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Electroweak Symmetry Breaking and the Minimal Supersymmetric Model

- The Higgs Sector of the Standard Model
  - Review EWSB in SM
  - How to find the Higgs (Tevatron, LHC, NLC)
  - Information from radiative corrections
  - Brief aside on 2 Higgs doublet models
- Problems with the SM
  - Unitarity, triviality,....
  - Quadratic corrections to M_h, naturalness
  - Unification?
- The MSSM
  - Majorana, Weyl, Dirac Fermions
  - Superfields
  - Particles, interactions
  - Breaking SUSY
- MSSM phenomenology
  - Higgs sector (Upper bound on M_h, Observation of multiple Higgs)
  - Collider phenomenology

- Unified MSSM models
  - Coupling unification
  - Proton decay
  - Radiative EWSB
  - More collider phenomenology

- SUSY and Radiative Corrections
  - $b \to s\gamma$
  - $(g-2)_\mu$
  - Global fits to precision measurements

- Beyond the MSSM
  - R parity violation
  - NMSSM
  - Gauge Mediated Symmetry Breaking
  - Anomaly Mediated Symmetry Breaking

- Distinguishing the SM and the MSSM
  - Decoupling limit of MSSM
  - Motivation for linear colliders

- Strong EWSB
  - Who need a light Higgs?
  - Topcolor, technicolor, etc...

Useful References:

Gauge Theories and Collider Physics:

- Collider Physics, Barger and Phillips
- Journeys Beyond the Standard Model, Ramond
- Gauge Theories of the Strong, Weak, and Electromagnetic Interactions, Quigg
- The Higgs Hunters Guide, Gunion et al

Supersymmetry:

- Supersymmetry and Supergravity, Wess and Bagger
- Introduction to Supersymmetry and Supergravity, Misra

Supersymmetric Model Building

- The MSSM, Djouadi et al, hep-ph/9901246
- A Supersymmetry Primer, S. Martin, hep-ph/9709356
- Weak-Scale Supersymmetry: Theory and Practice, Bagger, hep-ph/9604232
- Introduction to EWSB, Dawson, hep-ph/9901280

Abelian Higgs Model

Why are W and Z boson masses non-zero?

$U(1)$ gauge theory with single gauge field, A

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu},$$

$$F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu$$

$U(1)$ local gauge invariance:

$$A_\mu(x) \rightarrow A_\mu(x) - \partial_\mu \eta(x)$$

Mass term for A:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m^2 A_\mu A^\mu$$

Mass term violates local gauge invariance

We understand why $M_A = 0$

Add complex scalar field, ϕ, with charge $-e$:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \mid D_\mu \phi \mid^2 - V(\phi)$$

where

$$D_\mu = \partial_\mu - ieA_\mu$$

$$V(\phi) = \mu^2 \mid \phi \mid^2 + \lambda \left(\mid \phi \mid^2 \right)^2$$

$\mathcal{L}$ invariant under transformations:

$$A_\mu(x) \to A_\mu(x) - \partial_\mu \eta(x)$$

$$\phi(x) \to e^{-ie\eta(x)} \phi(x)$$

Case 1: $\mu^2 > 0$

QED with $m_A = 0$ and $m_\phi = \mu$

Case 2: $\mu^2 < 0$

$$V(\phi) = - \mid \mu^2 \mid\mid \phi \mid^2 + \lambda \left(\mid \phi \mid^2 \right)^2$$

Minimum energy state at:

$$\langle \phi \rangle = \sqrt{-\frac{\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$$

Rewrite ϕ:

$$\phi \equiv \frac{1}{\sqrt{2}} e^{i\frac{\chi}{v}} (v+h)$$

$\mathcal{L}$ becomes:

$$\begin{aligned}\mathcal{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - evA_\mu\partial^\mu\chi + \frac{e^2v^2}{2}A_\mu A^\mu \\ &+\frac{1}{2}\left(\partial_\mu h\partial^\mu h + 2\mu^2h^2\right) \\ &+\frac{1}{2}\partial_\mu\chi\partial^\mu\chi + (h,\ \chi \text{ interactions})\end{aligned}$$

Theory now has:

- Photon of mass $M_A = ev$
- Scalar field h with mass-squared $-2\mu^2 > 0$
- Massless scalar field χ

What about mixed $\chi - A$ propagator?
Remove by gauge transformation:

$$\begin{aligned}A'_\mu \equiv &A_\mu - \frac{1}{ev}\partial_\mu\chi \\ \phi' \equiv &e^{-i\frac{\chi}{v}}\phi = \frac{v+h}{\sqrt{2}}\end{aligned}$$

χ field disappears

We say that it has been "eaten" to give the photon mass
$\rightarrow$ Higgs mechanism

χ field called Goldstone boson

Higgs mechanism summarized:

Spontaneous breaking of a gauge theory by a non-zero VEV results in disappearance of Goldstone boson and its transformation into longitudinal component of massive gauge boson

What about gauge invariance?

Choice above called unitary gauge

- No χ field
- Bad high energy behaviour of A propagator

$$\Delta_{\mu\nu}(k) = -\frac{i}{k^2 - M_A^2}\left(g_{\mu\nu} - \frac{k^\mu k^\nu}{M_A^2}\right)$$

R_ξ gauges more convenient:

$$\mathcal{L}_{GF} = -\frac{1}{2\xi}\left(\partial_\mu A^\mu + \xi e v \chi\right)^2$$

- χ field is part of spectrum with $M_\chi^2 = \xi M_A^2$
- $\xi = 1$: Feynman gauge with massive χ
- $\xi = 0$: Landau gauge
  χ massless with no coupling to physical Higgs boson

Review of Standard Model

Standard model includes complex Higgs $SU(2)$ doublet, Φ

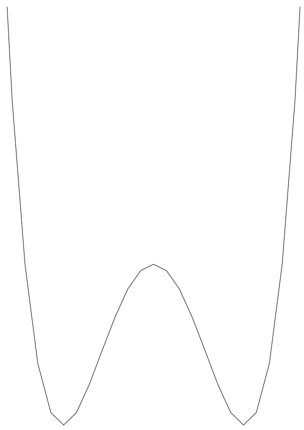
$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

Most general renormalizable $SU(2)$, $\Phi \to -\Phi$, invariant scalar potential

$$V = \mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi \right)^2$$

If $\mu^2 < 0$ then spontaneous symmetry breaking:

Why is $\mu^2 < 0$?



