PHYS 5326 – Lecture #15, 16, 17.5

Monday, Apr. 16, 2007
Dr. Jae Yu

1. Spontaneous Symmetry Breaking
2. Higgs Mechanism
3. Introducing SUSY
4. Super Symmetry Breaking
5. MSSM Higgs and Their Masses
6. Higgs Mass Theoretical Upper Bounds
7. SM Higgs Production Processes in Hadron Colliders
8. Winter 07 Experimental Results

Announcements

- This is the last make up class
- Venkat's thesis analysis lecture on Wednesday
  - Time: 1 – 2:30pm
  - Location: CPB126
- Given the shortage of time, we will not have 2nd term exam
- Evaluation
  - Term exam: 20%
  - Homework: 20%
  - Project report: 25%
  - Presentation: 15%
  - Total 80%

Spontaneous Symmetry Breaking

While the collection of ground states does preserve the symmetry in $\mathcal{L}$, the Feynman formalism allows to work with only one of the ground states. ➔ Causes the symmetry to break.

This is called "spontaneous" symmetry breaking, because symmetry breaking is not externally caused.

The true symmetry of the system is hidden by an arbitrary choice of a particular ground state. This is the case of discrete symmetry w/ 2 ground states.

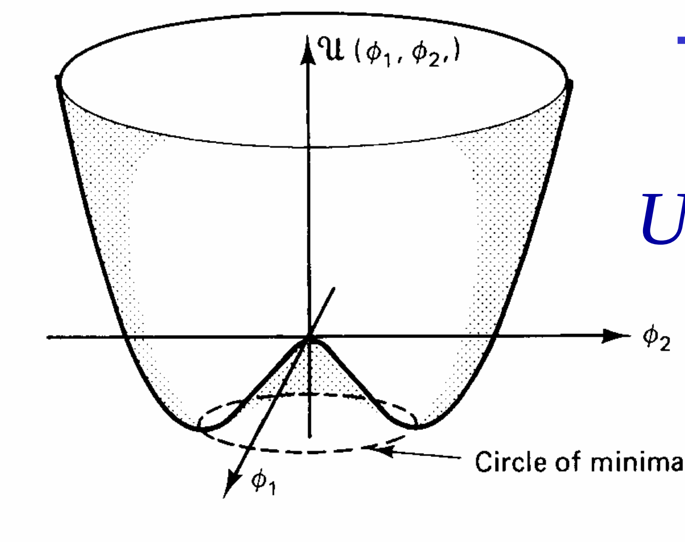
Spontaneous Breaking of a Continuous Symmetry

A lagrangian, $\mathcal{L}$, for two fields, ϕ_1 and ϕ_2 can be written

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu \phi_1\right)\left(\partial^\mu \phi_1\right) + \frac{1}{2}\left(\partial_\mu \phi_2\right)\left(\partial^\mu \phi_2\right)$$

$$+ \frac{1}{2}\mu^2\left(\phi_1^2 + \phi_2^2\right) - \frac{1}{4}\lambda^2\left(\phi_1^4 + \phi_2^4\right)$$

is even and is invariant under $\phi_1, \phi_2 \rightarrow -\phi_1, -\phi_2$.



The potential energy term becomes

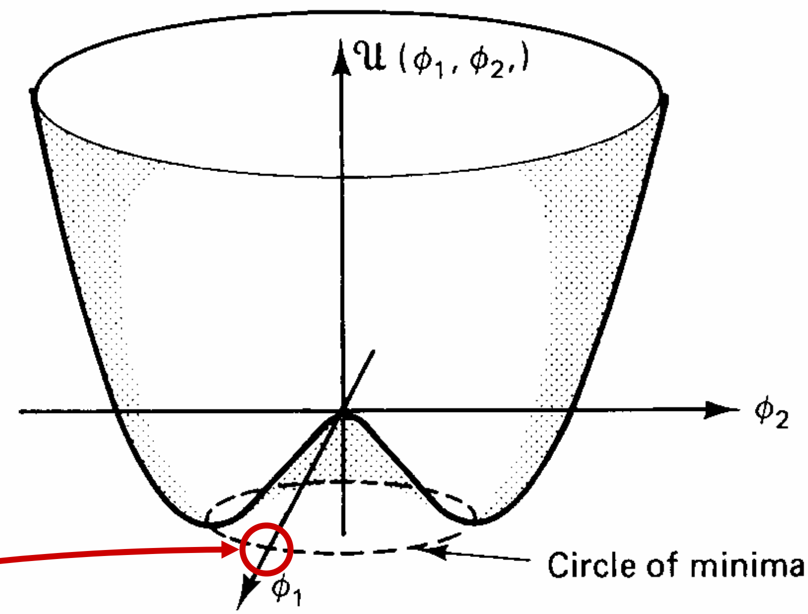
$$U = -\frac{1}{2}\mu^2\left(\phi_1^2 + \phi_2^2\right) + \frac{1}{4}\lambda^2\left(\phi_1^4 + \phi_2^4\right)$$

w/ the minima on the circle:

$$\phi_{1,\min}^2 + \phi_{2,\min}^2 = \mu^2/\lambda^2$$

Spontaneous Breaking of a Continuous Symmetry

To apply Feynman calculus, we need to expand about a particular ground state (the "vacuum"). Picking



$$\phi_{1,\min} = \mu/\lambda \text{ and } \phi_{2,\min} = 0$$

And introduce two new fields, η and ξ, which are the fluctuations about the vacuum:

$$\eta \equiv \phi_1 - \mu/\lambda \text{ and } \xi \equiv \phi_2$$

Spontaneous Breaking of a Continuous Symmetry

The new $\mathcal{L}$ becomes

$$\mathcal{L} = \left[\frac{1}{2}\left(\partial_\mu \eta\right)\left(\partial^\mu \eta\right) - \mu^2\eta^2\right] + \left[\frac{1}{2}\left(\partial_\mu \xi\right)\left(\partial^\mu \xi\right)\right]$$

$$+\left[\mu\lambda\left(\eta^3 + \eta\xi^2\right) - \frac{\lambda^2}{4}\left(\eta^4 + \xi^4 + 2\eta^2\xi^2\right)\right] + \frac{1}{4}\left(\mu^2/\lambda\right)^2$$

3point vtx

$\mathcal{L}_{KG}$ of the field η w/ the mass $m_\eta = \sqrt{2}\mu\hbar/c$

$\mathcal{L}_{free}$ of the massless field ξ

4point vtx

Spontaneous Breaking of Continuous Global Symmetry

- One of the fields is automatically massless.
- Goldstone's theorem says that breaking of continuous global symmetry is always accompanied by one or more **massless scalar (spin=0) bosons**, called the **Goldstone Bosons**.
- This again poses a problem because the effort to introduce mass to weak gauge fields introduces a massless scalar boson which has not been observed.
- This problem can be addressed if spontaneous SB is applied to the case of local gauge invariance.

Higgs Mechanism

$\mathcal{L}$ in page 3 can be simplified by combining two real fields into one complex field $\phi \equiv \phi_1 + i\phi_2; \quad \phi^*\phi = \phi_1^2 + \phi_2^2$

Using this new form of the field, the $\mathcal{L}$ looks exactly like that of a single scalar field

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu \phi\right)^* \left(\partial^\mu \phi\right) + \frac{1}{2}\mu^2 \phi^* \phi - \frac{1}{4}\lambda^2 \left(\phi^* \phi\right)^2$$

Now the rotational symmetry becomes invariance under U(1) gauge transformation, $\phi \to e^{i\theta}\phi$.

