An investigation of the sensitivity of LHC dark matter searches at $\sqrt{s} = 13$ TeV to dark Higgs models

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Declaration of Authorship

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

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Abstract

The 'Higgs Portal Dark Matter' model is introduced in this thesis and a dark Higgs boson is responsible for generating masses for dark sector particles and relaxing the DM relic abundance constraint by opening up a new annihilation channel. Since this thesis focuses on dark Higgs decaying to a pair of b-tagged jets, the experimental signature is one boosted double b-tagged jet with large missing energy. Two different search methods have been investigated in this thesis: the large-radius mono-jet search and the more "generic" missing energy + jets search using the CMS α_T analysis. The former is carried out by the ATLAS experiment, searching for a boosted double b-tagged large-radius jet with large missing energy. The latter is based on a CMS search, searching for resolved b-jets with specific kinematic variables and large missing energy. The reinterpretation of the large-radius search shows that signals with couplings according to the LHC recommendation can obtain significant exclusion limits. When the mass of the dark Higgs (m_s) is 50, 70 and 90 GeV, the mass of the Z' ($m_{Z'}$) up to 1800, 2000 and 1800 GeV are respectively excluded. The reinterpretation of the large-radius search shows that signals with couplings set to fulfil the DM relic abundance constraint can obtain significant exclusion limits. For $m_s = 50$, 70 and 90 GeV, $m_{Z'}$ up to 3300, 3450 and 3500 GeV are respectively excluded. The reinterpretation of the CMS α_T search shows that signals with couplings according to the LHC recommendation cannot obtain significant exclusion limits. However, the reinterpretation of the CMS α_T search shows that signals with couplings set to fulfil the DM relic abundance constraint can obtain significant exclusion limits. For $m_s = 50$, 70 and 90 GeV, $m_{Z'}$ up to 3600, 3700 and 3700 GeV are respectively excluded.

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1 Introduction

Our current knowledge of dark matter (DM) is very limited and comes from astrophysical and cosmological observations. Detecting and studying DM is very challenging, as it interacts very weakly with visible matter. Therefore, DM properties like its mass, coupling to visible matter, and structure are still unknown.

This thesis will focus on studying the dark Higgs model introduced in Ref. [1]. A large-radius jet search from ATLAS [2] and sub-jet kinematic variable search like α_T and $\Delta\phi^*_{min}$ from CMS [3,4] have been implemented in this thesis for reinterpretation. Large missing transverse momentum (MET) is required in both of these analyses to take DM production into account.

1.1 The evidence of dark matter

The concept of DM was first introduced by Fritz Zwicky [5]. In 1933, when calculating the mass of the Coma Cluster, Fritz Zwicky used the Virial Theorem to point out the discrepancy between visible matter and total matter.

After 1970s, DM had been accepted by the scientific community after detailed studies of galaxy rotation curves [6–9]. A rotation curve describes the dependence of the tangential velocity component (v_T) of gas or stars rotating around the galaxy to its distance (r) from the centre. As most of the luminous matter is located in the centre of the galaxy, a decrease of v_T as $1/\sqrt{r}$ would be expected if this was the only matter present. Figure 1.1 shows the observed rotation curve and the expected rotation curve from visible matter. As the tangential velocity increases at large radii, there must be other non-visible matter in the universe, which cannot produce electromagnetic radiation, but can contribute through gravitation. The huge discrepancy between the observed rotation curve and the expected rotation curve at large radii is a strong evidence for the existence of DM.

More recent proof of DM existence comes from the observation of the Bullet Cluster, two colliding galaxy clusters, in association with both X-ray and gravitational lensing measurements [10]. As shown in Fig. 1.2, the gravitational lensing map, which shows the total gravitational potential of the Bullet Cluster, does not follow the dominant baryonic mass component observed with X-ray data. From this discrepancy, one can conclude that the total matter distribution can not be explained by the baryonic component. This proves that another source of matter

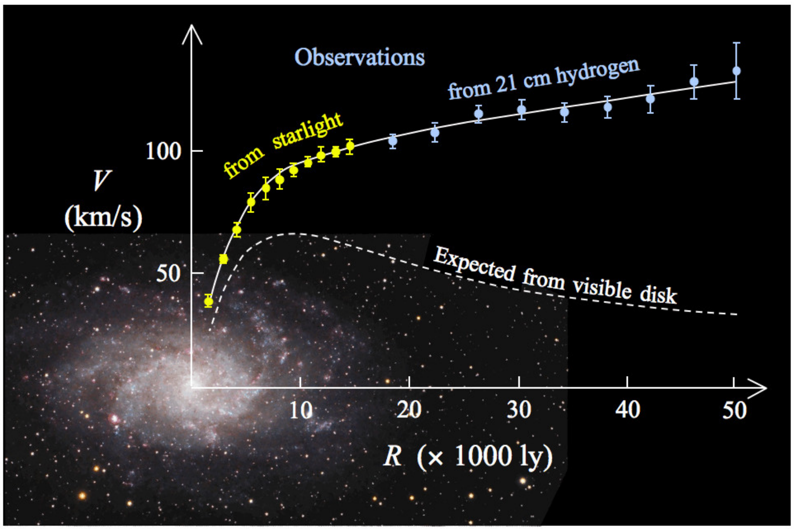


Figure 1.1: The rotation curve of galaxy M33. Figure taken from [11].

must be present in this system.

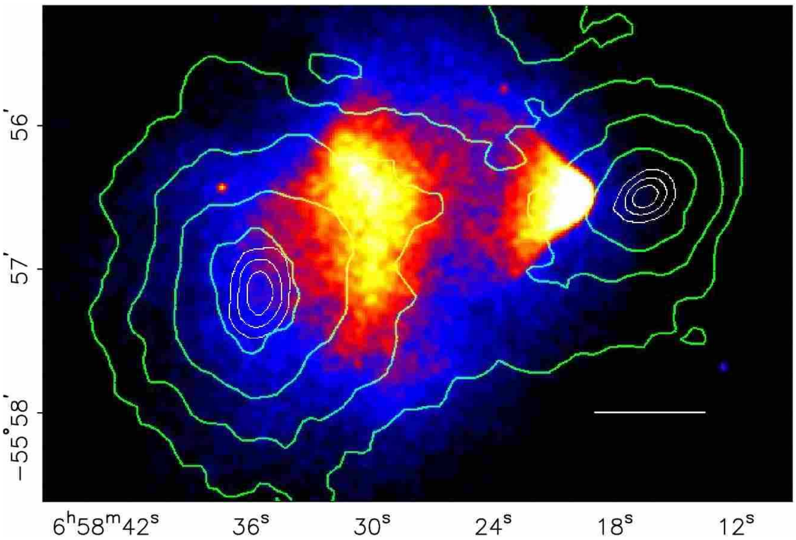


Figure 1.2: BulletCluster. The colour scale indicates the distribution of visible matter as observed with X-ray data and the green lines follow the distribution of all gravitating matter. Figure taken from [10].

1.2 Techniques of DM detection

There are three main methods of probing DM: production, direct and indirect detection.

Production In order to find out the properties of DM, experiments are trying to detect DM directly produced in high-energy collisions at particle colliders. Since DM candidates do not interact through electromagnetic and strong forces, detectors cannot directly measure DM candidates when they are produced in these kind of experiments. Therefore, the common signal in DM searches at colliders is missing transverse momentum (MET). We will discuss this method in more details with 'mono-jet' and 'mono-V' methods in Section 1.3.

Direct detection In this method, detectors are employed to probe for already-existing dark matter through the measurement of interactions between DM and target nuclei. When DM particle interacts with a nucleus, the recoil can ionise the matter in the detector, freeing electrons as an experimental signature. Because the probability of DM-nucleus scattering is quite small, detectors are usually located in deep underground laboratories in order to reduce the large background. In 2008, DAMA observed an annual modulation signature, which might be caused by DM [12]. However, the DAMA signal is difficult to reconcile with constraints from other experiments. Therefore, an unambiguous test for DAMA is required. The SABRE experiment [13] is designed to achieve this with lower residual background than DAMA.

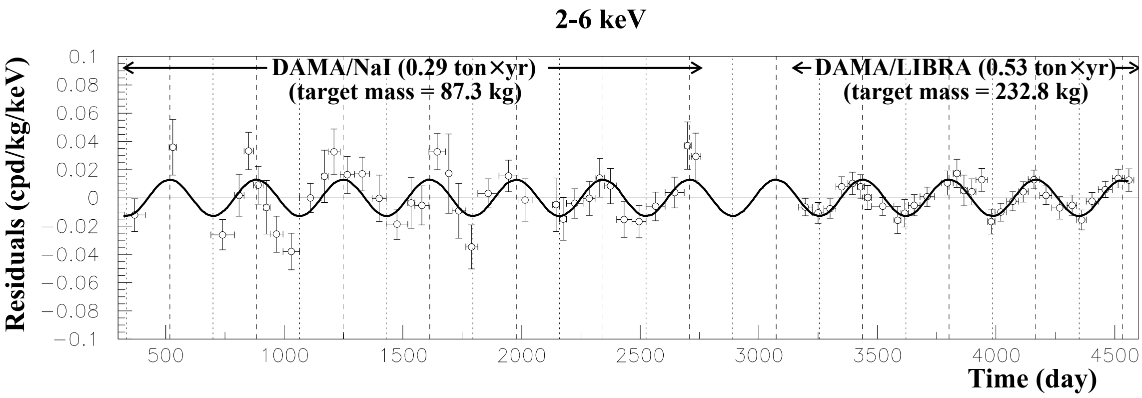


Figure 1.3: Annual modulation signature from DAMA, as shown in [12].

Indirect detection DM annihilations and decays in the universe can leave signatures in the cosmic rays, which can provide a chance for indirect DM detection. By looking at the energy spectrum of cosmic charged particles, photons, and neutrinos, theory-based measurements of DM properties can be performed [14]. In order to set stronger limits to DM properties, the most important part of this detection method is to find sensitive energy ranges where the background coming from ordinary astrophysics processes can be minimised. Table 1.1 taken from Ref. [15] shows a brief introduction to the recent, current and planned indirect DM experiments with the relative advantages and challenges.

Particles	Experiments	Advantages	Challenges
Gamma-ray, photons	Fermi LAT, MAGIC	point back to sources, spectral signatures	backgrounds
Neutrinos	IceCube, Super-Kamiokande	point back to sources, spectral signatures	backgrounds, low statistics
Cosmic rays	PAMELA, Fermi LAT	spectral signatures, low backgrounds for antimatter searches	diffusion, do not point back to sources

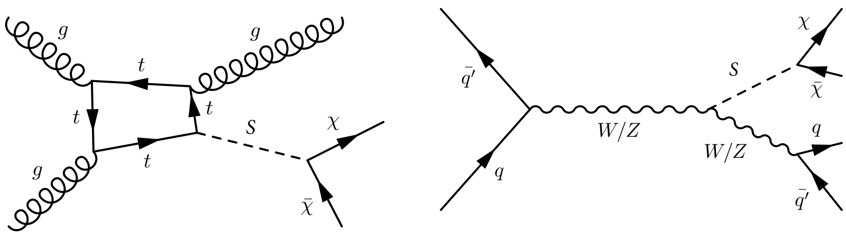
Table 1.1: Astroparticles for indirect dark matter searches, experiments, advantages, and challenges. Table taken from [15].

1.3 Current collider dark matter production review: mono-jet and mono-V productions

As a dark Higgs model introduced in Ref. [1] will be exploited to search for DM at colliders in this thesis, a more detailed explanation of the current DM searches at colliders based on the work in Ref. [16] will be given here. Reference [16] focuses on DM particles in final state with an energetic jet (mono-jet) or a hadronically decaying W or Z vector boson (mono-V) at colliders.

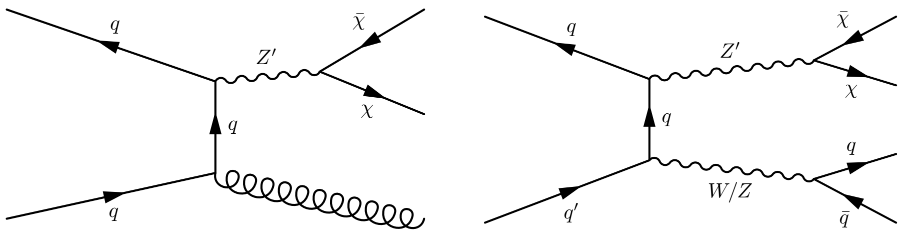
1.3.1 mono-jet and mono-V productions

As DM particles cannot produce any observable signals in the detector, mono-jet search can be performed by looking for jets radiated from the initial state that are recoiling against the produced dark matter. A typical signal in these searches is a single jet with a high transverse momentum (p_T) in association with large MET. In mono-V searches, typical final states are DM pairs in association with a weak vector boson. If the weak boson is at high p_T, its hadronic decay can be reconstructed as a large-radius jet due to the highly boosted decay products. Figure 1.4 and 1.5 show the mono-jet and mono-V production mechanisms for spin-0 (scalar or pesudoscalar, S) and spin-1 (Z') mediators.



(a) Mono-jet (b) Mono-V

Figure 1.4: Mono-jet and mono-V production diagrams for a spin-0 mediator, as shown in [17].



(a) Mono-jet (b) Mono-V

Figure 1.5: Mono-jet and mono-V production diagrams for a spin-1 mediator, as shown in [17].

1.3.2 Event selections and background estimation

Jets are reconstructed by particle flow algorithm [18, 19] and anti-k_t algorithm [20]. The jet momentum is calibrated to account for pileup [21] and further corrected for resolution [22].

In mono-jet searches, jets are reconstructed using anti-k_t algorithm with a radius of 0.4 (AK4 jets). The leading jet is required to have $p_T > 100$ GeV and $|\eta| < 2.5$ and events are required to have MET > 250 GeV. The QCD background is suppressed by setting the minimum azimuthal angle between missing transverse momentum $\vec{p}_T^{miss}$ and the first 4 leading jets with p_T >30 GeV greater than 0.5. The minimum azimuthal angle mentioned above will be referenced as $\Delta\phi(j_{1234}, \vec{p}_T^{miss})_{min}$. More details can be found in Ref. [16].

In mono-V searches, jets are reconstructed with a radius of 0.8 (AK8 jets) because reconstructing the W and Z boson decay as one AK8 jet is more efficient than by using two AK4 jets when the p_T of the weak bosons is high enough. In this analysis, W and Z bosons have $p_T > 250$ GeV, therefore the leading AK8 jet must have $p_T > 250$ GeV. Additionally, the leading jet is required to have $|\eta| < 2.4$. To be consistent with the masses of the gauge bosons, the leading jet invariant mass is required to be between 65 and 105 GeV. MET is required to be over 250 GeV and $\Delta\phi(j_{1234}, \vec{p}_T^{miss})_{min}$ is required to be greater than 0.5. In order to suppress boosted objects from the background of QCD jets with large invariant masses, the N-subjettiness variable τ_N [23] is introduced in this analysis. τ_N can probe the number of sub-jets within a jet. The lower τ_N is, the more likely a jet is to come from a N-prong decay. In this analysis, the ratio τ_2/τ_1 is an effective discriminating variable able to isolate 2-prong decays of W and Z bosons from the background of QCD jets with large invariant masses. In this analysis, the ratio of τ_2/τ_1 is required to be less than 0.6.

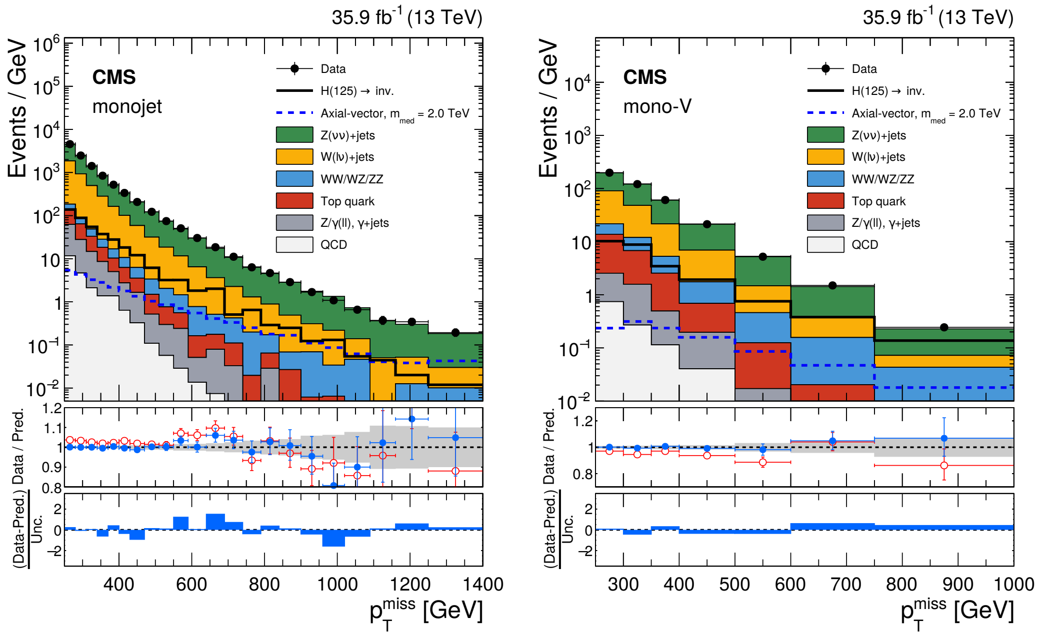
In both mono-jet and mono-V searches, the most dominant background comes from Z boson invisible decay, $Z(\rightarrow \nu\nu)$ + jets, and W boson leptonic decay, $W(\rightarrow l\nu)$ + jets, in which the lepton is failed to be detected.

1.3.3 Results

Figure 1.6 shows the MET distributions in mono-jet and mono-V searches with an integrated luminosity of 35.9 fb^{-1}.

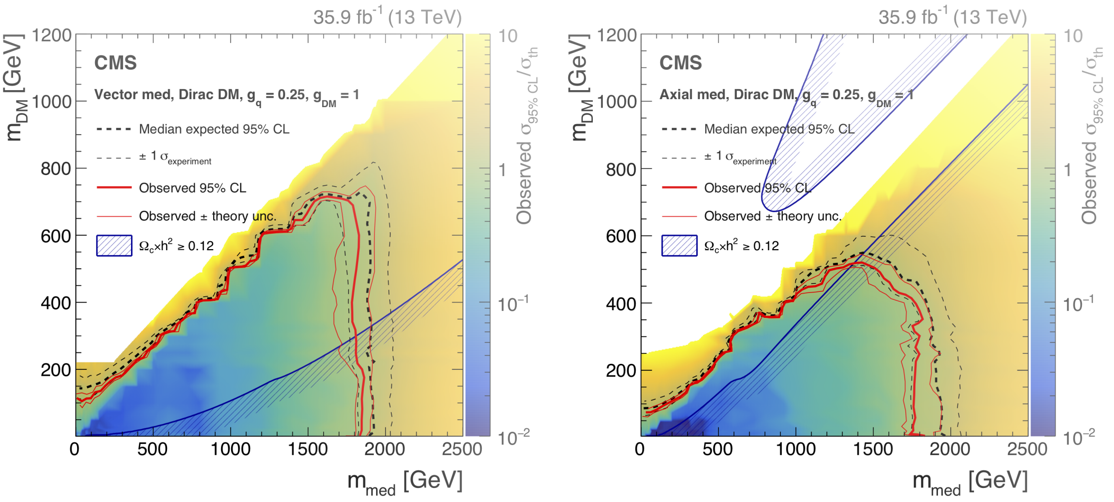
The upper limits at 95% confidence level (CL) [24, 25] are calculated based on the ratio of the signal cross-section to the predicted cross-section, σ/σ_{th}, with an integrated luminosity of 35.9 fb^{-1}. The asymptotic approximation [26] is also used in computing upper limits here. The limits are drawn in the $m_{med} - m_{DM}$ plane, where m_{med} stands for the mass of the mediator and m_{DM} is the DM mass. The region where the ratio σ/σ_{th} is less than one is excluded. And the region where the ratio σ/σ_{th} is over one is considered as a sensitive region for these analyses. Figure 1.7 shows the exclusion region for vector and axial-vector mediators at 95% CL with an integrated luminosity of 35.9 fb^{-1} and Fig. 1.8 shows the exclusion region for pseudoscalar mediators at 95% CL with an integrated luminosity of 35.9 fb^{-1}. The upper limits for scalar mediators at 95% CL with an integrated luminosity of 35.9 fb^{-1} are drawn through cross-section ratio σ/σ_{th} at $m_{DM} = 1$ GeV. Vector and axial-vector mediators with mass up to 1.8 TeV are excluded at 95% CL with an integrated luminosity of 35.9 fb^{-1}. And pseudoscalar mediators with mass up to 400 GeV are excluded at 95% CL with an integrated luminosity of 35.9 fb^{-1}. However, no significant exclusion region is expected in the scalar models at 95%

CL with an integrated luminosity of 35.9 fb^{-1}. Cosmological constraints from the Planck satellite experiments [27] are also shown in Fig. 1.7 and Fig. 1.8.



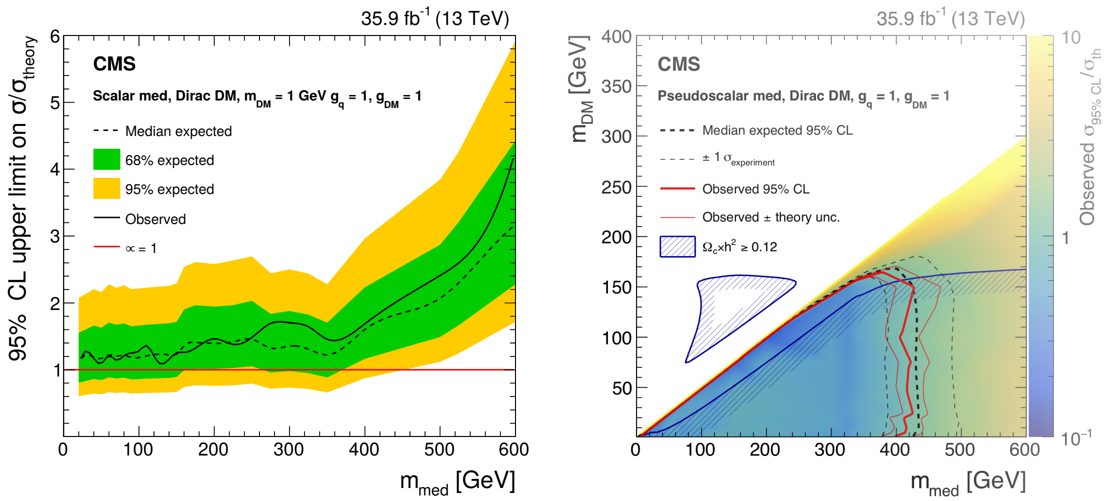
(a) Mono-jet (b) Mono-V

Figure 1.6: Observed MET distribution in mono-jet and mono-V signal regions with an integrated luminosity of 35.9 fb^{-1}. Left: the mono-jet search. Right: the mono-V search. MET > 1250 (750) GeV for the mono-jet (mono-V) search has been applied for the last bin. Two signal events are drawn here: one from 125 GeV Higgs boson decaying to invisible particles and the other from 2 TeV axial-vector mediator decaying to 1 GeV dark matter particles. Ratios of data with pre-fit background distributions (red points) and postfit expected background distributions (blue points) are performed. The gray bands refer uncertainties. The difference between data and prediction over the sum of uncertainties is also shown at the bottom. Figure taken from [16].



(a) Vector mediator (b) Axial-vector mediator

Figure 1.7: Exclusion limits at 95% CL with an integrated luminosity of 35.9 fb^{-1}. Left: the vector mediator. Right: the axial-vector mediator. The solid (dotted) red (blue) line refers the observed (expected) exclusion. One standard deviation has been drawn due to theoretical uncertainties from observed exclusion and statistical and systematic uncertainties from expected exclusion. The Planck satellite experiment constraints [27] are shown with dark blue lines. Figure taken from [16].



(a) Scalar mediator (b) Pseudoscalar mediator

Figure 1.8: The cross-section ratio plot at 95% CL is shown with an integrated luminosity of 35.9 fb^{-1}. Left: the scalar mediator. The benchmark for DM particle mass in this plot is 1 GeV. The dotted black line (solid balck line) refers expected (observed) upper limits on cross-section ratio. The red solid line refers the cross-section from theoretical predication is exactly the maximum cross-section which would be allowed at 95% CL. Exclusion limits at 95% CL with an integrated luminosity of 35.9 fb^{-1}. Right: the pseudoscalar mediator. The solid (dotted) red (blue) line refers the observed (expected) exclusion. One standard deviation has been drawn due to theoretical uncertainties from observed exclusion and statistical and systematic uncertainties from expected exclusion. The Planck satellite experiment constraints [27] are shown with dark blue lines. Figure taken from [16].

1.4 Thesis outline

This thesis aims to demonstrate that a search for the dark Higgs boson can be performed in the ongoing run at the Large Hadron Collider (LHC) and the dark Higgs can be a natural component in models of DM coupled to the spin-1 (Z') mediator. Until now, a review of DM evidences, three DM measurement techniques, and current DM searches at colliders based on the work in Ref. [16] have been given. Some particle physics basic concepts and essential theories together with 'Higgs Portal Dark Matter' model are introduced in Section 2. Section 3 begins with a brief introduction of ATLAS and CMS, two general-purpose LHC detectors currently employed to search for new physics. Signal event generations are also presented in Section 3. In this project, signal events are separately generated by considering the DM relic abundance constraint [28] and the LHC recommendation [29]. Based on Ref. [2] and Ref. [4], a large-radius mono-jet search from the ATLAS experiment and a more "generic" MET + jets search using α_T analysis from the CMS experiment are separately reinterpreted in Section 4 and Section 5. Discussion and conclusion for these two searches are given in Section 6 and Section 7.

2 Standard Model and 'Higgs Portal DM' model

2.1 Introduction to Standard Model

Standard Model (SM) is a theoretical model describing three known fundamental forces out of four and classifying all known elementary particles. SM can describe strong, weak, and electromagnetic interactions using a SU(3) × SU(2) × U(1) local gauge symmetry. Each type of interaction has at least one gauge boson as interaction mediator. Z^0 and $W^{\pm}$ bosons are the mediators for weak interaction; out of these two bosons, only $W^{\pm}$ can mediate flavour-changing interactions. Photons (γ) mediate electromagnetic interaction, and gluons (g) are the mediators of strong interaction. SM also encompasses three generations of elementary fermions, which are further divided into quarks and leptons. Both quarks and leptons can interact through the electromagnetic and weak force. Additionally, quarks can interact via strong force. Interaction strengths are described by constants. For strong force, its value is around 1 ($\alpha_S \approx 1$); for electromagnetic force is around 1/137 ($\alpha \simeq 1/137$); and for weak force is around 1/40 ($\alpha_{W/Z} \approx 1/40$). Finally, Higgs boson is included in SM in order to generate masses for particles through the spontaneous symmetry breaking mechanism, which will be explained in further details in Section 2.2.

