
Hadronic Dark Matter Searches at CMS at $\sqrt{s} = 13 \text{ TeV}$

Searches for semi-visible jets and invisibly decaying Higgs bosons

By

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ABSTRACT

H ere goes the abstract

DEDICATION AND ACKNOWLEDGEMENTS

This work is dedicated to my grandfather, Dato' Mahindar Singh Bhal, who was able to begin this journey with me but sadly unable to finish it. There are far too many people and too little space to individually thank everyone who has accompanied me during this PhD, but I'll try my best.

Firstly, to my supervisor, Dr. Henning Flächer. Your advice and guidance over the course of this degree has been instrumental to achieving it, as well as encouraging my growth as a researcher.

Secondly, to all my colleagues at the University of Bristol. Very little would have been achieved without your help. From scientific discussions in the pub to pub discussions in the physics building, they have all been fruitful either directly or by helping me detach from work. Special thanks are in order to Simone and Sam Maddrell-Mander in my cohort, who have put up with my complaining during the stressful times.

To my friends from Monmouth that include my best friends in the world, Mike, James, Sneddon, (Mini) Sam, and Matt Bristow. You've been on this adventure with me since our school days and had my back the entire time. We've been through the highest, lowest, and most hilarious times together. I can definitively say I would not be the person I am today without you.

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AUTHOR'S DECLARATION

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.

SIGNED: DATE:

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INTRODUCTION

The universe, in all its vastness, structure, natural laws and chaos, is comprised of only three principal components: visible matter, the ingredients of stars, planets and life, is the only one we interact with on a regular basis; dark energy, a force or manifestation of something even more mysterious, responsible for the accelerating expansion of the universe, is almost entirely unknown; and dark matter, a substance invisible in all sense of the word, that binds galaxies together and influences large scale structure in the cosmos, is the focus of this thesis.

1.1 Evidence for dark matter

The earliest evidence for a large, non-luminous component of the galaxy stretches back to the 1920s when Jacobus Kapteyn attempted to explain the motion of stars in the Milky Way [25]. Since then, a wealth of independent astrophysical observations have reinforced the existence of this [mass] not just in our own, but in countless other galaxies and cosmological bodies. The Coma Cluster is a famous example: 90 % of its mass is thought to be [supplied] by dark matter, confirmed by its large mass-to-light ratio of $400 M_{\odot}/L_{\odot}$ [36]. [Other evidence] is that the rotation curves of most galaxies are roughly flat [29], contrary to the expected Keplerian curve ($v \propto 1/\sqrt{r}$) expected from solely visible matter. On a galactic scale, dark matter is sprinkled in a mostly spherical halo that spans beyond the observable disc. The inclusive dark matter mass increases linearly [17] to compensate for the decline expressed by visible matter [7, 19]. Gravitational lensing is another observational tool subject to be

influenced by dark matter. Images of galaxies and other objects captured by this method appear distorted from a large gravitational field between the source and observer warping its local spacetime [23]. Arcs, ellipses and Einstein rings of smeared galaxies are often seen when dark matter is present.

While there are no widely-accepted estimations, it is believed that 85–95 % of the Milky Way's is comprised of dark matter [4, 5, 24]. [Though] these [estimations] include non-visible identifiable matter such as dim stars, black holes and neutron stars, the term “dark matter” typically reserved for the non-luminous, *non-baryonic* matter that pervades the cosmos. From the latest results of the Planck mission, the energy density of the observable universe is composed of 26.5 % dark matter [2]. This result follows the Lambda cold dark matter (Λ CDM) model to describe the constituents and evolution of the universe, which is often referred to as the cosmological analog of the standard model of particle physics (SM). From the calculations, postulations, and observations presented above, the following properties of dark matter can be deduced:

- It is electrically neutral since it does not interact with electromagnetic radiation.
- It is cold (non-relativistic). Its velocity within galaxies is similar to the inhabiting stars [6, 22], since the combination of visible and dark matter drives the measured rotation curves. One small caveat is that galactic dark matter would be cold since a velocity above the gravitational escape velocity of the galaxy would eject high speed particles.
- It is stable, at least on the timescale of the current age of the universe. Dark matter production is postulated to have occurred only in the early universe via a thermal freeze out mechanism [REF theory section]. Hence, the remaining fraction has been present for a considerable time. Since most galaxies are dominated by dark matter and the gravitational influence from only the visible matter is too small to maintain itself, they could not have developed without it. This supports the idea of “bottom-up” structure formation in the universe; smaller galaxies form around gravitational potential wells provided by coalescing dark matter, then merge to form larger structures [35].
- Its interaction with matter and itself is very weak, or even non-existent. The Bullet Cluster – consisting of two colliding galaxies, is the best example of this inference. From measurements of predominantly x-ray emission and gravitational lensing, it was found that while there is substantial dark matter present, interaction with itself and the visible matter surrounding it was minimal at most [9]. A kinematic explanation for the spherical distribution and low velocity of dark matter in galaxies can be explained

