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The parametrisation of cross sections for Dark Matter particle processes

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1 Abstract

Experiments at particle colliders provide experimental verifications of theories in particle physics, and allow to search for new particles. Computer programs are used to simulate particle collisions. Those so-called event generators can be used to prove theories and compare their results to actual collisions from the colliders. Even though those programs run on powerful computer systems, the event generation takes long and is also cost-intensive. Therefore, the aim of this thesis is to reduce this computation time in the aid of searches for new particles.

One of the goals of modern particle physics experiments, such as the ATLAS [1] and CMS detectors at the Large Hadron Collider [2], is to shed light on the problem of Dark Matter. The presence of matter in our universe, beyond known matter, is motivated by gravitational interaction. In this project, I simulated particle collisions producing particles that exist in theories of Dark Matter. I then parametrised the cross sections of these processes, a measure for the probability of this process occurring, depending on parameters of the Dark Matter theory studied, the mediator mass and Dark Matter mass. This parametrisation was initially studied using a simulation of many Dark Matter signal points with different mediator mass and Dark Matter mass, and then applied to a grid with fewer simulated points. Altogether, the parametrisation derived from the grid with fewer points shows cross-sections that are consistent with those of the full grid of points. This allows the generation of fewer signal points and to parametrise them instead, which then results in a much shorter computation time. These results are used for a publication on the constraints of Dark Matter searches performed at ATLAS, a particle detector, which uses data from the Large Hadron Collider (LHC).

2 Acknowledgement

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Contents

1	Abstract	2
2	Acknowledgement	3
3	Introduction	7
4	Theoretical and experimental details of Dark Matter	9
4.1	The evidence for Dark Matter	9
4.2	Production and relic density	10
4.3	Properties and possible candidates	10
4.4	Searches for Dark Matter	12
4.5	Results from different searches for Dark Matter at ATLAS	14
5	Tools and methods	17
5.1	Event generators	17
5.2	Analysis tools	18
6	Optimising the generation of events	19
6.1	Automatic generation of multiple templates	19
6.2	Parametrisation of event templates	20
6.3	Parametrisation of reduced data sets	23
7	Results	24
8	Conclusion and Outlook	30
A	Further figures	34
B	Fit parameters	35
C	Programs	38
D	Program: plotting and fitting	39

List of Figures

1	Different particle collisions could help to find Dark Matter. (a): Two Dark Matter particles combine to two standard particles, whereby the collision would be detected indirectly. (b): A Dark Matter and a standard particle interact, which could be detected directly. (c): Two standard particles combine and build two Dark Matter Particles in a collider. (d): Two standard particles from a particle collision combine into a mediator, which then decays into either Dark Matter or standard matter. This is the method used in this project. [12]	13
2	A particle collision creates a dijet-event in the Atlas Detector. First the particles in the jet are visible in the tracking chamber (dark grey cylinder). Then they are visible in the electromagnetic calorimeter (green cylinder) and in the hadronic calorimeter (red cylinder). [9]	13
3	The detection of the Higgs boson. At an invariant mass of 125 GeV a bump is visible over the background data. This indicates the resonance of the Higgs particle. [3]	13
4	Different experimental searches are used to analyse a model for an axial-vector DM mediator. They can exclude different areas in the on- and off-shell regions, which are separated by the mass line. The red region is excluded by the searches for missing transverse momentum, while the blue region is excluded by searches in dijet final states. [4]	15
5	The cross sections computed with event generators show regular structures in the $M_{DM} - M_{Med}$ plane.	20
6	The cross section retrieved from generated signal samples for a constant Dark Matter mass of 650 GeV exhibit exponential decay. It can therefore be fitted using this function.	21
7	For a constant mediator mass of 1750 GeV the data for the cross sections show a rising function, which is similar to a parabola. After the border between on- and off-shell stay the cross sections constant.	22
8	The absolute differences between the calculated cross sections and the for a constant Dark Matter fitted ones are large for small mediator masses and decrease for increasing mediator masses.	24

9	The relative differences between the calculated cross sections and the for a constant Dark Matter fitted ones build positive bands for small and large mediator masses. They are negative for mid-range mediator masses. In total they vary around 70% from the generated cross sections.	25
10	The absolute differences between the generated cross sections and the fitted ones with a constant mediator mass show a fan structure. The fans lie parallel to the mediator mass axis and abut on each other directly. Small islands with large deviations occur in the off-shell region.	26
11	The relative differences for the cross sections also show a fan structure parallel to the mediator mass axis. Beside small islands of larger deviations in the off-shell region, a band at mediator mass around around 2700 GeV is slightly visible.	27
12	The absolute differences between the original data set and the fitted reduced data set are in the order of 0.01 pb. A fan structure with alternating positive and negative deviations is visible and also some detached points with large deviations occur.	29
13	The relative differences between the original data set and the fitted reduced one show a fan structure with deviations of around 2%. Beside those fans two vertical lines at 2000 GeV and 2700 GeV are visible and some detached aberrations.	29
14	The fit for a constant mediator mass of 2700 GeV does not represent the data points precisely. It varies significantly for larger Dark Matter masses.	34
15	The fit for a constant mediator mass of 2000 GeV does not represent the data points precisely. It varies slightly for Dark Matter masses between 400 and 600 GeV.	34

3 Introduction

One of today's largest unsolved mysteries of physics is Dark Matter. Cosmologists observed the first evidence for Dark Matter more than eighty years ago, but we still do not know what Dark Matter is made of [13]. Over the years, many observations suggest the existence of Dark Matter, but its actual character and all its properties have not been proved yet, although there are many theories that make hypotheses on its particle nature. The experimental observation of Dark Matter particles, at particle colliders and other experiments, would help solving this puzzle.

The main theoretical model describing particle physics is the Standard Model (SM), which contains different types of particles. All particles contained in the SM and their properties have been experimentally verified. These particles can explain the visible matter and their interactions, such as the electromagnetic, weak and strong forces. Nevertheless, the SM is not the full theoretical explanation for our universe, because it does not explain Dark Matter. If a Dark Matter particle exists, it could interact with the known particles from the SM. The interaction between them could occur via a mediator particle. This mediator particle could also decay into known particles. This process would make the interaction observable in particle colliders. The main operating particle collider is the Large Hadron Collider (LHC).

To compare theoretical models with experimental results, software programs which simulate particle collisions are used. They can be used to prove if a theoretical model produces results coinciding with experimental evidence. They can also be used to simulate the presence of new phenomena, whose effects can then be also compared to experimental results. Those simulations generally require large computation powers and should therefore be optimised.

This thesis consists of the parametrisation of the cross section of Dark Matter processes. The cross section is a measure of the probability of particle collisions producing a given process, in this case an interaction between SM particles and mediators of a Dark Matter force, where the mediator is decaying to quarks. This is done by using an event generator for the calculation of the cross section for different mediator and Dark Matter masses. Those cross sections from the event generator were then fitted, and compared to a larger set of generated cross sections. The agreement between the cross sections from the fit and the generated cross sections show that this parametrisation of cross sections can reduce the required amount of generated points. However, not every fitting method showed acceptable results, and a generalisation for different parameters of the Dark Matter theory, such as the strength

of the interaction between the SM particles and the mediator particle, will require more work.

This thesis first introduces the most important theoretical concepts of Dark Matter. In the next chapter the tools used are presented, and their use is explained. The fifth chapter deals with the optimisation of the cross section fitting. The sixth chapter presents the results of this thesis work. In the end a short conclusion is drawn and an outlook is given.

4 Theoretical and experimental details of Dark Matter

4.1 The evidence for Dark Matter

For eighty years, scientists have observed different phenomena hinting at the existence of a new type of invisible matter, not included in the current Standard Model theory. The first observation of the presence of extra matter in the universe was made by Jan Hendrik Oort in 1932 by analysing the motion of stars in the Milky Way. He used the Doppler effect of moving stars to calculate their velocities. Those calculated velocities were so large that the stars should have been able to escape the gravitational potential of the visible mass in this galaxy. Due to this apparent contradiction to his observations he postulated that the Milky Way must consist of more mass than he could observe.

Only one year later, Fritz Zwicky postulated the presence of invisible matter from his observation of the Coma cluster [17]. He also used the Doppler effect to calculate velocity dispersions of galaxies to determine the cluster's mass by using the virial theorem. This calculated mass was about ten times bigger than the mass calculated from luminosity observations. Over the decades, many other different astronomical observations indicated the existence of Dark Matter. These observations are made on small scales like dwarf galaxies up to large scales like clusters.

Another important evidence for Dark Matter is found in microlensing. Microlensing is an effect which occurs from gravitational lenses that display two close by objects in one image. One important use of the microlensing effect is that it would give evidence of Dark Matter, as Dark Matter would work as gravitational lenses. The most recent evidence for Dark Matter from microlensing is the observation of the Bullet cluster. The Bullet cluster consists of two galaxy clusters which collided. Each cluster consists of three important components the stars and gas, which are visible, and of Dark Matter. The visible planets mostly pass by each other and do not drift apart. The gas in the clusters slows down significantly due to collisions, whereby the gas in the bigger cluster gets compressed and the gas in the smaller one shapes like a bullet. This can be observed by emitted X-rays. The Dark Matter component of the galaxies is analysed using gravitational lensing and does not seem to interact with each other. It passes through each other and keeps its initial form, signaling that Dark Matter does not have substantial interaction either with visible matter or with itself [11].

4.2 Production and relic density

After the Big Bang, the universe was in an initial hot and dense state, which expanded isotropically and homogeneously. This high energy density made the occurrence of particle productions in the early universe comparatively likely. This led to the production of massive and very energetic particles. The ratio between production and decay of particles was nearly balanced, leading to thermal equilibrium. Eventually, the universe expanded and the process of production and decay could not longer be kept stable because lighter particles did not have enough energy anymore. At this time, the density of particles "froze-out", which means that the density of a particle type stays constant [13]. This occurred, because the particular density became too low to support frequent interactions and therefore the conditions for thermal equilibrium were violated [13].

The remaining particle density of a specific particle is called its relic density and has many implications. It allows one to calculate the time of the "freeze-out". Another important application is to compare theoretical calculation of the relic density for a possible Dark Matter candidate with the observation. This means that one can predict, for different model conditions in the early universe, the relic abundances of a given model. If the Dark Matter particle in the model is to explain the relic density, those predictions should lie in the range that is measured experimentally. Therefore, the relic density can be used as a guiding principle towards the choice of theoretical parameters. The Dark Matter density, which is observed today by, for example, the Planck collaboration [6], should be the same as the one predicted by models, at the time in which Dark Matter decouples from thermal equilibrium.

4.3 Properties and possible candidates

One can draw conclusions about the properties of Dark Matter from different observations. The most relevant observation is that Dark Matter has to interact gravitationally, which is why the idea of particle Dark Matter was introduced. Another important property comes from observations of the Cosmic Background Explorer (COBE) [14]. COBE analysed fluctuations in the Cosmic Microwave Background (CMB), which were about $30 \pm 5 \mu\text{K}$ [13]. These variations are so small that they could not be the origin of the structure that can be observed in the universe today. The ordinary matter was not electrically neutral before the recombination and could only then, form structure due to electrostatic forces. Nevertheless, this time period was too small. Thus, an extra type of gravitational matter has to be electrically neutral to initiate the formation of today's structure in the universe.

Since Dark Matter is observable at the present time, a possible Dark Matter candidate has to be stable or have a lifetime which is longer than the existence of the universe. Another aspect of Dark Matter is that it should be non relativistic. This conclusion comes from the way in which Dark Matter forms hierarchical structures. This means that Dark Matter forms structures from small objects merging into larger objects. The opposite structuring would lead to the fragmentation of large objects into smaller ones. This type of non relativistic matter is also called cold Dark Matter.

Massive astrophysical compact halo objects (MACHOs) were proposed as a possible candidate for Dark Matter. They are massive cosmological objects, which do not have an inner nuclear fusion because of their low pressure. This makes them electromagnetically invisible. A MACHO behind another massive object could cause gravitational microlensing. Nonetheless, only a few MACHOs were found and were not enough to explain all of the Dark Matter in the universe. Therefore, another Dark Matter candidate must exist. [13]

The observation of Dark Matter effects inspired many theoretical efforts that could explain it, in terms of new particles. Postulated particles include the so-called Weakly Interacting Massive Particles (WIMPs, also known as χ), which satisfy many of the experimental observations of Dark Matter. They have a high mass, no electrical charge and they only interact weakly with other matter. They are promising candidates especially according to the so-called WIMP "miracle": for a WIMP with a mass similar to massive SM particles and a coupling strength similar to that of SM particles interacting weakly, the WIMP relic abundance is close to the one observed for Dark Matter.