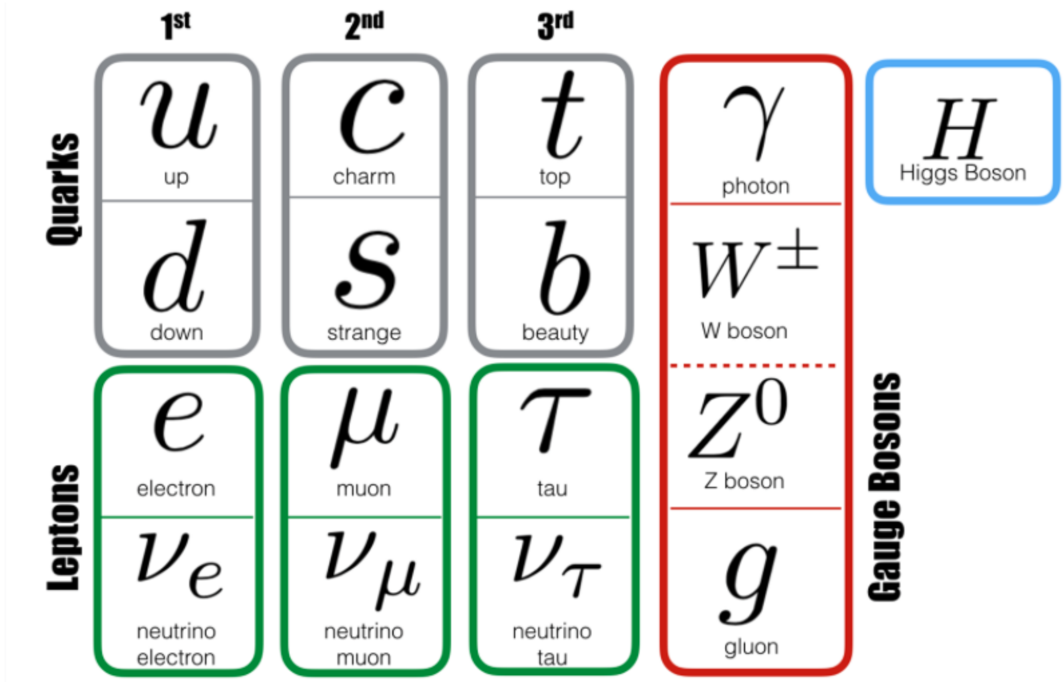
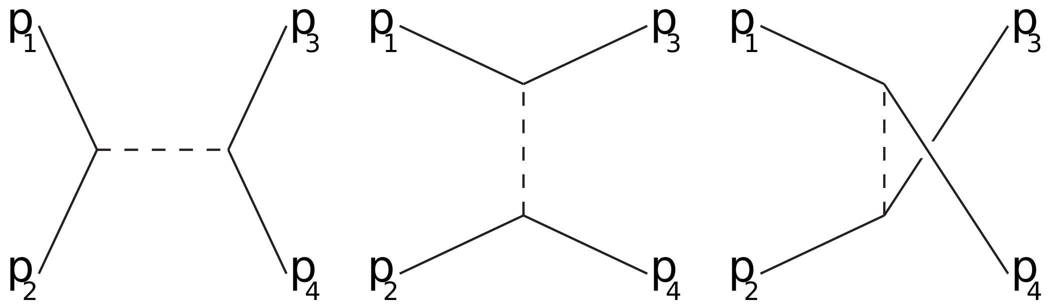


Figure 2.1: All the generations of elementary fermions and interaction mediators included in the Standard Model together with the Higgs boson. Figure taken from [30].

All the particle interactions can be described by Feynman diagrams. In these diagrams, x-axis is interpreted as time and y-axis as space. By reading from left to the right, the evolution from the initial to the final state of a system can be read. Anti-particles are drawn in Feynman diagrams as particles moving backwards in time. Energy, momentum, angular momentum are conserved in all interaction vertices in Feynman diagrams. Based on the Lorentz-invariant quantity carried by the mediator, defined in Eq. (2.1), Feynman diagrams can be categorised into s-, t- and u-channels. $\sqrt{s}$ is the total collision energy in the centre-of-mass frame.



(a) s-channel (b) t-channel (c) u-channel

$$s = (p_1 + p_2)^2, t = (p_1 - p_3)^2, u = (p_1 - p_4)^2. \tag{2.1}$$

Figure 2.2: Three types of Feynman diagrams together with the respective Lorentz-invariant quantities.

2.1.1 Cross-section and decay rate

When measuring particle interactions and decays, cross-sections and decay rates are the main experimental observables. Cross-section is a parameter directly connected to the probability for a certain process to happen. It is defined as

$$\sigma = \frac{\text{Number of events per unit time per target}}{\text{Incident flux}}. \tag{2.2}$$

In particle accelerator physics, the incident flux is also called instantaneous luminosity ($\mathcal{L}_{inst}$), a parameter that can be directly computed starting from the properties of the particle beam. The cross-section for any two-body → two-body scattering interaction process in the centre-of-mass frame is given by

$$\sigma = \frac{1}{64\pi^2 s} \frac{p_f^*}{p_i^*} \int |M_{fi}|^2 d\Omega^*, \tag{2.3}$$

where p_i^* and p_f^* are respectively the momentum of the initial and final state. $d\Omega^*$ stands for the solid angle element computed in the centre-of-mass frame. Finally, $|M_{fi}|^2$ is the square of the interaction matrix element, which is Lorentz-invariant and can be computed from theory. The invariant differential cross section for any two-body scattering interactions can be written as

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s |p_i^*|^2} |M_{fi}|^2. \tag{2.4}$$

Here, $|p_i^*|^2$ is a constant and it is calculated from energy and momentum conservation:

$$|p_i^*|^2 = \frac{1}{4s} [s - (m_1 + m_2)^2][s - (m_1 - m_2)^2]. \tag{2.5}$$

Eq. (2.4) applies to any rest frame because all quantities in the expression of $d\sigma/dt$ are Lorentz-invariant. Particle decay rate can be calculated from Fermi's Golden Rule,

$$\Gamma_{fi} = 2\pi |T_{fi}|^2 \rho(E_f), \tag{2.6}$$

where Γ_{fi} is the number of transitions per unit time from initial state $|i\rangle$ to final state $\langle f|$, T_{fi} is transition matrix element and $\rho(E_f)$ is the density of final state. Γ_{fi} depends on matrix element and the density of states. The former is computed from theory, the latter from kinematics. The two-body decay rate can be written in the rest frame ($E_i = m_i$) as

$$\Gamma_{fi} = \frac{|p^*|}{32\pi^2 m_i^2} \int |M_{fi}|^2 d\Omega, \tag{2.7}$$

where p^* is

$$p^* = \frac{1}{2m_i} \sqrt{[m_i^2 - (m_1 + m_2)^2][m_i^2 - (m_1 - m_2)^2]} \tag{2.8}$$

and m_1, m_2 stand for the masses of decay products from initial state $|i\rangle$.

2.1.2 Local gauge symmetry

The gauge bosons described in the SM are derived from the localisation of the SU(3) × SU(2) × U(1) gauge symmetry. To understand the importance of local gauge invariance in the SM, local U(1) gauge invariance will be considered as an example.

Under a U(1) local gauge transformation, the wave function $\psi(x)$ transforms as

$\psi(x) \to \psi^{'}(x) = e^{iq\chi(x)}\psi(x)$. To keep physics consistent, the Lagrangian must be invariant under this transformation. The Lagrangian of a free relativistic electron, $\mathcal{L}_0 = \overline{\psi}(i\gamma^\mu\partial_\mu - m_e)\psi$, is not invariant under a local U(1) transformation:

$$\mathcal{L}_0 \to \mathcal{L}_0 + \psi(x)\gamma^\mu\overline{\psi}\partial_\mu\chi e. \tag{2.9}$$

In order to obtain a gauge-invariant Lagrangian, the covariant derivative is introduced (here is $\partial_\mu \to D_\mu = \partial_\mu - ieA_\mu$). After applying the covariant derivative into $\mathcal{L}_0$, the final gauge-invariant Lagrangian of quantum electrodynamics (QED) is obtained:

$$\mathcal{L}_{QED} = \overline{\psi}(i\gamma^\mu\partial_\mu - m_e)\psi + e\overline{\psi}\gamma^\mu\psi A_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}. \tag{2.10}$$

The term $e\overline{\psi}\gamma^\mu\psi A_\mu$ is directly obtained from the covariant derivative and stands for the interaction between the massless gauge boson (here is photon) and the electron. $1/4F_{\mu\nu}F^{\mu\nu}$ has been added in order to consider the energy of the photon's electromagnetic field. The photon field A_μ transforms as $A_\mu \to A_\mu^{'} = A_\mu - \partial_\mu\chi$ under U(1) local gauge symmetry. By using the same mechanism, gluon, $W^\pm$ and Z^0 gauge bosons can be respectively introduced into SM when SU(3) and SU(2) local gauge symmetries are applied.

2.2 The Higgs Mechanism

2.2.1 Motivation

Although the local gauge invariance works well in describing the interactions in the Standard Model, it can only work for massless particles. As an example, if the photon were massive in QED, an additional term, $\frac{1}{2}m_\gamma^2 A_\mu A^\mu$, should be added up in Eq. (2.10). This term transforms as

$$\frac{1}{2}m_\gamma^2 A_\mu A^\mu \to \frac{1}{2}m_\gamma^2(A_\mu - \partial_\mu\chi)(A^\mu - \partial^\mu\chi) \neq \frac{1}{2}m_\gamma^2 A_\mu A^\mu \tag{2.11}$$

under U(1) local gauge transformation, which breaks the U(1) local gauge symmetry. This happens not only in U(1) local gauge symmetry of QED, but also in SU(2) $\times$ U(1) and SU(3) local gauge symmetries of electroweak and quantum chromodynamics (QCD). This implies that it is impossible to introduce masses for $W^\pm$ and Z^0 bosons, which are observed to be massive. In order to generate particle masses in SM, spontaneous symmetry breaking mechanism is necessary.

2.2.2 Spontaneous Symmetry Breaking

Spontaneous symmetry breaking (SSB) happens when a system falls from a symmetric state to a non-symmetric one in order to maintain the minimum energy level. To show how SSB can be used to introduce particle masses, the Lagrangian of a complex scalar field under the potential $V(\phi) = \mu^2(\phi^*\phi) + \lambda(\phi^*\phi)^2$ will be considered:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\phi_1)(\partial^\mu\phi_1) + \frac{1}{2}(\partial_\mu\phi_2)(\partial^\mu\phi_2) - \frac{1}{2}\mu^2(\phi_1^2 + \phi_2^2) - \frac{1}{4}\lambda(\phi_1^2 + \phi_2^2)^2. \tag{2.12}$$

ϕ_1 and ϕ_2 are the real and imaginary parts of the complex scalar field. If we only concentrate on the vacuum state, which is the lowest energy state with minimal potential energy, the λ corresponding to potential term in Equation (2.12) must be over zero in order to keep finite minimum for potential energy. If μ^2 is positive as well, the potential energy will have a minimum at $\phi_1 = \phi_2 = 0$ as shown in Fig. 2.3. However, if μ^2 is negative, the distribution of potential energy in ϕ_1 and ϕ_2 will look as in Fig. 2.3. In this case, the potential has infinite minima at

$$\phi_1^2 + \phi_2^2 = \frac{-\mu^2}{\lambda} = \nu^2, \tag{2.13}$$

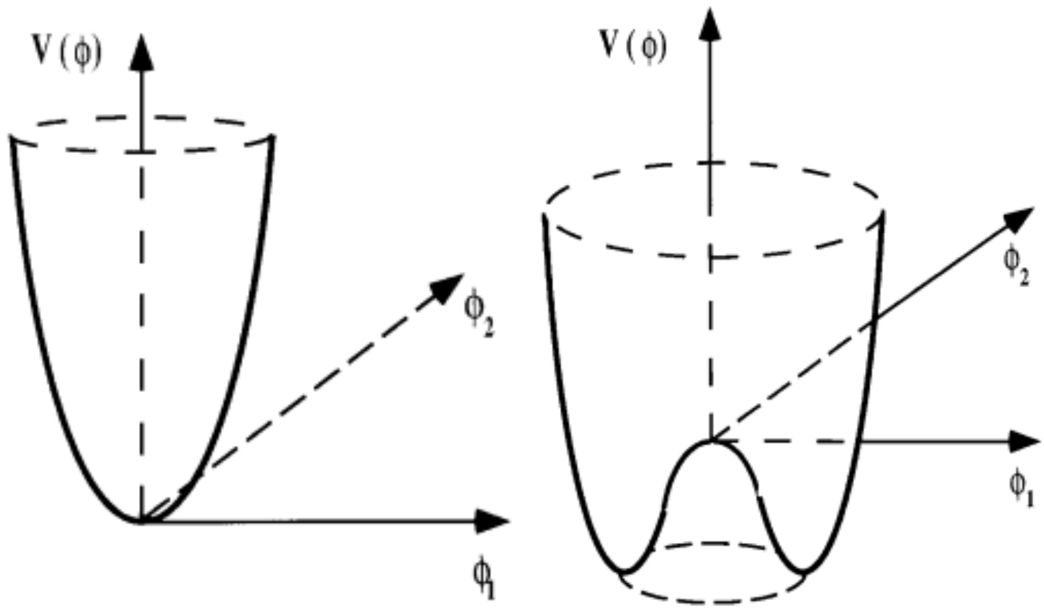
where ν is called vacuum expectation value. By choosing the vacuum state, the global U(1) symmetry has been spontaneously broken. In SM, a new field called Higgs field and the corresponding scalar boson called Higgs boson (H) is introduced. Through the SSB mechanism, Higgs field assumes a non-zero vacuum expectation value, and by interacting with particles, it generates their masses. Interaction terms between Higgs and vector bosons are naturally introduced in the SM Lagrangian when SSB is implemented. These terms enable to bind the masses of the $W^\pm$ and Z^0 to one of the main parameters of the SM, the electroweak mixing angle, θ_W:

$$\frac{m_W}{m_Z} = cos\,\theta_W. \tag{2.14}$$

SSB mechanism does not provide interaction terms which are able to provide masses to fermions. However, Yukawa couplings between the Higgs bosons and the fermions are manually introduced in the SM to this purpose. Yukawa couplings are the interaction strengths between fermions and Higgs bosons. These couplings are bound to the Higgs vacuum expectation value and the fermion masses through

$$m_f = \frac{\sqrt{2}}{2} g_f \nu. \tag{2.15}$$

where m_f is the fermion mass, g_f is the Yukawa coupling of this fermion and ν is the Higgs vacuum expectation value, which is ≈ 246 GeV. From Eq. (2.15), it can be concluded that the heavier a fermion is, the higher Yukawa coupling will be. Therefore, Higgs is more likely to interact with heavy particles and decay into them.



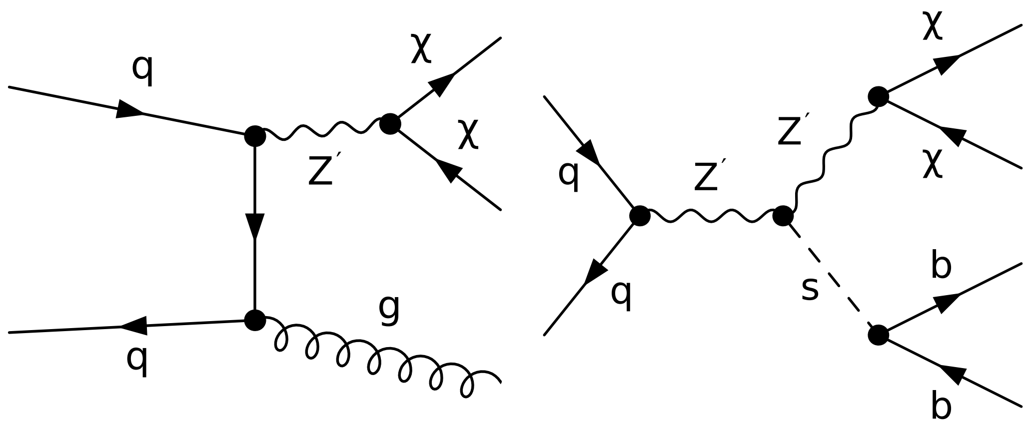
(a) the minimum potential energy at both fields = 0 (b) the minimum potential energy at $\phi_1^2 + \phi_2^2 = \nu^2$

Figure 2.3: The distribution of potential energy for a complex scalar field. ϕ_1 and ϕ_2 are the real and imaginary parts of the complex scalar field. Figure taken from [31].

2.3 Introduction to 'Higgs Portal DM' model

The 'Higgs Portal DM' model was firstly introduced in Ref. [1]. Three new types of particles are introduced in this model: Z', DM, and dark Higgs. Z' boson can couple to both SM quarks and DM. DM from this model is assumed to be the sole candidate for all the existing DM in the universe. In this thesis, the nature of this DM candidate will not be discussed. As the SM Higgs cannot generate mass for dark matter sectors in this model, the dark Higgs boson (s) has been introduced to provide a mechanism to generate masses for the dark matter particles. This mechanism enables to relax constraints coming from the dark matter relic abundance by opening up a new annihilation channel.

If the dark Higgs boson decays into SM particles via a small mixing with the SM Higgs boson, an experimental proof of the existence of such bosons can be found by looking for characteristic large-radius boosted jets in association with large missing transverse momentum (MET). In this project, we only look for dark Higgs decaying to a pair of b-tagged jets. The expected experimental signatures are double b-tagged jets from the dark Higgs decay and large MET from escaping DM particles. As the double b-tagged jets from the dark Higgs decay can possibly merge into one large-radius jet if the dark Higgs is sufficiently boosted, this large-radius jet can be used to efficiently discriminate signal from background as jets coming from dark Higgs processes would look differently than the ones from conventional mono-jet events, as shown in Fig. 2.4. In order to have a clear signature for this process, the only requirement is the production of any dark sector state with sufficient large momentum.



(a) Conventional mono-jet (b) Mono-dark-Higgs

Figure 2.4: Processes leading to missing energy signatures at the LHC. Left: a conventional mono-jet event. Right: a process leading to a mono-dark-Higgs signal. Figure taken from [1].

There are five free parameters in 'Higgs Portal DM' model: the mass of DM candidate (m_{DM}), two mediators' masses, Z' ($m_{Z'}$) and the dark Higgs (m_s), the coupling between mediator Z' and quarks (g_q), and the coupling between dark sector and mediator Z' (g_x). In this parametrisation, the coupling of the dark Higgs is not a free parameter as it is completely defined by setting above these five parameters.

3 Dark Higgs searches at the LHC

3.1 Overview of ATLAS and CMS detectors

Because a large-radius mono-jet search from the ATLAS experiment [2] and a MET + jets search using α_T analysis from the CMS experiment [4] will be both reinterpreted in this project, a brief overview of ATLAS and CMS detectors is given here.

ATLAS [32] and CMS [33] are two general-purpose detectors currently employed to search for new physics. Although with different and complementary technologies, the two detectors are both formed by a set of concentric cylindrical layers which will be presented in the following paragraph from the innermost to the outermost one.

The innermost part of these two detectors holds the tracking system, whose purpose is to measure the momenta and charge of charged particles. This layer is followed by the electromagnetic calorimeter, which is used to measure the properties of electrons and photons. Together with the electromagnetic calorimeter, the hadron calorimeter measures both charged and neutral hadrons. Finally, the outermost layer holds the muon chambers, which are employed to detect muons.

The two detectors are enveloped in different magnetic fields, that bend the tracks of charged particles and enable the measurement of their momentum and charge using the tracking system. In ATLAS, one solenoid and three toroid magnets are employed to generate the field, while one massive solenoid magnet is used in CMS.

A parameterised simulation of the ATLAS detector at $\sqrt{s} = 13$ TeV is performed for the large-radius mono-jet search. The simulation takes the ATLAS off-line jet mass resolution [34], b-tagging performance [2], and MET resolution [35] into account. The CMS detector b-tagging performance [4] at $\sqrt{s} = 13$ TeV is simulated in a similar manner in the MET + jets search using the α_T analysis.

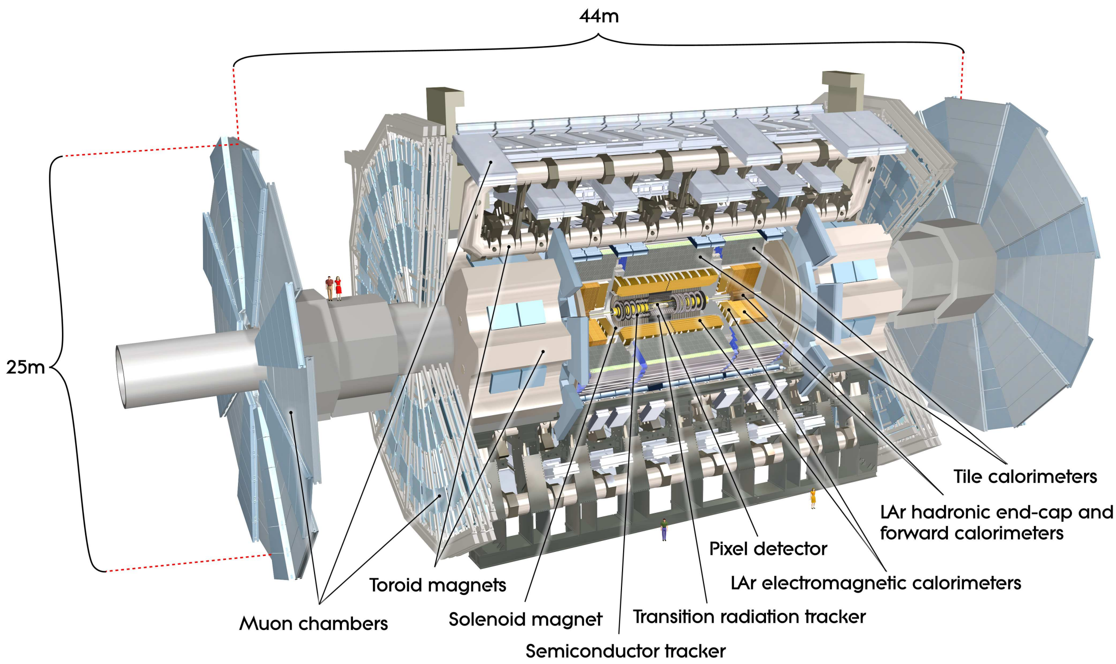


Figure 3.1: Schematic view of the ATLAS detector as shown in [32].

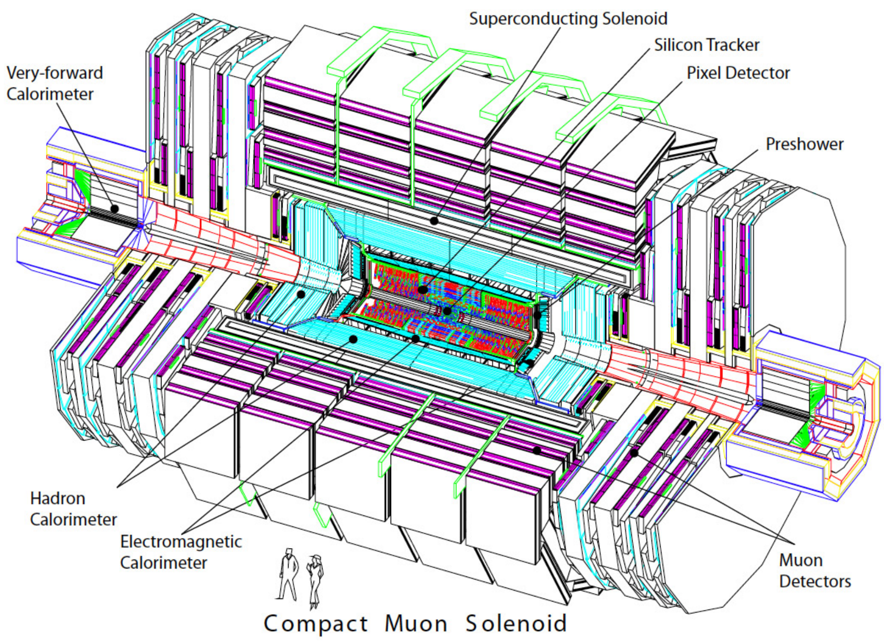


Figure 3.2: Schematic view of the CMS detector as shown in [33].

3.2 Signal generation

In this project, two different methods have been used to define the five free parameters of the 'Higgs Portal DM' model as introduced in Section 2.3. One is to consider couplings as recommended by LHC where $g_x = 1$ and $g_q = 0.25$ [29]. The other is to define couplings based on the DM relic abundance constraint from the universe and by assuming possible DM annihilation channels [28]. Parameter ranges considered in this project are shown in Table 3.1.

Coupling set	LHC	Astrophysics
g_x	1	$< (4\pi)^{1/2}$
g_q	0.25	0.25
m_s [GeV]	50, 70, 90	50, 70, 90
$m_{Z'}$ range [GeV]	(200, 3000)	(500, 4000)
m_{DM} range [GeV]	(100, 500)	(100, 800)

Table 3.1: The parameter ranges considered in this project with two coupling scenarios. In this table, LHC refers to the coupling scenario consistent with the LHC recommendation and Astrophysics refers to the coupling scenario considering the DM relic abundance constraint from the universe.

We use the same code to present both types of coupling scenario as described in Ref. [1]: both types of coupling scenario are generated through **micrOMEGAs v4.2.5** [36]. All signal events are generated by **MadGraph5_aMC@NLO v2.3.3** [37]. **Pythia 8** [38] and **Rivet v2.5.2** [39] are used for showering and event selection.

3.2.1 Coupling scenario in consistence with LHC collaborations

We generate all the signal events as recommended by LHC where $g_x = 1$ and $g_q = 0.25$ [29] because this coupling scenario has been widely used in current DM searches at colliders like Ref. [2], Ref. [16] and Ref. [40].

