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Towards Dark Matter through the Higgs Portal

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Abstract

The standard model of particle physics has proven to be one of the most successful theories in theoretical physics.
The discovery of the Higgs boson offers some new possibilities to solve some remaining problems.
One of those unsolved problems is the nature of dark matter. For theoretical physics the most important question is what it consists of.
This master thesis deals with finding a possible answer to this question.
The main idea is to explore what is beyond the standard model by using the Higgs portal model. In this model a scalar field is added to the standard model coupled to the Higgs. By this observable consequences of dark matter become accessible.
In this thesis this is investigated, and the dark matter field and the magnitude of the dark matter field are calculated.

Kurzfassung

Das Standardmodell der Teilchenphysik hat sich als eines der erfolgreichsten modelle the theoretischen Physik herausgestellt.
Die Entdeckung des Higgsbosons lieferte neue Möglichkeiten um einige noch ungelöste Probleme zu beheben.
Eines dieser ungelösten Probleme ist die Natur dunkler Materie. In der theoretischen Physik ist die wichtigste Frage, woraus dunkle Materie besteht.
Diese Masterarbeit beschäftig sich damit eine mögliche Antwort auf diese Frage zu finden.
Die idee ist über das Standardmodell hinaus danach zu suchen und dafür wird das Higgsportal Modell benutzt. Das Standardmodell wird durch ein Skalarfeld, welches an das Higgsfeld gekoppelt wird, erweitert um die Observablen zu berechnen.
In dieser Arbeit wird das dunkle Materie Feld und der Absolutbetrag des Feldes berechnet.

Contents

Chapter 1

Introduction

In physics the goal is to find out how nature works and what matter consists of. In the last decades particle physics made significant progress but there are still many unsolved mysteries. One of them is dark matter which does not only connect particle physics and astrophysics but it also gives a reason to explore the higgs portal which will be explained in chapter 3.
The detection of the higgs boson in 2012 could have been the first step for finding dark matter particles. Because the decay of the higgs boson could lead to particles in the hidden sector [6]. This already mentioned higgs portal is one of the unsolved problems in particle physics. The search for scalar dark matter though the higgs portal is the subject of this master thesis.
Our universe consits of only about 5% visible matter which can be described with the standard model of particle physics. The rest is about 70% dark energy and 25% dark matter [8]. These 95% are hardly explored so far.
Especially the search for dark matter is an important subject of current research in astrophysics and particle physics.
From astrophysical observations its existence and the fact that it interacts gravitationally is known. The distribution (see section 2.1.4) and the amount of dark matter in the universe are the most important questions in that case. Interesting about the distribution is that dark matter was mainly found in galaxy halos [17].
Particle physics aims to find out of which particles dark matter consists of and how they interact. It stands to reason that those are particles beyond the standard model because otherwise they should have been already detected. There are many possible canditates like neutrinos, axions or supersymmetric particles which will be explained in chapter 2.3. But the fact that the standard model conforms quite well with the results of CERN experiments it is reasonable to begin in the SM with the search for dark matter particles.
The main idea is to extend the standard model higgs lagrangian by a scalar

field which represents dark matter.

Chapter 2 gives an overview of dark matter in general. It discusses the astronomical evidences and possible alternatives.
In chapter 3 the higgs portal, with some possible extensions of the higgs lagrangian will be explained.
The model and the implementation will be discussed in chapter 4.
In chapter 5 the results will be presented.

Chapter 2

Dark Matter

Dark matter is non-luminous and not directly detectable. There is a strong evidence for its existence and that it makes up about 25% of the total energy density in our universe [8]. What one also can assume from astronomical observations is that it gravitationally interacting and self-interacting [8].

2.1 Astronomical Evidence

The obvious question is how one knows of the existence of dark matter. The answer is provided by astronomical observations as described in this chapter.

2.1.1 Galactic Rotation Curves

One of those astronomical observations are galactic rotation curves.
The rotation curves should decrease with $v \simeq \sqrt{\frac{1}{r}}$ because of the distribution of visible matter in the galaxies, but instead there were observed flat rotation curves $v \simeq constant$ [23].
This behavior implies the existence of non-luminous matter in the galaxies.

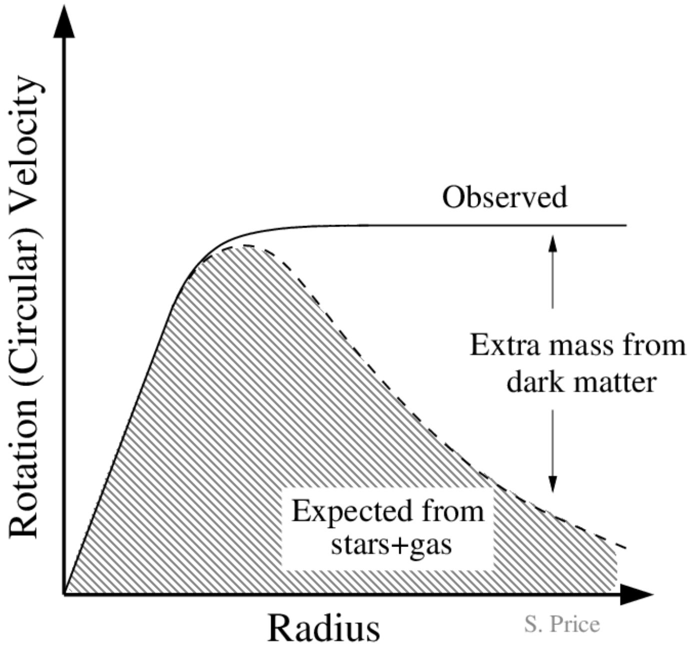

Figure 2.1: Galactic rotation curve from [1]

The density $\rho(r) \simeq \frac{1}{r^2}$ shows that most of this mass is present the halo of the galaxies [17].

2.1.2 Galaxy Clusters

In 1933 there were measured redshifts of galaxies in the Coma cluster. There were observed larger velocities of individual galaxies in relation to the cluster velocity than expected because of the total mass of the cluster, calculated from the masses of single galaxies [17]. So thats another hint for the existence of non-luminous matter which only interacts gravitationally.

2.1.3 Gravitational Lensing

Gravitational lensing that light from distant objects is distorted by intervening matter. It provides a more precise determination of the masses of galaxy clusters and thus another confirmation for the existence of dark matter [17]. The bullet cluster is the result of the collision of two galaxy clusters. By gravitational lensing the mass concentration of the cluster was determined. The mass which is accountable for the gravitational lensing is separated from the visible mass. Because the visible mass was slowed down by the collision and the invisible matter did not, because it does not interact with baryonic matter. That gives evidence that nearly all of the matter in the bullet cluster consits of dark matter [17].

2.1.4 Cosmic Microwave Background

CMB observations by WMAP and the PLANCK satellite show temperature fluctiations which are called anisotropies. That could be explained by the existence of Cold Dark Matter (CDM) ΛCDM with $\Omega_{CDM} = 0.2695$, where Λ is the cosmoligical constant. In the ΛCDM model the universe is almost flat and dominated by vacuum energy [8]. By PLANCK measurements the total masss density parameter was determined with $\Omega_m = 0.3175$. The baryonic density parameter is $\Omega_b = 0.048$ and so $\Omega_{CDM} = 0.2695$ [17]. In the early universe there could have been areas with more dark matter and thus a higher gravitational potential. That led to a higher concentration of visible matter and hence higher temperatures in those regions.
The ΛCDM model, which states that dark matter particles do not collide, explains the expansion and the large-scale structure of the universe quite good. But it does not predict the mass distribution of galaxies very well. Observations showed that galaxies with dark matter halos of different mass in their inner regions can have very similar rotation curves and that the density profiles of inner halos of dwarf galaxies are too dense so they do not fit with the ΛCDM simulations [5]. Ths diversity could be explained by strongly interacting dark matter [5], which will be described in section 3.2.

2.2 Dark Matter in our Solar System

The fact that dark matter moves through the galaxies and it interacts gravitationally leads to the assumption that a small amount could bind to the sun and the planets in our solar system.
That could happen if dark matter consists of weakly interacting massive particles. Because so the dark matter particles could scatter with nuclei where they lose momentum and will be bound to planets and stars [10].
Under the assumption that dark matter is self annihilating it could be possible that it has effects on planetary heat-flow and solar evolution [3].
But so far those are just hypotheses which cannot be proven yet. Experimental limits will be explained in section 2.5.3.

2.3 Theoretical Realizations

It is possible that dark matter consists of unknown subatomic particles. What we need for a dark matter candidate is a particle which is stable, selfinteracting and with gravitational interaction.

