The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2244-2

Summer School on Particle Physics

6 - 17 June 2011

Higgs and Electroweak Symmetry Breaking - II

Sally DAWSON

Brookhaven National Laboratory
USA

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

EW Symmetry Breaking: Where are we?

S. Dawson

Trieste, 2011

Lecture 2

Fermi Model

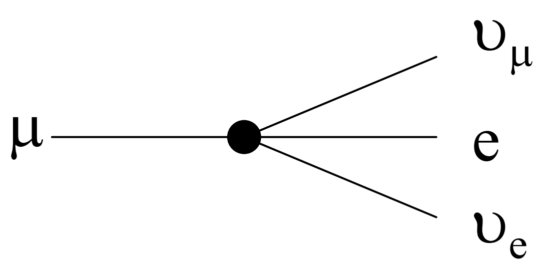
- Current-current interaction of 4 fermions

$$L_{FERMI} = -2\sqrt{2} G_F J_\rho^+ J^\rho$$

- Consider just leptonic current

$$J_\rho^{lept} = \bar{\nu}_e \gamma_\rho \left(\frac{1-\gamma_5}{2} \right) e + \bar{\nu}_\mu \gamma_\rho \left(\frac{1-\gamma_5}{2} \right) \mu + hc$$

- Only left-handed fermions feel charged current weak interactions
- This induces muon decay



This structure known since Fermi

$G_F = 1.16637 \times 10^{-5}\ \mathrm{GeV}^{-2}$

Fermion Multiplet Structure

- Ψ_L couples to $W^{\pm}$ (cf Fermi theory)
  - Put in SU(2) doublets
- Ψ_R doesn't couple to $W^{\pm}$
  - Put in SU(2) singlets
- Fix weak hypercharge to get correct couplings to photon

Put this in by hand

Leptons

- Include an SU(2) doublet of left-handed leptons

$$\Psi_L = \begin{pmatrix} \nu_L = \frac{1}{2}(1-\gamma_5)\nu \\ e_L = \frac{1}{2}(1-\gamma_5)e \end{pmatrix}$$

$I_3=\pm 1$

- Right-handed electron is SU(2) singlet, $e_R=(1+\gamma_5)e/2$
  - No right-handed neutrino
- Define weak hypercharge, Y, such that $Q_{em}=(I_3+Y)/2$
  - $Y_{eL}=-1$
  - $Y_{eR}=-2$

  To make charge come out right

**Standard Model has massless neutrinos—discovery of non-zero neutrino mass evidence for physics beyond the SM*

Fermions come in generations

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad u_R, \quad d_R, \begin{pmatrix} \nu \\ e \end{pmatrix}_L, \quad e_R$$

$$\begin{pmatrix} c \\ s \end{pmatrix}_L \quad c_R, \quad s_R, \begin{pmatrix} \nu \\ \mu \end{pmatrix}_L, \quad \mu_R$$

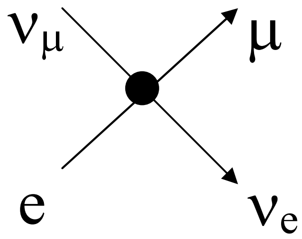
$$\begin{pmatrix} t \\ b \end{pmatrix}_L \quad t_R, \quad b_R, \begin{pmatrix} \nu \\ \tau \end{pmatrix}_L, \quad \tau_R$$

Except for masses, the generations are identical

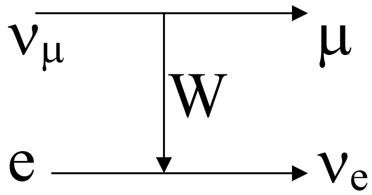
$$\psi_{L,R} = \frac{1 \mp \gamma_5}{2} \psi$$

Muon decay

- Consider $\nu_\mu\, e \rightarrow \mu\, \nu_e$
- Fermi Theory:



- EW Theory:



$$-i2\sqrt{2}G_F g_{\mu\nu}\bar{u}_\mu\gamma^\mu\left(\frac{1-\gamma_5}{2}\right)u_{\nu_\mu}\bar{u}_{\nu_e}\gamma^\nu\left(\frac{1-\gamma_5}{2}\right)u_e$$

$$\frac{ig^2}{2}\frac{1}{k^2-M_W^2}g_{\mu\nu}\bar{u}_\mu\gamma^\mu\left(\frac{1-\gamma_5}{2}\right)u_{\nu_\mu}\bar{u}_{\nu_e}\gamma^\nu\left(\frac{1-\gamma_5}{2}\right)u_e$$

For $|k| << M_W$, $2\sqrt{2}G_F = g^2/2M_W^2$

Higgs Parameters

- G_F measured precisely

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

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

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

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

- Trade μ^2, λ for v^2, $M_h{}^2$

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

$$v^2 = -\frac{\mu^2}{2\lambda}$$

$$M_h{}^2 = 2v^2\lambda$$

  - Large M_h $\rightarrow$strong Higgs self-coupling
  - A priori, Higgs mass can be anything

What about fermion masses?