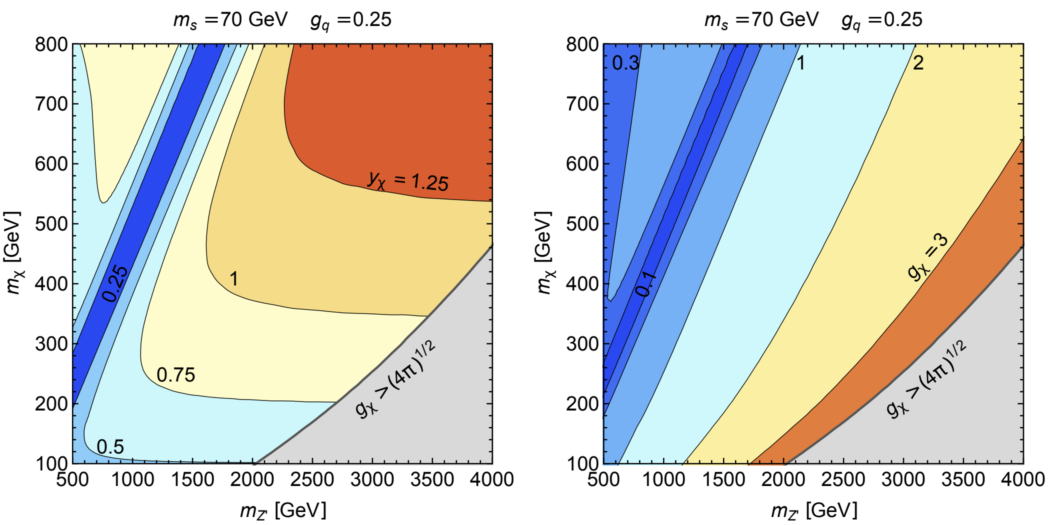
3.2.2 Coupling scenario considering the DM relic abundance constraint from the universe

Based on the mediators involved in the 'Higgs Portal DM' model and the astrophysical constraint of DM relic abundance from the universe, there are two characteristic DM annihilation channels in this model [1, 28]. The first annihilation channel can produce Z' through DM particles annihilate and Z' can then decay to SM particles. This process can be described as $\chi\chi \to Z' \to p\bar{p}$. The second annihilation channel can produce the dark Higgs s through DM particles annihilate and the dark Higgs

s can then decay into SM particles. This process can be described as $\chi\chi \to s \to p\bar{p}$. Each annihilation channel is related to one coupling parameter [1, 28]. In the annihilation involving the dark Higgs, DM Yukawa coupling y_x should be considered and for the annihilation channel mediated by the Z' boson, coupling g_x should be considered [1, 28]. In 'Higgs Portal DM' model, there is a specific relation between these two parameters

$$g_x = \frac{m_{Z'}}{m_{\rm DM}} \frac{y_x}{2\sqrt{2}}, \tag{3.1}$$

as the dark Higgs generates both the DM mass and the Z' mass [1]. Figure 3.3 taken from Ref. [1] shows the two parameters' distributions in a $m_{Z'} - m_{\rm DM}$ plane with fixed m_s and g_q numbers.



(a) y_x distribution (b) g_x distribution

Figure 3.3: y_x and g_x distributions under relic abundance for m_s = 70 GeV and g_q = 0.25. $g_x > 4\pi^{1/2}$ is the limitation of this process as g_x should remain perturbative. m_χ is the same as $m_{\rm DM}$. Figure taken from [1].

It can be concluded from Fig. 3.3 that $\chi\chi \to s \to$SM is the dominant DM annihilation channel when $m_{Z'} \gg m_{\rm DM}$ as y_x tend to become a small constant while g_x is quite large for $m_{Z'} \gg m_{\rm DM}$. It also can be observed from Fig. 3.3 that for $m_{\rm DM} \approx m_{Z'/2}$, $\chi\chi \to Z' \to p\bar{p}$ is the leading DM annihilation channel with a sufficient small g_x to provide relic abundance. Other types of annihilation channels [28] are not discussed in this analysis as they are less important in the considered regime where $m_{\rm DM}$ is not greater than $m_{Z'}$.

As can be seen from Fig. 3.3, in order to fulfil the relic density constraint, g_x needs to vary strongly as a function of $m_{Z'}$ and m_{DM}. In particular, the region of parameter space cannot be studied where $g_x > 4\pi^{1/2}$ for large $m_{Z'}$ because the theory becomes non-perturbative in this region.

3.2.3 Signal events with coupling scenario considering the DM relic abundance constraint from the universe

Before presenting any signal events with the coupling scenario considering the DM relic abundance constraint, this coupling scenario should be further discussed. As shown in Section 3.2.2, Figure 3.3 taken from Ref. [1] displays the g_x distribution under the constraint from the DM relic abundance for $m_s = 70$ GeV and $g_q = 0.25$.

Since we use the same tools as in Ref. [1] to compute the coupling scenario from the DM relic abundance constraint, we can compare the g_x distribution used in our analysis with the one in Ref. [1]. Figure 3.4 shows our g_x distribution under the DM relic abundance constraint for $m_s = 70$ GeV and $g_q = 0.25$.

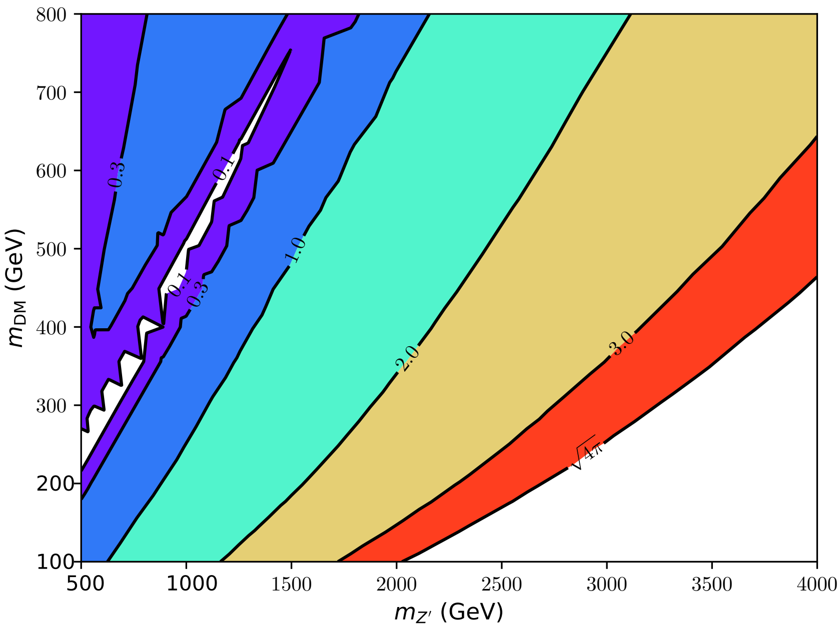


Figure 3.4: g_x distribution under DM relic abundance for $m_s = 70$ GeV and $g_q = 0.25$.

By comparing Figure 3.3 and Figure 3.4, it can be concluded that the couplings used in our signal generation are consistent with the one used in Ref. [1].

4 Dark Higgs search with large-radius jets

This chapter discusses the reinterpretation of the large-radius mono-jet search from the ATLAS experiment [2]. The dominant background samples and event selection requirements for the large-radius mono-jet search are discussed in Section 4.1. Validation between our analysis and the published ATLAS analysis is examined in Section 4.2 and our results for the reinterpretation of this search are presented in Section 4.3.

4.1 Interpretation of large-radius jets analysis

The large-radius mono-jet analysis from the ATLAS experiment searches for large missing transverse momentum (MET) from DM production together with a SM Higgs decaying to $b\bar{b}$ [2]. Here, we reinterpret this analysis into our 'Higgs Portal DM' model. The expected signal signatures are double b-tagged large-radius jets from the high p_T dark Higgs decay and large MET from DM particles. Therefore, the main SM backgrounds to this search are: processes ending up with double b-tagged large-radius jets; processes ending up with large-radius jets containing both b-quark jets and c-quark jets, where c-quark jets can be misidentified as b-quark jets. In both cases, large-radius jets must be produced in association with large MET.

4.1.1 Expected main backgrounds

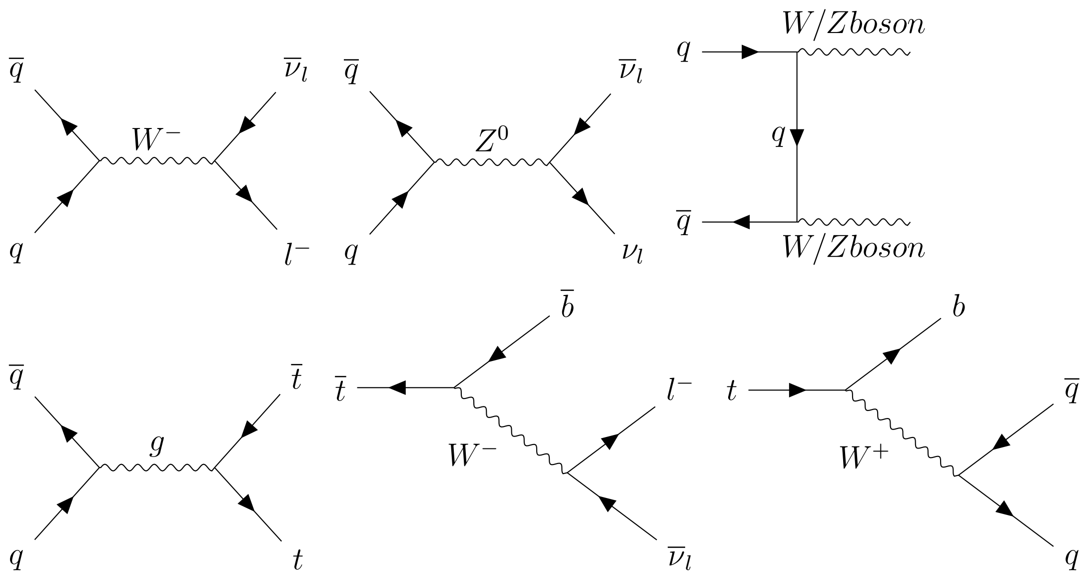


Figure 4.1: Feynman diagrams for most relevant Standard Model backgrounds. Top: W, Z and diboson events leading to MET. Bottom: $t\bar{t}$ background resulting from semi-leptonic decays of top pair production.

Figure 4.1 shows the dominant background samples for our dark Higgs search with large-radius jets.

$\boldsymbol{Z + b\bar{b}}$**:** One Z boson decay can contaminate our signal if the Z boson decays into a neutrino-antineutrino pair ($\nu\overline{\nu}$) together with a $b\bar{b}$ pair from gluon splitting. This process can be described as $pp \rightarrow Z(\rightarrow \nu\overline{\nu})\ b\bar{b}$.

$\boldsymbol{W + b\bar{b}}$**:** One W boson decay can contaminate our signal if the W boson decays leptonically and the charged lepton from the W decay is not identified. $b\bar{b}$ pair can come from gluon splitting. This process can be described as $pp \rightarrow W(\rightarrow l\nu)\ b\bar{b}$.

$\boldsymbol{t\bar{t}}$**:** $t\bar{t}$ can contaminate the signal through semi-leptonic decays. If a t-quark decays semi-leptonically, a large amount of MET can be measured when the charged lepton is not identified. If the other t-quark decays hadronically into a c-quark and a b-quark, double b-tagged large-radius jets can originate when this t-quark's p_T is large enough and the c-quark is mistagged as a b-quark. In the circumstance that the remaining t-quark hadronic decay does not produce a misidentified b-tagged signal, another b-tagged signal can be imitated by gluon splitting or misidentified light-flavour jets.

Diboson: Z boson pair-decays can contaminate our signal if one Z boson decays into a neutrino-antineutrino pair ($\nu\overline{\nu}$) and the other Z boson decays into a $b\bar{b}$ pair. This process can be described as $pp \rightarrow Z(\rightarrow \nu\overline{\nu})\ Z(\rightarrow b\bar{b})$. WZ pair-decays can also contribute when W boson decays leptonically and the charged lepton from W decay is not reconstructed, and Z boson decays into a $b\bar{b}$ pair. We describe this process as $pp \rightarrow W(\rightarrow l\nu)\ Z(\rightarrow b\bar{b})$. In addition, WW pair-decays can also contaminate the signal if one W boson decays leptonically and the charged lepton from its decay is not identified, and a c-quark from another W boson decay is misidentified as a b-quark. Another b-quark can be produced from gluon splitting.

We use the same background samples mentioned in Ref. [1]. Background samples have been generated using **MadGraph5_aMC@NLO v2.3.3** [37]. **Pythia 8** [38] is applied to background samples for showering. Finally, we run the same **Rivet v2.5.2** [39] analysis to both background samples and signals.

4.1.2 Event selection

The event reconstruction and selection are set up in the **Rivet v2.5.2** analysis following Ref. [2].

Event reconstruction: Large-radius jets are built using the anti-k_t algorithm [20] implementation in **FastJet v3.2.0** [41] with radius R = 1.0. All the final state particles except leptons are used in this large-radius jet reconstruction process. Large-radius jets are required to have both $p_T > 250$ GeV and pseudo-rapidity $|\eta| < 2.0$. Sub-jets are implemented in this analysis with the purpose of identifying fat-jet flavour. Sub-jets are built using the anti-k_t algorithm implementation in **FastJet v3.2.0** with radius R = 0.2. Sub-jets are required to have $p_T > 10$ GeV as well as $|\eta| < 2.5$. Sub-jets can only contribute to a large-radius jet if Δ R (sub-jet, fat-jet) < 1.1. We use the same b-tagging technique, the 'ghost-association' technique, as described in Ref. [42]. The ghost-association technique is used to match sub-jets to large-radius jets. A large-radius jet is double b-tagged only if two sub-jets inside the large-radius jet are b-tagged. In order to remove the soft part of the large-radius jet, we use the same trimming procedure described in Ref. [43]: sub-jets have been formed inside the large-radius jet with an radius of 0.2 by the k_t algorithm and discarded if they carry less than 5% of the total large-radius jet energy. We use the same muon correction as described in Ref. [1] to find muons coming from b-quark decays: muons are counted as a constituent of the large-radius jet if the distance between the $b-$tagged sub-jets which has been geographically matched to a large-radius jet, and the closest muon is less than 0.2, ΔR (b-tagged sub-jet, closest muon) < 0.2.

Contributions from pile-up are not considered in this analysis and the ATLAS detector response is approximated by the **Rivet v2.5.2** analysis. A parameterised simulation of the ATLAS detector at $\sqrt{s} = 13$ TeV is performed by taking the ATLAS off-line jet mass resolution [34], b-tagging performance [2], and MET resolution [35] into account. We use the same mass resolution procedure mentioned in Ref. [34]: the large-radius jet is smeared with a 10% mass resolution. Also, we use the same b-tagging efficiency as the ATLAS experiment [2]: an average efficiency of 70% is used in identifying track jets containing b-hadrons with probabilities of 18% for c-quark jets misidentification and 0.6% for light-flavoured jets misidentification. Finally, we use the same MET resolution as described in Ref. [35]: MET resolution follows $k\sqrt{\sum E_T}$, where the parameter k is around 0.5 GeV$^{1/2}$.

In order to suppress background samples and maximise the expected signal over background ratio (SG/BG), the event selection is applied as follows.

Event selection: In order to avoid low MET events, MET > 500 GeV is applied in this **Rivet v2.5.2** analysis. In **Rivet v2.5.2**, the negative sum of all visible object momentum is calculated as MET. In this large MET scenario, the dark Higgs decay products can merge into a large-radius jet and boost against the large MET resulting from DM production. In order to keep our analysis consistent with 'Higgs Portal DM' model predictions, we require the number of large radius jets to be one. In our analysis, we also reject isolated leptons only allowing leptons that originate from the large-radius jet. This rejects background events in which leptons are produced in pile-up interactions or SM gauge boson decays. As the dark Higgs decay products are merged at high energies, we expect the reconstructed large-radius jet mass to be equivalent to the mass of the dark Higgs. Therefore, mass windows in the reconstructed large-radius jet mass distribution can be used in order to improve our SG/BG ratio. Signals with different m_s can have different mass windows, which will be further discussed in Section 4.3.2.

4.2 Validation

In order to validate our **Rivet v2.5.2** analysis results, we compare them with the published ATLAS paper [2] and Ref. [1] as follows.

4.2.1 Comparison with ATLAS analysis

Since the ATLAS analysis [2] uses the same types of SM background as ours in the large-radius jet search with large MET, we apply our **Rivet v2.5.2** analysis to our SM background samples and compare our predicted number of events with ATLAS results. The event selection requirements are the same between our and ATLAS analyses. In Ref. [2], SM background distributions are presented over the mass window 80 GeV $< M_J <$ 280 GeV. Therefore, we simply apply the same mass window into our **Rivet v2.5.2** analysis. Table 4.1 shows the predicted number of events in our analysis and the ATLAS simulation [2].

3.2 fb^{-1}	$t\bar{t}$	$W + b\bar{b}$	$Z + b\bar{b}$	Diboson
ATLAS prediction from [2]	4.83±0.88	2.48±0.71	3.80±0.44	1.20±0.12
Prediction from [1]	2.83±0.12	1.16±0.06	2.42±0.07	0.56±0.02
Rescaling factors from [1]	1.7±0.3	2.1±0.6	1.6±0.2	2.1±0.2
Prediction from this analysis	3.00	1.32	2.34	0.98
Rescaling factors from this analysis	1.61	1.88	1.62	1.22

Table 4.1: Predicted number of events with 80 GeV $\leq m_J \leq$ 280 GeV according to this analysis, simulation from Ref. [1] and ATLAS simulation [2], as well as the resulting rescaling factors.

We present our results with an integrated luminosity of 3.2 fb^{-1} to be able to compare with both ATLAS [2] and Ref. [1] results. It can be concluded from Table 4.1 that our prediction is generally smaller than the ATLAS simulation by a factor of 1.2 to 1.9 among all the types of SM background. This discrepancy may result from the detector reconstruction in our **Rivet v2.5.2** analysis. There is no dedicated detector reconstruction applied in this analysis and we only use resolution smearing to physics objects as the detector response. To obtain consistent background numbers, we scale our results to the ATLAS background yields with the help of rescaling factors.

4.2.2 Comparison with DESY analysis

We observe a similar discrepancy between our simulation and the ATLAS analysis [2] as reported in the DESY analysis [1]. From Table 4.1, it can been concluded that our scaling factors are within the DESY rescaling factor uncertainties except diboson samples, in which we predict a number closer to ATLAS simulation than the DESY prediction. Figure 4.2 shows the SM background in the distribution of the reconstructed large-radius jet. The SM background samples are drawn after applying rescaling factors with an integrated luminosity of 3.2 fb^{-1}. Figure 4.2 agrees with SM background in the reconstructed large-radius jet mass distributions from Ref. [1].

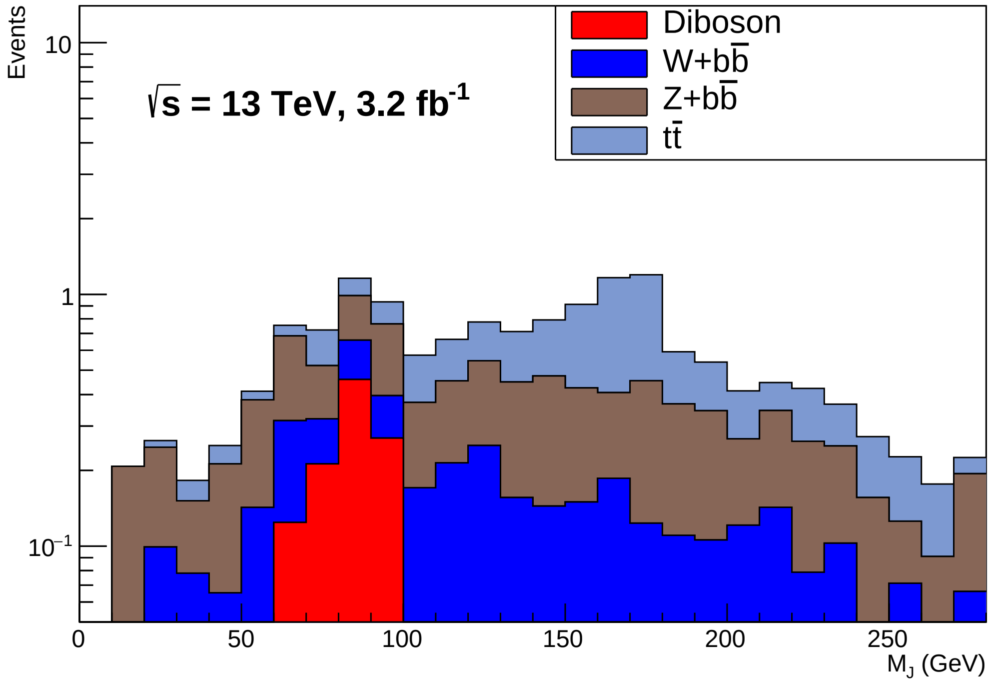


Figure 4.2: SM background under the reconstructed large-radius jet mass distributions with an integrated luminosity of 3.2 fb^{-1}. All event selection requirements except sensitive mass windows have applied to generate this plot.

By comparing our simulation results with ATLAS simulation results and DESY simulation results, we can conclude that our **Rivet v2.5.2** analysis is valid.

4.3 Results

This section will cover the results of our reinterpretation of the large-radius mono-jet search from the ATLAS experiment [2]. We scale our simulated samples to an integrated luminosity of 35.9 fb^{-1}, the same amount recorded by the ATLAS and CMS experiments in the 2016 data taking period, as mentioned in Section 4.3.1. As mentioned in Section 4.1.2, different m_s signals have different sensitive mass windows in the distribution of the reconstructed large-radius jet mass. We will use our generated signal events with $m_s = 50$, 70, and 90 GeV to optimise for different dark Higgs mass windows. In Section 4.3.2, we will present the large-radius jet mass window for each m_s signal taken into consideration in this study. The expected signal and background yield numbers will be shown in Section 4.3.3. Finally, Section 4.3.4 will present the exclusion limits we generated for both LHC [29] and relic density [28] coupling scenarios with different m_s.

In order to be consistent with Ref. [1] and Ref. [2], signal samples with coupling scenarios same as the LHC preference [29] will be presented from Section 4.3.2 to Section 4.3.3.

4.3.1 Scaling to 35.9 fb^{-1}

Figure 4.3 shows the SM background distribution after applying rescaling factors with an integrated luminosity of 35.9fb^{-1}.

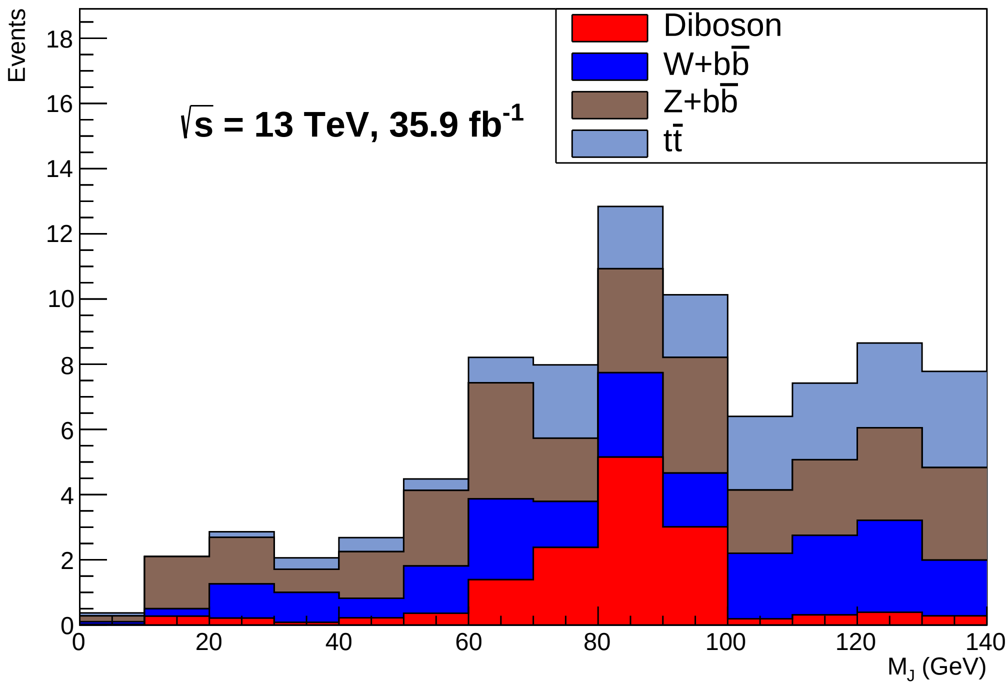


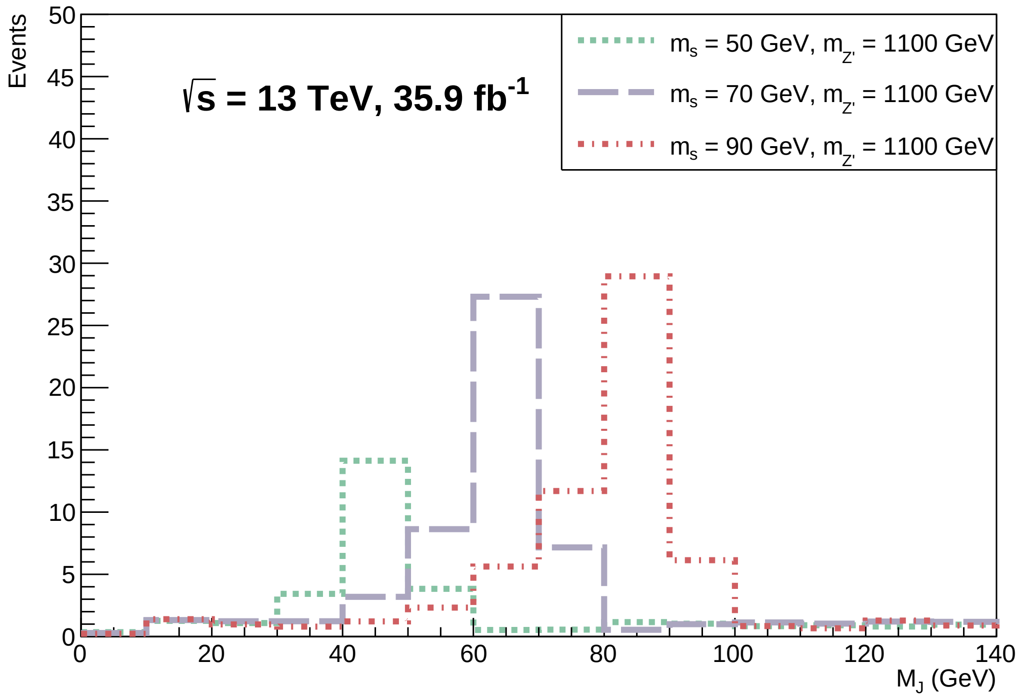
Figure 4.3: SM background in the reconstructed large-radius jet mass distribution with an integrated luminosity of 35.9 fb^{-1}. All event selection requirements except sensitive mass windows have been applied to generate this plot.