2.3.1 Neutrinos

The three Neutrinos would be useful dark matter candidates, because they are stable and do not experience electromagnetic or strong interactions. There could exist two kinds of dark matter, hot (relativistic) and cold (non - relativistic) dark matter. Standard model neutrinos would represent hot dark matter. From simulations it is known that HDM would cause a "top-down" scenario which means that large structures like galaxy cluster and galaxies formed before planets etc. By comparing those simulations with astronomical data it is clear that the universe has emerged in a "bottom - up" scenario.
Because of that and the very low masses of the standard model neutrinos it is impossible that they make up dark matter alone [11].

2.3.2 Axions

Another possible dark matter candidate was found by the attempt to solve the strong CP problem in quantum chromodynamics.
This problem occurs by the angle θ which describes the QCD vacuum state $|\theta\rangle = \sum_n e^{-\imath n\theta} |n\rangle$.
It turns out that $\bar{\theta} = \theta - arg det \mathcal{M} \leq 10^{-9}$, where $\mathcal{M}$ is the quark mass matrix. There is no reason why $\bar{\theta}$ should be that small [16].
The solution of this problem was the introduction of a spontaniously broken global $U(1)$ symmetry. This lead to the existence of a Nambu-Goldstone boson which was called axion.
Axions are stable and with masses in the range of $m_a \sim 10^{-6} - 10^{-4} eV$ they are possible dark matter candidates [11].

2.3.3 Supersymmetry

Not only the standard model contains possible dark matter candidates, but also supersymmetric extensions can.
Supersymmetry says that for every fermion there must exist a boson and for every boson there must exist a fermion with the same quantum numbers.

So there a several new electrically neutral and not strongly interacting particles, like gravitinos, sneutrinos, axinos and neutralinos. Neutralinos are the most studied dark matter candidates.
To be a useful dark matter candidate the lightest neutralino has to be stable. That can be ensured by the R-parity where the standard model particles have R-parity $P_R = +1$ and the superpartners have $P_R = -1$. From this follows that superpartners can only be created and destroyed in pairs, heavy superpartners can decay into lighter ones and the lightest of the superpartners can not decay. So the neutralinos would fulfill all the requirements for being dark matter [11].

2.3.4 SIMP/WIMP

The most promising dark matter candidates are WIMP (weakly interacting massive particles) and SIMP (strongly interacting massive particles) which will be described in sections 3.1 and 3.2.

2.4 Alternatives to Exotic Matter

Indeed there is mass in the universe which can not be detected and beside exotic matter it could be explained as follows.

2.4.1 MACHOs (Massive Astrophysical Compact Halo Objects)

One possibility to explain the missing mass in the universe would be compact objects that were less luminous than other objects, like brown dwarfs, black holes, neutron stars, etc. Those objects are called MACHOs. MACHOs are not directly detectable but could be responsible for gravitational lensing effects. So it was assumed that MACHOs represent dark matter. After collecting data for more than 6 years there has only been identified one microlensing canditate event [11]. So with MACHOs there can only be explained about 8% of the missing mass in the galaxies [11].

2.4.2 Modified Newtonian Dynamics (MoND)

The fact that dark matter only interacts gravitationally leads to the idea of modifying Newton's law of gravity. Modified Newtonian Dynamics explains phenomena like for instance the flat rotation curves in a way that there is no need for the existence of dark matter. The theory states that the behavior of gravity becomes asymptotically, $a = \sqrt{a_N a_0}$ with a_N = usual gravitational acceleration, when the acceleration is smaller than $a_0 = 1.2 \times 10^{-8}$ [22]. MoND was tested on some galaxy rotation curves and it has turned out that it would be an effectiv alternative for dark matter. But in galaxy clusters it only reduces the need of additional matter so a significant amount of dark matter is still needed [11]. An indication for MoND not being an alternative to dark matter is the, in section 2.1.2 described, bullet cluster. The theory can not explain the big amount of invisible mass without the postulation of additional matter [17].

2.5 Detection and Experimental Limits

The search for dark matter can be done in two different ways - direct and indirect detection.

2.5.1 Indirect Detection

Indirect detection of dark matter is done by astronomical observations. The possible decay or annihilation of the dark matter particles is observed. For instance γ-ray excesses could be indicators for dark matter. But it is very hard to distinguish them from other astrophysical effects [8].

2.5.2 Direct Detection

For a direct detection a signal of dark matter particles in detectors is necessary. These detectors are deep underground to reduce the cosmic ray background. Typically one searches for axion or WIMP dark matter. The interaction rate between the particles and the detector depends on the cross sections and masses. Also here the detection is very difficult. Because for low masses the detector sensitivity is limited by the energy threshold of the detector. And for high masses the number of particles decreases and so does the detector sensitivity [8].
Another way to detect WIMP dark matter is to look at the possible decay of the higgs boson into stable particles which are invisible for the detector. That is called higgs portal which will be discussed in chapter 3.

2.5.3 Exclusion Plots

It is widely believed that dark matter consists of WIMPs so many experiments are searching for this kind of dark matter. Figure 2.2 shows the upper limits of these experiments [14].

In this plot one can also see the low limit, where experiments will have to deal with neutrino background. A WIMP mass below 5 GeV/c2 will not be detected by most of the experiments [14].

Everything above the lowest curves (LZ) can be excluded. So to say this plot shows what does not represent dark matter.

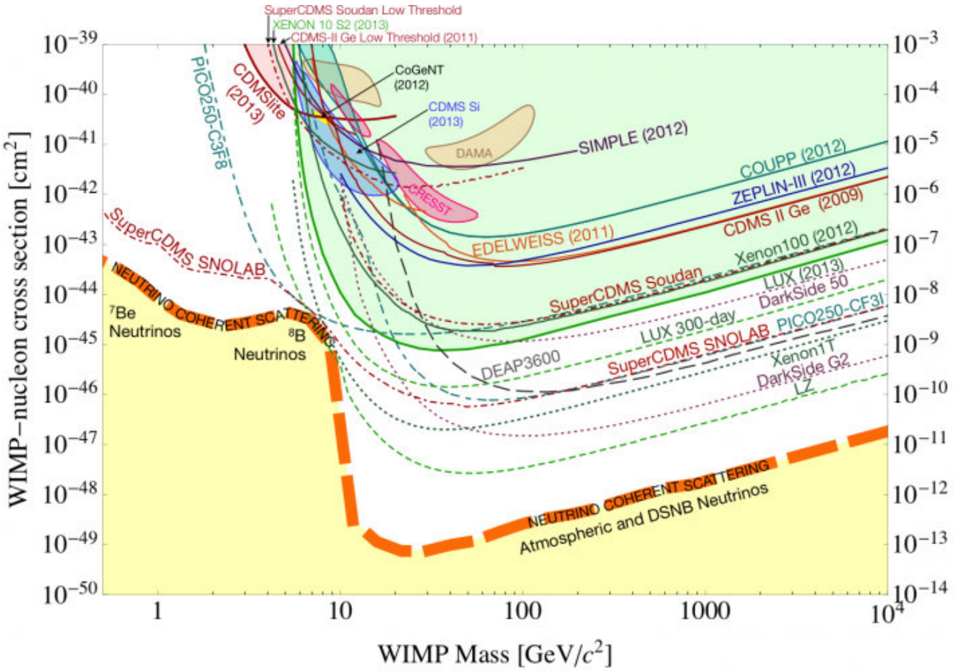

Figure 2.2: Plot taken from [9]; "*A compilation of WIMP-nucleon spin-independent cross section limits (solid curves), hints for WIMP signals (shaded closed contours) and projections (dot and dot-dashed curves) for direct detection experiments that are expected to operate over the next decade. Also shown is an approximate band where coherent scattering of 8B solar neutrinos, atmospheric neutrinos and diffuse supernova neutrinos with nuclei will begin to limit the sensitivity of direct detection experiments to WIMPs. Finally, a suite of theoretical model predictions is indicated by the shaded regions, with model references included." [9]*

Chapter 3

Higgs Portal

In 2012 the existence of the higgs particle was confirmed [7] which offered us the possibility to get more informations about whats beyond the standard model. It is presumed, that there is a hidden sector which can be explored by ob- serving phenomena in the visible standard model. A reasonable realization for that idea would be the Higgs portal which connects those two sectors by an invisible higgs decay to particles in the hidden sector. By adding the higgs sector to the standard model a very important feature came up. It is the ability to couple to the hidden sector and it is called higgs portal.
For the scalar case it is described by the interaction term $V_{portal} = \lambda_{h\phi}|H|^2|\phi|^2$ with ϕ as a hidden sector scalar [12].
Exploring the higgs portal is not only worth for the stability issues of the standard model, but also for searching dark matter [2].
In higgs portal dark matter models, the dark matter particles interact with the standard model particles only through higgs exchance processes [19]. There are several models for higgs portal dark matter, like scalar, fermion and vector dark matter [18]. These models will be described in section 3.1. The model which is used for this thesis is the scalar SIMP (strongly interacting massive particles) model.

