Middle East Technical University

Department of Physics

Advanced Selected Problems in Physics

# Studying Selected Tools for HEP: CalcHEP

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**Abstract**

CalcHEP has been introduced as a computational tool for high energy physics. Some basic examples argued in order to learn the usage of the package which prepared as a tutorial of CalcHEP. Higgs' two and tree body decay channels analysed and interpreted by using gnuplot alongside with CalcHEP. Also higgs production has been analysed, four main production channels argued. Batch mode example has been done by adding higgs decay to production from glue – glue fusion.

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# Introduction

With recent developments in High Energy Physics and accelerator technology, calculations needed to be more and more precise each and everyday. This brought higher order approximations in the equations and it become harder, even impossible to solve in certain cases. More and more different processes needed to be dig in which takes hours, maybe days.

Computational developments tent to decrease this time and user inaccuracies. They developed to calculate all possibilities, reveal to user, eliminate unnecessary processes, simulate experiment before doing it and draw diagrams which needed to measure. CalcHEP is just one of these packages and relatively basic one. By understanding CalcHEP user can easily adapt and use the other ones which are GRACE, HELAS, CompHEP, FeynArts-FormCalc, MADGRAPH, HELAC-PHEGAS, O'MEGA, WHIZARD and SHERPA. These are other packages that used in HEP. Some of them have more developed calculation system such as calculating higher order perturbations. However they are not user-friendly as CalcHEP which uses menu driven interface. In preceding sections one will see the features of CalcHEP in detail. In this section one will see an introduction of CalcHEP; usage, features, installation, user interface and some instructive examples to run CalcHEP. In Section 1; some needed knowledge is briefly reminded and in Section 2; Higgs decay channels analysed by using CalcHEP.

## 0.1 What is CalcHEP?

CalcHEP is a package that allows user to calculate elementary particle collisions and decays in the lowest order perturbation, calculates Feynman diagram integrations over multi-particle phase space and generate events. It includes most of the model Lagrangian's, such as Standard Model (SM), SM CKM=1 and SM CKM=1 with Higgs. Where CKM is the quark transformation matrix.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$CKM = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \tag{0.1}$$

where $V_{ud}$ for instance is the coupling constant of; Some further models are available at CalcHEP's

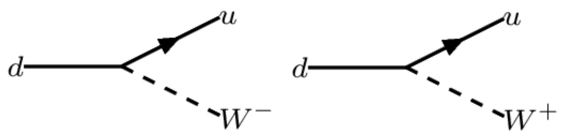



Figure 0.1: Where the diagram at left hand side is represented by $V_{ud}$ and right hand side represented by $V^*_{ud}$

*website*.

CalcHEP allows user to evaluate any decay and scattering processes within any user defined model, which means that user can change the source of model and easily apply new Lagrangian. By easy user interface, even without knowing any programming language, user can calculate lots of processes.On the other hand, it limited by tree-level processes, it does not include spin informations for out going particles and it has limitation on number of outputs and number of diagrams.

## 0.2 Installation

CalcHEP uses non-profit licence thus everyone can download it through

```
http://theory.sinp.msu.ru/~pukhov/calchep.html
```

The current file name is

```
calchep_3.4.3.tar.gz
```

by using the code below the file can be installed in to the directory. Note that it should be installed to the desired place such as packages/ under the home/ directory.

```
tar -xzf calchep_3.4.3.tar.gz
```

Now, the calchep directory has been formed. This directory includes following subdirectories:

- c_sources/: Includes the source codes of CalcHEP.
- lib/: The place that includes libraries during compilation.

- bin/: Contains executable scripts and binary files.
- pdTables/: Includes the tables of parton distribution functions.
- models/: Includes the models such as SM.
- work/: This is the directory that leads user to the interface.

In order to compile the calchep following script should be run from terminal.

```
cd calchep_3.4.cpc/
gmake
```

If needed files does not exists in the users computer, instead of gmake, make may the do the job. Now , in order to form the work directory user needs to copy the files of work/ directory to the desired place by using

```
./mkWORKdir ../name
```

Thus now by using ./calchep script the program can be initialized of course while user is in the <name> directory. For further information: [2, 5].

## 0.3 User Interface

CalcHEP has menu based user interface that allows easier control. One can see the CalcHEP's symbolic section menu chart from Figure 0.2. CalcHEP allows user to move around menu by only

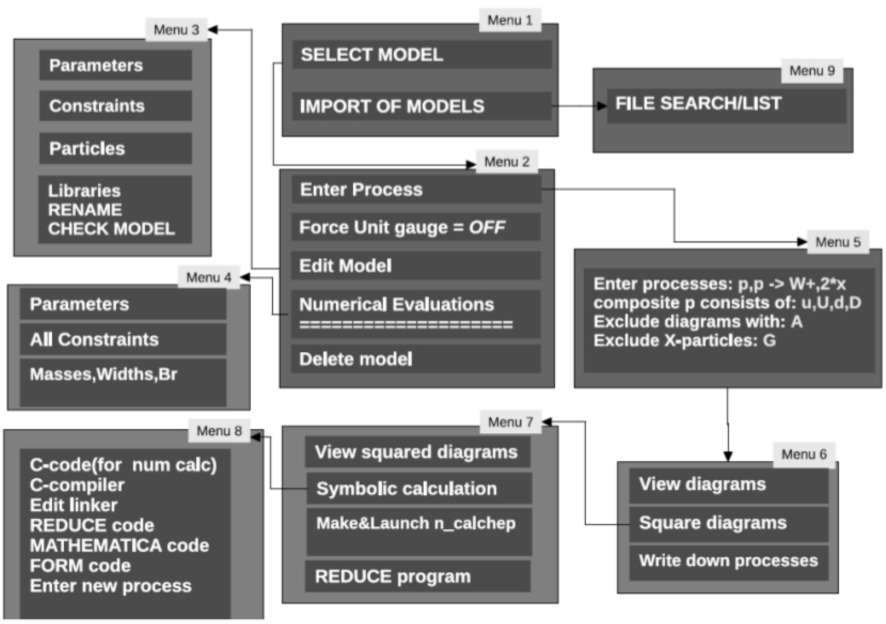



Figure 0.2: Menu table of CalcHEP for symbolic session . Taken from [2].

using mouse clicks, PgUp/PgDn, enter, escape and some F buttons for some specific functions such as:

- F1: Help
- F2: Manual
- F3: Models

- F4: Shows the Feynman diagrams for current process.
- F6: Allows user to edit the output files.
- F9: CalcHEP website.
- F10: Quit

Help section gives specific information for the current page. For instance, by entering results directory and using

```
./n_calchep
```

user can enter the numerical session of CalcHEP then, lets say user wants to edit cuts of the process, but does not know how to use the scripts. By selecting cuts and F1 one can display the scripts for that section and usage of each script. Now let us briefly analyse the symbolic and numerical section than carry out a simple example from [2].

### 0.3.1 Symbolic Calculation

By using;

```
./calchep
```

one can open the CalcHEP's Symbolic session. The first screen is the Model Choice and manipulation section. It allows user to chose best model that fits the process most. Additional models can be added by downloading or by changing scripts of the models. The second screen is model editing and process entering part basically by entering the "Enter Process" user can see the notation of particles and by writing the process it can be done. After entering the process Diagram screen will show up. User can view both ordinary and square diagrams and can download to a folder as a tex file. In the example part one can see how to apply these to a basic process.