4.3.2 Higgs mass window optimisations

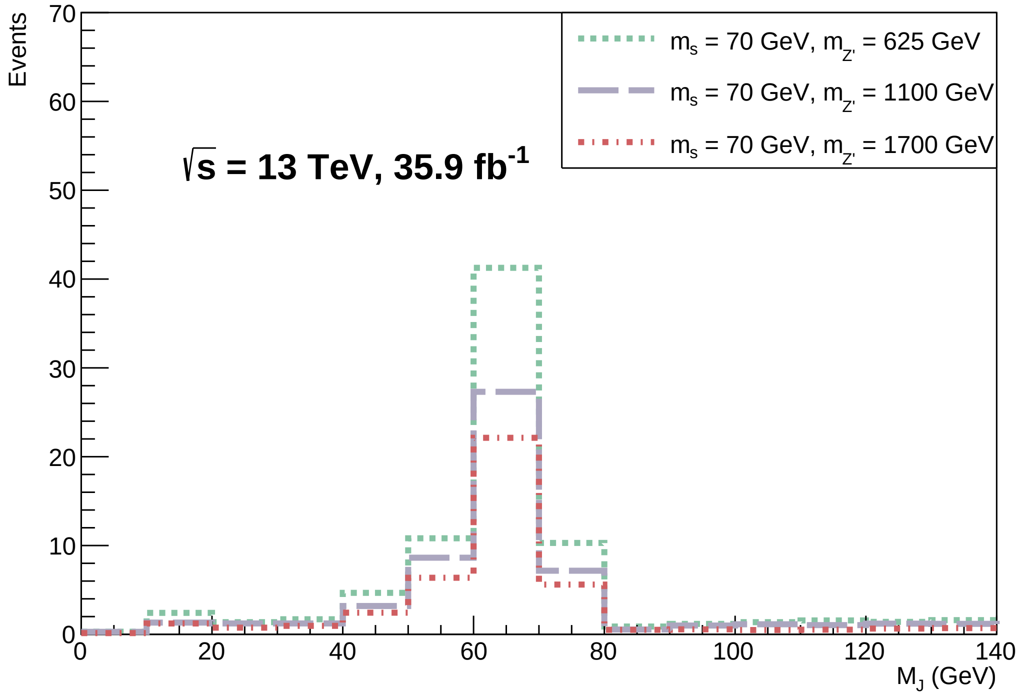
Different m_s signals have different sensitive mass windows in the distribution of the reconstructed large-radius jet mass. In order to optimise the dark Higgs mass windows for different m_s signals, we choose the same signal samples as Ref. [1]. The dark Higgs mass windows are set to maximise the expected significance. Figure 4.4 shows the reconstructed large-radius mass distribution for signal processes with different m_s and different $m_{Z'}$ with an integrated luminosity of 35.9 fb^{-1}. The signal processes are chosen according to the Ref. [1], using the coupling scenario suggested by the LHC working group [29]. Figure 4.4 shows that signal events always peak around the dark Higgs masses. Table 4.2 displays the mass windows that we chose for different m_s signals.

m_s [GeV]	mass range for the reconstructed large-radius jet
50	(30, 60)
70	(50, 80)
90	(60, 90)

Table 4.2: Expected mass windows in the different m_s distributions of the reconstructed large-radius jet mass. Mass windows are set to maximise the expected significance.



(a) Signal processes with different m_s



(b) Signal processes with different $m_{Z'}$

Figure 4.4: Reconstructed large-radius jet mass distributions for signal processes with different m_s and different $m_{Z'}$ with an integrated luminosity of 35.9 fb^{-1}. Signal processes are chosen according to the Ref. [1] preference and the coupling scenarios are the same as the LHC preference [29].

4.3.3 Expected signal and background yields

Table 4.3, Table 4.4 and Table 4.5 respectively show the yield numbers of three different m_s values after each event selection using the mass windows presented in Table 4.2. The background yield numbers are also presented in the same tables and the SM background uncertainties are computed by taking the relative uncertainties from the ATLAS paper [2]. The coupling scenario used by the LHC working group [29] has been assumed in this study. The signal samples are chosen to cover a wide range of $m_{Z'}$ as in Ref. [1]. All the simulated yield numbers for signal and background samples have been scaled to an integrated luminosity of 35.9 fb^{-1}.

Table 4.3, Table 4.4 and Table 4.5 show the number of events in the mass window for each signal we have taken into consideration.

35.9fb^{-1}	MET > 500 GeV	$N_{fat-jet} = 1$	No isolated leptons	30 GeV < M_J < 60 GeV
SM BG	4898.00	403.15	180.90	9.22±1.04
$m_{Z'} = 0.5$ TeV	654.41	58.72	58.67	32.07
$m_{Z'} = 1$ TeV	387.69	45.88	45.88	25.28
$m_{Z'} = 2$ TeV	142.75	18.03	18.03	10.25

Table 4.3: Predicted yield numbers for SM background and different signal samples with an integrated luminosity of 35.9 fb^{-1}. The signal samples are chosen as $g_x = 1$, $g_q = 0.25$ and $m_{\text{DM}} = 100$ GeV at $m_s = 50$ GeV as in Ref. [1]. The SM background uncertainties are computed by taking the relative uncertainties from the ATLAS paper [2].

35.9fb^{-1}	MET > 500 GeV	$N_{fat-jet} = 1$	No isolated leptons	50 GeV < M_J < 80 GeV
SM BG	4898.00	403.15	180.90	20.68±1.95
$m_{Z'} = 0.5$ TeV	538.85	110.06	110.02	76.92
$m_{Z'} = 1$ TeV	349.80	75.37	75.32	48.70
$m_{Z'} = 2$ TeV	140.02	37.38	37.32	25.73

Table 4.4: Predicted yield numbers for SM background and different signal samples with an integrated luminosity of 35.9 fb^{-1}. The signal samples are chosen as $g_x = 1$, $g_q = 0.25$ and $m_{\text{DM}} = 100$ GeV at $m_s = 70$ GeV as in Ref. [1]. The SM background uncertainties are computed by taking the relative uncertainties from the ATLAS paper [2].

35.9fb^{-1}	MET > 500 GeV	$N_{fat-jet} = 1$	No isolated leptons	60 GeV < M_J < 90 GeV
SM BG	4898.00	403.15	180.90	29.06±2.49
$m_{Z'} = 0.5$ TeV	458.83	128.77	128.62	86.13
$m_{Z'} = 1$ TeV	317.72	83.11	83.11	51.98
$m_{Z'} = 2$ TeV	134.40	45.69	45.61	29.64

Table 4.5: Predicted yield numbers for SM background and different signal samples with an integrated luminosity of 35.9 fb^{-1}. The signal samples are chosen as $g_x = 1$, $g_q = 0.25$ and $m_{\text{DM}} = 100$ GeV at $m_s = 90$ GeV as in Ref. [1]. The SM background uncertainties are computed by taking the relative uncertainties from the ATLAS paper [2].

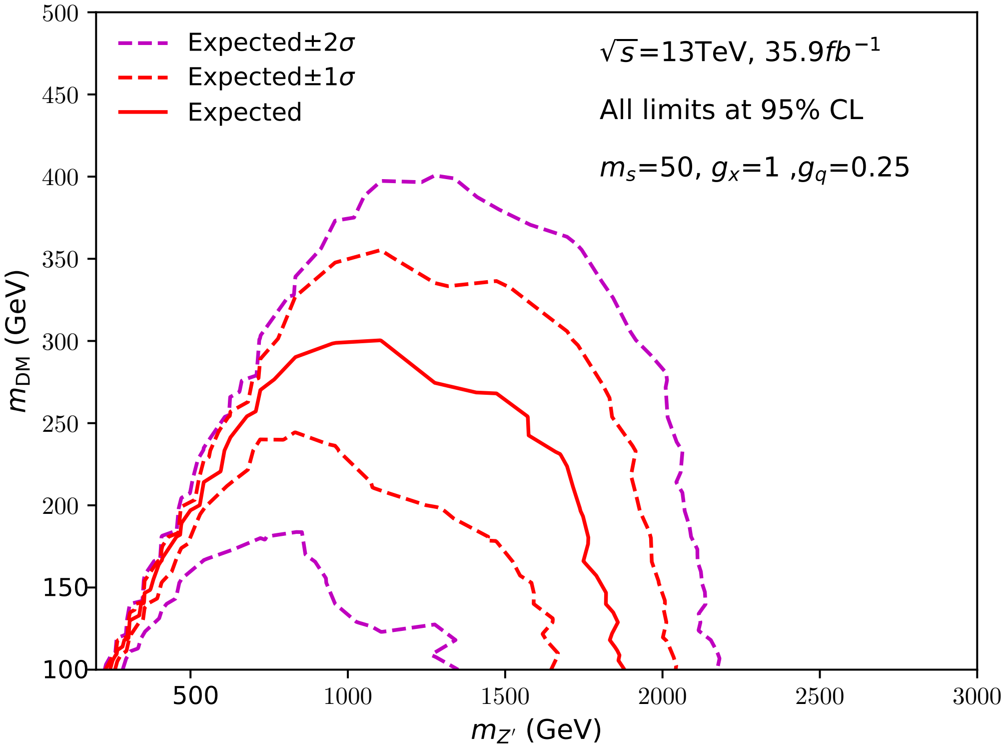
4.3.4 Exclusion limits

The upper limits at 95% confidence level (CL) [24,25] are calculated based on the excluded ratio of the signal cross-section to the predicted cross-section, σ/σ_{th}, with an integrated luminosity of 35.9 fb^{-1}. The results are displayed in the $m_{Z'} - m_{\rm DM}$ plane and regions where σ/σ_{th} ratio is less than one are considered as excluded regions. 95% CL means that if the signal were to be there, there is only a 5% (100% - 95%) chance we would miss it.

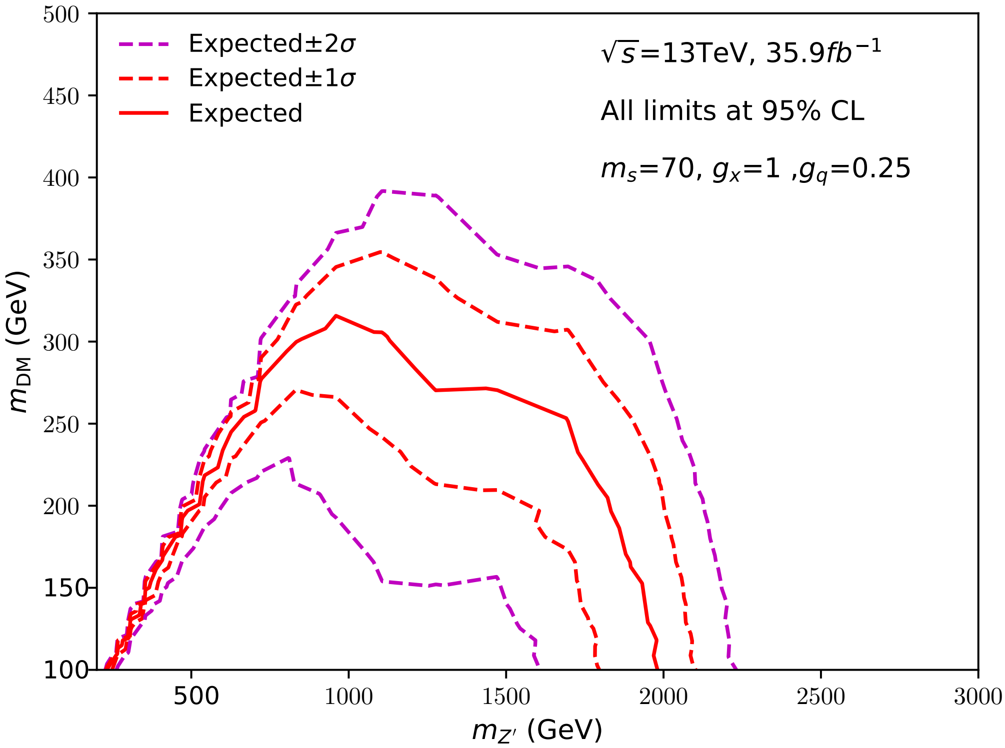
We use **HiggsCombineTool** [44] from **CMSSW_8_1_0** [45] to calculate the exclusion upper limits. The SM background statistic uncertainties are computed by taking the relative uncertainties from the ATLAS paper [2]. As in Ref. [46, 47], we use an additional 8% as our SM background systematic uncertainties for the large-radius jet tagging. A DM search with a SM Higgs decaying into a boosted $b\bar{b}$ pair is performed in Ref. [48]. In this search, a large-radius jet is also reconstructed to find the Higgs decay products. Based on the similarities between our implementation and Ref. [48], we use 15% as our signal systematic uncertainty. The asymptotic approximation [26] is used in computing exclusion limits. Finally, the upper limits are drawn using the linear interpolation [49] because our signal samples are discrete.

In this section, signal events with two types of coupling scenario are considered under m_s ranging from 50 GeV to 90 GeV. The 95% CL upper limits for fixed $m_{\rm DM}$ will be given as examples. Here, we choose $m_s = 70$ GeV, $g_x = 1$ and $g_q = 0.25$ as an example. For the rest of signal samples, their 1-D projections for fixed $m_{\rm DM}$ can be found in Appendix A.

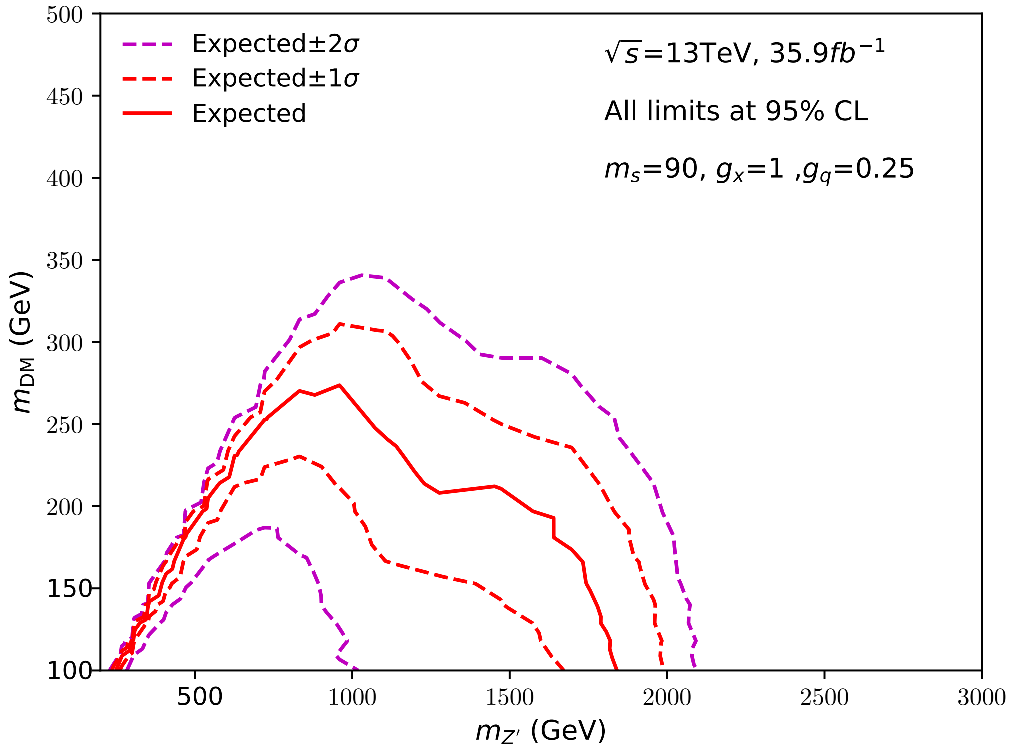
Signal samples with coupling scenario same as the LHC recommendation: Figure 4.5 (a), (b) and (c) respectively show the upper limits of $m_s = 50$, 70 and 90 GeV at 95% CL with an integrated luminosity of 35.9 fb^{-1}. The solid red line is the expected upper limit. One (two) standard deviation curves due to experimental uncertainty have been drawn in dashed red (purple). The region below the expected upper limit is excluded at 95% CL.



(a) $m_s = 50$ GeV, $g_x = 1$ and $g_q = 0.25$



(b) $m_s = 70$ GeV, $g_x = 1$ and $g_q = 0.25$

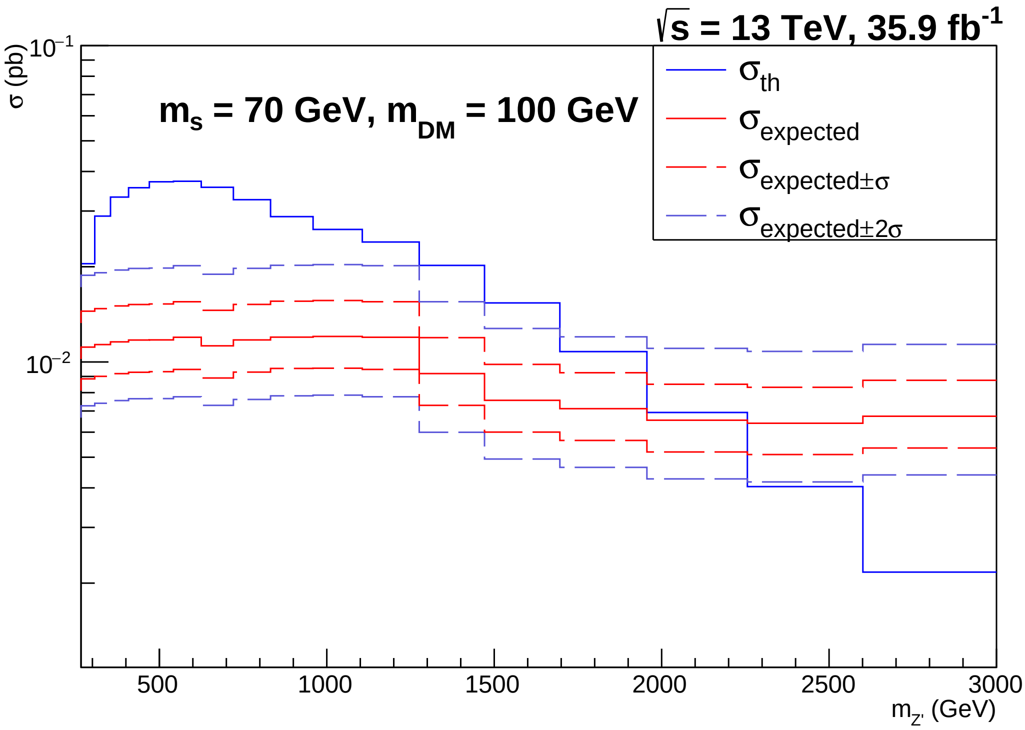


(c) $m_s = 90$ GeV, $g_x = 1$ and $g_q = 0.25$

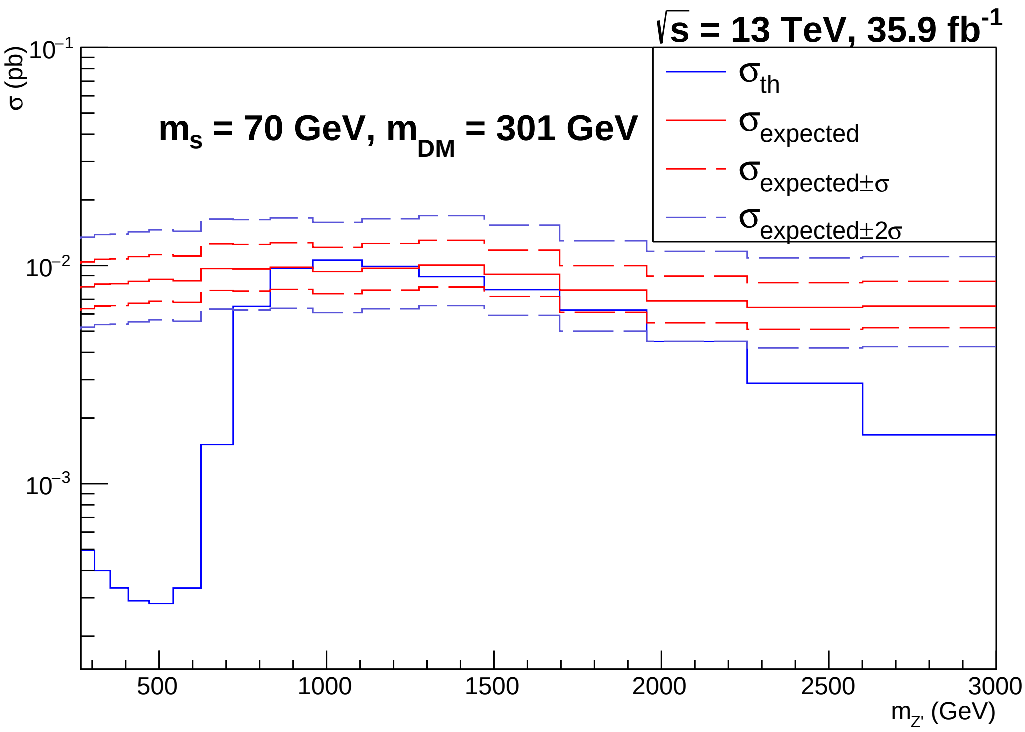
Figure 4.5: The expected exclusion region of the large-radius jet analysis at 95% CL with an integrated luminosity of 35.9 fb^{-1} at a centre-of-mass energy of 13 TeV. The inputs all correspond to m_s = 50, 70 and 90 GeV. The couplings are set according to the LHC recommendation [29]. The solid red line shows the expected upper limit and one (two) standard deviations arising from experimental uncertainties have been drawn using dashed red (purple) lines.

Exclusion limits at fixed $\mathbf{m_{DM}}$ = 100 GeV and 301 GeV for $\mathbf{m_s}$ = 70 GeV, $\mathbf{g_x}$ = 1 and $\mathbf{g_q}$ = 0.25: 95% CL upper limits for fixed m_{DM} can help in understanding the 2-D exclusions. We consider signals with $m_s = 70$ GeV, $g_x = 1$ and $g_q = 0.25$ as an example. Their 1-D projections for fixed m_{DM} are shown in Fig. 4.6.

Figure 4.6 (b) shows the theoretical cross-section and the expected upper limit on the cross-section with an integrated luminosity of 35.9 fb^{-1} for the boosted dark Higgs search as a function of $m_{Z'}$ for $m_s = 70$ GeV, $m_{\text{DM}} = 301$ GeV, $g_x = 1$ and $g_q = 0.25$. For $m_{Z'} < 600$ GeV region, the theoretical cross-section is two orders of magnitude smaller than that in the $m_{Z'} > 600$ region. As shown in Fig. 2.4 (b), $m_{Z'}$ needs to be > 600 GeV so it can decay into two DM particles of 301 GeV.



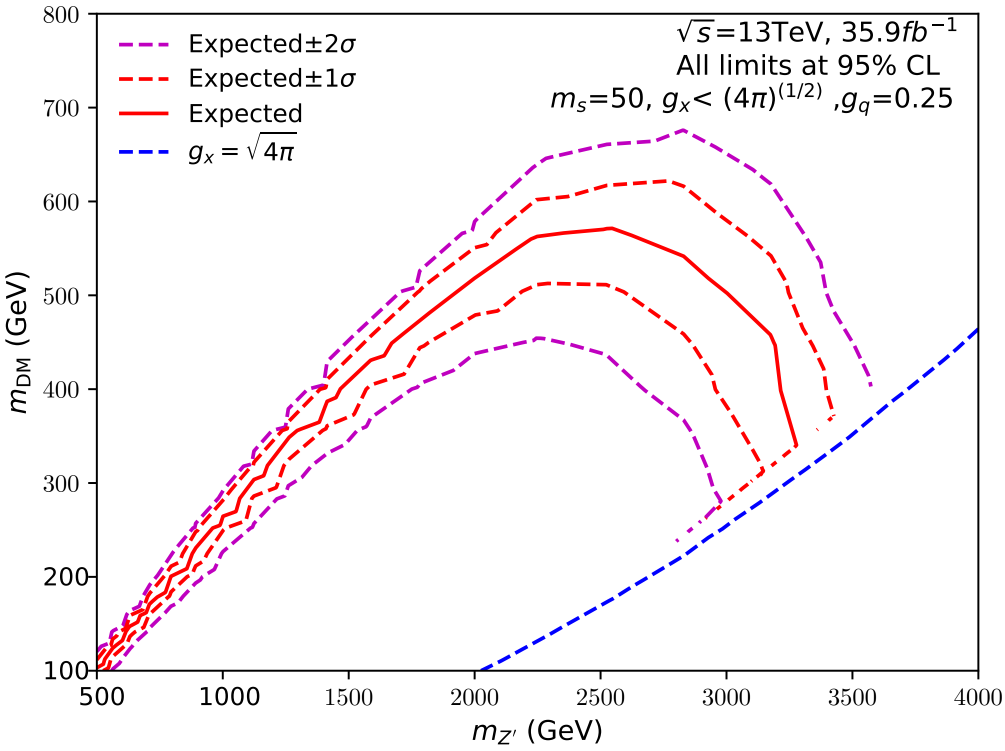
(a) $m_s = 70$ GeV, $m_{\mathrm{DM}} = 100$ GeV, $g_x = 1$ and $g_q = 0.25$



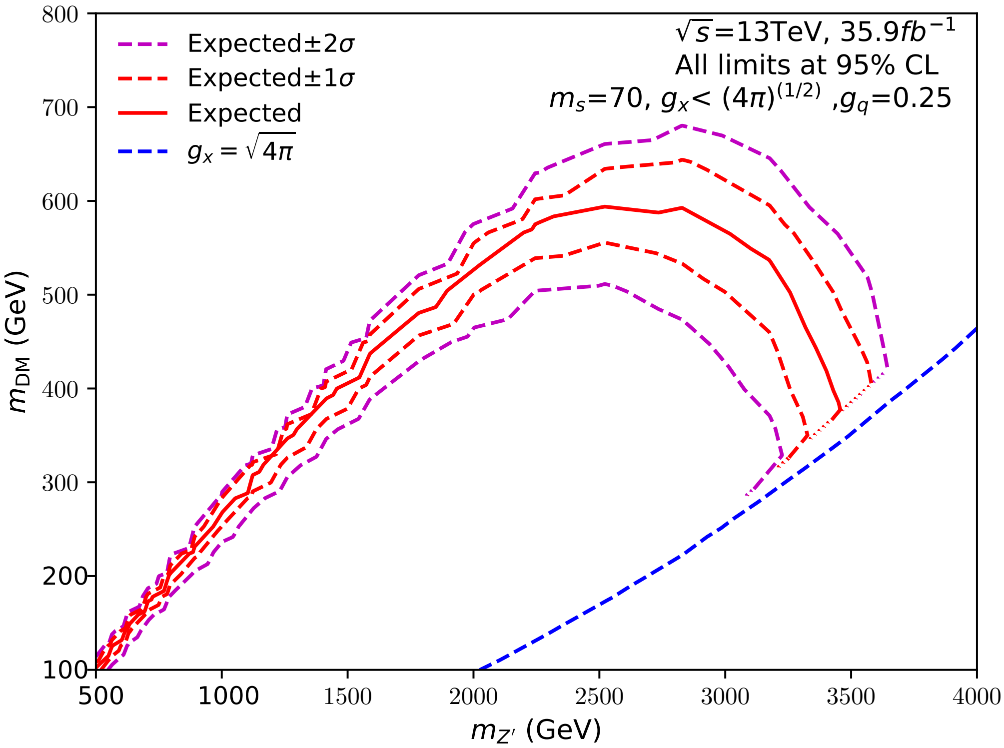
(b) $m_s = 70$ GeV, $m_{\mathrm{DM}} = 301$ GeV, $g_x = 1$ and $g_q = 0.25$

Figure 4.6: Expected 95% CL limits for $m_s = 70$ GeV with $m_{\mathrm{DM}} = 100$ and 301 GeV. The couplings are set according to the LHC recommendation [29]. The theoretical cross-section is shown as the blue solid line.