by its collisionless nature. During the formation of a galaxy or stellar system, visible matter frequently collides, dissipating angular momentum and collapsing into a disc.

1.1.1 Alternative theories to dark matter

Though little is known about dark matter itself since all evidence stems from its gravitational influence, there are alternative theories that may explain the observations presented above. However, the scientific community can exclude many of these. Mismeasurements of the amount of baryonic matter such as neutrinos, neutrons, and interstellar gas are among the simpler propositions.

The neutrino flux from stars, as well as the cosmic neutrino background [34], are precise and well-tested [REF]. Even considering the upper limits on neutrino masses [27], they cannot make a significant contribution to the dark matter content in the universe. This is even discounting their highly relativistic nature, where myriad experimental evidence suggests dark matter is cold.

One can also use the Cosmic Microwave Background to calculate the average photon and neutrino densities, and Big Bang Nucleosynthesis calculations to determine the baryonic matter density (see Ref. 18 for results with the latest Planck mission data). These can be compared to other measurements, e.g., mass-to-light ratios averaged across the universe, to reveal a discrepancy [15].

Neutrons cannot contribute to dark matter because isolated neutrons are unstable, decaying in a matter of minutes [28]. Decay into charged protons and electrons, they interact strongly with light and therefore contribute to the luminous matter content.

Modified Newtonian dynamics (MOND) is a hypothesis that aims to explain phenomena typically associated with dark matter instead by modifications to Newton's laws of motion. There exist many theories and interpretations derived from this principle, though any one strand that tries to explain an observation usually fails to satisfy other phenomena or apply to length scales that general relativity may predict well. For example, observations of the Bullet Cluster [9] have discredited many popular MOND models.

1.2 Overview of dark matter searches

While observational evidence has so far lain with astrophysics, a theoretical description and discovery of dark matter may fall into the realm of particle physics with the numerous, novel

experimental searches underway. The detection of dark matter can be classified into three distinct methods with unique signatures (with a visual summary in Fig. 1.1):

- **Direct:** dark matter may interact with visible matter on small scales, scattering SM particles [31]. The recoil these SM particles experience could be detected by highly-sensitive, low background experiments such as LUX-ZEPLIN (LZ) [3] that specialises in the search for WIMP dark matter at a large range of masses.
- **Indirect:** if dark matter interacts with itself, it may annihilate to produce showers of high energy photons or pions. Background estimation is difficult since the signatures can be highly model-dependent. The photons may be of a continuum – from hadronisation and radiation of the decay products – or contain features, such as internal radiation from the propagator in the interaction or from loop-level processes [14]. Large ranges of the annihilation cross section and dark matter mass can be probed with telescopes already searching for these [signatures].
- **Production:** dark matter may have been abundantly produced in the hot, early universe. High energy particle accelerators such as the LHC can reproduce these conditions, with the WIMP miracle (see Sec. 2.3) reinforcing the [fact dark matter may exist in these accessible mass ranges]. Many beyond the standard model (BSM) theories accommodate dark matter candidates with a diverse spectrum of final states that can be investigated by analysing LHC data.