- Fermion mass term:

$$L = m\overline{\Psi}\Psi = m\left(\overline{\Psi}_L\Psi_R + \overline{\Psi}_R\Psi_L\right)$$

← Forbidden by SU(2)xU(1) gauge invariance

- Left-handed fermions are SU(2) doublets

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

- Scalar couplings to fermions:

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

- Effective Higgs-fermion coupling

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

- Mass term for down quark:

$$\boxed{\lambda_d = \frac{M_d\sqrt{2}}{v}}$$

Fermion Masses, 2

- M_u from $\Phi_c = i\sigma_2\Phi^*$ (not allowed in SUSY)

$$\Phi_c = \begin{pmatrix} \overline{\phi}^0 \\ -\phi^- \end{pmatrix}$$

$$L = -\lambda_u \overline{Q_L} \Phi_c u_R + hc$$

$$\lambda_u = \frac{M_u \sqrt{2}}{v}$$

- For 3 generations, α, β=1,2,3 (flavor indices)

$$L_Y = -\frac{(v+h)}{\sqrt{2}} \sum_{\alpha,\beta} \left(\lambda_u^{\alpha\beta} \overline{u}_L^\alpha u_R^\beta + \lambda_d^{\alpha\beta} \overline{d}_L^\alpha d_R^\beta \right) + h.c.$$

Fermion masses, 3

- Unitary matrices diagonalize mass matrices

$$u_L^\alpha = U_u^{\alpha\beta} u_L^{m\beta} \qquad d_L^\alpha = U_d^{\alpha\beta} d_L^{m\beta}$$
$$u_R^\alpha = V_u^{\alpha\beta} u_R^{m\beta} \qquad d_R^\alpha = V_d^{\alpha\beta} d_R^{m\beta}$$

  - Yukawa couplings are ***diagonal*** in mass basis
  - No flavor changing effects in Higgs sector
  - Not necessarily true in models with extended Higgs sectors

Review of Higgs Couplings

- Higgs couples to fermion mass
  - Largest coupling is to heaviest fermion

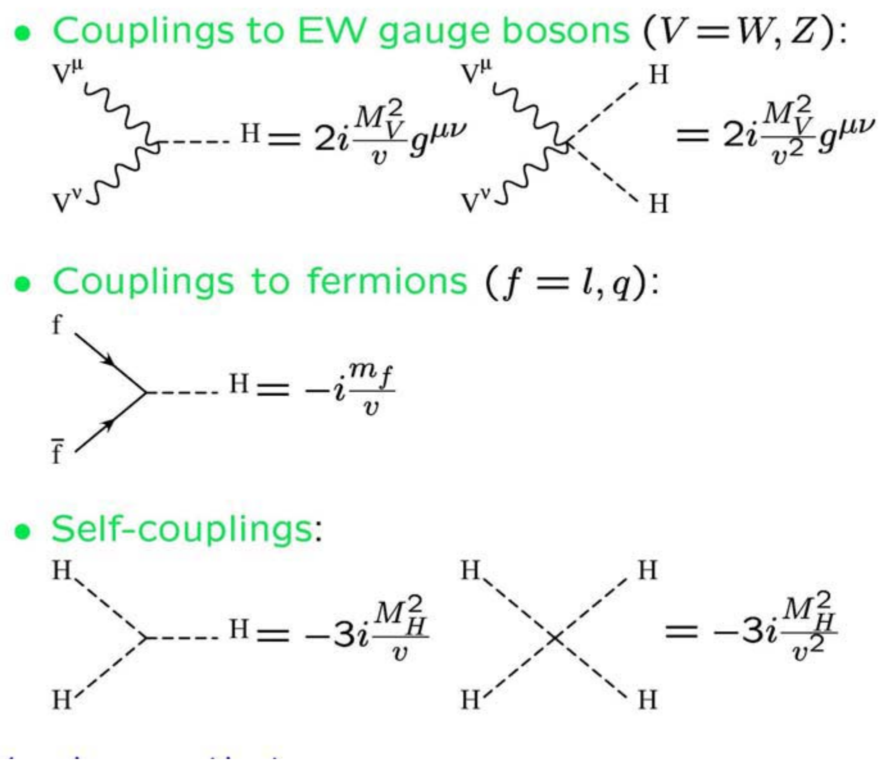
$$L = -\frac{m_f}{v}\bar{f}fh = -\frac{m_f}{v}\left(\bar{f}_L f_R + \bar{f}_R f_L\right)h$$

  - Top-Higgs coupling plays special role?
  - No Higgs coupling to neutrinos
- Higgs couples to gauge boson masses

$$L = gM_W W^{+\mu} W_\mu^- h + \frac{gM_Z}{\cos\theta_W} Z^\mu Z_\mu h + ...$$

- Only free parameter is Higgs mass!

