctuations of $|\phi|$ around *v*, the "Higgs boson", are a physical massive particle, known in QCD as the σ or the f_0; (very wide in QCD because $\sigma \rightarrow \pi\,\pi$ very rapidly.)

Technicolor – Scaled-up QCD

What if there were no Higgs vev in the real world?
- the up and down quarks would have been massless;
- SU(2) x SU(2) would have been exact, with SU(2)xU(1) gauged;
- the QCD vev would have broken electroweak SU(2)xU(1) → U(1) in the standard way;
*- the W and Z bosons would have eaten the pions and would have had mass of tens of **MeV**;*
*- and the σ **would** have been the Higgs boson!*

- Add a new QCD-like group – technicolor -- to SM
  - with two massless flavors of techniquarks,
  - symmetry group $SU(2)_L \times SU(2)_R \times U(1)_B$, and
  - strong coupling scale $\Lambda_{TC} \sim 1\ TeV$
- Gauge part of symmetry group: $SU(2)_w \times U(1)_Y$
- Then the strong technicolor interactions cause a composite operator, a techniquark-antitechniquark bilinear, to break

  $SU(2)_w \times U(1)_Y \rightarrow U(1)_{em}$

- Three TC-pions are absorbed into W^+, W^-, Z ; photon remains massless
- σ_{TC} = Higgs boson: heavy, wide resonance; decays very rapidly to *WW, ZZ*
- This <u>solves</u> the hierarchy problem, because Λ_{TC}/M_{pl} is naturally small

Why doesn't this work easily?

- If Λ_{TC} = 1 TeV, expect quantum corrections to classical SM of order $(m_W / \Lambda_{TC})^2 \sim 1\ \%$
  - *but SM precision tests work to 0.1 % – 1 %*
- Composite Higgs must couple to SM fermions and strongly distinguish different flavors
  - *but get large flavor changing neutral currents, disallowed by experiment*
- Composite Higgs boson must couple strongly to top quark

- *Resolve with non-QCD-like "Walking Technicolor" (some dynamical assumptions necessary)*
- *Possibly make top quark [and bottom quark?] composite too? Or at least **strongly coupled to technicolor sector**.*

Technicolor spectrum

- The spectrum of QCD has far more than just the π,σ.
- Similarly technicolor has much more than just the *W*, *Z*, *h*
- **Repeaters** for the *W*, *Z*, *h*
- **Repeaters** for top? bottom?
- Other spins, other group representations.
- Repeaters are expected for any composite system (think of atomic physics)

Detecting Technicolor?

- Unfortunately precision electroweak constraints imply large Λ_{TC}
- Only lowest states above W,Z probably in reach: ρ_{TC} mesons, 2-3 TeV
- Produce ρ_{TC} in *WW, WZ* Vector Boson Fusion, though very challenging to detect and study at LHC
- More work needed to understand best techniques, reach