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How friendly is the Higgs boson?

Ruud Peeters

Supervisor: Prof. Dr. R.H.P Kleiss

Radboud University Nijmegen

Preface

In 2012, a paper was published by David d'Enterria [3]. He multiplied the branching ratios of all the decay channels of the Higgs particle. This product was calculated as a function of the Higgs mass. The result was interesting: the product is a gaussian function, centered around 125 GeV/c^2. This mass is very close to the mass of the Higgs-like particle which was recently found at the LHC. It is within the error margins of the experiments at CERN. This result means that the Higgs particle is in a window of maximum oppurtunity, the Higgs mass is such that the combination of the branching ratios is maximized. In this reseach, this product is investigated and it is investigated whether this result is fundamental or if it is just a coincidence. This is done by correcting some of the branching ratios and by taking a closer look at how this product is calculated.

Contents

Chapter 1

Introduction

Similar material can be found in *Introduction to Quantum Mechanics* by David Griffiths [4]

1.1 The Standard Model

The Standard Model of particle physics is the model which describes the elementary particles of nature and their interactions. This model consists of four major blocks: the quarks, the leptons, the force carriers and the Higgs boson.

1.1.1 Quarks

Quarks are spin-1/2 particles. There are six different kinds of quarks. They can be divided into two groups: three quarks with charge +2/3, the other three quarks with charge -1/3. The quarks with charge +2/3 are the up, charm and top quark. The quarks with charge -1/3 are called the down, strange and bottom quark. The difference between the quarks in one group is the mass of the particles. These properties are summarized in table 1.1.

Table 1.1: Properties of quarks

Flavour	Charge (e)	Mass (MeV/c^2)
up	+2/3	2,3
charm	+2/3	$1,275 \cdot 10^3$
top	+2/3	$1,73 \cdot 10^5$
down	-1/3	4,8
strange	-1/3	95
bottom	-1/3	$4,18 \cdot 10^3$

1.1.2 Leptons

The leptons are also spin-1/2 particles. The 6 leptons are split into two groups: the charged ones and the neutral ones. The charged leptons are the electron (e^-), muon (μ^-) and tau (τ^-). They all have charge -1 and differ only by their mass. The neutral leptons are better known as neutrinos. The different neutrinos are closely linked to the charged leptons, which is why the three neutrinos are called the electron-neutrino, muon-neutrino and tau-neutrino. The masses of the neutrinos are unknown, but it is known that they need to have a non-zero mass. The properties of all the leptons are shown in table 1.2

Table 1.2: Properties of leptons

Flavour	Charge (e)	Mass (MeV/c^2)
e$^-$	-1	0,511
μ^-	-1	$105,7$
τ^-	-1	1777
ν_e	0	$< 2,2 \cdot 10^{-3}$
ν_μ	0	$< 0,17$
ν_τ	0	$< 15,5$

1.1.3 Force Carriers

In the Standard Model, forces are transmitted by particles. There are three fundamental forces. Each of these forces has its own force carrier(s):

- **The photon**. The photon is the force carrier of the electromagnetic force. Photons are massless particles. Photons have a spin of 1. The photon can only transmit a force between two charged particles. Since the photon is not charged, it has no self-coupling.

- **The gluon**. The strong nuclear force is transmitted by the gluon. Just like the photon, the gluon is massless. The strong force can only be transmitted between particles with a color. Since the gluon has both a color and an anticolor, it will couple to itself. This is a big difference with the electromagnetic force.

- **The W$^\pm$ and the Z**. The weak nuclear force has three force carriers: the neutral Z boson, the positive W$^+$ boson and the negative W$^-$ boson. These are the only massive force carriers. Because these particles have a non-zero mass, the weak nuclear force has a finite range.

1.1.4 The Higgs boson

The last particle in the Standard Model is the Higgs boson. This particle is an excitation in the Higgs field, the field that slows down particular particles to give them mass. This particle was only recently discovered at CERN. The ATLAS experiment and the CMS experiment independently calculated a Higgs mass around 125 GeV/c^2 [2].

The properties of all elementary particles are summarized in figure 1.1.

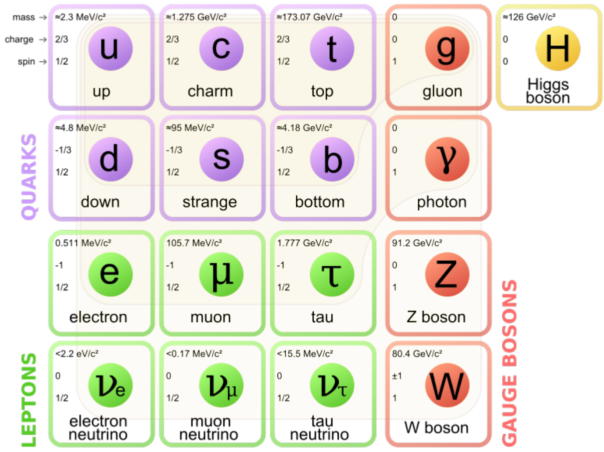


Figure 1.1: The elementary particles of the Standard Model [5]

Chapter 2

Theoretical Background

2.1 Higgs Decay

The Higss boson is a very unstable particle. It has a lifetime of about 10^{-22} seconds [6]. The particle will therefore decay before it can reach any part of the detector. It is thus necessary to measure the decay products of the Higgs particle. The decay rules state that a Higgs boson can only decay into:

- A quark and its anti-quark ($q\bar{q}$)
- A charged lepton and its antiparticle (l^-l^+)
- A pair of W or Z bosons (WW, ZZ)
- Two photons ($\gamma\gamma$)
- A Z boson and a photon (Zγ)

The probability for a Higgs boson to decay via a specific channel is given by its partial decay width (Γ_i). This is defined as the probability per unit time that a Higgs boson decays via this channel. It is multiplied by $\hbar$ to make it an energy. The partial decay width is a function of the Higgs mass. This is plausible, since the Higgs boson is more likely to decay into particles with less mass than the Higgs boson itself. The total decay width increases with increasing Higgs mass, since more and more channels are open at a higher Higgs mass. It is therefore hard to compare different channels at different Higgs masses. This is why the branching ratio (BR) was introduced. The branching ratio is the probability that a Higgs boson decays into a certain final state. It is defined as:

$$\mathrm{BR}_i \equiv \frac{\Gamma_i}{\sum_j \Gamma_j} = \frac{\Gamma_i}{\Gamma_{tot}}. \tag{2.1}$$

The branching ratio is such a useful quantity because it is dimensionless and its value is always between 0 and 1. It can therefore easily be compared between channels.