Review of Higgs Boson Feynman Rules



- Higgs couples to heavy particles
- ***No tree level coupling to photons (γ) or gluons (g)***
- $M_h^2=2v^2\lambda \Rightarrow$ large M_h is strong coupling regime

Recap

- Standard model is *predictive* theory
- Only missing piece is Higgs boson
- Can test predictions *experimentally*
- *Bottom line: everything hangs together*

Basics

- Four free parameters in gauge-Higgs sector (g, g', μ, λ)
  - Conventionally chosen to be
    - α=1/137.0359895(61)
    - G_F =1.16637(1) x 10^{-5} GeV $^{-2}$
    - M_Z=91.1875 $\pm$ 0.0021 GeV
    - M_h
  - Express everything else in terms of these parameters

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{\pi\alpha}{2\left(1-\frac{M_W^2}{M_Z^2}\right)M_W^2}$$

$\Rightarrow$ Predicts M_W

Inadequacy of Tree Level Calculations

- Mixing angle is predicted quantity
  - On-shell definition $\cos^2\theta_W = M_W^2/M_Z^2$
  - Predict M_W

$$M_W^2 = \pi\sqrt{2}\,\frac{\alpha}{G_F}\left(1-\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_F M_Z^2}}\right)^{-1}$$

$$s_W{}^2 c_W{}^2 = \frac{\pi\alpha}{G_F M_Z^2}$$

  - Plug in numbers:
    - M_W predicted =80.939 GeV
    - M_W experimental =80.399 $\pm$ 0.023 GeV
  - Need to calculate beyond tree level

Modification of tree level relations

$$G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2 \sin^2\theta_W}\frac{1}{(1-\Delta r)}$$

- Δr is a physical quantity which incorporates 1-loop corrections

- Contributions to Δr from top quark and Higgs loops

$$\Delta r^t = -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2}\left(\frac{\cos^2\theta_W}{\sin^2\theta_W}\right)$$

$$\Delta r^h = \frac{11 G_F M_W^2}{24\sqrt{2}\pi^2}\left(\ln\frac{M_h^2}{M_W^2}\right)$$

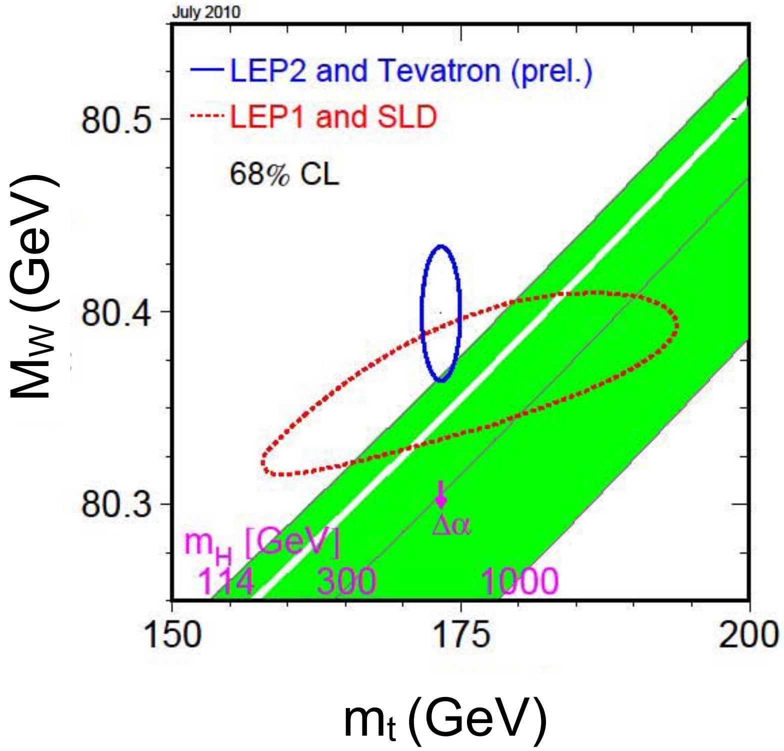
Extreme sensitivity of precision measurements to m_t

M_W vs m_t

- Logarithmic dependence on M_h

Direct measurement of W and top masses

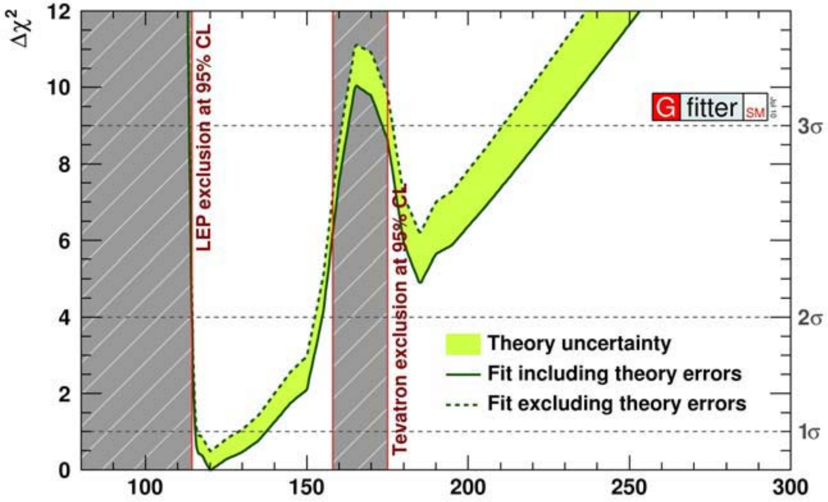
Masses inferred from precision measurements



Higgs boson wants to be light

Higgs Boson

- Standard Model Higgs expected to be light



M_h(GeV)

Note importance of theory uncertainties

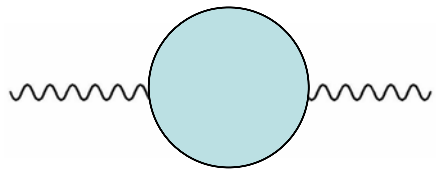
- This assumes the Standard Model!

