Dec. 18

Higgs Boson

I have now reviewed almost everything that we know about the Standard Model. In this lecture, I will discuss some things that we don't know.

We have now discovered all of the particles of the Standard Model except for the Higgs boson. In our discussion Wednesday, we saw that the Standard Model gives a very concrete picture of the Higgs boson and its couplings. In this lecture, I will present the Standard Model predictions for the Higgs boson decay pattern and production processes and describe how we might find it in collider experiments.

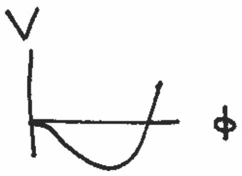
However, I should first issue a warning. All of the predictions of the Standard Model that I have discussed up to this point have been verified. The gauge couplings of the Standard Model form a tight and well-motivated structure. However, there are good reasons to believe that the theory of the Higgs boson that I will present in this lecture is wrong, or, at least, dramatically incomplete. At the end of the lecture, I will explain why I think this. I will also give a list of major unsolved problems in particle physics.

It is most convenient to discuss the couplings of the Higgs boson in the gauge in where

$$\Phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

This formula makes clear that the Higgs field contains one physical degree of freedom, the real scalar field $h(x)$. Let the Higgs potential be written

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



The minimum occurs at

$$v = \left|\frac{\mu^2}{\lambda}\right|^{\frac{1}{2}}$$

and near the minimum

$$V(h) = -\frac{\mu^2 v^2}{2} + \mu^2 h^2 + \cdots$$

so that

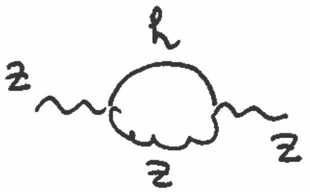
$$m_h^2 = 2\mu^2$$

So far, all of our predictions from the Standard Model have depended only on the coupling constants g_s, g, and g' and the Higgs vacuum expectation value v. So μ^2 is a new parameter, and we might as well exchange it for the Higgs mass m_h. The nonlinear coupling of the Higgs field is

$$\lambda = \frac{1}{2}\frac{m_h^2}{v^2} \qquad\qquad \frac{\lambda}{4\pi} = \frac{m_h^2}{8\pi v^2}$$

We know that $v = 246$ GeV, so $\lambda/4\pi$ becomes of the order of 1 for $m_h \approx 1$ TeV. This gives a rough upper bound for m_h.

Strictly within the Standard Model, there is a stronger bound that comes from the good agreement of the precision electroweak measurements with the theoretical predictions. A heavy Higgs boson gives additional contributions to the Z and W masses of the form



$$\sim \frac{\alpha_w}{4\pi} m_Z^2 \log \frac{m_h^2}{m_Z^2}$$

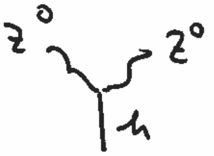
These corrections upset the good agreement of theory and experiment for $m_h > 180$ GeV. You should be aware that these corrections can be cancelled by corrections from other new particles that we might add to the theory. However, that would take us outside the Standard Model.

The couplings of the Higgs boson to gauge bosons and fermions are given by the Lagrangian

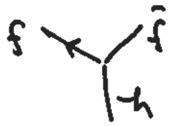
$$\delta\mathcal{L} = \frac{1}{2}\frac{g^2+g'^2}{4}(v+h)^2 Z_\mu Z^\mu + \frac{g^2}{4}(v+h)^2 W^+_\mu W^{\mu -} - \sum_f \frac{\lambda_f}{\sqrt{2}}(v+h)\bar{f} f$$

That is, the Higgs vertices are

$$= 2i\frac{m_W^2}{v} g^{\mu\nu}$$



$$= 2i\frac{m_Z^2}{v} g^{\mu\nu}$$



$$= -i\frac{m_f}{v}$$

The Higgs couples most strongly to the heaviest particles of the Standard Model. It couples extremely weakly to the particles that are easiest to accelerate—e, u, and d. This makes it challenging to construct a collider experiment that can find the Higgs boson.

