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SMR.1508 - 19

SUMMER SCHOOL ON PARTICLE PHYSICS

16 June - 4 July 2003

THE STANDARD MODEL AND HIGGS PHYSICS

Lecture V

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7.) <u>Higgs Phenomenology</u>

For a nice review, see: <u>S. Dawson hep-ph/9901280</u>
Trieste Lectures

Basic Parameters of the Standard Model include λ_0, v_0 and many Yukawa Couplings ($\sim$72 Parameters).

$\downarrow$

m_H, m_W or m_Z, all fermion masses & mixing
(modulo neutrino see-saw)

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix}\omega_1 + i\omega_2 \\ H + v_0 + iz\end{pmatrix} \qquad \omega^{\pm}, z \text{ isotriplet}$$

$$\mathcal{L}_\phi = \left|\left(\partial^\mu + i g_{2_0}\frac{\tau^i W^{i\mu}}{2} + i g_0'\frac{B^\mu}{2}\right)\phi\right|^2 + \underline{\tfrac{1}{2}\mu_0^2\phi^\dagger\phi - \lambda_0(\phi^\dagger\phi)^2}$$

$$\underbrace{-G_{ij}\,\bar{L}_j\,\phi R_i + h.c.}_{\substack{e,\mu,\tau \\ d,s,b}\}\text{ masses}} \quad \underbrace{-\tilde{G}_{ij}\,\bar{L}_j\,\tilde{\phi} R_i + h.c.}_{\substack{\nu_1,\nu_2,\nu_3 \\ u,c,t}\}\text{ masses}} \qquad \tilde{\phi} = \frac{1}{\sqrt{2}}\begin{pmatrix}H + v_0 - iz \\ -\omega_1 + i\omega_2\end{pmatrix}$$

$$V(\phi) = -\lambda_0\Big(\phi^\dagger\phi - \underbrace{\mu_0^2/2\lambda_0}_{\text{identify as } \frac{1}{2}v_0^2}\Big)^2$$

identify as $\frac{1}{2}v_0^2$ (see later discussion)

$$m_H^{0\,2} = 2\lambda_0 v_0^2$$
$$m_W^{0\,2} = g_{2_0}^2 v_0^2/2 \quad \rightarrow \quad v_0 \simeq 247\,\text{GeV} \rightarrow \underline{m_H \simeq 350\sqrt{\lambda}\,\text{GeV}}$$

SM contains 3 massless Goldstone bosons $\omega^{\pm}, z$ which become $W_L^{\pm}, Z_L$ in the unitary gauge + <u>H = Higgs Scalar</u>.

$\underline{m_H > 114.4\,\text{GeV}}$ LEP II Bound
$\underline{m_H \lesssim 185\,\text{GeV}}$ Precision Loop Tests } Relatively Light

<u>Other reasons to believe light Higgs</u>?

$\lambda_0 \phi^4$ is a trivial theory (non-interacting) on its own. Given a value of $\lambda(\mu)$ at high μ, it gets screened to zero at low μ

Lattice $\rightarrow m_H < 640\,\text{GeV}$ avoid triviality

Alternative $\frac{d\lambda}{dt} = \frac{3\lambda^2}{4\pi^2}$ $t = \ln Q^2/Q_0^2$, $\lambda = \frac{m_H^2}{2v}$

$$\lambda(Q) = \frac{\lambda(Q_0)}{\underbrace{\left[1 - \frac{3\lambda(Q_0)}{4\pi^2}\ln Q^2/Q_0^2\right]}_{\text{Landau Pole}}}$$

<u>Require $\lambda(\Lambda)$ stay finite up to scale Λ</u> (large)

$$m_H^2 < \frac{8\pi^2 v^2}{3\ln(\Lambda^2/v^2)}$$

$\underline{\Lambda \simeq 10^{16}\,\text{GeV} \rightarrow m_H < 160\,\text{GeV}}$ (170 GeV) other int.