Higgs Mechanism

$\mathcal{L}$ can be made invariant under local gauge transformation by introducing a vector field, A^μ, and replacing the partial derivatives with covariant ones. The new $\mathcal{L}$ then becomes

$$\mathcal{L} = \frac{1}{2}\left[\left(\partial_\mu - \frac{iq}{\hbar c}\right)\phi^*\right]\left[\left(\partial^\mu + \frac{iq}{\hbar c}\right)\phi\right] + \frac{1}{2}\mu^2\phi^*\phi - \frac{1}{4}\lambda^2\left(\phi^*\phi\right)^2 - \frac{1}{16\pi}F^{\mu\nu}F_{\mu\nu}$$

We then can break the symmetry as we did before by introducing new fields $\eta \equiv \phi_1 - \mu/\lambda$ and $\xi \equiv \phi_2$.

Higgs Mechanism

The new $\mathcal{L}$ is written in terms of η and ξ as

$$\mathcal{L} = \left[\frac{1}{2}\left(\partial_\mu \eta\right)\left(\partial^\mu \eta\right) - \mu^2\eta^2\right] + \left[\frac{1}{2}\left(\partial_\mu \xi\right)\left(\partial^\mu \xi\right)\right]$$

$$+\left[-\frac{1}{16\pi}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}\left(\frac{iq}{\hbar c}\frac{\mu}{\lambda}\right)^2 A^\mu A_\mu\right] - 2i\left(\frac{q}{\hbar c}\frac{\mu}{\lambda}\right)\left(\partial_\mu \xi\right)A^\mu$$

$$+\left\{\frac{q}{\hbar c}\left[\eta\left(\partial_\mu \xi\right) - \xi\left(\partial_\mu \eta\right)\right]A^\mu + \left(\frac{q}{\hbar c}\right)^2\left[\frac{\mu}{\lambda}\eta + \frac{1}{2}\left(\xi^2 + \eta^2\right)\right]\left(A^\mu A_\mu\right)\right.$$

$$\left. -\mu\lambda\left(\eta^3 + \eta\xi^2\right) - \frac{\lambda^2}{4}\left(\eta^4 + \xi^4 + 2\eta^2\xi^2\right)\right\} + \frac{1}{4}\left(\mu^2/\lambda\right)^2$$

$\mathcal{L}_{free}$ of the massless Goldstone boson ξ

Bad term!!

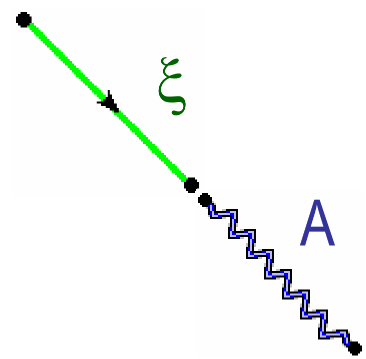
$\mathcal{L}_{KG}$ of the scalar field η w/ the mass $m_\eta = \sqrt{2}\mu\hbar/c$

$\mathcal{L}_{proca}$ of the free gauge field A^μ w/ the mass $m_A = 2\sqrt{\pi}q\mu/\lambda c$

Higgs Mechanism

Issues with the new $\mathcal{L}$ are the unwanted Goldstone boson ξ and the term

$$-2i\left(\frac{q}{\hbar c}\frac{\mu}{\lambda}\right)\left(\partial_\mu \xi\right)A^\mu$$



which can be interpreted as one point vertex interaction between scalar field ξ and vector field A^μ.

This kind of terms indicate that the fundamental particles in the theory are identified incorrectly. Both problems can be resolved exploiting gauge invariance of $\mathcal{L}$.

Higgs Mechanism

Since the complex field in $\mathcal{L}$ is $\phi \equiv \phi_1 + i\phi_2$,

The U(1) gauge transformed field is written

$$\phi \rightarrow \phi' = e^{i\theta}\phi = (\cos\theta + i\sin\theta)(\phi_1 + i\phi_2)$$
$$= (\phi_1\cos\theta - \phi_2\sin\theta) + i(\phi_2\cos\theta + \phi_1\sin\theta)$$

The transformed field, ϕ', becomes real by picking θ that makes the complex term 0.

$$\phi_2\cos\theta + \phi_1\sin\theta = 0 \quad \Rightarrow \quad \theta = -\tan^{-1}(\phi_2/\phi_1)$$

Under this condition, since $\phi' \equiv \phi_1' + i\phi_2'$, ϕ'_2 is 0, making the transformed ξ become 0, eliminating it from $\mathcal{L}$.

Higgs Mechanism

In this gauge, the new $\mathcal{L}$ becomes

$$\mathcal{L} = \left[\frac{1}{2}\left(\partial_\mu \eta\right)\left(\partial^\mu \eta\right) - \mu^2\eta^2\right] + \left[-\frac{1}{16\pi}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}\left(\frac{iq}{\hbar c}\frac{\mu}{\lambda}\right)^2 A^\mu A_\mu\right]$$

$$+\left\{\left(\frac{q}{\hbar c}\right)^2\left[\frac{\mu}{\lambda}\eta + \frac{1}{2}\eta^2\right]\left(A^\mu A_\mu\right) - \mu\lambda\eta^3 - \frac{\lambda^2}{4}\eta^4\right\}$$

$$+\frac{1}{4}\left(\mu^2/\lambda\right)^2$$

$\mathcal{L}_{proca}$ of the free gauge field A^μ
w/ the mass $m_A = 2\sqrt{\pi}q\mu/\lambda c$

$\mathcal{L}_{KG}$ of the scalar field η
w/ the mass $m_\eta = \sqrt{2}\mu\hbar/c$

This $\mathcal{L}$ has all the necessary properties

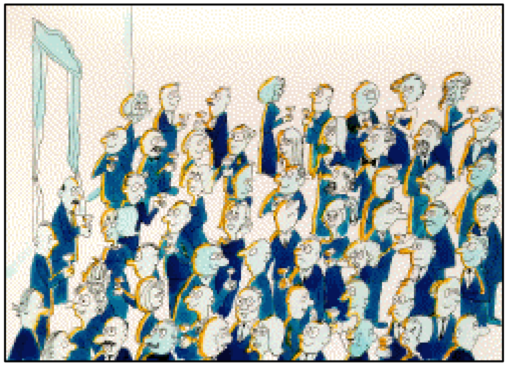
1. No massless Goldstone boson (ξ) & no bad single point interaction term
2. Massive gauge field, A^μ
3. A single massive scalar boson, η, (the Higgs boson)

Higgs Mechanism

- The new $\mathcal{L}$ describes the same physical system
  - A particular gauge ($\theta = -\tan^{-1}(\phi_2/\phi_1)$)has been chosen
  - Keep the Feynman calculus still valid
- Symmetry has been spontaneously broken, giving masses to gauge field and producing a massive scalar boson
  - The massive gauge vector boson picks up another degree of freedom, the longitudinal polarization, compared to two transverse ones originally.
  - The longitudinal polarization came from Goldstone boson
  - The original ghost Goldstone boson has been eaten by the gauge boson, giving mass to the gauge vector boson and the longitudinal polarization.
- In SM, the Higgs boson is responsible for <u>mass of weak vector bosons, leptons and quarks</u>

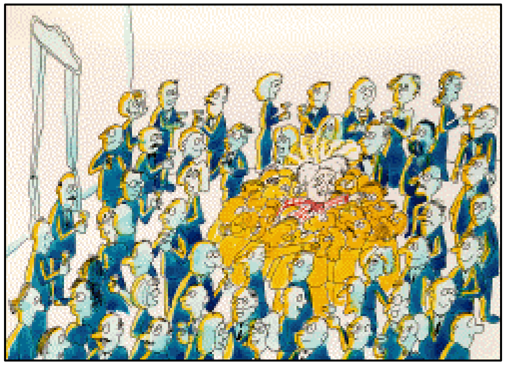
The Higgs Mechanism

The Higgs Particle



To understand the Higgs mechanism, imagine that a room full of physicists chattering quietly is like space filled with the Higgs field.

... a well-known scientist walks in, creating a disturbance as he moves across the room and attracting a cluster of admirers with each step ...



... this increases his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field...

... if a rumor crosses the room, ...

... it creates the same kind of clustering, but this time among the scientists themselves. In this analogy, these clusters are the Higgs particles.