When the branching ratios of the different channels are known, the product of the branching ratios can be computed. This is defined as:

$$P_{\mathrm{BR}}(m_H) \equiv \prod_{i=1}^{N} \mathrm{BR}_i = \frac{\prod_{i=1}^{N} \Gamma_i}{(\Gamma_{tot})^N}, \tag{2.2}$$

where N is the number of decay channels. This product is the function that we are interested in.

2.2 On-shell and off-shell decay

Basic conservation rules state that the four-momentum has to be conserved in a collision. This translates in the relation

$$E^2 = p^2c^2 + m^2c^4. \tag{2.3}$$

This relation states that the energy in a collision will be divided between rest mass energy and kinetic energy. When a particle is created, you will need at least an energy of $E = mc^2$. It will have zero kinetic energy and thus obey the above equation. As it turns out, this is not always the case. It is actually possible to create particles while the energy should not be enough to create them. These particles, which are classicaly not permitted, are called off-shell particles. The particles that do obey the energy-mass relation are called on-shell particles.

An example of a decay into off-shell particles is the decay of a Higgs boson into two W bosons. A W boson has a mass of 80 GeV. So, when the Higgs boson has a mass less than 160 GeV, it should not be able to decay into two W bosons. It turns out that this decay is possible, although the branching ratios drops rapidly with decreasing Higgs mass. There is also a restriction on these off-shell particles. They are not allowed to travel macroscopic distances. They will decay almost immediatly after they are created. But since the decay products usually have a smaller mass, the decay products can be produced on-shell and they can be detected. This enables the detection of the off-shell particles.

Chapter 3

Reproducing the paper

The first goal of the research was to reproduce the results of David d'Enterria. From there on, some alterations could be made to test whether the results of d'Enterria are really meaningful.

3.1 HDECAY

To eventually compute the product of the branching ratios of the Higgs boson, these branching ratios had to be obtained. This was done using HDECAY [1]. This program calculates the branching ratios for (almost) all decay channels of the Higgs boson as a function of the Higgs mass. It does not only calculate the branching ratios for the Higgs boson in the Standard Model, but it can also compute them for some supersymmetrical theories. In this research, only the Standard Model Higgs boson was investigated.

HDECAY needs a number of input parameters, such as the masses of the different quarks and the coupling constants of the elementary forces. In the paper by d'Enterria, some of these inputparameters were given. To keep the research as close to the original results as possible, these parameters were also used. The parameters which were not given in the paper remained unchanged.

In HDECAY, the user can decide the range of Higgs masses that should be computed as well as the number of steps in which this range is divided. In this research, the Higgs mass ranged from 10 GeV to 1000 GeV, in 10 000 steps.

3.2 Adding the $\mathrm{u\bar{u}}$, $\mathrm{d\bar{d}}$ and $\mathrm{e^+e^-}$ decay

HDECAY does not include the decay into $\mathrm{u\bar{u}}$, $\mathrm{d\bar{d}}$ and $\mathrm{e^+e^-}$, since they are of no interest in the search for the Higgs boson, their branching ratios are to small to play a role. However, when calculating the product, it is important to include the processes with a small branching ratios too. Therefore, it is necessary to insert the branching ratio for these particles. The formulas for these branching ratios are:

$$\mathrm{BR}_{\mathrm{u\bar{u}},\mathrm{d\bar{d}}}(m_{\mathrm{H}}) \approx \left(\frac{m_{\mathrm{u,d}}}{m_s}\right)^2 \cdot \mathrm{BR}_{\mathrm{s\bar{s}}}(m_{\mathrm{H}}), \qquad \mathrm{BR}_{e^+e^-}(m_{\mathrm{H}}) \approx \left(\frac{m_{e^-}}{m_{\mu^-}}\right)^2 \cdot \mathrm{BR}_{\mu^+\mu^-}(m_{\mathrm{H}}). \tag{3.1}$$

When these branching ratios are combined with the results of HDECAY, graph 3.1 is obtained. This result can be compared with the graph in the paper.

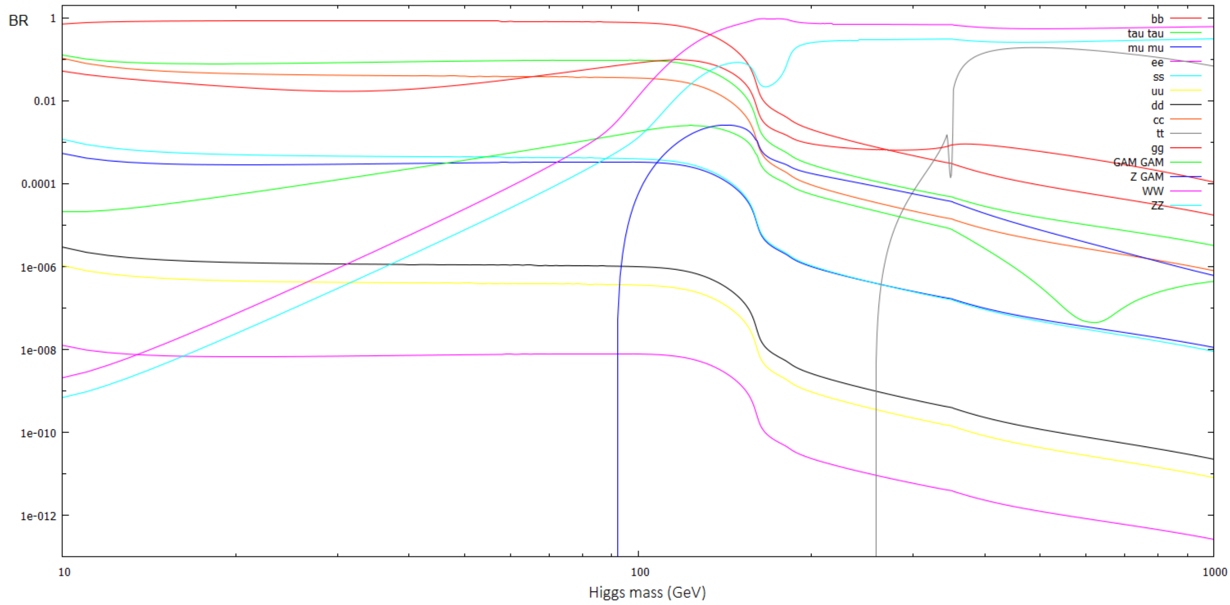


Figure 3.1: The branching ratios as computed by HDECAY

This graph looks very similar to the one in the paper by d'Enterria [3]. However, there is one difference between the two. In the $t\bar{t}$ channel, there is a small dip around 350 GeV/c^2. This is probably a small error in HDECAY. The region around 350 GeV/c^2 is exactly where there is a transition between one on-shell top quark and two on-shell top quarks. The calculations for these two cases are different and apparently they don't match exactly. This anomaly did not affect the final results, since it is located around 350 GeV. This region is far away from the region of interest. The product of the branching ratios will be approximately zero in this region, so it did not influence the results. Because the gains of correcting this minor error were much less than the effort in correcting it, it was decided to retain this small deviation.