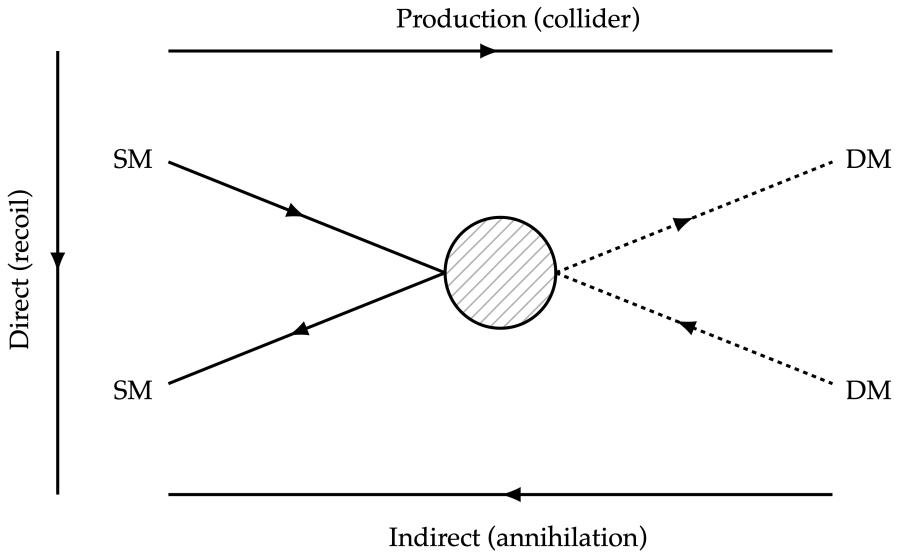


Figure 1.1: A visual representation of the three main types of dark matter detection: direct (dark matter recoiling from standard model particles); indirect (annihilation of dark matter); and production (dark matter created in high energy physics collisions).

1.2.1 Dark matter searches at the LHC

Since its detection at the CMS experiment from the production mechanism is the focus of this thesis, it is important to establish the current state of dark matter searches at the Large Hadron Collider (LHC), the world's most powerful particle accelerator that provides data for CMS. Both machines are described in detail in Sec. 3, and as such only a summary will be provided here. The LHC principally collides protons at centre of mass energies up to $\sqrt{s} = 13$ TeV. These [absurdly] high energies allow the conditions in the very early universe to be simulated in which heavy, unstable particles were created in abundance. As such, many theories can be investigated that postulate heavy particles that do not exist in the universe today. Some of these, such as supersymmetry (SUSY) [26], sterile neutrinos [16], and Kaluza-Klein states [20] contain dark matter candidates that can be specifically searched for, or indirectly discovered if a theory is experimentally proven. Despite the standard model providing precise predictions of three of the four fundamental forces and the particles that they interact with, it does not substantiate the existence of dark matter; hence why BSM theories are popular. Fig. 1.2 illustrates the masses and interaction cross sections of many dark matter candidates. WIMPs (highlighted by the purple rectangle) are the subject of many searches at the LHC since the expected mass ranges and cross sections are accessible there.

Two avenues are usually considered when attempting to discover dark matter: explicit searches for the signatures of dark matter production, and anomalies in precision measurements. The former is quite common, with many theories and models tested at the LHC's general purpose detectors, ATLAS and CMS.

There is significant motivation to study dark matter from a wider, as well as a more personal, viewpoint. It is important to understand how the universe operates, and dark matter opens up the potential for new physics that improves our understanding of nature. My personal interests include the blend of particle physics and astrophysics, and the opportunity to discover and add to humanity's collective wisdom. With 137 fb^{-1} from CMS during Run-2 at $\sqrt{s} = 13$ TeV, there is great potential to constrain some of the properties of dark matter. This thesis showcases the motivation for, and results of, searches for invisibly decaying Higgs bosons and semi-visible jets with the full Run-2 dataset collected by the CMS experiment.

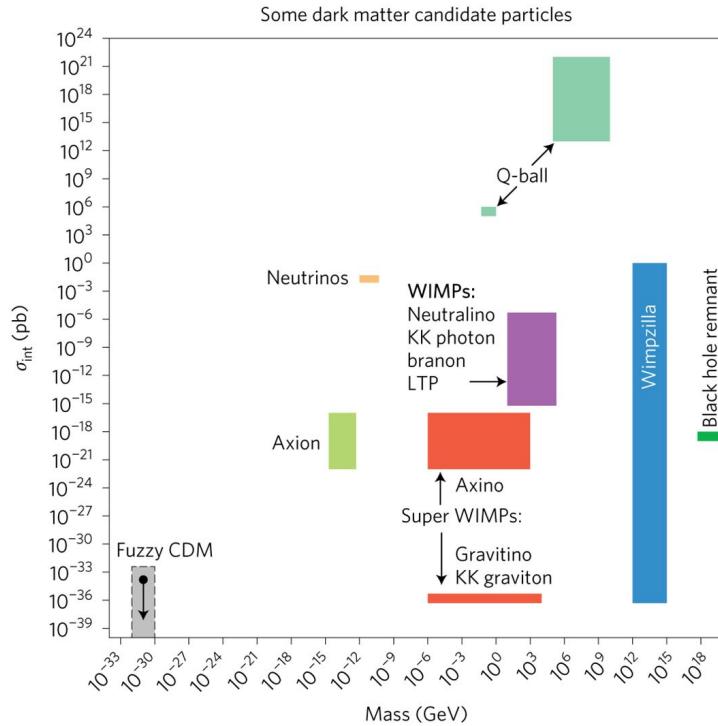


Figure 1.2: The expected masses and interaction cross sections of some dark matter candidates. The centre of mass energy of the LHC is best suited to targeting WIMPs. Figure acquired from Ref. 14.