Minimum of potential at:

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

[See Chapter 6, Quigg or TASI94, hep-ph/9411325]

Couple Φ to $SU(2)\times U(1)$ gauge bosons

$$\mathcal{L}_s = (D^\mu \Phi)^\dagger \left(D_\mu \Phi\right) - V(\Phi)$$

$$D_\mu = \partial_\mu + i\frac{g}{2}\tau \cdot W_\mu + i\frac{g' Y}{2} B_\mu .$$

Generate mass for W, Z; h physical particle,

Just like Abelian Higgs Model:

$$\Phi' = \frac{1}{\sqrt{2}} e^{\frac{-i\vec{\omega}\cdot\vec{\tau}}{v}} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

$\omega_i \rightarrow \omega^{\pm}, z$ "Goldstone Bosons"

$Q_{em}\langle\Phi\rangle = \frac{(\tau_3+Y)}{2}\langle\Phi\rangle = 0$

Count degrees of freedom:

- Massless gauge bosons have 2 transverse dof
- Massive gauge bosons also have longitudinal dof

Before spontaneous symmetry breaking:

- Massless W_μ^i, B_μ 8 dof
- Complex Φ 4 dof
- Total: 12 dof

After spontaneous symmetry breaking:

- Massive $W^{\pm}, Z$ 9 dof
- Massless γ 2 dof
- Physical Higgs boson, h 1 dof

Muon decay, $\mu \to e\nu_e\overline{\nu}_\mu$, fixes v:

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{1}{2v^2}$$

$v^2 = (\sqrt{2}G_F)^{-1} = (246\ \ GeV)^2$

Higgs potential has 2 free parameters, μ^2, λ

$$V = \mu^2\Phi^\dagger\Phi + \lambda\left(\Phi^\dagger\Phi\right)^2$$

Trade μ^2, λ for v^2, M_h^2:

$$V = \frac{M_h^2}{2}h^2 + \frac{M_h^2}{2v}h^3 + \frac{m_h^2}{8v^2}h^4$$

$$\begin{aligned} v^2 &= -\frac{\mu^2}{2\lambda} \\ M_h^2 &= 2v^2\lambda \end{aligned}$$

- Large M_h $\to$ strong Higgs self-couplings
- a priori, Higgs mass can be anything

Scalar couplings to fermions:

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

with left handed $SU(2)$ fermion doublet:

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

Effective Higgs-fermion coupling:

$$-\lambda_d \frac{1}{\sqrt{2}} (\overline{u}_L, \;\; \overline{d}_L) \begin{pmatrix} 0 \\ v+h \end{pmatrix} d_R + h.c.$$

Mass term for down quark:

$$\lambda_d = \frac{m_d \sqrt{2}}{v}$$

m_u from $\Phi^c \equiv i\tau_2 \Phi^*$ (not allowed in SUSY)

For 3 generations, $i, j = 1, 3$ (flavor indices)

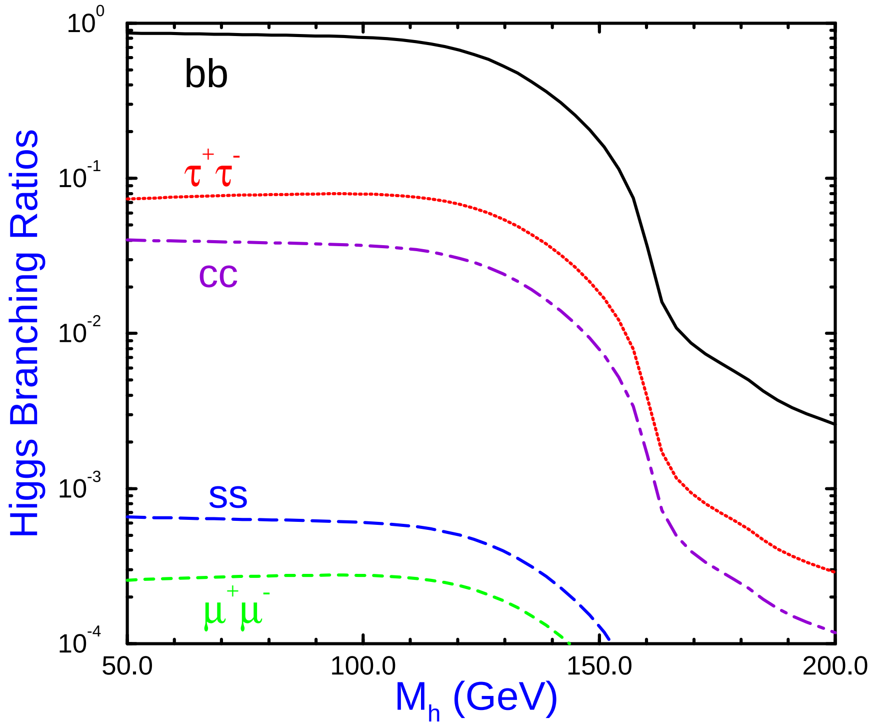
$$\mathcal{L}_Y = -\frac{(v+h)}{\sqrt{2}} \sum_{ij} \left(\lambda_u^{ij} \overline{u}_L^i u_R^j + \lambda_d^{ij} \overline{d}_L^i d_R^j \right) + h.c.$$

Unitary matrices diagonalize mass matrices:

$$\begin{array}{ll} u_L^i = U_u^{ij} u_L^{mj} & \qquad d_L^i = U_d^{ij} d_L^{mj} \\ u_R^i = V_u^{ij} u_R^{mj} & \qquad d_R^i = V_d^{ij} d_R^{mj} \end{array}$$

- Yukawa couplings are diagonal in mass basis
- Neutral currents remain flavor diagonal
- Not necessarily true in models with extended Higgs sectors

- Fermion couplings fixed
- No explanation for masses though....
- Higgs decays to heaviest fermion pair allowed



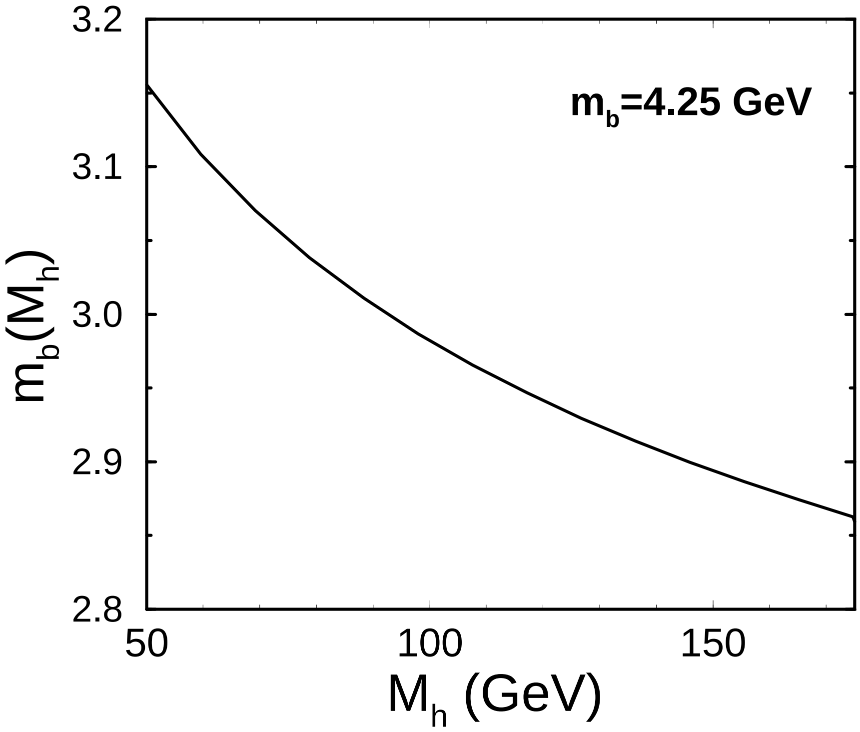
$$\frac{\Gamma\left(h \to b\overline{b}\right)}{\Gamma\left(h \to \tau^+\tau^-\right)} \sim N_c \frac{m_b^2}{m_\tau^2}\left(\frac{\beta_b}{\beta_\tau}\right)^3, \qquad \beta_i = \sqrt{1 - \frac{4m_i^2}{M_h^2}}$$