3.3 Calculating the product

After computing all the branching ratios succesfully, the goal was to calculate the product of the branching ratios. This was done by writing a Python script. This script combined several actions: it combined all the branching ratios in one file, added the branching ratios of the decays that were not computed in HDECAY and it calculated the product of all these branching ratios. This script would later be extended to enable the user to determine various parameters. The first version of the product, where simply all branching ratios are multiplied, yielded figure 3.2.

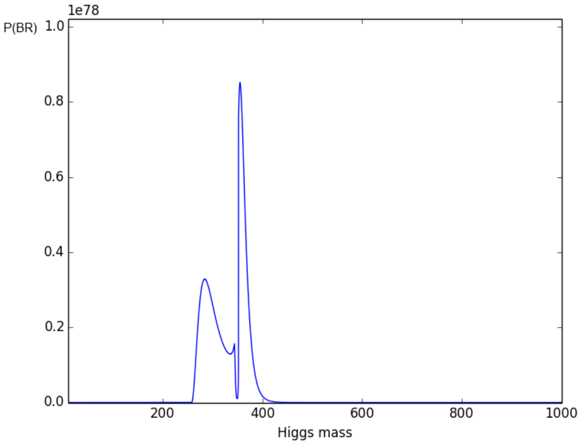


Figure 3.2: The first attempt at the product of the branching ratios

This doesn't look like a gaussian peak around the measured Higgs mass. After another reading of the paper, it was found that the $t\bar{t}$ channel was completely omitted in the paper. This had to be done because this branching ratio was set to zero in HDECAY when the mass of the Higgs boson is less than about 260 GeV/c^2. When the branching ratios are multiplied, the product will always be zero if one of the ratios is zero. This behaviour is visible in the graph above. The product drops to zero at 260 GeV/c^2. The product has some strange shape above this mass, but this is not very relevant, since all the information below this threshold mass is not used. The result would still be standing if this threshold is real, but it is not. HDECAY does not compute the branching ratios for these processes when the branching ratio is so small that it is of no interest to experimental particle physicists.

Since the goal at this point was still to reproduce the results of the paper, the next step was to omit the decay into a $t\bar{t}$ pair. This resulted in figure 3.3.

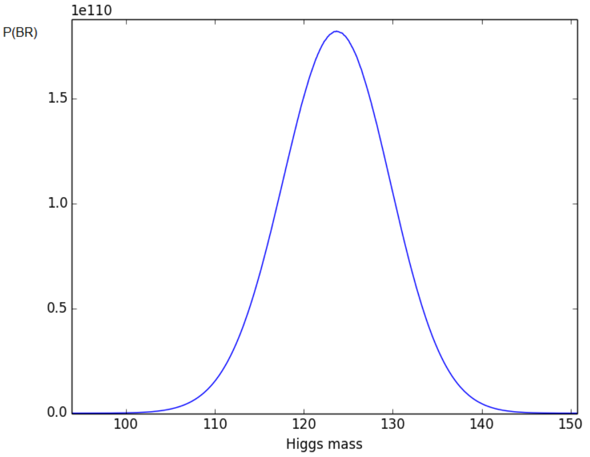


Figure 3.3: The second attempt of the product of the branching ratios

This finally looks like a gaussian peak around 125 GeV/c^2. When a gaussian curve is fitted through the data points, a mean value of 123.7 GeV/c^2 is obtained. This is not the exact same value that was found in the paper, but HDECAY has an error of about 10% for each branching ratio and there could be some minor differences in the input parameters. This research is focussed on trying to change the mean value of this curve. It is therefore not very important that there is a small deviation from the results of the paper.

Another small remark about this plot is that the product of a number of values between zero and one should be smaller than one. In these plots, the product is much larger than one. This happens because the product was multiplied by a factor 10^{150}. This was necessary because Python could not cope with numbers smaller than 10^{-308}. The product was sometimes smaller than this value, so this had to be corrected. This modification does not influence the results, since only the shape and the mean value are the parameters of interest.

Chapter 4

Modifications to branching ratios

4.1 Zγ decay

When we take a look at the branching ratio of the Zγ channel (figure 3.1), it is clear that the branching ratio drops to zero at a Higgs mass of 91 GeV. This is exactly the mass of the Z boson. This happens because HDECAY does not include the decay to a off-shell Z boson. This had to be corrected, since this decay is possible. It was unknown how this branching ratio depended on the Higgs mass. This was approximated by stating that the branching ratios of the Zγ decay has the same slope as the ZZ decay in the region below 91 GeV. This approximation may not be very accurate, but it was found that changing this branching ratio did not influence the outcome at all, so it does not make much of a difference how correct this approximation is.

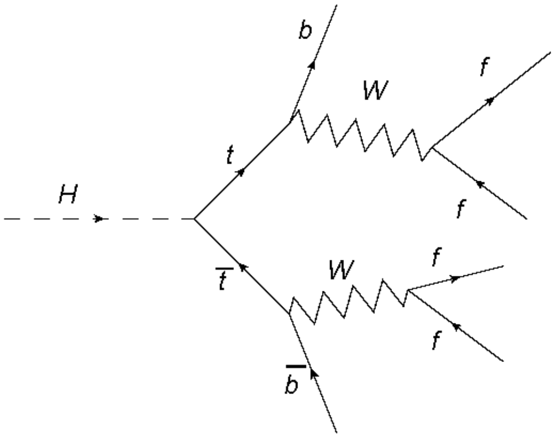
4.2 $t\bar{t}$ decay

At first, the same procedure was used for the $t\bar{t}$ decay. But while the Zγ decay did not influence the outcome, the $t\bar{t}$ decay did matter. It was therefore necessary to take a closer look at this decay. After some discussion it was concluded that it would take too much time to calculate the decay into two off-shell top quarks. Therefore, only an approximation of the branching ratio was computed.

Top quarks are very unstable particles. So, when a Higgs boson decays into a $t\bar{t}$ pair, the top quarks will decay almost immediately. The top quark will produce a bottom quark and a W^+ boson, the antitop quark will produce the antiparticles $\bar{b}$ and W^-. The bottom quarks will practically always be produced on-shell, there is a chance however that the W bosons are produced off-shell. Whether none, one or two W bosons are produced off-shelll depends on the mass of the Higgs boson.

