Investigation of a dark matter particle in the Higgs Portal model

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Bachelor Thesis (BSc)

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Graz

2016

Abstract

The Higgs-Portal Theory suggests that a possible candidate for the dark matter particle (D) could have a significant coupling to the Higgs field which means that when the Higgs particle decays two dark matter particles could be produced.

Current research has promoted theories of invisibly decaying Higgs particles. Non-vanishing probabilities for the Higgs to decay invisibly have been especially notable for the ZH mode.

Based on these theories the decay $p\ p \to Z\ H$ has been examined. By simulating the process at the LHC for the ZH mode with H decaying into DD with the event generator SHERPA, different properties of this dark matter candidate are investigated. The self-coupling of the dark matter particle has been kept constant, whereas its mass and coupling strength to the Higgs field have been varied. Since it cannot be detected directly the missing energy has to be studied. Also neutrinos can only be found as missing energy so one has to distinguish whether the signal is coming from a dark matter particle or a neutrino. Therefore the quantity of interest R has been defined as ratio of the sum of the dark matter signal and neutrino signal to the neutrino signal.

Notable areas in the phase diagram turned out to be those with large values of mass where R approaches 1 and large values of coupling strength for which R increases. Furthermore, a maximum at about 60 GeV of mass stands out.

In this thesis, the two mentioned theories are introduced and the results from the simulations are presented.

Contents

Chapter 1

Introduction

First indications for the existence of dark matter were found by Fritz Zwicky in 1933 while observing the Coma Galaxy Cluster. He deduced its mass from the motion of some of its galaxies and compared the value to that derived from their brightness. He found that they differed significantly and inferred that there must be some kind of "invisible" mass which he called dark matter. [1] Further research followed to confirm the existence of dark matter. Since around 1980 the necessity for its existence is widely accepted and it has been regarded as one of the major unsolved problems in astronomy.

Since this time the question of what dark matter is, has been one of the big questions in physics that are yet to be answered. Currently some of the most promising candidates include MACHOs (Massive Astrophysical Compact Halo Objects) and WIMPs (Weakly Interacting Massive Particles) .

More generally speaking, massive particles (MP) which can interact either weakly or strongly form an interesting class of plausible candidates. The so-called Higgs Portal Dark Matter belongs to this group which is going to be subject of this thesis. In general, the Higgs Portal model is a model in which the Higgs field couples to a newly introduced field. The Higgs sector allows for coupling to the hidden sector and is still renormalizable which leads to numerous interesting theories. Among other options, it would allow for a new field for the dark matter particles to couple to the Higgs field. Therefore in processes where Higgs particles are produced also dark matter particles could be produced. [3]

During the past decades the idea of an invisibly decaying Higgs boson has come up and led to research exploring its possibilities. [4] Invisible means in this case that it decays into particles that cannot be detected directly. Previous research has studied the possibilities of detecting the Higgs over this invisible channel. This included various options for the final states i.e. the particles into which the Higgs could decay invisibly. If this holds true, the data produced in the experimental pursuit of the Higgs particle itself could contain information about this hidden sector. There are many possibilities what these so-called hidden sector particles could be and therefore many different final states into which the Higgs could go. One possibility would be that it goes into a Higgs and two dark matter particles. This would be imaginable because hidden sector particles can be stable and couple weakly to the standard model sector. [3]

One possibility for an invisible decay would be the decay of the Higgs particle into

two dark matter particles (D). As mentioned, these particles cannot be detected directly but it is possible to look for missing energy which cannot be assigned to any other particle. However in the standard model the neutrinos also cannot be detected directly and therefore have to be accounted for as background when considering missing energy.

An especially interesting decay mode in terms of signal strength compared to the background signal turns out to be the ZH mode where the protons decay into a Z boson and a Higgs particle. [4] For this reason the process $p\ p \to Z\ H\ D\ D$ is studied throughout this thesis. Using the event generator SHERPA [1], the process is simulated and the signal compared to the neutrino signal. Within the here suggested model different properties of the dark matter particle are imaginable. In this thesis the self-coupling of the dark matter particle has been kept constant, whereas its mass and coupling strength to the Higgs field have been varied. Simulations of various combinations of these parameters are shown and notable areas in the resulting phase diagram are pointed out with possible explanations. Upcoming and further research starting from these results is denoted.

[1] see SHERPA references, p.27

Chapter 2

Dark Matter

In this chapter the explanations follow closely [1].

The first to suggest the existence of dark matter were Dutch astronomers Jacobus Kapteyn in 1922 who studied stellar velocities and Jan Oort in 1932 who studied (though erroneous) stellar motions in the local galactic neighborhood.

The discoveries made by Fritz Zwicky in 1933 described before were then the first indications for the existence of some invisible mass which he called "dunkle Materie", dark matter.

Further strong evidence came from the research done by Vera Rubin using galaxy rotation curves. She measured the velocity curve of edge-on spiral galaxies (which consist of a flat rotating disk of stars, gas and dust) with great accuracy. From this she deduced their masses and found discrepancies to the masses inferred from their brightness. This work led to a broad acceptance of the existence of dark matter and made the question of what dark matter is to one of the major quests in astronomy and particle physics, which as yet remains unsolved.

Analysis of Cosmic Microwave Background (CMB) anisotropies lead to the conclusion that the Universe is practically flat with $\Omega_{tot} = 1$. Combining the CMB data and data from studying super novae Ia at high redshift the total energy density of matter can be deduced to be $\Omega_m \approx 0.3$. This includes baryonic and dark matter. From Big Bang Nucleosynthesis data today's fraction of the baryon energy density is set to be $\Omega_B \approx 0.05$. This is what is considered ordinary matter. Of this only a small fraction is contributed by stars $\Omega_{stars} \approx 0.003 - 0.1$ and most of it is made up by gas in the interstellar medium and non-luminous bodies like planets. The remaining 0.7 is accounted for by dark energy.

2.1. Observational evidence

The galaxy rotation curve mentioned above plots the velocity *v(r)* of the gas cloud around the galaxy against the distance r from the center of the galaxy. This velocity can be measured from the Doppler shift of spectral lines.

Setting the centripetal force equal to Newton's universal law of gravitation one obtains:

$$\frac{v(r)^2}{r} = \frac{G_N M(r)}{r^2} \rightarrow v(r) = \sqrt{\frac{G_N M(r)}{r}} \tag{2.1}$$

with *M(r)* being the total mass within the radius r. So for the velocity it is expected that $v \propto r^{-1/2}$ but observation shows that for large r $v \approx const$ and therefore $M(r) \propto r$. This means that the galaxy's mass stretches out farther than the optical observations suggest. Up until today large numbers of galaxy rotation curves have been measured and the results confirm the theory of dark matter. The data suggests that every galaxy is surrounded by a halo of dark matter about ten times more massive than the stars contained in the galaxy.