3.1 WIMP Models

For higgs portal WIMP (weakly interacting massive particles) models there could be three different kinds, where the WIMP is a scalar S, a vector V_μ or an antisymmetric tensor field $B_{\mu\nu}$.
The first Lagrangian is for a scalar, the second for vector and the third one for the tensorfield.

$$\mathcal{L}_S = \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{1}{2}m_S^2 S^2 - \lambda_S S^4 - c_S H H^\dagger S^2 \tag{3.1}$$

[20]

$$\mathcal{L}_V = -\frac{1}{4}V^{\mu\nu}V_{\mu\nu} + \frac{1}{2}m_V^2 V^\mu V_\mu - \lambda_V (V^\mu V_\mu)^2 + c_V H H^\dagger V^\mu V_\mu \tag{3.2}$$

[20]

$$\mathcal{L}_B = \frac{1}{4}\partial_\lambda B^{\mu\nu}\partial^\lambda B_{\mu\nu} - \frac{1}{2}\partial^\mu B_{\mu\nu}\partial_\rho B^{\rho\nu} - \frac{1}{4}m_B^2 B^{\mu\nu}B_{\mu\nu} - \lambda_B B_{\mu\nu}B^{\nu\lambda}B_{\lambda\rho}B^{\rho\mu} - c_B H H^\dagger B^{\mu\nu}B_{\mu\nu} \tag{3.3}$$

[20]

The m is the mass parameter, lambda the quartic self coupling and c is the coupling strength between the Higgs and the WIMP or SIMP.
If it's a weakly or a strongly interacting particle depends on the λ. If the λ is big, its strongly interacting and if its small, its weakly interacting. [20]
One can calculate the invisible decay rate of the Higgs boson as follows.

$$\Gamma_S(m_H, m_S, c_S) = \frac{c_S^2}{8\pi}\frac{v^2}{m_H}\sqrt{1 - \frac{4m_S^2}{m_H^2}} \tag{3.4}$$

[20]

A possible decay of a higgs into two dark matter particles could be $pp \rightarrow ZH \rightarrow ZHDMDM$. Figure 3.1 shows a schematic diagram of the decay.

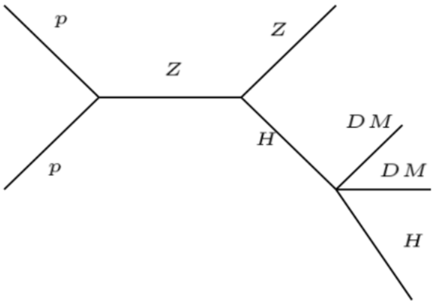

Figure 3.1: Decay $pp \rightarrow ZH \rightarrow ZHDMDM$

In that case v is the vacuum expectation value of the Higgs with about 246GeV. The decay rate is important for an exploration at CERN [20].

$$\Gamma_V(m_H, m_V, c_V) = \frac{c_V^2}{32\pi}\frac{v^2}{m_H}\frac{m_H^4 - 4m_H^2 m_V^2 + 12m_V^4}{m_V^4}\sqrt{1 - \frac{4m_V^2}{m_H^2}} \tag{3.5}$$

[20]

$$\Gamma_B(m_H, m_B, c_B) = \frac{c_B^2}{4\pi}\frac{v^2}{m_H}\frac{m_H^4 - 4m_H^2 m_B^2 + 6m_B^4}{m_B^4}\sqrt{1 - \frac{4m_B^2}{m_H^2}} \tag{3.6}$$

[20]

3.2 Scalar SIMP Model

As already mentioned in section 2.1.4 the ΛCDM model works for large-scale structures but does not describe the mass distribution in galaxies very well. Strongly interacting massive particles as dark matter particles could solve this problem.
In the outer regions of galaxies the ΛCDM model is working successfully. In the inner regions, the density profile is changed by thermalization as a result of the self-interaction [5]. This thermalization creates large cores, reduces the density of dark matter [15] and forces particles out of the center so that the circular velocity is reduced in contrast to the ΛCDM predictions [5].
In star dominated galaxies, so highly luminous galaxies, thermalization creates smaller and denser cores which forces the rotation curve to be flat [15]. So this explains the similar rotation curves which were mentioned in section 2.1.4.

The scalar SIMP higgs portal model is described by extending the Higgs lagrangian by a scalar dark matter field. This can be seen in the following equation.

$$\mathcal{L} = (D^\mu \phi_H^\dagger)(D_\mu \phi_H) + \mu^2 \phi_H^\dagger \phi_H - \lambda_H(\phi_H^\dagger \phi_H)^2 + \frac{1}{2}\partial^\mu \phi \partial_\mu \phi - \frac{1}{2}m^2\phi^2 - \lambda\phi^4 - kP\phi_H\phi_H^\dagger\phi^2 \tag{3.7}$$

Where ϕ_H is the standard model higgs doublet and ϕ is the scalar dark matter.

With $\phi_H = \begin{pmatrix} \phi_H^+ \\ \phi_H^0 \end{pmatrix}$, $D_\mu \phi_H = (\partial_\mu + igT^i W_\mu^i + i\frac{1}{2} g B_\mu)\phi_H$ and W_μ^i and B_μ are the $SU(2)_L$ and $U(1)_Y$ gauge bosons [21].

The addition of a singlet scalar field to the standard model is the simplest extension because it needs just three more parameters. And those are a mass m, a self-coupling λ and a coupling to the higgs field kP (see equation 3.7. It is renormalizable and one can get stable and heavy particles with strong self-interaction. For the stability a Z_2 symmetry is needed which is described in section 4.

Chapter 4

Implementation

For the implementation a singlet scalar field was added to the gauged higgs lagrangian, as described in section 3.2.
From equation 3.7 there was done a lattice regularization and so the dark matter part of the action looks as follows:

$$S_{DarkMatter} = \sum_x \left\{ -2\kappa \sum_{\mu=1}^{4} \phi(x)\phi(x+\hat{\mu}) + \phi(x)^2 + \lambda[\phi(x)^2 - 1]^2 - kPHH^{\dagger}\phi(x)^2 \right\} \tag{4.1}$$

[13] Where ϕ is the dark matter field and kP is the higgs portal coupling.
κ and λ are related to the bare mass (m_0) and the bare coupling (g_0) through $a^2m_0^2 = \frac{1-2\lambda}{\kappa} - 8$ and $g_0 = \frac{6\lambda}{\kappa^2}$ where a is the lattice spacing [13].

It has a Z_2 symmetry which is required to get a stable particle, because by mapping $\phi \to -\phi$ the lagrangian will remain invariant under this symmetry. The standard model is even and the scalar field is odd concerning the Z_2 symmetry, so $\langle \phi HH \rangle = - \langle \phi HH \rangle = 0$. For a decay there are needed two dark matter particles $\langle \phi\phi ... \rangle$.

The $\lambda\phi^4$ term, with $\lambda = 1.0$ in the simulation, ensures the strong self coupling and the $m^2\phi^2$ term ensures the big mass of the particle.
For the simulation there was taken an already existing code [4], which makes lattice calculations of the electroweak sector, and it was extended by the dark matter part.

For the simulation the following constants for the gauged higgs lagrangian (see chapter 3) were used: $\beta_{SM} = 4.0$, $\kappa_{SM} = 0.285$ and $\lambda_{SM} = 1.03$.
The dark matter field ϕ (i.e. the field over all configurations), with $\langle \phi \rangle =$

$\langle\sum_x \phi(x)\rangle$, the magnitude of the field $|\phi|$ ($\langle|\phi|\rangle$) and the W propagator were plottet by using the CERN ROOT library.
A propagator is a two-point function which describes the probability amplitude for a particle to propagate from one point to another. The W propagator is given by $D^{ab}_{\mu\nu} = \left\langle W^a_\mu W^b_\nu \right\rangle$, with $W_\mu = \frac{1}{2agi}\left(U_\mu(x) - U_\mu(x)^\dagger\right) + \mathcal{O}(a^2)$ [4].
The simulation was written in c++ and it was done by using a metropolis algorithm [13]. The metropolis alogrithm was used because it is the easiest and most reliable way for the implementation. It is because the calculation of expectation values for a scalar field theory is equivalent to calculating expectation values of a statistical field theory [24]. A short view into the code can be seen in chapter 7.
The first things which were calculated, were the average ϕ and the magnitude of ϕ. That was just for testing the metropolis, so the higgs portal coupling constant was set to zero and the lattice size to 4^4.
To get the initial value for the metropolis update a gaussian random number generator was used. By using an exponential function the probability was calculated and so the acceptance rate was about 50%.