Another important theoretical concept for the explanation of Dark Matter is the extension of the Standard Model using Supersymmetry (SUSY). SUSY extends the Standard Model by adding supersymmetric partners to the particles of the Standard Model. This doubles the amount of particles and gives a large variety of new possible Dark Matter candidates. WIMP candidates are the neutralino, the sneutrino and the gravitino, whereby the neutralino is the only particle that would be stable enough, has a significant high relic density and would be cold Dark Matter. The neutralino itself is a superposition of the neutral superpartners of the Higgs and gauge bosons. Another aspect that supports the neutralino as a Dark Matter candidate is that it is the lightest supersymmetric partner (LSP) in most SUSY versions. Although SUSY offers a very promising Dark Matter candidate, not one single supersymmetric particle has ever been observed in detectors.

Besides the introduction of a new particle, one could theorise that the gravity model, which would be used to explain that the observations are not interpreted correctly. This would lead to the idea of a modified gravity, which does not need a new kind of matter. Those models still face several problems and are not able to explain everything that can be observed [13]. One example is that they cannot explain the density and temperature profiles in galaxy clusters. They can also be applied only to large structures as galaxies while Dark Matter can explain observations on many different length scales. For this reason, theories explaining Dark Matter as a particle are still the main experimentally pursued target.

4.4 Searches for Dark Matter

The search for Dark Matter is based on the assumption that a Dark Matter particle can interact with particles from the Standard Model. This interaction would be transmitted by a new particle, which is called the mediator [7]. This new mediator would be the propagator of a new force, similar to the W and Z bosons, and for this reason it is called Z' . This mediator could be produced by the annihilation of two SM particles, which then decay into either SM particles or Dark Matter particles (cf. figure 1). Those processes are, therefore, called either visible or invisible. In this project only visible processes with two particles from the standard model are considered.

The analysed collisions in this thesis are called dijet events, since the mediator decays into quarks. Jets are formed when two quarks create new quark-anti-quark pairs in the Quantum Chromo Dynamics process of hadronization and fragmentation. This process can occur multiple times and then form a measurable amount of hadrons. The direction of all those particles is identical with the one of the two initial particles. A cone of particles flying in the same direction is then called a jet. The models used in this project produce only events with two jets in the final state. They are, therefore, called dijet events. An aspect that should not be neglected is that Dark Matter might have couplings to other standard particles, which are not taken into account yet. That would cause further decay possibilities and different experimental signatures.

Those dijet events are under examination in the ATLAS detector in Switzerland (cf. figure 2). The ATLAS experiment, which started its first measurements in 2009, is one of the detectors recording collisions from the Large Hadron Collider (LHC). The ATLAS detector itself consists of multiple detectors, which surround the inner collision pipe cylindrically. The inner detector is a tracking chamber for charged particles, which measures the particle's charge and momentum. The next detectors are two calorimeters, an electromagnetic and a

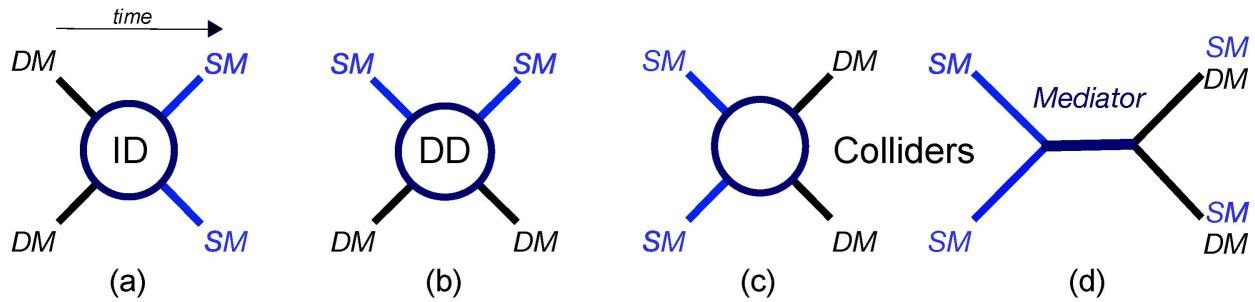


Figure 1: Different particle collisions could help to find Dark Matter. (a): Two Dark Matter particles combine to two standard particles, whereby the collision would be detected indirectly. (b): A Dark Matter and a standard particle interact, which could be detected directly. (c): Two standard particles combine and build two Dark Matter Particles in a collider. (d): Two standard particles from a particle collision combine into a mediator, which then decays into either Dark Matter or standard matter. This is the method used in this project. [12]

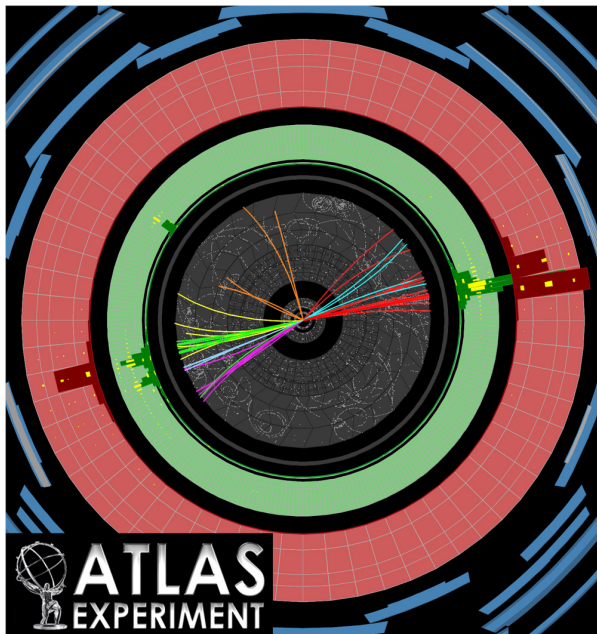


Figure 2: A particle collision creates a dijet-event in the Atlas Detector. First the particles in the jet are visible in the tracking chamber (dark grey cylinder). Then they are visible in the electromagnetic calorimeter (green cylinder) and in the hadronic calorimeter (red cylinder). [9]

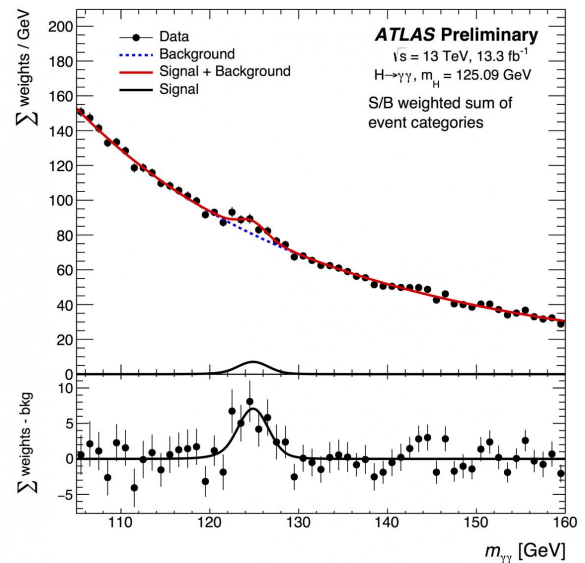


Figure 3: The detection of the Higgs boson. At an invariant mass of 125 GeV a bump is visible over the background data. This indicates the resonance of the Higgs particle. [3]

hadronic one. The first one determines the energy of electric charged particles and photons. The hadron calorimeter absorbs energy from particles that interact by the strong force and therefore mostly hadrons. The last detector is a Muon Spectrometer, which measures the momentum of muons.

At the LHC, many dijet events are produced and are recorded by the ATLAS detector [10]. These dijet events are used for the search for Dark Matter mediators. This energy produces many dijets, wherefore they are very useful for the search for Dark Matter. A new particle would be seen by the ATLAS detector as a bump in the invariant mass distributions (cf. figure 3) [10]. The invariant mass is the mass of a moving parent particle in its rest frame. The invariant mass is a conserved quantity in particle collisions [10], regardless of the reference frame. Only the rest energy which is equal to the invariant mass times speed of light squared can be used for the creation of new, real particles.

4.5 Results from different searches for Dark Matter at ATLAS

The search for Dark Matter involves different experimental methods that complement each other. In addition of looking for excesses in the invariant mass distribution of two jet events, one can look for missing transverse energy in the event, as Dark Matter particles are invisible to the detector.

The simplest theories of Dark Matter have four parameters: the coupling g_{DM} of the mediator-DM-DM vertex, the coupling g_q for all mediator-quark-quark vertices, the Dark Matter mass M_{DM} and the mediator mass M_{med} . In addition, the interaction type can be either vectorial or axial. In this study, the couplings and type of interaction are fixed but the Dark Matter and mediator masses are varied.

As mentioned before the relic abundance of Dark Matter is an important value for particle searches. Therefore, the possible combinations of Dark Matter mass and mediator mass for which the Dark Matter abundance is known as $\rho h^2 = 0.118$ are calculated. They form continuous lines in the M_{med} - M_{DM} -plane. Other areas with either higher or lower values are then called overabundant and underabundant regions.

Another important object in the M_{med} - M_{DM} -plane is the straight line $2 \cdot M_{DM} = M_{med}$. It consists of the points at which the mediator and its energy would decay into two Dark Matter particles. It also separates the plane into two areas, the one below is called on-shell and the one above off-shell. The on-shell region is characterised by the satisfaction of classical concepts and the conservation of energy-momentum. The off-shell region is characterised

by the violation of this conservation. It, however, allows virtual particles, which only exist during processes and not as long-lasting final particles.

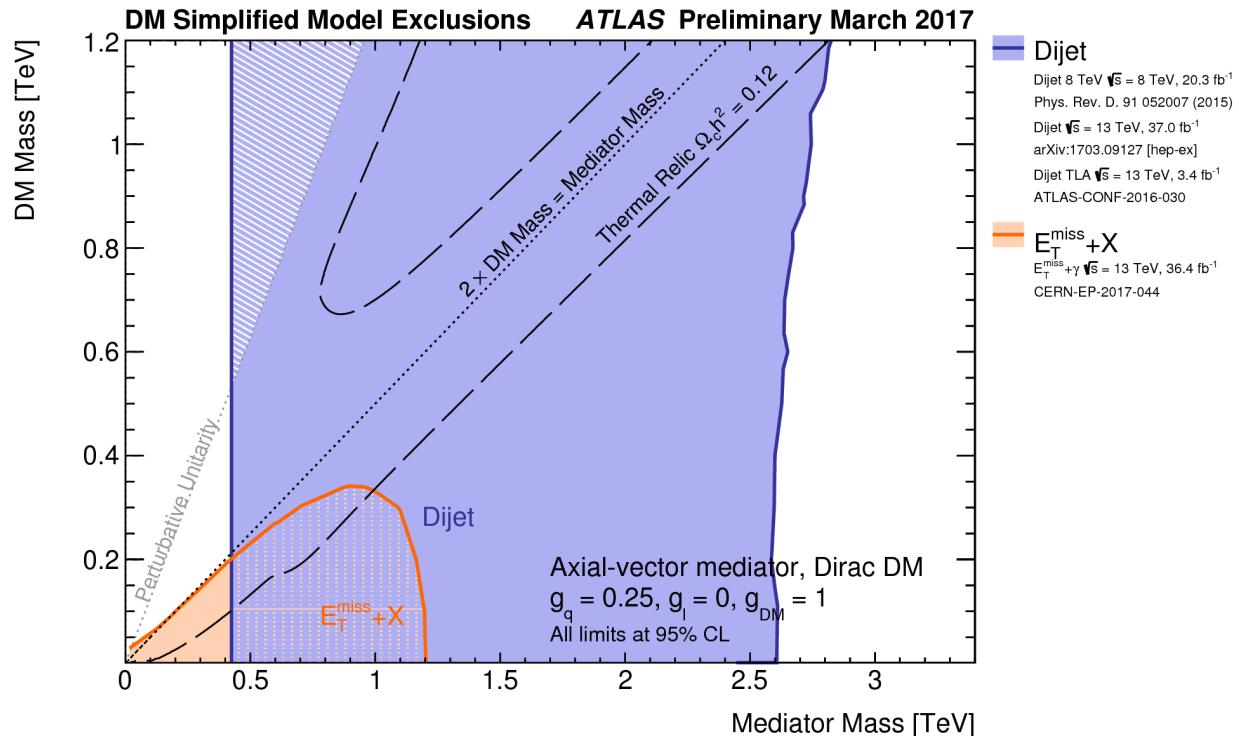


Figure 4: Different experimental searches are used to analyse a model for an axial-vector DM mediator. They can exclude different areas in the on- and off-shell regions, which are separated by the mass line. The red region is excluded by the searches for missing transverse momentum, while the blue region is excluded by searches in dijet final states. [4]

For the axial vector model with the coupling constants $g_{DM} = 1.5$ and $g_q = 0.25$ two overabundant regions occur (cf. figure 4). One is below the mass line and seems to be nearly a straight line. The other one is above the mass line and occurs for mediator masses greater than 0.5 TeV. Except the thermal relic and mass lines the main part of the summary plot consists of data from different event types. They characterise the zones for which the specific event has been tested and an appearance of dark matter can be excluded. They are excluded here because they do not fulfil the criterion:

$$\mu = \frac{\sigma_{exp}}{\sigma_{theor}} \quad (1)$$

$$\begin{cases} \text{excluded} & \text{if } \mu < 1 \\ \text{not excluded} & \text{if } \mu > 1 \end{cases} \quad (2)$$

Here μ is the ratio between the experimentally observed cross section and the one obtained from the event generation. Points with a ratio smaller than one are excluded, as the experiment would have been able to observe such a signal if it had been there.