Another way to observe the effects of the existence of dark matter is gravitational lensing. As a direct consequence of Einstein's theory of general relativity very massive objects such as galaxy clusters bend the light coming from the source to an observer in a way similar to an optical lens. Observations of this effect led to the conclusion that the masses of the clusters inferred from the visible parts of the galaxy could not account for the lensing effects detected.

Also measurements of the Cosmic Microwave Background temperature fluctuations show that non-baryonic matter has to be included in order to account for the observational data.

The Bullet Cluster is said to be the best evidence for dark matter. It consists of two subclusters that collided and passed through each other about 150 Myr ago. Apparently stars, baryonic matter in form of gas and dark matter behave quite differently during collision. This implies that dark matter interpreted as a modification of gravity at kpc scale can be ruled out. The stars mostly just passed through, hardly affected by the collision. The hot gas interacted electromagnetically and concentrated at the center of the system. Without dark matter it would be expected that the gravitational lensing effects would follow the baryonic matter but observation showed that this is not the case. Most of the cluster's mass was not affected by the collision. This is interpreted as to imply that most of the mass consists of weakly interacting dark matter.

2.2. Possible candidates

Ever since its existence had been discovered, the major question has been and remains what dark matter is. Over the years many suggestions have been made and a number of those were ruled out. Despite this fact, there are still many possibilities and no direct clues which one would be favorable. Some of the (supposedly) most promising candidates will be shortly presented.

MACHOs (MAssive Compact Halo Objects)

At first astronomers began to search for MACHOs to investigate whether they could account for the missing mass. They are objects made up from ordinary mass such as black holes, neutron stars and brown dwarfs. However promising they seemed at first,

they could be ruled out as dark matter candidates quickly. Black holes and neutron stars are both massive and can be dark but in order to account for all the dark matter they would have to be observed more often which is not case. Additionally, since they are remnants of super novae great amounts of energy and heavy elements should be released which are not detected sufficiently often.

Brown dwarfs are stars that are too light to produce nuclear reactions in order to shine. But even though they fulfill the requirements and also have been observed using gravitational lensing, there is no evidence of a large enough population to account for all the dark matter in the Universe.

WIMPs (Weakly Interacting Massive Particles)

WIMPs are particles that interact only via the weak nuclear force, through the Higgs Portal or have a very small electric charge. They interact with ordinary matter and are expected to have a mass in the GeV or TeV range which would make it possible to detect them. They seem to be very promising because of the so-called WIMP miracle: particles with a mass of 100 GeV-1 TeV subject to the nuclear force in the primordial plasma should have decoupled at an energy of about 10 GeV. This would mean their abundance today would be expected to be $\Omega_m \approx 0.3$ which would be in agreement with observation. Before their mass limits were found, neutrinos were considered a possible candidate for dark matter but it is now known that their mass is by far too small to account for all the dark matter in the Universe.

Particles self-interacting strongly are also possible candidates and form together with the WIMPs the group of massive particles (MP). The particles under investigation in this thesis belong to the group of the MPs.

Lightest Supersymmetric particle

Supersymmetry is a possible theory to solve the hierarchy problem. This problem leads to the necessity to protect the Higgs mass from quantum corrections that would make it huge. It is suggested that every boson and fermion has a supersymmetric partner from the other group. The lightest one of these partners would make a possible dark matter candidate. Under so-called R-parity this particle would be stable. Currently the neutralino seems to be one of the best candidates. It is a superposition of the bino (super-partner of the gauge boson associated with the symmetry group $U_Y(1)$),the neutral wino (super-partner of the neutral gauge boson associated with $SU_L(2)$) and the neutral Higgsino (super-partner of the Higgs scalar). Other possibilities include the gravitino and the sneutrino, of which the latter would not be a possible candidate in the minimal supersymmetric extension of the standard model but could be an option in more advanced models. So far, no super-partners could be detected at the LHC and other experiments.

Axion

A theory that could solve the strong CP-problem in QCD proposes to introduce a new global U(1) symmetry that is spontaneously broken at low energies about 100 MeV. This would lead to the existence of a spin-0 particle which is called the axion. It is considered to have a small mass but would nonetheless be a viable candidate for dark matter. Experiments to find it have been carried out during the past years but it hasn't been found.

Chapter 3

Theory

3.1. Higgs Portal Model

Many theories that exceed the Standard Model (SM) and are subject of research include a hidden sector. This means they include quantum fields and corresponding particles that do not interact directly via the known gauge bosons of the SM. It can be theoretically motivated that these sectors consist of $\mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)$ singlet fields. Since SM fields couple to a variable number of the SM gauge fields it is also imaginable that there exist additional gauge fields which transform under the new gauge symmetries but not under the familiar ones. [2]

One of these models is called the Higgs Portal or Hidden Valley model. The Higgs sector in the SM is somewhat special because it allows for direct coupling to the hidden sector and is still renormalizable. Therefore, information about the properties of the Higgs boson could deliver information about what lies beyond the SM. The confirmation of the existence of the Higgs particle with mass $m_H \approx 125$ GeV in 2012 was a major discovery confirming the Standard Model. The mentioned indirect information about the hidden sector has become more available through the discovery. This will even be more so with the data of the LHC that still has to be evaluated and the data that will be produced in the future. Even though the properties of the discovered Higgs boson are consistent with the Standard Model, it is also possible that it decays through channels that are not predicted by the SM.

This new information about the "hidden world" is especially interesting with regards to dark matter. Hidden sector particles are considered a feasible dark matter candidate because they can be stable and couple very weakly to the SM sector. [3]

As a consequence of this, the Higgs could be decaying into particles that do not interact with the detectors. This means that the Higgs could be coupling to a particle that constitutes parts or all of the dark matter.

In order to account for quantum number conservation of the Higgs boson and the dark matter particle, it is necessary that the virtual Higgs with higher energy goes into a Higgs and two dark matter particles. The Feynman diagram of this process is shown in fig. 3.1.

3.2. Invisibly decaying Higgs particle

The idea of the invisibly decaying Higgs particle became especially important during the search for the Higgs particle because it suggested that the search had to be extended to this invisible decay channel.

