LECTURE 12: Z Boson Physics and Neutral Currents

Overview:

-Higgs Boson (cont.)

-Z width

-Problem set #2 (last problem)

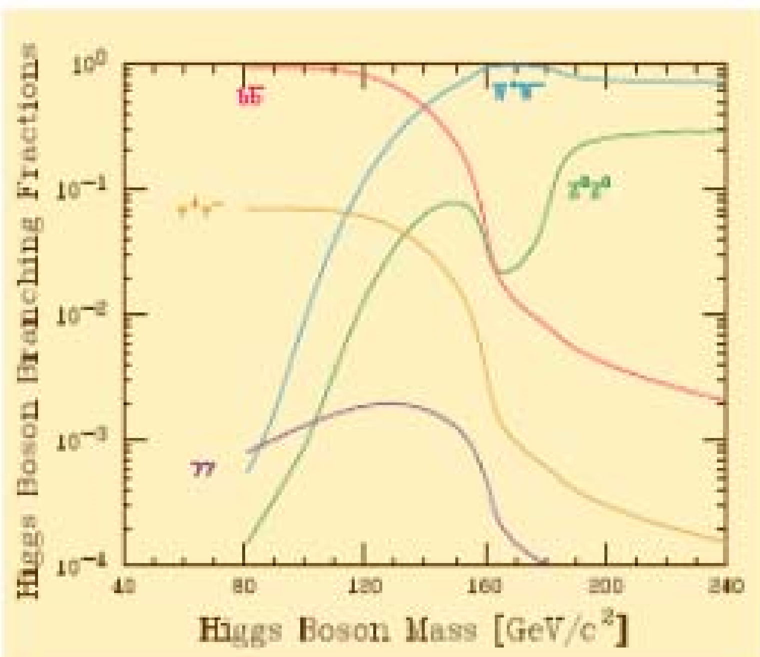
(I used Quigg, Griffiths, my thesis as references)

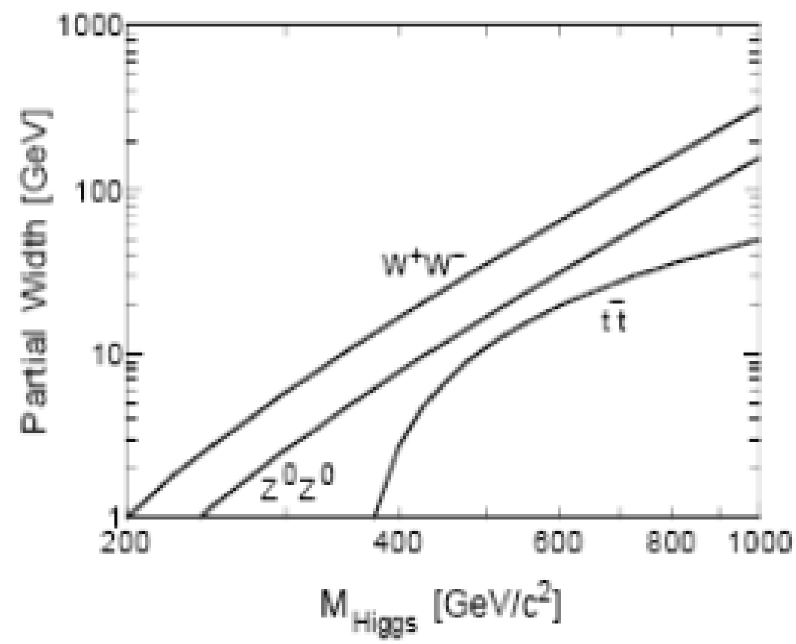
THE HIGGS BOSON (cont)

NOTES:

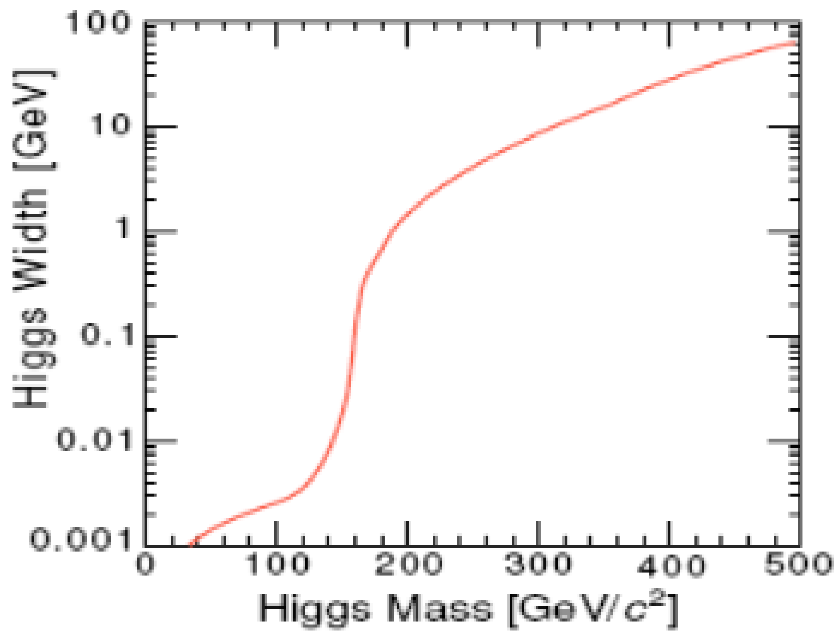
- in the limit where $M_H \gg M_W$, Γ becomes $\propto M_H^2 \cdot M_H$ instead of $M_F^2 \cdot M_H$ why?

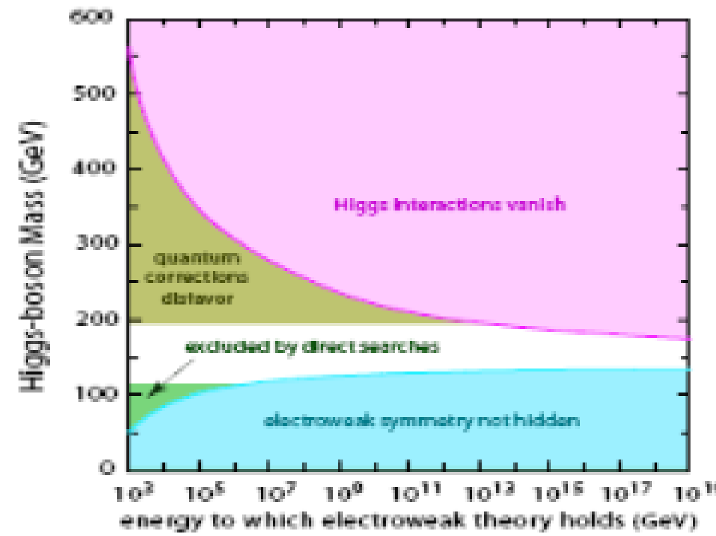
- Why do we set a factor of 1/2 for Z bosons? (The obvious answer does not tell the full story)





THE HIGGS BOSON (cont.)





$\boxed{\text{Theory limits on the Higgs}}$

Unitarity in $W^+W^- \to W^+W^-$ cross section imply that m_H should be $\lesssim 900$ GeV

$\to$ Higgs or new physics at 1 TeV ...

THE HIGGS BOSON (cont.)

TRIVIALITY : evolution of renormalized coupling given by :

$$\lambda_R(Q) = \frac{\lambda(v)}{1 - \frac{3}{2\pi^2}\lambda(v)\log\left(\frac{Q}{v}\right)}$$