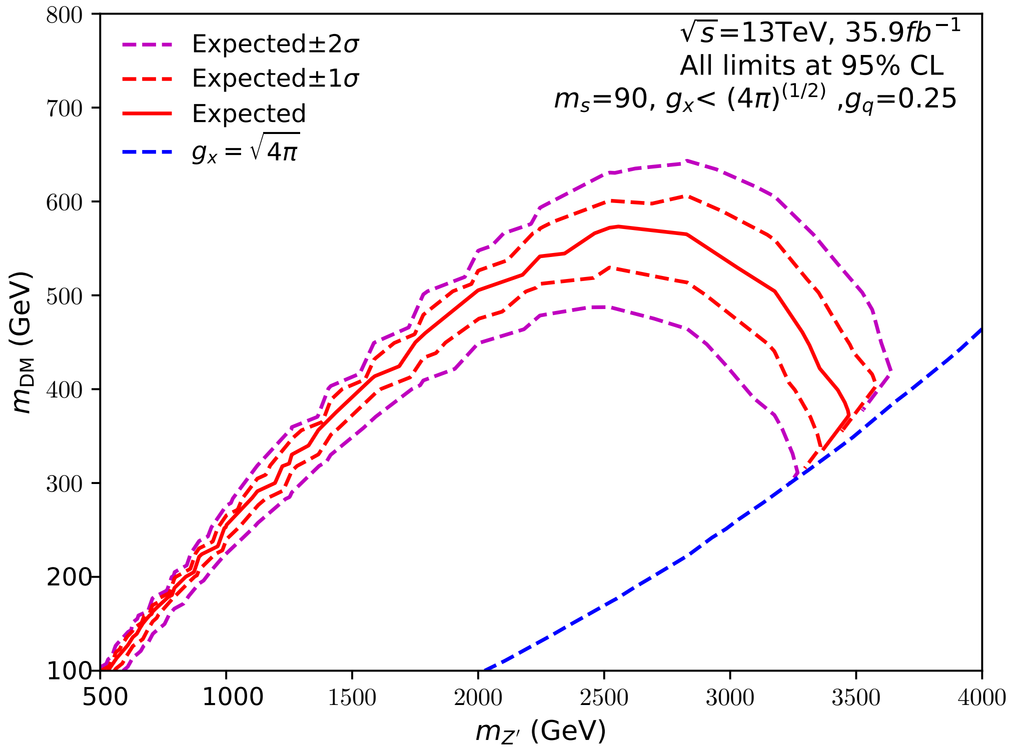
Signal events with coupling scenario considering DM relic abundance constraints from the universe: Figure 4.7 (a), (b) and (c) respectively show the upper limits for $m_s = 50$, 70 and 90 GeV at 95% CL with an integrated luminosity of 35.9 fb^{-1}. The solid red line is the expected upper limit and one (two) standard deviations have been drawn using dashed red (purple) lines from experimental uncertainties. All the regions below the expected upper limit is excluded at 95% CL. The dashed blue line indicates the region with $g_x = (4\pi)^{1/2}$ beyond which the theory becomes non-perturbative.



(a) $m_s = 50$ GeV, $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$



(b) $m_s = 70$ GeV, $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$



(c) $m_s = 90$ GeV, $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$

Figure 4.7: The expected exclusion region of the large-radius jet analysis at 95% CL with an integrated luminosity of 35.9 fb^{-1} at a centre-of-mass energy of 13 TeV. The inputs all correspond to $m_s = 50$, 70 and 90 GeV. The coupling g_x is chosen to fulfil the relic density constraint [28]. The solid red line shows the expected upper limit and one (two) standard deviations from experimental uncertainties have been drawn using dashed red (purple) lines. All the regions below the expected upper limits are excluded. The dashed blue line indicates the region where $g_x = (4\pi)^{1/2}$.

5 Dark Higgs search with jets and MET (α_T) analysis

This section focuses on the reinterpretation of the CMS α_T analysis. The α_T analysis is a generic analysis used to search for new physics like supersymmetry (SUSY) and DM. The α_T analysis used in both Ref. [3] and Ref. [4] can be reinterpreted in terms of the 'Higgs Portal DM' model. To estimate backgrounds in this reinterpretation, we use the data recorded by the CMS experiment in 2016 together with the estimated background numbers provided in Ref. [4]. We generate 'Higgs Portal DM' signal models and implement the event selection of Ref. [4]. We validate our signal generation procedure by comparing with a SUSY benchmark point that is also used in Ref. [4], and that has a similar final state as the 'Higgs Portal DM' model.

Section 5.1 concentrates on the event reconstruction and selection of the CMS α_T analysis. We employ the very same method as Ref. [4] for consistency. In Section 5.2, we investigate our reconstruction performance for the SUSY T2bb model and we discuss the similarities between SUSY T2bb signature and our simulation. The accuracy of our event selection can be tested by comparing our SUSY T2bb results with published results from Ref. [3] and Ref. [4]. Finally, Section 5.3 contains all the results of our reinterpretation.

5.1 Interpretation of the α_T analysis

The event selection of the CMS α_T analysis has been implemented in this section. In this analysis, jets are defined using the anti-k_t algorithm [20] with $\Delta\mathrm{R} = 0.4$. This analysis uses the number of jets, n_{jet}, the number of jets stemming from b-quark decays, n_b, the total visible hadronic energy, H_T, and the missing energy, H_T^{miss}, as discriminating variables. While our expected signal consists of two b-jets and missing energy, we allow for extra jets from initial or final state radiation. All the events are generated by **MadGraph5_aMC@NLO v2.3.3** [37]. **Pythia 8** [38] and **Rivet v2.5.2** [39] are respectively used for showering, and detector modelling and event selection. Table 5.1 taken from Ref. [4] shows the event selection requirements used for the signal region. Pile-up is not simulated for these signal samples. An approximated CMS detector response is performed in the **Rivet v2.5.2** analysis. We require the usage of the b-tagging technique [4] to identify jets coming from the dark Higgs. We assume an average efficiency of 69% in identifying sub-jets containing b-hadrons and a misidentification probability of 18% for c-quark jets and 1% for light-flavoured jets.

5.1.1 Event selections

Physics object acceptances		
Jet	$p_T > 40$ GeV, $\|\eta\| < 2.4$	
Photon	$p_T > 25$ GeV, $\|\eta\| < 2.5$, isolated in cone $\Delta R < 0.3$	
Electron	$p_T > 10$ GeV, $\|\eta\| < 2.5$, $I^{rel} < 0.1$ in cone $0.05 < \Delta R(p_T) < 0.2$	
Muon	$p_T > 10$ GeV, $\|\eta\| < 2.5$, $I^{rel} < 0.2$ in cone $0.05 < \Delta R(p_T) < 0.2$	
Single isolated track (SIT)	$p_T > 10$ GeV, $\|\eta\| < 2.5$, $I^{track} < 0.1$ in cone $\Delta R < 0.3$	
Baseline event selection		
All-jet f nal state	Veto events containing photons, electrons, muons, and SITs within acceptance	
p_T^{miss} quality	Veto events based on f lters related to beam and instrumental effects	
Jet quality	Veto events containing jets that fail identif cation criteria or $0.1 < f_{h^\circ}^{j_1} < 0.95$	
Jet energy and sums	$p_T^{j_1} > 100$ GeV, $H_T > 200$ GeV, $H_T^{miss} > 200$ GeV	
Jets outside acceptance	$H_T^{miss} / p_T^{miss} < 1.25$, veto events containing jets with $p_T > 40$ GeV and $\|\eta\| > 2.4$	
Signal region	Baseline selection +	
α_T threshold (H_T range)	0.65 (200–250 GeV), 0.60 (250–300), 0.55 (300–350), 0.53 (350–400), 0.52 (400–900)	
$\Delta\varphi^*_{min}$ threshold	$\Delta\varphi^*_{min} > 0.5$ ($n_{jet} \geq 2$), $\Delta\varphi^{*25}_{min} > 0.5$ ($n_{jet} = 1$)	
Nominal categorization schema		
n_{jet}	1	(monojet)
	≥2a	(a denotes asymmetric, $40 < p_T^{j_2} < 100$ GeV)
	2, 3, 4, 5, ≥6	(symmetric, $p_T^{j_2} > 100$ GeV)
n_b	0, 1, 2, 3, ≥4	(can be dropped/merged vs. n_{jet})
H_T boundaries	200, 400, 600, 900, 1200 GeV	(can be dropped/merged vs. n_{jet}, n_b)
H_T^{miss} boundaries	200, 400, 600, 900 GeV	(can be dropped/merged vs. n_{jet}, n_b, H_T)

Table 5.1: The event selection requirements used in signal regions and control regions. Table taken from [4].

The **Rivet v2.5.2** analysis has been set up as follows. Both track jets and calo-jets are reconstructed through **FastJet v3.2.0** [41] and anti-k_t algorithm [20] with a size parameter of 0.2 and 0.4, respectively. Events are vetoed if they contain an isolated electron [50] or muon [51] with $p_T > 10$ GeV to exclude charged leptons coming from any source other than b-quark decays. Track jet can be matched to a calo-jet if the distance between the closest track jet and a calo-jet is less than 0.4. Events are also vetoed if they contain an isolated photon [52] with $p_T > 25$ GeV. Calo-jets are required to have $p_T > 40$ GeV and $|\eta| < 3.0$. Events containing only one calo-jet are vetoed and the most energetic calo-jet in every selected event is required to have $p_T > 100$ GeV and $|\eta| < 2.5$. The missing transverse momentum

(MET) is calculated as the negative vector sum of the momentum of all the final-state hadrons and charged leptons. The total hadronic energy in the event H_T is calculated as the total scalar sum of all calo-jets, $H_T = \sum_{i=1}^{N_{jet}} p_T^{j_i}$. The negative vector sum of all calo-jets, defined as $H_T^{miss} = -|\sum_{i=1}^{N_{jet}} \mathbf{p}_T^{j_i}|$, is used in this analysis for estimating MET and H_T^{miss}/MET is required to be less than 1.25.

H_T >200 GeV and H_T^{miss} >130 GeV are required in each event as a baseline selection. The α_T variable [3, 53–56] is introduced here to suppress multi-jet events with MET originating from mismeasurements. For di-jets events, α_T is defined as

$$\alpha_T = \frac{p_T^{j_2}}{M_T},$$
$$M_T = \sqrt{(\sum_{i=1}^{2} p_T^{j_i})^2 - (\sum_{i=1}^{2} p_x^{j_i})^2 - (\sum_{i=1}^{2} p_y^{j_i})^2} = \sqrt{(H_T)^2 - (H_T^{miss})^2}, \tag{5.1}$$

where $p_T^{j_2}$ refers to the transverse momentum of the less energetic calo-jet and the M_T is the transverse mass of the di-jet system. For multi-jet events that contain more than 2 jets, an equivalent α_T variable can be reconstructed by combining two pseudo-jets [56]. This equivalent system is formed by finding the di-jet system that minimises the H_T difference(ΔH_T) between the two pseudo-jets. The two pseudo-jets and the definition of α_T for more than 2-jet system is

$$\alpha_T = \frac{1}{2}\frac{H_T - \Delta H_T}{\sqrt{{H_T}^2 - (H_T^{miss})^2}}. \tag{5.2}$$

In this analysis, an H_T-dependent α_T selection has been applied to optimise background suppression. The azimuthal angle variable ($\Delta\phi^*_{min}$) is the minimum angle between one jet and the H_T^{miss} from all the rest jets in the same event [57]. Requiring $\Delta\phi^*_{min} > 0.5$ rejects events where H_T^{miss} is pointing in the direction of a (mismeasured) jet.

5.2 Validation

In order to verify our implementation of the CMS α_T analysis event selection, we compare the selection efficiency at every step of the event selection. All the CMS α_T analysis data shown below are taken from both Ref. [3] and Ref. [4]. As will be discussed below, we validated our selection and the kinematic distribution against

Ref. [3]. During the course of this work, Ref. [4] appeared and we updated and validated our event selection against this reference which is used for the final results. The modelling of the kinematic distributions should be unaffected by this change. We compare the event selection for two SUSY T2bb models: T2bb(375, 300) and T2bb(800, 50) for comparison with Ref. [3], and T2bb(1000, 100) and T2bb(550, 450) for comparison with Ref. [4]. In all the T2bb sample names, the first number refers to the mass of bottom squark ($m_{\tilde{b}}$) and the second number refers to the mass of lightest supersymmetric particle (m_{LSPs}).

The diagram for the SUSY T2bb model can be found in Figure 5.1. Bottom squarks ($\tilde{b}$) are generated and decay into b quarks and the lightest supersymmetric particles (LSPs). The SUSY T2bb model is parameterised in terms of the mass of bottom squark ($m_{\tilde{b}}$) and LSP (m_{LSP}). The experimental signature for SUSY T2bb is two b-tagged jets with large MET from LSPs, which is similar to our 'Higgs Portal DM' experimental signature where we also expect two b-tagged jets with large MET from DM production. Therefore, it is reasonable to compare SUSY T2bb results.

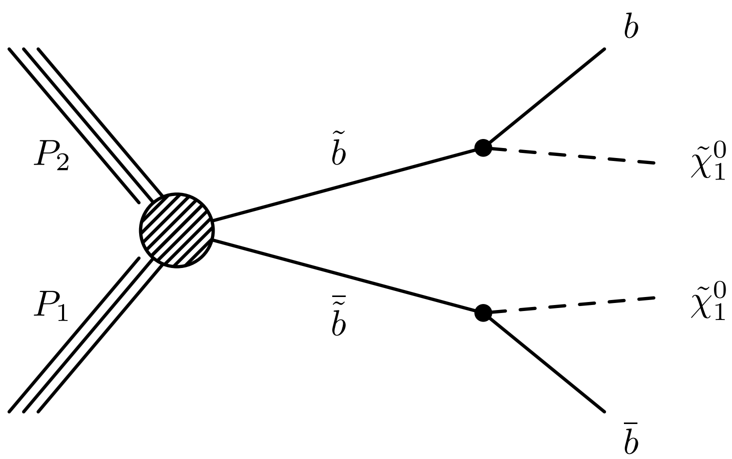


Figure 5.1: Feynman diagram of the SUSY T2bb model. The diagram shows the direct production of bottom squarks. Figure taken from [3].

For each T2bb samples taken under consideration, a table has been built for comparing the inclusive and exclusive signal efficiency between CMS simulation results and our reinterpretation results after each selection as shown in Section 5.2.1 (Table 5.2 to Table 5.5). Exclusive signal efficiency is the efficiency of that specific selection step and inclusive signal efficiency is the cumulative efficiency of every selection step. Because the α_T analysis considers four variables (n_{jet}, n_b, H_T, H_T^{miss}), those four variables' distributions are shown in Figure 5.2 and Figure 5.3 as a comparison with Ref. [3]. The four variables are compared before and after selections as shown in Section 5.2.2.

5.2.1 Cutflow tables

Table 5.2 and Table 5.3 present the comparison between our reinterpretation and the CMS simulation from Ref. [3]. We can conclude that the maximum difference for T2bb(375,300) between our reconstruction and CMS simulation is 9% and the maximum difference for T2bb(800,50) between our reconstruction and CMS simulation is 5%. Following the publication of Ref. [4], we updated our event selection against this reference (see Table 5.4 and Table 5.5). Ref. [4] is used for the final results of our reinterpretation. It can be concluded that the maximum difference for T2bb(1000,100) between our reconstruction and CMS simulation is 11% and the maximum difference for T2bb(550,450) between our reconstruction and CMS simulation is 14%.

2.3 fb^{-1}	$RA1$		$Rivet$		Diff.($RA1/Rivet$)	
	incl.	excl.	incl.	excl.	incl.	excl.
begin	100		100			
lep veto	99	0.99	100	1.00	0.95	0.99
track jet matching	94	0.95	100	1.00	1.01	0.95
photon veto	94	1.00	99.3	0.99	0.95	1.01
fwd. jet veto	81	0.86	89.9	0.91	1.04	0.95
$N_{jet} > 2$	61	0.75	65.3	0.73	0.98	1.04
$p_T^{j_1} > 100$	36	0.59	39.4	0.60	1.00	0.98
$\lvert\eta^{j_1}\rvert < 2.5$	34	0.94	37.3	0.95	0.99	1.00
$H_T > 200$	30	0.88	33.2	0.89	0.95	0.99
$H_T^{miss} > 130$	18	0.60	21.0	0.63	0.91	0.95
$\frac{H_T^{miss}}{E_T^{miss}} < 1.25$	15	0.83	19.2	0.91	1.07	0.91
α_T	7.2	0.48	8.6	0.45	0.98	1.07
$\Delta\phi^*_{min}$	4.5	0.63	5.5	0.64	0.99	0.98

Table 5.2: Inclusive and exclusive signal efficiency comparison for T2bb(375,300) between CMS-SUS-15-005 α_T analysis (RA1) [3] and this search (Rivet). The CMS-SUS-15-005 analysed samples correspond to an integrated luminosity of 2.3 fb^{-1} at a centre-of-mass energy of 13 TeV.

2.3 fb^{-1}	*RA*1		*Rivet*		Diff.(*RA*1/*Rivet*)	
	incl.	excl.	incl.	excl.	incl.	excl.
begin	100		100			
lep veto	99	0.99	100	1.00	0.97	0.99
track jet matching	96	0.97	100	1.00	1.00	0.97
photon veto	95	0.99	99.1	0.99	0.95	1.00
fwd. jet veto	81	0.85	88.8	0.90	1.00	0.95
$N_{jet} > 2$	80	0.99	88.0	0.99	1.00	1.00
$p_T^{j_1} > 100$	80	1.00	87.9	1.00	1.00	1.00
$\lvert\eta^{j_1}\rvert < 2.5$	80	1.00	87.5	1.00	1.00	1.00
$H_T > 200$	80	1.00	87.5	1.00	1.01	1.00
$H_T^{miss} > 130$	75	0.94	81.6	0.93	1.00	1.01
$\frac{H_T^{miss}}{E_T^{miss}} < 1.25$	72	0.96	78.4	0.96	1.02	1.00
α_T	62	0.86	65.9	0.84	0.98	1.02
$\Delta\phi^*_{min}$	39	0.63	42.5	0.64	0.99	0.98

Table 5.3: Inclusive and exclusive signal efficiency comparison for T2bb(800,50) between CMS-SUS-15-005 α_T analysis (RA1) [3] and this search (Rivet). The CMS-SUS-15-005 analysed samples correspond to an integrated luminosity of 2.3 fb^{-1} at a centre-of-mass energy of 13 TeV.

35.9 fb^{-1}	*RA*1		*Rivet*		Diff.(*RA*1/*Rivet*)	
	incl.	excl.	incl.	excl.	incl.	excl.
begin	100		100			
lep veto	100	1.00	99.9	1.00	0.97	1.00
track jet matching	97	0.97	99.9	1.00	1.00	0.97
photon veto	96	0.99	98.8	0.99	0.99	1.00
$N_{jet} > 2$	95	0.99	98.4	1.00	0.96	0.99
$p_T^{j_1} > 100$	91	0.96	98.4	1.00	1.00	0.96
$H_T > 200$	91	1.00	98.3	1.00	1.00	1.00
$H_T^{miss} > 200$	82	0.90	88.6	0.90	1.11	1.00
fwd. jet veto($\lvert\eta^{j_1}\rvert < 2.4$)	70	0.85	67.9	0.77	1.02	1.11
$\frac{H_T^{miss}}{E_T^{miss}} < 1.25$	70	1.00	66.4	0.98	1.00	1.02
α_T	62	0.89	58.9	0.89	0.97	1.00
$\Delta\phi^*_{min}$	40	0.65	39.2	0.67	1.00	0.97

Table 5.4: Inclusive and exclusive signal efficiency comparison for T2bb(1000,100) between CMS-SUS-16-038 α_T analysis (RA1) [4] and this search (Rivet). The CMS-SUS-16-038 analysed samples correspond to an integrated luminosity of 35.9 fb^{-1} at a centre-of-mass energy of 13 TeV.

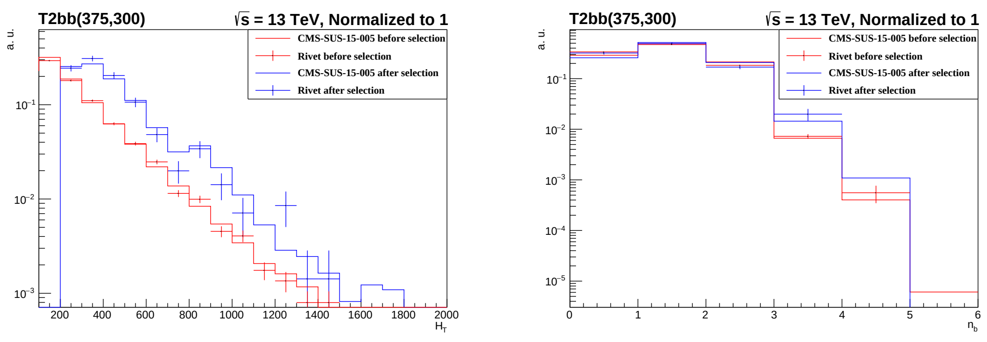
35.9 fb^{-1}	*RA1*		*Rivet*		Diff.(*RA1*/*Rivet*)	
	incl.	excl.	incl.	excl.	incl.	excl.
begin	100		100			
lep veto	99	0.99	100.0	1.00	0.96	0.99
track jet matching	95	0.96	100.0	1.00	1.01	0.96
photon veto	95	1.00	99.2	0.99	0.96	1.01
$N_{jet} > 2$	79	0.83	85.5	0.86	0.89	0.96
$p_T^{j_1} > 100$	52	0.66	63.0	0.74	0.95	0.89
$H_T > 200$	45	0.87	57.6	0.91	0.99	0.95
$H_T^{miss} > 200$	18	0.40	23.3	0.40	1.14	0.99
fwd. jet veto($\lvert\eta^{j_1}\rvert < 2.4$)	15	0.83	17.0	0.73	0.97	1.14
$\frac{H_T^{miss}}{E_T^{miss}} < 1.25$	14	0.93	16.3	0.96	1.03	0.97
α_T	9	0.64	10.2	0.63	1.02	1.03
$\Delta\phi^*_{min}$	6.3	0.70	7.0	0.69	0.99	1.02

Table 5.5: Inclusive and exclusive signal efficiency comparison for T2bb(550,450) between CMS-SUS-16-038 α_T analysis (RA1) [4] and this search (Rivet). The CMS-SUS-16-038 analysed samples correspond to an integrated luminosity of 35.9 fb^{-1} at a centre-of-mass energy of 13 TeV.

It can be concluded from above that our reconstruction is compatible with the CMS α_T analysis and our implementation can reproduce CMS official results with sufficient accuracy.

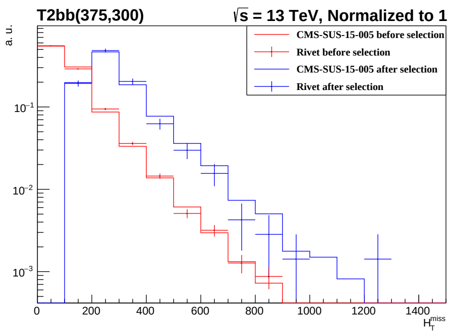
5.2.2 Kinematic distributions

n_{jet}, n_b, H_T, H_T^{miss} distributions are shown in Figure 5.2 and Figure 5.3 as a comparison with Ref. [3]. The variables' distributions for Ref. [4] are not available.

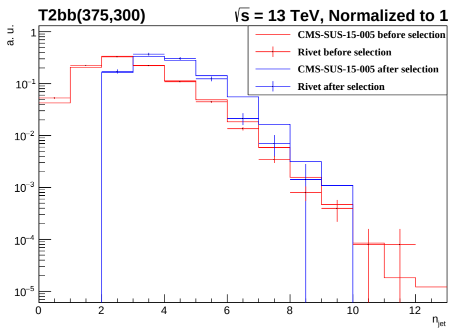


(a) H_T

(b) n_b

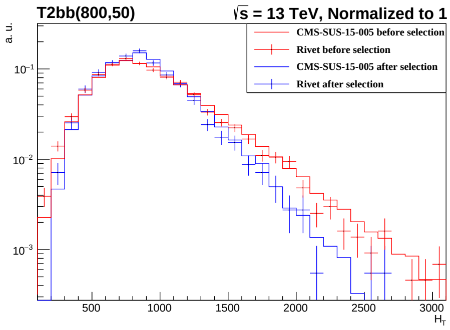


(c) H_T^{miss}

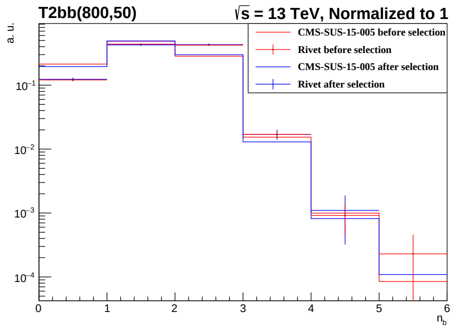


(d) n_{jet}

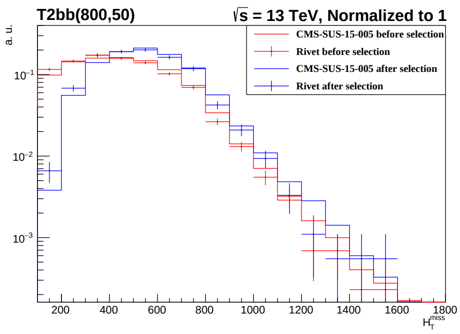
Figure 5.2: Comparison of distributions for (a) H_T, (b) n_b, (c) H_T^{miss}, and (d) n_{jet} between Ref. [3] and this analysis for SUSY T2bb(375,300). Before and after selection distributions for (a) H_T, (b) n_b, (c) H_T^{miss}, and (d) n_{jet} are all considered.



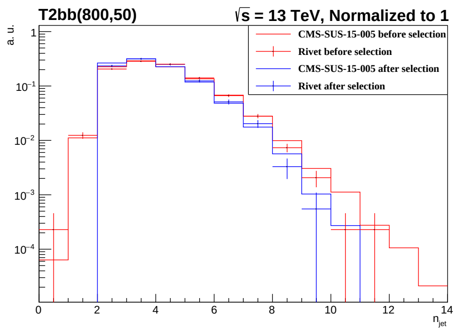
(a) H_T



(b) n_b



(c) H_T^{miss}



(d) n_{jet}

Figure 5.3: Comparison of distributions for (a) H_T, (b) n_b, (c) H_T^{miss}, and (d) n_{jet} between Ref. [3] and this analysis for SUSY T2bb(800,50). Before and after selection distributions for (a) H_T, (b) n_b, (c) H_T^{miss}, and (d) n_{jet} are all considered.

It can be concluded from above that our reconstruction is compatible with the CMS α_T analysis and our implementation can reproduce CMS official results with sufficient accuracy.