The possibility for such invisible decay modes for the Higgs boson is given in numerous theories including models with: light neutralinos, spontaneously broken lepton number, radiatively generated neutrino masses, additional singlet scalar(s) and/or right handed neutrinos in the extra dimensions of TeV scale gravity. [4]

It is possible to detect a Higgs boson through different decays, most notably at LHC via its associated production with a gluon, W or Z boson. Of these, the first two cases have a very large background and therefore a small signal/background ratio whereas the decay into a Z boson provides a clean signal for missing energy. [4] For this reason the process investigated in this thesis is $p\ p \rightarrow Z\ H \rightarrow Z\ H\ D\ D$. In order to guarantee for a stable dark matter particle, a new quantum number is introduced in the model: dark matter parity. The dark matter particles are assigned a dark matter parity of -1 and any standard model particle is assigned 1. This leads to the fact that the dark matter particles cannot decay into SM particles and explains the necessity to have two Ds and an H as final states: Produced as a pair the product of their dark matter parity numbers yields 1 again.

The process shown in the Feynman diagram[1] in fig. 3.1 will be investigated throughout this thesis. The Higgs Portal model explains the combined production of H and DD of which the dark matter particles can only be detected via missing energy according to the idea of an invisibly decaying Higgs particle.

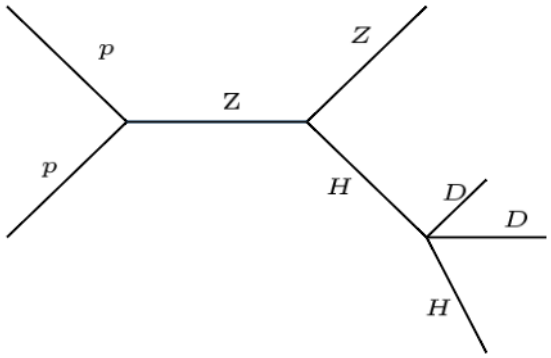


Figure 3.1.: Feynman diagram of the process under investigation

[1] all Feynman diagrams have been created with http://feynman.aivazis.com/

Chapter 4

Methods

4.1. Event generators

Event generators are a vital part of research especially concerning particle physics since they offer a connection between a theory and the corresponding experiment. The complexity of how they work lies within the great number of modifications of tree-level perturbative quantum field theory. These modifications are necessary in order to accurately simulate collision and decay processes and include different forms of bremsstrahlung and loop diagram corrections.

PYTHIA, HERWIG and SHERPA are currently the major hadronic event generators and are widely used to simulate experiments.

4.2. Sherpa

In this thesis, the event generator SHERPA 2.2.0 [1] has been used to produce the data. SHERPA is a Monte Carlo event generator that simulates particle collisions at high-energy colliders. It is based on a tree-level matrix-element generator in order to calculate hard scattering processes. SHERPA is able to simulate the outcome of processes within the Standard Model and partially beyond.

As many other event generators, SHERPA relies on the principle that possible events can be separated into different well-defined phases. Numerical approximations are applied at every phase to describe the current status. [5]

The hard process is the main part of the event simulation and can be calculated in fixed order perturbation theory. This is done by computations based on matrix elements, which are provided by special programs called matrix-element (ME) generators.

Next, the QCD bremsstrahlung is modeled by parton showers in an approximation to exact perturbation theory. These partons are then made into hadrons again by applying phenomenological fragmentation models.

Now, the initial hadrons have decayed into particles that can be detected.

[1] see SHERPA references, p.27

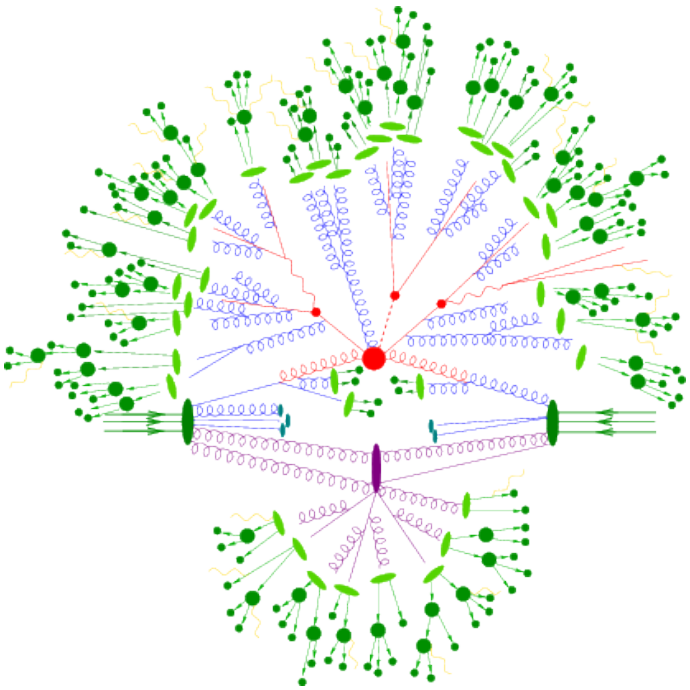


Figure 4.1.: Representation of phases calculated by event generators (source: [5])

In order to get an even more precise result, QED bremsstrahlung is simulated and included.

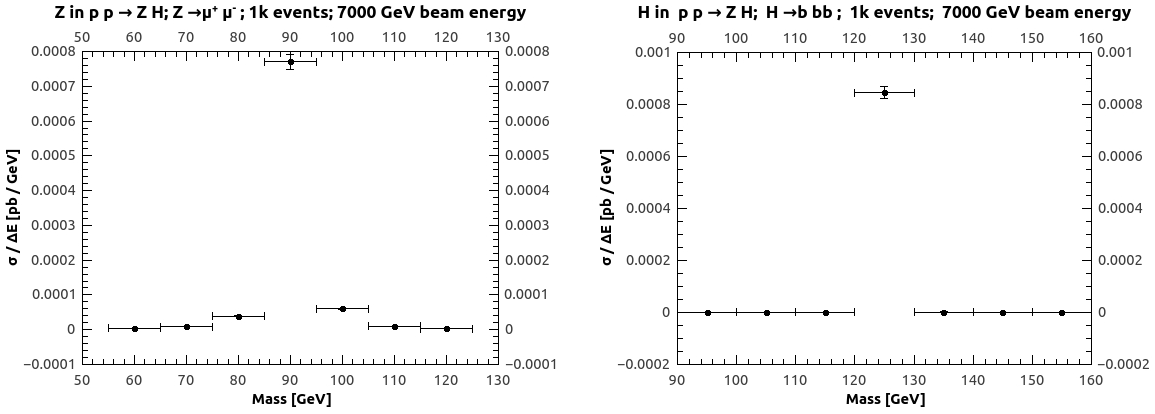
Additional difficulties in the simulations arise through so-called semi-hard or secondary hard processes: When hadrons collide, remnants of the incoming hadrons may again interact. In theses cases, no complete first-principles theory is available and so phenomenological models are employed again. [6]

4.3. Usage of Sherpa

SHERPA has a great number of possible applications and possibilities to generate events. It includes the Standard Model of Particle Physics and some other models.

