

**PHZ 6358: Standard Model I**  
**Fall Term 2015**  
**Homework Set 5**

Due Friday, November 13, 2015

**Reading:** CalcHEP manual; S. Dawson, “The SM intermediate Higgs boson”, hep-ph/9703387.

**Note:** This is a lengthy assignment, so start working on it early. You may choose to work with one or several partners, but do specify this on your writeup. Also, if you need extra time, you may work on it up to Thanksgiving.

**Problem 1. Input parameters in CalcHEP.** Let us critically review the values of the default input parameters in CalcHEP. Browse through the *Particles* and *Parameters* lists. Are there any inputs whose values need to be updated? If so, make a list of those, with their correct values. Notice that the default for the Higgs mass is  $m_h = 120$  GeV. What is the value of the Higgs width?

**Problem 2. Higgs interactions in CalcHEP.** Using your favourite source for the SM Feynman rules (e.g. textbook, lecture notes from the Field Theory class, etc.) check that the Higgs interactions in Table *Lagrangian* are programmed correctly. Check for both their structure and the prefactor.

**Problem 3. Higgs boson branching fractions.** For the range of Higgs masses  $100 < m_h < 400$  GeV, plot:

- (a) the Higgs boson partial widths to  $b\bar{b}, \tau^+\tau^-, c\bar{c}, s\bar{s}, \mu^+\mu^-, W^+W^-, ZZ$  and  $t\bar{t}$ ;
- (b) the total Higgs boson width  $\Gamma_h$ ;
- (c) the branching fractions for the final states listed above.

Based on the results from parts (a) and (b), justify qualitatively the result of part (c).

Hint: In order to select all two body final states simultaneously, type  $2*x$  for the final state.

**Problem 4. Higgs boson production cross-section at an  $e^+e^-$  collider.** Reproduce the analogue of Fig. 13 from hep-ph/9703387, but use only one (the measured) value for the Higgs mass:  $m_h = 125$  GeV. (Did you change the default value of  $\Gamma_h$ ? Why?)

Hint: As a sanity check you may want to check for a single value of  $E_{CM}$  that your answers agree with those in Fig. 13 for  $m_h = 100$  or  $m_h = 200$  GeV.

**Problem 5. Triple gauge boson couplings.** The LEP experiments have measured the energy dependence of the total  $W^+W^-$  cross-section, i.e.  $\sigma(e^+e^- \rightarrow W^+W^-)$  as a function of the CM energy of the collider  $\sqrt{s}$ .

- (a) Dig out the relevant plot from the web.
- (b) Then use CalcHEP to prove the existence of the Non-Abelian triple gauge boson coupling ( $WWZ$ ).

**Problem 6. Higgs production at the Tevatron.** The main production process used for a discovery of a light ( $m_h < 140$  GeV) Higgs boson at the Tevatron is  $p\bar{p} \rightarrow Wh$ . In this exercise we shall calculate its cross-section using CalcHEP.

(a) Start up CalcHEP and generate the diagrams for  $p\bar{p} \rightarrow W^+h$  and  $p\bar{p} \rightarrow W^-h$ . Without doing any calculations, try to guess and rank the first few dominant subprocesses according to their importance.

(b) Calculate the cross-section for  $p\bar{p} \rightarrow W^\pm h$  at the Tevatron ( $E_{CM} = 2$  TeV) as a function of the Higgs mass  $m_h$ , for  $100 < m_h < 200$  GeV. *Hint: The cross-section is a slowly varying function of  $m_h$ , so you will only need to compute it at 3-4 points.*

(c) Check your guesses from (a) against the numerical results from (b).

**Problem 7. Higgs production at the Tevatron: signal versus background.** For a Higgs discovery in  $p\bar{p} \rightarrow Wh$  at the Tevatron, one makes use of the decays  $W \rightarrow \ell\nu$  and  $h \rightarrow b\bar{b}$ . The final state signature is therefore  $\ell\nu b\bar{b}$ . The main background is  $Wb\bar{b}$  production, where the  $b$ 's were produced through a gluon, photon or a  $Z$ . On the same plot, show the  $b\bar{b}$  invariant mass distribution  $M_{b\bar{b}}$  for the  $Wh$  signal and the  $Wb\bar{b}$  background. Notice that because of the very small Higgs width  $\Gamma_h$ , the signal will peak very sharply at  $M_{b\bar{b}} = m_h$ . In reality, however, the energy of the  $b$ -jets is not perfectly measured, which results in an uncertainty in  $M_{b\bar{b}}$  of order 10%. An easy way to account for the poor mass resolution and thus make our plot more “realistic”, is to simply inflate the Higgs width  $\Gamma_h$  to  $0.1m_h \sim 12$  GeV.

*Hint: You may need to use the option “regularization” to constrain  $M_{b\bar{b}}$  near the  $s$ -channel gluon, photon,  $Z$  or  $H$  resonances.*

**Problem 8. Playing with CalcHEP. [Optional, recommended for HE theorists]** Use the analytical tools in CalcHEP to verify some of the results from Chapter 5 of Peskin&Schroeder. Try to make as many cross-checks of the final answers as you can think of. Consider

(a)  $e^-\mu^- \rightarrow e^-\mu^-$ .

(b) Compton scattering.

(c) Pair annihilation.

(d) Bhabha scattering. *Hint: Be careful to regulate the cross-section by using a cut on the forward angle  $\theta$ .*

(e)  $e^+e^- \rightarrow \gamma + B$  from problem 5.5.