The way this plot is made is by generating many signal points with different Dark Matter and mediator masses. For every data point the above criterion is used to check, whether a Dark Matter process is excluded or not. The large amount of point has to be generated, because no region is likelier than others.

5 Tools and methods

This project does not work with data from the actual ATLAS experiment, but with simulated events. This theoretical and computer based work requires different programs, data formats and tools.

5.1 Event generators

An important part of this thesis is the generation of events with computer software instead of using a real particle collider. The event generator and the parton shower program generate the outcome of collision events, and then different programs simulate the interaction with the detectors to reproduce the same inputs for the reconstruction of real data events. This enables an analysis of particle collisions, even without a real collision. In this project an event generator called MadGraph [8] and a generator called Pythia [16] which bunches many particles in a parton shower were used. The difference between a single parton and a parton shower is that the shower contains multiple partons and can, therefore, easier be seen as single object.

The general approach is using the Monte Carlo method as following. The simulation starts with the first possible step of a possible particle collision, according to the Feynman rules. There the possible bifurcations and probabilities for the possible processes are calculated, which is in other words the calculation of the matrix elements and the corresponding cross sections. [15] A decision is then made randomly with the Monte Carlo Method. Further vertices in the Feynman diagram are added sequentially. The order of degrees of freedom for a single particle can exceed ten easily, therefore the addition of a single particle requires much more computation time.

The final state of one event can have a large number of outgoing particles, which would make the calculation of the matrix element significantly more elaborate. Therefore, they are often factorised using parton showers, which include many particles, which have a similar overall behaviour [16]. Normally the hard process from the Feynman diagram is calculated and then extra processes with higher orders of the calculation are added using the parton shower. The calculation of single events in matrix elements can be very precise and it gives good results for jets that are well separated in the detector. Theoretical calculations for the leading order and the next-to-leading order exist for the Dark Matter models considered in this thesis, but only the leading order is used. Parton showers instead are approximations and can therefore not guarantee a high level of precision. Nevertheless, they are very useful for jet structures and approximate what happens in a real particle collision.

MadGraph is an event generation software program written in Python by a collaboration of physicists. MadGraph5 calculates the matrix element and then calculates cross sections and generates events. It also provides a possibility to generate events according to the next-leading order (NLO) precision. For the generation, it is required to specify the parameters of the theory, the interaction and the particles which occur in the initial and final state. MadGraph then generates all possible Feynman diagrams - depending on the chosen order - and then calculates the matrix elements at a given phase space point. [8]

Pythia is a multipurpose event generator, which is able to perform matrix element evaluations, parton showering, particle decays and much more [16]. It can read in the output of the matrix element evaluation from MadGraph5 and then proceed with further processes such as parton showers, and that is how it is used in this project.

5.2 Analysis tools

The ROOT software framework is developed by CERN physicists for data analysis in particle physics [5]. It contains statistic tools, commonly used functions of high-energy physics and visualization of large data sets in histograms. In this project the ROOT Python version PyROOT was used for the read-in, fitting and plotting of data from the output of the event generation.

The first things that were done with the data after the event generation with MadGraph and the addition of the parton shower with Pythia were changes in the data format. Therefore, the output which comes as a text file was transformed into a ROOT ntuple. Different intermediate file formats such as EVNT and TRUTH3 were used. This format change reduces the data amount.

6 Optimising the generation of events

The work in this project consisted of three basic steps. The first one was to modify a python script, which uses the Madgraph event generator to produce many templates with different parameters automatically on a computing cluster. The next step was then to find parametrisations for the cross sections of those events. The last step was to prove that a reduction of generated events is achieved through the parametrisation.

6.1 Automatic generation of multiple templates

The generation of multiple signal templates is implemented in a program called "runjobs" (cf. appendix C), written in the programming language Python. This program writes many small programs "batchjob" (cf. appendix C) as shell scripts for the operating system Linux. Each batchjob program runs the event generator by using different inputs and creates one template.

The runjobs program is used to define the general simulation parameters. It determines the properties of the further events by writing the mediator masses, Dark Matter masses and coupling constant into the batchjob programs.

The batchjob program starts then the single event generations by using the MadGraph and Pythia event generators. The important part of the further analysis are the parameters of the simulation, which are written in capital letters. The COM_ENERGY describes the centre of mass energy or also known as rest mass, the RUN_NUMBER is an internal parameter for the number of templates, the NUMBER_EVENTS corresponds to the number of events generated for one template and the RANDOM_SEED is used to vary the Monte Carlo starting point, because otherwise the output would be the same in every simulation. The file, which is defined under INPUT_JOB_OPTIONS contains information for the particle collision like the different masses.

After the computation of all templates for specific mediator masses M_{Med} and Dark Matter masses M_{DM} , the results can then be processed. The most interesting aspect of the final output for this thesis is the cross section of the event.

For the chosen model of an axial vector mediator with Dark Matter couplings 1.0 and a coupling to quarks of 0.25, the cross sections are plotted over the mediator masses M_{Med} and Dark Matter masses M_{DM} (cf. figure 5). The cross section varies over the whole plane between nearly 0 up to 8 pb.

The first visible aspect is that for a constant mediator mass M_{Med} it increases for larger Dark

Matter masses M_{DM} . In the first part of those rows it increases faster than in areas with higher Dark Matter masses, where it stays constant at a maximal cross sections after the off-shell transition. The second visible behaviour occurs for constant Dark Matter masses M_{DM} . Here, the cross section decreases for larger mediator masses M_{Med} . It decreases fast in the beginning and falls down rapidly. For Dark Matter masses over 2000 GeV it is almost zero. Those two aspects are very important because if they show a systematic behaviour for various masses, then this behaviour can be parameterised.

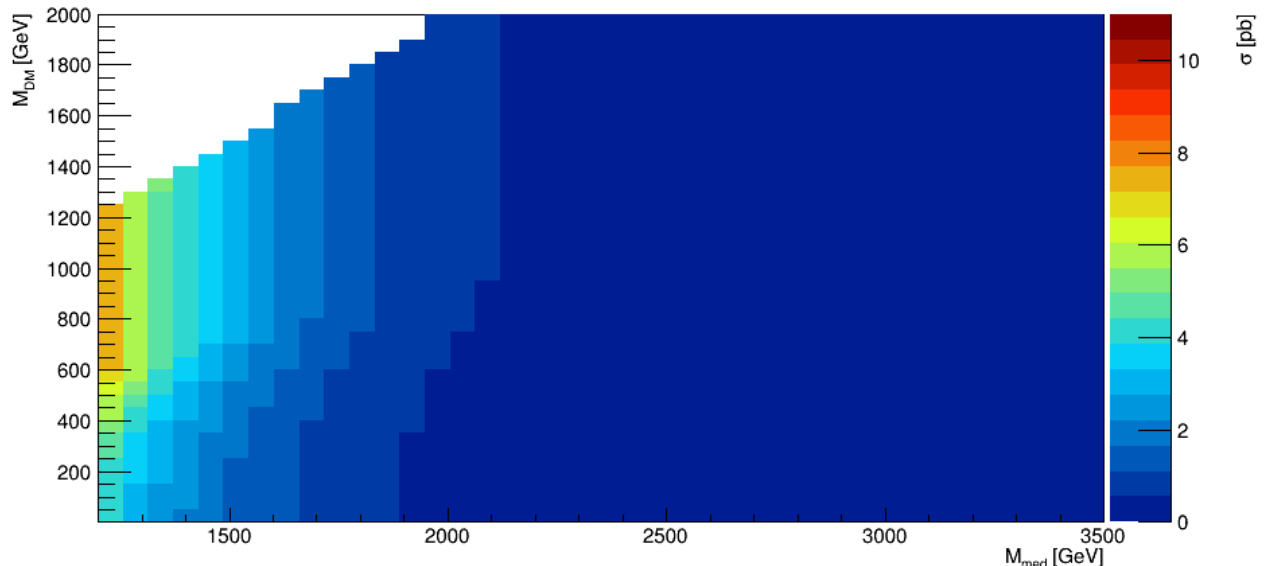


Figure 5: The cross sections computed with event generators show regular structures in the $M_{DM} - M_{Med}$ plane.

6.2 Parametrisation of event templates

In this thesis, we use the idea that the computed cross-sections are parameterisable as a function of Dark Matter and mediator mass. Therefore, the $M_{DM} - M_{Med}$ plane has been "sliced" in two different ways. The first kind of slices have a constant Dark Matter mass and variable mediator masses. The other slices instead have a constant mediator mass.

The first set of slices in constant Dark Matter mass was fitted with a modified exponential. The initial idea for doing this came from the fact that the data points on a log-log scale show a linear behaviour. Therefore, the fit function was chosen to $xsec(M_{Med}) = exp([0] \cdot log(M_{Med}) + [1])$. The parameters vary for different M_{DM} and lie in the ranges of multiple orders of magnitudes.

In figure 6 a representative slice of the set is shown. The M_{DM} is fixed at 650 GeV and

generated data points exist for 28 different mediator masses. The fit itself intersects all error ranges well. This supports two important conclusions. Firstly, the computed data points show a systematic behaviour. Secondly, the chosen function is sufficiently similar to the actual behaviour. The figure of merit χ^2 for this particular plot is 8.039 with the parameters $[0]=-5.859$ and $[1]=43.840$ and 26 degrees of freedom. This small χ^2 value indicates that a fit with less data points or with smaller errors would be possible. The resulting fit parameters for all plots can be found in the appendix B.

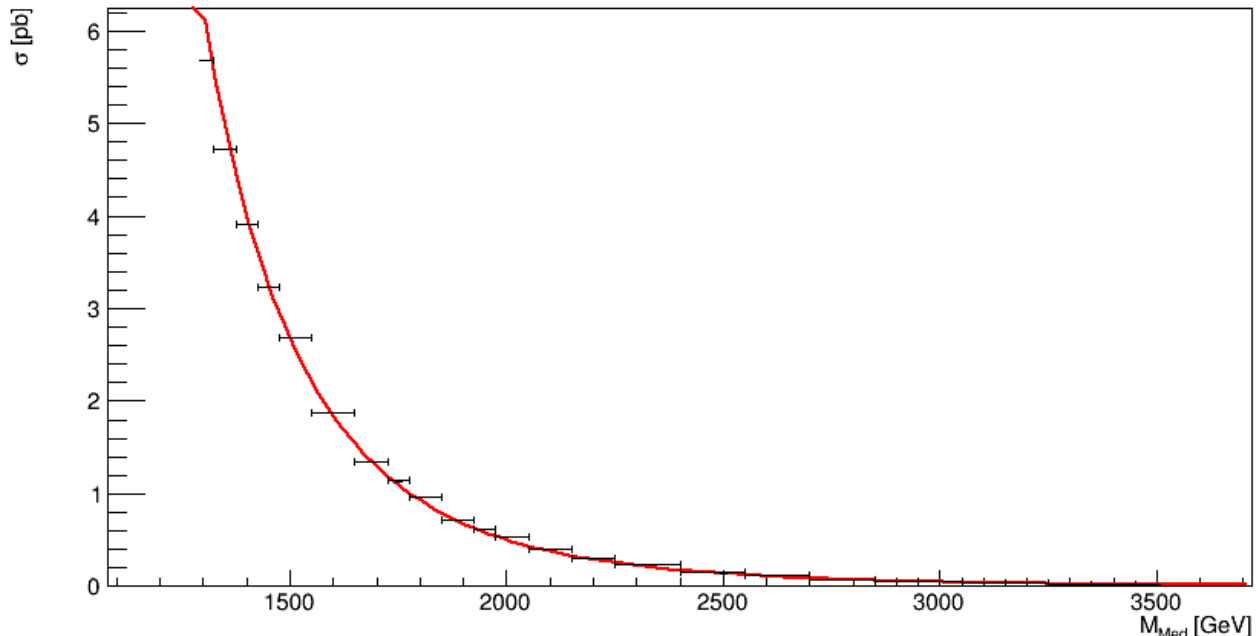


Figure 6: The cross section retrieved from generated signal samples for a constant Dark Matter mass of 650 GeV exhibit exponential decay. It can therefore be fitted using this function.