I will now review the partial widths for Higgs decay into its possible final states. Another consequence of the Higgs couping to mass is that the Higgs should decay dominantly into the heaviest species available. For $m_h > 160$ GeV, the dominant decays will be to W^+W^- and Z^0Z^0. The partial widths to these final states are not hard to compute:

$$\Gamma(h^0 \to W^+W^-) = \frac{\alpha_w}{16}\frac{m_h^3}{m_W^2}\left(1-4\frac{m_W^2}{m_h^2}+12\frac{m_W^4}{m_h^4}\right)\left(1-\frac{4m_W^2}{m_h^2}\right)^{1/2}$$

$$\Gamma(h^0 \to Z^0Z^0) = \frac{\alpha_w}{32}\frac{m_h^3}{m_W^2}\left(1-4\frac{m_Z^2}{m_h^2}+12\frac{m_Z^4}{m_h^4}\right)\left(1-\frac{4m_Z^2}{m_h^2}\right)^{1/2}$$

Note that the results are larger than expected by a factor

$$\left(\frac{m_h^2}{m_W^2}\right)$$

The enhancement comes in the decay rates to pairs of longitudinally polarized vector bosons. This enhancement is similar to the one discussed in the previous lecture for the top quark decay to longintudinally polarized W bosons. The enhancement factor is

$$\frac{m_h^2}{m_W^2} \sim \frac{\lambda}{g^2}$$

It reflects the fact that the longitudinal vector bosons came from the Goldstone bosons in the Higgs multiplet, and so the Higgs should couple to these with the Higgs coupling strength rather than with the gauge coupling.

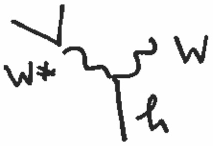
Below the threshold for $h \to W^+W^-$, the dominant decay channel for the Higgs is $h \to b\bar{b}$. The rate of Higgs decay to $f\overline{f}$ is predicted to be

$$\Gamma(h^0 \to f\bar{f}) = \frac{\alpha_w}{8} m_h \left(\frac{m_f}{m_h}\right)^2 \cdot \left(1-\frac{4m_f^2}{m_h^2}\right)^{3/2} \cdot N_f$$

where $N_f = 1$ for leptons, $N_f = 3$ for quarks. The coefficient of this expression is smaller than the one in the rate of decay to W^+W^- by the factor

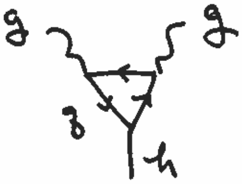
$$\frac{1}{2}\frac{m_b^2}{m_W^2} \sim 2\times10^{-3}$$

This is sufficiently small that Higgs decays to off-shell W and Z bosons



still have large branching ratios in a substantial region below the threshold for Higgs decay to two on-shell W's.

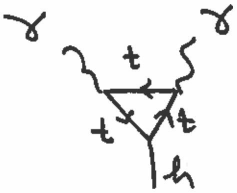
The small size of $\Gamma(h \to b\bar{b})$ also means that processes that occur only via 1-loop diagrams can compete. For example, $h \to gg$ is possible through the diagram



The $hq\bar{q}$ vertex is proportional to m_q, and the diagram itself can be as large as $1/m_q$ in the limit of a heavy quark. So, oddly, only quarks with mass $2m_q > m_h$ give a significant contribution. The contribution from the top quark in the loop is

$$\Gamma(h \to gg) = \frac{\alpha_w \alpha_s^2}{288\pi^2}\frac{m_h^3}{m_W^2}$$

which gives a 5% branching ratio for a Higgs of mass $m_h = 120$ GeV. Similarly, the diagrams



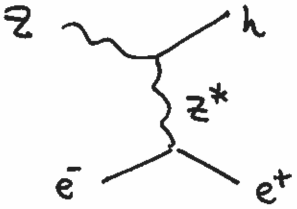
give a decay rate to $\gamma\gamma$

$$\Gamma(h \to \gamma\gamma) = .027 \, \frac{\alpha_w \alpha^2}{\pi^2} \, \frac{m_h^3}{m_W^2}$$

which amounts to a branching ratio of 2×10^{-3} for $m_h = 120$ GeV.

The full pattern of Higgs branching ratios predicted by the Standard Model is shown in Figs p. 2, 3, and 4. The first of these figures shown the mass region below the $h \to W^+W^-$ threshold. Here, the Standard Model Higgs has a complex pattern of decays involving many possible final states. The next figure shows the pattern in the vicinity of the WW and ZZ thresholds. Note how the turn-on of the decay to WW eats away at the rate for $h \to ZZ^*$ just below the ZZ threshold. The third of the figures shows the case of a high mass Higgs. Note that the decay to top quarks never becomes dominant because of the strong-coupling enhancement of the decay to longitudinal W and Z bosons discussed above.