$\lambda(v) \to 0$ when $Q \to \infty$ i.e. Trivial theory
free field theory

if Higgs potential valid up to 10^{16} GeV

the $m_H \lesssim 170$ GeV

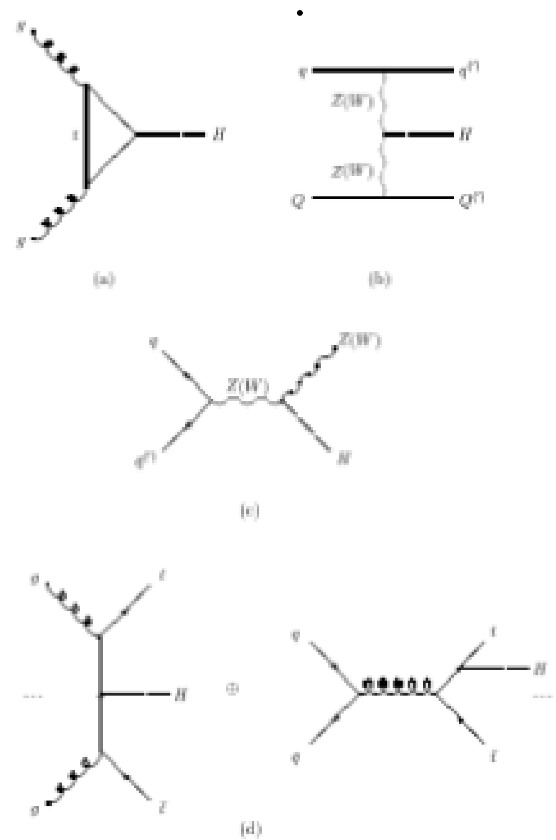
1 TeV $m_H \lesssim 640$ GeV

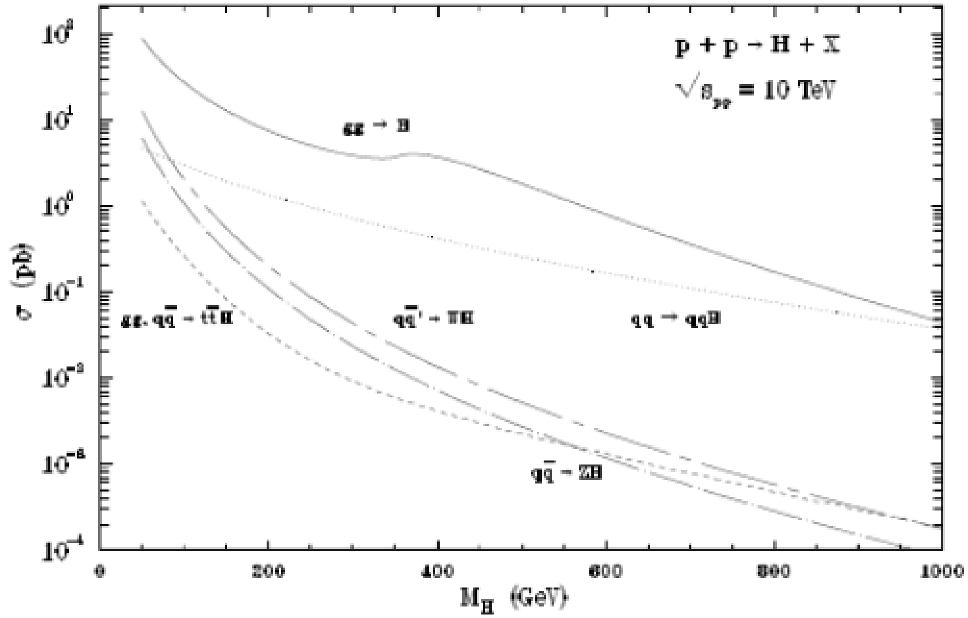
Vacuum stability :

$$V(\varphi) \sim \mu^2 \varphi^T\varphi + \lambda(Q_0)(\varphi^T\varphi)^2 + B_\lambda (\varphi^T\varphi)^2 \log\left(\frac{Q^2}{Q_0^2}\right)$$