After testing if the metropolis is working correctly the portal coupling was turned on and the calculations were made with the lattice sizes 8^4, 16^4 and 24^4. To obtain the coupling constants there was done a scan of parameter ranges, because they are not yet known.
So some values for the coupling constants were inserted and too see if those are correct, the massive gauge bosons should not be affected. So the W propagator should still have a mass about 80 GeV.

Chapter 5

Results

In this chapter the results will be explained in the following way.
Section 5.1 shows the behavior of ϕ and $|\phi|$, which are labeled in the plots as D and $|D|$.
In section 5.2 there can be seen the plots of the W propagator $D(p) = \delta_{\mu\nu} D^{ab}_{\mu\nu} \delta^{ab}$, $(p^2 + m^2)D(p)/Z$ and p.

In figures 5.1 and 5.7 the kappa, which represents the mass of the dark matter particle, was set to $\kappa = 0.124$, because there is no symmetry breaking on tree level expected [4]. The portal coupling was varied from $kP = 0.001$ to $kP = 1000$.
In that case no changes appeared, so the portal coupling was fixed to $kP = 10$ and the kappa was varied between $\kappa = 0.01$ and $\kappa = 0.2$.

A short summary can be seen in table 5.1.

κ	kP	Impact on weak sector	Broken Z_2 symmetry
0.124	0	no	no
0.2	10	yes	yes
0.15	10	yes	yes
0.13	10	yes	no
0.05	10	yes	no
0.01	10	yes	no

Table 5.1: Summary of Results

5.1 Phasediagram

Figure 5.1 shows the already mentioned case with no changes.

In figure 5.2, with $\kappa = 0.2$, one can see, that the dark matter values do not scatter around zero. That means the Z_2 symmetry is spontaniously broken and the dark matter particle would not be stable.
Alternatively that could mean that the metropolis is not working correctly, but there is an indirect reference that this is not the case. Namely that there is less spreading than in figure 5.1.

Figure 5.3 the Z_2 is also not broken, but, in contrast to figure 5.2, ϕ scatters around a negative value.

Something interesting happens at $\kappa = 0.13$ in figure 5.4. One would expect that the Z_2 symmetry is not broken at $\kappa = 0.125$ and below on tree level but here the ϕ values are scattering already around zero.

In the last two plots kappa is set to $\kappa = 0.05$ and $\kappa = 0.01$.
In figure 5.5 there is a wider scattering of the measured ϕ. That could indicate a lighter mass of the dark matter particle.
So figure 5.6 could mean that the particle is heavier and so the electroweak sector might not be affected very strong. For a LHC signal a strong influence is needed.

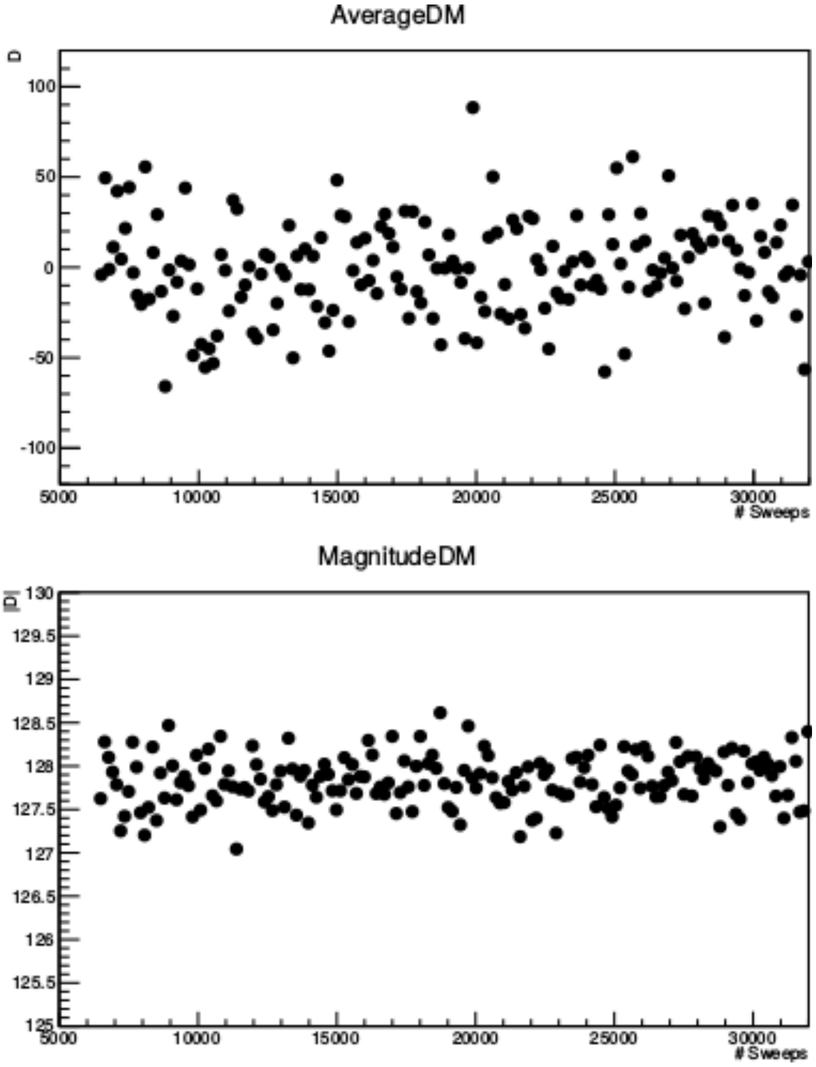

Figure 5.1: ϕ (AverageDM), $|\phi|$ (MagnitudeDM); portal coupling kp=0, kappa=0.124

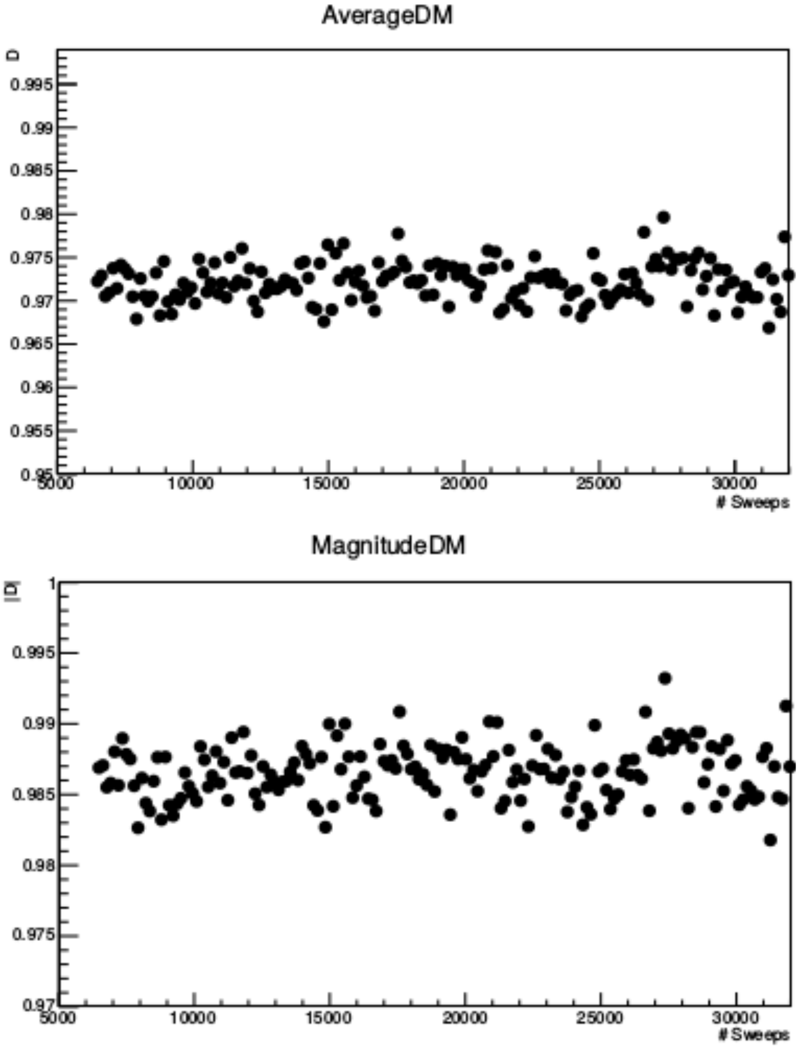

Figure 5.2: ϕ (AverageDM), $|\phi|$ (MagnitudeDM); portal coupling kp=10, kappa=0.2