To search for the Higgs at colliders, we must first produce it. For this, we need a high-mass initial particle to couple to the Higgs. The most sensitive search so far has been conducted at LEP, using the process $e^+e^- \to Z^0h^0$,



In this reaction, the Higgs is produced together with a Z^0 which recoils at a fixed energy. If we can recognize this Z^0, we can in principle find the Higgs independently of its decay mode. Results from the highest center of mass energies attained at LEP are shown in Figs p. 4. The experiments shown here are searching explicitly for

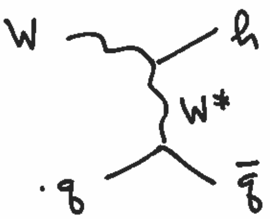
$$e^+e^- \to Z^0 h^0$$
$$\hookrightarrow b\bar{b}$$

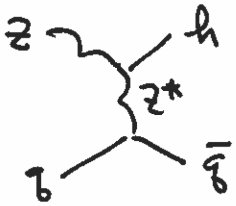
since $b\bar{b}$ is the dominant decay product expected in the relevant Higgs mass range. The three graphs show the $b\bar{b}$ 2-jet mass distribution with loose, medium, and tight cuts to identify the b quarks. You see a clear signal from the process

$$e^+e^- \to Z^0 Z^0$$
$$\hookrightarrow b\bar{b}$$

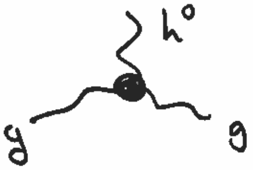
Maybe there is a hint of an excess at high mass values, but it no proof that that Higgs is there. These experiments at LEP exclude a Standard Model Higgs boson with mass up to 114 GeV.

The CDF and DO experiments at the Fermilab Tevatron are now searching for the Higgs boson using the reactions





to search for a relatively low mass Higgs, just beyond the LEP limit, They are also using reaction $gg \to h^0$,



with the characteristic Higgs decay $h \to W^+W^- \to \ell^+\nu\ell^-\overline{\nu}$ to search for a Higgs with mass near the WW threshold. Figs p. 6 shows the current status of these searches. The second search technique asks for events with two leptons and large missing momentum. No events are seen above background, and so a strong limit on the production of the Higgs can be placed in this mass region. The figure thus shows the LEP exclusion of Higgs bosons below 114 GeV and a new exclused region from the Tevatron. In other regions, the figure shows the level of Higgs production cross section that is excluded in their search, but these limits (the solid curve labelled 'Observed') still lie somewhat above the cross section levels predicted in the Standard Model.

The new proton-proton collider LHC is now turning on at CERN. The LHC is expected to reach a center of mass energy of 14 TeV and event rates corresponding to 10^5 events per year for a process with a 1 pb cross section. At the energies of the LHC, two new search methods open up.

First, because the gluon density in the proton increases dramatically at small x, higher proton energy at a collider means that many more gluons have the energy to produce Higgs bosons through $gg \to h^0$. The dominant Higgs decay models such as $h \to b\bar{b}$ are difficult to find in this reaction. For a 120 GeV Higgs, the cross section for

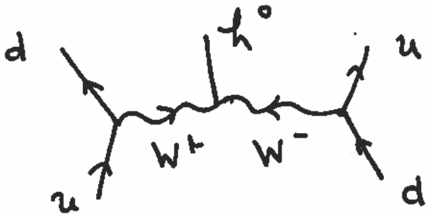
$$gg \to h^0 \to b\bar{b}$$

is expected to be about 30 pb, while the cross section for $pp \to b\bar{b}$ with b jets of $k_T \sim 60$ GeV is expected to be about 10 μb. However, heavy Higgs bosons that can decay to ZZ should be visible through the process

$$gg \to h^0 \to Z^0 Z^0 \to \ell^+\ell^- \quad \ell^+\ell^-$$

Figs p. 7 shows some simulations of this signal in the CMS experiment at the LHC, for Higgs masses of 140 GeV and 200 GeV. For a low mass Higgs, there is no such obvious search mode. The best method available is to look for the rare decay $h \to \gamma\gamma$, recognizing the Higgs as a small resonance on top of the large but smooth $\gamma\gamma$ background from $q\bar{q} \to \gamma\gamma$ and π^0 production. Figs p. 8 shows a simulatiuon of this search from CMS. Note that the expected Standard Model signal has been multiplied by 10; still, a signal of the expected size should be statistically significant.

A second possible mode for the Higgs search uses the reaction



One looks for the two high energy forward jets in coincidence with a characteristic Higgs decay. Figs p. 9 shows a simulation of the signal expected with the Higgs decay $h \to \tau^+\tau^-$. The figures shows two peaks from the processes

$$W^+W^- \to Z^0, h^0 \to \tau^+\tau^-$$

The peak from Z^0 production provides a nice calibration for the Higgs search.