Here, it has been used to simulate the proton collisions at the LHC as quark anti-quark decays. It has built-in selectors, of which the selector on the invariant mass has been applied here. A file including information about the process and selectors is used by SHERPA as input which then produces a value for the cross section of the process as output.

Figures 1 and 2 show the results for the decays $p\ p \to Z\ H$ with $Z \to \mu^+\mu^-$ and $H \to b\ \bar{b}$.



(a) Z (b) Higgs

Figure 4.2.: decays $p\ p \to Z\ H$ with $Z \to \mu^+\mu^-$ and $H \to b\ \bar{b}$

The masses of the two particles can be found from the maxima of the curves and match perfectly the experimentally found masses for the Z boson and the Higgs particle.

In order to use Sherpa to simulate a process that includes dark matter particles, this new Dark Matter Model has to be included. The model has been generated with the package FeynRules[2] and can be included into Sherpa by using the Universal FeynRules Output (UFO) interface.

The parameters for the mass of the dark matter particle (MDM) and its coupling strength to the Higgs field (PCS) could be varied in the UFO interface and were included into SHERPA in this way. Then the simulation was run for the two processes $p\ p \to Z\ H\ D\ D$ and $p\ p \to Z\ H\ \nu_x\ \nu_x$. Here ν_x indicates any of the three neutrino flavours. The neutrino final state has to be considered because both the neutrino signal and a dark matter signal could only be studied by examining missing energy. The neutrino cross section has been simulated within the dark matter model and for comparison in a reference standard model. The selector cuts have been chosen as $[M_{inv}, M_{inv} + 20GeV]$ meaning that the interval size has been chosen to be 20 GeV, unless otherwise indicated. An example Run.dat which was run by SHERPA in order to produce the data shown in this thesis is attached in appendix A.

[2]see FeynRules references, p.28

Chapter 5

Relativistic mechanics and background signal

In this chapter, the underlying kinematics and the background signal coming from the neutrinos are being considered.

5.1. Relativistic mechanics

Particle collisions can be described by applying relativistic mechanics. The key point here is four-momentum conservation. The four-momentum is defined as:

$$p^\mu = \left(\frac{E}{c}, \mathbf{p}\right) = (E, \mathbf{p}) \tag{5.1}$$

with $\mathbf{p} = (p_x, p_y, p_z)$ being the three-momentum and E the energy. Here and in the following natural units with $c = \hbar = 1$ are applied.

In a particle collision the four-momentum is equal to the sum of the four-momenta of the particles participating in the collision $p^\mu = \sum_A p_A^\mu$. This sum has to obey four-momentum conservation which means that it has to be the same before and after the collision:

$$p_{before}^\mu = p_{after}^\mu \rightarrow \sum_A p_A^\mu = \sum_{A'} p_{A'}^\mu \tag{5.2}$$

The index A indicates the particles present before the collision and A' after the collision. The laws of conservation in non-relativistic mechanics for mass, energy and three-momentum are replaced by this conservation law of four-momentum in relativistic mechanics.

The invariant mass is an important quantity in relativistic mechanics and will in this thesis be used to specify the cuts used in SHERPA. It is (in natural units) defined as

$$M^2 = E^2 - p^2 \tag{5.3}$$

with p being the absolute value of the three-momentum.

Example: $e^+e^- \to \mu^+\mu^-$

In this example it is assumed that the electron and positron collide exactly face on which means they have exactly opposite three-momentum. The same is assumed for the muons, separating in exactly opposite directions. Four-momentum conservation leads to:

$$\begin{pmatrix} E_1 \\ \mathbf{p_1} \end{pmatrix} + \begin{pmatrix} E_2 \\ -\mathbf{p_1} \end{pmatrix} = \begin{pmatrix} E_3 \\ \mathbf{p_2} \end{pmatrix} + \begin{pmatrix} E_4 \\ -\mathbf{p_2} \end{pmatrix} \tag{5.4}$$

The two terms on the left side of the equation represent the electron and positron and the two terms on the right side represent the muon and anti-muon. Since the three-momenta cancel out, this leads to $E_1 + E_2 = E_3 + E_4$. The energies E_1 and E_2 are the energies of the beams that collide and can therefore be set to a certain value by the experiment and be chosen equal $E_1 = E_2$. As a consequence: $E_1 = E_2 = E_3 = E_4$.

Then the absolute values of the three-momenta can be calculated :

$$p_1 = {E_1}^2 - {M_e}^2 \tag{5.5}$$

$$p_2 = {E_3}^2 - {M_\mu}^2 = {E_1}^2 - {M_\mu}^2 \tag{5.6}$$

Example: $e^+e^- \to Z, \quad Z \to \mu^+\mu^-$

A similar description can be done when considering that the electron and positron do not decay directly into muon and anti-muon but decay into a Z boson which then decays further. The following Feynman diagram represents this process.

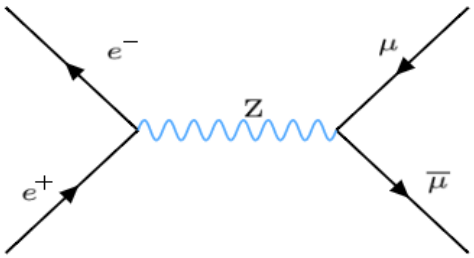


Figure 5.1.: Feynman diagram of $e^+e^- \to Z, \quad Z \to \mu^+\mu^-$

The calculation can be split up into two steps just as the describtion suggests.

$$\begin{pmatrix} E_1 \\ \mathbf{p_1} \end{pmatrix} + \begin{pmatrix} E_2 \\ -\mathbf{p_1} \end{pmatrix} = \begin{pmatrix} E_5 \\ \mathbf{p_3} \end{pmatrix} \tag{5.7}$$

$$\begin{pmatrix} E_5 \\ \mathbf{p_3} \end{pmatrix} = \begin{pmatrix} E_3 \\ -\mathbf{p_2} \end{pmatrix} = \begin{pmatrix} E_4 \\ -\mathbf{p_2} \end{pmatrix} \tag{5.8}$$

For the same reasons explained above, it follows that $E_1 + E_2 = E_5 = 2E_1$. And:

$$p_3 = {E_5}^2 - {M_Z}^2 = 4{E_1}^2 - {M_Z}^2 \tag{5.9}$$

These equations describe the process completely. Simulations for this process where the final states includes the Z and H can be seen in section 4.3.