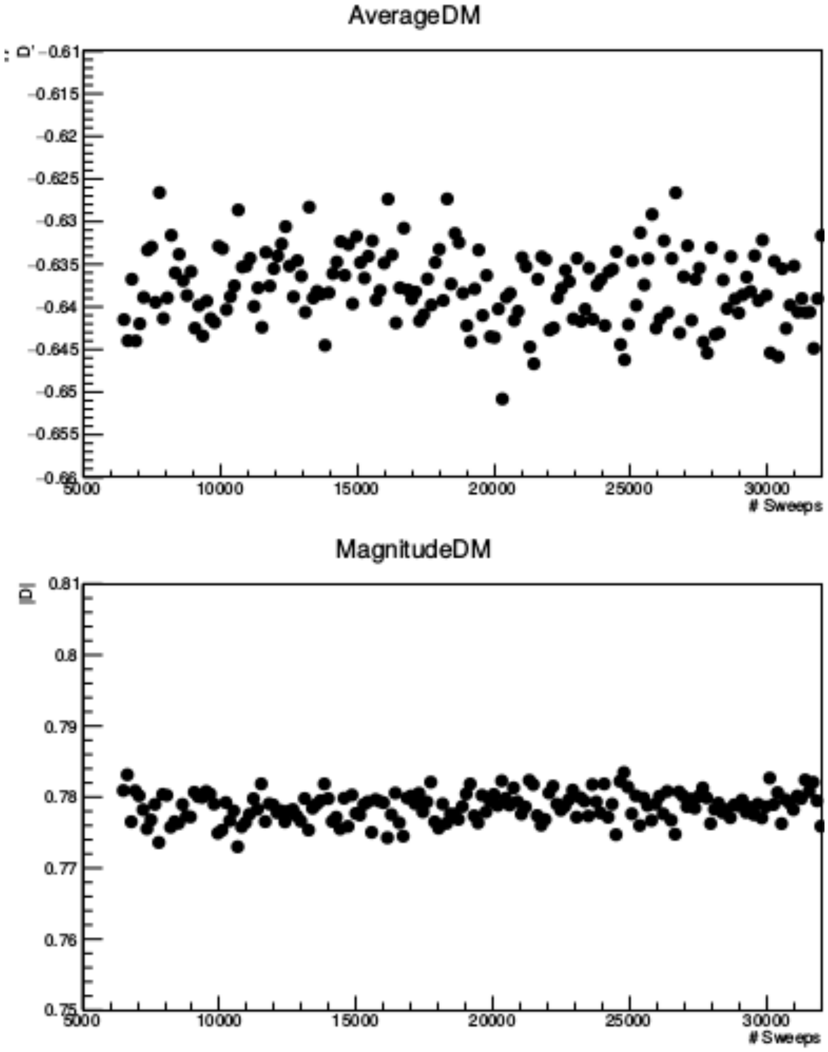

Figure 5.3: ϕ (AverageDM), $|\phi|$ (MagnitudeDM); portal coupling kp=10, kappa=0.15

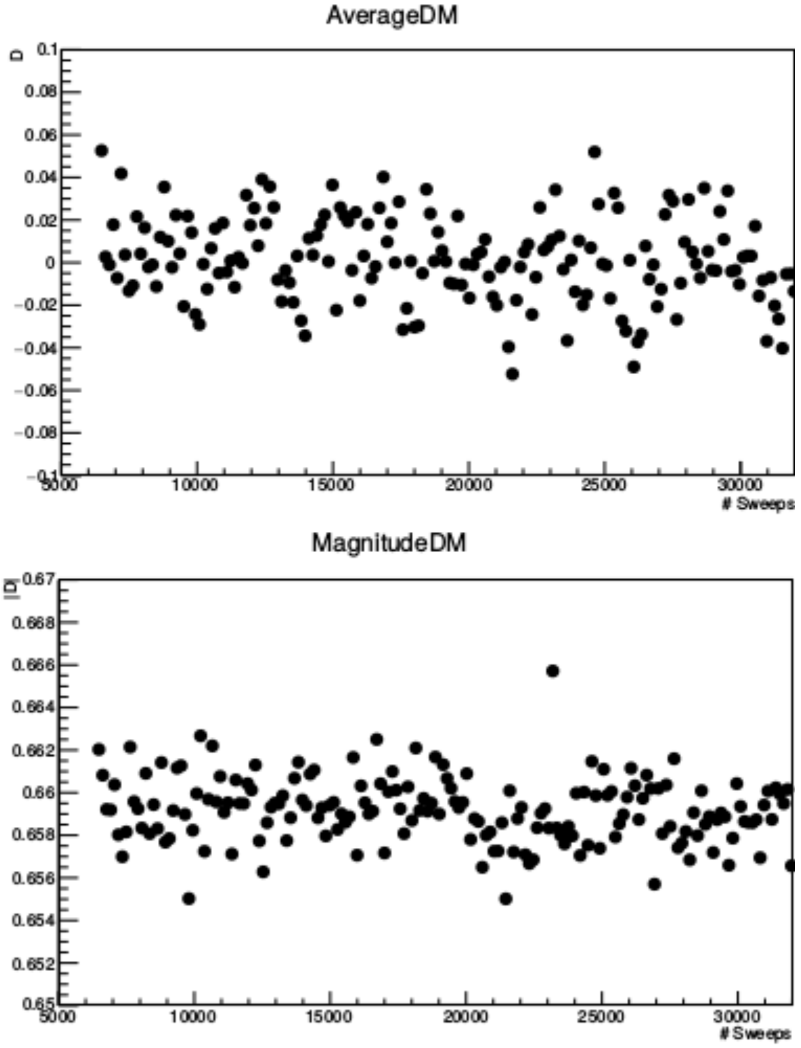

Figure 5.4: ϕ (AverageDM), $|\phi|$ (MagnitudeDM); portal coupling kp=10, kappa=0.13

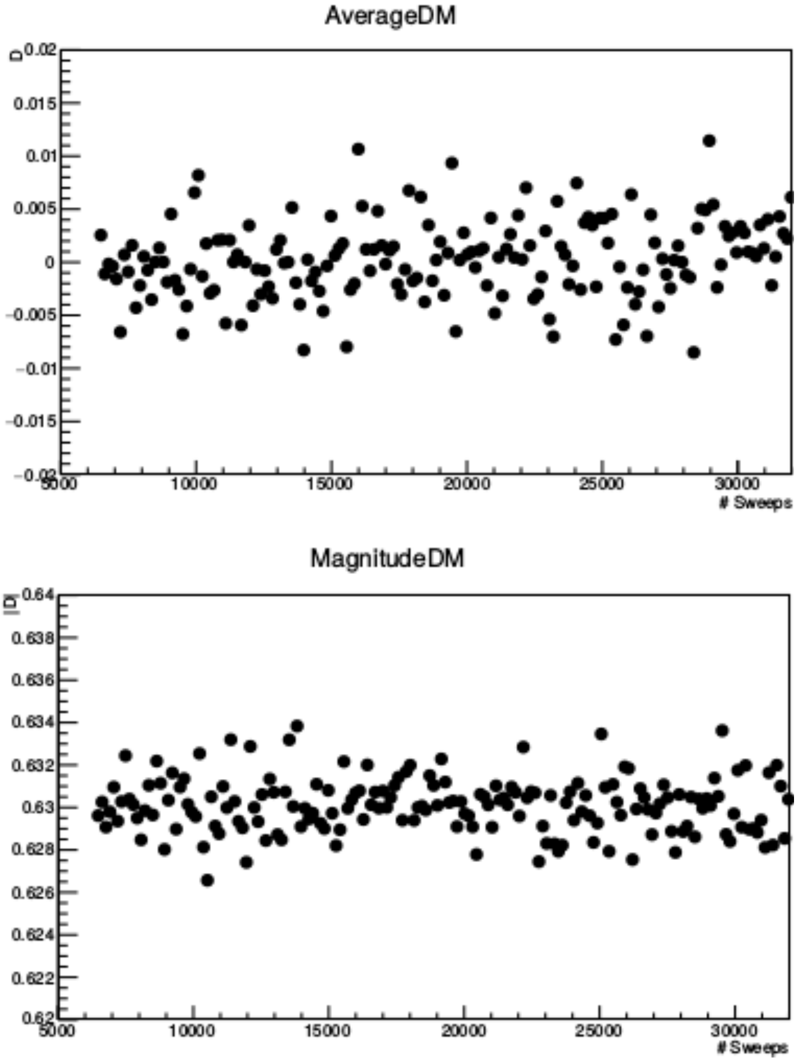

Figure 5.5: ϕ (AverageDM), $|\phi|$ (MagnitudeDM); portal coupling kp=10, kappa=0.05