4.2.1 Two off-shell W bosons

When the Higgs mass is less than the mass of one W boson, there is not enough energy to produce either W boson on-shell. So, both W bosons will be produced off-shell. They will therefore decay almost directly into a pair of fermions. This leads to the following Feynman diagram:



The Higgs mass dependence of the decay width of this channel can be calculated using this diagram. To do this, the first step is to calculate the matrix element corresponding to this diagram. The only parts of the matrix element which depend on the Higgs mass, are the momenta of the outgoing fermions. These momenta are proportional to the square root of the Higgs mass:

$$\mathcal{M} \sim (u)^6 \sim (\sqrt{m_H})^6 \sim m_H^3. \tag{4.1}$$

To calculate the decay width, it is also necessary to compute the phase space of this decay. To calculate this, the following rule was used:

$$V \sim (E^2)^{n-2}. \tag{4.2}$$

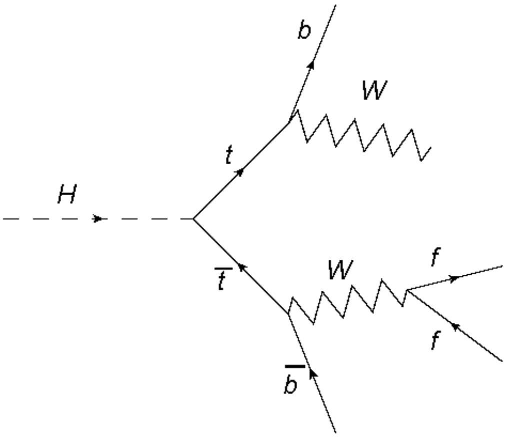
In this equation, E is the energy scale of the system (proportional to the Higgs mass in this case) and n is the number of outgoing particles. In the case of two off-shell W bosons, there are 6 outgoing particles, so the phase space will be proportional to m_H^8. The decay width can then be computed as:

$$\Gamma \sim \frac{1}{F}|\mathcal{M}|^2 V \sim \frac{1}{m_H} \cdot (m_H^3)^2 \cdot m_H^8 \sim m_H^{13}, \tag{4.3}$$

with F the fluxfactor. This factor compensates for the number of incoming particles per second. The fluxfactor is proportional to the energy scale of the system. So in this case, the fluxfactor is proportional to the Higgs mass.

4.2.2 One off-shell W boson

When the Higgs mass is higher than the mass of one W boson, but lower than the mass of two W particles, only one W boson can be produced on-shell. This results in the following Feynman diagram:



The calculation of the decay width is similar to the case of two off-shell bosons. Only the number of outgoing particles changes. This affects both the matrix element and the phase space. Since there are only four outgoing fermions, the matrix element will now be proportional to:

$$\mathcal{M} \sim (u)^4 \sim (\sqrt{m_H})^4 \sim m_H^2. \tag{4.4}$$

While the phase space goes with:

$$V \sim (E^2)^{n-2} \sim m_H^6. \tag{4.5}$$

This results in a decay width of:

$$\Gamma \sim \frac{1}{F}|\mathcal{M}|^2 V \sim \frac{1}{m_H} \cdot (m_H^2)^2 \cdot m_H^6 \sim m_H^9. \tag{4.6}$$

So far, only the decay widths have been calculated, but the quantity of interest is the branching ratio. To obtain the branching ratio, the decay width for a certain channel has to be divided by the total decay width. This was done using the decay width computed by HDECAY.

With both the Zγ decay and the t$\bar{\text{t}}$ decay modified, the branching ratios look like figure 4.1:

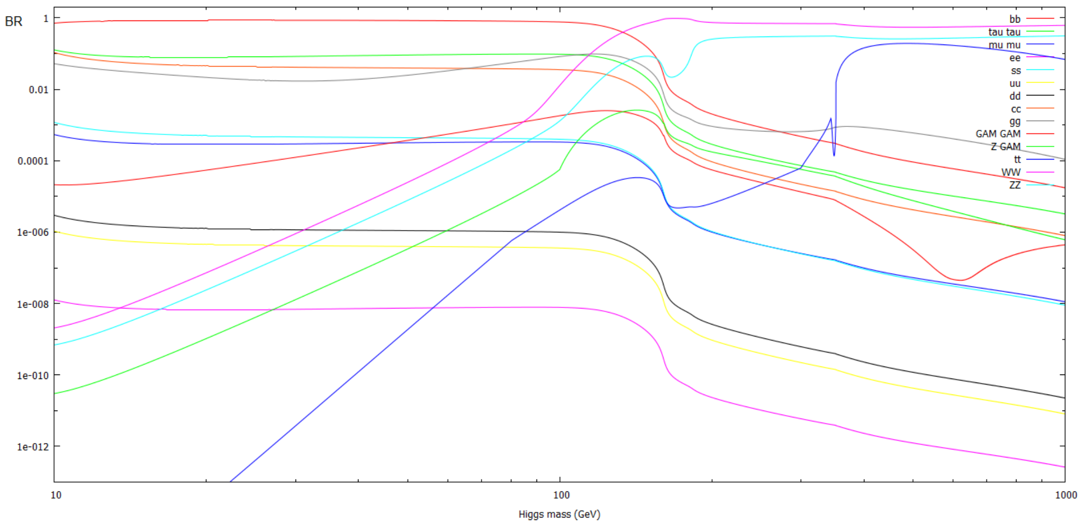


Figure 4.1: The branching ratios with the modifications

There is however one final remark. To check whether these calculations are valid, the branching ratio for the WW decay for two off-shell W bosons was also calulated. Since this decay is included in HDECAY, the calculations can be compared to the actual values. It was found that there was a error of about 8% in the branching ratio. When this result is applied to the t$\bar{\text{t}}$ decay, the exponent in the t$\bar{\text{t}}$ decay width will change. In the region of interest (one off-shell W boson) the exponent will not be exactly 9, but it will most likely be somewhere between 8 and 10. This results in an uncertainty in the branching ratio of the t$\bar{\text{t}}$ decay.

Chapter 5

Other alterations

In addition to changing the branching ratios themselves, there are some other ways to make alterions to the product. These alterations include adding spin, adding color and omitting certain decay channels.

5.1 Spin

It can be argued that each different final quantum state should be treated as an independent decay channel. These individual decay channels have an individual branching ratio. These branching ratios should be multiplied instead of the previous setup, in which only decays into different particles are treated as different decays. This does not matter for most applications of the branching ratio, but when they are multiplied, it is very important to distinguish them.

One of the quantum numbers that has to be taken into account is spin. The Higgs boson itself is a spin-0 particle. So, when a Higgs boson decays into two fermions, there are two possible configurations: the particle has spin-up and the antiparticle has spin-down, or the other way around. This means that the branching ratio for a decay into fermions consists of two parts. There is no reason to assume one of these configurations is more likely to occur, so we assume that these two fractions are equal.