Standard Model prefers light (M_h < 158 GeV) Higgs boson

Quantum Corrections

- Relate tree level to one-loop corrected masses

$$-i\Pi^{\mu\nu}_{XY} =$$



$$\Pi^{\mu\nu}_{XY}(k^2) = g^{\mu\nu}\Pi_{XY}(k^2) + k^\mu k^\nu B_{XY}(k^2)$$

$$M^2_{V0} = M^2_V + \Pi_{VV}(M^2_V)$$

- Majority of corrections at one-loop are from 2-point functions

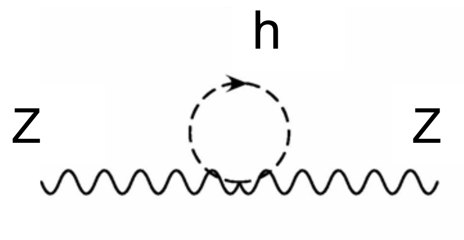
Example of Quantum Corrections

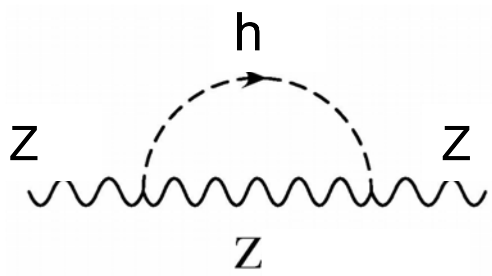
- Example: $$\rho = \frac{M_W^2}{M_Z^2 \cos_W^2} = 1 + \delta\rho$$

$$\boxed{\delta\rho = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}}$$

Experimentally, $\rho \sim 1$

Higgs Contribution to $\delta\rho$





- Higgs contributions have divergences which are cancelled by contributions of gauge boson loops
- Higgs contributions alone aren't gauge invariant
- Keep only terms which depend on M_h

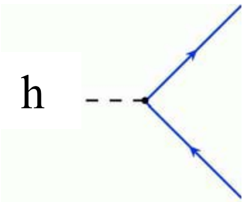
$$\delta\rho = \frac{-3\alpha}{16\pi c_W^2} \log\left(\frac{M_h^2}{M_W^2}\right)$$

Looking for the Higgs Boson

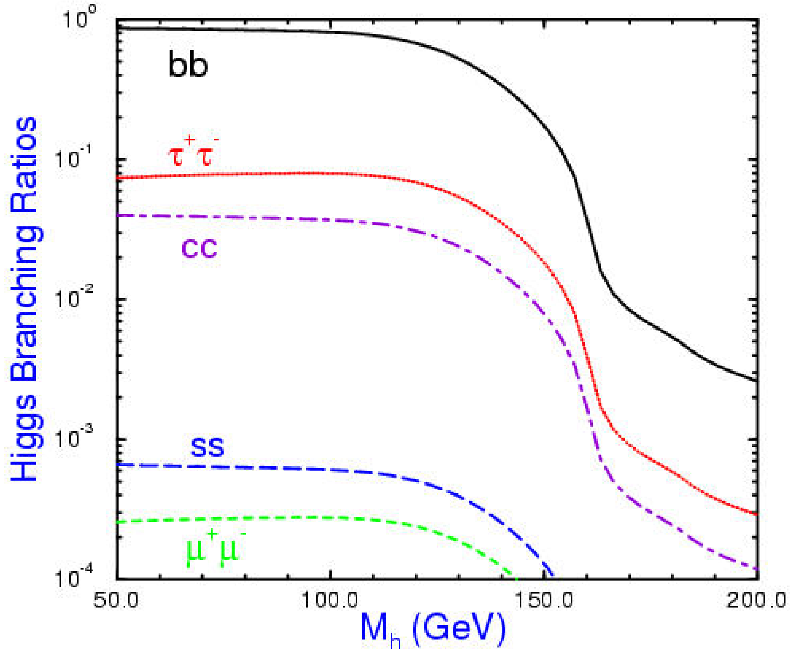
- Standard Model Higgs boson expected to be light, < 150 GeV
- But…. Limits assume Standard Model, so look for Higgs boson in all mass regions
- Higgs couplings are absolute prediction, so for a given Higgs boson mass, we can calculate everything

Higgs Decays

- $h \to f\bar{f}$ proportional to m_f^2



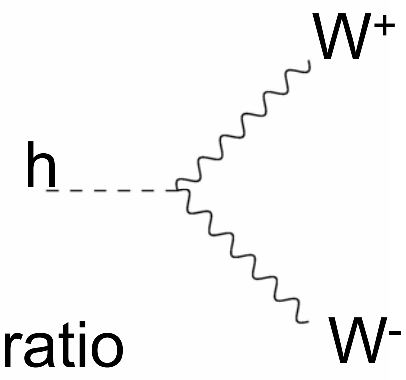
$$\frac{BR(h \to b\bar{b})}{BR(h \to \tau^+\tau^-)} \approx N_c \left(\frac{m_b^{\;2}}{m_\tau^{\;2}} \right)$$