SM valid up to Planck scale $\to$ $m_H \gtrsim 130$ GeV

Higgs production at the LHC

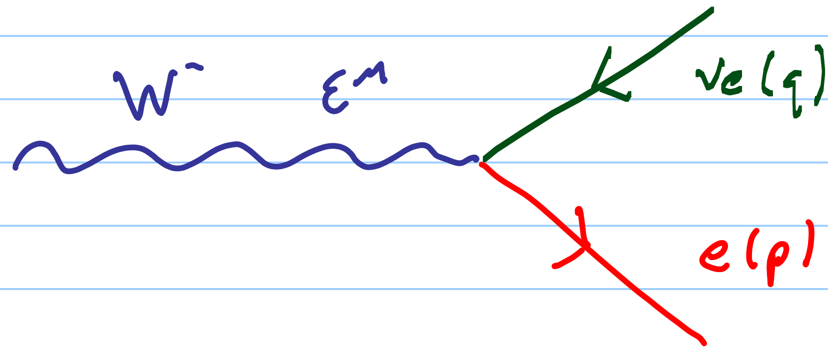




Let's look at slides from Chris Quigg, academic lectures part 5.

Z Boson Decay

A reminder from lecture 8 where we studied $W \to e\nu$:



$\to \bar{\nu}_e$ going forward, ν_e going backward

$$\mathcal{M} = -i\left(\frac{G_F M_W^2}{\sqrt{2}}\right)^{1/2} \bar{u}(p)\,\gamma_\mu\,(1-\gamma_5)\,v(q)\,\varepsilon^\mu$$

$\varepsilon^\mu \equiv (0, \hat{\varepsilon})$ is the polarization vector of the W

$\to$ we neglect the electron mass

$$|\mathcal{M}|^2 = \frac{G_F M_W^2}{\sqrt{2}} \,\mathrm{Tr}\left[\not{\varepsilon}\,(1-\gamma_5)\,\not{q}\,(1+\gamma_5)\,\not{\varepsilon}^*\,\not{p}\right]$$

$$= \frac{G_F M_W^2}{\sqrt{2}} \; 2\,\mathrm{Tr}\left[(1+\gamma_5)\,\not{\varepsilon}\,\not{q}\,\not{\varepsilon}^*\,\not{p}\right]$$

W decay

7

$$|M|^2 = \frac{8 G_F M_W^2}{\sqrt{2}} \left((\varepsilon \cdot q)(\varepsilon^* \cdot p) - (\varepsilon \cdot \varepsilon^*)(p \cdot q) + (\varepsilon \cdot p)(\varepsilon^* \cdot q) \right.$$
$$\left. + i \varepsilon_{\mu\nu\rho\sigma} \varepsilon^\mu q^\nu \varepsilon^{*\rho} p^\sigma \right]$$

let's pick the longitudinal polarization for the W: $\varepsilon^\mu = (0; 0, 0, 1) = \varepsilon^{\mu *}$ (helicity 0)

$\rightarrow$ the $\varepsilon_{\mu\nu\rho\sigma}$ term vanishes

$$p = \frac{M_W}{2}(1, \sin\theta, 0, \cos\theta)$$
$$q = \frac{M_W}{2}(1, -\sin\theta, 0, -\cos\theta)$$

$$|M|^2 = \frac{8 G_F M_W^2}{\sqrt{2}} \cdot \frac{M_W^2}{4} \left(-\cos^2\theta - -1 \cdot [1 + \sin^2\theta + \cos^2\theta] - \cos^2\theta \right.$$
$$= \frac{4 G_F M_W^4}{\sqrt{2}} \sin^2\theta$$

W Decay

$$\frac{d\Gamma}{d\Omega} = \frac{|M|^2}{64\pi^2 M_W} = \frac{G_F M_W^3}{16\pi^2\sqrt{2}} \sin^2\theta$$

$$d\Gamma = \cdot \frac{G_F M_W^3}{16\pi^2\sqrt{2}} \int_0^{2\pi} d\varphi \int_0^{\pi} \sin\theta \, \sin^2\theta \, d\theta$$

$$\text{int} = -\cos\theta + \frac{\cos^3\theta}{3} \Big|_0^{\pi} = 1 - \frac{1}{3} - (-1 + 1/3)$$

$$= \frac{2}{3} + \frac{2}{3} = \frac{4}{3}$$

$$\boxed{\Gamma = \frac{G_F M_W^3}{16\pi^2\sqrt{2}} \cdot 2\pi \cdot \frac{4}{3} = \frac{G_F M_W^3}{6\pi\sqrt{2}}}$$