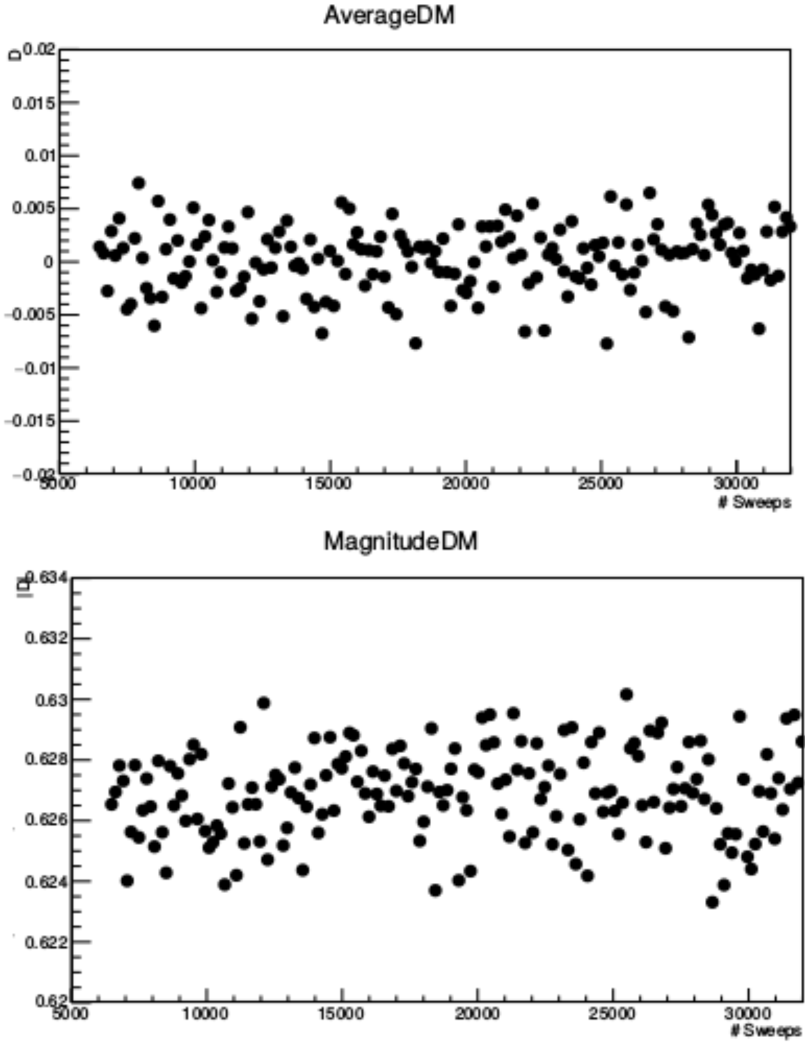

Figure 5.6: ϕ (AverageDM), $|\phi|$ (MagnitudeDM); portal coupling kp=10, kappa=0.01

5.2 W Propagator

Figure 5.7 shows the W propagator with higgs portal coupling $kP = 0$ and $\kappa = 0.124$. So the dark matter field has no influence at the gauged higgs lagrangian. This can be noted, because the dashed line, which is the W propagator without any interaction, and the points are nearly concuring.

The Figures 5.8 and 5.9, with $kP = 10$, $\kappa = 0.2$ and $\kappa = 0.15$, show that the

W propagator is affected quite strong. That means that the Z_2 symmetry is spontaniously broken and the mass of the W boson is under $80 GeV$.

The case with $\kappa = 0.13$, where the Z_2 symmetry is not broken is shown in 5.10.

Figures 5.11 and 5.12 show the W Propagator with a not broken symmetry and the mass of the W boson with about $80 GeV$. That indicates a stable dark matter particle. But compared to figure 5.10 it does not fit quite well in the ultraviolet sector. Which could indicate quantum fluctuations of dark matter.