- Identifying b quarks important for Higgs searches

For $M_h < 2M_W$, decays to $b\bar{b}$ most important

Higgs Decays to W/Z

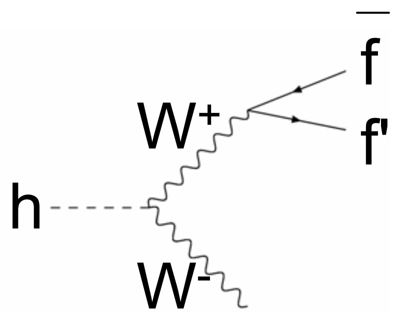


- Tree level decay

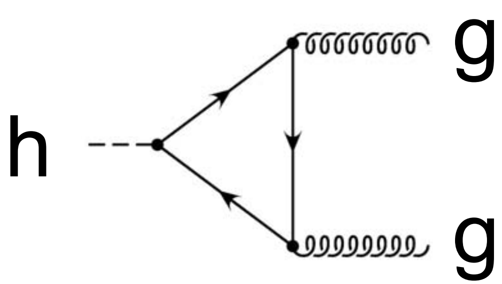
$$\Gamma(h \to W^+W^-) = \frac{\alpha}{16 s_W^2} \frac{M_h^3}{M_W^2} \sqrt{1-x_W}\left(1 - x_W + \frac{3}{4}x_W^2\right)$$

- Below threshold, h→WW* with branching ratio W* →ff' implied
- Final state has both transverse and longitudinal polarizations

$$x_W = 4\frac{M_W^2}{M_h^2}$$



Higgs Decays to Gluons



- Top quark contribution most important
- Doesn't decouple for large m_t
- Decoupling theorem doesn't apply to particles which couple to mass (ie Higgs!)
- Decay sensitive to extra generations

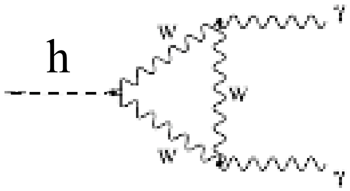
$$\Gamma(h \to gg) \approx \frac{\alpha_s^2 \alpha}{72\pi^2 s_W^2} \frac{M_h^3}{M_W^2} + O\left(\frac{M_h^2}{M_t^2}\right)$$

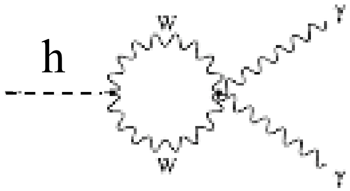
Higgs Decays to Photons

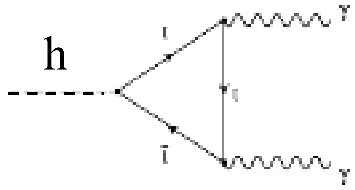
- Dominant contribution is W loops
- Contribution from top is small

$$\Gamma(h \to \gamma\gamma) \approx \frac{\alpha^3}{256\pi^2 s_W^2} \frac{M_h^3}{M_W^2} \left| 7 - \frac{16}{9} + \ldots \right|^2$$