$\underline{\Lambda \simeq 3\,\text{TeV} \rightarrow m_H < 600\,\text{GeV}}$

The larger m_H turns out to be, the closer "new physics"

One scenario, $\Lambda \sim \mathcal{O}(\text{TeV})$, $m_H \sim \mathcal{O}(\text{TeV})$ and "newphys" $\mathcal{O}(\text{TeV})$

Precision Loops Nullified by strong coupling

<u>Vacuum Stability</u> $\lambda > 0$ (Potential Unbounded Below)

all the way to 10^{16} validity

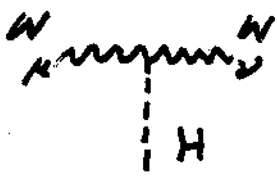
$$\underline{m_H > 130\,\text{GeV}\,!}$$

This is interesting since in SUSY, the lightest Higgs

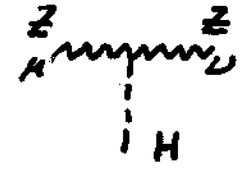
$$\underline{m_h \lesssim 130\,\text{GeV}}$$

<u>Higgs Decay Properties</u> Depend on its mass

Heavy Higgs $m_H > 2m_W$ or $2m_Z$ $\quad \underline{H \to W^+W^-\ (ZZ)}$ Dominate



$i g_{2_0} m_W^0 g_{\mu\nu}$



$\dfrac{i g_{2_0} m_Z^0}{\cos\theta_W^0} g_{\mu\nu}$

$$\mathcal{M}(H \to W^+W^-) = i g_2 m_W \epsilon_\mu(k_1) \epsilon^\mu(k_2)$$

$$\sum_{pol} |\mathcal{M}|^2 = g_2^2 m_W^2 \left(g_{\mu\nu} - \frac{k_{1\mu}k_{1\nu}}{m_W^2}\right)\left(g^{\mu\nu} - \frac{k_2^\mu k_2^\nu}{m_W^2}\right)$$

use $(k_1+k_2)^2 = m_H^2$ $\quad$ Integrate over phase-space exercise

$$\Gamma(H\to W^+W^-) = \frac{g_2^2}{64\pi}\frac{m_H^3}{m_W^2}\left(1-\frac{4m_W^2}{m_H^2}\right)^{1/2}\left(1-4\frac{m_W^2}{m_H^2}+12\frac{m_W^4}{m_H^4}\right)$$

$$\Gamma(H\to ZZ) = \frac{g_2^2}{128\pi}\frac{m_H^3}{m_W^2}\left(1-\frac{4m_Z^2}{m_H^2}\right)\left(1-4\frac{m_Z^2}{m_H^2}+12\frac{m_Z^4}{m_H^4}\right)$$

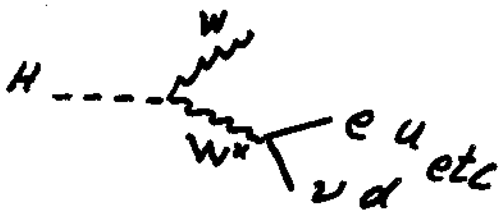
Note that these decay widths grow as m_H^3! (not m_H)

Leading Term $\Gamma(H\to ZZ) = \frac{1}{2}\Gamma(H\to W^+W^-)$ isospin rel.

$\Gamma_H(m_H \simeq 1\,\text{TeV}) \simeq 500\,\text{GeV}$ Very Broad drops fast for lighter Higgs