### 0.3.2 Numerical Session

This session allows user to calculate branching ratios, decay width, simulation of these, preparing Monte Carlo simulations and also arrange cuts, phase space mapping, QCD coupling, constraints etc.. (see Figure 0.3) Here is some of the basic parts that beginner users need.

## 0.4 Some Examples on CalcHEP's Features

Let us work on an example from [2] to understand the basic usage of CalcHEP. Now by opening symbolic session of CalcHEP, choose SM and enter the following process;

```
Enter Process: p,p->W+,b,B
composite 'p' consists of: u,U,d,D,s,S,c,C,b,B,G
composite 'W' consists of: W+,W-
Exclude diagrams with: W+>2,A>1,Z>3
```

This will calculate the p-p collision without taking in to acount the processes have more than two $W^+$, one $\gamma$ and tree Z. By pressing enter one can proceed to the next screen which have view diagrams, square diagrams and write down process parts. User can view the diagrams and print them out as tex file by pressing "l" (see Appendix A). With the same manner user can view the square diagrams. By selecting square diagrams user can construct 5076 diagram in a

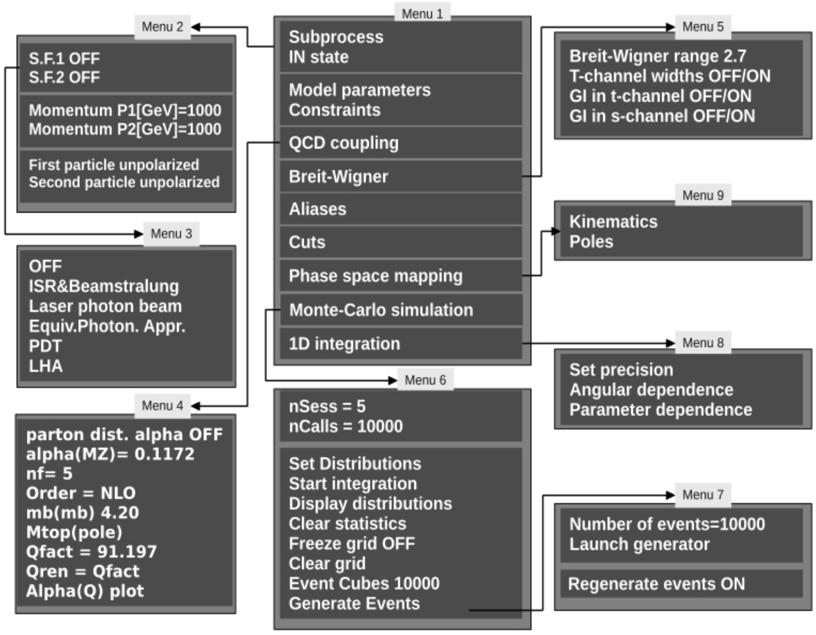



Figure 0.3: Menu table of CalcHEP for numerical session. Taken from [5].

short notice. Now, let us proceed to numerical session by selecting symbolic calculation (it may take a while) and then select C-compiler. After a long wait numerical session will show up.

This window it the numerical part of CalcHEP. User can arrange the date as needed and take branching ratio graphs, Monte Carlo simulations etc. User can view the sub-processes by selecting it. Now let us proceed to in state and do following arrangements;

```
S.F.1: PDT:cteq6m(proton)
S.F.2: OFF
First  particle momentum[GeV]  = 7000
Second particle momentum[GeV]  = 7000
First  particle unpolarized
Second particle unpolarized
```

This way user can get the same conditions with LHC. By selecting QCD coupling and doing the following changes user can arrange strong interaction coupling constant.

```
alpha(MZ)=  0.1172
Mtop(pole)= 175.00
```

Note that Breit-Wigner section is the part that get rid of the singularities. Let us define aliases as;

```
Jet   |u,U,d,D,s,S,c,C,G
```

which construct the jets in out parton distribution. Note that pressing ESC will save your changes and turn back to numerical session. Now, let us arrange cuts as follows, which arrange our jet cone angle, pseudo-rapidity of the particle set and transverse momentum of the particle set.

```
Parameter |> Min Bound <|> Max bound
T(b)      |20             |
```

```
T(B)       |20          |
N(b)       |-5          |5
N(B)       |-5          |5
J(b,B)     |0.5         |
```

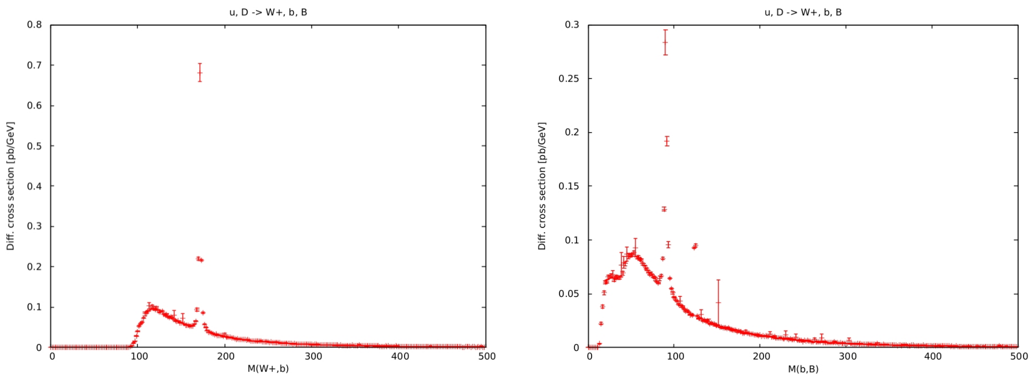
Now arranging the phase space mapping and setting regularization part as;

```
Momentum  |> Mass <|> Width <| Power
45        |MZ      |wZ       |2
45        |Mh      |wh       |2
34        |Mtp     |wt       |2
35        |Mtp     |wt       |2
```

Then by selecting Monte Carlo simulation and setting distributions as;

```
Parameter_1|> Min_1<|> Max_1
M(W+,b)     |0        |500
M(b,B)      |0        |500
```

and after starting integrations let us display the distributions by selecting $M(W+, b)$ and then 300 and same with $M(b, B)$, will give us the following graphics: In the Figure 0.4(b) one see tree




(a) Differential Cross Section vs Mass of W and b.

(b) Differential Cross Section vs Mass of b and $\bar{b}$.

Figure 0.4: Graphs from the process of $p + p \longrightarrow W^+ + b + \bar{b}$.

peaks 90 GeV, 125 GeV and 170 GeV where b$\bar{b}$ comes from Z, higgs and top quark respectively. On the other hand, in the Figure 0.4(a) one sees only one peak which is at 170 GeV which comes from decay of top quark.