Courtesy of CERN. The concept was inspired by Prof. David J. Miller of University College London.

Issues with Higgs

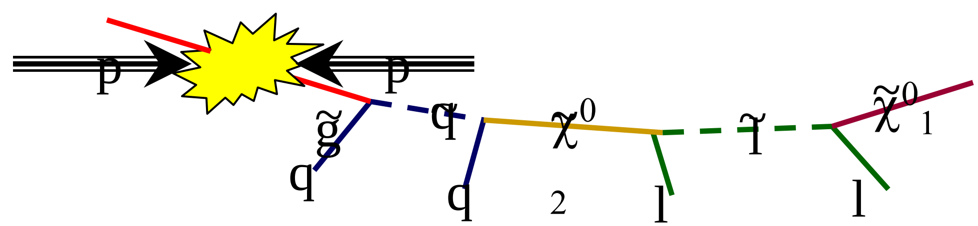
- Haven't been observed at any laboratories yet.
- The Higgs potential is completely unknown.
- Does not explain why fermion masses are what they are.
- Minimal SM loop corrections give quadratic divergences to the mass of Higgs.
- Other Symmetry breaking models…
- How many Higgs?
- What are the couplings (Yukawa?)? How strong are they?

Introduction to Super Symmetry

- An alternate solution to resolve mass hierarchy issue caused by the quadratic divergences.
- A symmetry that relates particles of differing spins
- Particles are combined in superfields which contain the fields differing by spin ½.
- Scalars and fermions in superfields have the same coupling to gauge bosons and cause the quadratic divergence to cancel
- The $\mathcal{L}_{\mathrm{SUSY}}$ contains scalar and fermion pairs of equal mass
  - SUSY connects particles of different spins but all other characteristics are the same
- SUSY is a broken symmetry because there is no partner of particles with the same mass but different spin➔ non-zero mass splitting between partners is an indication of broken symmetry

Introduction to Supersymmetry

- Motivation for Supersymmetry (SUSY):
  - Hierarchy Problem: SUSY stabilizes Higgs mass against loop correction.
  - Grand Unification: SUSY modifies running of SM gauge couplings "just enough" to give
    Grand Unification at single scale. (SUSY is needed in String theories).
  - Dark Matter: R-parity conservation causes the Lightest SUSY Particle (LSP) to be stable
- SUSY particles (gluinos and squarks) are expected to be produced in the proton-proton collision.
- Long decay chains and large mass differences between SUSY states; many high P_T objects are observed (lepton, jets, b-jets).
- If R-Parity is conserved, cascade decays to stable undetected LSP; large E_T^{miss} signatures.
- A typical decay chain of SUSY particles:



SUSY Particle Spectrum

Standard Model Particles		SUSY Partners		
Particles	States	Sparticles	States	Mixtures
quarks (q)	$\begin{pmatrix} u \\ d \end{pmatrix}_L$, u_R, d_R	squarks ($\tilde{q}$)	$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_L$, $\tilde{u}_R$, $\tilde{d}_R$	
(spin-$\frac{1}{2}$)	$\begin{pmatrix} c \\ s \end{pmatrix}_L$, c_R, s_R	(spin-0)	$\begin{pmatrix} \tilde{c} \\ \tilde{s} \end{pmatrix}_L$, $\tilde{c}_R$, $\tilde{s}_R$	
	$\begin{pmatrix} t \\ b \end{pmatrix}_L$, t_R, b_R		$\begin{pmatrix} \tilde{t} \\ \tilde{b} \end{pmatrix}_L$, $\tilde{t}_R$, $\tilde{b}_R$	$\tilde{t}_{1,2}$, $\tilde{b}_{1,2}$
leptons (l)	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$, e_R	sleptons ($\tilde{l}$)	$\begin{pmatrix} \tilde{e} \\ \tilde{\nu}_e \end{pmatrix}_L$, $\tilde{e}_R$	
(spin-$\frac{1}{2}$)	$\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$, μ_R	(spin-0)	$\begin{pmatrix} \tilde{\mu} \\ \tilde{\nu}_\mu \end{pmatrix}_L$, $\tilde{\mu}_R$	
	$\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$, τ_R		$\begin{pmatrix} \tilde{\tau} \\ \tilde{\nu}_\tau \end{pmatrix}_L$, $\tilde{\tau}_R$	$\tilde{\tau}_{1,2}$
gauge/Higgs bosons	g, Z, γ, h, H, A	gauginos/Higgsinos	$\tilde{g}$, $\tilde{Z}$, $\tilde{\gamma}$, $\tilde{H}_1^0$	$\tilde{\chi}^0_{1,2,3,4}$
(spin-1, spin-0)	$W^\pm$, $H^\pm$	(spin-$\frac{1}{2}$)	$\tilde{W}^\pm$, $\tilde{H}^\pm$	$\tilde{\chi}^\pm_{1,2}$
graviton (spin-2)	G	gravitino (spin-$\frac{3}{2}$)	$\tilde{G}$	

Some SUSY Models

- MSSM: Minimal SUSY extension of the SM (MSSM) brings 105 additional free parameters into the theory, thus making a systematic study of the full parameter space difficult. Since SUSY is a broken symmetry one can reduce the number of parameters by constraining the SUSY breaking. The origin of the SUSY breaking and its mediation to the MSSM sector are key features of SUSY models.
- mSUGRA: In the minimal Supergravity (mSUGRA) model which is used as a standard benchmark model, the SUSY breaking is transmitted from the hidden sector to the observable sector by gravity. The gauginos, scalars masses and the trilinear couplings are assumed to be unified at the Grand Unification (GUT) scale leading to only five free parameters: m_0, $m_{1/2}$, A_0, $\tan(\beta)$, $\mathrm{sgn}(\mu)$.
- GMSB: In the Gauge Mediated SUSY breaking models the breaking is mediated by gauge interactions. LSP are taken to be nearly massless gravitinos. The NLSP can be either neutral or charged. In the case it is neutral, it is the lightest combination of Higgsinos and gauginos, and behaves in the same way as the neutralino in the mSUGRA model, except for its decay. If the lifetime is short the events will contain two hard photons and missing energy, which provide a distinguished signature against any other SUSY model.
- AMSB: Another possibility is that the hidden sector of the theory does not have the right structure to provide masses through either the mSUGRA or GMSB mechanisms. Instead, the leading contributions come from a combination of gravity and anomalies. This model is known as Anomaly Mediated SUSY Breaking (AMSB) and predicts a different pattern of signatures and masses.

Minimal Supersymmetric Model (MSSM)

Uses the same $SU(3)xSU_L(2)xU_Y(1)$ gauge symmetry as the Standard Model and yields the following list of particles

Chiral Superfield

Superfield	$SU(3)$	$SU(2)_L$	$U(1)_Y$	Particle Content
$\hat{Q}$	3	2	$\frac{1}{3}$	$(u_L, d_L), (\tilde{u}_L, \tilde{d}_L)$
$\hat{U}^c$	$\bar{3}$	1	$-\frac{4}{3}$	$\bar{u}_R, \tilde{u}_R^*$
$\hat{D}^c$	$\bar{3}$	1	$\frac{2}{3}$	$\bar{d}_R, \tilde{d}_R^*$
$\hat{L}$	1	2	-1	$(\nu_L, e_L), (\tilde{\nu}_L, \tilde{e}_L)$
$\hat{E}^c$	1	1	2	$\bar{e}_R, \tilde{e}_R^*$
$\hat{H}_1$	1	2	-1	$(H_1, \tilde{h}_1)$
$\hat{H}_2$	1	2	1	$(H_2, \tilde{h}_2)$

Vector Superfield

Superfield	$SU(3)$	$SU(2)_L$	$U(1)_Y$	Particle Content
$\hat{G}^a$	8	1	0	$g, \tilde{g}$
$\hat{W}^i$	1	3	0	$W_i, \tilde{\lambda}_i$
$\hat{B}$	1	1	0	$B, \tilde{b}$

Majorana fermion partners

Higgs Sector in MSSM

In SM $\mathcal{L}$ for EW interactions, fermion masses are generated by the Yukawa terms in $\mathcal{L}$

$$\mathcal{L} = -\lambda_d \overline{Q}_L \Phi d_R - \lambda_u \overline{Q}_L \Phi^c u_R + h.c.$$

Higgs coupling to d quark

Higgs coupling to u quark

In MSSM, the term proportional to $\Phi^c = -i\tau_2\Phi^*$ is not allowed, requiring an introduction of another scalar doublet to give τ_3=1 for $SU(2)_L$ fermion doublet mass.