For the decay into massive vector bosons, there are three possible configurations. The W and Z boson are both spin-1 particles, so the possible configurations are: both particles have $m_s = 0$, one particle has $m_s = +1$ and the other one has $m_s = -1$, or the other way around. This means that the branching ratio of the decay into massive vector bosons is divided into three equal parts. These fractions have to be considered as different branching ratios. So each decay has a branching ratio of $\frac{1}{3}\mathrm{BR}_{V\overline{V}}$.

For gluons and photons, the argument is similar to the fermions. Both of these particles are spin-1, but since they are massless, one degree of freedom is lost. This results in two possible spin states for these particles: a spin-up and a spin-down state. So when a pair of gluons or photons is produced, there are again two possible configurations. The branching ratios is thus split up into two equal parts.

The last decay process which has to be examined is the Zγ-channel. The Z boson has three possible spin states, the photon has only two. Therefore, there are two possible configurations: the photon has spin-up and the Z-boson has spin-down, or the other way around. So, the branching ratio of this process is divided in two equally large parts.

5.2 Color

For the quarks, there is another quantum number which can be used to distinguish the particles. This quantum number is color. It was proposed in 1964 as an explanation of the existence of the Δ^{++}-particle. This particle consists of three up-quarks. The spin of the particle was measured to be 3/2, so all the up-quarks have to be in the same spin configuration. Howerer, the Pauli exclusion principle says that this in not possible if there is no other quantum number. Therefore, color was introduced as a new quantum number.

In experiments it was found that there are three colors (red, blue and green) and three anticolors (anti-red, anti-blue and anti-green). A quark has one of these colors, a anti-quark has an anticolor and gluons have both a color and a anticolor. A bound state has to be colorless, which means that it has to consist of either a color and an anticolor or a combination of three different colors or three different anticolors.

The consequence of this new quantum number, is that there are three different ways in which a Higgs boson can decay into a quark-antiquark pair. The Higgsboson itself is colorless, so the combination of the colors of the quark and the antiquark has to be colorless as well. The final state therefore has to consist of a quark with a certain color and an antiquark with the anticolor. The three possible outcomes (red-antired, blue-antiblue and green-antigreen) are all equally probable. The branching ratio for each quark decay channel should thus be divided by three.

A similar argument holds for gluons, but there are 8 independent gluon states. Therefore, the branching ratios of each individual decay channel is $\frac{1}{8}\mathrm{BR}_{gg}$.

All these possible configurations are summarized in table 5.1.

Table 5.1: Possible alterations and their consequences to the product of the branching ratios

Decay channel	# spin configurations	# color configurations	Contribution to product
$q\overline{q}$	2	3	$(\frac{1}{6}BR_{q\overline{q}})^6$
WW, ZZ	3	1	$(\frac{1}{3}BR_{V\overline{V}})^3$
gg	2	8	$(\frac{1}{16}BR_{gg})^{16}$
l^-l^+	2	1	$(\frac{1}{2}BR_{l^-l^+})^2$
$\gamma\gamma$	2	1	$\frac{1}{2}BR_{\gamma\gamma}^2$
$Z\gamma$	2	1	$(\frac{1}{2}BR_{Z\gamma})^2$

5.3 Loop channels

Since the Higgs particle is the excitation of the field which gives masses to all particles, the Higgs boson only couples to massive particles. This means that the Higgs boson cannot decay directly into the massless gluons and photons. They can only be produced by top quark loops or W boson loops. In such Feynman diagrams, the coupling with the Higgs boson is only made by particles in the loop and not by the photons and gluons which emerge from the loop. It can therefore be argued that the branching ratios for the channels with gluons and photons should not be seen as individual channels, but as contributions to the $\mathrm{t\bar{t}}$ and WW channel. The $\gamma\gamma$, $Z\gamma$ and gg decay should therefore be omitted.

Chapter 6

Results

After making the various adjustments both in the branching ratios and in calculating the product, the effects of these scenarios can be computed and compared. This was done by writing a Python script which was able to take all these modifications into account (section 9.1). The script was written in such a way that the user could decide which modifications should be taken into account. The script could also correct the branching ratios for the Zγ decay and the t$\bar{\text{t}}$ decay, where the exponent in the region $m_W < m_H < 2m_W$ could be determined by the user. After calculating the product of the branching ratios, a gaussian curve was fitted through the data points to determine the mean value of the curve accurately.

For future reference, the product of the branching ratios without any of the adjustments is a gaussian curve with a mean value of 123.7 GeV.

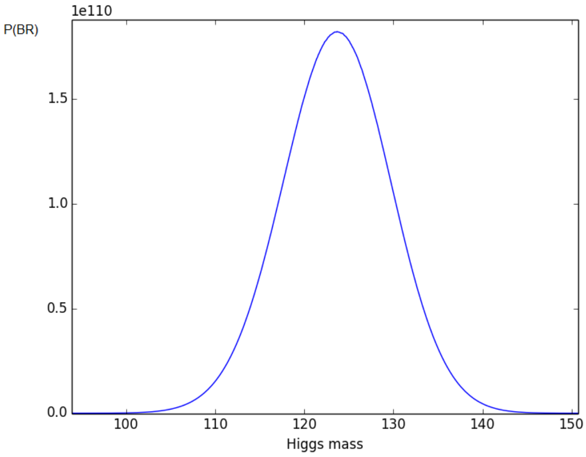


Figure 6.1: The product of the branching ratios, without t$\bar{\text{t}}$ and without any adjustments

6.1 The effect of spin and color

In section 6.1 and 6.2, the branching ratios of the Zγ and t$\bar{\text{t}}$ decay are not changed. It was therefore necessary to omit the t$\bar{\text{t}}$ decay in these calculations.

When the different spin states are included in the product, the graph alters a bit. The mean value changes from 123.7 GeV to 126.5 GeV (Appendix figure 9.1). This change of about 3 GeV may not be very large, it does mean that the various spin states do influence the overal curve.

When only the different color combinations are taken into account (so the spin states are not included), the curve changes again. This time, the mean value lies significantly lower. The mean value of this curve lies at 116.9 GeV (Appendix figure 9.2). This is about 10 GeV from the Higgs mass found at CERN.

It is reasonable to state that the combination of these modifications is more important than the individual modifications. The argument for both alterations was after all that all different quantum states should be included as different decays. When this product is computed, the mean value is 119 GeV (figure 6.2).