Process under consideration

In the process under consideration in this thesis the Z boson goes into Z and H which then further goes into H and D D:

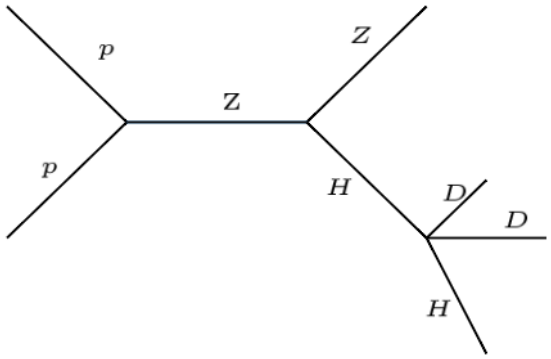


Figure 5.2.: Feynman diagram of the process under investigation

For the simulations the invariant mass has to be calculated from the mass of the dark matter particle MDM, here denoted as m:

$$M_{eff}^2 = (p_1 + p_2)^2 \tag{5.10}$$

In the rest frame this becomes:

$$M_{eff}^2 = (m + m(0,0,0))^2 = 4m^2 \tag{5.11}$$

Therefore, the lower bound for the invariant mass is $M_{inv} = 2m = 2MDM$ which has been chosen as the lower bound for the selector cuts in SHERPA as explained in section 4.3.

The simulation of the whole process with the final state being Z H D D is subject of this thesis and the results will be shown in chapter 6.

5.2. Neutrino background

Dark matter particles cannot be detected directly in detectors. However after identifying the processes that take place in the detector it is possible to reduce the signal

to an amount of missing energy that cannot be identified with any known process. Investigating this missing energy would be a possibility to indirectly detect dark matter particles.

Neutrinos are being detected in the same way since they only interact via weak interaction. An example for the creation of an neutrino is the β^--decay which describes the decay of a neutron into a proton, an electron and an anti-electron-neutrino. Since neutrinos hardly interact with matter, most of today's existing neutrinos have been created shortly after the big bang and have simply remained. Additionally, neutrinos are being produced all the time at major events in the universe such as super novae and during the creation of stars. A number of neutrinos is also being produced by mankind at particle accelerators and nuclear power plants. According to the standard model of elementary particles, neutrinos do not have masses but observation has shown that they do have masses, however very small. There are three different flavors, each relating to its charged partner: electron-, mu-, and tau-neutrino. Specific detectors, so-called Cherenkov detectors, have been built to detect neutrinos during the past years. They make use of the fact that when neutrinos interact weakly with certain elements or molecules Cherenkov radiation is produced. These detectors lie deep underground in order to shield them from cosmic and other radiation because the neutrino signal itself is so weak.
At other detectors such as the LHC, neutrinos cannot be detected in this way but they do show up as missing energy. For this reason, they also have to be considered when making simulations. In order to distinguish the missing energy signal coming from neutrinos and from the dark matter particle, the ratio of the sum of the neutrino signal and dark matter signal in the newly introduced model to the neutrino signal in the standard model will be calculated and plotted in the following.

Chapter 6

Results and Interpretation

As described before, when analysing the missing energy the neutrino signal has to be accounted for. For this reason the quantity shown in the following plots is:

$$R = \frac{\sigma_{\nu\nu}^{DM} + \sigma_{DD}^{DM}}{\sigma_{\nu\nu}^{SM}} \tag{6.1}$$

here, DM (Dark matter Model) and SM (Standard Model) represent the model used in SHERPA to create the values.

6.1. Chosen values and overview

In the dark matter model the parameters that are examined in this thesis are the mass of the dark matter particle MDM and the coupling between the Higgs field and the dark matter field PCS. In order to investigate a broad spectrum of possible values they were chosen approximately logarithmically equidistant for the mass between 10 and 10^3 GeV and for the coupling strength between 10^{-3} and 10^3. The simulation was run for all possible combinations and R according to eq.(6.1) was plotted.
The following values were used

$$MDM : 10, 18, 30, 45, 50, 60, 90, 150, 250, 400, 700, 1000$$

$$PCS : 0.01, 0.04, 0.15, 0.6, 1, 2.5(, 10, 35, 120, 400, 700, 1000)$$

For a coupling of 10 and higher the resulting values for R were irrelevantly large and therefore not included in the following plots.
To get an overview over the influence of the two parameters on the output for R, the following plots show all combinations of MDM and PCS and *log(R)* on the z-axis.