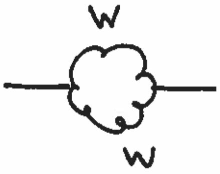
Figs p. 10 shows a summary of the expected sensitivity of a variety of Higgs search techniques at the LHC as a function of the Higgs mass. With a large event sample, perhaps obtained after 2–3 years of high quality running at the design energy, the LHC experiments should be able to discover the Higgs boson over its entire allowed mass range if the Standard Model predictions for its couplings are correct.

In principle, this discovery could finish the story of the Standard Model. However, I do not think this is what will happen.

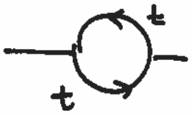
The Standard Model has a real weakness in its description of the Higgs potential $V(\phi)$. This potential has a symmetry-breaking minimum. However, there is no explanation of the form of this potential. We are just instructed to write it down. Ordinarily in physics, when important symmetries are spontaneously broken, there is a clear physical mechanism that causes this breaking. We see this in superconductors and in magnets, and in the theory of chiral symmetry breaking in the strong interactions discussed earlier in these lectures. But for the Higgs field of the Standard Model, there is none.

Instead, we find the following troubling information: Symmetry breaking in the Standard Model depends entirely on the sign of the parameter μ^2. There is no *a priori* reason to choose one sign over the other. Worse, when we compute the radiative corrections to this parameter, we find additive ultraviolet divergent corrections. These corrections are of different sign for different species in the loop,

$$\sim + \frac{\lambda}{(4\pi)^2}\Lambda^2$$



$$\sim + \frac{g^2}{(4\pi)^2}\Lambda^2$$



$$\sim -\frac{\lambda_t^2}{(4\pi)^2}\Lambda^2$$

Thus, the Standard Model cannot give us a coherent theory of the value of μ^2 or even tell us whether this parameter should be positive or negative.

This is a major problem, but it is not the only open problem in particle physics. Perhaps I should list a few more:

- We do not understand why the gauge symmetry of the Standard Model is $SU(3) \times SU(2) \times U(1)$ or why the quantum numbers of the quarks and leptons are as they are. A possible explanation is that the Standard Model arises by symmetry breaking of a large simple *grand unification* group such as $SU(5)$ or $SO(10)$. In string theory, $SU(3) \times SU(2) \times U(1)$ can arise from arrays of 3, 2, and 1 *D-branes* stretched across extra space dimensions. Many other models have been proposed; we do not know which, if any, if right.

- We do not understand how gravity fits into this picture of the microscopic interactions. Quarks, leptons, and gauge bosons do couple to gravity. Is there a unification of forces that includes this? String theory gives a possible answer. Are there others?

- We have not come to the end of the story of CP violation. We saw that the Kobayashi-Maskawa model seems to explain all CP violation observed in particle physics so far. However, we also se a macroscopic example of CP violation in the universe, in the fact that there are baryons and electrons everywhere but very few antiprotons and positrons. In inflationary cosmology, the universe began in a state of zero net baryon and lepton number. To evolve from that state to the one we see, we need baryon- and lepton-number violating interactions (which the Standard Model actually supplies) but also a source of CP violation to break the matter-antimatter symmetry. The KM phase parameter turns out to be ineffective in the early universe at temperatures above the b quark mass. There must be another source of CP violation in the laws of Nature. It has been suggested that the new CP violating terms are associated with neutrino masses, or with the top quark, or with new particles related to the Higgs bosons. We do not know.

- We do not know the identity of the major components of the universe, dark energy and dark matter. Dark energy seems especially mysterious, and it is not clear whether we are yet framing questions about dark energy correctly. Dark matter, on the other hand, is quite concrete. It is a new form of matter, not included in the Standard Model, that is stable, slowly moving, neutral, and weakly interacting. There are many theories by which dark matter could have been produced in the early universe in amounts consistent with the abundance currently observed. The most attractive of these theories have dark matter particle masses of about 100 GeV.

- And, finally, we do not know the physical origin of the symmetry-breaking that gives rise to the masses of all of the particles in the Standard Model. Here again, the natural energy scale would seem to be set by the parameter $v \sim 250$ GeV.

It is tantalizing that, while the first three of these problems might be solved at energy scales well beyond those we can soon reach experimentally, the last two problems could very well benefit from new information at energy scales of a few hundred GeV. In the next few years, the new experiments at the LHC will explore this range of energies. It is quite possible that these experiments will turn up the crucial clues that will allow us to solve these problems and go a step further beyond the current Standard Model. This is the promise of the coming era in particle physics—your era. I wish you the best of fortune pursuing these goals in the coming years.