- Discuss dark matter: motivation, evidence for its existence (and why it can't be neutrinos/dead stars/interstellar debris, etc.), detection methods and how we can probe it at the LHC (production).
- Briefly outline particle accelerators and their function, the fact that we can use them to potentially discover dark matter or infer more of its properties, and the models that will be discussed in more detail to try and achieve this outcome.
- The introduction probably doesn't need to be too long, maybe only a few pages. Compare length with other people's theses (ask Ben Krikler for a copy of his, look at Alex's and Lana's).

THEORY

This is the theory chapter.

– Give an overview of the fundamental forces and particles.

- Discuss the Standard Model in detail, emphasising certain aspects as they relate to dark matter and the Higgs field (and boson).
- Briefly recap dark matter, referencing descriptions in introduction. But go into more theoretical descriptions and motivations and how they relate to potentially discovering it at the LHC (WIMP miracle).
- Discuss the theory behind combined Higgs to inv.: only SM process in which Higgs decays invisibly is $H \rightarrow ZZ \rightarrow 4\nu$ with branching ratio of 0.1 % [21], whilst the current observed experimental limit is 19 % from CMS [33] and 26 % from ATLAS [1]. If new, invisible particles couple to Higgs, branching ratio will be enhanced. Constraining \mathcal{B} can also exclude some dark matter models.
- Discuss the theory behind the semi-visible jets analysis (main sources from Refs. 10, 11): strongly interacting dark sector in Hidden Valley scenario with a portal to the visible sector. Mentioning dark quarks χ , dark confinement scale Λ_{dark} , dark hadronisation and decay, running coupling α_{dark} , etc.
- Explain some of the phenomenological/experimental event characteristics that overlap with both analyses, i.e., what a jet is, and maybe energy sums like p_T^{miss} , H_T , H_T^{miss} , etc.

2.1 The standard model of particle physics

2.2 Limitations of the standard model

2.3 Theoretical motivations for, and descriptions of, dark matter

2.3.1 Measuring the branching ratio for the invisible decays of the Higgs boson

2.3.2 Searches for semi-visible jets

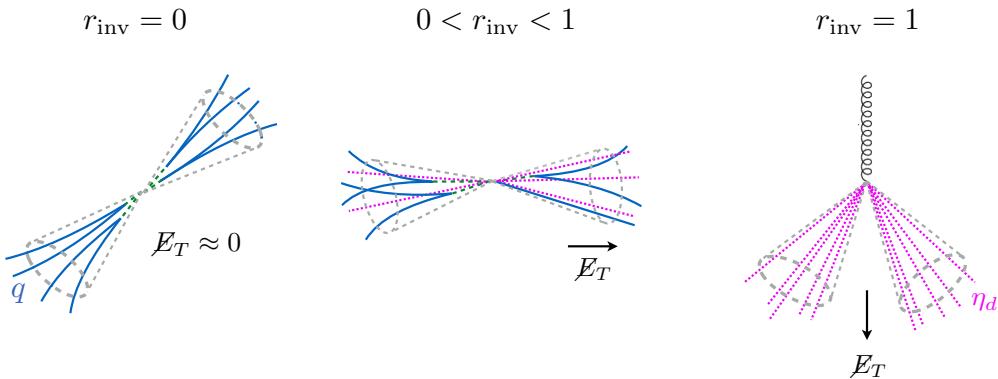
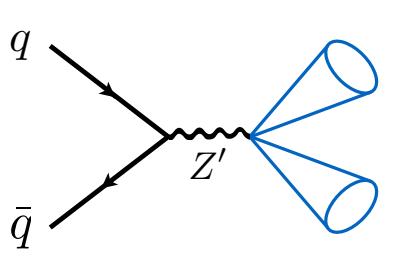
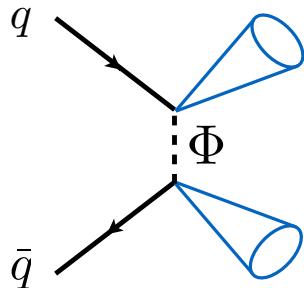


Figure 2.1: The typical direction of the missing transverse energy \cancel{E}_T (or p_T^{miss}) relative to the semi-visible jets as a function of their invisible fraction r_{inv} [11].