Thus, MSSM has two higgs doublets, Φ_1 and Φ_2.

Supersymmetric Scalar Potential

Through the requirement of supersymmetric gauge invariance and demand for perturbative algebra to be valid, the scalar potential in MSSM is

$$V = |\mu|^2\left(|\Phi_1|^2 + |\Phi_2|^2\right) + \frac{g^2 + g'^2}{8}\left(|\Phi_1|^2 - |\Phi_2|^2\right)^2 + \frac{g^2}{2}\left|\Phi_1^* \cdot \Phi_2\right|^2$$

This potential has its minimum at $\langle\Phi_1^0\rangle = \langle\Phi_2^0\rangle = 0$, giving $\langle V\rangle = 0$, resulting in no EW symmetry breaking.

It is difficult to break supersymmetry but we do know it must be broken.

Soft Supersymmetry Breaking

The simplest way to break SUSY is to add all possible soft (scale ~ M_W) supersymmetry breaking masses for each doublet, along with arbitrary mixing terms, keeping quadratic divergences under control.

The scalar potential involving Higgs becomes

$$V_H = \left(|\mu|^2 + m_1^2\right)|\Phi_1|^2 + \left(|\mu|^2 + m_2^2\right)|\Phi_2|^2 - \mu B \varepsilon_{ij}\left(\Phi_1^i + \Phi_2^j + h.c\right)$$

$$+ \frac{g^2 + g'^2}{8}\left(|\Phi_1|^2 - |\Phi_2|^2\right)^2 + \frac{g^2}{2}\left|\Phi_1^* \cdot \Phi_2\right|^2$$

The quartic terms are fixed in terms of gauge couplings therefore are not free parameters.

Higgs Potential of the SUSY

The Higgs potential in SUSY can be interpreted as to be dependent on three independent combinations of parameters

$$|\mu|^2 + m_1^2; \quad |\mu|^2 + m_2^2; \quad \mu B$$

Where B is a new mass parameter.

If μB is 0, all terms in the potential are positive, making the minimum, <V>=0, back to $<\Phi_1^0> = <\Phi_2^0> = 0$.

Thus, all three parameters above should not be zero to break EW symmetry.

SUSY Breaking

Symmetry is broken when the neutral components of the Higgs doublets get vacuum expectation values:

$$\langle \Phi_1 \rangle \equiv v_1; \quad \langle \Phi_2 \rangle \equiv v_2$$

The values of v_1 and v_2 can be made positive, by redefining Higgs fields.

When the EW symmetry is broken, the W gauge boson gets a mass which is fixed by v_1 and v_2.

$$M_W^2 = \frac{g}{2}\left(v_1^2 + v_2^2\right)$$

SUSY Higgs Mechanism

Before the EW symmetry was broken, the two complex $SU(2)_L$ Higgs doublets had 8 DoF of which three have been observed to give masses to W and Z gauge bosons, leaving five physical DoF.

These remaining DoF are two charged Higgs bosons ($H^{+/-}$), a CP-odd neutral Higgs boson, A^0, and 2 CP-even neutral higgs bosons, h^0 and H^0.

It is a general prediction of supersymmetric models to expand physical Higgs sectors.

SUSY Higgs Mechanism

After fixing $v_1^2 + v_2^2$ such that W boson gets its correct mass, the Higgs sector is then described by two additional parameters. The usual choice is

$$\tan\beta \equiv \frac{v_2}{v_1}$$

And M_A, the mass of the pseudoscalar Higgs boson.

Once these two parameters are given, the masses of remaining Higgs bosons can be calculated in terms of M_A and $\tan\beta$.

The μ Parameter

The μ parameters in MSSM is a concern, because this cannot be set 0 since there won't be EWSB. The mass of Z boson can be written in terms of the radiatively corrected neutral Higgs boson masses and μ;

$$M_Z^2 = 2\left[\frac{M_h^2 - M_H^2 \tan^2\beta}{\tan^2\beta - 1}\right] - 2\mu^2$$

This requires a sophisticated cancellation between Higgs masses and μ. This cancellation is unattractive for SUSY because this kind of cancellation is exactly what SUSY theories want to avoid.

The Higgs Masses

The neutral Higgs masses are found by diagonalizing the 2x2 Higgs mass matrix. By convention, h is taken to be the lighter of the neutral Higgs.

At the tree level the neutral Higgs particle masses are:

$$M_{h,H}^2 = \frac{1}{2}\left\{M_A^2 + M_Z^2 \mp \sqrt{\left(M_A^2 + M_Z^2\right)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta}\right\}$$

The pseudoscalar Higgs particle mass is:

$$M_A^2 = \frac{2|\mu B|}{\sin 2\beta}$$

Charged scalar Higgs particle masses are:

$$M_{H^\pm}^2 = M_W^2 + M_A^2$$

Relative Size of SUSY Higgs Masses

The most important predictions from the masses given in the previous page is the relative magnitude of Higgs masses

$$M_{H^\pm} > M_W$$

$$M_{H^0} > M_Z$$

$$M_{h^0} < M_A$$

$$M_{h^0} < M_Z \left|\cos 2\beta\right|$$

However, the loop corrections to these relationship are large. For instance, M_h receives corrections from t-quark and t-squarks, getting the <u>correction of size ~ $G_F M_t^4$</u>

Loop Corrections to Higgs Masses

The neutral Higgs boson masses become

$$M_{h,H}^2 = \frac{1}{2}\left\{M_A^2 + M_Z^2 \pm \sqrt{\left(\left(M_A^2 + M_Z^2\right)\cos 2\beta + \frac{\varepsilon_h}{\sin^2\beta}\right)^2 + \left(M_A^2 + M_Z^2\right)^2 \sin^2 2\beta}\right\}$$

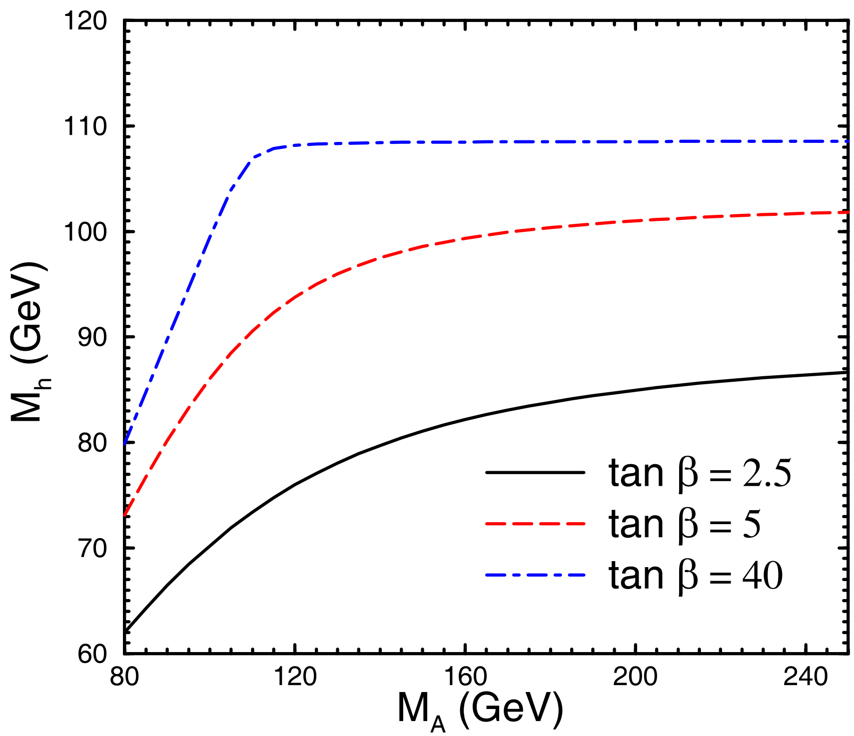
Where ε_h is the one-loop correction

$$\varepsilon_h \equiv \frac{3G_F}{\sqrt{2}\pi^2} M_t^4 \log\left(1 + \frac{\tilde{m}^2}{M_t^4}\right)$$

M_h has upper limit for $\tan\beta > 1$.

$$M_h^2 = M_Z^2 \cos^2 2\beta + \varepsilon_h$$

Mass of CP-even h^0 vs M_A and tanβ



M_h plateaus with M_A>300GeV/c^2

For given values of tanβ and the squark masses, there is an upper bound on the lightest higgs mass at around 110GeV for a small mixing and 130 GeV for large mixing.