The second set of slices with a constant mediator mass shows a behaviour which is more complicated. It can be separated into two areas, whereby the cross section grows in the first area (on-shell) and stays constant in the second one (off-shell). Therefore, only the first area is fitted, using a polynomial curve. The fit function was then chosen to $xsec(M_{DM}) = [0] \cdot (M_{DM})^{[1]} + [2]$. As it can be seen in representative plot 7 the fit at a constant mediator Mass 1750 GeV intersects with all points within their error ranges and the corresponding $\chi^2 = 0.295$ shows that the fit function is a good choice, even though the fit is underconstrained. The fit parameters of $[0]=2.306e-07$ $[1]=2.2$ and $[2]=0.780$ are only valid for this particular example. Only the power of the polynomial seems to be around 2.2 for nearly all fits. The starting point for the constant has been chosen to $M_{DM} = 0.5 \cdot M_{Med}$, as discussed later in the next chapter.

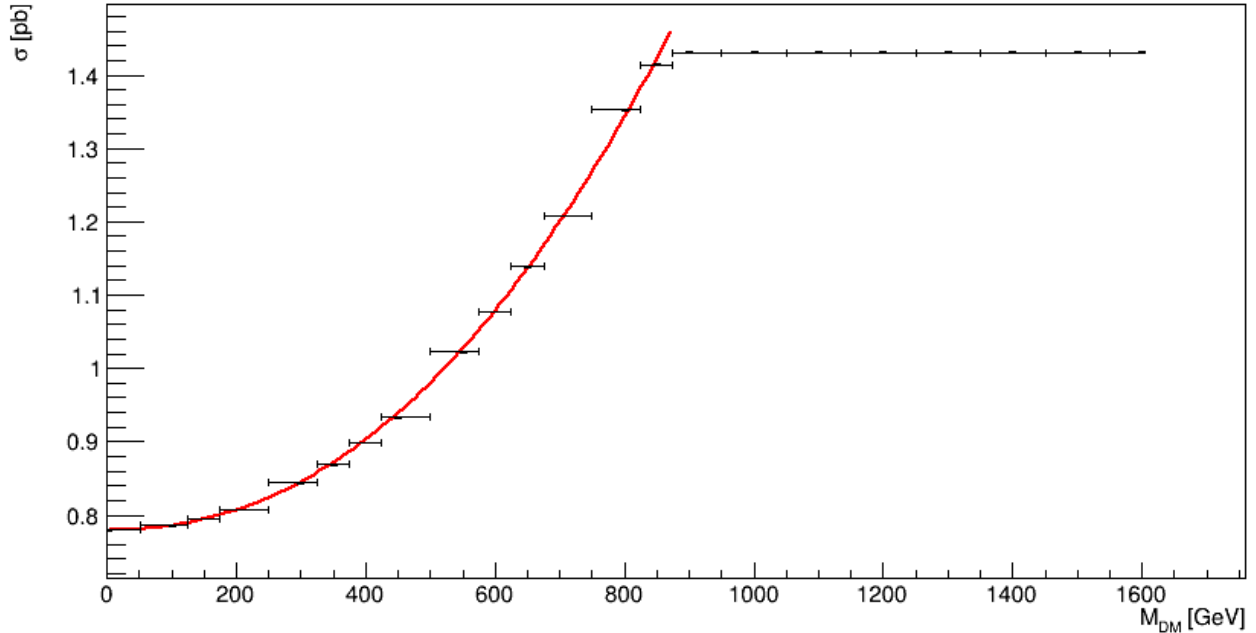


Figure 7: For a constant mediator mass of 1750 GeV the data for the cross sections show a rising function, which is similar to a parabola. After the border between on- and off-shell stay the cross sections constant.

The above plots are only one example for each set of slices, and for each slice the fit parameters vary. Therefore, a code (cf. appendix D) was written, which loops over different masses. The fit with constant mediator mass $xsec(M_{DM}) = [0] \cdot (M_{DM})^{[1]} + [2]$ needed a very precise input for the [0] and [2] parameters. Therefore two loops were implemented, whereby the inner one goes over a reasonable range for every parameter. If this does not fit the data points properly, then the outer loop raises the precision of the inner loop by a factor of ten. This does not expand the range of the parameters, but increases the number of parameters. They are then ten times closer by each other. This improves the chance that the initial parameters are closer to the final ones. If the fit is then successful and the corresponding χ^2 is small enough, both loops are exited and the next slice is fitted. For this data set χ^2 was chosen to be smaller than 5, because for this value all slices were fitted successfully. This technique allows a relatively fast and precise way for fitting different slices, which require well chosen input parameters.

6.3 Parametrisation of reduced data sets

The interim results that the cross sections seem to follow rules and are fittable can now be used for improvements of the event generation. Since the computing time for the actual event generation takes very long, it is the aim of this thesis to reduce it by estimating the cross sections rather than calculating them. The computing time for the fits in comparison is negligible. Therefore, the idea is to reduce the number of generated templates and to fit the missing points in the Dark Matter / mediator mass grid, instead of generating them. Based on this idea, half of the points from the data set were taken away and the remaining ones were fitted again. This can lead to two consequences: on the one hand it could become easier to find fit parameters, which represents the points well since there are fewer points, but on the other hand it could also decrease the quality of the cross sections because the fit function might miss the removed points. The results of this test are described in the next chapter.

7 Results

The quality of the parametrised cross section values can be analysed in an absolute and in a relative comparison to the original cross section. In the following the two fitting models will be analysed separately and then contrasted.

The differences of the cross sections for the original data and the parametrised data with constant Dark Matter mass are large (cf. figure 8). The values vary from around -0.1 up to 3.5 pb. Despite the large deviation of 3.5 pb, most of the values have got a deviation smaller than 1 pb. The large deviations occur for small mediator masses around 1000 and 1100 GeV and middle Dark Matter masses between 800 and 1200 GeV. For mediator masses over 1700 GeV the deviations vary only slightly between $+0.1$ and -0.1 pb.

If one brings back into consideration the exponential fit function for this data set, it is easy to imagine that the fit for small mediator masses close to zero entails a large risk. This means that it is likely that the exponential fit describes small values very well, but increases too fast for large values. This seems to happen in this area. The fact that the estimated values for small mediator masses and Dark Matter masses higher than 1200 GeV are closer to the generated ones is misleading, because if one compares this to the original data in figure 5 it is easy to see that there are no data points, which results in a zero deviation.

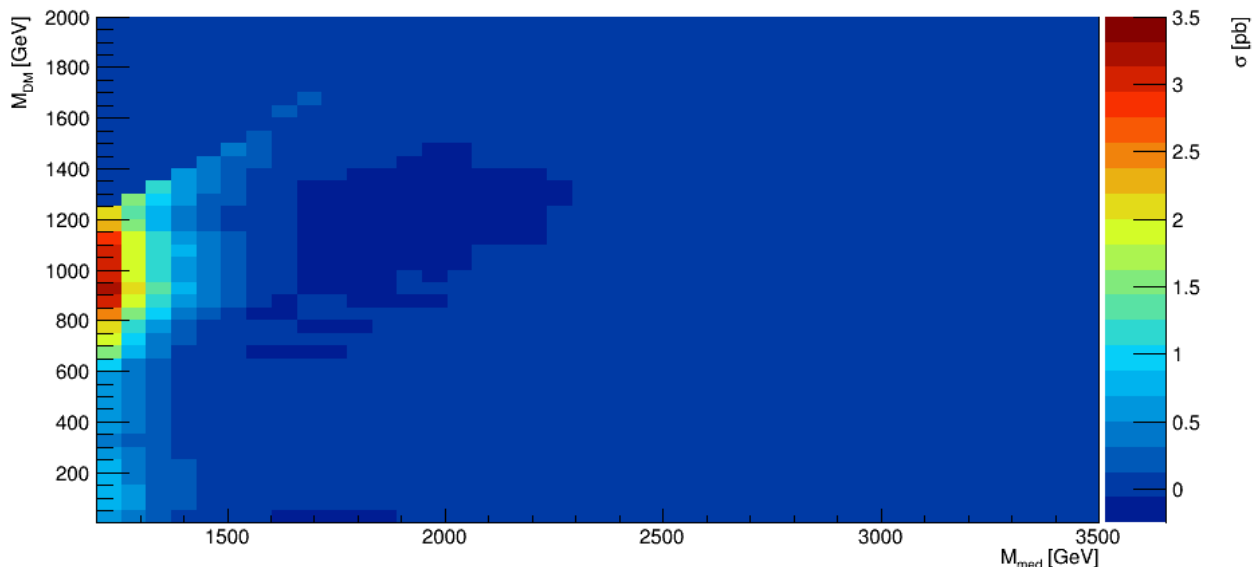


Figure 8: The absolute differences between the calculated cross sections and the for a constant Dark Matter fitted ones are large for small mediator masses and decrease for increasing mediator masses.

Since the previous analysis took only the absolute deviations of cross sections into consideration, the next step is to analyse the relative differences. Therefore, the absolute differences are divided by the values of the cross sections. This result is visualised in figure 9.

The relative deviations show interesting systematics. The first thing to notice are their values from -25% to 45%. As assumed the largest deviations occur in the previously mentioned area for small mediator masses and middle Dark Matter masses. The effect of too large values in the beginning of the fit is also visible for larger Dark Matter masses, where it forms a straight line from $(M_{Med} = 1000 \text{ GeV}, M_{DM} = 1250 \text{ GeV})$ to $(M_{Med} = 2000 \text{ GeV}, M_{DM} = 2000 \text{ GeV})$. The next interesting area lies in between mediator masses of 1500 GeV and 3000 GeV. Here many of the fitted values are smaller than the originally generated values. The absolute differences go up to -25%. Then, right to this band the deviations are again positive and rise up to 23%. To summarize: there are three areas from the left to the right with large positive deviations, middle negative deviations and middle positive deviations. They are separated by small bands without any deviation around $M_{Med} = 1500 \text{ GeV}$ and $M_{Med} = 3000 \text{ GeV}$. If the fits for a particular Dark Matter mass start at higher mediator masses, the areas are a bit shifted towards higher mediator masses.

It is also considerable that single badly fitted data rows are visible as for example at $M_{DM} = 250 \text{ GeV}$, which then leads to the light arrow stripe for higher mediator masses.

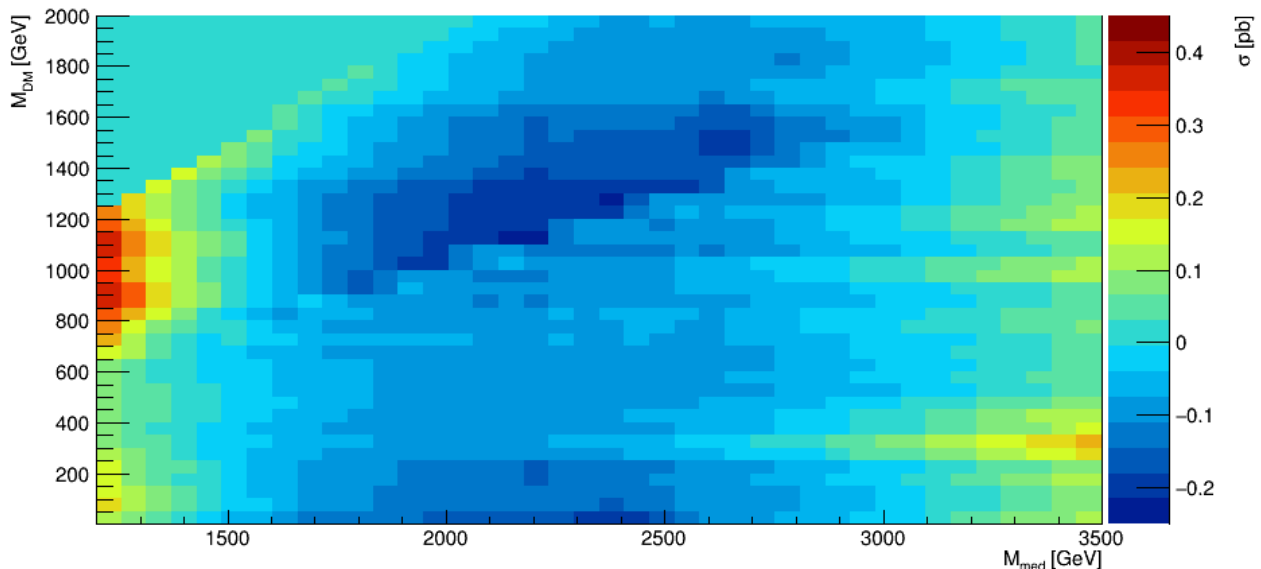


Figure 9: The relative differences between the calculated cross sections and the for a constant Dark Matter fitted ones build positive bands for small and large mediator masses. They are negative for mid-range mediator masses. In total they vary around 70% from the generated cross sections.