What if $m_H < 2m_W$ (160 GeV) But not too light

$H\to WW^*$ (W^* = virtual W) Dominates

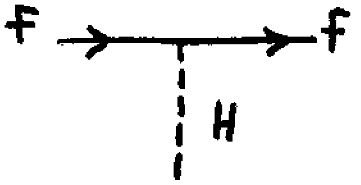


$$\Gamma(H\to WW^*) \sim \frac{3g^4 m_H}{512\pi^3}\times O(1)$$

dominant decay for $m_H \gtrsim 130\,\text{GeV}$

Higgs narrow $\Gamma_H \lesssim 10\,\text{MeV}$

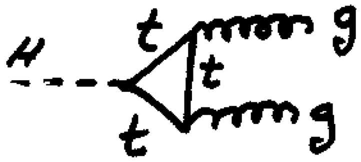
For $m_H \lesssim 130\,\text{GeV}$ $H\to b\bar{b}$ dominates



$$\frac{-ig_{2o}m_f^0}{2m_W^0} \to \Gamma(H\to f\bar{f}) = (3)\frac{g_2^2}{32\pi}\frac{m_f^2 m_H}{m_W^2}\left(1-\frac{4m_f^2}{m_H^2}\right)^2$$

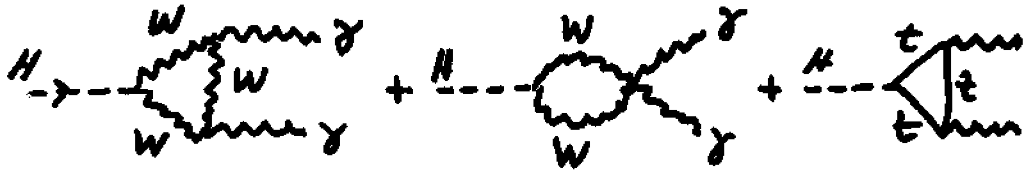
color

Interesting loop induced decays

$H \to gg$ 

$\sim \alpha_s(m_H)$ suppression

$BR \sim$ Few % For $m_H < 150\,GeV$

$H \to \gamma\gamma$ 

$BR \sim 10^{-3}$ for $m_H < 150\,GeV$

$H \to \gamma\gamma$ Very Clean but requires high statistics.

$gg \to H$ Dominant Production Mechanism at LHC

Higgs Discovery and Study Strategy Depends on Mass

Golden Decay $H \to ZZ$, $Z \to \ell^+\ell^-$, $Z \to \ell^+\ell^-$ $\}$ 4 leptons

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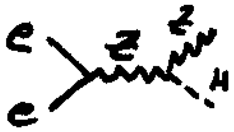
Past Search: $e^+e^- \to ZH$, $H \to b\bar{b}$ $\qquad m_H > 114.4\,GeV$ at LEP II



Current $\quad p\bar{p} \to WH + X$ at the Tevatron
$\qquad\quad ZH$

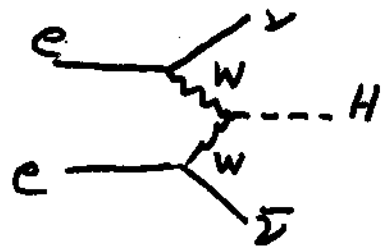
Need $\gtrsim 10\,fb^{-1}$ to cleanly discover $\quad$ expect $\lesssim 8\,fb^{-1}$
(borderline)

Future LHC (2007-2008)

For $m_H \lesssim 200\,GeV$, study $gg \to H \to \gamma\gamma$
$gg \to H \to WW^*, ZZ^*$
$gg \to t\bar{t}H$, $H \to b\bar{b}, WW^*, \gamma\gamma$
etc

Measure some BR. $\sim \pm 10\%$
$\Gamma_H \sim \pm 10\text{-}25\%$

Precision Higgs Studies e^+e^- Linear Collider (250-500 GeV)



$\Gamma_H \sim \pm 5\%$, Coupling HWW, HZZ, $Ht\bar{t}$, $Hb\bar{b}$, $H\tau^+\tau^-$, Hgg, $H\gamma\gamma$.
$\pm 5\%$

Higher Energy Study HH production - Measure λ

If the Higgs is narrow, sit at resonance
$\gamma\gamma \to H$ or $\mu^+\mu^- \to H$
use polarization?

Electroweak Equivalence Theorem

At very high energies, $W^\pm$ + Z interactions are equivalent to $\omega^\pm$ + z Goldstone Bosons up to corrections of $O\left(\frac{m_W^2}{s}\right)$.