Suggested Reading

- S. Dawson, "Introduction to Electroweak Symmetry Breaking," hep-ph/9901280: sections 10 & 11.
- Higgs search at TeVatron: http://fnth37.fnal.gov/higgs/higgs.html
- J. Gunion, H. Haber, G. Kane, S. Dawson, "The Higgs Hunter's Guide," Perseus Publishing: Ch. 4.
- G. Kane "The Supersymmetry Soft-Breaking Lagrangian – Where Experiment and String Theory Meet"
- M. Spira and P. Zerwas, "Electroweak Symmetry Breaking and Higgs Physics," hep-ph/9803257

Higgs Particle Searches

- What are the Higgs particles we are looking for?
  - Standard Model Higgs: Single neutral scalar
  - MSSM Higgs: Five scalar and pseudoscalar particles
    - h^0, H^0, $H^{+/-}$ and A^0
  - Higgs in Other Models
- What are the most distinct characteristics of Higgs particles?
  - In both SM and MSSM, the Higgs particles interact with fermions through Yukawa coupling whose strength mostly is set by the fermion masses.

Theoretical M_H Upper Bound in SM

From the $SU_2 x U_1$ $\mathcal{L}$

$$\mathcal{L} = |D\phi|^2 - \frac{\lambda}{2}\left[|\phi|^2 - \frac{v^2}{2}\right]^2 - g_d \bar{d}_L \phi d_R - g_u \bar{u}_L \phi^c u_R + h.c.$$

Where, the scale v is the EWSB scale, $v = 1\Big/\sqrt{\sqrt{2}G_F} \approx 246GeV$, and the mass of the Higgs particle and fermions are

$$M_H = \lambda v^2 \qquad m_f = \frac{g_f v}{\sqrt{2}}$$

Where λ is the quartic coupling and g_f is the Yukawa coupling

Theoretical M_H Upper Bound in SM

While M_H cannot be predicted in SM, internal consistency and extrapolation to high energies can provide upper and lower bounds.

Based on the general principle of t-E uncertainty, particles become unphysical if their masses grow indefinitely. Therefore M_H must be bound to preserve the unitarity in the perturbative regime.

From an asymptotic expansion of a $W_L W_L$ S-wave scattering, an upper limit on M_H can be obtained:

$$M_H^2 \leq 2\sqrt{2}\pi / G_F \approx (850 GeV)^2$$

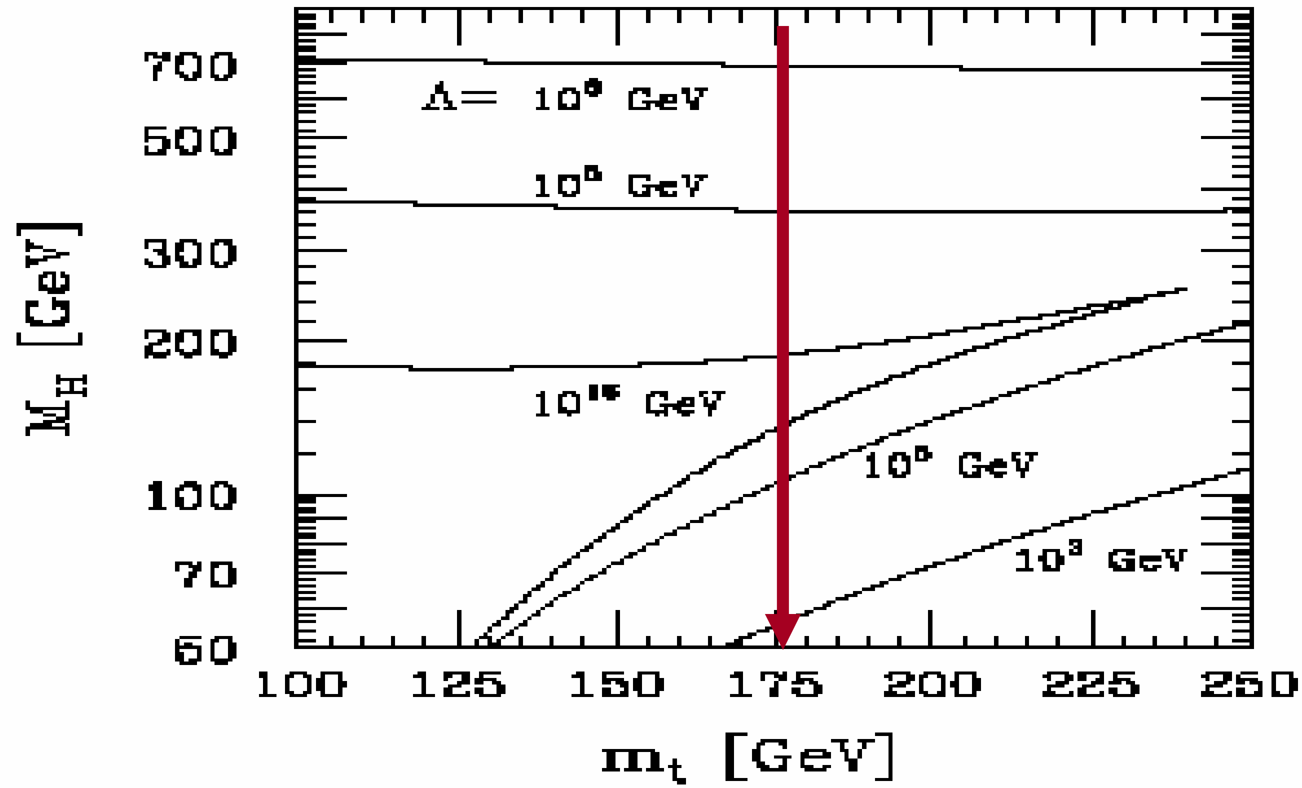
Theoretical M_H Upper Bound in SM

The SM tells that there is no new physics between EWSB scale (~1TeV) and the GUT scale (10^{19}GeV). This can provide a restrictive upper limit because the SM can extend to a scale Λ before a new type of strong, short range interaction can occur between fundamental particles.

From the variation of quartic Higgs coupling, λ, and the top-Higgs Yukawa coupling, g_t, with energy parameterized by $t=\log(\mu^2/v^2)$, and requiring $\lambda(\Lambda)$ to be finite, one can obtain the Higgs mass upper bound

$$M_H^2 \le 8\pi^2 v^2 \Big/ 3\log\left(v^2/\lambda^2\right)$$

Theoretical M_H Upper Bound in SM



For the central m_t=175GeV/c^2

Λ_{SM}	M_H
1 TeV	$55 \le M_H \le 700\,GeV/c^2$
10^{19}GeV	$130 \le M_H \le 190\,GeV/c^2$

SM Higgs Properties

- Profiles of Higgs Particles determined by its mass
- The Yukawa coupling of Higgs to fermions set by the fermion mass, m_j, and to the electroweak gauge bosons by their masses, M_V.

$$g_{ffH} = \left[\sqrt{2}G_F\right]^{1/2} m_f$$

$$g_{VVH} = 2\left[\sqrt{2}G_F\right]^{1/2} M_V^2$$

Physical observables, the total decay width, lifetime and branching ratio to specific final states are determined by these parameters.