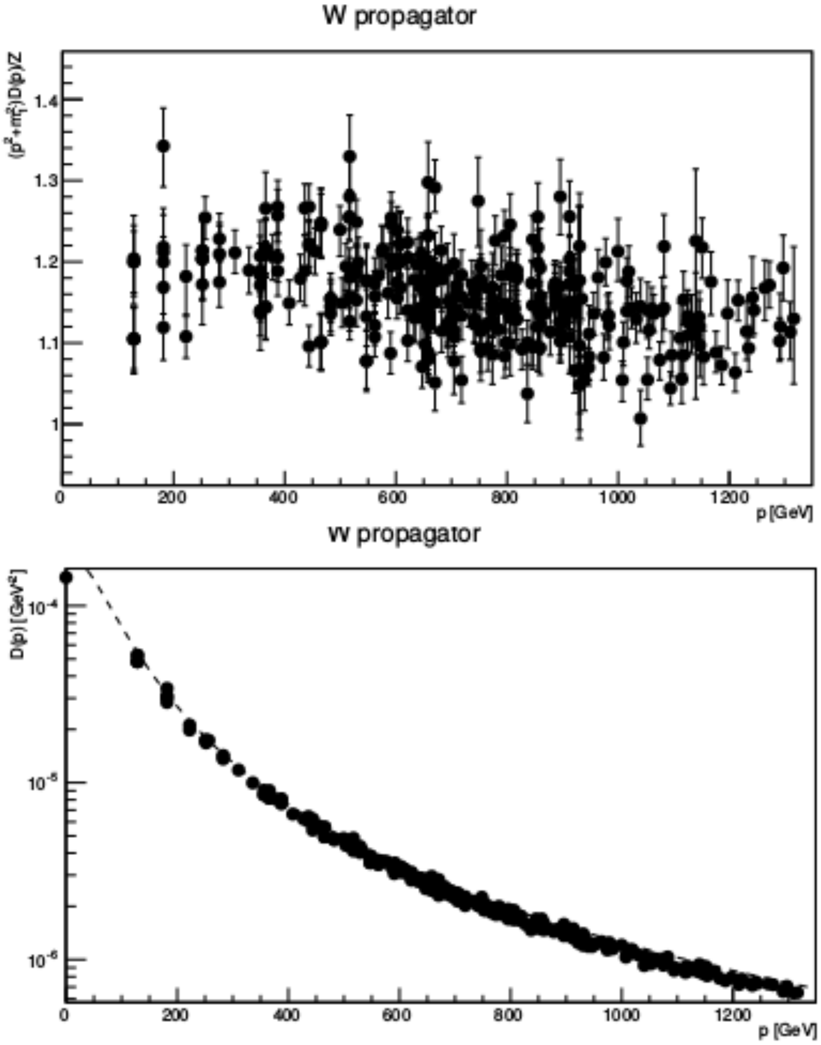

Figure 5.7: W propagator; portal coupling kp=0, kappa=0.124

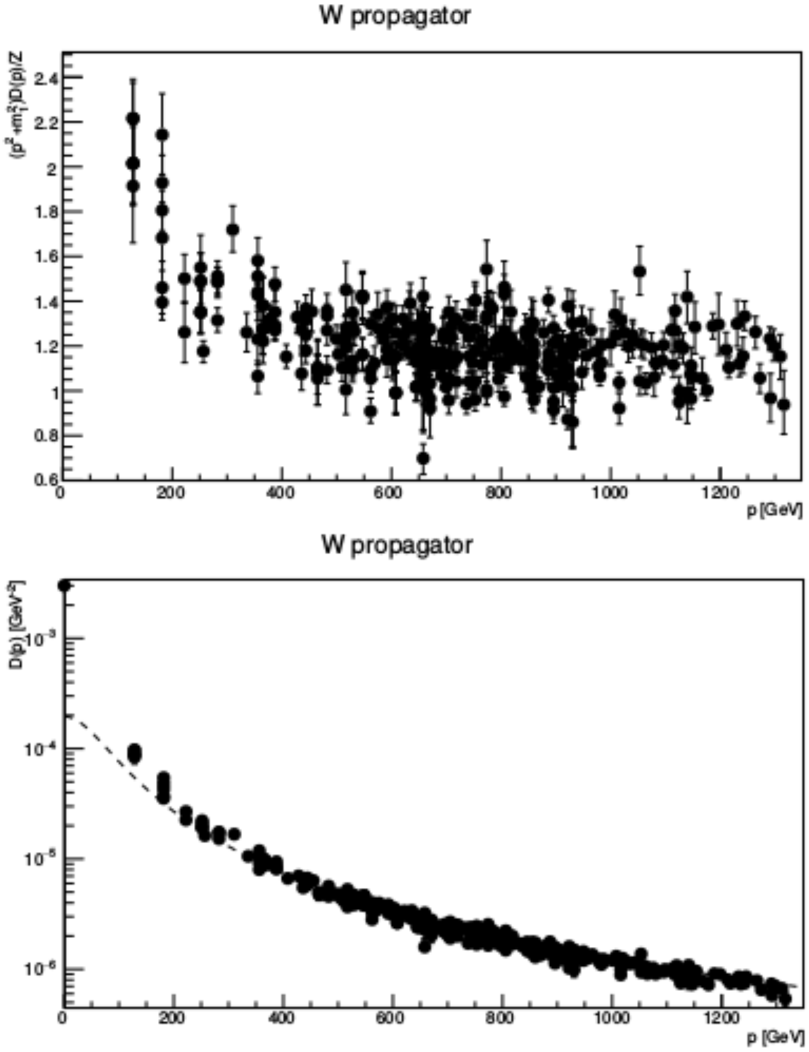

Figure 5.8: W propagator; portal coupling kp=10, kappa=0.2

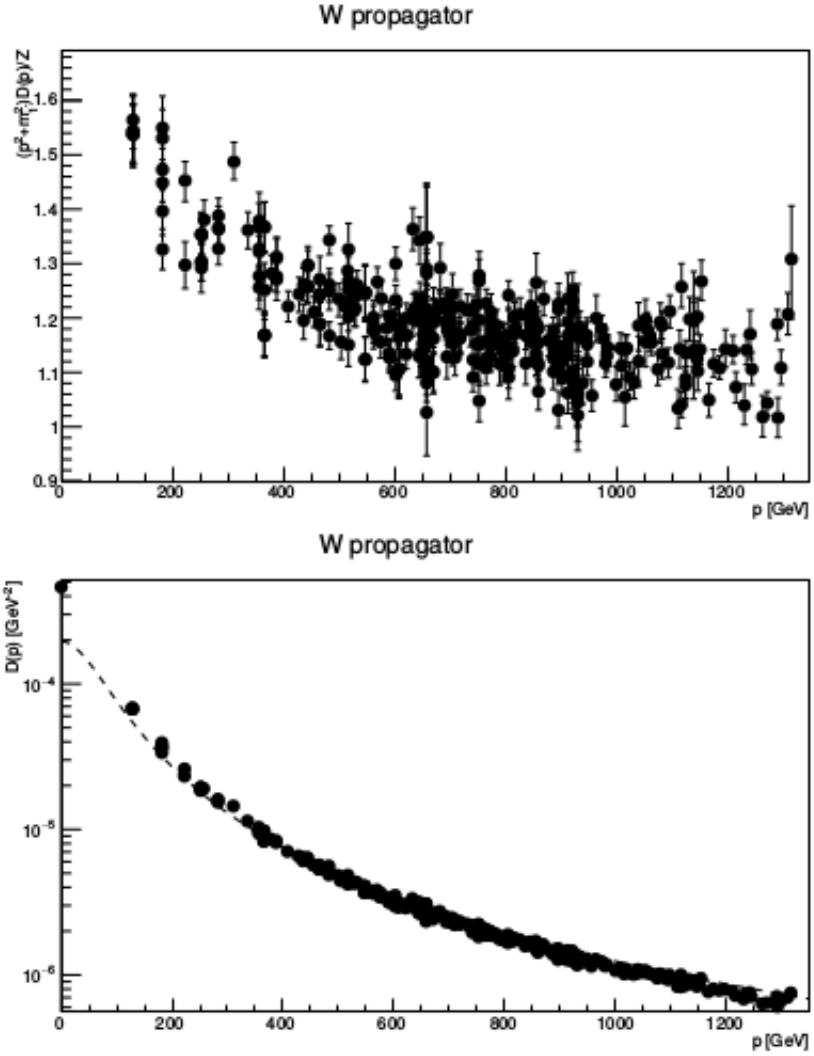

Figure 5.9: W propagator; portal coupling kp=10, kappa=0.15

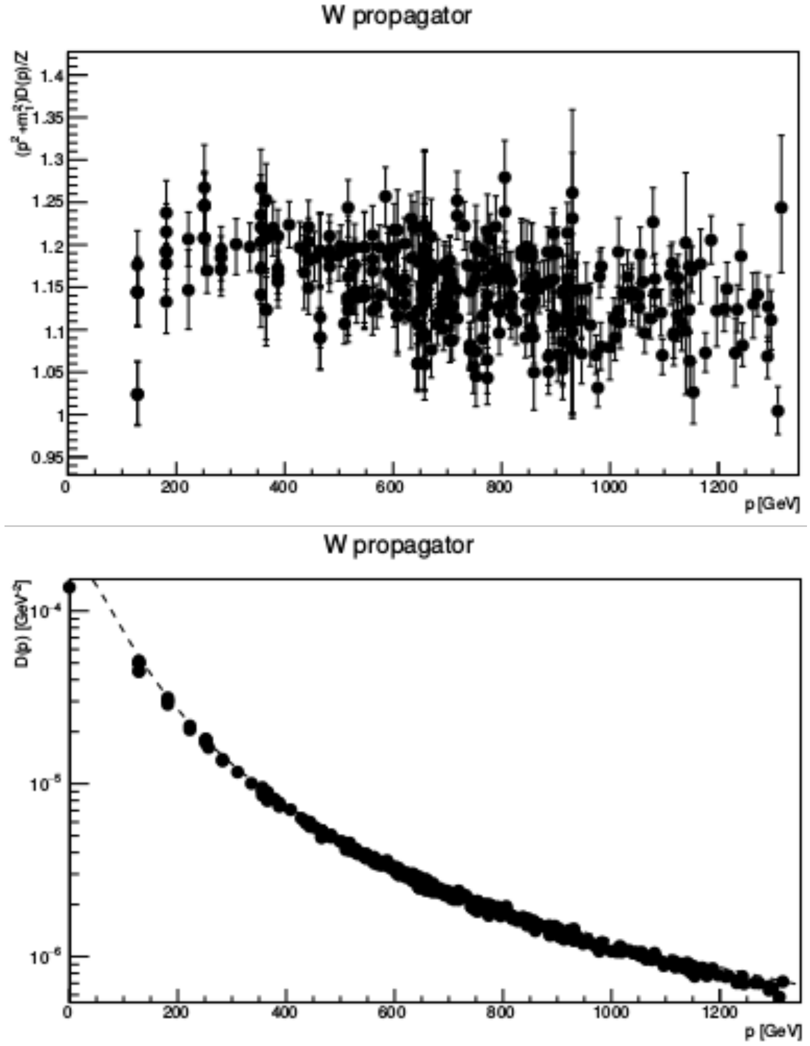

Figure 5.10: W propagator; portal coupling kp=10, kappa=0.13

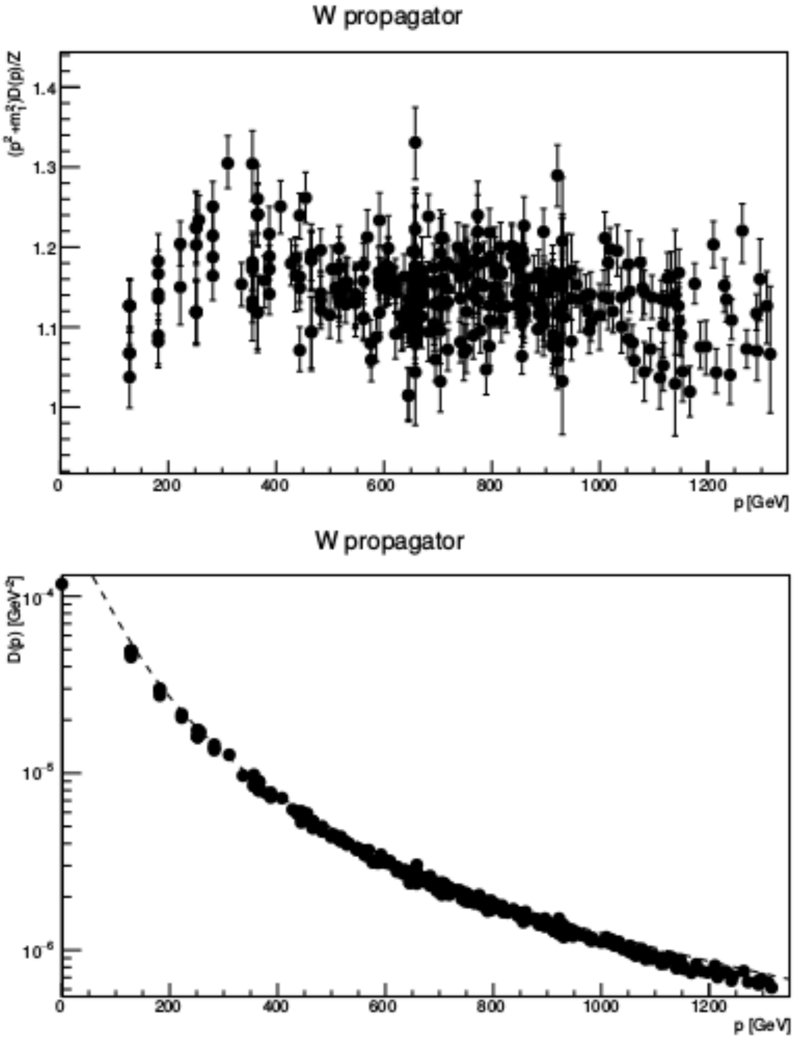

Figure 5.11: W propagator; portal coupling kp=10, kappa=0.05

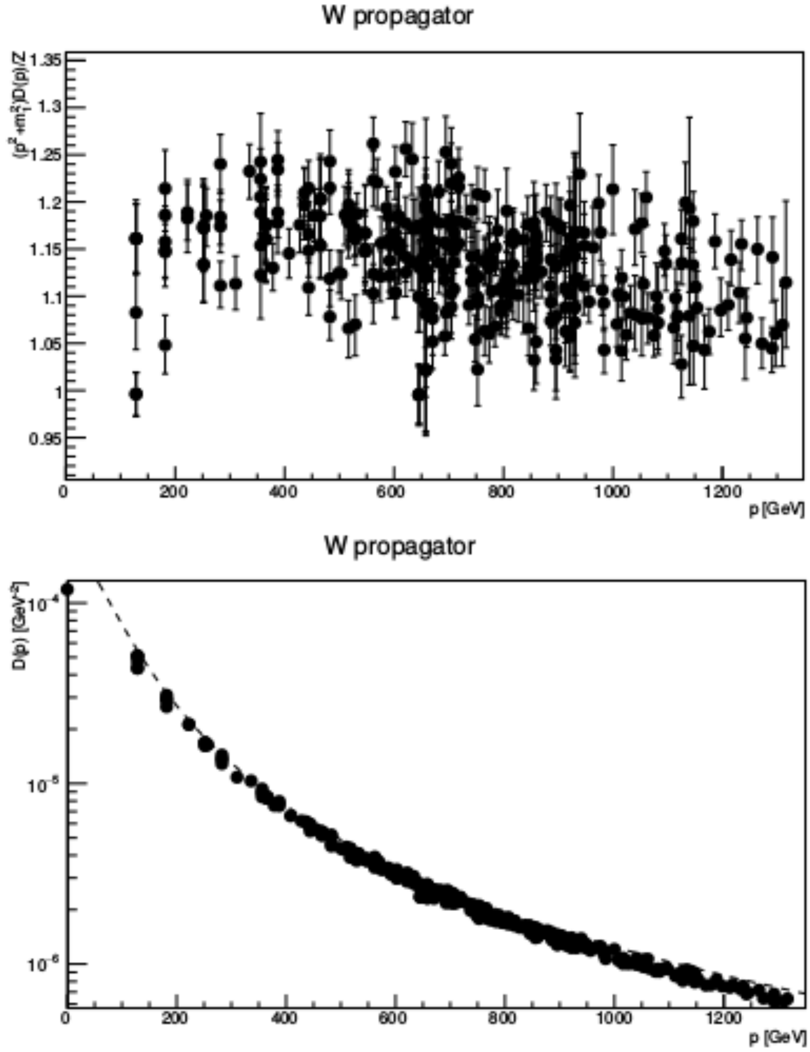

Figure 5.12: W propagator; portal coupling kp=10, kappa=0.01

Chapter 6

Conclusion and Outlook

Here is a summary of what was done in this thesis. First of all the question was what is the most promising and simplest way to use the higgs portal for the dark matter search. The answer was the extension of the higgs lagrangian by a scalar field with strong self interaction. The strong self interaction is important because it could be the solution for the galaxy diversity problem 2.1.4 and it does not alter the weak interaction.
There was considered a decay of two dark matter particles $\langle\phi\phi ...\rangle$. A decay of the higgs boson would also be possible but it would be to hard to calculate. The simulation was done by using an already existing code which calculates interactions of the weak sector of the standard model. A metropolis algorithm was used and after the successful testing it the program ran on a cluster.
The average dark matter field and the magnitude of it were calculated and plottet.
It was important that the Z_2 was not broken and the W propagator was not influeced too much by the dark matter field. So the mass of the W boson had to stay at about 80 GeV.
This goal was reached at a kappa value of $\kappa = 0.13$ an below. That was surprising because we expected that phenomenon at $\kappa = 0.125$ and below.

All in all it is indeed possible that dark matter is represented by a scalar field which can be explored by the higgs portal. So this thesis could be the basis for a promising dark matter research. Maybe one day it is possible to prove the nature of dark matter at CERN or other colliders. Which would solve the issue of about 23% of the matter in our universe.

Chapter 7

Appendix

7.1 Code

Calculation of dark matter action

```
inline long double CalculateDMAction(long double &Sdm)
{
        Sdm=0.L;
        vec v; v.mu=0;
   for(v.t=0;v.t<kNt;++v.t) {
      for(v.z=0;v.z<kNz;++v.z) {
         for(v.y=0;v.y<kNy;++v.y) {
            for(v.x=0;v.x<kNx;++v.x) {

               long double phi2=0.L;