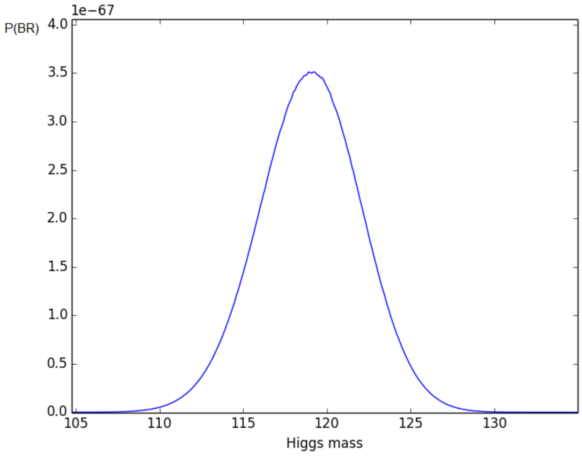


Figure 6.2: The product of the branching ratios including both spin and color states

This result is stronger than the previous results. It says that when different quantum states are treated as different decay channels, the mean value of the gaussian curve changes significantly. The mean value is still fairly close to the Higgs mass, but it is not as spot on as the results in the paper by d'Enterria.

6.2 Omitting loop mediated channels

In addition to distinguishing different spin and color states, there is also the option of omitting the loop mediated channels. When these decay channels are omitted, the mean value of the product will change from 123.7 to 121.1 GeV (Appendix figure 9.3). When this result is combined with the spin and color result mentioned before, the mean value will differ even more from the actual Higgs mass. The mean value with these three alterations combined is 117.2 GeV (figure 6.3).

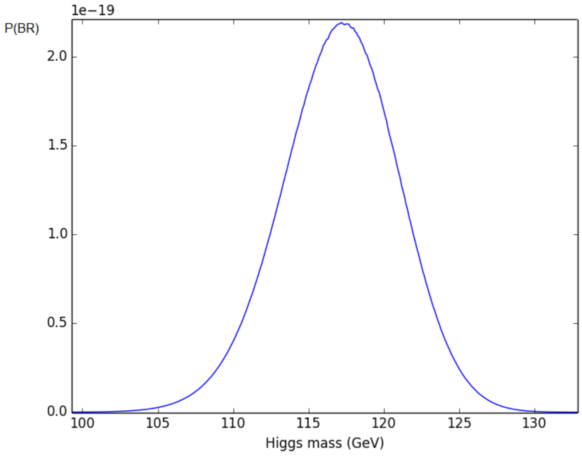


Figure 6.3: The product of the branching ratios without the loop channels, with the different spin and color states

6.3 Including the alterations to the Zγ and t$\bar{\text{t}}$ channel

So far, the mean value has changed slightly with each additional modification. The next step is to include the changes in the Zγ and t$\bar{\text{t}}$ channel.

First we take a look at the effect of these individual modifications on the product of the branching ratios. The Zγ does not influence the results very much, since the changes are made in the region below 100 GeV. In this region, the product of the branching ratios is approximately zero, so a change in one of the branching ratios does not influence the result. In the case of the t$\bar{\text{t}}$ decay, the change in the branching ratio will influence the result. The region where this channel is altered, is exactly the region of interest. When the product is calculated with only the modifications in the branching ratios, the mean value will change to 125.0 GeV (Appendix figure 9.4).

The final step is to combine all these modifications (distinguishing spin and color states, omitting loop mediated channels and correcting the branching ratios of the Zγ and t$\bar{\text{t}}$ channels). When this is done, the mean value equals 120.9 GeV.

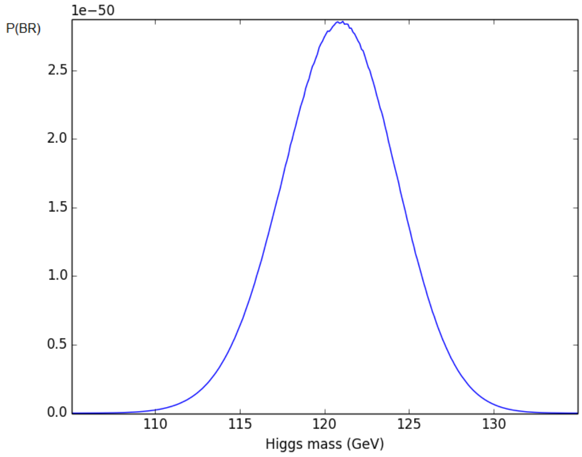


Figure 6.4: The product of the branching ratios with all alterations

As argued in section 4.2, there remains one unknown parameter. This is the exponent of the decay width for the $\mathrm{t\bar{t}}$ decay in the region $m_W < m_H < 2m_W$. This exponent will probably be somewhere between 8 and 10. When the product is calculated for these different values, the mean value ranges from 120.3 to 121.5 GeV.

Chapter 7

Conclusion

The first goal of the research was to reproduce the results by David d'Enterria. The branching ratios could be reproduced, although there was a small drop in the $t\bar{t}$ decay. Calculating the product of the branching ratios worked out as well, although the mean value deviated a little bit from the value found by d'Enterria.

The next step was to add some modifications to both the branching ratios as well as how the product was calculated. With all these modifications, the peak of the graph is around 121.5 GeV, a significant difference from the previous result. This is a deviation of 2 to 3 GeV compared to the previous value. Although this is not a huge difference, it looks like the result of David d'Enterria was coïncidental. In order to keep the mean value at 124 GeV, the exponent of the decay width should be much larger than 10. Since this is very unlikely, we can conclude that the Higgs boson does not have the mass at which the combination of all the branching ratios is optimized.

Chapter 8

Discussion

It looks like the results by d'Enterria are disproved. There is however some uncertainty in this result. For example, there is some uncertainty in the calculated branching ratios of the $\mathrm{t\bar{t}}$ decay. The slope of the decay width in the interesting mass range could range from 8 to 10. Although this is a fairly large uncertainty, it does not influence the result that much. In order to get close to the original value of 123.7 GeV, the exponent should be much larger than 10.

There is also the uncertainty in the calculations of the branching ratios by HDECAY. There is an uncertainty of about 10% in each branching ratio. This is a rather big uncertainty. It could influence the results significantly.

As mentioned before, there is a deviation from the results of the paper when the product is calculated without any alterations. This deviation is probably due to a difference in an input parameter, but it could be helpful to find out if this is really the case, or if a mistake was made in the calculation.

It could also be the case that there are more alterations possible. Since (almost) all of the alterations that were made in this research had a significant effect on the product, it could be that there are other alterations that change the mean value back to the original value.