Generally, the method of fitting the data for a constant Dark Matter mass can result in

large deviations. They mainly occur from the function's form and its precision. Relative deviations in a range of 70% are not acceptable as they do not represent the generated cross sections.

The other method, which fitted for constant mediator masses shows much better results. The absolute differences between the original computed and the fitted data are in between -0.045 and 0.025 pb (cf. figure 10). The high deviations occur less often than smaller deviations. Over a mediator mass of 2000 GeV the differences are not greater than 0.01 pb and not smaller than 0.02 pb. The large deviations are seen in two interesting areas. They are in bands, which lie directly next to each other. The band with the positive deviations starts at the lowest mediator mass $M_{Med} = 1200$ GeV and in between $M_{DM} = 200$ GeV and $M_{DM} = 400$ GeV. It then linearly increases, whereby its contours fade out. It is visible until a mediator mass of $M_{Med} = 2700$ GeV, where it lies between $M_{DM} = 400$ GeV and $M_{DM} = 1400$ GeV. The band with large negative deviations lies directly above the other band and starts for the smallest mediator mass between $M_{DM} = 500$ GeV and $M_{DM} = 600$ GeV. It then fades away faster than the other band and is not visible anymore after $M_{Med} = 2200$ GeV. Besides those two bands other areas with larger deviations are visible, whereby they do not seem to follow a systematic structure.

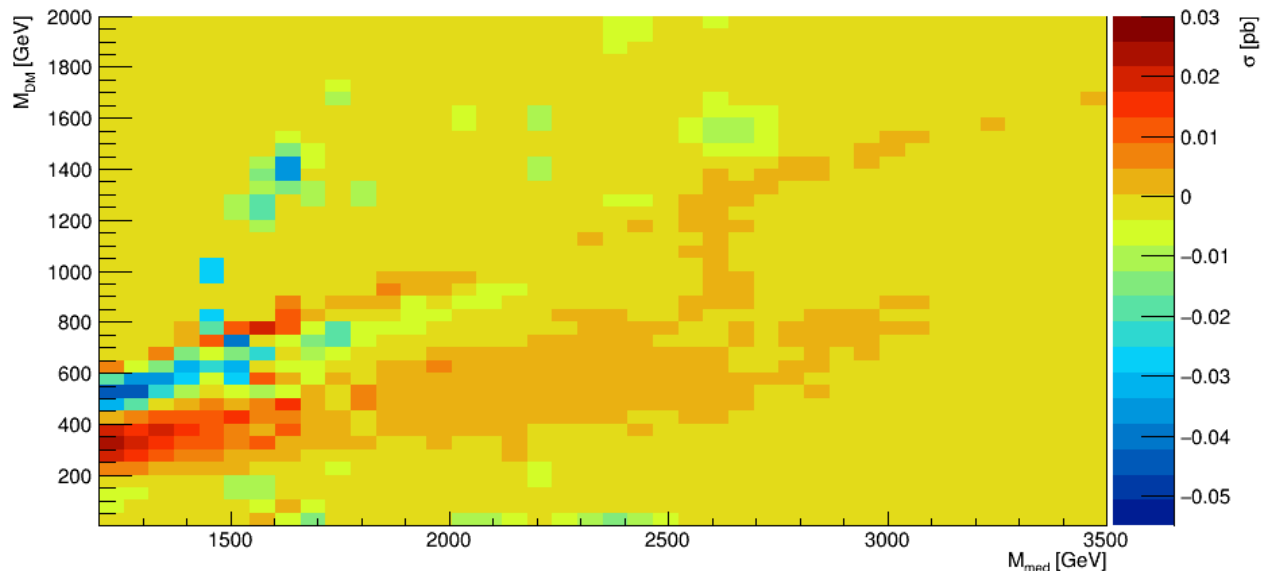


Figure 10: The absolute differences between the generated cross sections and the fitted ones with a constant mediator mass show a fan structure. The fans lie parallel to the mediator mass axis and abut on each other directly. Small islands with large deviations occur in the off-shell region.

The relative of deviations of this fitting method are in a range of -7% and $+2\%$ (cf. figure

11). In comparison to the absolute deviations the relative ones show some new behaviours and previously detected ones seem to be less important. A very interesting observation is the form of the highest deviations. They seem to occur in one faint stripe at $M_{Med} = 2650$ GeV. This indicates that this particular fit deviates strongly from the original data. The highest negative deviations are not very systematically distributed. They occur for small Dark Matter masses between $M_{Med} = 2300$ GeV and $M_{Med} = 2500$ GeV. This corresponds to a too high constant parameter [2] for the fitting function $xsec(M_{DM}) = [0] \cdot (M_{DM})^{[1]} + [2]$. Beside the two areas with the highest deviations, there are also other smaller deviations that would appear once the larger deviations are excluded. They probably show a more important behaviour, even though their magnitudes are much lower. If one excludes those high deviations, a fan structure is visible. The fans of the relative deviations are at very similar positions as the ones for the absolute deviations are. Nevertheless, they are much better visible for the relative amplitudes. It is easy to see that for lower Dark Matter masses the fit values seem to be smaller than the actual data, but then represent it very well until the transition between on- and off-shell at $M_{DM} = 0.5 \cdot M_{Med}$. If for those areas the fitting form $xsec(M_{DM}) = [0] \cdot (M_{DM})^{[1]} + [2]$ is taken into account it represents a sagging fit or in other words a too small initial constant value [2] and a too high parameter [1].

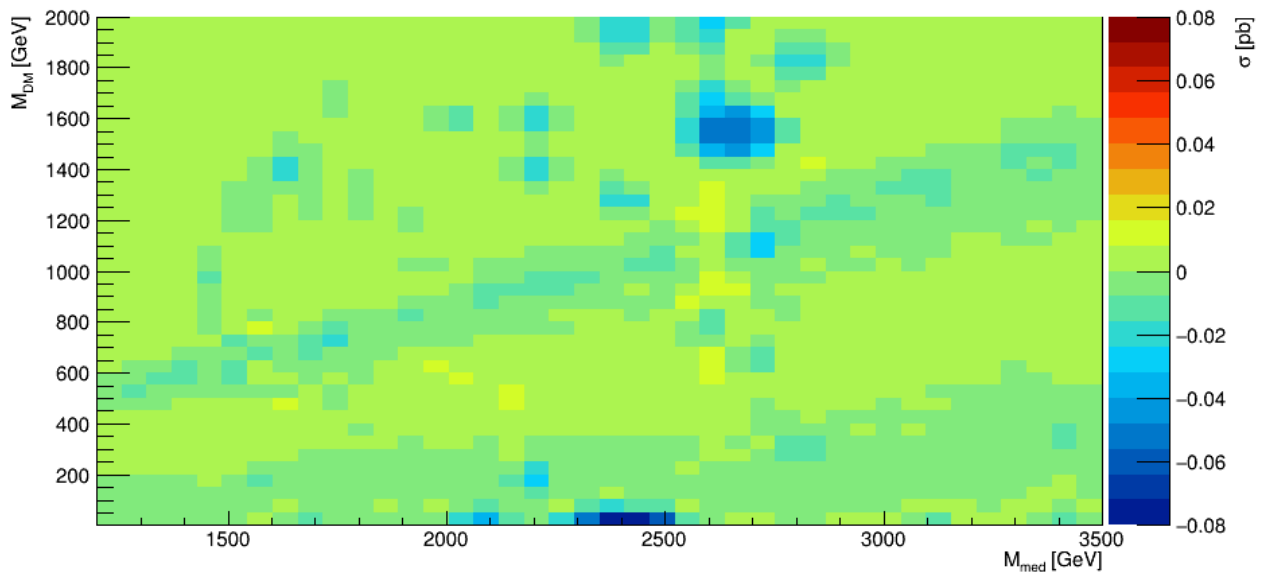


Figure 11: The relative differences for the cross sections also show a fan structure parallel to the mediator mass axis. Beside small islands of larger deviations in the off-shell region, a band at mediator mass around around 2700 GeV is slightly visible.

If the different fit methods are compared against each other, the second one, which fits over a constant mediator mass shows better results for the absolute and the relative deviations. The reason for this better performance cannot be explained easily, but one possibility

might be that the two loops to set the parameters of the fitting function and the fit itself require a longer computation time, but also result in a higher precision. Even though the second method also has some weaknesses, e.g. a failed fit and the on-off-shell transition, it is chosen for the further analysis, which compares the cross sections parameterisation from fewer data points to the full set of generated signal cross sections.

The cross section fit with the method of constant mediator mass for the data set with half of the points shows many similarities to the one with the full amount of points. The first visible structure are the same bands as before. They lie at the same positions, but they are sharper than for the other data set. However, the absolute differences are larger than before. They tend to 0.03 pb for the largest positive deviation at $M_{Med} = 1200$ GeV $M_{DM} = 250 - 400$ GeV. The largest negative deviations occur also in the negative band above the positive one. Their maximum value is -0.055 pb.

In comparison to the full set of generated signal cross sections, the reduced set does not show large differences in the absolute values (cf. figure 12). The extrema are slightly higher and many structures are seen in both data sets. Especially the single islands of strong deviations occur in both graphs with the same absolute deviation. Their origin is not clear, but since the relative deviations are small, this method can be still used to reduce the computation time of signals.

The relative deviations show more significant differences between the two data sets (cf. figure 13). The most apparent one is a strip with large positive deviations at $M_{Med} = 2700$ GeV. The relative deviations extend up to 6%, whereby in the other data set deviations of only 1% were visible. This large difference can be explained easily, if one takes a look at the corresponding plot in figure 14. It is clearly visible that the fit fails to reproduce the larger Dark Matter mass data points. Therefore, the difference is mostly visible in higher areas of the on-shell region. Another area in which a difference is visible is at $M_{Med} = 2000$ GeV and between $M_{DM} = 300$ GeV and $M_{DM} = 700$ GeV. Also here a look at the corresponding fit in figure 15 gives a direct explanation. As before the fit for the reduced data set is too high in this area and does not reproduce the data point well, even though it intersects with the error range.

Beside those two failed fits no large differences can be seen. The general band structure is nearly the same and also the islands of strong deviations occur at the same position with the same values. Interestingly the reduced data set has sometimes even smaller deviations

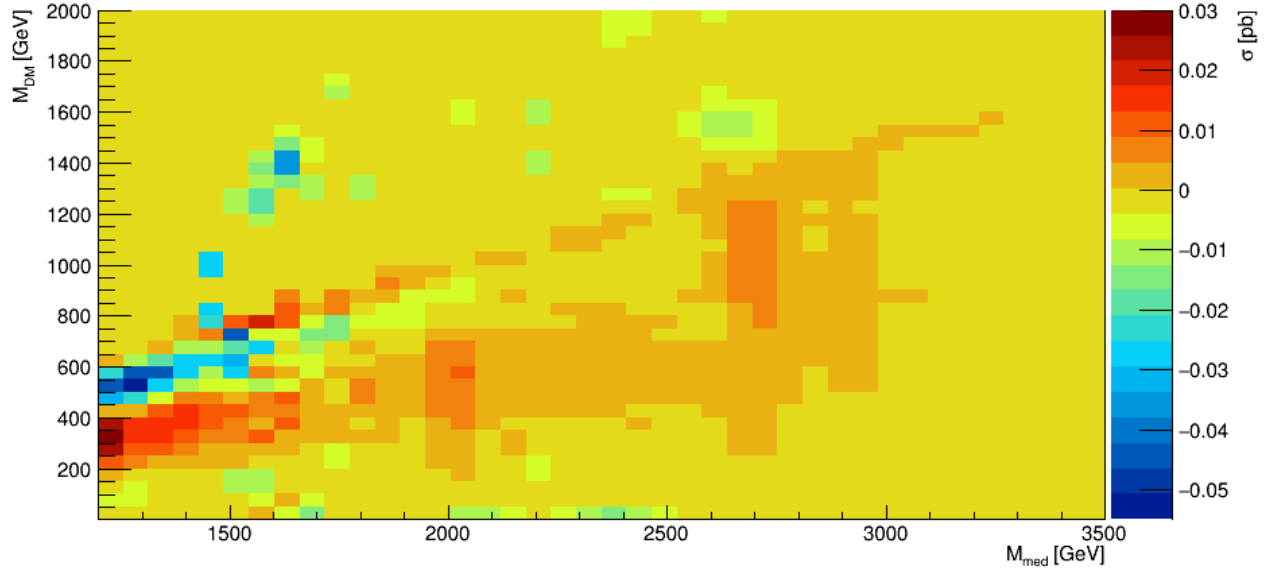


Figure 12: The absolute differences between the original data set and the fitted reduced data set are in the order of 0.01 pb. A fan structure with alternating positive and negative deviations is visible and also some detached points with large deviations occur.

than the complete one.