Example: Loop Corrections to $H \to W^+W^-$ for $m_H \gg m_W$

Remember $\Gamma(H \to W^+W^-) = \dfrac{g_2^2 m_H^3}{64\pi\, m_W^2}\left\{1 + O\left(\frac{m_W^2}{m_H^2}\right)\right\}$

Consider the Higgs Lagrangian Alone $\qquad \omega = \dfrac{\omega_1 + i\omega_2}{\sqrt{2}}$

$$\mathcal{L}_{Higgs} = -\lambda_0\Big(\omega^\dagger\omega + \tfrac{1}{2}z^2 + \tfrac{1}{2}H^2 + v_0 H + \underbrace{\tfrac{1}{2}v_0^2 - \mu_0^2/2\lambda_0}_{\text{leave} \neq 0 \text{ mass counter term}}\Big)^2 + \text{K.E. terms}$$

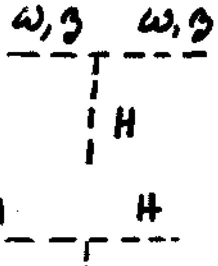
$\lambda_0 = g_{2_0}^2 m_H^{0\,2}/8 m_W^{0\,2}$

cancels tadpoles + Goldstone masses

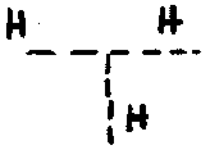
Propagators:

$\dfrac{i}{p^2 - m_H^2}$

$\dfrac{i}{p^2}$



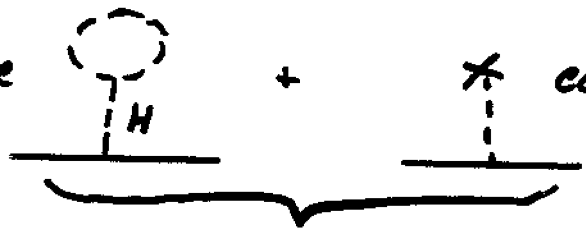
$-\dfrac{ig_2}{2}\dfrac{m_H^2}{m_W}$ $\quad \to \quad \Gamma(H \to \omega^+\omega^-) = \dfrac{g_2^2 m_H^3}{64\pi\, m_W^2}$ $\Big\}$ as above



$= -i\,\dfrac{3g_2}{2}\dfrac{m_H^2}{m_W}$

Use $\mathcal{L} = -g_{2_0}^2 \frac{m_H^{\circ\,2}}{8 m_W^{\circ\,2}} \left\{ w^\dagger w + \frac{1}{2} z^2 + \frac{1}{2} H^2 + \frac{2 m_W^\circ}{g_{2_0}} H + \frac{2\,\delta T}{g_{2_0} m_H^{\circ 2}/m_W^\circ} \right\}^2$

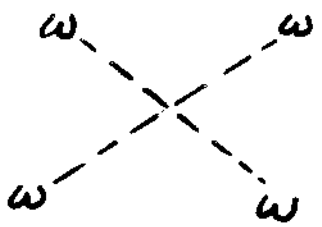
$\delta T = \lambda_0 v_0 (v_0^2 - \mu_0^2/\lambda_0)$ Tadpole Counterterm

tadpole  counterterm cancel

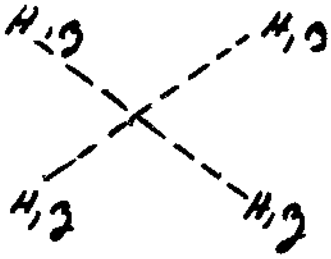
Generally Ignore (Throw Away)

Must Subtract Mass Counterterm From ww, zz, HH

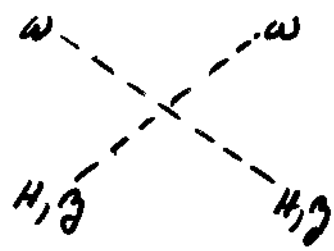
<u>Other Feynman Rules</u>



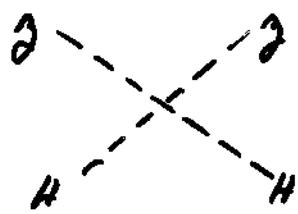
$-i \frac{g_2^2}{2} \frac{m_H^2}{m_W^2}$