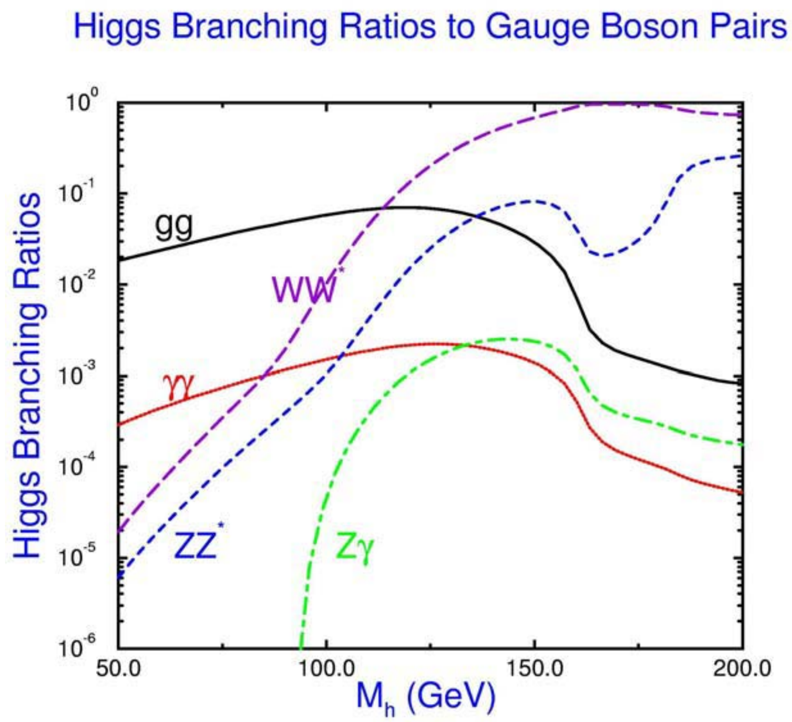
W top





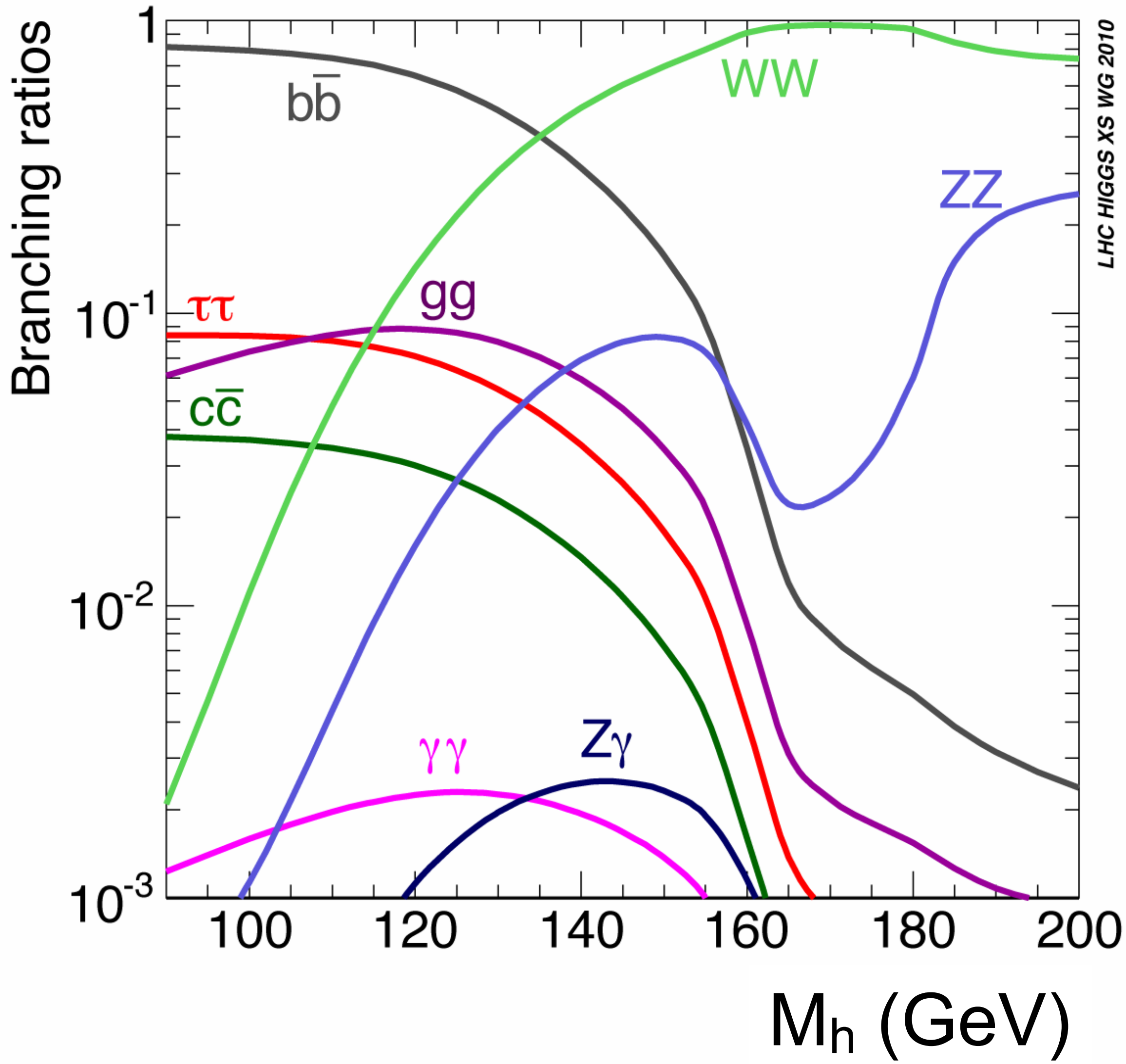


Higgs decays to gauge bosons



For any given M_h, not all decay modes observable

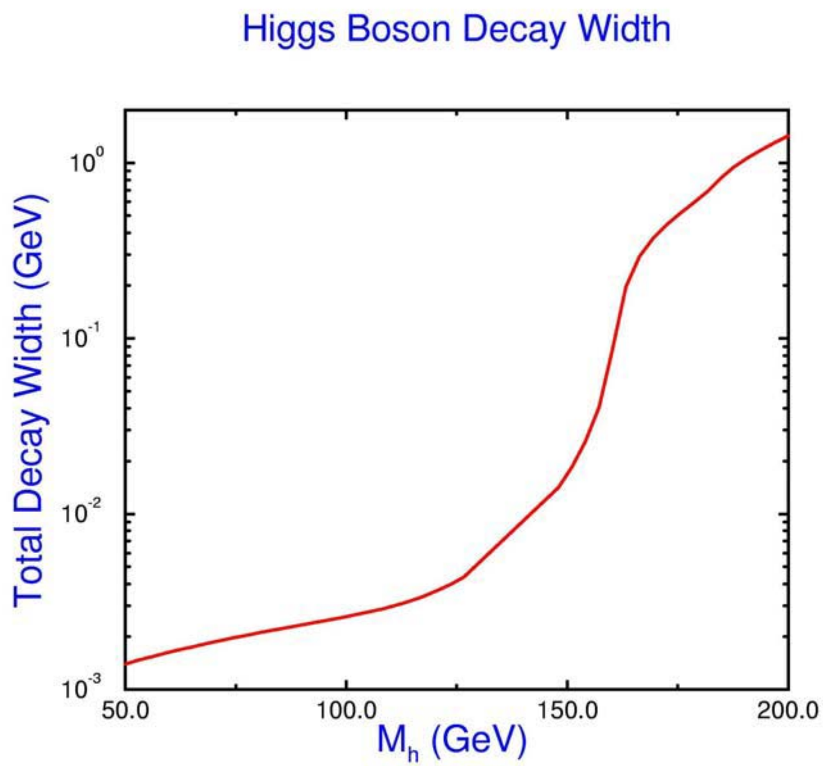
Higgs Branching Ratios



Total Higgs Width

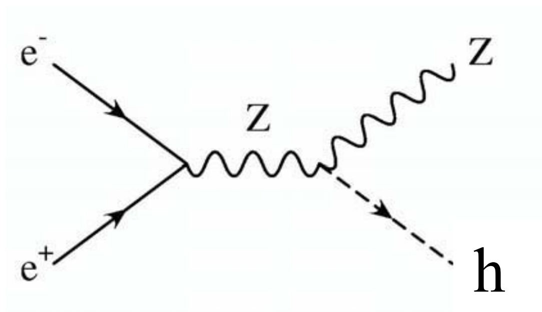
- Small M_h, Higgs is narrower than detector resolution
- As M_h becomes large, width also increases
  - No clear resonance
  - For $M_h \sim 1.4$ TeV, $\Gamma_{tot} \sim M_h$

$$\Gamma(h \to W^+W^-) \approx \frac{\alpha}{16\sin^2\theta_W} \frac{{M_h}^3}{{M_W}^2}$$
$$\approx 330 GeV \left(\frac{M_h}{1 TeV}\right)^3$$



Higgs Searches at LEP2

- LEP2 searched for $e^+e^- \to Zh$
- Rate turns on rapidly after threshold, peaks just above threshold, $\sigma \sim \beta^3/s$
- Measure recoil mass of Higgs; ***result independent of Higgs decay pattern***
  - $P_{e-} = \sqrt{s}/2(1,0,0,1)$
  - $P_{e+} = \sqrt{s}/2(1,0,0,-1)$
  - $P_Z = (E_Z, p_Z)$
- Momentum conservation:
  - $(P_{e-} + P_{e+} - P_Z)^2 = P_h^2 = M_h^2$
  - $s - 2\sqrt{s}\, E_Z + M_Z^2 = M_h^2$



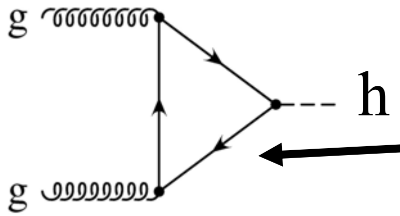
LEP2 limit, $M_h > 114.1$ GeV

Higgs production at Hadron Colliders

- Many possible production mechanisms; Importance depends on:
  - Size of production cross section