β^3 is characteristic of scalar decays

$\Gamma(\text{Pseudoscalar} \to \overline{f}f) \sim \beta$

- Which m_b?
- Significant reduction of rate from running of m_b

$$m_b\left(\mu^2\right) = m_b\left(m_b^2\right)\left(\frac{\alpha_s\left(m_b^2\right)}{\alpha_s\left(\mu^2\right)}\right)^{-12/23}$$



$h \to W^+W^-$

From $(D_\mu \Phi)^\dagger (D^\mu \Phi)$:

$$\frac{1}{2}\left[\frac{g^2}{2} W_\mu^+ W^{-\mu}\,(v+h)^2 + \frac{g^2}{4\cos^2\theta_W} Z^\mu Z_\mu\,(v+h)^2\right]$$

$h \to W^+W^-$ has the matrix element

$$-i\mathcal{A} = i\frac{g^2 v}{2}\epsilon_+^*\epsilon_-^* = igM_W\epsilon_+^*\epsilon_-^*$$

Polarization sum:

$$\Sigma\epsilon_{+\mu}^*\epsilon_{+\nu} = -g_{\mu\nu} + \frac{p_\mu^+ p_\nu^+}{M_W^2}$$

Matrix element squared:

$$\mid \mathcal{A} \mid^2 = \frac{g^2 M_h^4}{4M_W^2}\left(1 - 4\frac{M_W^2}{M_h^2} + 12\frac{M_W^4}{M_h^4}\right)$$

Below threshold, $h \to W^* W^*$ with $BR(W^* \to f\overline{f}')$ implied

Interesting physics involves longitudinal gauge bosons:

$$
\begin{aligned}
p_V &= (E_V, 0, 0, \vec{p_V}) \\
\epsilon_T &= \frac{1}{\sqrt{2}}(0, 1, \pm i, 0) \\
\epsilon_L &= \frac{1}{M_V}(|\, \vec{p_V}\,|, 0, 0, E_V) \rightarrow \frac{p_V^\mu}{M_V}
\end{aligned}
$$

Cross sections involving V_L can grow with energy

Decays involving V_L enhanced:

Re-look at $h \rightarrow W_L^+ W_L^-$:

$$
-i\mathcal{A} = igM_W \epsilon_L^* \epsilon_L^* \sim g\frac{M_h^2}{M_W}
$$

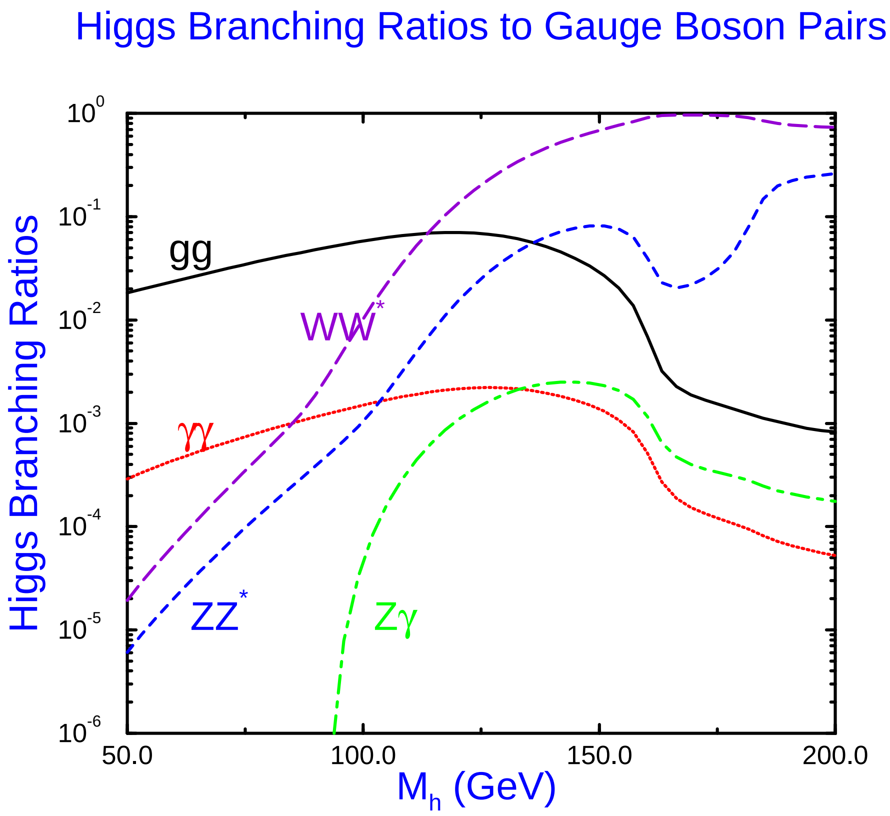
$$
\frac{\Gamma(h \rightarrow V_T V_T)}{\Gamma(h \rightarrow V_L V_L)} = \frac{x_V^2}{(2 - x_V^2)}
$$

$$
x_V \equiv \frac{4M_V^2}{M_h^2}
$$

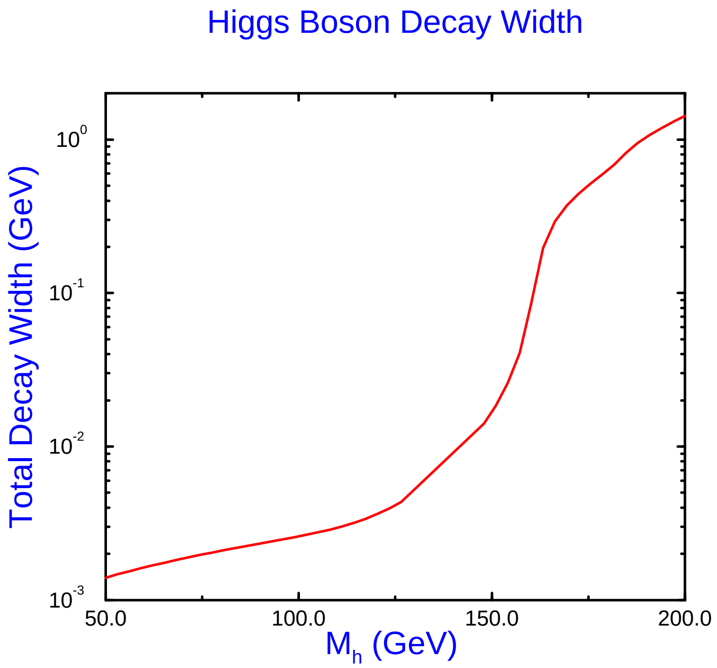
- Decays to gg, $\gamma\gamma$ through loops
  $\rightarrow$ sensitive to new physics

$$\mathcal{L}_{eff} \sim C\frac{h}{v}F^{\mu\nu}F_{\mu\nu}$$

  $\rightarrow$ Dimension 5 operator; finite amplitude
- gg BR not useful due to 2-jet backgrounds
- $\gamma\gamma$ BR maximum for $120\ GeV < M_h < 140\ GeV$
- Note turn on of WW^*, ZZ^*
- WW^*, ZZ^* need BRs for $W^* \rightarrow \overline{f}f'$



Total width sensitive function of mass



- Small M_h, Higgs is narrower than detector resolution
- Large M_h, no clear resonance

$$\Gamma\left(h \to W^+W^-\right) \sim \frac{\alpha}{16 \sin^2\theta_W} \frac{M_h^3}{M_W^2}$$

$$\sim 330 \; GeV \left(\frac{M_h}{1 \; TeV}\right)^3$$

For $M_h \sim 1.4 \; TeV$, $\Gamma_{tot} \sim M_h$

- To compute Higgs branching ratios, including all known QCD corrections, use program HDECAY

http://mspira.home.cern.ch/mspira/proglist.html
[Program also has SUSY branching ratios]

Higgs Theory testable because all couplings known!!