$= 227$ MeV (For $M_W = 80.4$)
$G_F = 1.166 \times 10^{-5}$ GeV^{-2}

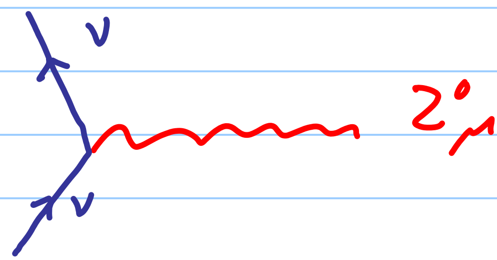
Total width: 2.06 GeV

Z DeCAY

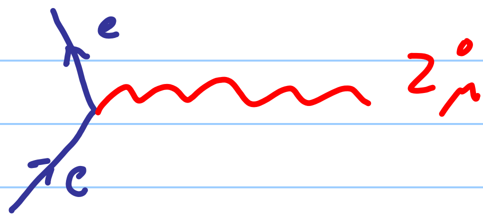
The W decay amplitude

$$\mathcal{M} = -i\left(\frac{G_F M_W^2}{\sqrt{2}}\right)^{1/2} \bar{u}(p)\,\gamma_\mu\,(1-\gamma_5)\,v(q)\,\varepsilon^\mu :$$

Needs to be modified for the Z given Feynman rules:



$$\frac{-i}{\sqrt{2}}\left(\frac{G_F M_Z^2}{\sqrt{2}}\right)^{1/2} \bar{\nu}\,\gamma_\mu\,(1-\gamma_5)\,\nu$$



$$\frac{-i}{\sqrt{2}}\left(\frac{G_F M_Z^2}{\sqrt{2}}\right)^{1/2} \bar{e}\,\gamma_\mu\left[2 s_W^2\,(1+\gamma_5) + (2s_W^2-1)\,(1-\gamma_5)\right] e$$

$$s_W = \sin\theta_W$$

So $Z \to \nu_e \bar{\nu}_e$ is straightforward:

$$|\mathcal{M}(Z\to\nu_e\bar{\nu}_e)|^2 = \frac{1}{2}\,\frac{M_Z^2}{M_W^2}\,|\mathcal{M}(W\to e\,\nu_e)|^2$$

$$\rightarrow \Gamma(Z\to\nu\bar{\nu}) = \frac{G_F M_Z^3}{12\pi\sqrt{2}}$$

Z DECAY (cont.)

$$\Gamma(Z \to e^+e^-) = \Gamma(Z \to \nu\bar{\nu})\left[(2\sin^2\theta_w - 1)^2 + (2\sin^2\theta_w)^2\right]$$

$$\boxed{\begin{aligned} &\left[2s_w^2 + 2s_w^2\gamma_5 + 2s_w^2 - 2s_w^2\gamma_5 - 1 + \gamma_5\right] \\ &= \left[2s_w^2 + (2s_w^2 - 1) - \gamma_5\right] \\ &\qquad \to \gamma_5 \text{ contribution will vanish as in } W \text{ case} \end{aligned}}$$

We have $M_W \simeq 80.4$ GeV

$\Gamma(W \to e\nu) \simeq 225$ GeV

$M_Z \simeq 91.2$ GeV

$\Gamma(Z \to e^+e^-) \simeq 84$ GeV

$\Gamma(Z \to \bar{\nu}_e\nu_e) \simeq 166$ GeV

note

How do we measure $Z \to \nu\bar{\nu}$?