# 1 Terminology

## 1.1 Decay Width

Decay width is basically the uncertainty of the particle, if we are talking about a decay process. If one take a particle, say electron, as a wave packet, which it is, the width of the wave packet shows the stability of the particle. For electron the wave packet is Dirac-Delta function which gives a singularity. The decay rate, $\Gamma$, the probability per unit time that any given particle will disintegrate.

$$\frac{dN(t)}{dt} = -\Gamma N(t) \Rightarrow N(t) = N(0)e^{-\Gamma t}$$

where N(t) is the number of the particles we have. Thus we can conclude that lifetime of a particle defined as;

$$\tau = \frac{1}{\Gamma_{tot}}$$

we have $\Gamma_{tot}$ there because particle may decay in many different channels. For Kaon, for instance

$$K^+ \begin{cases} \mu^+ + \nu_\mu & : \Gamma_1 \\ \pi^+ + \pi^0 & : \Gamma_2 \\ \pi^+ + \pi^+ + \pi^- & : \Gamma_3 \\ e^+ + \nu_e + \pi^0 & : \Gamma_4 \end{cases} \tag{1.1}$$

Thus the decay width is;

$$\Gamma_{tot} = \sum_i^N \Gamma_i = \Gamma_1 + \Gamma_2 + \Gamma_3 + \Gamma_4$$

### 1.2 Branching Ratio

Branching ratio is the probability for each decay channel, if we are talking about decays of course. As we displayed decay width from Kaon in equation (1.1),

$$K^+ \begin{cases} \mu^+ + \nu_\mu & : 69\% \\ \pi^+ + \pi^0 & : 21\% \\ \pi^+ + \pi^+ + \pi^- & : 6\% \\ e^+ + \nu_e + \pi^0 & : 5\% \end{cases}$$

where the percentages are the probability of detecting that particular decay channel. This shows that branching ratio is defined as;

$$BR_1 = \frac{\Gamma_1}{\Gamma_{tot}}$$

## 2 Two and Tree Body Decay Channels of Higgs Boson

In this part Higgs decay has been analysed by using CalcHEP and compared with experimental data. According to the SM Higgs Boson has tree different possible decay channel type such as;

$$h \longrightarrow 2 * x \tag{2.1a}$$

$$h \longrightarrow WW^* \longrightarrow Wl\nu_l \tag{2.1b}$$

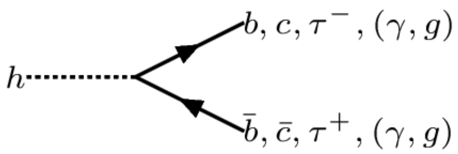
$$h \longrightarrow ZZ^* \longrightarrow Zl^+l^- \tag{2.1c}$$

where $2*x$ denotes for two body decays of Higgs such as b,c, $\tau$, ($\gamma$, g)[1] and anti-pair of these. Also $W^*$ and $Z^*$ are elements of sub-process which one wont detect and $l$ corresponds to leptons, $\nu_l$ is neutrino of corresponding lepton. CalcHEP is able to draw these processes in LaTeX(for details see Appendix A) for general processes equations (2.1a) and (2.1b) goes as follows; where as mentioned before the parenthesis in Figure 2.1(a) includes different sub-processes (see footnote 1). Also CalcHEP calculates all possible channels of process such as; As one can see from Figure 2.2 the first diagram middle Z is member of sub-process which shown as $Z^*$. Also the square diagrams can be drawn, for instance the square diagram of Figure 2.1(b) is drawn in Figure 2.3;

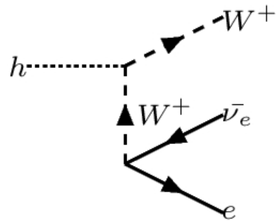
By using CalcHEP we analysed two body decays of Higgs[2]. For this we choose SM CKM=1 and we defined process as

[1] Note that $\gamma$ and g is in parenthesis because their decay has different sub-processes, for instance photon's sub-process includes tree $\tau$. And also one should also note that they don't have anti-pairs

[2] One can not analyse both tree and two body decays at the same time.




(a) Feynman diagram of two body decay of Higgs. Note that $t$,$\bar{t}$ decay does not included, since we know that $M_{t\bar{t}} \simeq 346.14\ GeV$ and Higgs has been predicted to be about $125\ GeV$ we don't need to look that far.




(b) Feynmann diagram of $WW^*$ decay channel of Higgs. Note that there can be any lepton instead of electron. Of course diagram will change accordingly.

Figure 2.1: Generalized Feynmann diagrams of Higgs decay

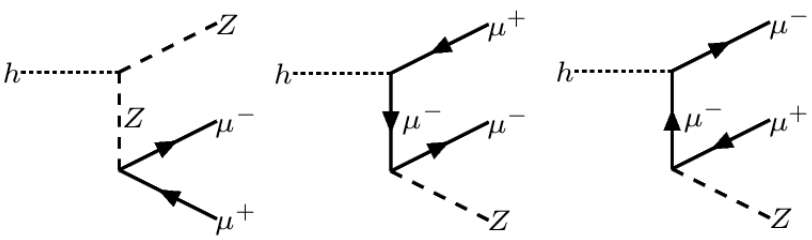



Figure 2.2: These are tree possible channels of Z$\mu$ decay channel of Higgs.

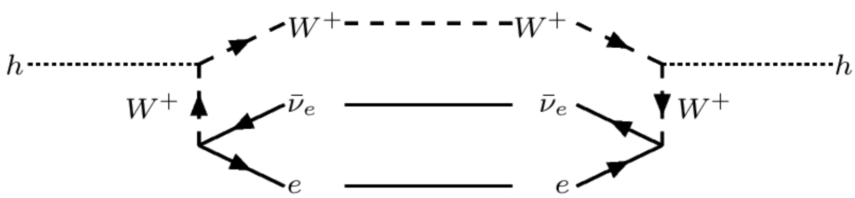



Figure 2.3: Square diagram of Figure 2.1(b)

```
Enter Process: h->2*x
```

without excluding anything, one can see the possible decay diagrams which are t, b, c, $\tau$, $\mu$, W, Z. By clicking enter for each process Feynman diagrams can be observed and by simply clicking ”l” LaTeX files of each can be written in to the result file.

SM suggests tree possible mass region which Higgs can be seen, which is Light $M \leq 120\ GeV$, Middle $120\ GeV \leq M \leq 160\ GeV$ and Heavy $M \geq\ 160 GeV$. In order to make these decay channels possible kinematically, the mass of Higgs should be greater than those of total mass of outputs. Thus in Light region we have;

$$M_h \begin{cases} \geq M_{b\bar{b}} \simeq\ 8.36\ GeV \\ \geq M_{c\bar{c}} \simeq\ 2.55\ GeV \\ \geq M_{\tau^+\tau^-} \simeq\ 3.55\ GeV \end{cases} \tag{2.2}$$

at the Middle region we have;

$$M_h \begin{cases} \geq M_{WW^*} \simeq\ 160.8\ GeV \\ \geq M_{ZZ^*} \simeq\ 182.4\ GeV \end{cases} \tag{2.3}$$

and since Heavy region is to large to seek Higgs its unnecessary to investigate in that region. On the other hand, each region has their pros and cons. LHC works at strong interaction region thus the Light and Middle regions has lots of noise due the jets from proton proton collisions. Thus It’s hard to detect Higgs decay in that region. Heavy region includes vector bosons, thus It’s in the electroweak region which have less noise. For instance, for proton-proton collusion if one exclude all the results but b, $\bar{b}$, W we get these possibilities; as one can see from Figure 2.4,