5.3 Results

5.3.1 Expected signal yields

The dataset in Ref. [4] is binned in 224 bins as a result of binning in n_{jet}, n_b, H_T, and H_T^{miss}. We identify the most sensitive bins for our analysis using the Asimov Test [58]. The Asimov Test is given by

$$[2((s+b)\ln[\frac{(s+b)(b+\sigma_b^2)}{b^2+(s+b)\sigma_b^2}] - \frac{b^2}{\sigma_b^2}\ln[1+\frac{\sigma_b^2 s}{b(b+\sigma_b^2)}])]^{1/2}, \tag{5.3}$$

where s is the expected number of events from signal, b is the expected number of events from background and σ_b is the background uncertainty. The Asimov Test is a significance calculation taking small statistics and background uncertainties into account [58]. We choose 5 benchmark points from signal samples with the DM relic abundance constraint as signal inputs in Asimov Test: $(m_s, m_{Z'}, m_{\rm DM})$ = (70, 2000, 200), (70, 2520, 318), (70, 3175, 318), (50, 3175, 318), (90, 3175, 318). We obtain our background numbers and uncertainties from Ref. [4]. After applying Asimov Test, we selected 17 sensitive bins for dark Higgs search by looking for the best test scores. Table 5.6 shows the 17 sensitive bins we selected.

N_{jet}	N_{bjet}	H_T(low)	H_T(high)	H_T^{miss}(low)	H_T^{miss}(high)	bkg	bkg_{err}	$data$	$(70, 2000, 200)$	$(70, 2520, 318)$	$(70, 3175, 318)$	$(50, 3175, 318)$	$(90, 3175, 318)$
2	0	1200	inf	900	inf	20.9	9.39	19	3.89	1.51	2.01	1.98	1.88
2	1	600	900	600	inf	27.1	8.64	31	42.43	16.59	8.04	8.51	7.33
2	1	900	1200	600	900	7.4	2.43	12	15.33	7.58	5.02	4.82	4.11
2	1	900	1200	900	inf	3.2	1.47	6	13.13	8.22	5.98	6.83	6.46
2	1	1200	inf	600	900	2.1	0.70	1	3.26	0.98	0.49	0.77	0.54
2	1	1200	inf	900	inf	2	0.89	4	6.62	4.19	4.19	4.56	4.65
2	2	600	inf	600	inf	2.3	0.76	2	2.31	0.98	0.83	0.69	1.20
3	1	600	900	600	inf	32.7	8.04	42	25.42	7.73	3.99	3.72	4.29
3	1	900	1200	600	900	15.4	3.74	10	14.18	5.84	3.20	3.58	3.26
3	1	900	1200	900	inf	4.4	1.58	6	7.35	4.00	2.36	2.40	2.15
3	1	1200	inf	900	inf	3.5	1.27	4	5.88	3.85	3.10	2.63	2.90
3	2	1200	inf	900	inf	0.3	0.11	0	0.63	0.30	0.28	0.20	0.24
4	1	600	900	600	inf	17.2	4.07	19	8.93	3.32	1.09	1.37	1.35
4	1	900	1200	600	900	12.3	2.98	11	8.51	3.66	1.36	1.71	1.35
4	1	900	1200	900	inf	1.8	0.74	1	1.68	1.17	0.79	0.84	0.69
4	1	1200	inf	900	inf	2.9	1.09	4	3.47	2.19	1.55	1.48	1.22
5	1	1200	inf	900	inf	1.6	0.67	2	1.89	1.09	0.51	0.43	0.47

Table 5.6: The CMS-SUS-16-038 α_T analysis (RA1) dataset [4] and 5 'Higgs Portal DM' model benchmarks' final yield numbers after all selections in 17 chosen most sensitive bins. The 5 benchmarks are shown as (m_s, $m_{Z'}$, m_{DM}).

5.3.2 Exclusion limits

The upper limits at 95% confidence level (CL) [24, 25] are calculated based on the ratio of the signal cross-section to the predicted cross-section, σ/σ_{th}, with an integrated luminosity of 35.9 fb^{-1}. The results are drawn in the $m_{Z'} - m_{\text{DM}}$ plane and regions where σ/σ_{th} ratio is less than one are regarded as excluded regions. 95% CL means that if the signal were to be there, there is only a 5% (100% - 95%) chance we would miss it.

We use **HiggsCombineTool** [44] from **CMSSW_8_1_0** [45] to calculate the exclusion upper limits. We apply 2016 CMS recorded data, estimated SM background and background statistic uncertainties for each sensitive bin from Ref. [4] into our analysis. We use 8% as our SM background systematic uncertainties as motivated from Ref. [3, 4]. The asymptotic approximation [26] is used in computing exclusion limits. Finally, the upper limits are drawn through the linear interpolation [49] because our signal samples are discrete.

In this section, signal events with two types of coupling scenarios are both considered under m_s ranging from 50 GeV to 90 GeV. The 95% CL upper limits for fixed m_{DM} will be given as examples. Here, we choose $m_s = 70$ GeV, $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$ as an example. For the rest of signal samples, their 1-D projections for fixed m_{DM} can be found in Appendix B.

Signal samples with coupling scenario same as the LHC recommendation: Figure 5.4 shows the 95% CL upper limit for $m_s = 50$ GeV corresponding to an integrated luminosity of 35.9 fb^{-1}. The solid red line is the expected upper limit and one (two) standard deviations have been drawn using dashed red (purple) lines resulting from experimental uncertainties. All the regions below the expected upper limits are excluded.

Figure 5.5 (a) and (b) show the 95% CL upper limits for $m_s = 70$ and 90 GeV with $m_{\text{DM}} = 100$ GeV, respectively. It can be seen that no parameter space can be excluded for $m_s = 70$ GeV nor 90 GeV because the expected upper limit on the cross-section is always higher than the theoretical cross-section.

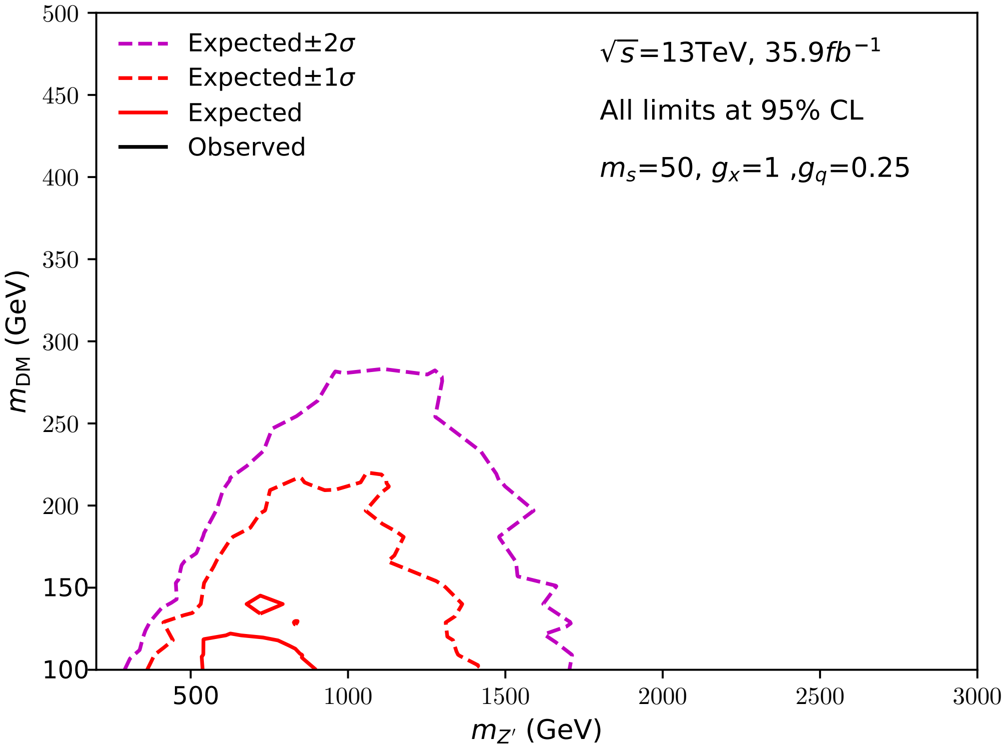
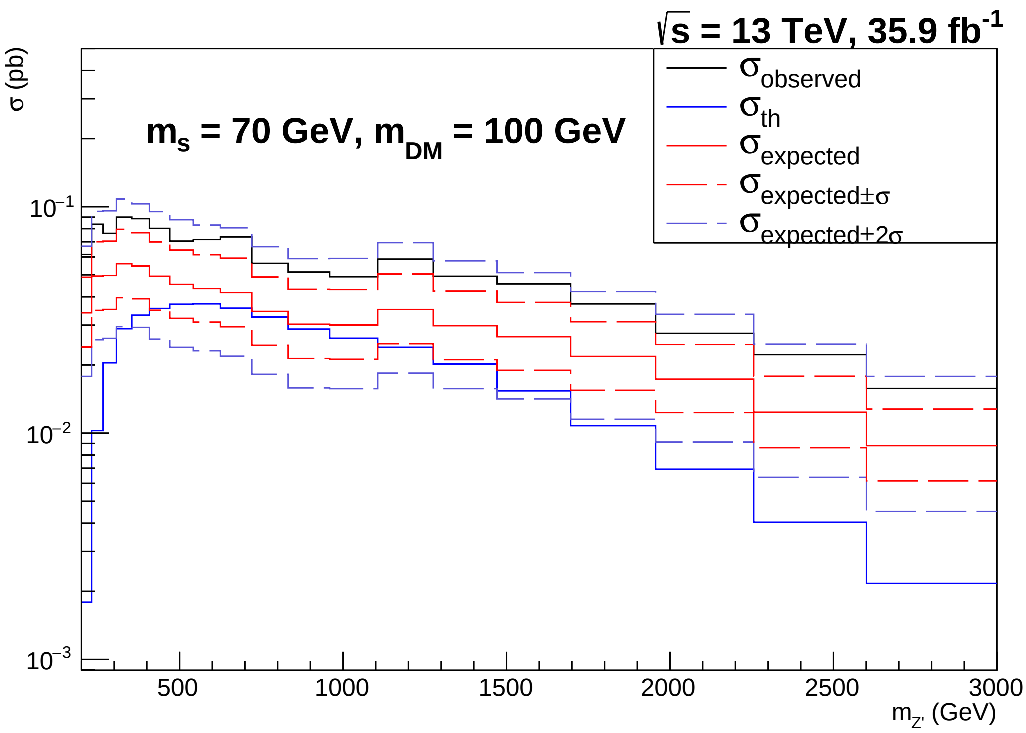
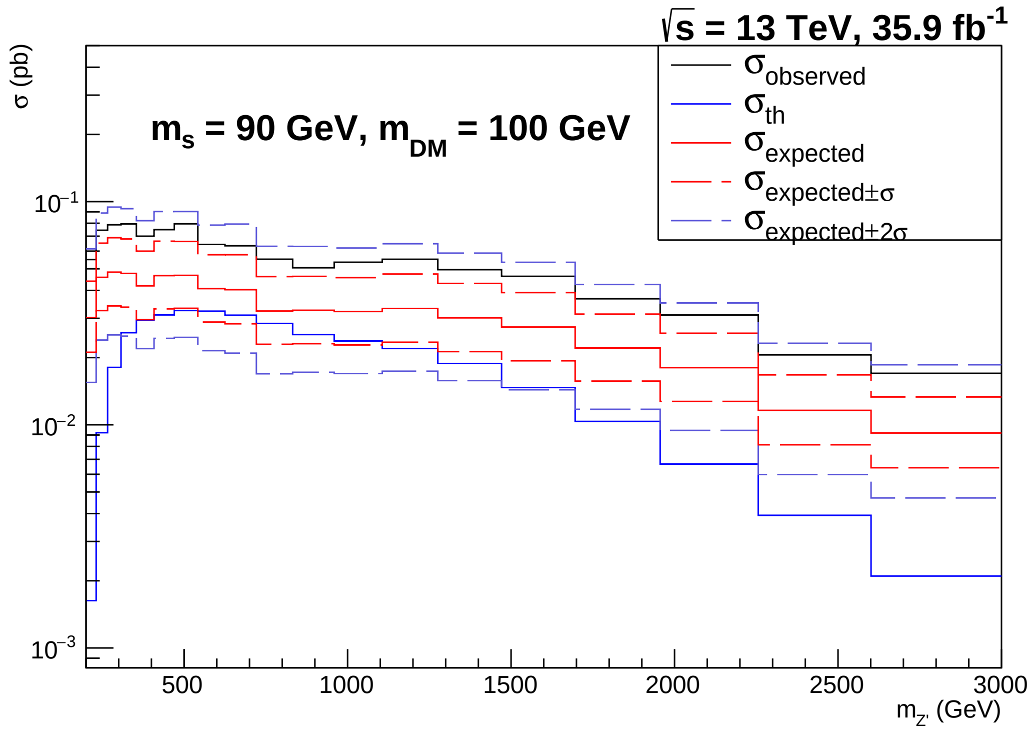


Figure 5.4: The expected exclusion region of the α_T analysis at 95% CL with an integrated luminosity of 35.9 fb^{-1} at a centre-of-mass energy of 13 TeV. The inputs all correspond to $m_s = 50$ GeV. The couplings are set according to LHC recommendations [29]. The solid red line shows the expected upper limit and one (two) standard deviations arising from experimental uncertainties have been drawn using dashed red (purple) lines.



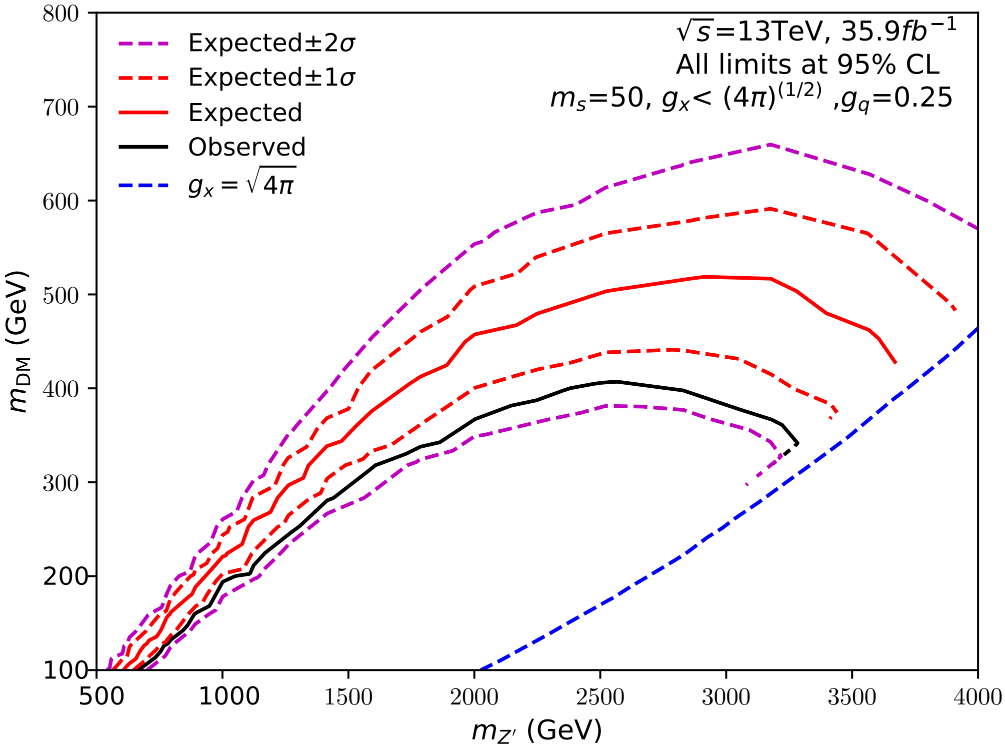
(a) $m_s = 70$ GeV, $g_x = 1$ and $g_q = 0.25$



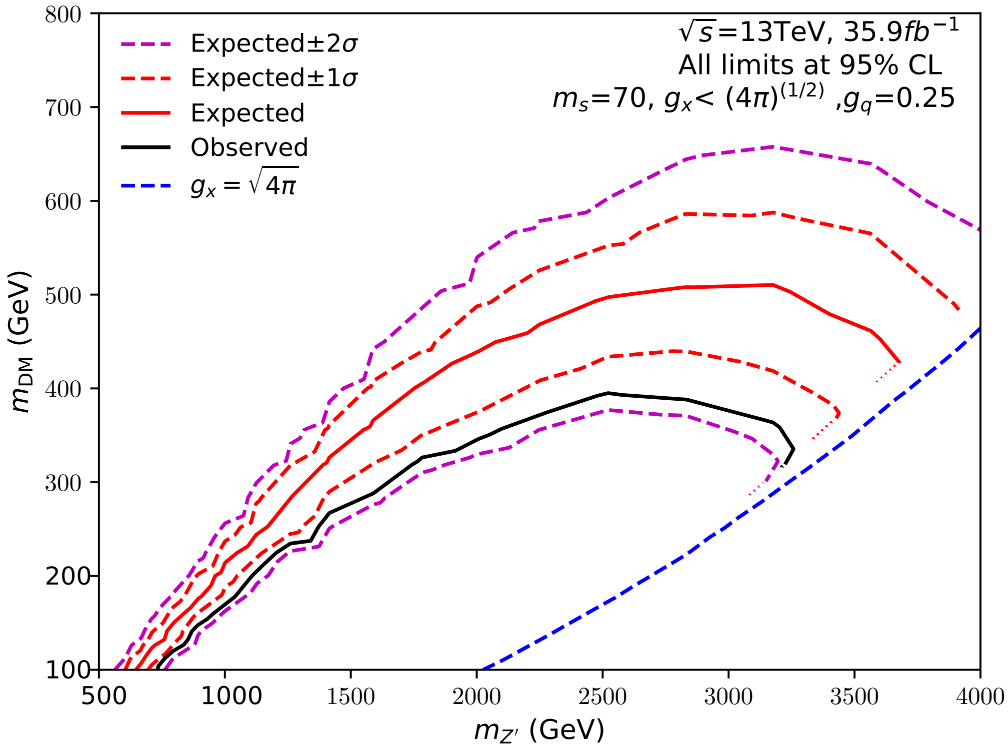
(b) $m_s = 90$ GeV, $g_x = 1$ and $g_q = 0.25$

Figure 5.5: Expected and observed 95% CL limits for $m_s = 70$ and 90 GeV with $m_{\rm DM} = 100$ GeV, respectively. The couplings are set according to LHC recommendations [29]. The theoretical cross-section is shown as the blue solid line.

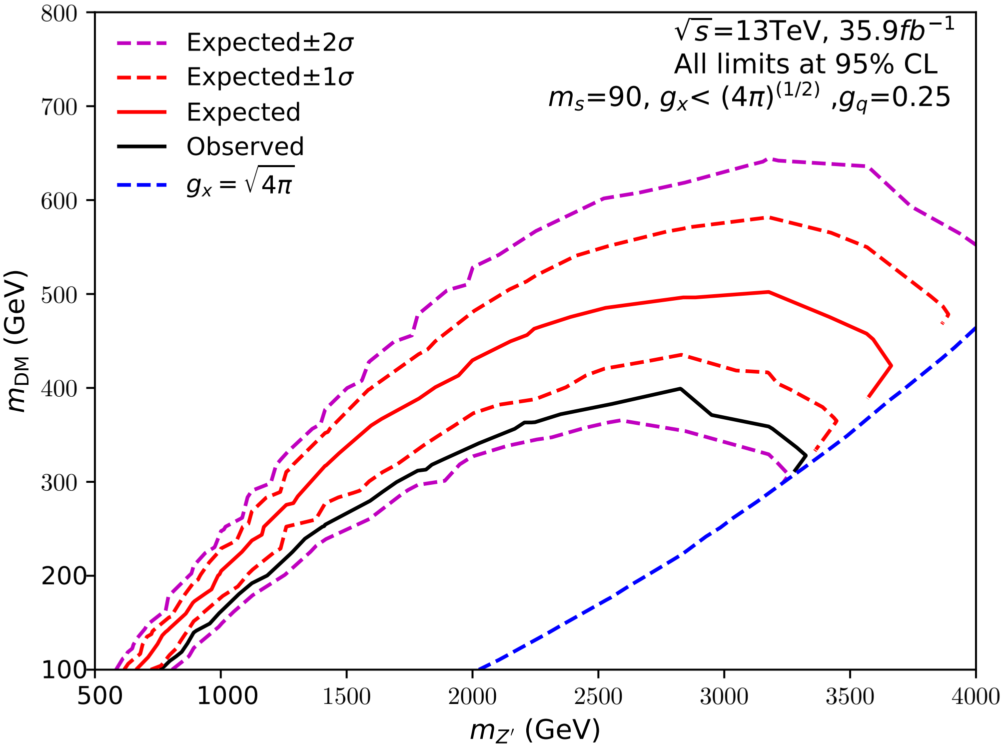
Signal events with coupling scenario considering the DM relic abundance constraint from the universe: Figure 5.6 (a), (b) and (c) respectively show the upper limits for $m_s = 50$, 70 and 90 GeV at 95% CL with an integrated luminosity of 35.9 fb^{-1}. The solid black line is the observed upper limit. The solid red line is the expected upper limit and one (two) standard deviations have been drawn using dashed red (purple) lines from experimental uncertainties. All the regions below the observed upper limit is excluded. The dashed blue line indicates the region with $g_x = (4\pi)^{1/2}$ beyond which the theory becomes non-perturbative.



(a) $m_s = 50$ GeV, $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$



(b) $m_s = 70$ GeV, $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$

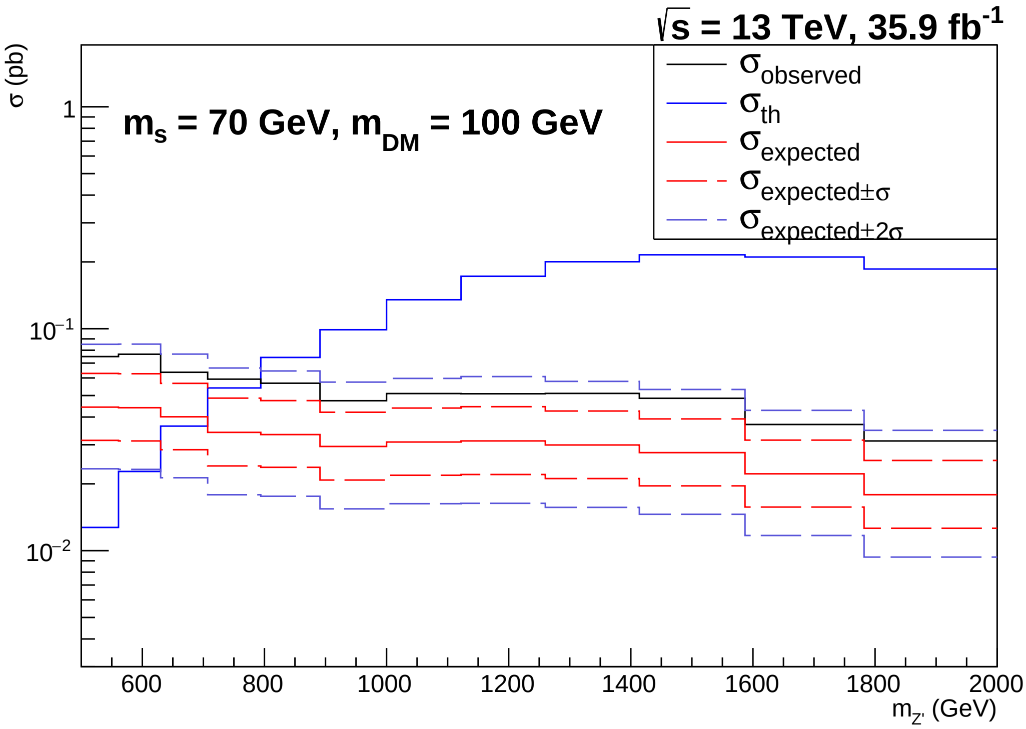


(c) $m_s = 90$ GeV, $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$

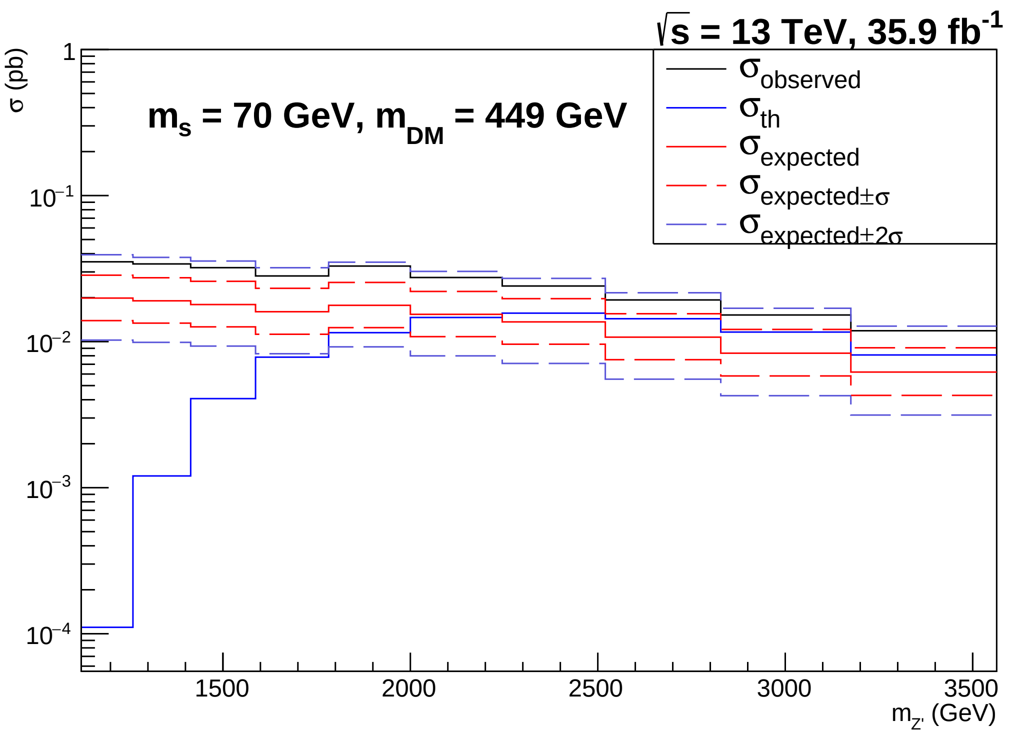
Figure 5.6: The expected exclusion region of the α_T analysis at 95% CL with an integrated luminosity of 35.9 fb^{-1} at a centre-of-mass energy of 13 TeV. The inputs correspond to $m_s = 50$, 70 and 90 GeV. The coupling g_x is chosen to fulfil the relic density constraint [28]. The solid black line shows the observed upper limits. The solid red line shows the expected upper limits and one (two) standard deviations from experimental uncertainties have been drawn using dashed red (purple) lines. All the regions below the observed upper limits are excluded. The dashed blue line indicates the region where $g_x = (4\pi)^{1/2}$.