$-i \frac{3 g_2^2 m_H^2}{4 m_W^2}$



$-i \frac{g_2^2 m_H^2}{4 m_W^2}$



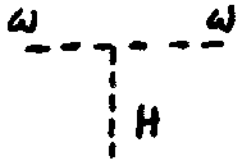
$-i \frac{g_2^2 m_H^2}{4 m_W^2}$

Counterterms $\quad m_H^{\circ 2} = m_H^2 - \delta m_H^2$

$m_W^{\circ 2} = m_W^2 - \delta m_W^2$

Subtract $\Pi(0)$ Goldstone Boson Self-Energy

Radiative Corrections $H \to \omega^+\omega^-$ $m_H^2 \gg m_W^2$

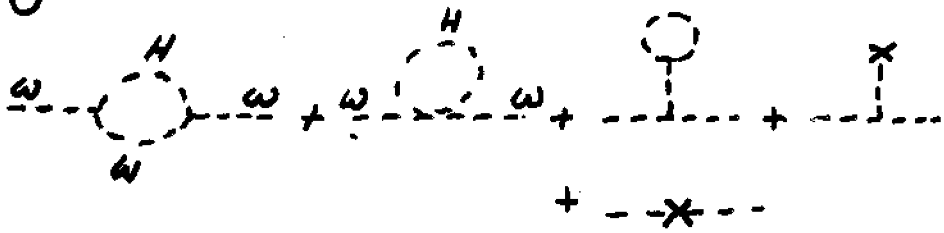


$$\frac{ig_{2o}}{2}\frac{m_H^{o2}}{m_W^o} = \frac{ig_2}{2}\frac{m_H^2}{m_W}\left\{1-\frac{\delta m_H^2}{m_W^2}+\frac{1}{2}\frac{\delta m_W^2}{m_W^2}\right\}$$

$$\frac{\delta m_W^2}{m_W^2} = \frac{g_2^2}{16\pi^2}\left(\frac{1}{8}\frac{m_H^2}{m_W^2}\right)$$ Finite Mass Counterterm

Scalar Self-Energies

$\omega\omega$ $\quad -i\Pi(q^2) =$



$$-i\Pi(0) = -i\frac{g_2^2}{16\pi^2}\frac{m_H^4}{m_W^2}\,\frac{3}{4}\left\{\frac{1}{n-4}-\ln\frac{\mu}{m_H}-\frac{1}{2}\right\}$$

HH $\quad -i\Pi_H(q^2) =$

$\Pi(0)$ counterterm

$$\delta m_H^2 = \mathrm{Re}\,\Pi_H(q^2)\Big|_{q^2=m_H^2} = \frac{g_2^2}{16\pi^2}\frac{m_H^2}{m_W^2}\left\{3\left(\frac{1}{n-4}-\ln\frac{\mu}{m_H}\right)-3+\frac{9\pi}{8\sqrt{3}}\right\}$$

$$Z_\omega^{1/2} = 1+\frac{g_2^2}{16\pi^2}\frac{m_H^2}{m_W^2}\left(-\frac{1}{16}\right)$$