(a) s -channel



(b) t -channel

Figure 2.2: Example Feynman diagrams for the two main production modes of semi-visible jets [11]. A Z' boson mediates the s -channel process while a bifundamental Φ mediates the t -channel process.

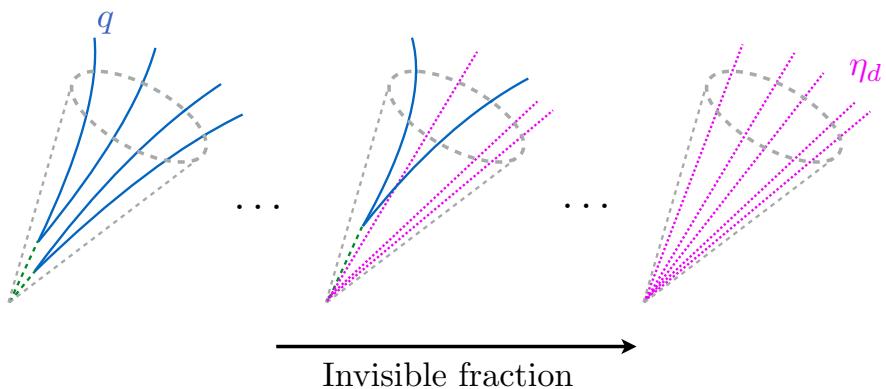


Figure 2.3: The constituents of a semi-visible jet as a function of its invisible fraction r_{inv} [11].

THE LHC AND THE CMS EXPERIMENT

This is the detector chapter.

- Explain CERN and the LHC in more detail.

- Give an overview of the CMS experiment and detector (including all subsystems, object identification, algorithms for event/object reconstruction like Particle Flow and anti- k_T algorithm, and algorithms for tagging objects like b -jets). Explain geometry as well (ϕ , η – with a description (angle between particle/object and beam axis) and equation, also noting the boundaries between barrel, end cap and HF).
- As a subsection in this chapter, discuss the Level-1 Trigger in depth. Emphasise the jet and energy sum triggers as I've worked on them, and Calorimeter Layer-2 for the same reason. Tie into SVJ and Hinv since they're hadronic searches.

3.1 The Large Hadron Collider

Deep underground beneath the Franco-Swiss border lies the Large Hadron Collider (LHC), a synchrotron particle accelerator 27 km in circumference. Predominantly a proton collider, lead and xenon ions have also been injected for novel and unique studies. Four principle experiments are situated at their own interaction points where the two beams of particles are brought into contact: CMS (Compact Muon Solenoid), a general purpose detector with interests in precision measurements, searches for new physics, and many other avenues; ATLAS (A Toroidal LHC ApparatuS), another general purpose detector with similar aims to

CMS; LHCb, designed to study the decay of B hadrons; and ALICE (A Large Ion Collider Experiment), primarily studying heavy ion collisions and the quark-gluon plasma.

The LHC began operating in 2010 at a centre of mass energy of $\sqrt{s} = 7 \text{ TeV}$ (teraelectron volts), 3.5 TeV per beam. A modest increase to 8 TeV was achieved by the end of Run-1 in 2013. After upgrades were performed, the LHC resumed operation in 2015, further pushing the frontiers of high energy physics with a centre of mass energy of $\sqrt{s} = 13 \text{ TeV}$. While valuable data was taken, it was not until 2016 when Run-2 of the LHC began. This period ended in 2018 with 158.64 fb^{-1} of pp collisions delivered, 146.45 fb^{-1} of which were recorded by CMS who certified 137.19 fb^{-1} suitable for analysis [12, 13]. A breakdown by year is presented in Tab. 3.1.

Integrated luminosity	2016	2017	2018	Full Run-2
Delivered by LHC (fb^{-1})	40.99	49.79	67.86	158.64
Recorded by CMS (fb^{-1})	37.80	44.98	63.67	146.45
Certified by CMS (fb^{-1})	35.92	41.53	59.74	137.19

Table 3.1: The integrated luminosity delivered by the LHC during Run-2 which were recorded and certified by CMS. Numbers obtained from Refs. 12, 13.