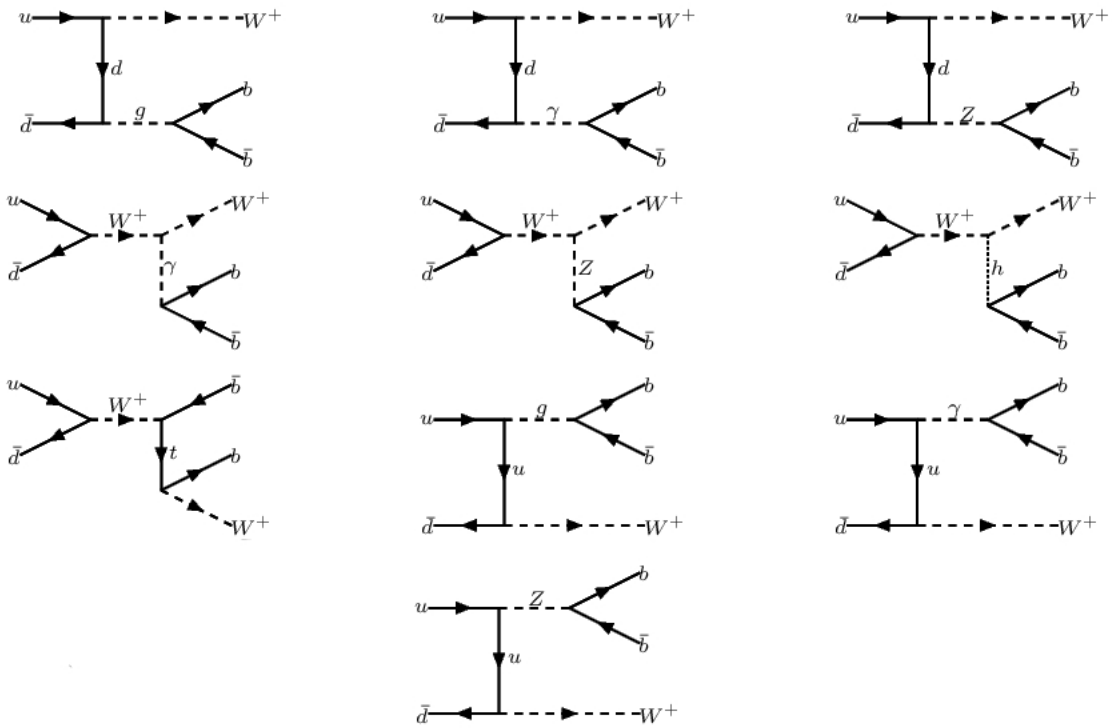


Figure 2.4: $p + p \longrightarrow W + b + \bar{b}$

there is only 10% probability to have b, $\bar{b}$ from Higgs decay. And from

$$p + p \longrightarrow Z + b + \bar{b}$$

one gets 22.2% of decays from Higgs. This supports the noise claim at Light and Middle regions.

We calculate the branching ratios of higgs decay channels by combining each process under gnuplot. Note that CalcHEP does not do both two and tree body decays at the same time thus when user do the two body decays program calculates the branching ration with respect to that. Thus while adding tree body decays to the data user should redefine the branching ratios by using decay width of the each process. After arranging these by series of codes, as expected we get Figure 2.5. One can see that just at the end of the Middle region, $WW^*$ channel started.

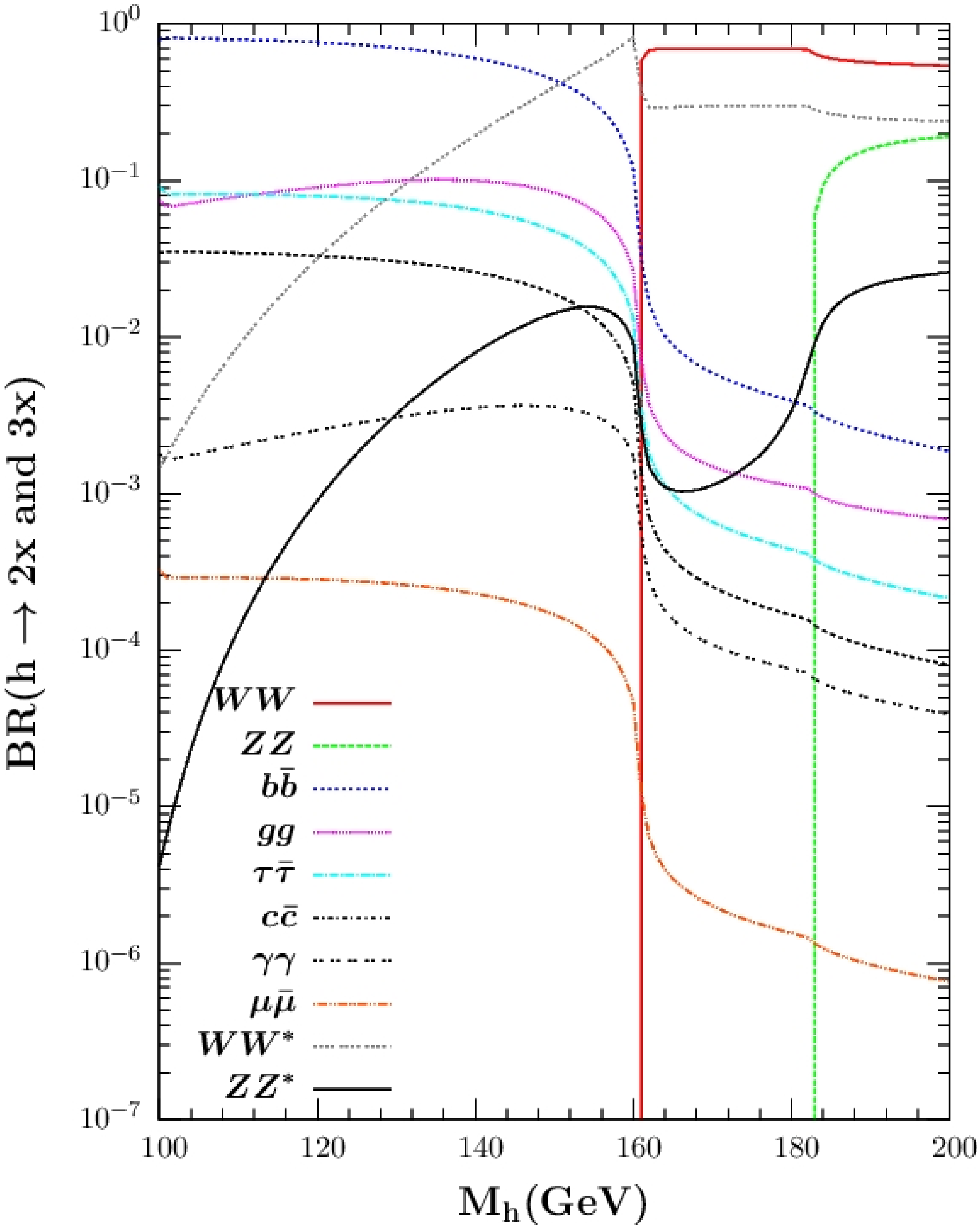



Figure 2.5: Branching Ratio vs Mass of Higgs.

As mentioned in equation (2.3), the mass of $WW$ is about 160.77 GeV. Thus the probability of finding other processes are decreased and about 182.38 GeV $ZZ$ channel started and again others decreased. Note that $WW^*$ and $ZZ^*$ are increased with $ZZ$ and $WW$ which means that these have contribution to each other processes. If one extends the graph through 300 GeV, $t\bar{t}$ channel will start and others probability will start to decrease.