- Fermions: $\frac{m_i}{v}\overline{\psi}_i\psi_i h$
- Gauge Bosons, $W^{+\mu}W^{-\nu}h$: $gM_W g^{\mu\nu}$

  $Z^\mu Z^\nu h$: $\quad \frac{gM_Z}{\cos\theta_W}g^{\mu\nu}$
- Self-couplings $\sim M_h^2$

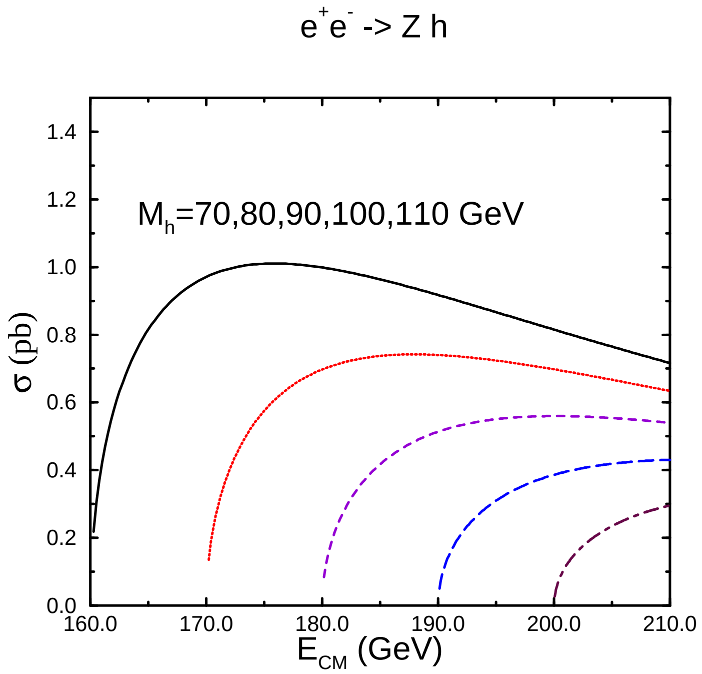
  Measurement of Higgs self-coupling, λ, tests Higgs mechanism

Higgs mass only free parameter; everything calculable

Precise measurements of couplings test theory (eg, SUSY couplings can be very different from SM)

LHC, Tevatron will discover Higgs, Next Linear Collider will tell us what is

Direct Higgs Searches at LEP2



- $e^+e^- \to Zh$ (tests ZZh vertex)

$$\sigma\left(e^+e^- \to Zh\right) = \frac{\pi\alpha^2\beta_{Zh}\left[\beta_{Zh}^2 + 12\frac{M_Z^2}{s}\right]\left[1+\left(1-4\sin^2\theta_W\right)^2\right]}{192s\sin^4\theta_W\cos^4\theta_W\left(1-M_Z^2/s\right)^2}$$

$$\beta_{Zh}^2 \equiv (1-\frac{M_h^2+M_Z^2}{s})^2 - \frac{4M_h^2M_Z^2}{s^2}$$

- Rate turns on rapidly after threshold; best measurement just above threshold, $\sigma \sim \frac{\beta_{Zh}^3}{s}$
- Searches include $Z \to e^+e^-, \mu^+\mu^-, \nu\overline{\nu}, q\overline{q}$

($e^+e^- \to Zh$, continued)

- Measure recoil mass of Higgs; result independent of Higgs decay pattern

$$p_{e^-} = \frac{\sqrt{s}}{2}(1,0,0,1)$$
$$p_{e^+} = \frac{\sqrt{s}}{2}(1,0,0,-1)$$
$$p_Z = (E_Z, \vec{p_Z})$$

- Momentum conservation:

$$\left(p_{e^+} + p_e^- - p_Z\right)^2 = p_h^2 = M_h^2$$
$$s - 2\sqrt{s}E_Z + M_Z^2 = M_h^2$$

- Current LEP2 limit (4 experiments, 2×10^7 Z's):

$$\sqrt{s_{max}} = 209 \ GeV$$

$$M_h > 114.1 \ GeV$$

Hints of a signal at $M_h = 115.6 \ GeV$

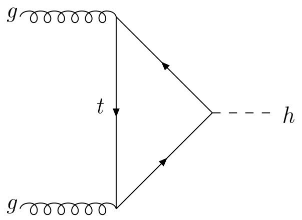
Angular distribution of Higgs has characteristic pattern of scalar:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} \sim \sin^2\theta$$

Pseudo-scalar $\sim 1 + \cos^2\theta$

Searches at LHC

Gluon fusion dominant production mechanism at LHC



- SM: dominant contribution from top quark loop
  $(t\bar{t}h \sim \frac{M_t}{v})$

$$\hat{\sigma}\left(gg \to h\right) = \frac{16\pi^2}{M_h}\left(2J+1\right)\left(\frac{1}{64}\right)\left(\frac{1}{4}\right)2\Gamma\left(h \to gg\right)\delta\left(\hat{s} - M_h^2\right)$$

- $J = 0$ for h
- $\frac{1}{64}$ is color average
- $\frac{1}{4}$ is spin average
- 2 undoes $\frac{1}{2}$ in $\Gamma(h \to gg)$

Lowest order cross section:

$$\hat{\sigma}\left(gg\to h\right) = \frac{\alpha_s^2}{1024\pi v^2}\mid\sum_q F_{1/2}\left(\tau_q\right)\mid^2 \delta\left(M_h^2-\hat{s}\right)$$
$$\equiv \hat{\sigma}_0\left(gg\to h\right)\delta\left(1-\frac{\hat{s}}{M_h^2}\right)$$

- $\tau_q\equiv 4M_q^2/M_h^2$, $\hat{s}$ is gg center of mass energy

$$F_{1/2}\left(\tau_q\right)\equiv -2\tau_q\left[1+\left(1-\tau_q\right)f\left(\tau_q\right)\right]$$
$$f\left(\tau_q\right)=\left[\sin^{-1}\left(\sqrt{1/\tau_q}\right)\right]^2, \qquad \text{if } \tau_q\geq 1$$
$$=-\frac{1}{4}\left[\log\left(\frac{x_+}{x_-}\right)-i\pi\right]^2, \qquad \text{if } \tau_q<1$$