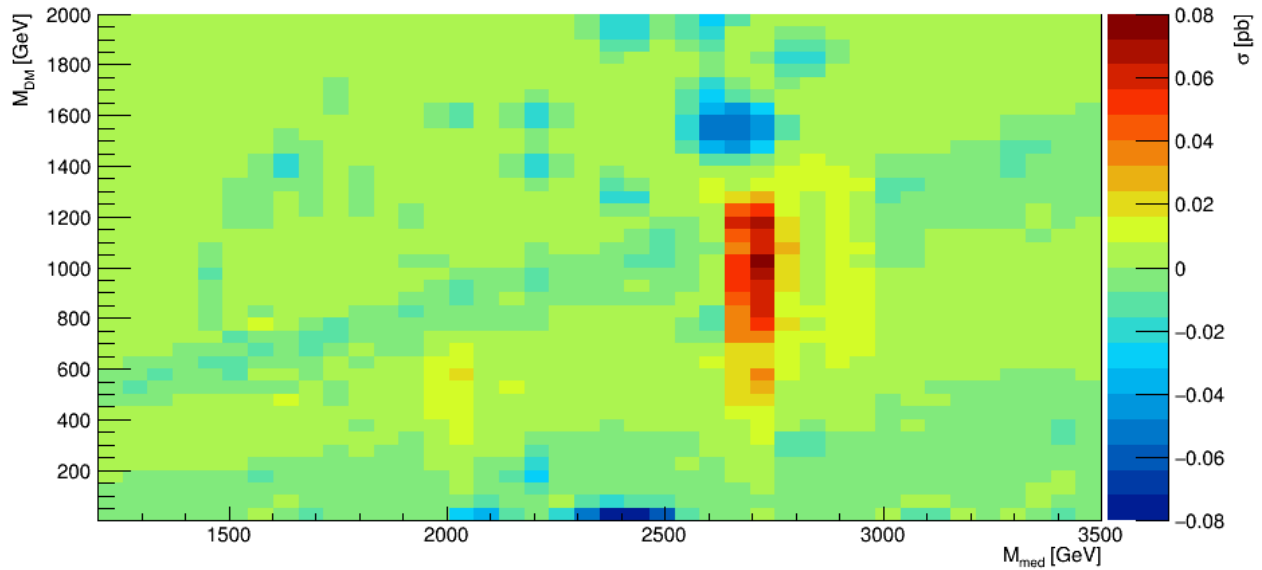


Figure 13: The relative differences between the original data set and the fitted reduced one show a fan structure with deviations of around 2%. Beside those fans two vertical lines at 2000 GeV and 2700 GeV are visible and some detached aberrations.

8 Conclusion and Outlook

The initial idea to reduce the calculation time for the cross sections of many Dark Matter signal processes when using event generators was approached by fitting the cross section to obtain values for the areas between computed data points. Two different methods were used. One of them fitted the cross sections in the mediator mass-Dark Matter mass-plane by taking slices with constant Dark Matter masses and the other one used a constant mediator mass. The fitting algorithm and functions used showed different results and different problems for the two methods. The fits over a constant Dark Matter mass converged more easily and accepted less precise initial parameters. This resulted in a faster computation process. The fits over a constant mediator mass instead needed more exact initial parameters and therefore it was more likely that they failed. This was solved by using χ^2 as a quality criterion and repeating the fit if the fit had failed. That results in a longer computation time. In the context of computation time and simplicity the fit over the constant Dark Matter mass is more appealing than the other one.

However, since the computation time of parametrisation in either method is negligible in comparison to the computation time of the event generation, only the precision of the two methods in estimating the generated cross section should be used to decide which method to prefer. The fitted cross sections with constant Dark Matter masses show significant deviations to the originally computed ones. Areas with relative deviations of more than +40% and -20% occur. The largest differences are mostly seen in areas where the exponential function increases too fast. Deviations of such an order are not acceptable and would distort further analyses too much. Therefore, this method was not longer taken into consideration. The second method showed only relative deviations up to +2% and -7%. This was considered as an acceptable range, wherefore the further evaluation was made with this method.

The fits for a reduced set of signal points with the second method show only slight differences to the complete data set. The relative deviations are between +6% and -8%. This is a degradation with a difference of 5% points. In comparison to the total range of nine or respectively twelve percent points this is a small degradation. It is, therefore, estimated as acceptable. Nevertheless, various differences still occur from the full calculation. The most important one comes from a failed fit, this could be solved by using a smaller χ^2 to establish the goodness of a fit, which would result in a longer computation time. If that does not work, a better fitting algorithm has to be applied. Another important improvement could be done at the transition between on- and off-shell. Here, could a smooth transition instead of the hard one - chosen in this project - produce better results. Other artefacts like the small islands in the off-shell region cannot be explained yet because there both the fitting function

and the computed cross sections should be constant.

In summary, it can be seen that by fitting the cross sections over a constant mediator mass the computation time can be reduced significantly, as one does not need to generate as many signal points. The strategy applied in this thesis showed good results with having very few complications.

Even though this work proves that it is generally possible to parametrise the Dark Matter signal cross sections it is still pending to clarify that this is generally applicable, and if not what are its restriction. An analytical calculation for the cross sections would speed up further analyses as well.

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A Further figures

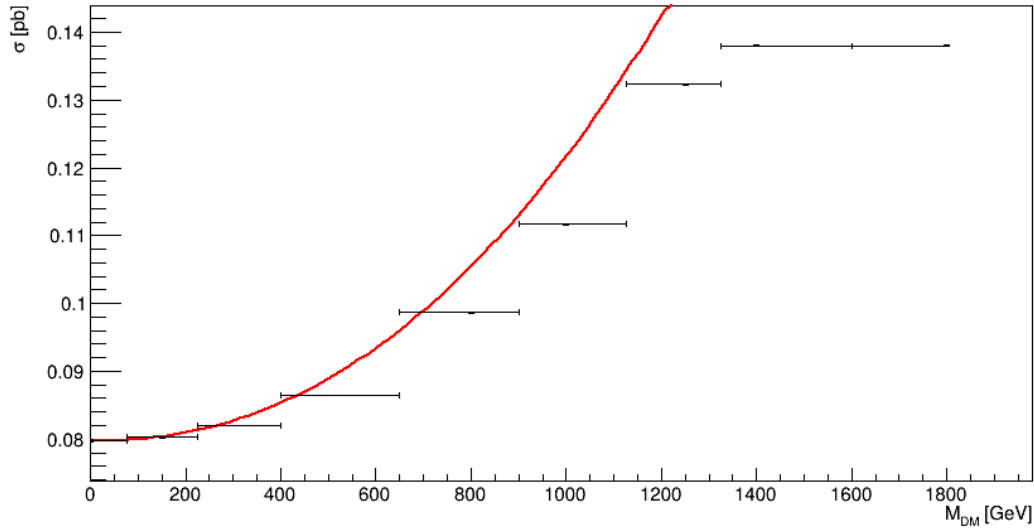


Figure 14: The fit for a constant mediator mass of 2700 GeV does not represent the data points precisely. It varies significantly for larger Dark Matter masses.

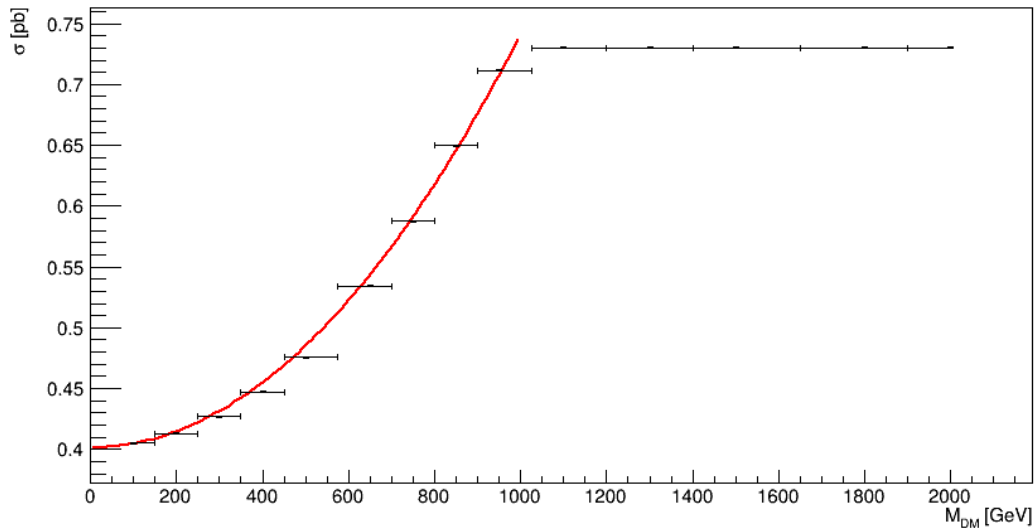


Figure 15: The fit for a constant mediator mass of 2000 GeV does not represent the data points precisely. It varies slightly for Dark Matter masses between 400 and 600 GeV.

B Fit parameters

Table 1: Fit parameters for constant Dark Matter masses

Mdm	[0]	[1]	χ^2
1	-5.14569993356	38.05802082	17.80341732
100	-5.3095245756	39.3492464784	46.605605171
150	-5.30723953708	39.317567111	33.4755430507
200	-5.31292150533	39.3979345233	35.2655182302
250	-5.3887708937	39.9678595871	29.5281509227
300	-5.16135541292	38.3251182769	14.3514594821
350	-5.33823850123	39.6571316486	15.4299404028
400	-5.45255996198	40.5475701379	15.6749557201
450	-5.54336648475	41.2805718575	16.0129375018
500	-5.62993943124	41.9591318088	13.5667045765
550	-5.69882908662	42.5359887605	9.69717274801
600	-5.76193257763	43.0473804479	10.9841543384
650	-5.85920230019	43.8403622576	8.03945496109
700	-5.86948653659	43.9457966989	26.7079943166
750	-6.06979461932	45.5628382989	3.0708873141
800	-5.77601023937	43.3328912288	44.8475695379
850	-6.22595386193	46.8503959397	1.91703483808
900	-5.93611897926	44.5821731816	79.4822476661
950	-6.3705486912	48.064413978	1.14509585728
1000	-5.80003683112	43.5690387156	70.0697815768
1050	-6.57736169743	49.7694143568	0.235199401503
1100	-5.8302563636	43.8133947341	87.1385933657
1150	-6.66595929868	50.549415	0.128285236834
1200	-5.50274789908	41.3627062148	66.355720123
1250	-6.86625023762	52.2064680709	0.150330382367
1300	-5.69742427154	42.8198108672	45.1611943504
1350	-6.89782147423	52.5281696426	0.0802522067732
1400	-5.54671197401	41.7471585585	31.8960855897
1450	-7.04714319207	53.7717365873	0.0143912159147
1500	-5.75003241206	43.2959344822	27.2478877404
1550	-7.08940883558	54.1637215811	0.00992714731102
1600	-5.58712336657	42.0733360244	9.44267600045
1650	-7.06574225825	54.0093433043	0.00137531823137
1700	-5.6607621256	42.6909251372	4.0019895344
1750	-5.7067341041	42.9445255533	8.18003483657e-10
1800	-5.77738269619	43.5732435327	7.84166541265
1900	-5.84876968813	44.1251799287	2.24843367209
2000	-5.96292755575	45.0682242236	2.63659139208