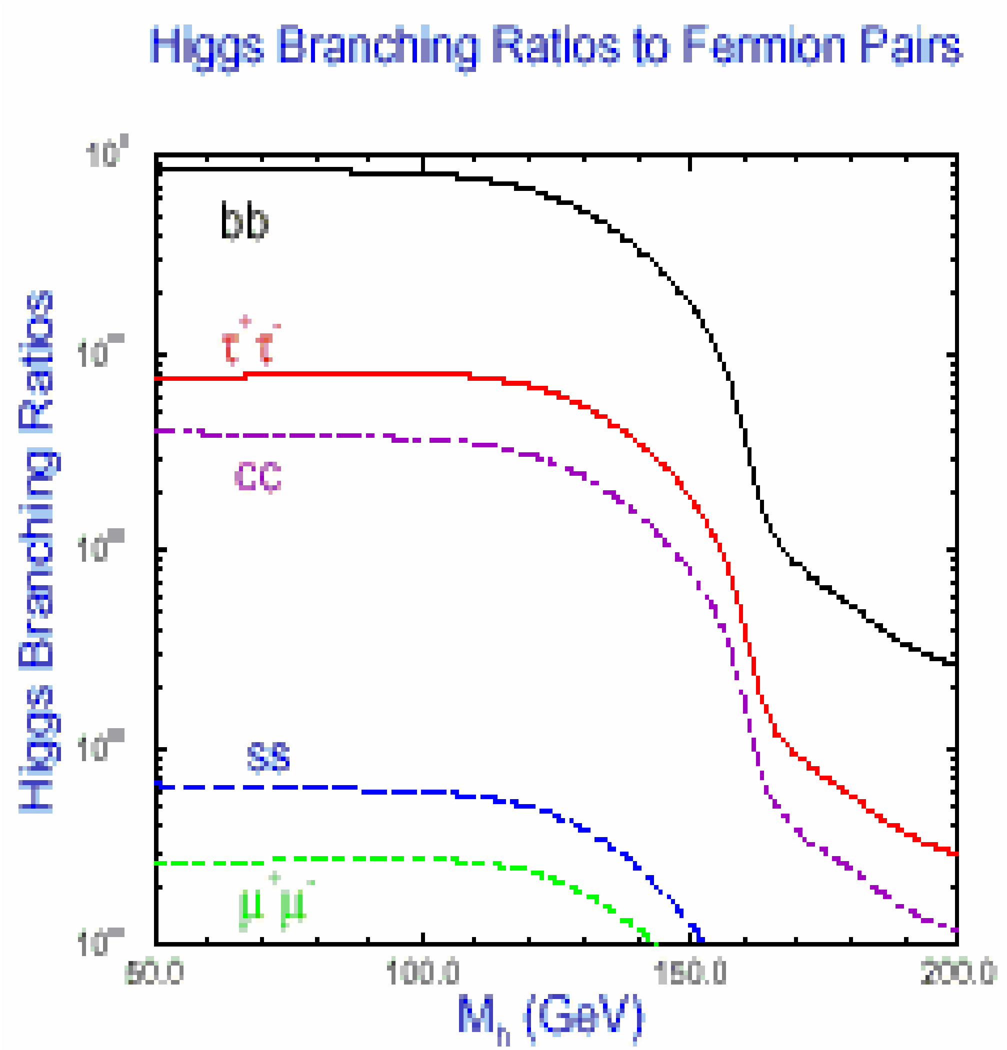
Higgs Decay to Fermions

Higgs partial decay width to fermions are

$$\Gamma\left(H \to f\overline{f}\right) = N_c \frac{G_F}{4\sqrt{2}\pi} g_{ffH} m_f^2\left(M_H^2\right) M_H$$

Number of color quantum numbers, 1 or 3

For M_H=100GeV,
$m_b(M_H^2)$~3GeV,
$m_c(M_H^2)$~0.6GeV



Higgs Decay to Gauge Boson Pairs

$$\Gamma(H \to VV)$$
$$= \delta_V \frac{G_F}{16\sqrt{2}\pi} M_H^3 \left(1 - 4x + 12x^2\right) \beta_V$$

Where $x = M_V^2 / M_H^2$ and

$\delta_V = 2$ or 1 for W or Z

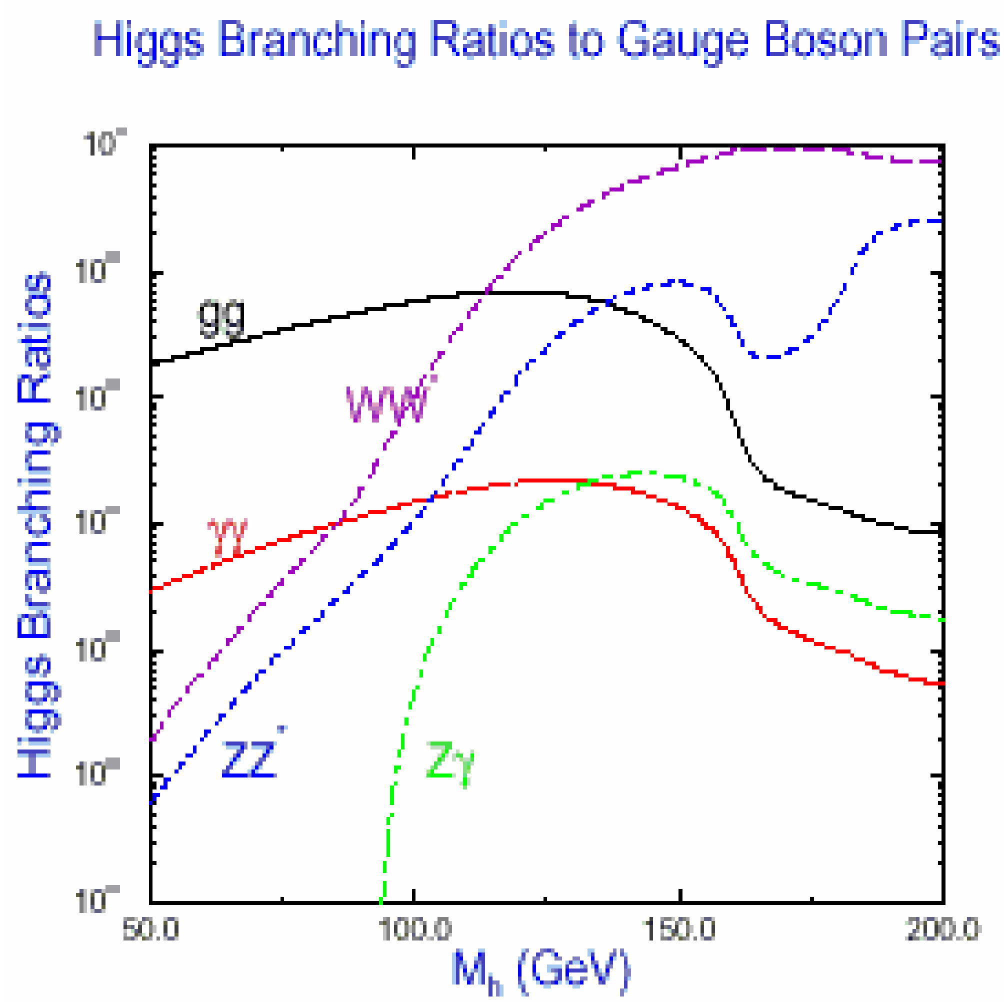
$$\Gamma\left(H \to VV^*\right)$$
$$= \frac{3G_F^2 M_V^4}{16\pi^3} M_H R(x) \delta_V^{'}$$