with

$$x_\pm = 1\pm\sqrt{1-\tau_q}$$

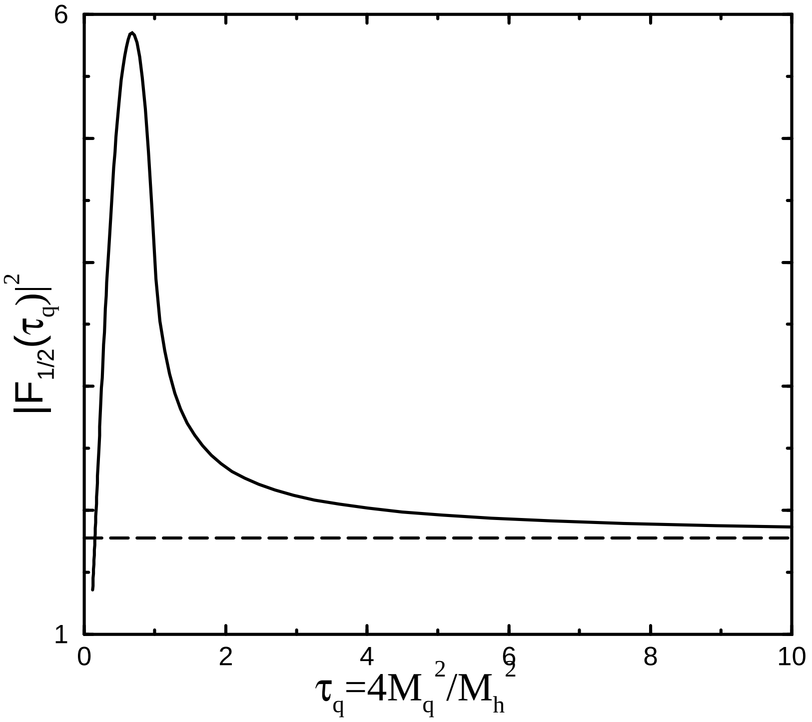
- Light quark contributions small, $\frac{M_b}{M_h}\to 0$:

$$F_{1/2}\to\left(\frac{M_b}{M_h}\right)^2\log\left(\frac{M_b}{M_h}\right)$$

Heavy quark limit, $\frac{M_t}{M_h} \to \infty$:

$$F_{1/2} \to -\frac{4}{3}$$
$$\hat{\sigma}_0 \left(gg \to h\right) \to \frac{\alpha_s^2}{576\pi v^2}$$

- Good approximation to rate below $t\bar{t}$ threshold
- Heavy quark limit rapidly approached; limit useful for QCD corrections
- Gluon fusion counts number of heavy quarks

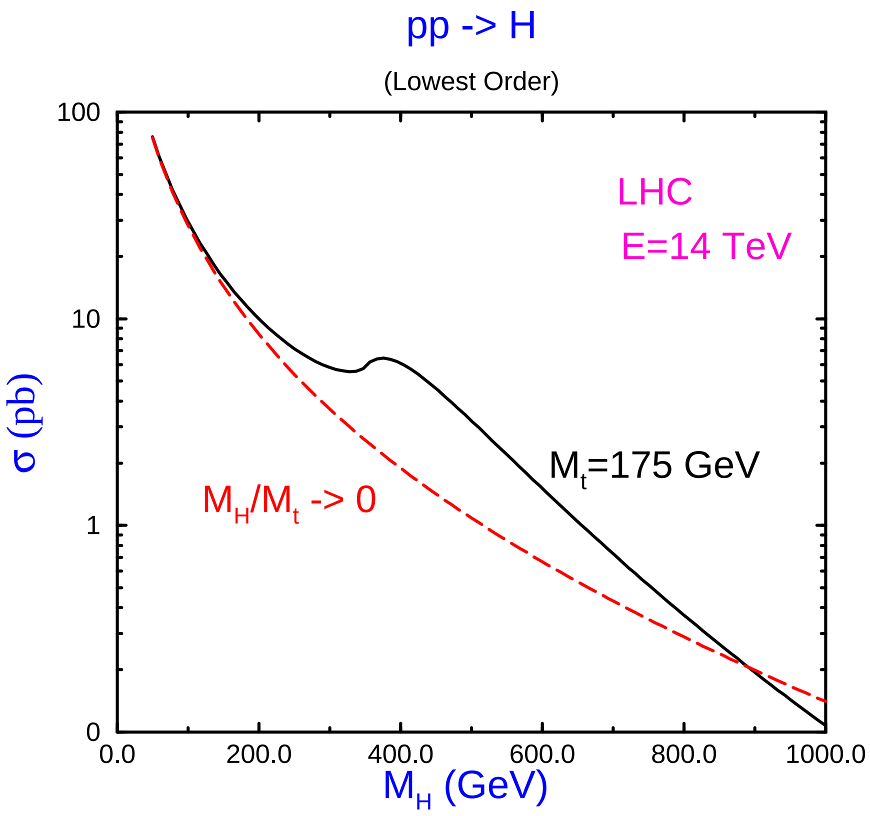


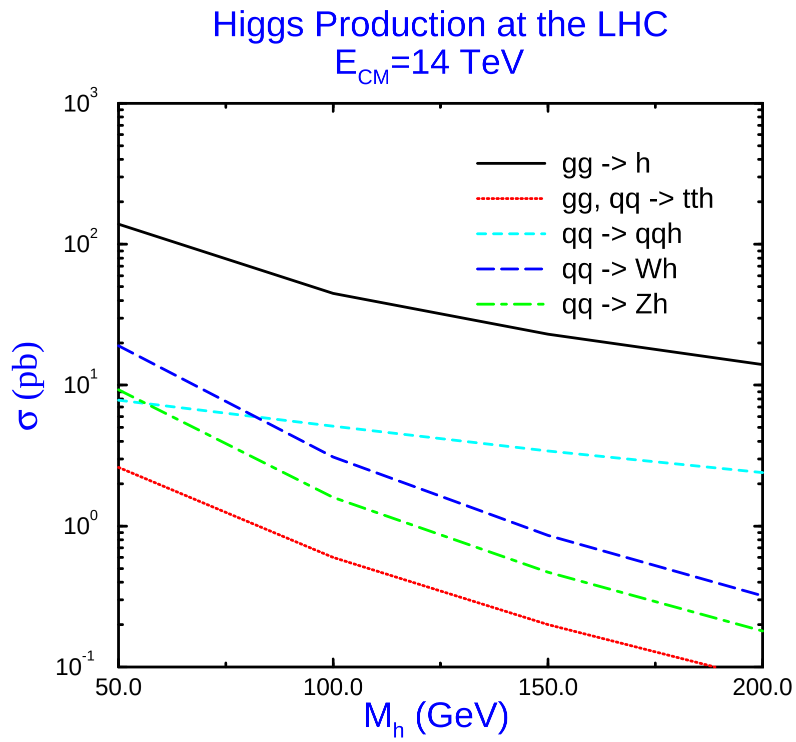
Integrate with gluon structure functions:

$$\sigma_0\left(pp \to h\right) = \hat{\sigma}_0 z \int_z^1 \frac{dx}{x} g\left(x\right) g\left(\frac{z}{x}\right)$$

$z \equiv M_h^2/S$, S is the hadronic center of mass energy

[Details of $gg \to h$ in TASI94, hep-ph/9411325]