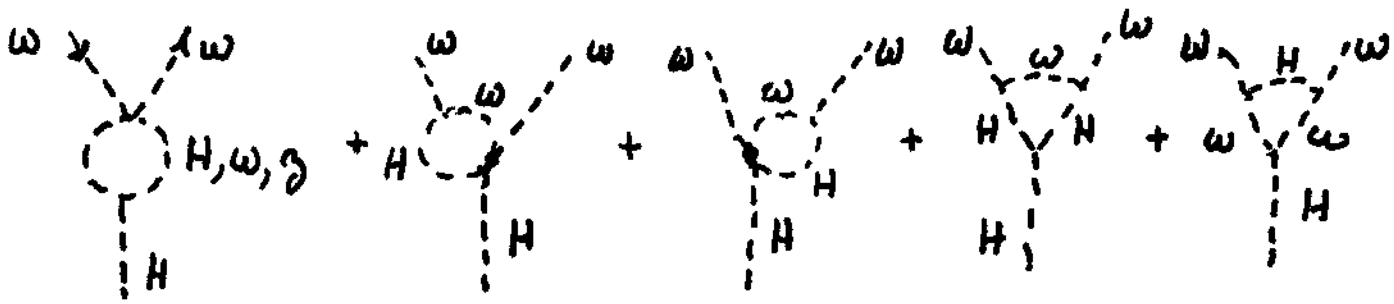
$$Z_H^{1/2} = 1+\frac{g_2^2}{16\pi^2}\frac{m_H^2}{m_W^2}\left(\frac{3}{4}-\frac{3\pi}{8\sqrt{3}}\right)$$

$$Z_H^{1/2}Z_W = 1+\frac{g_2^2}{16\pi^2}\frac{m_H^2}{m_W^2}\left(\underbrace{\frac{3}{4}-\frac{3\pi}{8\sqrt{3}}-\frac{1}{8}}_{\frac{5}{8}-\frac{3\pi}{8\sqrt{3}}}\right)$$

Total $\delta m_W^2,\ \delta m_H^2,\ Z_W,\ Z_H^{1/2}$

$$1-\frac{g_2^2}{16\pi^2}\frac{m_H^2}{m_W^2}\left(3\left(\frac{1}{n-4}-\ln\frac{\mu}{m_H}\right)-\frac{59}{16}+\frac{3\pi}{2\sqrt{3}}\right)$$

Proper Vertex Diagrams:



$$1+\frac{g_2^2}{16\pi^2}\frac{m_H^2}{m_W^2}\left\{3\left(\frac{1}{n-4}-\ln\frac{\mu}{m_W}\right)-\frac{5}{2}+\frac{3\pi}{8\sqrt{3}}+\frac{5\pi^2}{48}\right\}$$ divergence cancels

Total $-i\frac{g_2}{2}\frac{m_H^2}{m_W}\left(1+\frac{g_2^2}{16\pi^2}\frac{m_H^2}{m_W^2}\left(\frac{19}{16}-\frac{3\sqrt{3}\,\pi}{8}+\frac{5\pi^2}{48}\right)\right)$

$$\Gamma(H\to\omega^+\omega^-)=\frac{g_2^2}{64\pi}\frac{m_H^3}{m_W^2}\left(1+\frac{g_2^2}{8\pi^2}\frac{m_H^2}{m_W^2}\underbrace{\left(\frac{19}{16}-\frac{3\sqrt{3}\,\pi}{8}+\frac{5\pi^2}{48}\right)}_{0.175}\right)$$

cancellation

Even for $m_H \simeq 1\,\text{TeV}$, Rad. Corr. $\sim +15\%$

EW Equivalence Th. useful for strong WW scattering at H.E.

9.) Outlook + Conclusion

Standard Model Tested at Tree + Quantum Loop Levels

Works to $\pm 0.1\%$ EW Tremendous Success!

No Big Surprises Yet? (Heavy Top, Long τ_b, Neutrino Mass + Mixing, ...)

3 Prong Exp. Assault

E. Colliders - LHC (pp at 14TeV) $\rightarrow$ Higgs (Finally)
SUSY
Other?

e^+e^- LC - Precision Studies $H, W^\pm, Z$, SUSY
m_t ...

Lower Energy: e^-e^- (?), Atomic P.V., ep, $\nu_\mu e$ ..
Precision Measurements

Rare Effects: Proton Decay, e.d.m.s, $\mu \to e\gamma$, ... Dark Matter...
Revolutionary Neutrinos ...

You Can't Discover If You Don't Look

Good Luck