3.2 The CMS experiment

3.2.1 Jet energy corrections in the Level-1 Trigger

Jet energy corrections (JEC) are necessary to compensate for various losses when recording jet properties in the trigger. These losses depend on the transverse momentum p_T and pseudorapidity η . The calibrations ensure that the performance of the trigger is uniform across the detector. Firstly, some ideal (or reference) jets are needed to compare against given L1 jets. Since Monte Carlo datasets are used for the calibrations, the reference jets we use are the generator-level jets (or GenJets). These are stable, simulated particles clustered with the anti- k_T algorithm algorithm [8] to form the jet. The state of these jets are post-hadronisation, before detector interaction. L1 jets need to be matched against the GenJets. From there, various studies can be performed such measuring the response ($\langle p_T^{\text{L1}} / p_T^{\text{ref.}} \rangle$) of the detector, and its position and energy resolutions.

Once Calorimeter Layer-1 experts have derived scale factors for the physics objects, they are applied in Layer-2 where the calibrations are conducted. For jets, ntuples are created from the specified dataset and the L1 jets are matched to the GenJets using the variable ΔR :

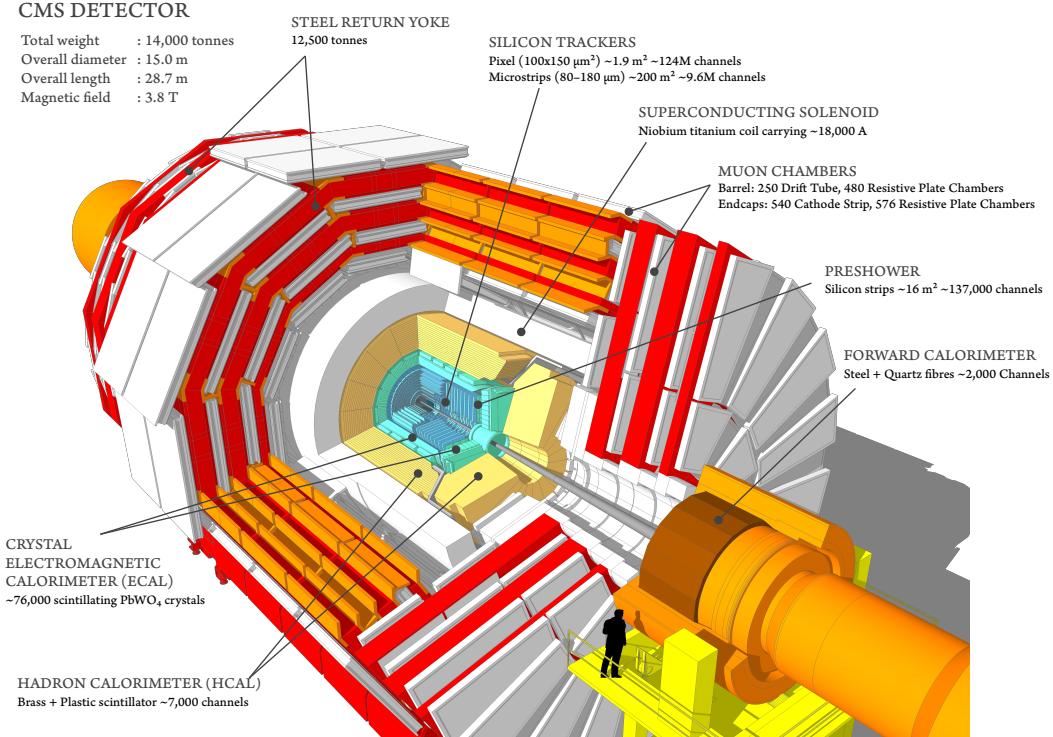


Figure 3.1: A cutaway diagram of the CMS detector with all of the principal components labelled. This detector configuration was used for the 2017–18 data taking years, where the coverage of the pixel detectors in the silicon tracker were upgraded from 1 m^2 (66 million channels) to 1.9 m^2 (124 million channels). Image taken from Ref. 30.

$$(3.1) \quad \Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

where ϕ is the azimuthal angle of the jet. The algorithm used to match the jets does so by inspecting each L1 jet in descending p_T and searching for a reference jet with $\Delta R < 0.25$. If there is more than one match, the reference jet with the smallest ΔR is taken. Then the next L1 jet (and so on) follows the same procedure, with the previous reference jet removed from the matching collection. Calibrations are then derived. The reciprocal of the response vs. p_T^{L1} is plotted for each $|\eta|$ bin and correction curves are fitted to them (see Fig. 3.5). Once tuned such that the fit captures the low- p_T spike and high- p_T plateau, closure tests are conducted as the final step. The ntuples are remade with JECs and then matched with the reference jets to check that the calibrations have been properly applied. Plots such as Fig. 3.6 are then passed to the Trigger Studies Group to check over and continue the chain of trigger corrections and object calibrations.