  - Size of branching ratios to observable channels
  - Size of background
- Importance varies with Higgs mass
- Need to see more than one channel to establish Higgs properties and verify that it is a Higgs boson

Production Mechanisms in Hadron Colliders

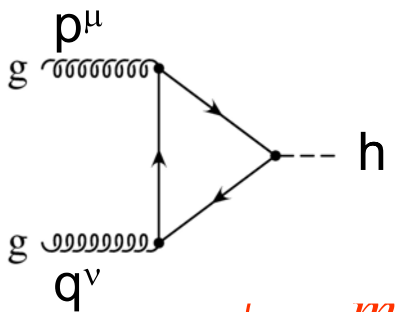
- Gluon fusion
  - Largest rate for all M_h at LHC and Tevatron
  - Gluon-gluon initial state
  - Sensitive to top quark Yukawa λ_t



Largest contribution is top loop

In Standard Model, b-quark loop contribution small

Gluon Fusion (in detail!)



$$p \cdot q = \frac{M_h^2}{2}$$

$$iA = -(-ig_s)^2 Tr(T_A T_B)\left(-i\frac{m}{v}\right)\int \frac{d^n k}{(2\pi)^n}\frac{T^{\mu\nu}}{D}(i)^3 \varepsilon_\mu(p)\varepsilon_\nu(q)$$

$$D = (k^2 - m^2)((k+p)^2 - m^2)((k-q)^2 - m^2)$$

Combine denominators
$$\frac{1}{ABC} = 2\int_0^1 dx \int_0^{1-x} \frac{dy}{(1 - Ax + By + C(1-x-y))^3}$$

$$\frac{1}{D} \to 2\int dxdy \frac{1}{(k^2 - m^2 + 2k\cdot(px - qy))^3}$$

Shift momentum
$$k' = k + px - qy$$

$$\frac{1}{D} \to 2\int dxdy \frac{1}{(k'^2 - m^2 + M_h^2 xy)^3}$$

Gluon Fusion

- Numerator $T^{\mu\nu} = Tr\left[(k+m)\gamma^{\mu}(k+p+m)(k-q+m)\gamma^{\nu}\right]$

$$T^{\mu\nu} \to 4m\left[g^{\mu\nu}(m^2 - k^2 - \frac{M_h^2}{2}) + 4k^{\mu}k^{\nu} + p^{\nu}q^{\mu}\right]$$