               long double dm2=0.L;

                       for(int c1=0;c1<kNc;++c1)
      {
                     phi2+=(fPhi[v.t][v.z][v.y][v.x][c1]*
                     conj(fPhi[v.t][v.z][v.y][v.x][c1])).real();

      };

                     dm2+=dm[v.t][v.z][v.y][v.x]*dm[v.t][v.z][v.y][v.x];

                          for(int mu=0;mu<kD;++mu) {
        vec u=vpmap(vadd(v,e[mu],mu));
```

```
          Sdm+=-2.L*dmkappa*dm[v.t][v.z][v.y][v.x]*
          dm[u.t][u.z][u.y][u.x];

        };
        Sdm+=-kP*phi2*dm2+dm2+dmlambda*sqr(dm2-1.L);
            };
          };
        };
      };

             return Sdm;
    };
```

Metropolis update for dark matter

```
    inline void UpdateDarkMatter(vec v)
  {
        long double newdm=dm[v.t][v.z][v.y][v.x]+
        GaussRand(fCACFdm/kBeta);

        long double a=dmact;

        long double oldphi2=0.L;
        long double olddm2=0.L;
        long double newdm2=0.L;
        for(int c1=0;c1<kNc;++c1)
        {
                oldphi2+=(fPhi[v.t][v.z][v.y][v.x][c1]*
                conj(fPhi[v.t][v.z][v.y][v.x][c1])).real();

        };

                olddm2+=dm[v.t][v.z][v.y][v.x]*dm[v.t][v.z][v.y][v.x];
                newdm2+=newdm*newdm;

                        for(int mu=0;mu<kD;++mu) {
          vec u=vpmap(vadd(v,e[mu],mu));
          vec w=vpmap(vadd(v,ne[mu],mu));


          a+=2.L*dmkappa*dm[v.t][v.z][v.y][v.x]*dm[u.t][u.z][u.y][u.x];
```

```
      a-=2.L*dmkappa*newdm*dm[u.t][u.z][u.y][u.x];
      a+=2.L*dmkappa*dm[w.t][w.z][w.y][w.x]*dm[v.t][v.z][v.y][v.x];
      a-=2.L*dmkappa*newdm*dm[w.t][w.z][w.y][w.x];
    };

    a-=-kP*oldphi2/*olddm2*/+olddm2+dmlambda*sqr(olddm2-1.L);
    a+=-kP*oldphi2/*newdm2*/+newdm2+dmlambda*sqr(newdm2-1.L);

    if(Accept(dmact,a)) {
      dmact=a;
      dm[v.t][v.z][v.y][v.x]=newdm;
      fAcceptanceCounter++;
    };
};
```

Calculation of $|\phi|$

```
  inline long double MeasureMdm(void)
{
  long double Mdm=0.L;
  long double Mdm1=0.L;
  for(int t=0;t<kNt;++t)
  {
  for(int z=0;z<kNz;++z)
  {
      for(int y=0;y<kNy;++y)
      {
      for(int x=0;x<kNx;++x)
      {
                 Mdm1+=dm[t][z][y][x]*dm[t][z][y][x];

          Mdm+=sqrt(Mdm1);
      };
      };
  };
  };

  return Mdm;
};
```

Calculation of ϕ

```
inline long double MeasureAvdm(void)
```

```
{
  long double Avdm=0.L;
  long double Avdm1=0.L;
  for(int t=0;t<kNt;++t)
  {
  for(int z=0;z<kNz;++z)
  {
      for(int y=0;y<kNy;++y)
      {
      for(int x=0;x<kNx;++x)
         Avdm1+=dm[t][z][y][x];
      {

          Avdm+=Avdm1;
      };
      };
  };
  };
  return Avdm;
};
```

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