In order to see the dominance of processes user can focus to a certain mass value, between 120-130 GeV for instance. Thus by simply changing codes parameters in gnuplot we get; User

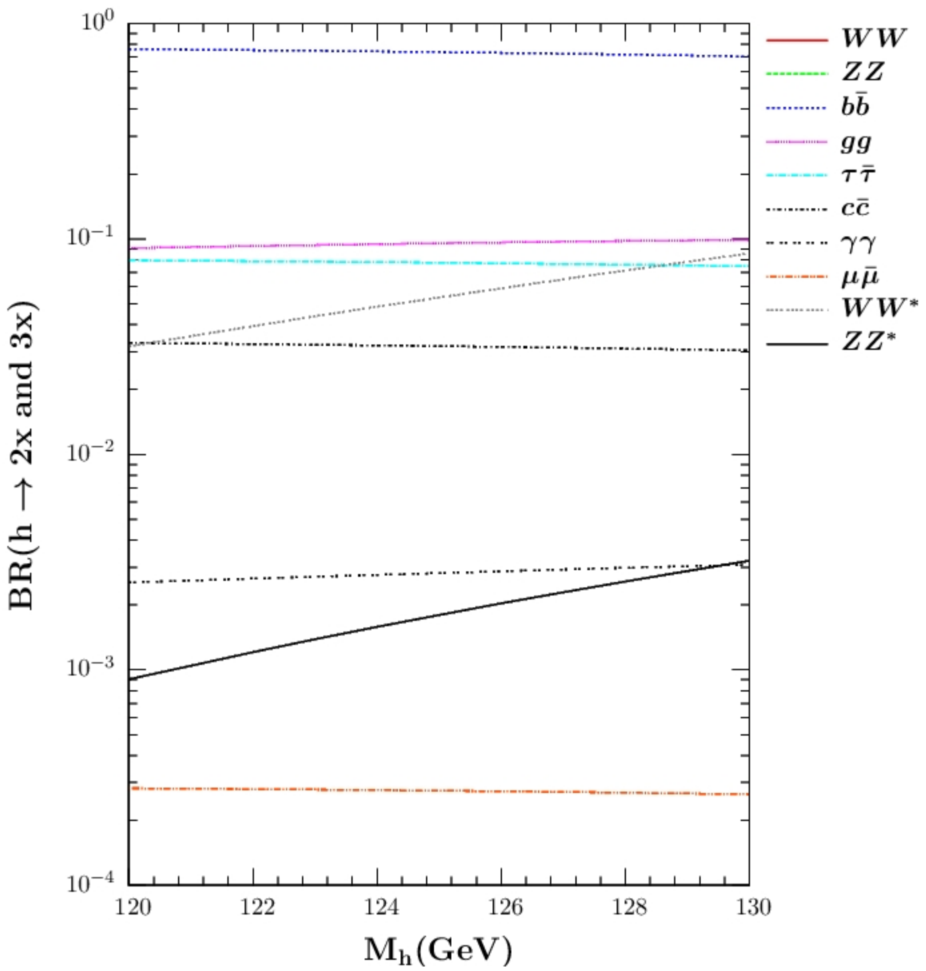
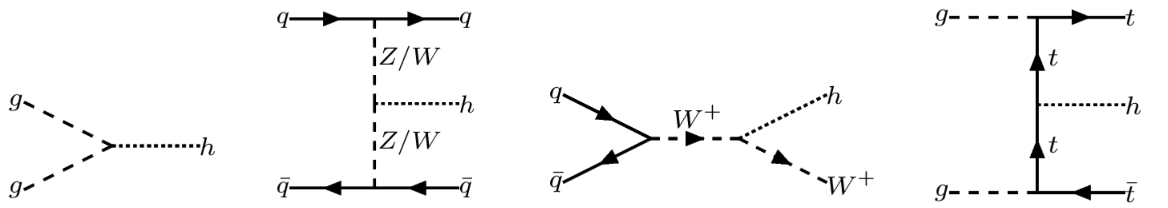



Figure 2.6: Branching Ratio vs Mass of Higgs.

can see the dominance of $b\bar{b}$ in that energy region thus before doing the experiment we know which channel to see most in which energy region.

# 3 Standard Model Higgs Production

Among many, there are four main production channels in proton – proton collisions for a center of mass energy of 14 TeV. Figure 3.1 shows these production channels. Gluon fusion, Figure 3.1(a), is the dominant process over the whole mass spectrum. It includes loop of top quarks ($tt\bar{t}$), note that top quark has 35 times strong Higgs coupling than other heaviest quark, bottom, due to it's mass. The other dominant channel is Vector Boson fusion, Figure 3.1(b), due to exchange of W/Z boson between two quarks, process has been able to produce higgs. After vector boson fusion, associative production with W, Figure 3.1(c), comes forth which includes one off-shell and one on-shell W boson. And the last one is associative production with a top pair, Figure 3.1(d).Even though the associative productions has lower branching ratios than fusion channels they have clear signatures which can be used for Middle mass region. As done in previous section for higgs decay channels, since we are not able to produce all the production channels at once,




(a) Gluon fusion diagram. Note that there should be a loop which is totally dominated by the top quark due to the strong Higgs coupling to the heavy top quark.

(b) Vector boson fusion

(c) Associative production with W where W can be + or - depending on initial quark pair.

(d) Associative production with a top pair. Note that it can also be a quark pair.

Figure 3.1: Four main Higgs production channels.

we run CalcHEP for all possible channels such as;

$$gg \longrightarrow h\ ,\ b\bar{b} \longrightarrow h\ ,\ q\bar{q} \longrightarrow Wh\ ,\ q\bar{q} \longrightarrow Zh\ ,\ q\bar{q} \longrightarrow q\bar{q}h\ ,\ pp \longrightarrow t\bar{t}h\ ,\ q\bar{b} \longrightarrow q\bar{t}h \tag{3.1}$$

Note that, pp indicates a quark or gluon pair. Now by combining these branching ratios and scale, one will end up with following graph. As expected since gluon fusion offers strong higgs

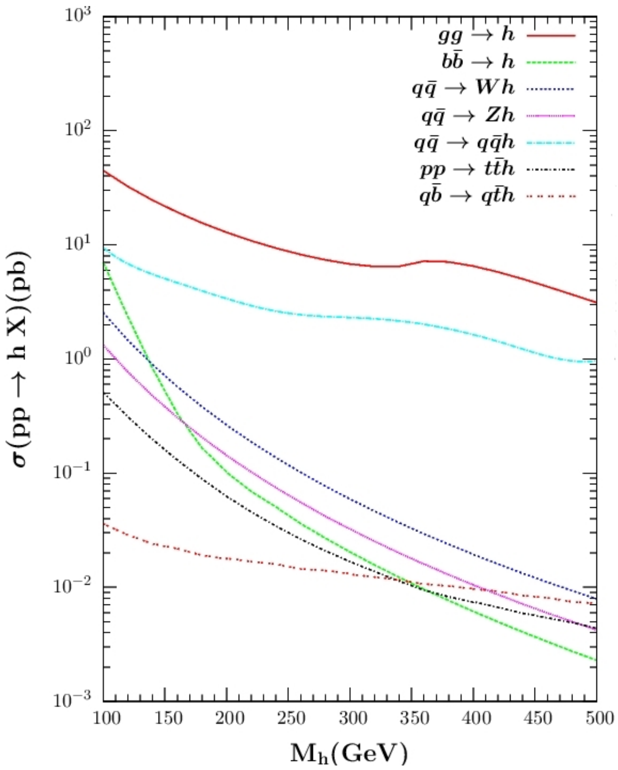



Figure 3.2: Standard Model Higgs Production.

coupling it includes greatest branching ratio.