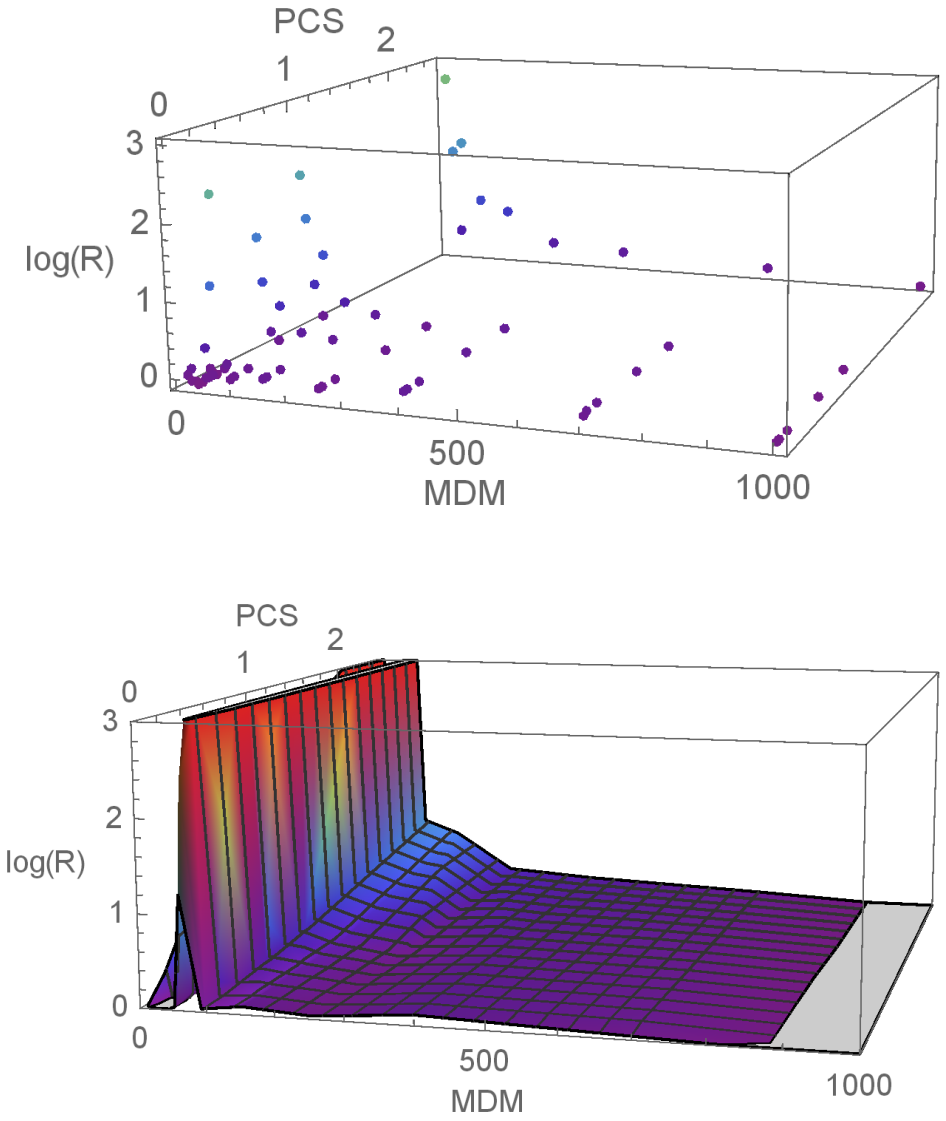


Figure 6.1.: Logarithmic scatter and surface plot for all values of R

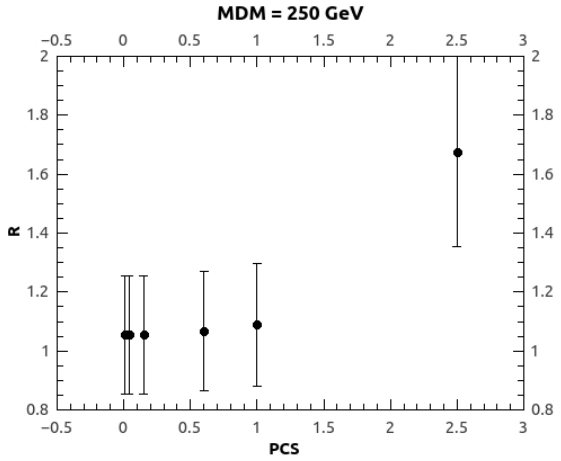
The plots show various regions of interest that will be further discussed in the following sections. These features are:

- For large masses R evens out and seems to be approaching a value of $log(R) = 0$ i.e. R=1 asymptotically
- Large values of PCS lead to an increase in R
- In general small values of MDM seem favourable
- Especially at around 60 GeV a maximum appears

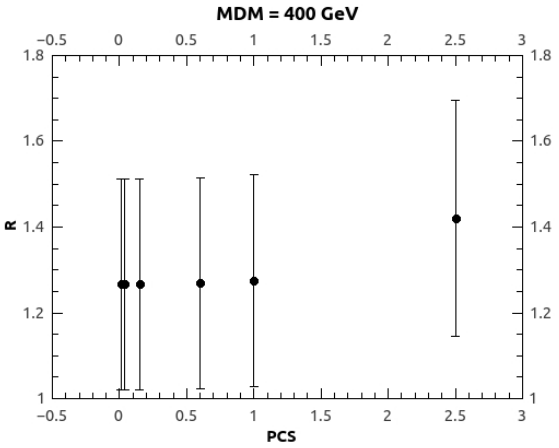
6.2. Large values of MDM

The plots in figure 6.1 show clearly that *log(R)* becomes very small for large values of MDM. The following plots show some examples where MDM is kept constant at a certain value and PCS is varied.

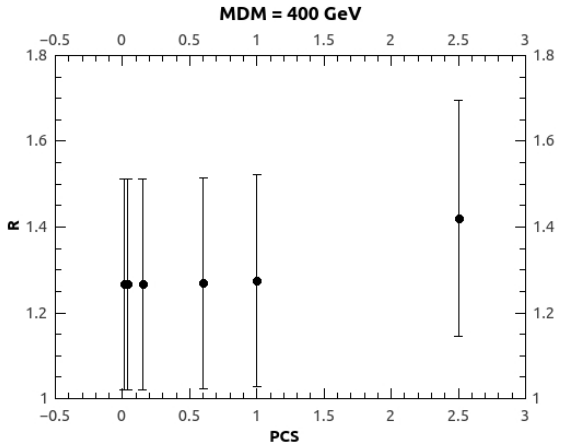
For increasing values of MDM R approaches a value of 1 and therefore the signal coming from the dark matter particle goes to zero. The reason for this is that the accelerator does not have sufficient energy to produce particles having such a high mass. The energy in the simulations throughout this thesis is chosen to be 7 TeV per beam which is what is possible at the LHC at CERN at the moment.



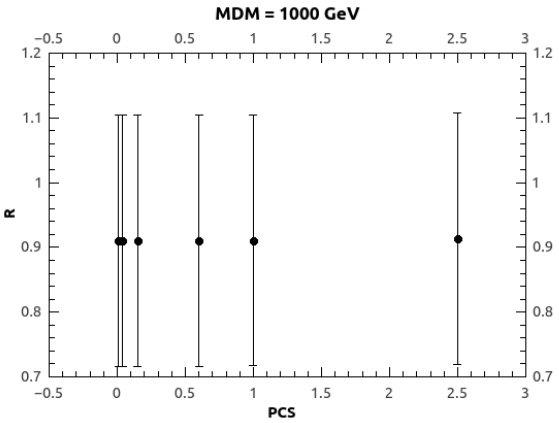
(a) MDM = 250 GeV



(b) MDM = 400 GeV



(c) MDM = 700 GeV



(d) MDM = 1000 GeV

Figure 6.2.: Plots for large values of MDM

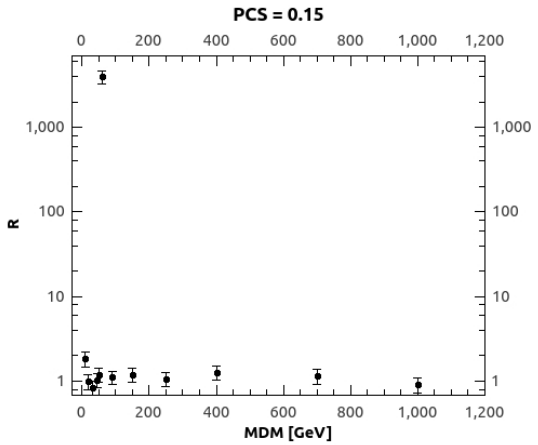
Since the protons each consist of three quarks the maximum effective energy would be a third of the accessible energy, so 2-3 TeV. This is the reason why the maximum chosen MDM investigated here was 1000 GeV (which has an invariant mass of 2000 GeV). In fact, an even distribution of the energy is only expected for quarks. Since also anti-quarks were considered, for which the parton distribution function does not have a maximum at one third, the available energy is even smaller.