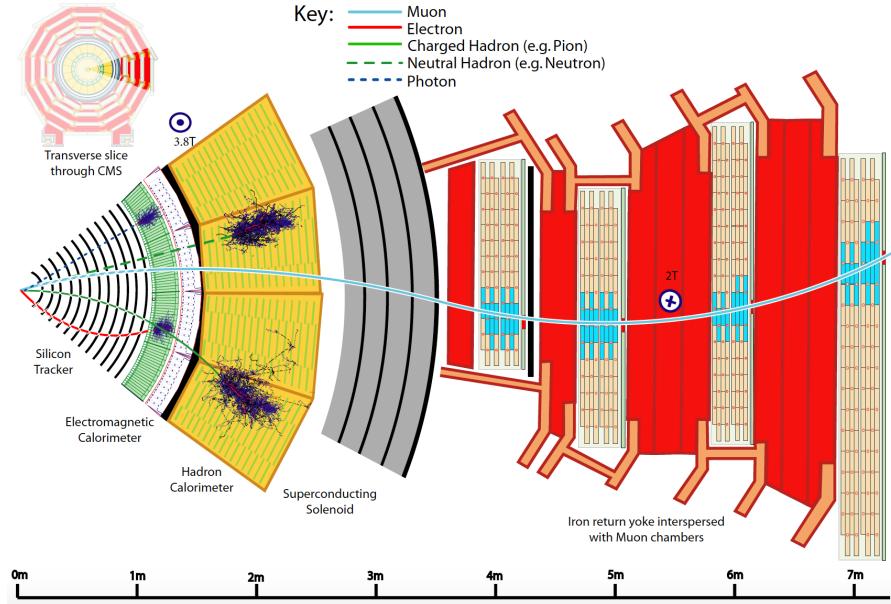


Figure 3.2: A transverse slice through the CMS detector with the main subsystems and components visible (figure obtained from Ref. 32). Several particles produced at the primary vertex and their interactions with the detector are also depicted.

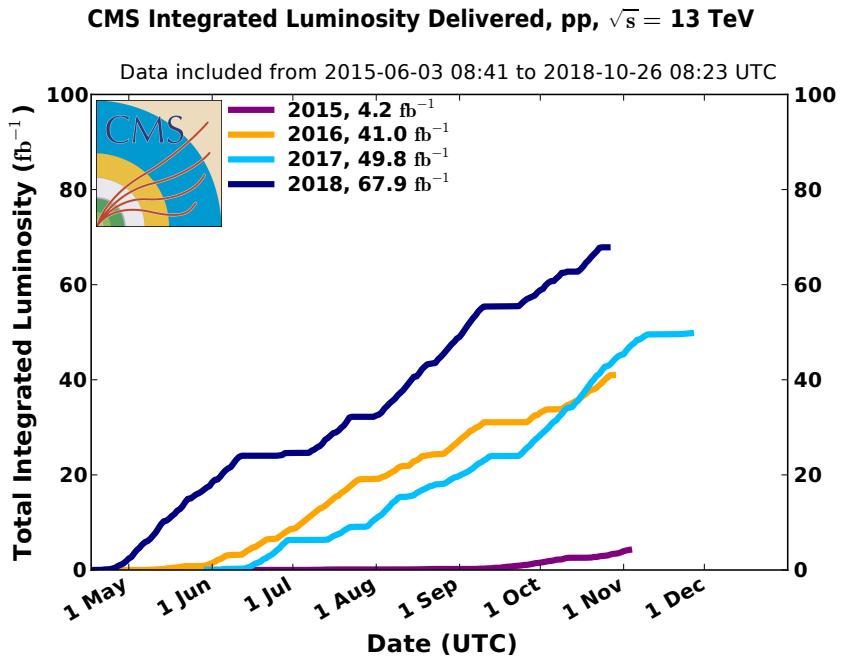


Figure 3.3: The integrated luminosity of pp collision data collected by CMS during 2015 and Run-2 of the LHC. Figure obtained from Ref. 12.