Exclusion limits at fixed $\mathbf{m_{DM}} = 100$ GeV and 449 GeV for $\mathbf{m}_s = 70$ GeV, $\mathbf{g}_x < (4\pi)^{1/2}$ and $\mathbf{g}_q = 0.25$: To help understand the behaviour of the 2-D limit plots, we look at the 95% CL limit for selected fixed DM masses as a function of $m_{Z'}$. We consider signals with $m_s = 70$ GeV, $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$ as an example. Their 1-D projections for fixed $m_{\rm DM}$ are shown in Fig. 5.7.

For the rest of signal samples, their 1-D projections for fixed $m_{\rm DM}$ can be found in Appendix B.



(a) m_s = 70 GeV, $m_{\rm DM}$ = 100 GeV, $g_x < (4\pi)^{1/2}$ and g_q = 0.25



(b) m_s = 70 GeV, $m_{\rm DM}$ = 449 GeV, $g_x < (4\pi)^{1/2}$ and g_q = 0.25

Figure 5.7: Expected and observed 95% CL limits for m_s = 70 GeV with $m_{\rm DM}$ = 100 and 449 GeV. The couplings are set to fulfil the relic density constraint [28]. The theoretical cross-section is shown as the blue solid line.

6 Discussion

6.1 Large-radius jet analysis comparison

Both Ref. [1] and our large-radius jet reinterpretation are trying to reproduce the ATLAS simulation [2]. Both analyses are introducing rescaling factors in order to be compatible with ATLAS background estimation [2]. From Table 4.1, it can be concluded that our analysis is compatible with Ref. [1] and the largest rescaling factor difference between our simulation and that of Ref. [1] is less than 0.8. Our simulation is slightly closer to ATLAS background estimation compared to Ref. [1].

Figure 4.4 shows the reconstructed large-radius jet mass distribution for signal processes with different m_s and different $m_{Z'}$. It can be concluded that the signal processes always peak as expected at around the mass of the dark Higgs when reconstructing the mass of the large-radius jet. Ref. [1] and Ref. [2] also obtain the same result, which can be treated as a confirmation of our reinterpretation.

We choose different mass windows for different m_s signals in the distributions of large-radius jet mass in order to maximise the expected significance. And by looking at the exclusion limits that we draw for different signal samples, some conclusions can be drawn.

Figure 4.5 (a), (b) and (c) are the exclusion limits for $m_s = 50$, 70 and 90 GeV for signal samples with coupling scenario set to the LHC recommendation [29]. It can be seen that for both $m_s = 50$ and 70 GeV, the expected upper limits peak at around $m_{\text{DM}} = 300$ GeV while the expected upper limits peak at around $m_{\text{DM}} = 270$ GeV for $m_s = 90$ GeV. This is because there are more SM background events at around 90 GeV from diboson production. For $m_s = 50$, 70 and 90 GeV, $m_{Z'}$ up to 1800, 2000 and 1800 GeV are respectively excluded.

Figure 4.7 (a), (b) and (c) are the exclusion limits for $m_s = 50$, 70 and 90 GeV for signal samples fulfilling the DM relic abundance constraint. For $m_s = 50$, 70 and 90 GeV, $m_{Z'}$ up to 3300, 3450 and 3500 GeV are respectively excluded. By comparing with Ref. [1], it can be seen that our exclusion limits are comparable with Ref. [1].

6.2 α_T analysis comparison

We implement the CMS α_T analysis and validate it with the help of SUSY T2bb samples by comparing the selection efficiencies at different stages of the event selection. Table 5.2 and Table 5.3 show the comparison between our reinterpretation and CMS simulation from Ref. [3]. It can be seen that the maximum difference for T2bb(375, 300) between our reinterpretation and CMS simulation is 9% and the maximum difference for T2bb(800, 50) between our reinterpretation and CMS simulation is 5%. The four key variables' distributions ($n_{jet}, n_b, H_T, H_T^{miss}$) are shown in Fig. 5.2 and Fig. 5.3 for comparison. As Ref. [4] appeared while working on this analysis, we updated our numbers and reinterpretations (see Table 5.4 and Table 5.5). It can be seen that the maximum difference for T2bb(1000, 100) between our reinterpretation and CMS simulation is 11% and the maximum difference for T2bb(550, 450) between our reinterpretation and CMS simulation is 14%.

We use Asimov Test [58] to find the sensitive bins for our dark Higgs search, taking small statistics and background uncertainties into account [58]. In the end, 17 bins are selected as sensitive bins and Table 5.6 shows those bins in detail. It can be seen that some bins are more sensitive to $m_s = 70$ GeV signals while other bins are more sensitive to $m_s = 50$ and 90 GeV signals. This is because we want to find sensitive bins that can cover a wide range of m_s distribution in 'Higgs Portal DM' model.

The exclusion limits are drawn in different signal coupling scenarios with different m_s distributions.

Figure 5.4 is the exclusion limits of $m_s = 50$ GeV for signal samples with coupling scenarios same as the LHC recommendation [29]. As we can see, the expected exclusion limit is relatively weak. 95% CL exclusion plots for fixed $m_{\rm DM}$ and $m_s = 50$ GeV are shown in Appendix B. Figure 5.5 (a) and (b) show the 95% CL expected upper limits for $m_s = 70$ and 90 GeV with $m_{\rm DM} = 100$ GeV. It can be concluded that no significant expected upper limits can be drawn for $m_s = 70$ GeV nor 90 GeV because the expected upper limit on the cross-section is always higher than the theoretical cross-section.

Figure 5.6 (a), (b) and (c) are the 95 % exclusion limits for $m_s = 50$, 70 and 90 GeV for signal samples fulfilling the DM relic abundance constraint. For $m_s = 50$, 70 and 90 GeV, $m_{Z'}$ up to 3600, 3700 and 3700 GeV are excluded.

7 Conclusion

In this thesis we have presented two complementary methods to search for dark matter (DM) at high-energy colliders under a 'Higgs Portal Dark Matter' model.

The 'Higgs Portal Dark Matter' model proposes a dark Higgs boson that can generate masses for the dark sector particles. This model enables to relax constraints from DM relic abundance by opening up a new annihilation channel. The experimental signature for 'Higgs Portal Dark Matter' model is a large-radius jet from the dark Higgs decay and large missing transverse momentum (MET) from the DM production. Since this thesis focuses on dark Higgs decaying to a pair of b-tagged jets, the experimental signature for our search is one boosted double b-tagged jet from the dark Higgs decay together with large MET from escaping DM particles.

Two different searching methods have been investigated in this thesis: the large-radius mono-jet search and the more "generic" MET + jets search using the CMS α_T analysis. The former was carried out by the ATLAS experiment, searching for a large-radius jet containing at least two b-tagged sub-jets with large MET. The latter is based on a CMS search, searching for resolved b-jets with specific kinematic variables and large missing energy.

The reinterpretation of the large-radius search shows that signals with couplings according to the LHC recommendation can obtain significant exclusion limits. When the mass of the dark Higgs (m_s) is 50, 70 and 90 GeV, the mass of the Z' ($m_{Z'}$) up to 1800, 2000 and 1800 GeV are respectively excluded. The reinterpretation of the large-radius search shows that signals with couplings set to fulfil the DM relic abundance constraint can obtain significant exclusion limits. For $m_s = 50$, 70 and 90 GeV, $m_{Z'}$ up to 3300, 3450 and 3500 GeV are respectively excluded.

The reinterpretation of the CMS α_T search shows that signals with couplings according to the LHC recommendation cannot obtain significant exclusion limits. However, the reinterpretation of the α_T search shows that signals with couplings set to fulfil the DM relic abundance constraint can obtain significant exclusion limits. For $m_s = 50$, 70 and 90 GeV, $m_{Z'}$ up to 3600, 3700 and 3700 GeV are respectively excluded.

The two search methods are complementary in this 'Higgs Portal Dark Matter' model and they both probe significant regions of parameter space of the model. The CMS α_T search uses four variables to identify regions of phase-space that are sensitive to a large number of signals, resulting in many signal bins. The large-radius jet search only has one sensitive bin with variable mass windows to identify sensitive regions.

The presented analysis does not use a dedicated detector reconstruction but only applies a resolution smearing to physics objects in particular jets. A future improvement could be to change this and to generate signal samples with a dedicated detector reconstruction to obtain more accurate results.

The analysis presented in this thesis focuses on the dark Higgs s-channel $b\bar{b}$ decay. Searching for dark Higgs t-channel decay could be the next step.

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Appendices

A Exclusion limits at fixed m$_{\text{DM}}$ for different signal samples according to the large-radius mono-jet search

Figure A.1 to Figure A.4 are from signals with g_x =1 and $g_q = 0.25$. Figure A.5 to Figure A.10 are from signals with $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$.

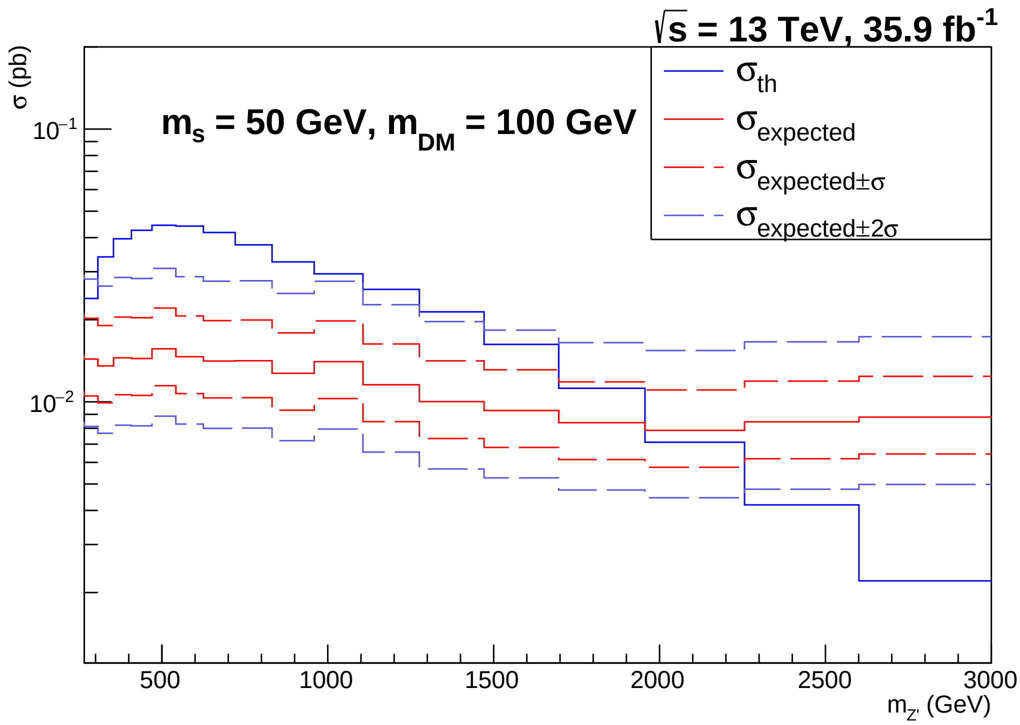

Figure A.1: Expected 95% CL limits for $m_s = 50$ GeV, $g_x = 1.0$ and $g_q = 0.25$ with $m_{\text{DM}} = 100$ GeV.

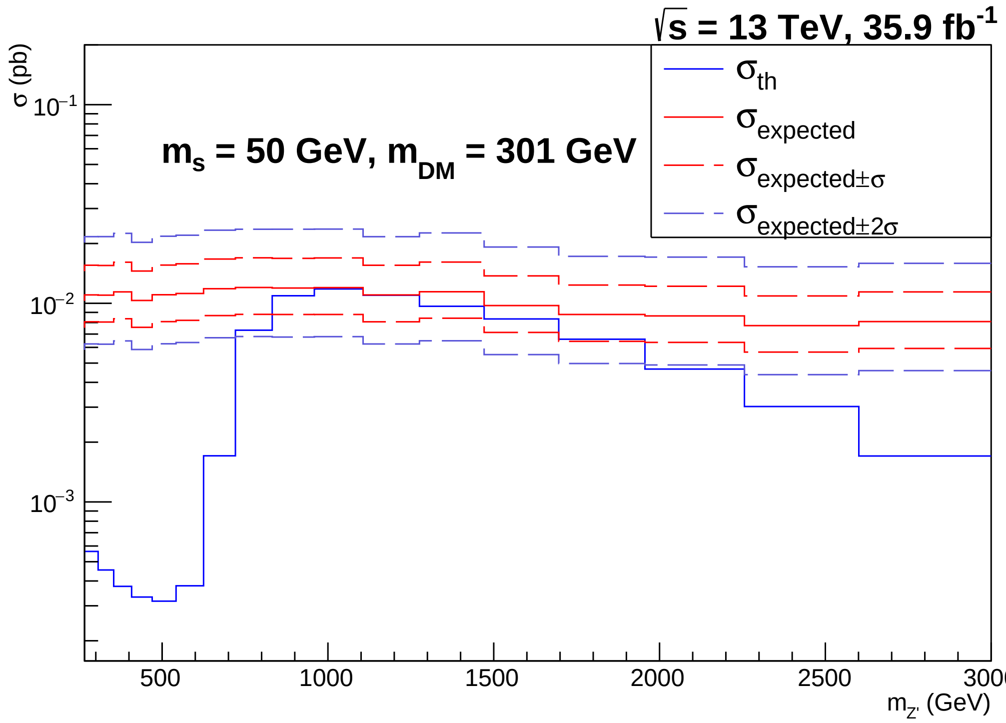

Figure A.2: Expected 95% CL limits for $m_s = 50$ GeV, $g_x = 1.0$ and $g_q = 0.25$ with $m_{\mathrm{DM}} = 301$ GeV.

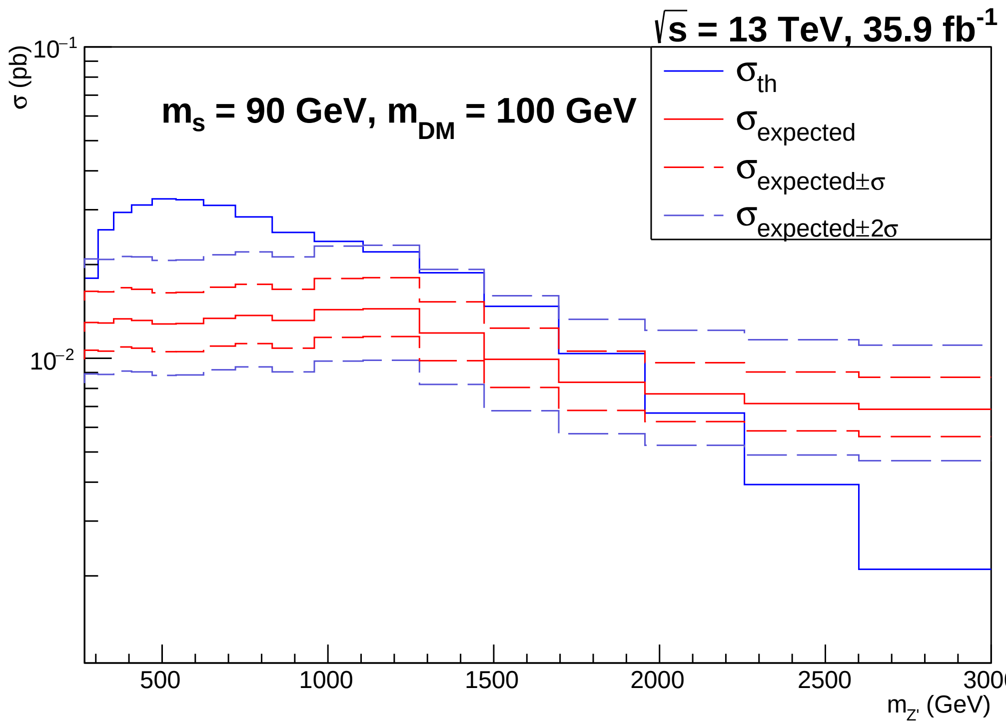

Figure A.3: Expected 95% CL limits for $m_s = 90$ GeV, $g_x = 1.0$ and $g_q = 0.25$ with $m_{\mathrm{DM}} = 100$ GeV.

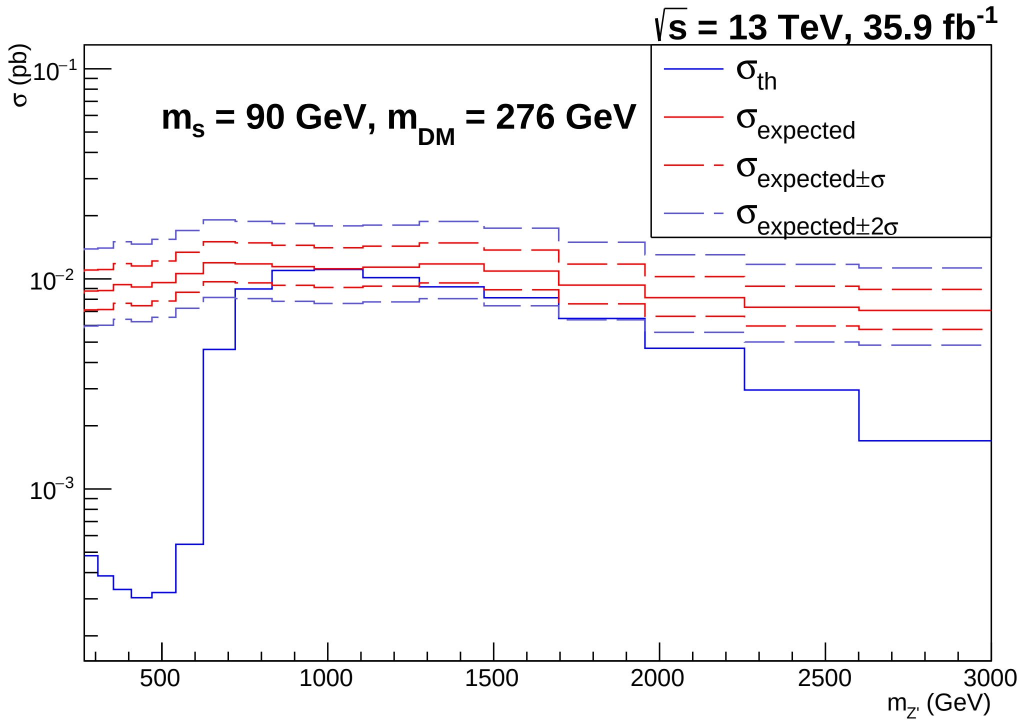

Figure A.4: Expected 95% CL limits for $m_s = 90$ GeV, $g_x = 1.0$ and $g_q = 0.25$ with $m_{\mathrm{DM}} = 276$ GeV.

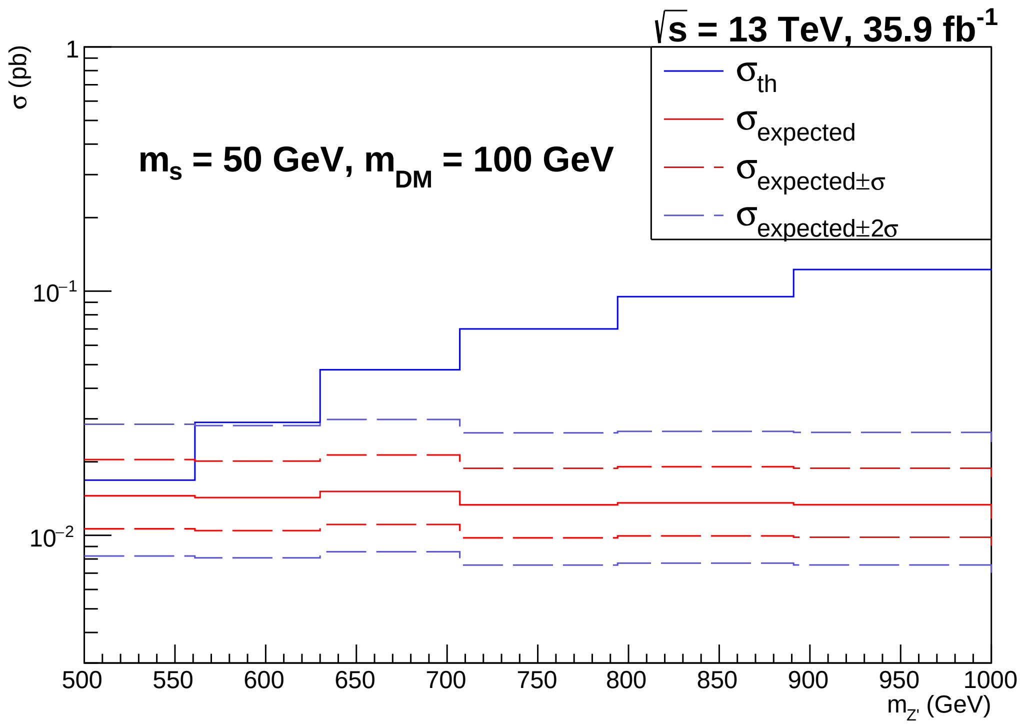

Figure A.5: Expected 95% CL limits for $m_s = 50$ GeV, $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$ with $m_{\mathrm{DM}} = 100$ GeV.

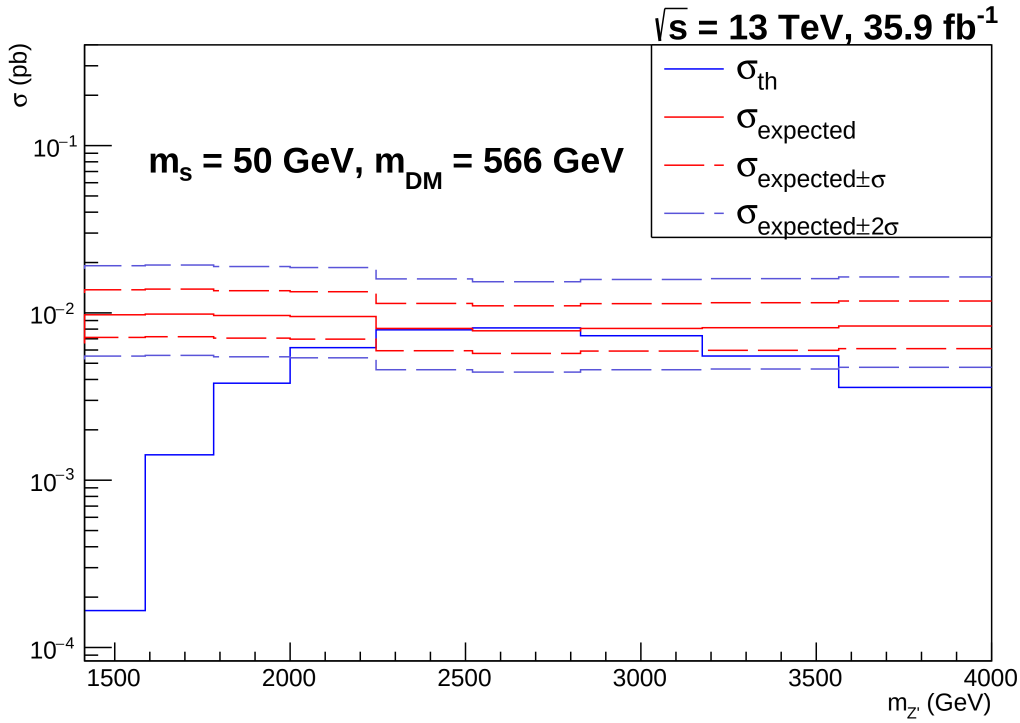

Figure A.6: Expected 95% CL limits for $m_s = 50$ GeV, $g_x < (4\pi)^{1/2}$and $g_q = 0.25$ with $m_{\text{DM}} = 566$ GeV.

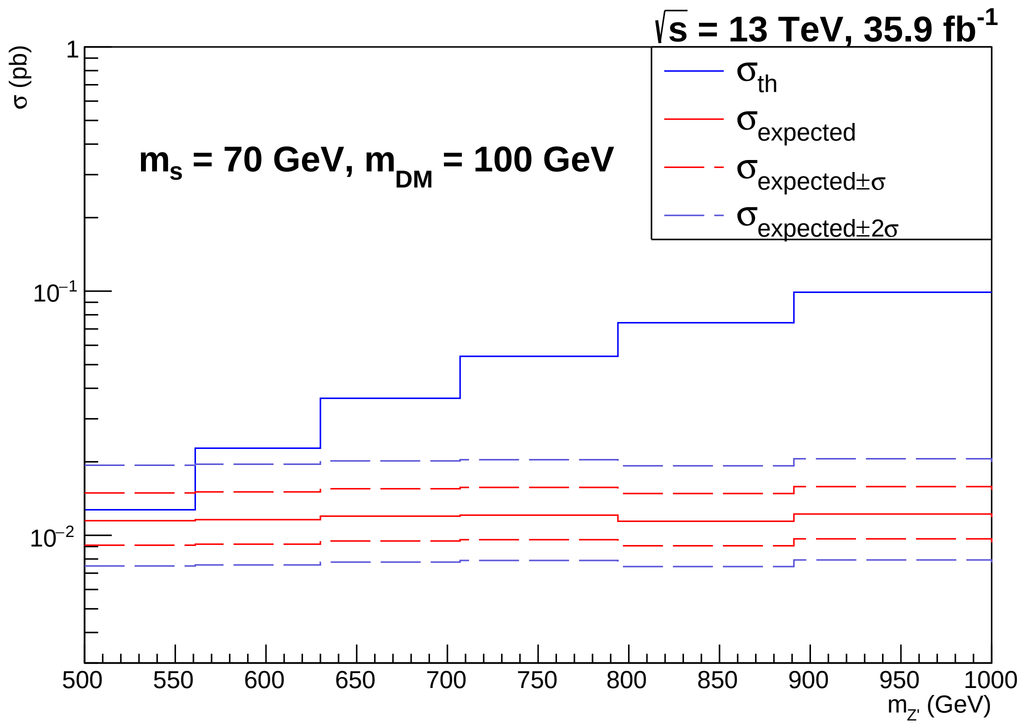

Figure A.7: Expected 95% CL limits for $m_s = 70$ GeV, $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$ with $m_{\text{DM}} = 100$ GeV.