Table 2: Fit parameters for constant mediator masses

M_{Med}	max cross section	[0]	[1]	[2]	χ^2
1200	8.043000	2.69701392437e-06	2.22085691778	4.2700194736	0.297080578743
1250	6.742000	2.34919868164e-06	2.2	3.58799633411	0.207451070389
1300	5.677000	1.79435296579e-06	2.2	3.02901951882	0.558135915311
1350	4.804000	1.40555642127e-06	2.2	2.56700057511	0.264036366216
1400	4.081000	1.09598422494e-06	2.2	2.18700386897	0.474186117679
1450	3.481000	8.67931667955e-07	2.2	1.86900660545	0.300761556434
1500	2.977000	6.74075255809e-07	2.2	1.60400039924	0.205434604645
1550	2.557000	5.41371865213e-07	2.2	1.3789930962	0.0503795684309
1600	2.202000	4.44877218045e-07	2.2	1.1910220544	0.104587400804
1650	1.903000	2.44856646456e-07	2.25561971659	=1.03321997327	0.188622548035
1700	1.648000	2.23282762139e-07	2.23555729291	0.897331053277	0.990146317948
1750	1.431000	2.30635262925e-07	2.2	0.77933365598	0.295367981767
1800	1.246000	1.90404380569e-07	2.2	0.679158745225	1.03892231327
1850	1.087000	1.20030886915e-07	2.23935003567	0.595170974297	0.341632207336
1900	0.950700	1.27052046909e-07	2.2	0.520519831049	1.41556696189
1950	0.832400	1.053695089e-07	2.2	0.457371337326	0.991143903715
2000	0.730200	7.09353157121e-08	2.23016915266	0.403104598168	0.898225643539
2100	0.566500	5.66324154748e-08	2.20830729359	0.313950328307	1.62641918344
2200	0.441200	4.18414831044e-08	2.2	0.245997045559	1.20006883512
2300	0.346100	2.57784790388e-08	2.21957618332	0.194325519112	2.13006745114
2400	0.272900	1.90424560447e-08	2.21419829762	0.154216389679	0.571898872351
2500	0.216400	1.23123847785e-08	2.22888311051	0.123162547046	0.785173243504
2600	0.172400	1.14553944958e-08	2.2	0.0987022746635	1.70655730262
2700	0.138000	7.91275752215e-09	2.2	0.0797014370035	1.15139431143
2800	0.110900	5.85670890073e-09	2.2	0.0646019914909	1.3095204325
2900	0.089500	4.30101242968e-09	2.2	0.0526084365147	4.70342135748
3000	0.072520	3.19646396092e-09	2.20024756012	0.043013081679	2.13419858636
3100	0.058940	2.26020425888e-09	2.20605227188	0.0353551455104	3.07513544164
3200	0.048040	1.47832090298e-09	2.22632684885	0.0291699569165	4.13811895883
3300	0.039340	1.33144376223e-09	2.2	0.0241374872991	2.6791666458
3400	0.032300	1.01157945426e-09	2.19853353054	0.0200624317056	2.13539411235
3500	0.026640	5.95640785315e-10	2.23538504919	0.0167373837639	3.1550102338

Table 3: Fit parameters for constant mediator masses with a reduced amount of data points

M_{Med}	max cross section	[0]	[1]	[2]	χ^2
1200	8.043000	3.07154866607e-06	2.2	4.26999491174	0.0187152658945
1250	6.742000	2.34761631197e-06	2.2	3.58799613708	0.0228801368781
1300	5.677000	1.78696109913e-06	2.2	3.02899995123	0.0754269452942
1350	4.804000	1.40166611451e-06	2.2	2.56699700121	0.0284411045987
1400	4.081000	1.09937901618e-06	2.2	2.18699732401	0.028644913409
1450	3.481000	8.64150687978e-07	2.2	1.86899934368	0.0279062416456
1500	2.977000	6.74161998348e-07	2.2	1.6039977025	0.0227334872893
1550	2.557000	5.40251034168e-07	2.2	1.3789990656	0.00320436535521
1600	2.202000	4.41974916599e-07	2.2	1.19100241248	0.0150977940214
1650	1.903000	2.38518040433e-07	2.26016581566	=1.03316197184	0.0155370889672
1700	1.648000	2.38572050212e-07	2.22509072587	0.897165387073	0.14322127668
1750	1.431000	1.95662998993e-07	2.22668586979	0.779302852583	0.0211447839472
1800	1.246000	1.91506934791e-07	2.2	0.679104279655	0.0608232431981
1850	1.087000	1.31884579022e-07	2.22479756392	0.595014994795	0.0560766592164
1900	0.950700	1.26931244611e-07	2.2	0.520501206944	0.19572665445
1950	0.832400	1.05242024832e-07	2.2	0.457304959647	0.0998810524047
2000	0.730200	2.88246862908e-07	2.02312784069	0.401294709816	0.894275234004
2100	0.566500	4.81954261072e-08	2.23336828339	0.314004380525	0.060168347289
2200	0.441200	4.17818576635e-08	2.2	0.245999332627	0.20716680039
2300	0.346100	2.26477798956e-08	2.23963715259	0.194329735621	0.0889428761026
2400	0.272900	1.81269135252e-08	2.22187107539	0.154201291479	0.0313175906838
2500	0.216400	1.31324702965e-08	2.21929712844	0.123141604292	0.171130847906
2600	0.172400	1.18829452648e-08	2.18967461282	0.0987018477061	0.0657681156816
2700	0.138000	1.05201700501e-08	2.2	0.0796769073446	3.52561949378
2800	0.110900	4.08354599641e-09	2.25223256961	0.0646005224832	0.0957636141316
2900	0.089500	4.57820693675e-09	2.2	0.0525890089414	2.01996896815
3000	0.072520	3.38030306556e-09	2.19192358225	0.0430016709973	0.318430443585
3100	0.058940	1.99807854388e-09	2.2243305817	0.0353543697106	0.098881710641
3200	0.048040	1.45686150593e-09	2.22895618911	0.0291614613652	0.339799018181
3300	0.039340	1.4486365357e-09	2.18820670078	0.0241310047781	0.396331535487
3400	0.032300	8.77019853668e-10	2.2189332232	0.0200662267583	0.0976457896602
3500	0.026640	6.87460744149e-10	2.21497289461	0.0167310514213	0.598647378193

C Programs

The used programs can be found on the GitLab of CERN:

```
https://gitlab.cern.ch/atlas-phys-exotics-dmSummaryPlots/DMMassMediatorMass/  
tree/master/MakeSignalTemplates
```

For further access data please contact the Division of Particle Physics at Lund University.

D Program: plotting and fitting

```
import os
import ROOT
from ROOT import TCanvas, TGraph2D, TF1, TGraph2DErrors, Math,
    TMath
from XcrossPar import signalCrossSectionDict
from ParameterDict import signalParameterDict
from CrossError import errorDic
#import scipy.special

batch=True
skip=False

if batch:
    ROOT.gROOT.SetBatch(1)

#from array import array

###Functions

#loop on the graph, and check where the next point is on the x
    axis – take half that distance as the error
#warning: errors are asymmetric
def fixErrors (theGraph) :

    #do first point by hand
    xPoint = ROOT.Double()
    xPointPlusOne = ROOT.Double()
    yPoint = ROOT.Double()
    yPointPlusOne = ROOT.Double()
    theGraph.GetPoint(0, xPoint, yPoint)
    theGraph.GetPoint(1, xPointPlusOne, yPointPlusOne)
    xPointError = (xPointPlusOne - xPoint)/2.
    theGraph.SetPointEXhigh(0, float(xPointError))
```

```

theGraph.SetPointEXlow(0, 0)

#all points except for last
for iPoint in xrange(1,theGraph.GetN()-1) :
    #we have to be careful with pyROOT: it wants a special
    format to retrieve the points off a graph
    xPoint = ROOT.Double()
    xPointPlusOne = ROOT.Double()
    xPointMinusOne = ROOT.Double()
    yPoint = ROOT.Double()
    yPointPlusOne = ROOT.Double()
    yPointMinusOne = ROOT.Double()
    theGraph.GetPoint(iPoint, xPoint, yPoint)
    theGraph.GetPoint(iPoint+1, xPointPlusOne, yPointPlusOne)
    theGraph.GetPoint(iPoint-1, xPointMinusOne, yPointMinusOne)
    xPointErrorHigh = (xPointPlusOne - xPoint)/2.
    xPointErrorLow = (xPoint - xPointMinusOne)/2.
    theGraph.SetPointEXhigh(iPoint, float(xPointErrorHigh))
    theGraph.SetPointEXlow(iPoint, float(xPointErrorLow))

#do last point by hand
#do first point by hand
xPoint = ROOT.Double()
xPointMinusOne = ROOT.Double()
yPoint = ROOT.Double()
yPointMinusOne = ROOT.Double()
theGraph.GetPoint(theGraph.GetN()-1, xPoint, yPoint)
theGraph.GetPoint(theGraph.GetN()-2, xPointMinusOne,
    yPointMinusOne)
xPointError = (xPoint - xPointMinusOne)/2.
print "last point error", xPointError
theGraph.SetPointEXlow(theGraph.GetN()-1, float(xPointError))
theGraph.SetPointEXhigh(theGraph.GetN()-1, 0)

#import AtlasStyle
from AtlasStyle import *

```



```

AtlasStyle ()

g=open ('plotdic.py', 'w+')
g.write (" alldic=")

##Arrays for 2D plot
xmed=array.array ('d', [])
ydm=array.array ('d', [])
zsec=array.array ('d', [])
xmedErr=array.array ('d', [])
ydmErr=array.array ('d', [])
zsecErr=array.array ('d', [])

##Dictionaries for 1D plot
#key : mMed, value : mDM dictionary
#mDM dictionary key : mDM, tuple (xsec, xsecErr)
#this is an ordered dictionary: see https://pymotw.com/2/collections/ordereddict.html
CrossSectionDictionary_MMed = {}
CrossSectionDictionary_MDM = {}

for mykey, myvalue in signalParameterDict.iteritems():
    try :
        DSID = mykey
        ParameterDict = myvalue
        CrossSection = signalCrossSectionDict [mykey] [" xsec "]
        CrossSection_Error = errorDic [mykey] [" xsec_error "]
        MMed = ParameterDict [" mmed "]
        MDM = ParameterDict [" mdm "]
        xmed.append (MMed)
        ydm.append (MDM)
        zsec.append (CrossSection)

```

```

    g.write(" { %i :{ 'MMed':%f, 'MDM':%f, 'CrossSection':%f },\n" %(
DSID, MMed, MDM, CrossSection))
    #print (" { %i :{ 'MMed':%f, 'MDM':%f, 'CrossSection':%f },\n" %(
DSID, MMed, MDM, CrossSection))
    ##Dictionary with MMed as a key
    #if the MMed entry is already there, append the entry for mDM
    #if not, create it
    try :
        CrossSectionDictionary_MMed [int (MMed) ] [int (MDM) ] = (
CrossSection , CrossSection_Error)
    except :
        CrossSectionDictionary_MMed [int (MMed) ] = {}
        CrossSectionDictionary_MMed [int (MMed) ] [int (MDM) ] = (
CrossSection , CrossSection_Error)
    ##Dictionary with MDM as a key
    #if the MDM entry is already there, append the entry for MMed
    #if not, create it
    try :
        CrossSectionDictionary_MDM [int (MDM) ] [int (MMed) ] = (
CrossSection , CrossSection_Error)
    except :
        CrossSectionDictionary_MDM [int (MDM) ] = {}
        CrossSectionDictionary_MDM [int (MDM) ] [int (MMed) ] = (
CrossSection , CrossSection_Error)

except :
    continue

g.write('}')
g.close

for mykey in errorDic:
    #try :
        DSID = mykey
        CrossSection_Error = errorDic [mykey] [" xsec_error "]
        zsecErr.append (CrossSection_Error)