Where $\delta_W^{'} = 1$ and

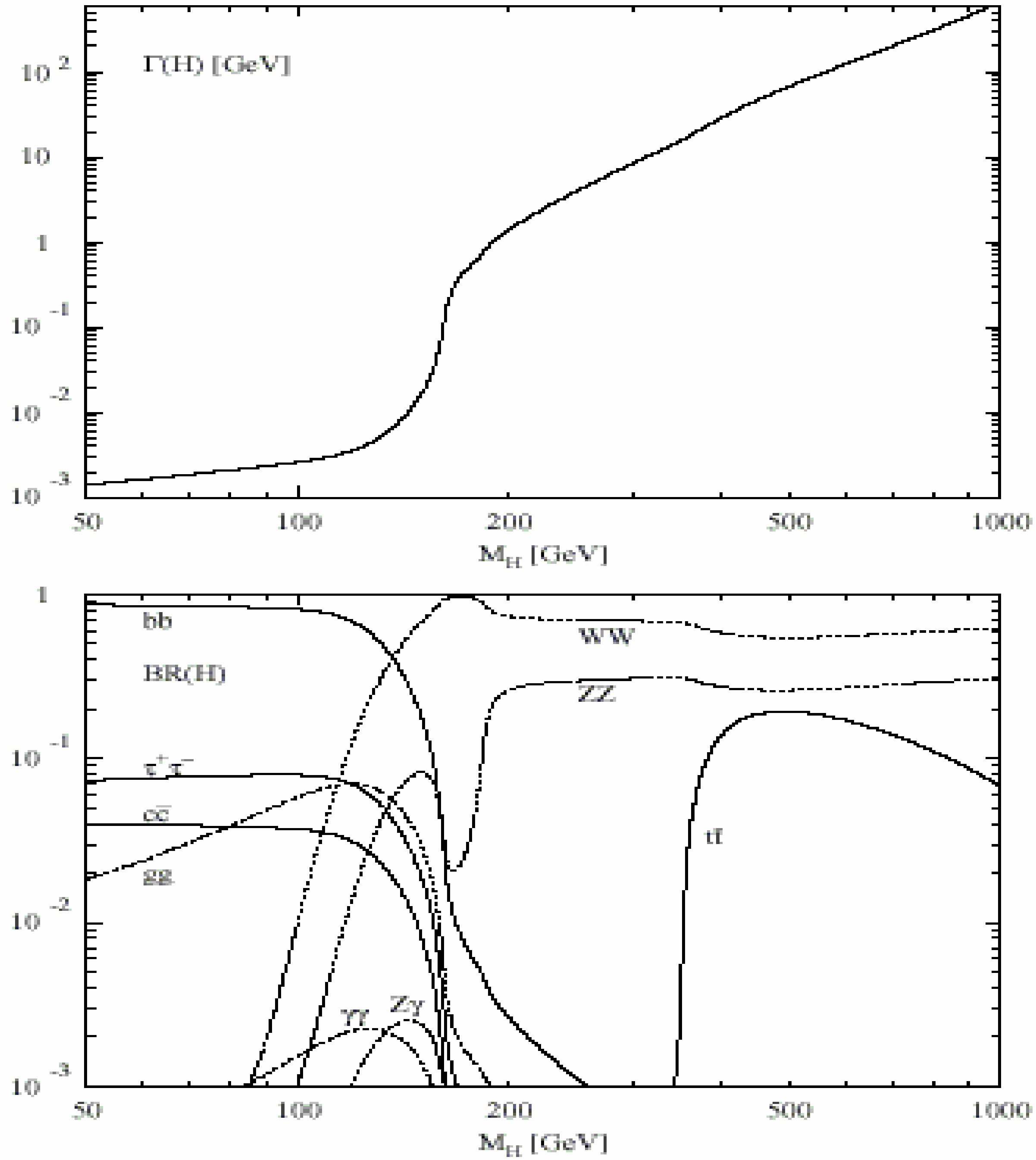
$\delta_Z^{'} = 7/12 - 10\sin^2\theta_W / 9 + 40\sin^4\theta_W / 27$

$$\Gamma(H \to \gamma\gamma)$$
$$= \frac{3G_F^2 \alpha^2}{128\sqrt{2}\pi^3} M_H^3 \left| \frac{4}{3} N_c e_t^2 - 7 \right|^2$$

Valid in the limit $M_H^2 << 4M_W^2, 4M_t^2$

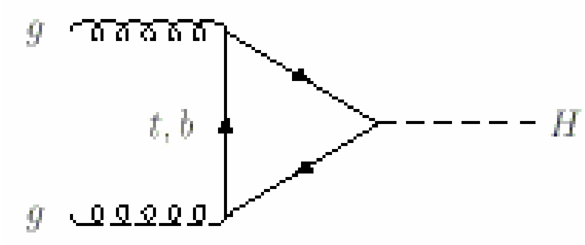


Summary of SM Higgs Branching Ratio



Higgs Production Processes at Hadron Colliders

Gluon fusion: $gg \rightarrow H$

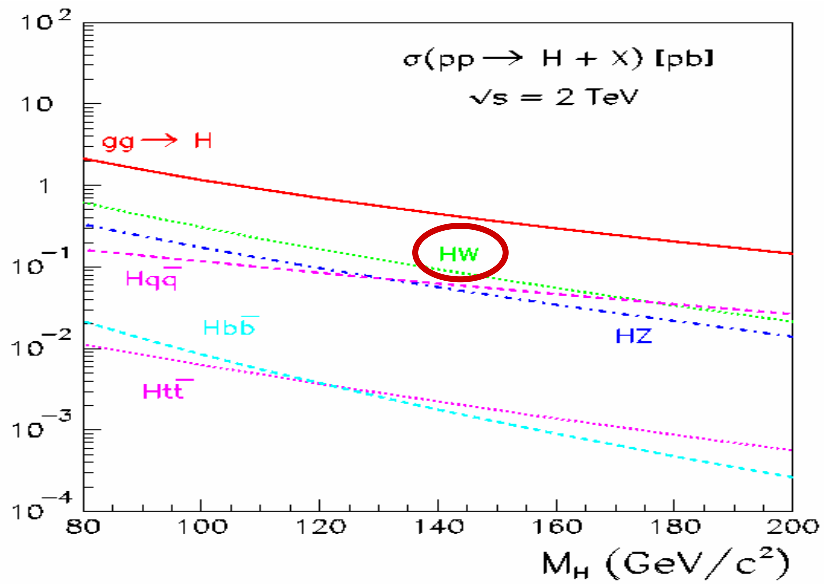


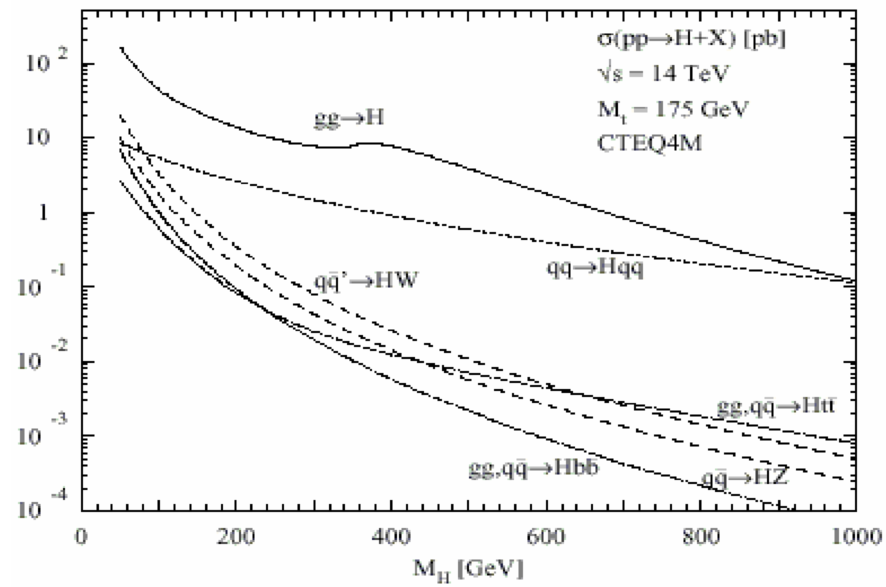
WW, ZZ Fusion: $W^+W^-,\ ZZ \rightarrow H$