# 4 Batch Mode: Four-Body Decay Channel of Higgs Boson

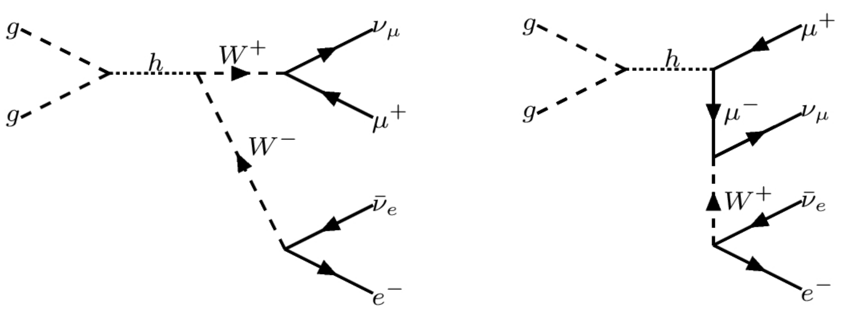
Batch mode offers user several usefulness. Due to python script, which form the basis of batch mode, by defining the capacity of computers CPU user can use computer with parallel computing system more effectively. User can define more than one process and generate events accordingly, such as;

```
###############################################
#  Process Info                               #
#  Process specifies the process.  More than  #
#       one process can be specified.  Cuts,  #
#       regularization and QCD scale should   #
#       be specified for each one.            #
#  Decay specifies decays.  As many decays    #
#       as are necessary are allowed.         #
#  Composite specifies composite particles    #
#       present in the processes or decays.   #
###############################################
Process:   p,p->W,b,B
Decay:     W->le,n
Composite: p=u,U,d,D,s,S,c,C,b,B,G
Composite: W=W+,W-
Composite: le=e,E,m,M
Composite: n=ne,Ne,nm,Nm
Composite: jet=u,U,d,D,s,S,c,C,b,B,G
```

Here, W,b and $\bar{b}$ has been produced through proton collusion then W decayed to a lepton and according neutrino. And compositions defined below the processes. For our particular example, we will analyse production of higgs through gluon fusion and it's decay to $W^+W^-$ and again their decay to four lepton, which will give us the four body decay of higgs.

$$g + g \longrightarrow h \longrightarrow W^+ + W^- \longrightarrow e^- + \bar{\nu}_e + \mu^+ + \nu_\mu \tag{4.1}$$

Analysing process under SM(CKM=1 with hGG/AA) model selection and excluding diagrams with muon, will give us Figure 4.1(a). Note that we are not able to see diagrams through batch mode. If we wont exclude muon we will have one more diagram to deal with which is Figure 4.1(b). Note that it is important to observe $WW^*$ channel here because it provide us the




(a) diagrams with muon has been excluded.

(b) If user wont exclude muon from the process, such diagram will be appear as background noise.

Figure 4.1: $g + g \longrightarrow h \longrightarrow W^+ + W^- \longrightarrow e^- + \bar{\nu}_e + \mu^+ + \nu_\mu$

significant sign of existence of higgs. Thus one should avoid the noise as possible. Now under the SM(CKM=1 with hGG/AA) user can write down the process as;

```
Process:    G,G->e,Ne,M,nm
Remove :    M,m
```

Note that to avoid unnecessary noise excluding muon is mandatory.

```
pdf1:       cteq6l (proton)
pdf2:       cteq6l (proton)
```

Here pdf1 and pdf2 defines the proton beams which in our case proton – proton collision.

```
p1:         7000
p2:         7000
```

This section selects the total energy to 14 TeV such as LHC.

```
Run parameter: Mh
Run begin:     120
Run step size: 5
Run n steps:   3
```

This defines the higgs mass.

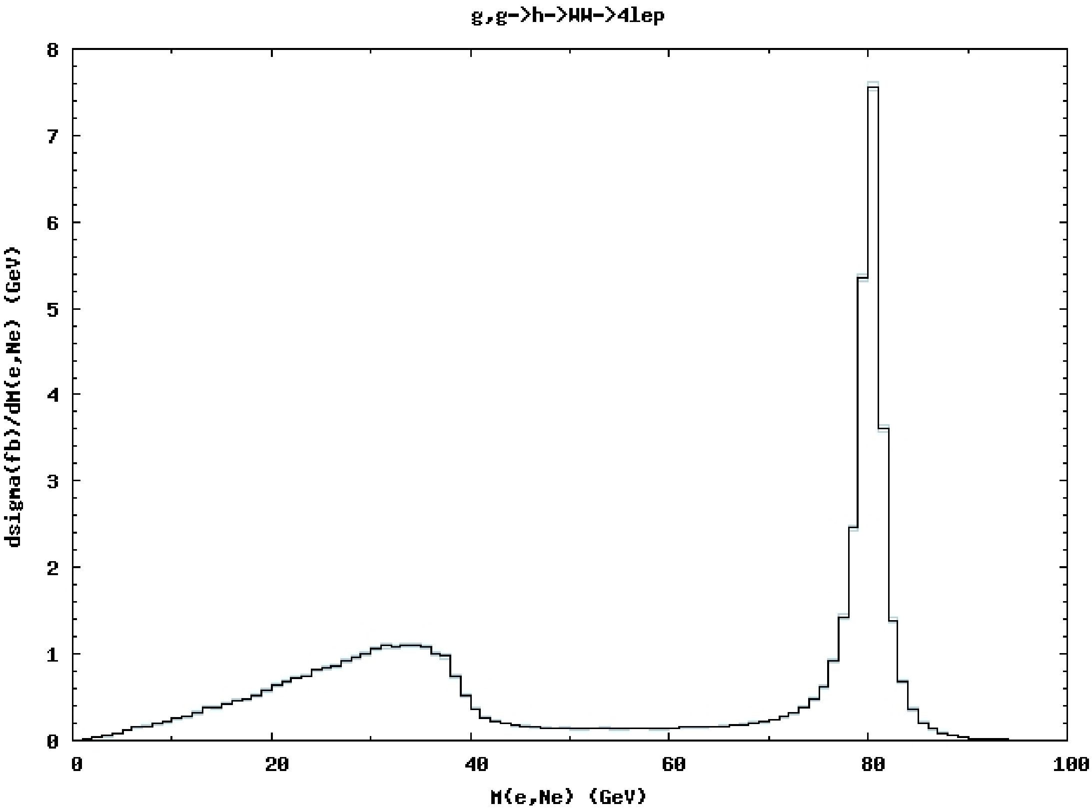
```
Kinematics :      12 -> 34, 56
Kinematics :      34 -> 3 , 4
Kinematics :      56 -> 5 , 6
```

And finally here user shapes the phase space of the interactions, which says 12 goes to 34 and 56 than 34 separates from each other such as 56[3]. The rest of the batch script is about the graphs and events that user wants to set. In order to check the higgs mass we started from gluon masses, Figure 4.4(a), which gives us the exact peak at the higgs mass. Then user can check the W mass which decays to an electron and anti – electron neutrino which leads us to Figure 4.2(a). Note that there is two peak one is at 80 GeV which is the mass of W as expected and the other rather small peak is due to the W that produces anti–muon and muon neutrino in the case of its become on-shell the W comes from electron may carry less energy than its actual, since it's off–shell its possible. Then to make a cross check user can obtain the graph of the mass of anti–muon and muon neutrino, Figure 4.2(b), which gave us same result as before. This initial peak can be seen clearly by subtracting neutrinos and observing transverse mass of anti–muon and electron, Figure 4.3(a), where transverse mass is defined as;