Initial LHC Luminosity, $\mathcal{L} = 30 \ \ fb^{-1}$

$\sigma \sim 15 \ \ pb \sim 15,000 \ \ fb$

$\rightarrow 450,000$ events/year

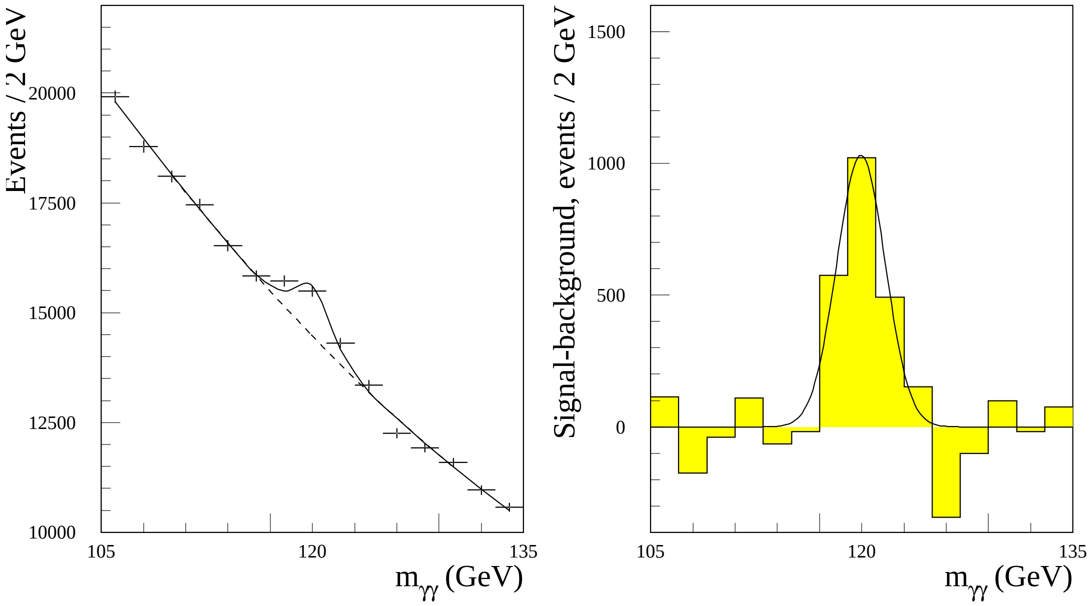
$BR(h \rightarrow \gamma\gamma) \sim 10^{-3}$ for $M_h \sim 120 \ \ GeV$
$\rightarrow 450$ events/year

Further reductions for detector efficiencies, etc...

- Large QCD backgrounds to dominant $h \to b\bar{b}$ decay
- Look at rare decay, $h \to \gamma\gamma$

$$BR(h \to \gamma\gamma) \sim 10^{-3}$$

- Signal shows sharp peak in $M_{\gamma\gamma}$ since $\Gamma_h \sim$ MeV
- Large background from $q\bar{q} \to \gamma\gamma$, jet-jet; naively 8 orders of magnitude larger than signal. Need γ/jet rejection $\sim \mathcal{O}(10^{-4})$



(ATLAS with $M_h = 120\ GeV$, $\mathcal{L} = 100\ fb^{-1}$)

- Fit background from data

$M_h > 140\ GeV,\ h \rightarrow ZZ$ with $BR \sim \frac{1}{3}$

- Many events
- $Z \rightarrow l^+ l^-$ ("Gold-plated" events)
- Observe in this channel up to $M_h \sim 1\ TeV$

$$N_{events} \sim \sigma\,(pp \rightarrow h) \times BR\,(h \rightarrow ZZ)$$

$$\times \quad \left[BR\left(Z \rightarrow e^+e^-, \mu^+\mu^-\right)\right]^2 \times (luminosity)$$

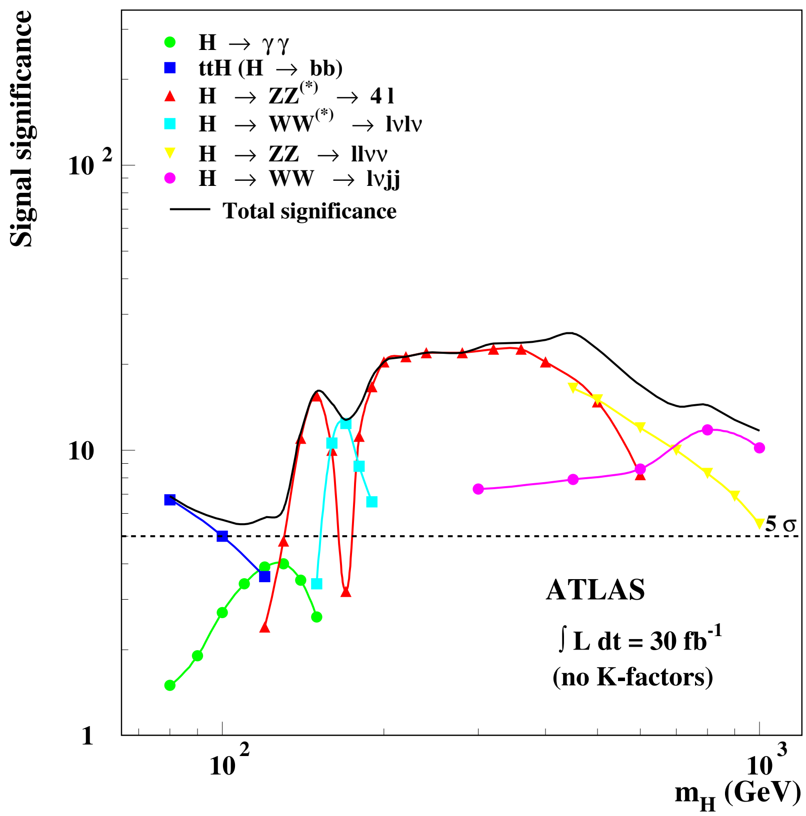
$$\sim (1000\ fb)\left(\frac{1}{3}\right)(.06)^2\left(30\ fb^{-1}\right)$$

~ 36 events

- Discovery $=$

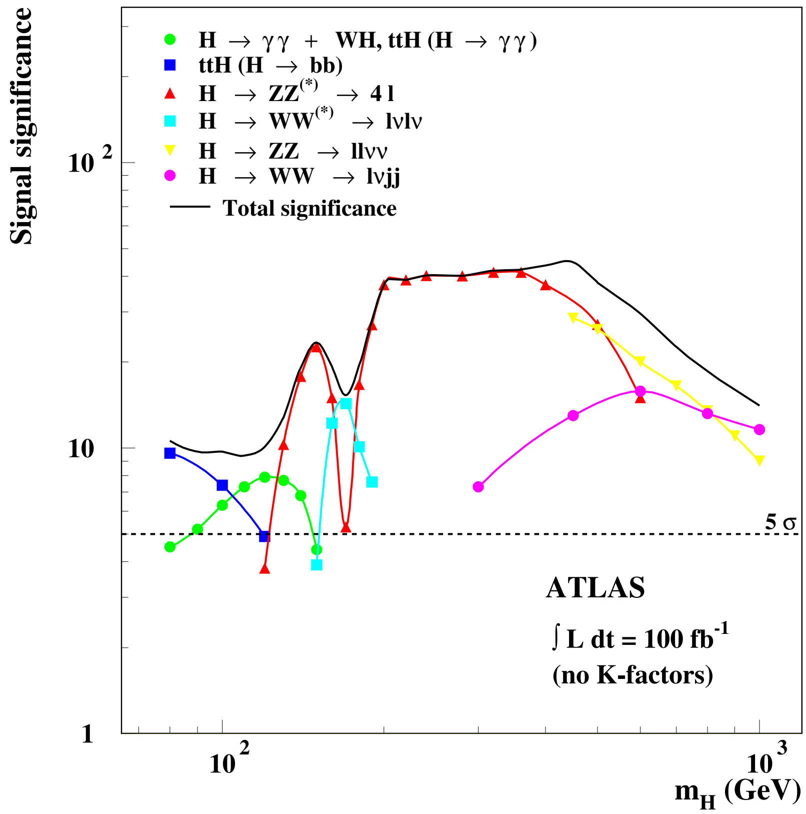
$$\frac{N_{\text{signal}}}{\sqrt{N_{\text{background}}}} > 5$$

LHC with Low Luminosity (2006?)