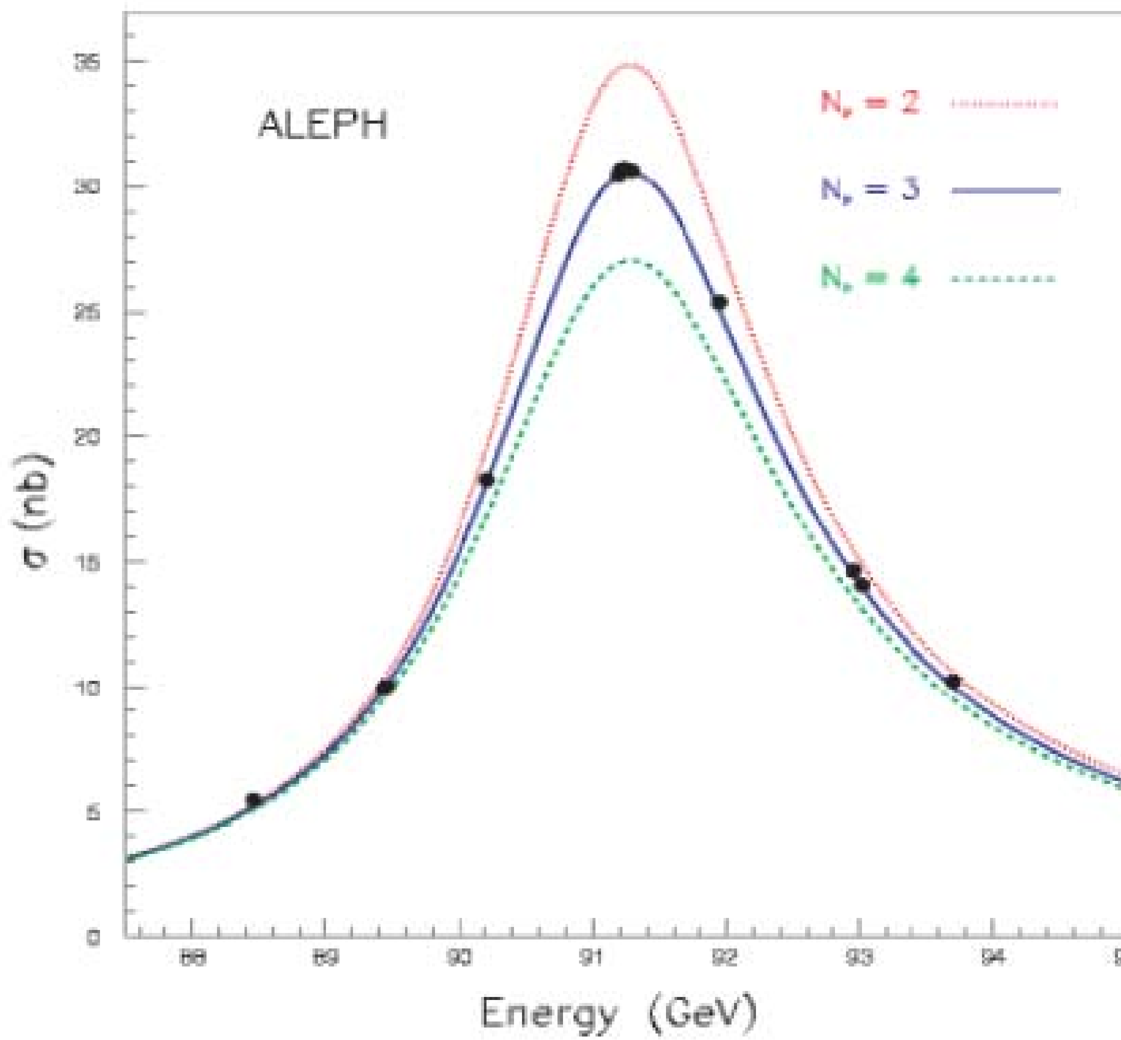
Z decay (cont.)

Most precise method is "indirect": look at Z lineshape:

Obtain Γ_{TOT} from lineshape. Subract Γ_{had}, $\Gamma_{e,\mu,\tau}$ and

get $\Gamma_{inv} \sim 500$ MeV

$\Rightarrow$ 3 neutrino families below $\frac{M_Z}{2}$



Z Boson PHysics

Problem set #2 problem #3

→ Calculate $\sigma\,(e^+e^- \to Z \to \mu^+\mu^-)$

Problem set #2 has 3 problems and due date is thursday March 13 1pm