Additionally, some of the energy is needed to produce the Higgs particle and the Z boson which reduces the available energy again by about 200 GeV.

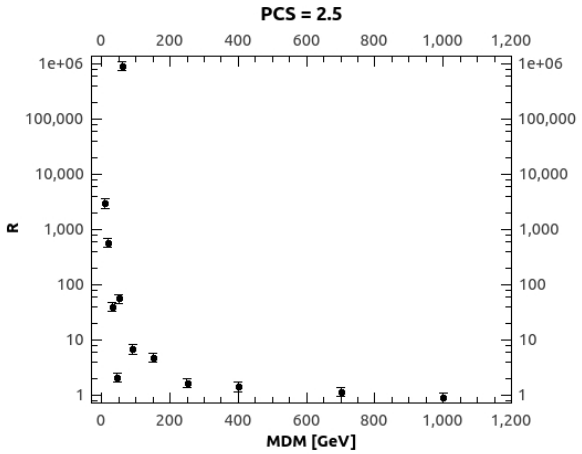
For these reasons only particles up to a certain mass can be produced and R approaches 1 since only the neutrino signal is present.

6.3. Large values of PCS

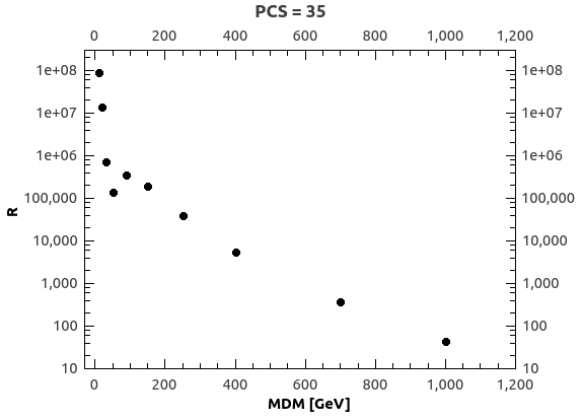
Especially in regions of smaller MDM it can be seen in figure 6.1 that R increases with increasing PCS. For this reason the following plots show the results for PCS kept constant at large values and varying MDM. As extreme examples also the plots for PCS = 1000 and PCS = 35 are included to show the fast growth even though the resulting Rs for PCS bigger than 2.5 were not shown in figure 6.1. For comparison, the plots for PCS = 0.15 and PCS = 2.5 are shown.



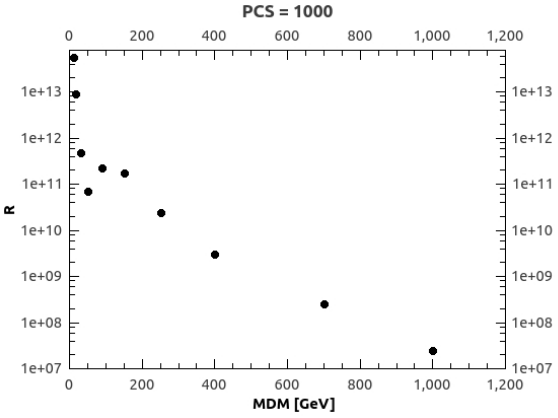
(a) PCS = 0.15



(b) PCS = 2.5



(c) PCS = 35



(d) PCS = 1000

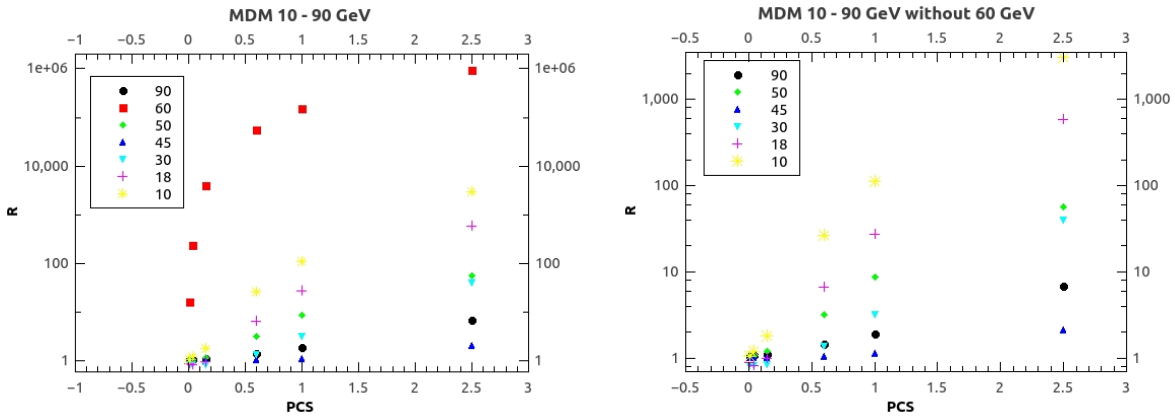
Figure 6.3.: Plots for large values of PCS

The reason for the fast increase of R with increasing PCS lies in the nature of the coupling. The coupling is described quantum mechanically by an operator. By calculating the cross section, which can be interpreted as a probability, the square of the absolute values has to be taken. Therefore the cross section depends on the squared coupling

strength of the Higgs field to the dark matter field. This means that for large values of PCS the signal is influenced by an extremely large factor which is the reason for the steep increase.

6.4. Small values of MDM

In the region of small values of MDM there seem to be generally larger values for R with an extreme maximum around 60 GeV. The following plots show the regions next to this maximum.