- Shift momenta, drop linear terms, use $\int d^n k' \frac{k'^{\mu}k'^{\nu}}{(k'^2 - A)^r} = \frac{1}{n} g^{\mu\nu} \frac{k'^2}{(k'^2 - A)^r}$

$$\begin{aligned} iA \quad &= -\frac{2g_s^2 m^2}{v}\delta_{AB}\int \frac{d^n k'}{(2\pi)^n}\int dxdy\left\{g^{\mu\nu}\left(m^2 + k'^2\left[\frac{4}{n} - 1\right] + M_h^2\left[xy - \frac{1}{2}\right]\right)\right. \\ &\left. + p^{\mu}q^{\nu}[1 - 4xy]\right\}\frac{2dxdy}{(k'^2 - m^2 + M_h^2)^3}\varepsilon_{\mu}(p)\varepsilon_{\nu}(q) \end{aligned}$$

- Dimension regularization: $\frac{d^n k'}{(2\pi)^n}\frac{k'^2}{(k'^2 - A)^3} = \frac{i}{32\pi^2}(4\pi\mu^2)^{\varepsilon}\frac{\Gamma(1+\varepsilon)}{\varepsilon}(2-\varepsilon)A^{-\varepsilon}$

$$\frac{d^n k'}{(2\pi)^n}\frac{1}{(k'^2 - A)^3} = -\frac{i}{32\pi^2}(4\pi\mu^2)^{\varepsilon}\Gamma(1+\varepsilon)A^{-1-\varepsilon}$$

Gluon Fusion

- Answer:

$$A(gg \to h) = -2\frac{\alpha_s^2 m^2}{2\pi v}\delta_{AB}\left(g^{\mu\nu}\frac{M_h^2}{2} - p^\nu q^\mu\right)$$

2 diagrams

$$\cdot \int dx dy \frac{1-4xy}{m^2 - M_h^2 xy}\varepsilon_\mu(p)\varepsilon_\nu(q)$$

- Gauge invariant form:

$$A(gg \to h) = \frac{\alpha_s}{4\pi v}\delta_{AB}F_{1/2}\left(\frac{4m^2}{M_h^2}\right)\left(g^{\mu\nu}\frac{M_h^2}{2} - p^\nu q^\mu\right)\varepsilon_\mu(p)\varepsilon_\nu(q)$$

$$F_{1/2}\left(\frac{4m^2}{M_h^2}\right) = -4\int dx dy \frac{1-4xy}{1-\frac{M_h^2}{m^2}xy}$$

Gluon Fusion

- Turn it into a partonic cross section

$$\hat{\sigma}_{gg\to h}(\hat{s}) = \frac{1}{4\cdot 64}\frac{1}{2\hat{s}}|A|^2 d\Phi_1$$

Spin & color average

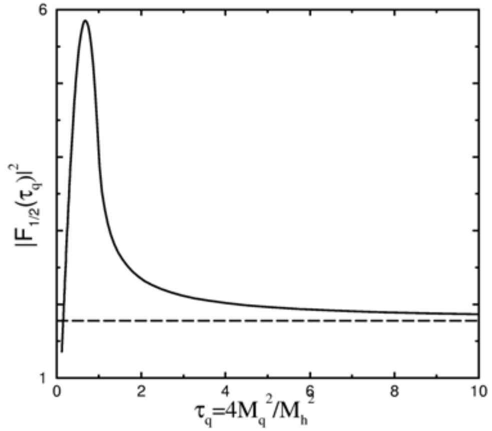
$$d\Phi_1 = \frac{2\pi}{M_h^2}\delta\left(1-\frac{M_h^2}{\hat{s}}\right)$$

$$\hat{\sigma}_{gg\to h}(\hat{s}) = \frac{\alpha_s(\mu_R)^2}{1024\pi v^2}\left|F_{1/2}\left(\frac{4m^2}{M_h^2}\right)\right|^2 \delta\left(1-\frac{M_h^2}{\hat{s}}\right)$$

Gluon Fusion

- Lowest order cross section:
  - $\tau_q=4m_q^2/M_h^2$
  - Light Quarks: $F_{1/2}\rightarrow(m_b/M_h)^2\log^2(m_b/M_h)$
  - Heavy Quarks: $F_{1/2}\rightarrow -4/3$

$$\hat{\sigma}_{gg\rightarrow h}(\hat{s})=\frac{\alpha_s(\mu_R)^2}{1024\pi v^2}\left|\sum_q F_{1/2}(\tau_q)\right|^2\delta\left(1-\frac{M_h^2}{\hat{s}}\right)$$



- Rapid approach to heavy quark limit: Counts number of heavy fermions
- NNLO corrections calculated in heavy top limit