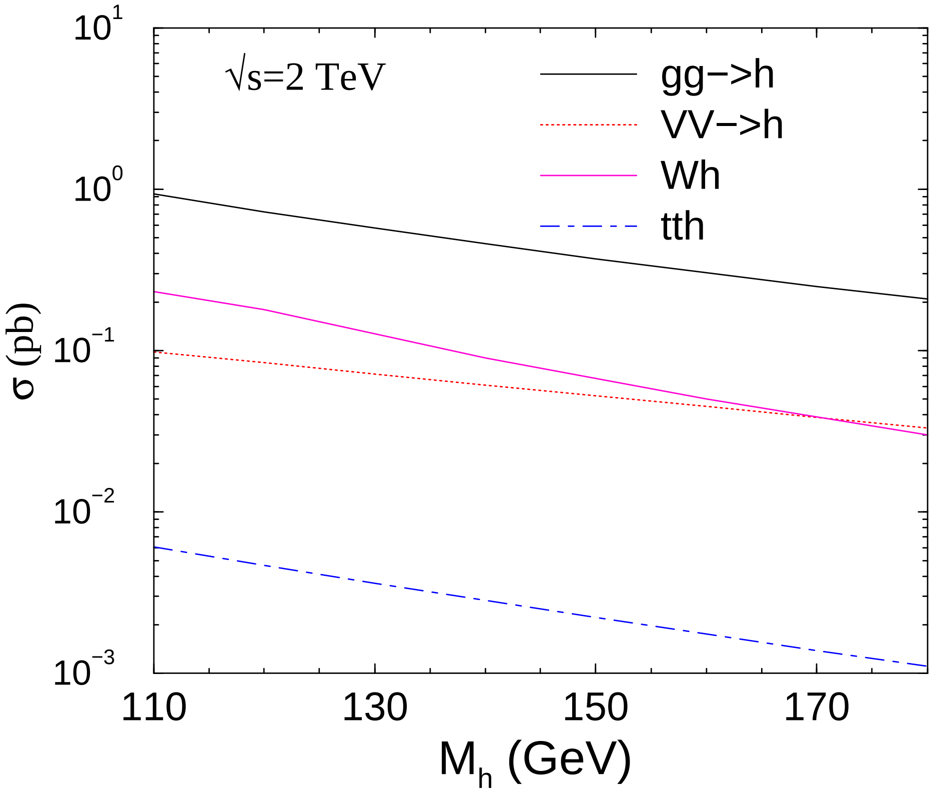


LHC with High Luminosity (2008?)

- With higher luminosity, Higgs observable in several channels in most mass regions



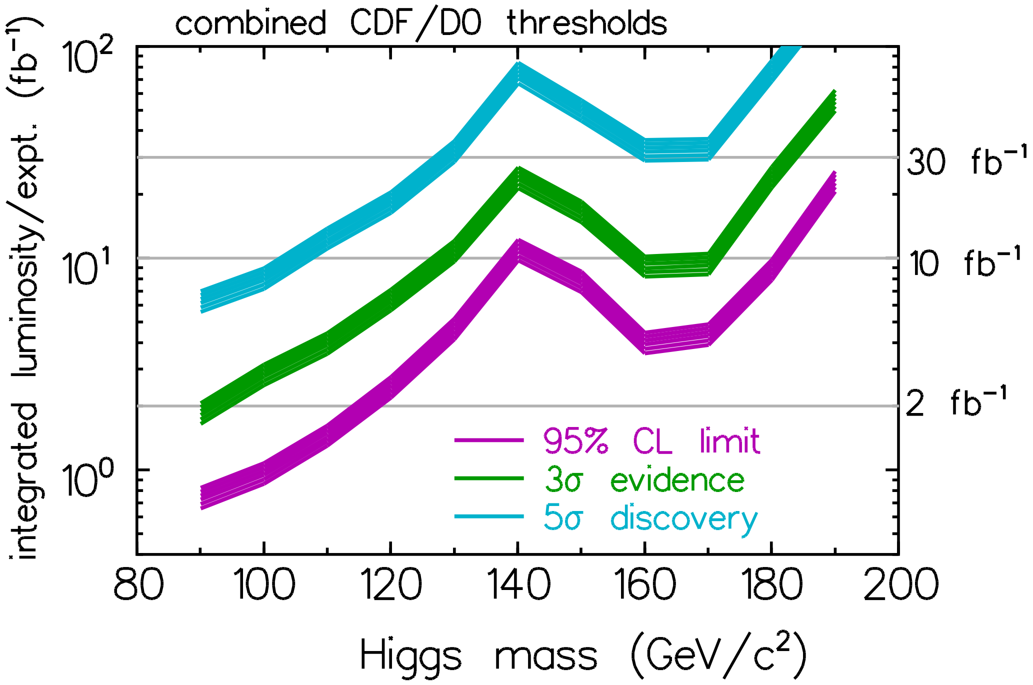
What about the Tevatron?



- Note small rates
- Below $M_h \sim 140\ GeV$, use

$$q'\overline{q} \to Wh,$$
$$W \to l\nu, h \to b\overline{b}$$

- Above $M_h \sim 140\ GeV$, $h \to WW^*$
- Add many channels to get observable signals



[Carena et al, hep-ph/0010338]

Limits from Precision Measurements

SM has special relation:

$$M_W = \cos\theta_W M_Z$$

Consequence of Higgs doublets only:

$$\left(D_\mu\langle\Phi\rangle\right)^\dagger \left(D^\mu\langle\Phi\rangle\right)$$

If several multiplets:

$$D_\mu\langle\Phi\rangle \to \left[\frac{g}{\sqrt{2}}\left(\tau^+W_\mu^+ + \tau^-W_\mu^-\right) + g\tau_3W_3 - g'\tau_3B\right]\langle\Phi\rangle$$

Use:

$$\frac{(\tau_3+Y)}{2}\langle\Phi\rangle = 0$$

Gauge boson masses become:

$$\begin{aligned}\left(D_\mu\langle\Phi\rangle\right)^\dagger \left(D^\mu\langle\Phi\rangle\right) =& \Sigma_\Phi \frac{g^2}{2}\left[\tau\left(\tau+1\right) - \tau_3^2\right] 2W^+W^-\langle\Phi\rangle^2 \\ &+ \Sigma_\Phi \tau_3^2\left(g^2+g'^2\right) Z^2\langle\Phi\rangle^2\end{aligned}$$

This gives:

$$\rho \equiv \frac{M_W^2}{\cos^2\theta_W M_Z^2} = \Sigma_\Phi \frac{\left[\tau\left(\tau+1\right) - \tau_3^2\right]\frac{1}{2}}{\tau_3^2}$$

Only Higgs doublets or singlets, then $\rho = 1$

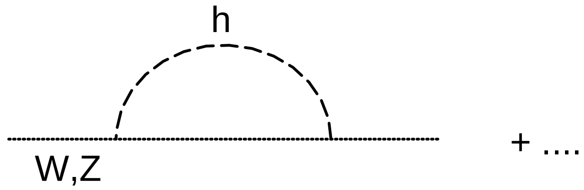
$$\rho_{exp} = .9998 \pm .0008$$

Higgs contributes to radiative corrections:

- Without a Higgs boson EW radiative corrections are infinite:

$$\frac{\delta M_W^2}{M_W^2} = \frac{3\alpha}{16\pi \sin^2\theta_W}\frac{1}{\epsilon}$$

Singularity cancelled by Higgs:



- Contributions to EW observables $\sim log(M_h)$

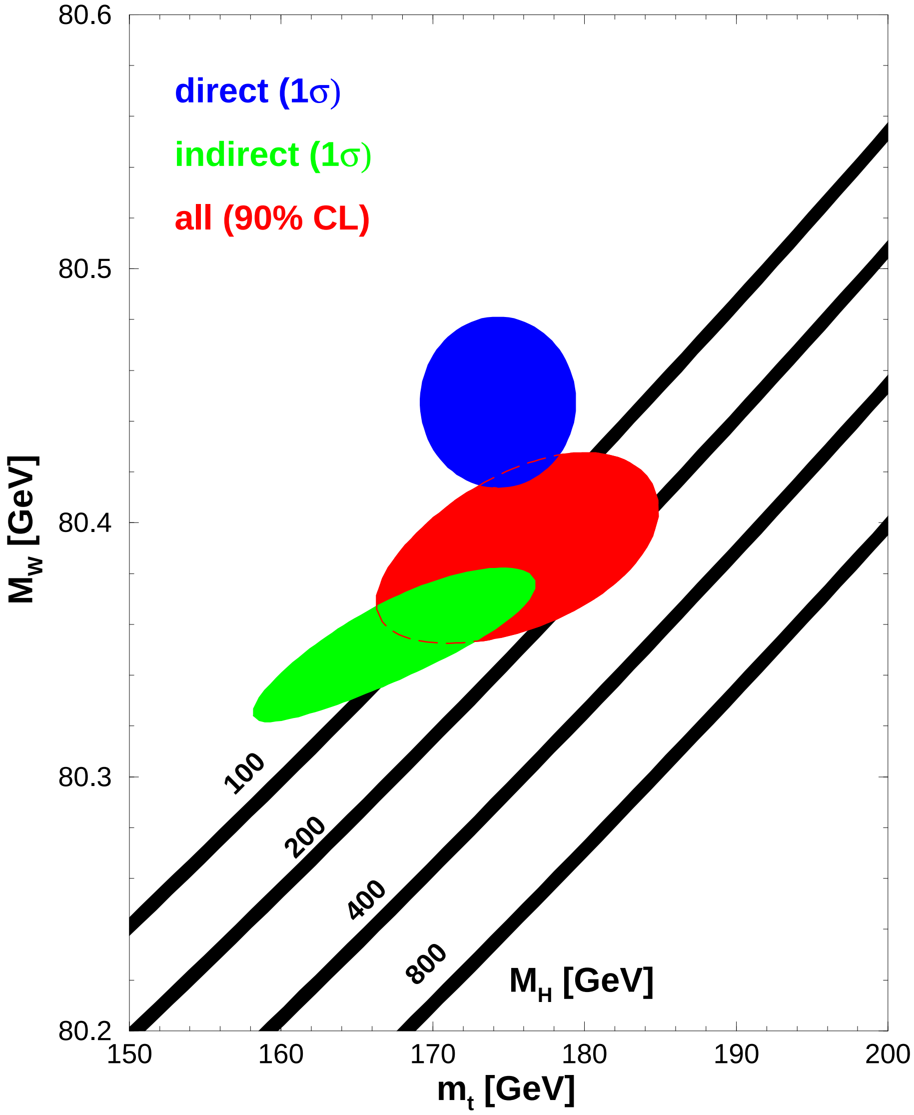
$$M_W = 80.3805\ GeV - .0581 \log\left(\frac{M_h}{100\ GeV}\right) - .0078 \log^2\left(\frac{M_h}{100\ GeV}\right) - .537\left[\left(\frac{M_t}{175\ GeV}\right)^2 - 1\right] - .085\left[\frac{\alpha_s(M_Z)}{.118} - 1\right]$$

Current world average: $M_W = 80.433(47)\ GeV$

95% cl limit is $M_h < 195\ GeV$

- Limits on M_h from radiative corrections assume SM [Peskin, Snowmass 2001]

[Langacker, Snowmass 2001]



2-Higgs Doublet Model

Add 2 complex doublets Φ_1 and Φ_2

Require invariance under $\Phi_1 \to -\Phi_1$

Higgs potential has 6 real parameters and a phase:

$$
\begin{aligned}
V\left(\Phi_1, \Phi_2\right) = & \lambda_1 \left(\Phi_1^\dagger \Phi_1 - v_1^2\right)^2 \\
& + \lambda_2 \left(\Phi_2^\dagger \Phi_2 - v_2^2\right)^2 \\
& + \lambda_3 \left[\left(\Phi_1^\dagger \Phi_1 - v_1^2\right) + \left(\Phi_2^\dagger \Phi_2 - v_2^2\right)\right]^2 \\
& + \lambda_4 \left[\left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) - \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right)\right] \\
& + \lambda_5 \left[Re\left(\Phi_1^\dagger \Phi_2\right) - v_1 v_2 \cos\zeta\right]^2 \\
& + \lambda_6 \left[Im\left(\Phi_1^\dagger \Phi_2\right) - v_1 v_2 \sin\zeta\right]^2
\end{aligned}
$$

By construction, minimum of potential at:

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}$$

$$\langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 e^{i\zeta} \end{pmatrix}$$

Ratio of vacuum expectation values: $\tan\beta = \frac{v_2}{v_1}$

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

If $\lambda_5 = \lambda_6$ then $V = ...\lambda_5 \mid \phi_1^\dagger \phi_2 - v_1 v_2 e^{i\zeta} \mid^2$

Phase rotated away by redefinition of Φ_i (happens in SUSY)

Couple scalars to $SU(2) \times U(1)$ gauge bosons as in SM

Count degrees of freedom:

Before spontaneous symmetry breaking:

- Massless W^i_μ, B_μ 8 dof
- 2 Complex Φ_i 8 dof
- Total: 16 dof

After spontaneous symmetry breaking:

- Massive $W^\pm, Z$ 9 dof
- Massless γ 2 dof
- 2 neutral Higgs bosons, h^0, H^0 2 dof
- 2 charged Higgs bosons, $H^\pm$ 2 dof
- 1 neutral Higgs boson, A^0 1 dof

6 free parameters (neglecting ζ):
4 Higgs masses, $\tan\beta$, mixing angle in neutral Higgs sector

- No unique choice for Higgs-fermion couplings
- Must avoid FCNCs
- Model 1:
  - Φ_1 doesn't couple to fermions
  - Φ_2 couples just like SM
- Model 2:
  - Φ_1 couples to down-type quarks
  - Φ_2 couples to up-type quarks

Exercises related to today's lecture

- Compute $\Gamma(h \to b\overline{b})$
- Compute $\hat{\sigma}(gg \to h)$
- Compute $\delta M_W^2 = (...) \log(\frac{M_h^2}{M_W^2})$
- Why is a $\mu^+\mu^-$ collider interesting for Higgs physics?