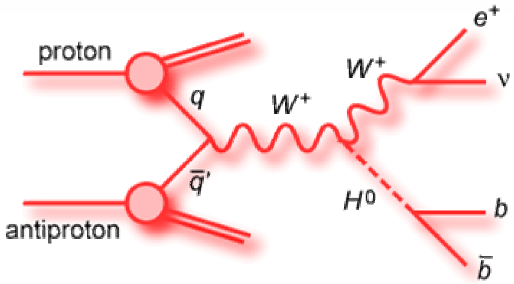
Higgs-strahlung off W,Z: $q\bar{q} \rightarrow W^*,\ Z^* \rightarrow W, Z + H$

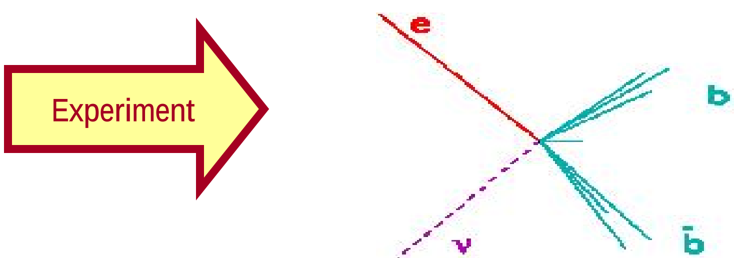
Higgs Bremsstrahlung off top: $q\bar{q}, gg \rightarrow t\bar{t} + H$

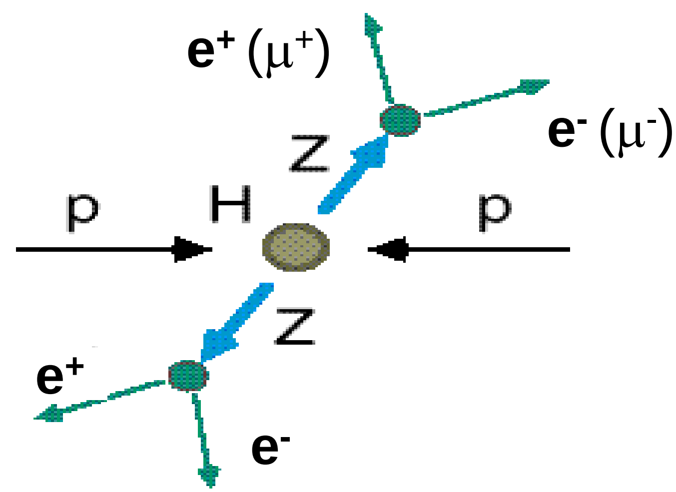
Higgs Production X-Sec at 2TeV and 14TeV





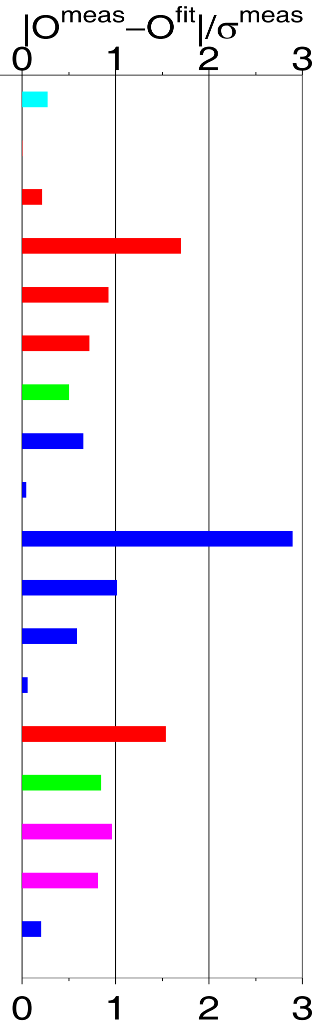


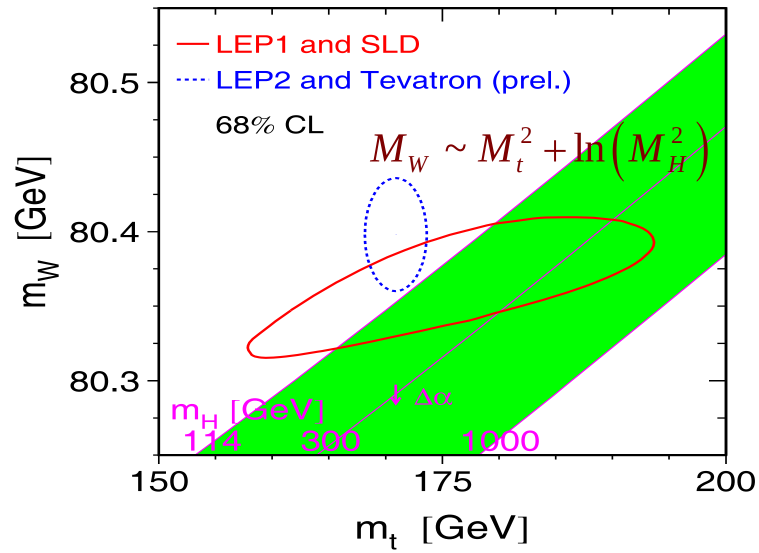


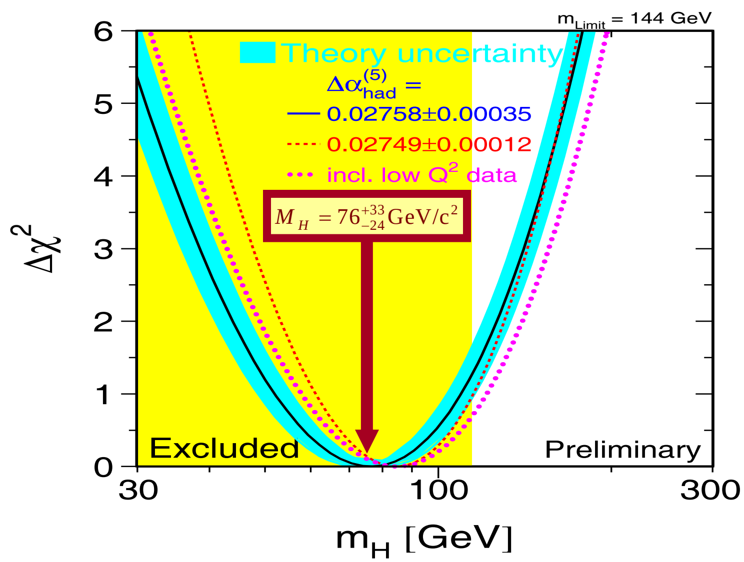


What do we know as of Winter 07?

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3







LEP EWWG: http://www.cern.ch/LEPEWWG

$114.4 < M_H < 182$ GeV

Homework

- Derive the new $\mathcal{L}$ in page 6 in this lecture.
- Derive the new $\mathcal{L}$ for two fields in page 10 in this lecture
- Show that one of the two scalar fields could be massless when the choice of minima were made at

$$\phi_1 = \frac{\mu}{\sqrt{2\lambda}}; \;\; \phi_2 = -\frac{\mu}{\sqrt{2\lambda}}$$

- Derive the new $\mathcal{L}$ in page 13 of this lecture
- Due Wednesday, Apr. 25

Homework Assignment

- Study the summary SM Higgs branching ratio plot in slide 43 and plan experimental strategies to search for Higgs particles in the following two scenarios
  - M_H=115GeV
  - M_H >150GeV
- Due: Monday, Apr. 30