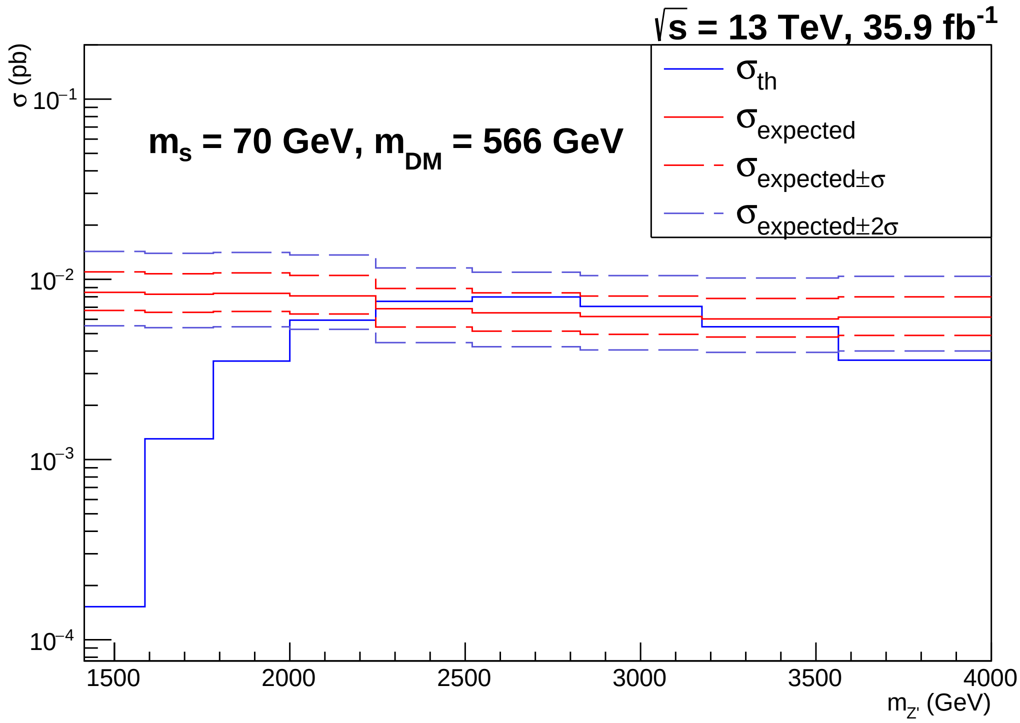

Figure A.8: Expected 95% CL limits for $m_s = 70$ GeV, $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$ with $m_{\mathrm{DM}} = 566$ GeV.

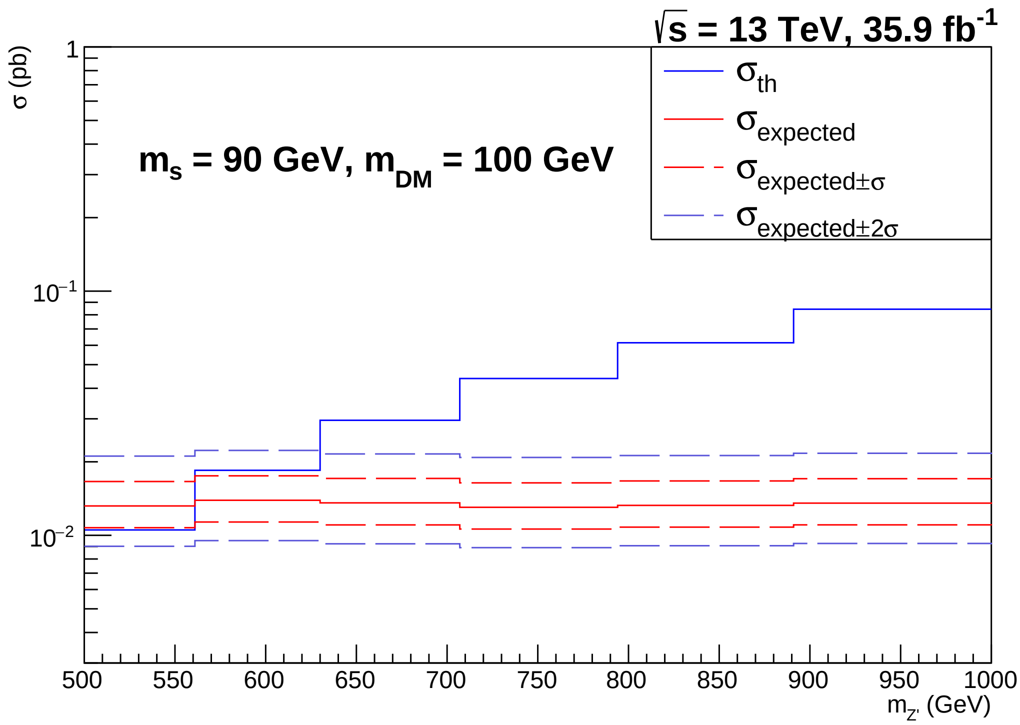

Figure A.9: Expected 95% CL limits for $m_s = 90$ GeV, $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$ with $m_{\mathrm{DM}} = 100$ GeV.

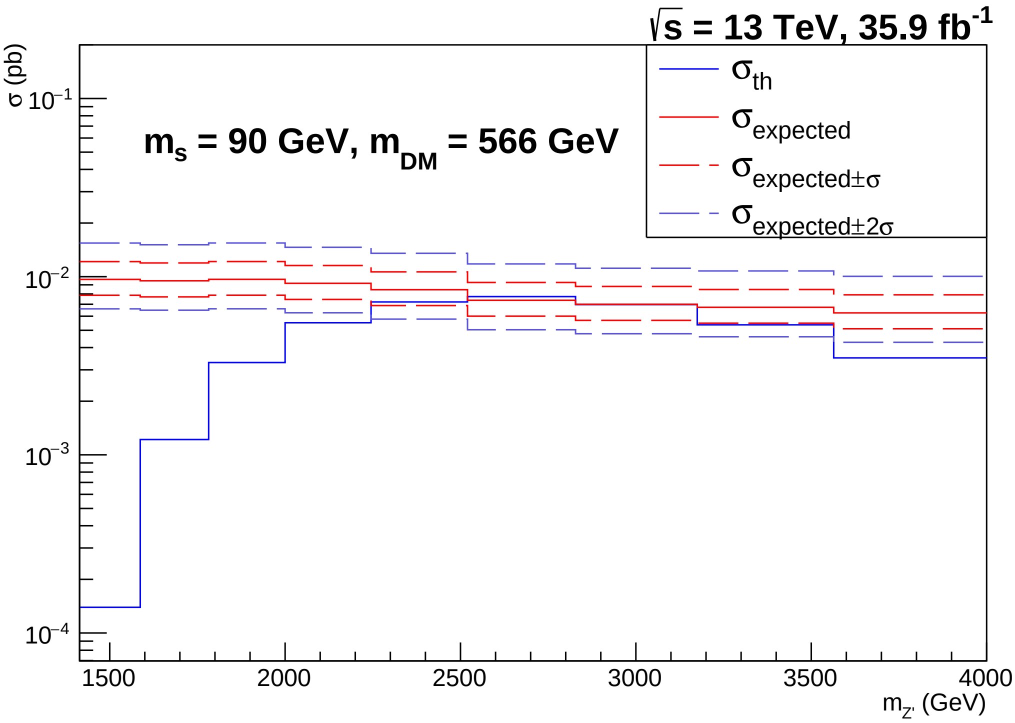

Figure A.10: Expected 95% CL limits for $m_s = 90$ GeV, $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$ with $m_{\rm DM} = 566$ GeV.

B Exclusion limits at fixed m_{DM} for different signal samples according to the α_T multi-jet search

Figure B.1 to Figure B.4 are from signals with $m_s = 50$ GeV, $g_x = 1$ and $g_q = 0.25$. Figure B.5 to Figure B.8 are from signals with $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$.

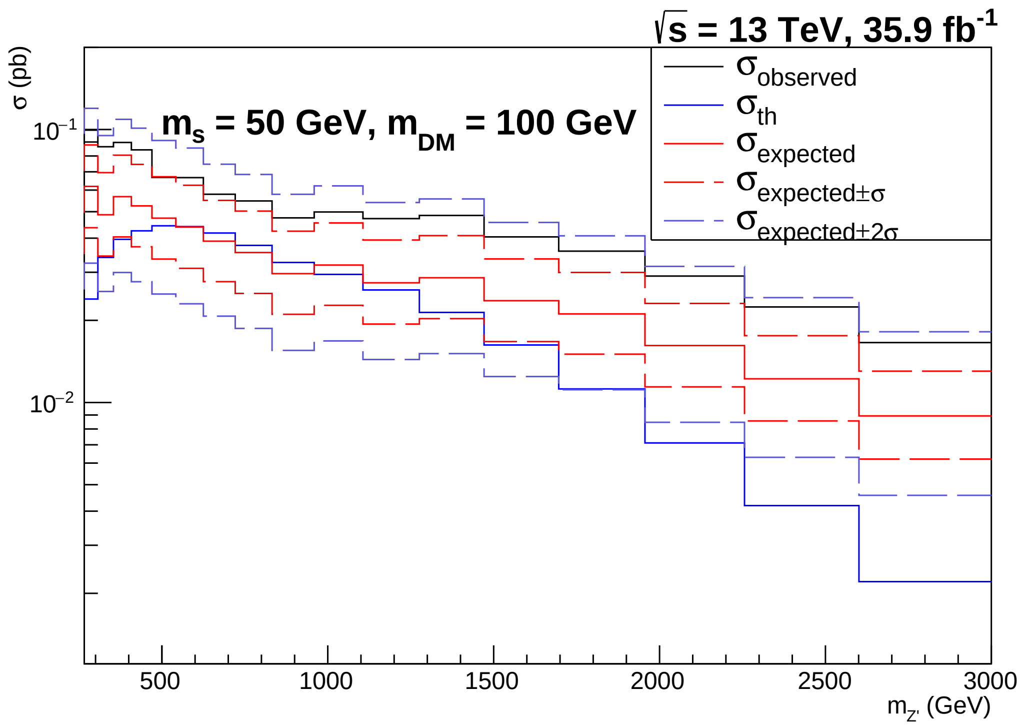

Figure B.1: Expected and observed 95% CL limits for $m_s = 50$ GeV, $g_x = 1.0$ and $g_q = 0.25$ with $m_{\mathrm{DM}} = 100$ GeV.

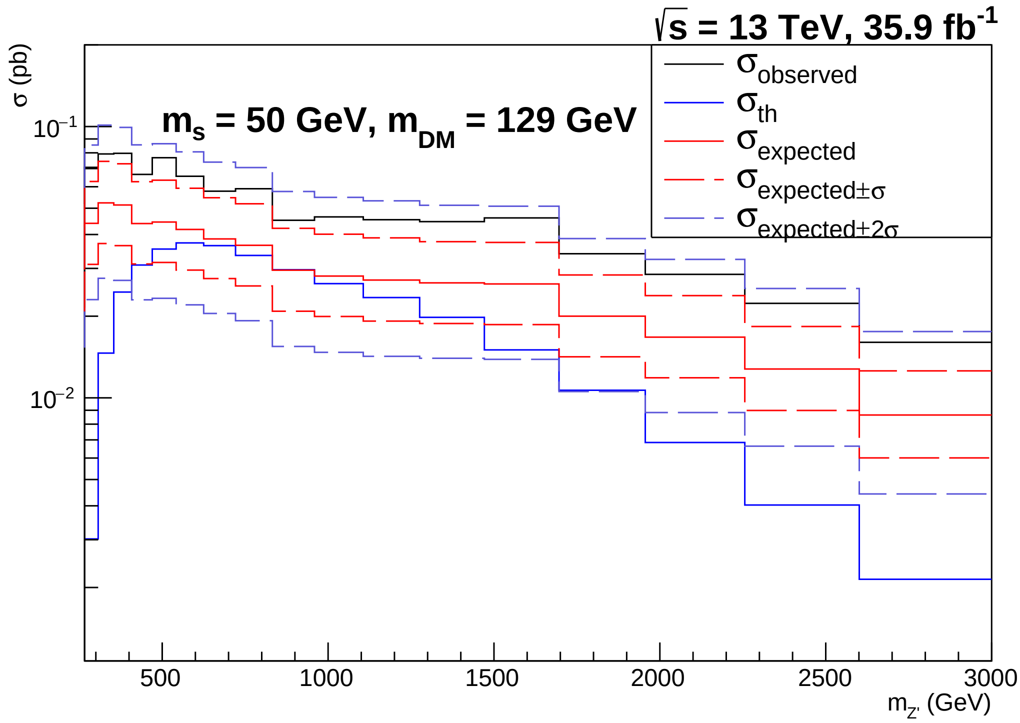

Figure B.2: Expected and observed 95% CL limits for $m_s = 50$ GeV, $g_x = 1.0$ and $g_q = 0.25$ with $m_{\mathrm{DM}} = 129$ GeV.

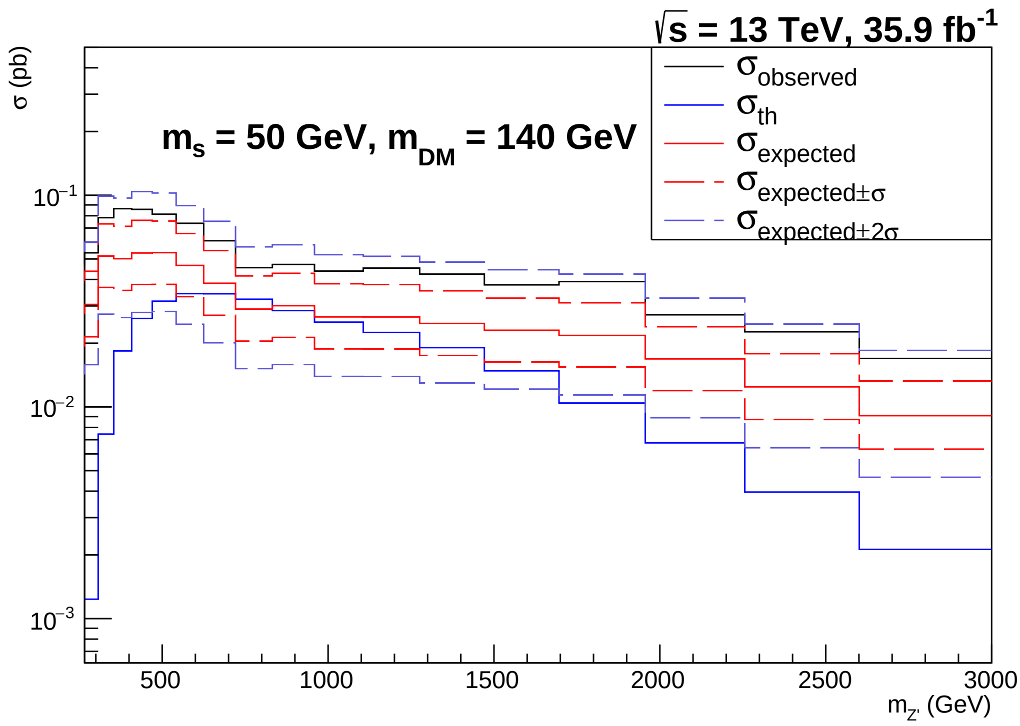

Figure B.3: Expected and observed 95% CL limits for $m_s = 50$ GeV, $g_x = 1.0$ and $g_q = 0.25$ with $m_{\mathrm{DM}} = 140$ GeV.

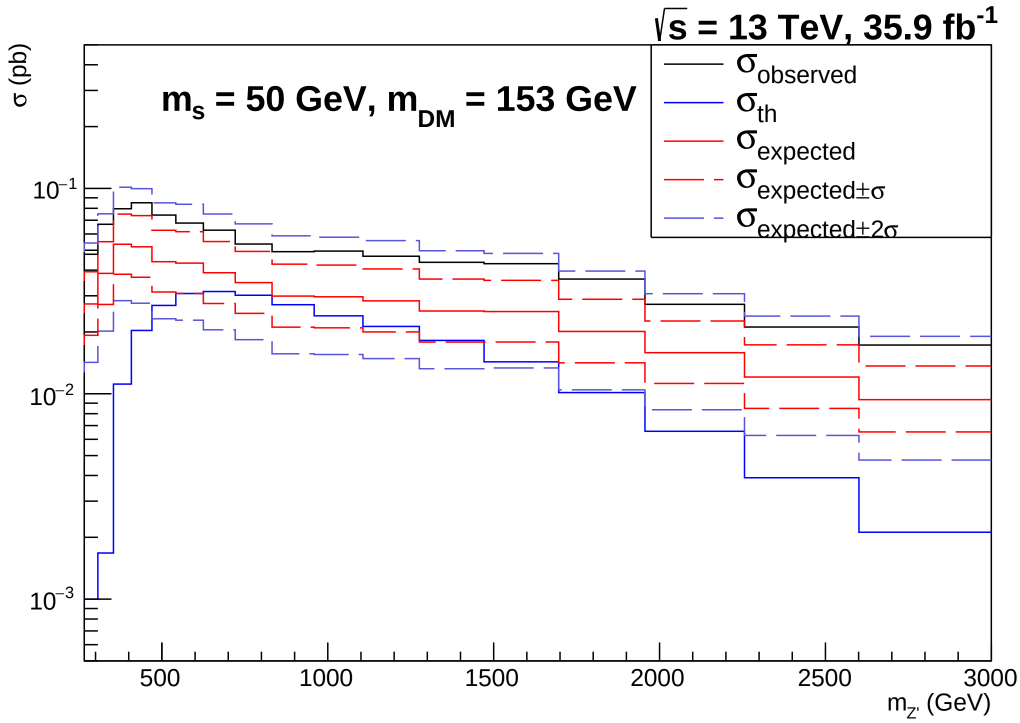

Figure B.4: Expected and observed 95% CL limits for $m_s = 50$ GeV, $g_x = 1.0$ and $g_q = 0.25$ with $m_{\rm DM} = 153$ GeV.

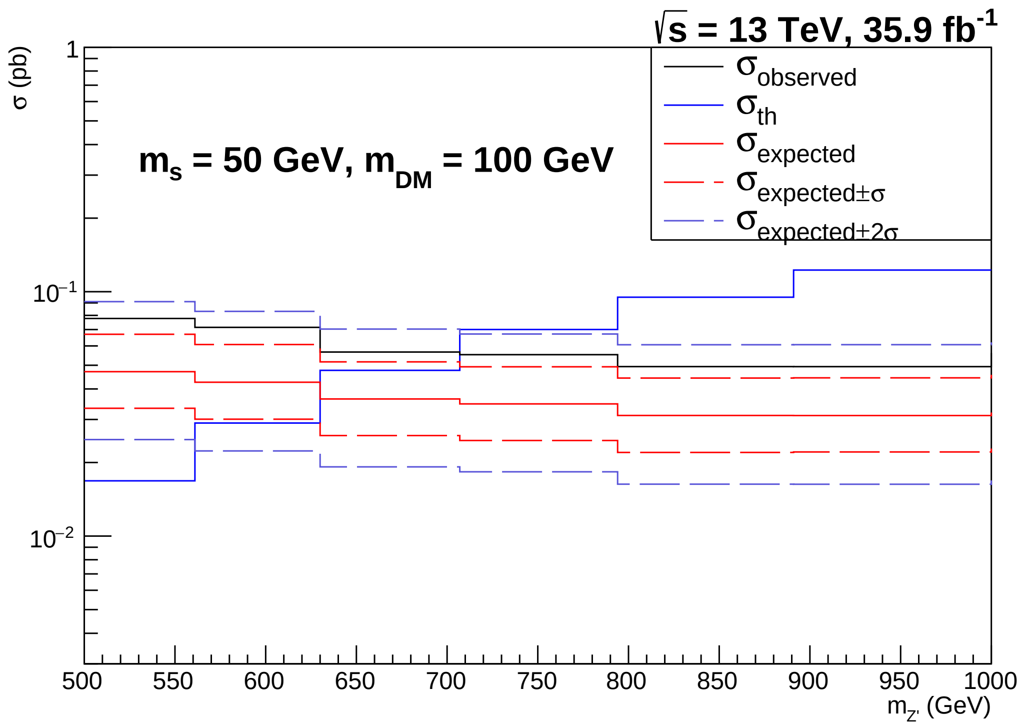

Figure B.5: Expected and observed 95% CL limits for $m_s = 50$ GeV, $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$ with $m_{\rm DM} = 100$ GeV.

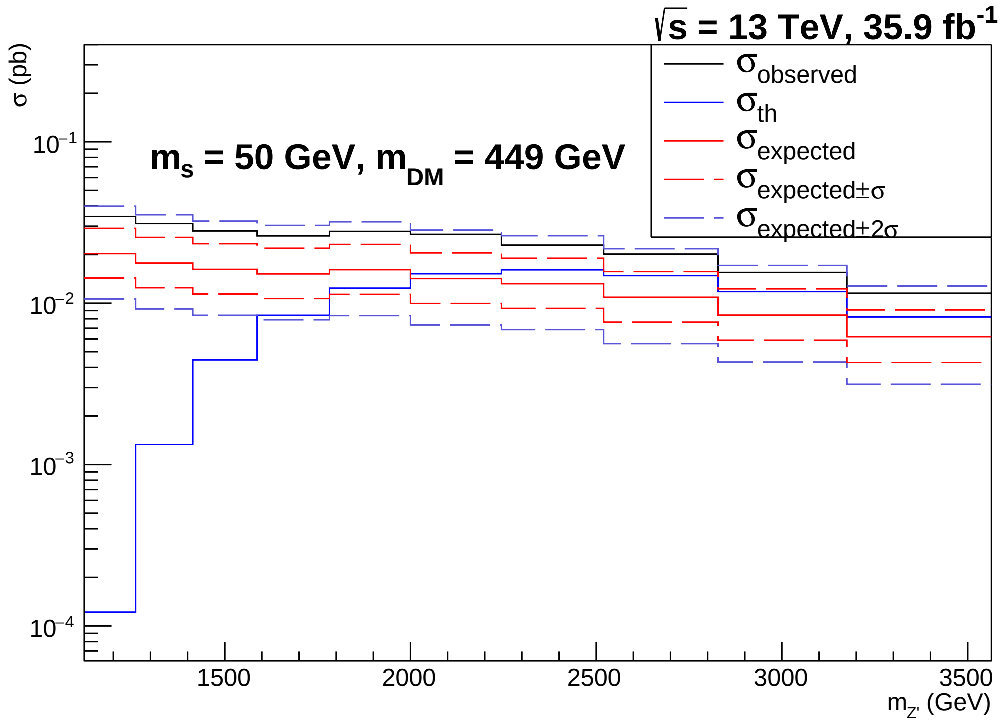

Figure B.6: Expected and observed 95% CL limits for $m_s = 50$ GeV, $g_x < (4\pi)^{1/2}$and $g_q = 0.25$ with $m_{\mathrm{DM}} = 449$ GeV.

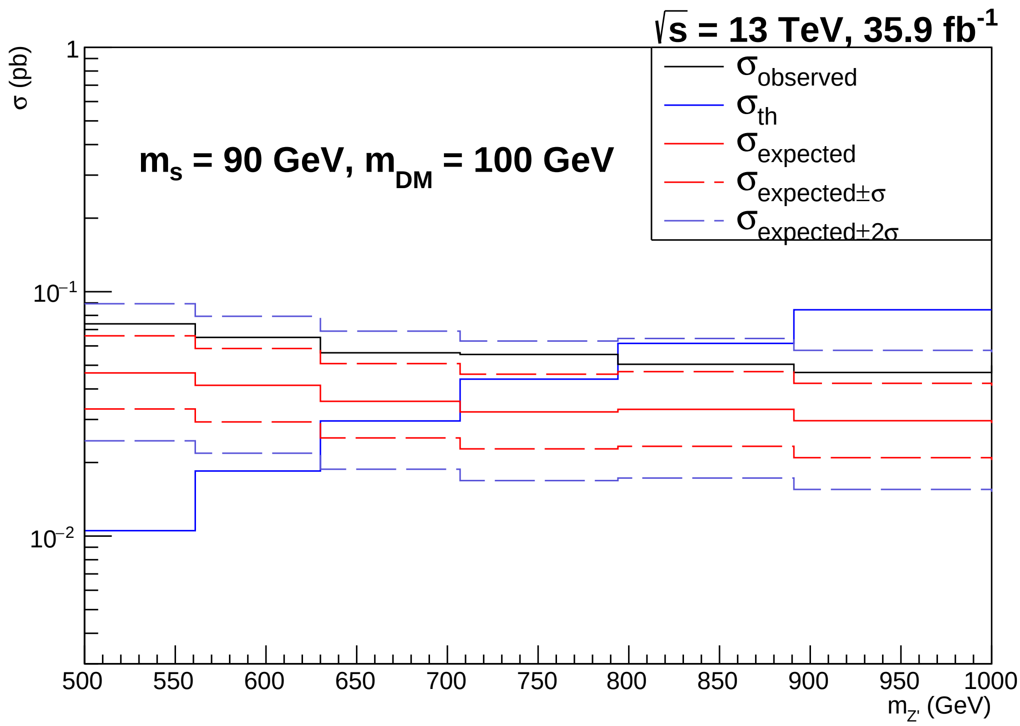

Figure B.7: Expected and observed 95% CL limits for $m_s = 90$ GeV, $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$ with $m_{\mathrm{DM}} = 100$ GeV.

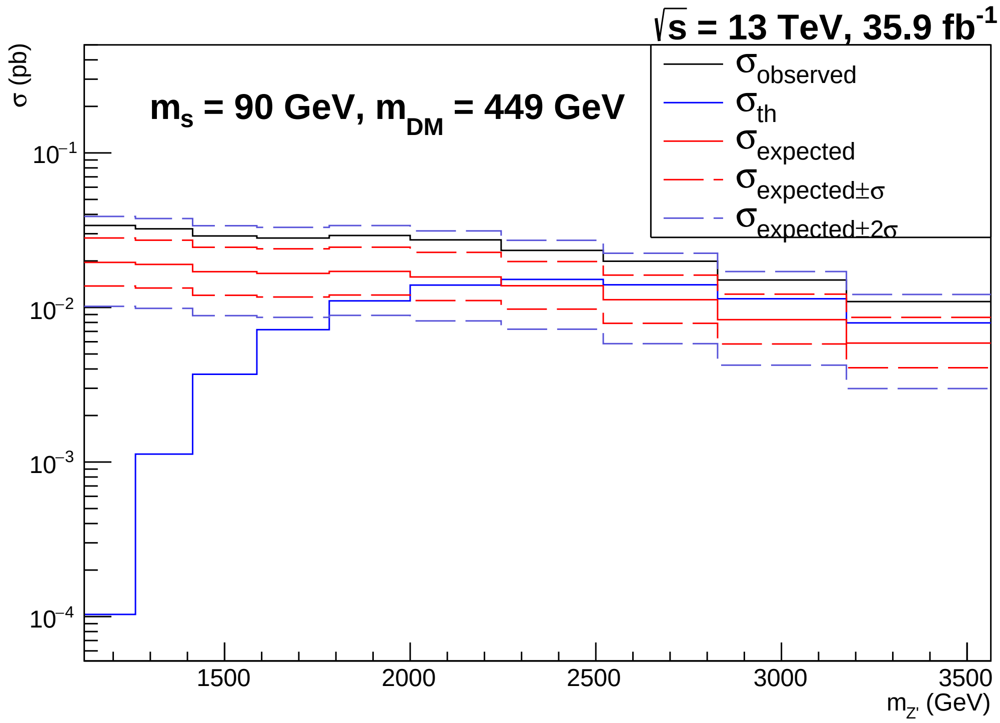

Figure B.8: Expected and observed 95% CL limits for $m_s = 90$ GeV, $g_x < (4\pi)^{1/2}$ and $g_q = 0.25$ with $m_{\text{DM}} = 449$ GeV.