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Chapter 9

Appendix

9.1 Python script

```
import numpy as np
import matplotlib.pyplot as plt
import math
import pylab as plb
from scipy.optimize import curve_fit
from scipy import asarray

fileinput = ’br.sm1’                                                #The inputfiles and
    the outputfiles
fileinput2 = ’br.sm2’
fileoutput1 = ’product.txt’
fileoutput2 = ’brs.txt’

#The user can decide which decay channels are taken into account in calculating the
    product
verval = input("Do you want to take these decay channels into account (1 is yes, 0 is
    no) \nbb, tau tau, mu mu, ee, ss, uu, dd, cc, tt, gg, Gamma Gamma, Z Gamma, WW,
    ZZ \n")
v = list(map(int,verval.split()))          #The inputstring is split up and stored in
    a list

kleur = input(’Do you want to consider different color states as different decay
    channels? (Y/N) \n’)
if kleur == ’Y’:
       qu = 3                      #There are 3 color states for quarks and 8 for
           gluons
       gl = 8
else:
       qu=gl=1

spin = input(’Do you want to take different spin states into account? (Y/N)\n’)
if spin == ’Y’:
       s1 = 2               #Some decay channels have 2 different spin states,
           others have 3
       s2 = 3
else:
       s1=s2=1

f = open(fileinput,’r’)                    #Open the first inputfile in read-mode
f2 = open(fileinput2,’r’)                  #Open the second inputfile in read-mode
```

```
f_out1 = open(fileoutput2, "w")     #Open the first outputfile in write-mode

lines = f.readlines()                      #The lines of the inputfiles are being read
lines2 = f2.readlines()

count = len(lines)                                #The number of lines of the
    inputfiles is being calculated

Me = 0.510998928E-3                               # The mass of the electron, muon,
    up quark, down quark and strange quark
Mm = 0.105658367
Mu = 3E-3
Md = 5E-3
Ms = 0.1

h = [0]*count                                     # An empty list is created with a
    length equal to the number of lines in the datafiles
k = 0

x1 = 20                                                  #These constants are used
    to modify some of the branching ratios
x2 = 60
x3 = 300

y1 = 0.2416E-7
y2 = 0.2604E-4
y3 = 0.6222E-4

ex = 9                                                   #The exponents found in
    section 4.2 are used to correct the tt decay
ex2 = 13
#-------------
# Writing the BRs to one document
#-------------

#The goal of this section is to combine the two datafiles in one file and adding some
    channels that HDECAY does not compute.

for l in range(count):                     # In this loop, all non-zero elements in
    the Z GAM column are determined and the ratio with the ZZ channel is stored in
    the list 'h'
              if l>2:
                     x2 = list(map(float,lines2[l].split()))
                     if (x2[3] != 0 and x2[0] > 100):
                            h[k] = x2[3]/x2[5]
                            k = k + 1
g = h[0]                                                 # The first element of 'h'
    is used lated to get branching ratio of Z GAM parallel to ZZ. In the graph, this
    number is the distance between the branching ratios at 100 GeV

for i in range(count):                     # The lines of the datafile are read one
    by one
       if i>2:                                           # The first three lines are
           text, so they are skipped
              z = list(map(float,lines[i].split()))      # For each line, the
                  branching ratios of the channels in the first datafile are stored
                  in the list 'z'
```

```
x = list(map(float,lines2[i].split()))     # The branching ratios from
    the second datafile are stored in the list 'x'
f_out1.write(str(z[0]) +" ")                       # Each line starts
    with the corresponding Higgs mass
for j in range(1,len(z)):                                 # This loop
    runs through the columns of datafile 1
       if j == 3:
                  # In case of the muon decay, the electron positron
           decay is calculated
               a = (Me/Mm)**2 * (z[j])
               f_out1.write("%25s %25s" % (z[j], a))      # The values
                  of the muon decay and the electron positron decay
                  are written to outputfile 1

       elif j == 4:                                              # In
           case of the strange quark decay, the up and down quark
           decay is calculated
               b = (Mu/Ms)**2 * (z[j])
               c = (Md/Ms)**2 * (z[j])
               f_out1.write("%25s %25s %25s" % (z[j], b, c))
                          # All these values are written to outputfile 1
       elif j==6:
               if z[0] <= 300:
                                               # When the Higgs mass
                  is smaller than 300 GeV, a new value is computed for
                  the tt decay
                      if z[0] > 80.4:
                             fx = y3*(z[0]/x3)**(ex)
                                                       # This is done
                                 by using the two slopes calculated in
                                 section 4.2
                      else:
                             fx = y3*(80.4/300)**ex*(z[0]/80.4)**ex2
                      f_out1.write("%25s" % (fx))
               else:
                      f_out1.write("%25s" % (z[j]))
       else:
               f_out1.write("%25s" % (z[j]))       # In the case of all
                  the other decay channels, the branching ratio is
                  copied to outputfile 1

for k in range(1, len(x)-1):                       # This loop runs
    through the lines of datafile 2
       if k==3:
                  # In case of the Z GAM decay, the branching ratio
           for M_H < 100 is change to keep the Z GAM line parallel to
           the ZZ line
               if x[0] <= 100 :
                      c = x[5]*g
                                 # The value g = h[0] found at the
                          beginning is used
                      f_out1.write("%25s" % (c))
               else:
                      f_out1.write("%25s" % (x[k]))
       else:
               f_out1.write("%25s" % (x[k])) # The branching ratios are
                  copied to outputfile 1.
f_out1.write("\n")
```

```
f.close()                            # De different input and outputfiles are closed
f2.close()
f_out1.close()

#----------------
#Calculating the product of the branching ratios
#----------------

#In this section, the product of the branching ratios is computed, including the
    choices made by the user

brsfile = open(fileoutput2, "r")            # The file with all the branching ratios
    (from now on, the datafile) is now opened in read-mode
productfile = open(fileoutput1, "w") # The second outputfile is opened in write-mode

lines3 = brsfile.readlines()                # The lines of the datafile are read

count3 = len(lines3)                               # The number of lines of this file
    is counted

for q in range(count3):                            # q runs through the lines of the
    datafile
        y = 10**150                                                  # The product is
            enlarged to ensure the value is not too small for Python
        t = list(map(float,lines3[q].split())) # For each line 'q', the branching
            ratios are stored in the list 't'
        for w in range(len(t)-1):           # For each line 'q' of the datafile, 'w'
            runs through list 'v' to decide if a decay channel should be taken into
            account
                if v[w] == 1:                      # A decay channel is only used in
                    the product when the user wants it
                        if w ==0 or w==4 or w ==5 or w==6 or w ==7 or w==8:       # If
                            'w' corresponds to one of the quark decay channels, the
                            correct number of spin states and color states is used
                                y = y*((1/(qu*s1))*(t[w+1]))**(qu*s1)
                        elif w==1 or w==2 or w==3 or w==10 or w==11:              #
                            Similar for the lepton decay channels, the channels with
                            one or two photons,
                                y = y*((1/(s1))*(t[w+1]))**(s1)
                        elif w==9:
                                                                 # for the gluons
                                y = y*((1/(gl*s1))*(t[w+1]))**(gl*s1)
                        elif w==12 or w==13:
                                                  # and for the ZZ and WW decay.
                                y = y*((1/(s2))*(t[w+1]))**(s2)
                        else:
                                y = y*t[w+1]
        if q == 0:
                                 #When the product is computed, the Higgs mass and
            the value of the product are written to the correct outputfile
                productfile.write(str(t[0]) + " " + str(y))                #To ensure
                    the data can be plotted correctly, the first line does not start
                    with a newline command
        else:
                productfile.write("\n" + str(t[0]) + " " + str(y))
```

```
productfile.close()          # The files are closed
brsfile.close()

#--------------------------------
#      Het product plotten
#--------------------------------

#The goal of this section is to plot the product and fit a gaussian curve through the
    data points

p = input('Wil je de Gaussische fit ook laten zien? (Y/N) \n')          #The user
    decides if he wants to plot the gaussian fit.
f3 = open(fileoutput1,'r')                                       #Open the file with
    the values of the product

dat = f3.read()                                                         #The data is
    read

data = dat.split('\n')                                           #The different lines
    are seperated
x = [row.split(' ')[0] for row in data]           #The first component of a line is
    the x value, the second component is the y value
y = [row.split(' ')[1] for row in data]
n=len(x)

def gaus(t,a,x0,sigma):                                          #The gaussian curve
    is defined, it will later be used to fit the data points
       return a*np.exp(-(t-x0)**2/(2*sigma**2))

xdata = np.array(x, dtype=float)                          #The data is stored in
    arrays as 'float'
ydata = np.array(y, dtype=float)

xmax = 0
ymax = 0
for i in range(n):                                                      #The maximum
    of the data points is determined. The corresponding x value is the mean value of
    the distribution
       if ydata[i]>ymax:
              xmax = xdata[i]
              ymax = ydata[i]
mean=xmax
sigma = (sum((xdata-mean)**2/n))**(1/2)           #The deviation is calculated

popt, pcov = curve_fit(gaus, xdata, ydata,p0=[max(ydata),mean,sigma]) #The function
    'curve_fit' changes the parameters of the gaussian function so that it fits the
    data points the best way possible
print('[a,x0,sigma] =',popt)                              #These parameters (The
    factor before the exponent, the mean value and the deviation) are printed
def f(p):                                                                      #The
    parameters are used in the gaussian function
       return gaus(p,popt[0],popt[1], popt[2])

plt.plot(xdata,ydata, label = 'data')             #The data points are plotted
if p == 'Y':                                                            #If the user
    decides to plot the gaussian fit, this curve is plotted in the same graph.
       plt.plot(xdata,f(xdata), label = 'fit', marker = '+')
plt.axis([10,1000,0,max(ydata)*1.2])
```

```
plt.xlabel('Higgs mass (GeV)')
plt.show()
f3.close()
```