```

```

                xmedErr.append(0)
                ydmErr.append(0)
            #except:
            #        continue

c1 = TCanvas( 'c1', '2D plot', 200, 10, 1000, 500 )

##Make the 2D plot

#c1.Divide(2,2)
#c1.SetGrid()
#c1.GetFrame().SetFillColor( 21 )
#c1.GetFrame().SetBorderSize( 12 )
#c1.cd(1)

gr = TGraph2DErrors(750, xmed, ydm, zsec, xmedErr, ydmErr, zsecErr
    )
gr.Draw('COLZ')
#gr.Draw('AP')
gr.SetLineWidth(1)
gr.SetLineColor(5)
gr.GetHistogram().GetXaxis().SetTitle('M_{med} [GeV]')
gr.GetHistogram().GetYaxis().SetTitle('M_{DM} [GeV]')
gr.GetHistogram().GetZaxis().SetTitle('#sigma [pb]')
gr.GetHistogram().GetZaxis().SetRangeUser(0, 11)
gr.SetMarkerColor(4)
gr.SetMarkerStyle(1)
gr.SetMarkerSize(20)
c1.Modified();
#gr.Draw('COLZ')
c1.SetRightMargin(0.15)

c1.Update()
#c1.SaveAs('2d.png')
```

```
c1. Clear
```

```
xmed_scanMmed = array.array('d', [])  
ydm_scanMmed  = array.array('d', [])  
zsec_scanMmed = array.array('d', [])
```

```
if not batch:  
    raw_input()
```

```
##Make the 1D plots
```

```
#for key, value in CrossSectionDictionary_MDM.iteritems() :  
# print key  
# for secondkey, secondvalue in value.iteritems() :  
#     print secondkey, secondvalue
```

```
#the dictionary is made like this:
```

```
#key = mediator mass
```

```
#1350.0
```

```
#values = DM mass, (cross section, cross section error)
```

```
#600.0 (4.427, 0.003206)
```

```
#350.0 (3.104, 0.002302)
```

```
# etc
```

```
#make histogram for this particular value of mediator mass  
independent by how many MDM values you have by counting the  
entries of the mDM dictionary (same for the MMed version)
```

```
# 1. loop over m Med
```

v

```
# 2. do fits missing out every other point
```

```
# 3. make new TH2s
```

```
# 4. add, subtract, etc these
```

```
# 5. change fit function to quadratic in the on+shell regime plus  
a constant above          v
```

```
skipAlternatPoints = False
```

```
mMed=0
```

```
g=open('parameteroutput.txt','w+')
```

```
for DSID in signalParameterDict:
```

```
    if signalParameterDict[DSID]['mmed']!=mMed:
```

```
        mMed=signalParameterDict[DSID]['mmed']
```

```
        g.write('Mmed= %i \n \n' %mMed)
```

```
        xsecmax=0
```

```
        mdmmax=0
```

```
        DSIDmax=100000
```

```
        for DSID2 in signalParameterDict:
```

```
            if signalParameterDict[DSID2]['mmed']==  
mMed and mdmmax<signalParameterDict[DSID2]['mdm'] and DSIDmax<  
DSID2:
```

```
                mdmmax=signalParameterDict[DSID2]  
][['mdm']
```

```
                DSIDmax=DSID2
```

```
        while DSIDmax not in errorDic:
```

```
            DSIDmax -= 1
```

```
        xsecmax=errorDic[DSIDmax]['xsec']
```

```

g.write('xsecmax= %f \n' %xsecmax)
constfunc=TF1('constfunc',str(xsecmax),0.5*mMed
,2000)

#make a new TGraphErrors (1D this time) with the
number of mDM bins
mDMGraph = ROOT.TGraphAsymmErrors()
mDMGraph.SetName("XSecVsMDM_MMed"+str(mMed))
#loop
iPoint=0
oddpar=0
for mDM in sorted(CrossSectionDictionary_MMed [mMed
]) :
    if skip and oddpar==1:
        oddpar=0
        continue
    (xsec, xsec_error) = CrossSectionDictionary_MMed
[mMed] [mDM]
mDMGraph.SetPoint(iPoint, int(mDM), xsec)
#not optimal to have an error of zero here... fix
it later
mDMGraph.SetPointError(iPoint, 0, 0, xsec_error,
xsec_error)
iPoint=iPoint+1
oddpar=1

#let's fix the errors before doing anything else
fixErrors(mDMGraph)

mDMGraph.Draw("APE")

```

```

mDMGraph. GetXaxis () . SetTitle ("M_{DM} [GeV] ")
mDMGraph. GetYaxis () . SetTitle ("#sigma [pb] ")
c1. Update ()
c1. SaveAs ("XSecVsMDMLMed"+str (mMed) + ".png")

```

```

myfit=TF1( 'myfit' , '[0]*x**[1]+[2]' , 0 , 0.5*mMed)

```

```

myfit. SetParName (0 , 'p0 ')
myfit. SetParName (1 , 'p1 ')
myfit. SetParName (2 , 'p2 ')

```

```

myfit. GetXaxis () . SetTitle ('M_{DM} [GeV] ')
myfit. GetYaxis () . SetTitle ('#sigma [pb] ')
fitres=mDMGraph. Fit ('myfit' ,"SQ" , '' , 0 , 0.5*mMed)

```

```

chi=myfit. GetChisquare ()

```

```

run0=1

```

```

run=1

```

```

while chi>5 or chi<0.00001 or a>0.0001 or a<0 or b
<2 or b>3 or c<0 :

```

```

if run0==7: break

```

```

for run in range(0,10**run0):

    parm=(10**(-(10**(-run0)*run+run0
+5)))

    a=myfit.SetParameter(0,parm)
    b=myfit.SetParameter(1,2.2)
    c=myfit.SetParameter(2,4-4*10**(-
run0)*run)

    myfit.GetAxis().SetTitle('M_{DM}
[GeV]')

    myfit.GetAxis().SetTitle('#sigma
[pb]')

    fitres=mDMGraph.Fit('myfit',"SQ
",'',0,0.5*mMed)

    a=myfit.GetParameter(0)
    b=myfit.GetParameter(1)
    c=myfit.GetParameter(2)

    chi=myfit.GetChisquare()
    run=run+1

    fitres.Draw('E')
    c1.Update
    if chi<5 and chi>0.00001 and a
<0.0001 and a>0 and b>2 and b<3 and c>0: break

    run0=run0+1

    fitres.Draw('E')

    c1.Update

```



```

        g.write
        g.write('p0=%s          p1=%s          p2=%s \n
chi = %s \n \n \n \n' %(a,b,c,chi))
        c1.SaveAs("XSecVsMDM_MMed"+str(mMed)+"_fit.root")
        c1.SaveAs("XSecVsMDM_MMed"+str(mMed)+"_fit.png")

#
for DSID in signalParameterDict:
    if signalParameterDict[DSID]['mmed']!=mMed
: continue

    mDM = signalParameterDict[DSID]['mdm']
    xs_fit = myfit.Eval(mDM)
    xs_fit = min(xsecmax, xs_fit)

    xmed_scanMmed.append(mMed)
    ydm_scanMmed.append(mDM)
    zsec_scanMmed.append(xs_fit)

else:
    continue

for i in range(len(zsec_scanMmed)):
    if zsec_scanMmed[i] < 0:
        print i, xmed_scanMmed[i], ydm_scanMmed[i], zsec_scanMmed[i]
        zsec_scanMmed[i] = 0

gr_mMed = TGraph2D(len(xmed_scanMmed), xmed_scanMmed, ydm_scanMmed
, zsec_scanMmed)
gr_mMed.Draw('COLZ')
gr_mMed.SetLineWidth(1)
gr_mMed.SetLineColor(5)

```

```

gr_mMed.GetHistogram().GetXaxis().SetTitle('M_{med} [GeV]')
gr_mMed.GetHistogram().GetYaxis().SetTitle('M_{DM} [GeV]')
gr_mMed.GetHistogram().GetZaxis().SetTitle('#sigma [pb]')
gr_mMed.GetHistogram().GetZaxis().SetRangeUser(0, 11)
gr_mMed.SetMarkerColor(4)
gr_mMed.SetMarkerStyle(1)
gr_mMed.SetMarkerSize(20)
c1.Modified()
c1.Update()
#c1.SaveAs('2d_mMed.png')

#exit()
chi=1000
xmed_scanMdm = array.array('d',[])
ydm_scanMdm = array.array('d',[])
zsec_scanMdm = array.array('d',[])

#start with one MDM, and do one plot of cross-section as a
function of MMed
for mDM in range(1,2001):
    try:

        #make a new TGraphErrors (1D this time) with the
number of mDM bins
        mMedGraph = ROOT.TGraphAsymmErrors()
        mMedGraph.SetName("XSecVsMDMLMDM"+str(mDM))
        #loop
        iPoint=0
        oddpar=0
        for mMed in sorted(CrossSectionDictionary_mDM[mDM
])) :

            #print mMed
            if skip and oddpar==1:
                oddpar=0

```

```

        continue
        (xsec, xsec_error) =
CrossSectionDictionary_MDM [mDM] [mMed]
        mMedGraph.SetPoint(iPoint, int(mMed), xsec)
        #not optimal to have an error of zero here...
but we fix it later
        mMedGraph.SetPointError(iPoint, 0, 0,
xsec_error, xsec_error)
        iPoint=iPoint+1
        oddpar=1

fixErrors(mMedGraph)

mMedGraph.Draw("AP")
mMedGraph.GetAxis().SetTitle("M_{Med} [GeV]")
mMedGraph.GetAxis().SetTitle("#sigma [pb]")
c1.Update()
c1.SaveAs("XSecVsMDMLMDM"+str(mDM)+".png")

#try one fit

myfit=TF1('myfit', 'exp([0]*log(x)+[1])', 1199, 3000)
myfit.SetParName(0, 'p0')
myfit.SetParName(1, 'p1')
myfit.SetParameter(0, -5.7)
myfit.SetParameter(1, 43)

myfit.GetAxis().SetTitle('M_{DM} [GeV]')
myfit.GetAxis().SetTitle('#sigma [pb]')

```

```

fitres=mMedGraph.Fit('myfit',"SQ")
chi=myfit.GetChisquare()
print 'Chi2=',chi
fitres.Draw('E')
#c1.SetLogx()
#c1.SetLogy()
c1.Update
a=myfit.GetParameter(0)
b=myfit.GetParameter(1)

c1.SaveAs("XSecVsMDMLMDM"+str(mDM)+"_fit.root")
c1.SaveAs("XSecVsMDMLMDM"+str(mDM)+"_fit.png")
g.write('Mdm= %s \n p0=%s \n p1=%s \n chi = %s \n \n \n \n' %(mDM, a,b,chi))

for DSID in signalParameterDict:
    if signalParameterDict[DSID]['mdm']!=mDM:
continue

        mMed = signalParameterDict[DSID]['mmed']
        xs_fit = myfit.Eval(mMed)

        xmed_scanMdm.append(mMed)
        ydm_scanMdm.append(mDM)
        zsec_scanMdm.append(xs_fit)

except:
    continue

```

```

for i in range(len(zsec_scanMdm)):
    if zsec_scanMdm[i] < 0:
        print i, xmed_scanMdm[i], ydm_scanMdm[i], zsec_scanMdm[i]
        zsec_scanMdm[i] = 0

gr.mDM = TGraph2D(len(xmed_scanMdm), xmed_scanMdm, ydm_scanMdm,
    zsec_scanMdm)
gr.mDM.Draw('COLZ')
gr.mDM.SetLineWidth(1)
gr.mDM.SetLineColor(5)
gr.mDM.GetHistogram().GetXaxis().SetTitle('M_{med} [GeV]')
gr.mDM.GetHistogram().GetYaxis().SetTitle('M_{DM} [GeV]')
gr.mDM.GetHistogram().GetZaxis().SetTitle('#sigma [pb]')
gr.mDM.GetHistogram().GetZaxis().SetRangeUser(0, 11)
gr.mDM.SetMarkerColor(4)
gr.mDM.SetMarkerStyle(1)
gr.mDM.SetMarkerSize(20)
c1.Modified()
c1.Update()
#c1.SaveAs('2dmDM.png')

hist_orig = gr.GetHistogram()
hist_mMed = gr_mMed.GetHistogram()
hist_mDM = gr_mDM.GetHistogram()

hist_orig.Draw('colz')
c1.Update()

```

```
c1.SaveAs(' hist_orig.png')
```

```
hist_mMed.Draw(' colz')
```

```
c1.Update()
```

```
c1.SaveAs(' hist_mMed.png')
```

```
hist_mDM.Draw(' colz')
```

```
c1.Update()
```

```
c1.SaveAs(' hist_mDM.png')
```

```
hist_diff_mMed = gr_mMed.GetHistogram()
```

```
hist_diff_mMed.Add(hist_orig, -1)
```

```
hist_diff_mMed.GetAxis().SetRangeUser(-0.055, 0.03)
```

```
hist_diff_mMed.Draw(' colz')
```

```
c1.Update()
```

```
c1.SaveAs(' hist_orig_diff_mMed.png')
```

```
hist_diff_mDM = gr_mDM.GetHistogram()
```

```
hist_diff_mDM.Add(hist_orig, -1)
```

```
hist_diff_mDM.GetAxis().SetRangeUser(-0.25, 3.5)
```

```
hist_diff_mDM.Draw(' colz')
```

```
c1.Update()
```

```
c1.SaveAs(' hist_orig_diff_mDM.png')
```

```
hist_orig_difffrac_mMed= gr_mMed.GetHistogram()
```

```
hist_orig_difffrac_mMed.Divide(gr.GetHistogram())
```

```
hist_orig_difffrac_mMed.GetAxis().SetRangeUser(-0.08, 0.08)
```

```
hist_orig_difffrac_mMed.Draw(' colz')
```

```
c1.SaveAs(' hist_orig_difffrac_mMed.png')
```

```
hist_orig_difffrac_mDM = gr_mDM.GetHistogram()
```

```
hist_orig_difffrac_mDM.Divide(gr.GetHistogram())
```

```
hist_orig_difffrac_mDM . GetZaxis () . SetRangeUser ( -0.25, 0.45 )  
hist_orig_difffrac_mDM . Draw ( ' colz ' )  
c1 . SaveAs ( ' hist_orig_difffrac_mDM . png ' )
```