(a) MDM 10 - 90 GeV

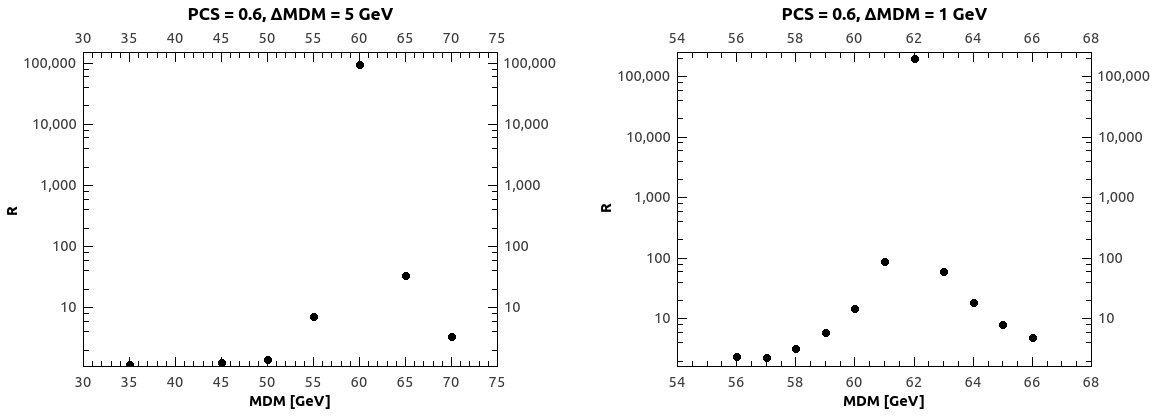
(b) MDM 10 - 90 GeV without 60 GeV

Figure 6.4.: Plots for small values of MDM

At first R decreases with MDM and reaches a minimum at 45 GeV. Then it continues and reaches the before discovered maximum at 60 GeV after which R decreases again. The minimum can be explained with the Z production. An MDM of 45 GeV corresponds to an invariant mass of 90 GeV which is approximately the mass of the Z boson. For this reason the neutrino signal is very high for this value. Therefore R is dominated by the neutrino signal and gets close to 1. The maximum at 60 GeV will be further investigated in the next section.

6.5. Maximum at 60 GeV

The maximum around 60 GeV is especially remarkable. Therefore it is examined in greater detail by reducing the interval width of the cut. The following plots show the results of simulations with 5 GeV and 1 GeV steps of MDM.



(a) $\Delta MDM = 5GeV$ (b) $\Delta MDM = 1GeV$

Figure 6.5.: Simulations for PCS = 0.6 with smaller intervals for MDM

It can be noted that the maximum is approached from both sides and lies actually at about 62 GeV. This corresponds to an invariant mass of 124 GeV which is consistent with the today accepted value for the Higgs boson of 125.36 ± 0.37 (stat) ± 0.18 (syst) GeV [7].

The extreme production of dark matter particles at this mass can be explained by the resonant production of the Higgs particle. Just as the Z production can be seen in an increasing neutrino signal also the H production can be seen as an increasing dark matter signal.

Chapter 7

Summary and Outlook

In this thesis the signal strength for a dark matter particle with varying properties within the Higgs Portal model has been investigated. Simulations with the event generator SHERPA[1] have been carried out for different values of the mass of the dark matter particle (MDM) and its coupling strength to the Higgs field (PCS). The values that have been used are shown in section 6.1.

To account for the neutrino signal which is also detected as missing energy the quantity that is shown in the plots is:

$$R = \frac{\sigma_{\nu\nu}^{DM} + \sigma_{DD}^{DM}}{\sigma_{\nu\nu}^{SM}} \tag{7.1}$$

here, DM (Dark matter Model) and SM (Standard Model) represent the model used in SHERPA to create the values.

The associated phase diagram which includes all studied values of MDM and PCS and the corresponding value of R is shown in fig. 6.1. Here, values of R with PCS>2.5 are not included.

The notable areas in the phase diagram which were investigated in more detail are: large values of MDM, large values of PCS, small values of MDM and a maximum at 60 GeV. For large values of MDM R approaches a value of 1 because the accelerator does not have sufficient energy to produce particles having such a high mass (fig.6.2). The energy of the beams is 7 TeV but effectively way less energy is available.

The main reasons for this are that the protons each consist of three quarks and also anti quarks are included which reduces the available energy.

For large values of PCS R appears to be generally higher (fig.6.3). This can be explained with the nature of the coupling. The cross section depends on the squared coupling strength of the Higgs field to the dark matter field. This means for large values that the signal is influenced by an extremely large factor which is the reason for the steep increase.

Generally speaking, small values of MDM seem favourable (fig.6.4). When having a more detailed look, it becomes apparent that at first R decreases with MDM and reaches a minimum at 45 GeV, then increases and reaches a maximum at 60 GeV. The minimum

[1] see SHERPA references, p.27

can be explained by the Z production with a corresponding invariant mass of 90 GeV which is approximately the mass of the Z boson. For this reason the neutrino signal is very high for this value and R gets close to 1.
A remarkable maximum is reached at about 60 GeV. Figures with smaller interval steps around 60 GeV are shown in fig. 6.5. It can be noted that the maximum is approached from both sides and lies actually at about 62 GeV. This corresponds to an invariant mass of 124 GeV which is consistent with the today accepted value for the Higgs boson of 125.36 ± 0.37 (stat) $\pm$ 0.18 (syst) GeV [7].

The extreme production of dark matter particles at this mass can be explained by the resonant production of the Higgs particle. Just as the Z production can be seen as an increasing neutrino signal also the H production can be seen as an increasing dark matter signal.

The plots show areas in the phase diagram where large signals for R can be expected. Experiments can further narrow down the diagram to areas with values of R that can be seen by experiments today.

In this thesis both cases for a strongly and weakly interacting dark matter particle were included since here only orders were considered in which the self-coupling constant does not contribute significantly. The investigation of a strongly interacting dark matter particle is subject of an upcoming master's thesis to reduce the phase diagram shown in fig. 6.1 to areas which are consistent with current experiments.

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Appendix A

Run.dat

```
(run){
  # general settings
  EVENTS 100;

  # me generator setup
  ME_SIGNAL_GENERATOR Comix;
  SCALES VAR{Abs2(p[0]+p[1])};

  # model setup
  MODEL DM_Model_UFO;

  # LHC beam setup:
  BEAM_1 2212; BEAM_ENERGY_1 7000;
  BEAM_2 2212; BEAM_ENERGY_2 7000;
}(run)

(processes){
  Process 1 -1 -> 23 25 6000 6000;
  Process 2 -2 -> 23 25 6000 6000;
  Process 3 -3 -> 23 25 6000 6000;
  Process 4 -4 -> 23 25 6000 6000;
  CKKW pow(10,-2.25);
  Max_Order (16,16);
  End process;
}(processes)

(selector){
  Mass 6000 -6000 60. 80.
}(selector)
```

```
(ufo){
block yukawa
        1 0.00504
        2 0.00255
        3 0.101
        4 1.27
        5 4.7
        6 172
        11 0.000511
        13 0.10566
        15 1.777
block ckmblock
        1 0.227736
block mass
        23 91.1876
        11 0.000511
        13 0.10566
        15 1.777
        2 0.00255
        4 1.27
        6 172
        1 0.00504
        3 0.101
        5 4.7
        25 125.09
block sminputs
        1 127.9
        2 1.16637e-05
        3 0.1184
block frblock
        1 61.5
        2 0.6
        3 1

decay 23 2.4952
decay 24 2.085
decay 6 1.50833649
decay 25 0.004
}(ufo)
```