9.2 Graphs

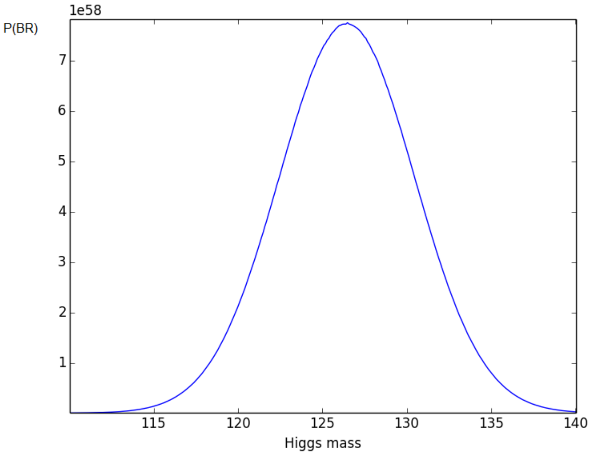

Figure 9.1: Product including different spin states
$\mu = 126.5$ GeV

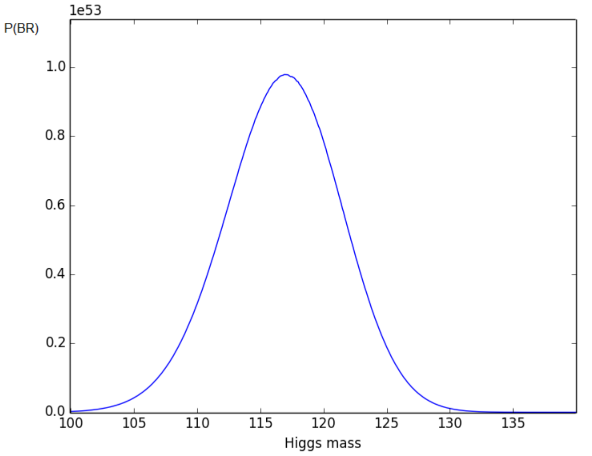

Figure 9.2: Product including different color states
$\mu = 116.9$ GeV

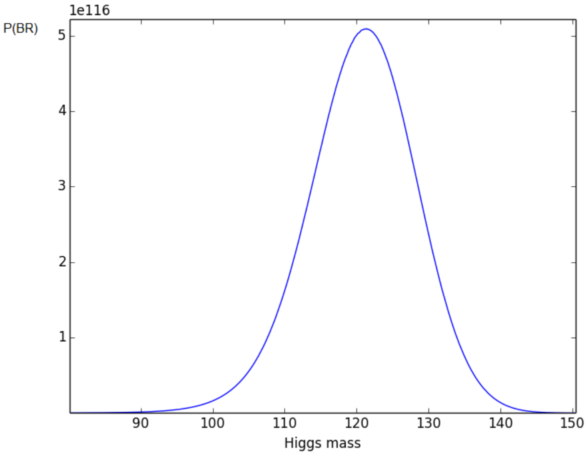

Figure 9.3:
Product without loop mediated processes
$\mu = 121.1$ GeV

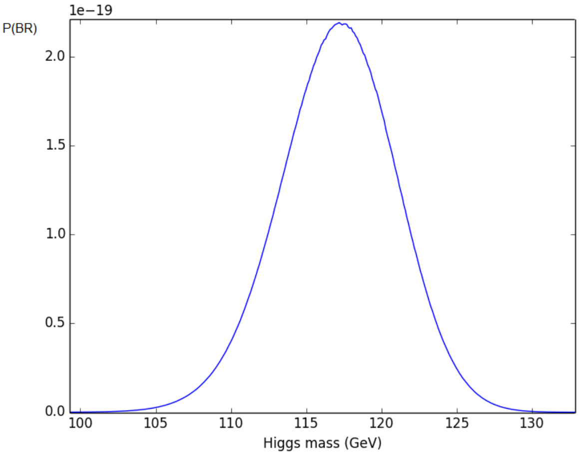

Figure 9.4: Product with modified Zγ and t$\bar{\text{t}}$ BR
$\mu = 125.0$ GeV