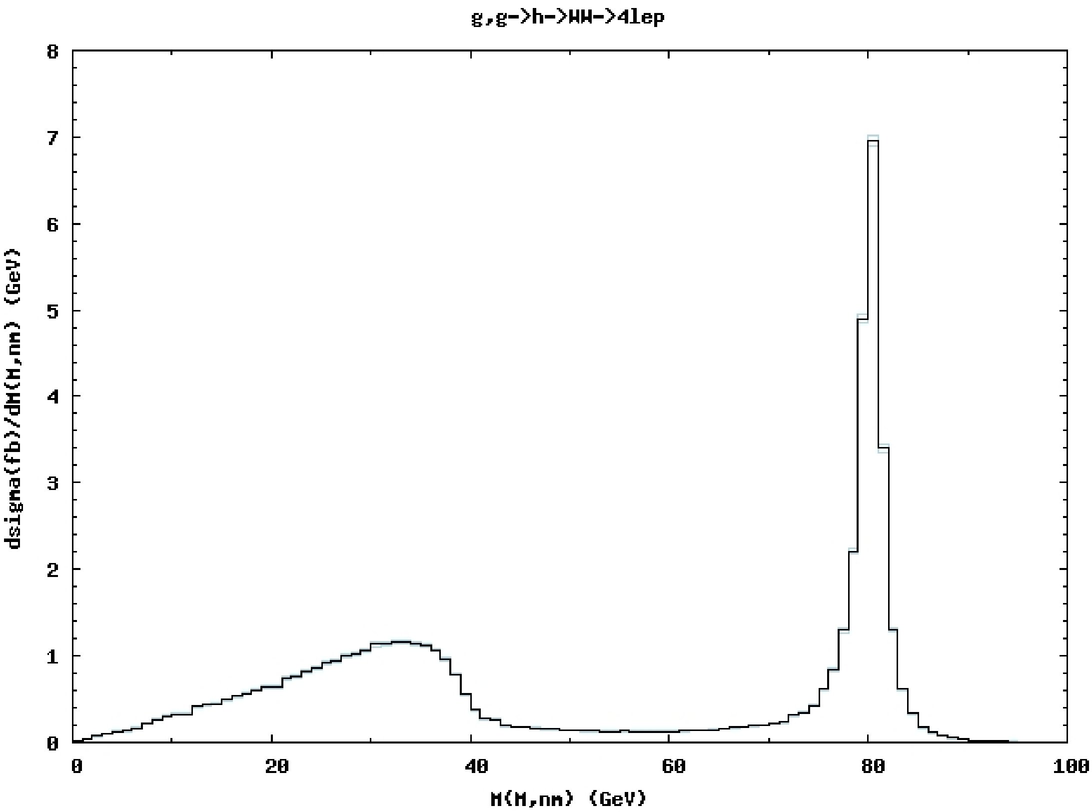
$$M_T^2 = (E_{T1} + E_{T2})^2 - (\mathbf{p}_{T1} + \mathbf{p}_{T2})^2 \tag{4.2}$$

And if one take the transverse momentum of electron and anti–electron neutrino Figure 4.3(b). Note that there is slight difference between the graphics of mass and transverse mass. Since neutrino can be approximated as massless mass is only depend on electron and anti–muon. However, by the definition of transverse mass it includes energies thus one can observe the contribution from neutrinos.

[3]These numbers are numbers of the particles not amount just labels.

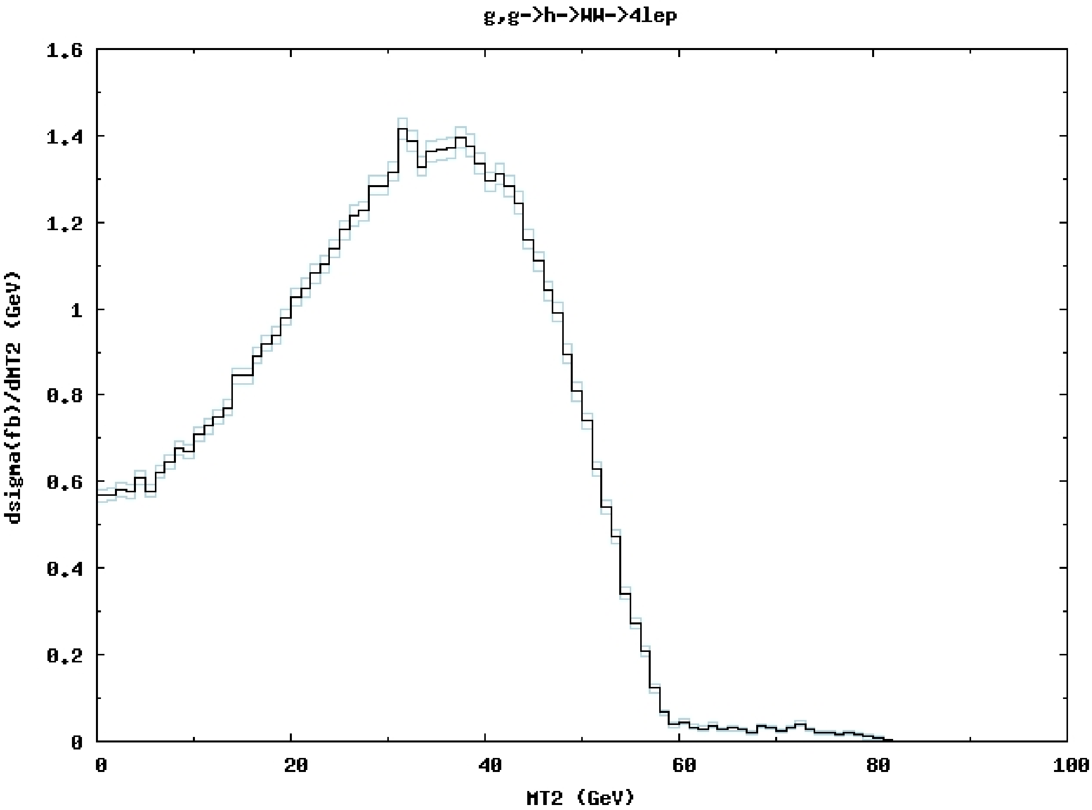



(a) Mass of electron and anti–electron neutrino vs Cross Section

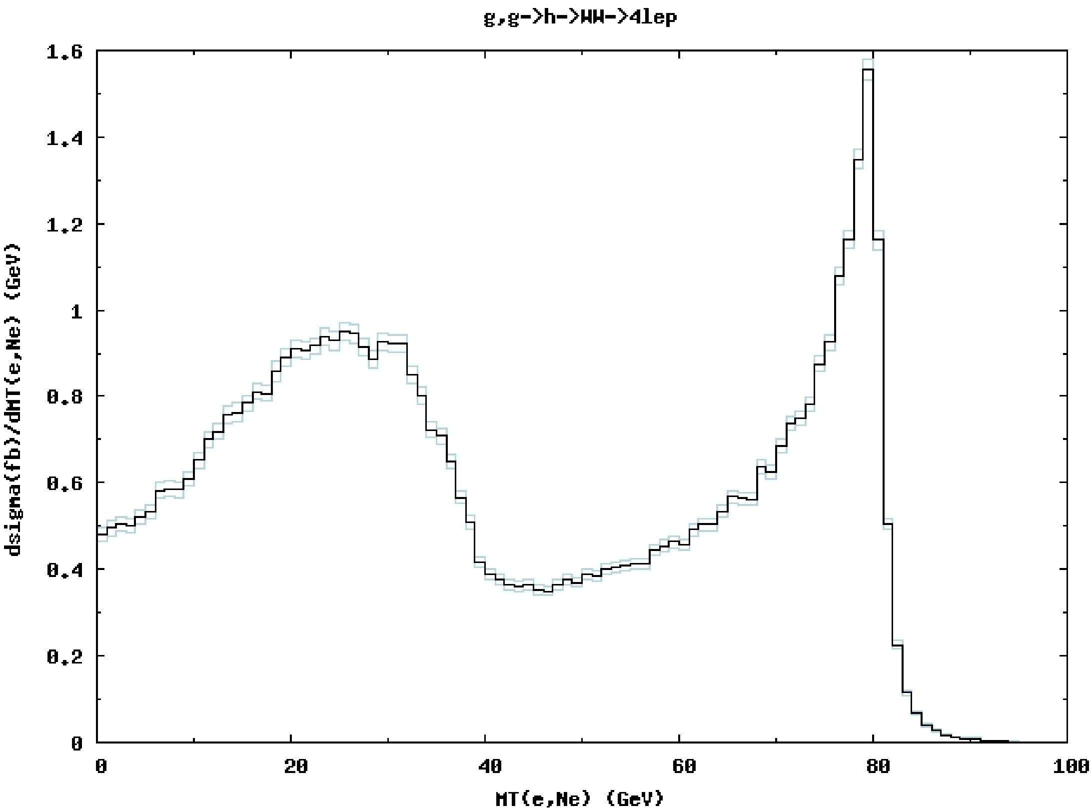



(b) Mass of anti–muon and muon neutrino vs Cross Section

Figure 4.2: $gg \longrightarrow$4lep

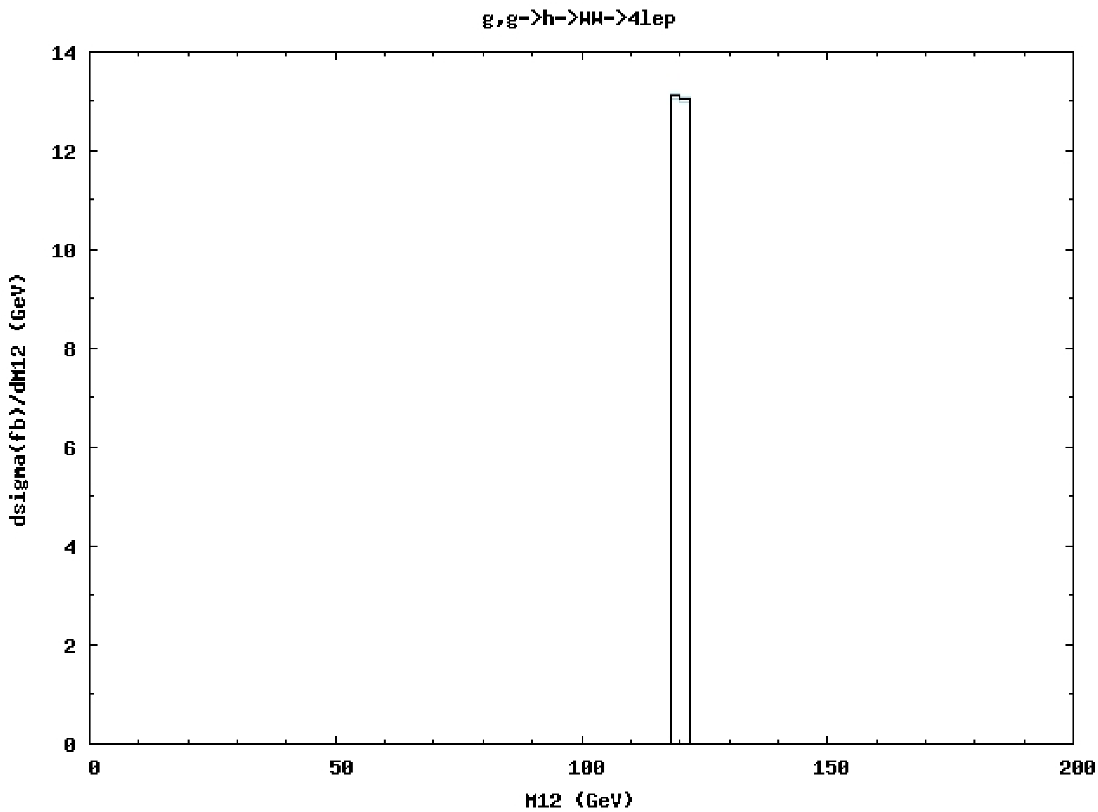



(a) Transverse mass of anti–muon and electron vs Cross Section




(b) Transverse mass of anti–electron neutrino and electron vs Cross Section

Figure 4.3: $gg \longrightarrow$4lep



(a) Total gluon mass vs Cross Section

Figure 4.4: $gg \longrightarrow$4lep

# Appendices

## Appendix A Drawing Feynman Diagram of a Process in LaTeX

Unfortunately CalcHEP does not give the exact code in order to compile in texmaker due to some updates. The initials of your LaTeXcode comes as;

```
%\documentstyle[axodraw]{article}
%\begin{document}
```

First of all user should delete the comment outs. Note that this style is outdated one should write this code as;

```
\documentclass{article}
\usepackage{axodraw}
\begin{document}
```

Then after compiling from texmaker one should compile from terminal because one need tree steps of compilation. User can use the following compilation process;

```
> latex name.tex
> dvips name.dvi
> ps2pdf name.ps
```

After this series of compilation one can have the ps file of desired diagram. Also user should download axodraw.sty file. Note that axodraw does not work along jpg and png files these files should be turned to eps.

# References


[1] Belyaev, A., Christensen, N. D., & Pukhov, A. (2012). Calchep 3.4 for collider physics within and beyond the standard model. Preprint submitted to Elsevier, Retrieved from http://arxiv.org/abs/1207.6082v2

[2] Belyaev, A. (2013). Practical introduction into selected tools for high energy physics. Unpublished manuscript, Department of Physics, Southampton University & Rutherford Appleton LAB.

[3] Belyaev, A., Christensen, N., Pukhov, A.(2013). CalcHEP 3.4 for collider physics within and beyond the Standard Model, Computer Physics Communications 184, (pp. 1729-1769) DOI: 10.1016/j.cpc.01.014 (arXiv:1207.6082 [hep-ph])

[4] Kong, K. (2012). TASI 2011: Calchep and Pythia tutorials. Unpublished manuscript, Department of Physics and Astronomy, University of Kansas, Retrieved from http://arxiv.org/abs/1208.0035v1

[5] Pukhov, A., Belyaev, A., & Christensen, N. (2012). Calchep calculator for high energy physics a package for the evaluation of feynman diagrams, integration over multi-particle phase space, and event generation. User's manual for version 3.3.6. Unpublished manuscript, Department of Physics, Southampton University & Rutherford Appleton LAB.