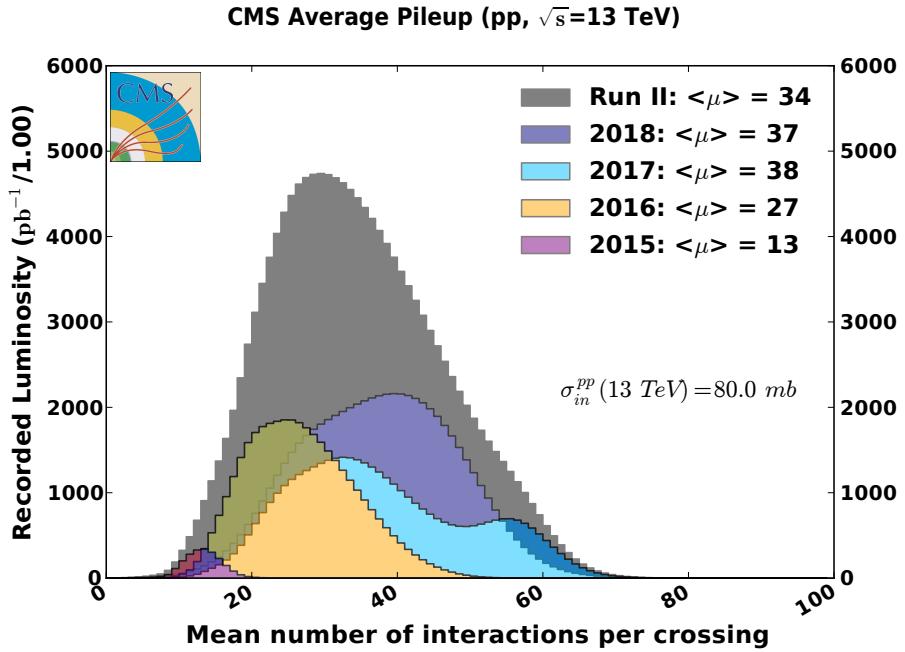


Figure 3.4: The average number of pileup interactions at CMS during 2015 and Run-2 of the LHC. Figure obtained from Ref. 12.

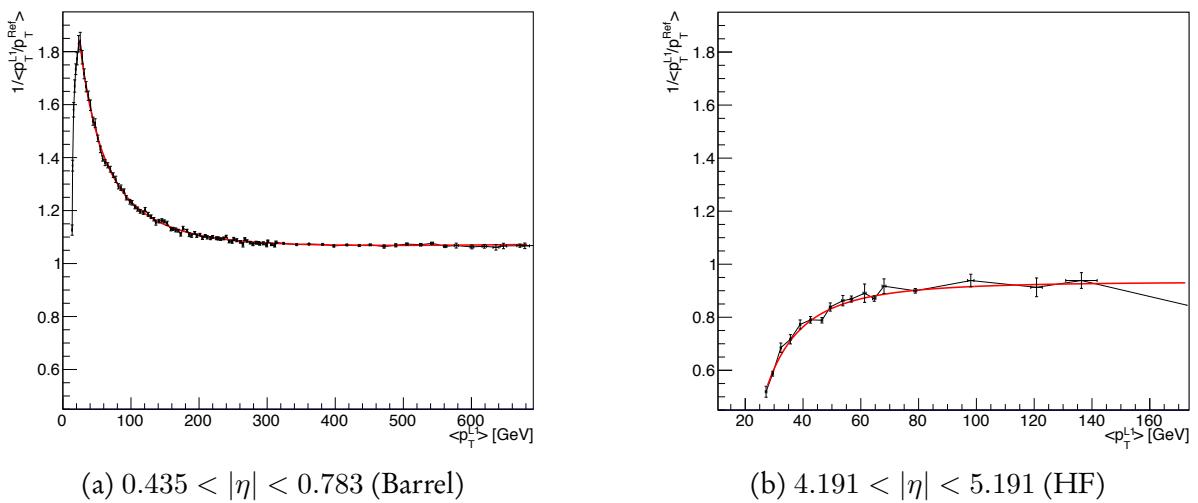


Figure 3.5: Examples of correction curves used to calibrate the jet energies in two $|\eta|$ bins. The response is plotted against the p_T of the Level-1 jet and a complex function produces a fit. These plots are from the jet energy corrections performed on 2018 QCD Monte Carlo.

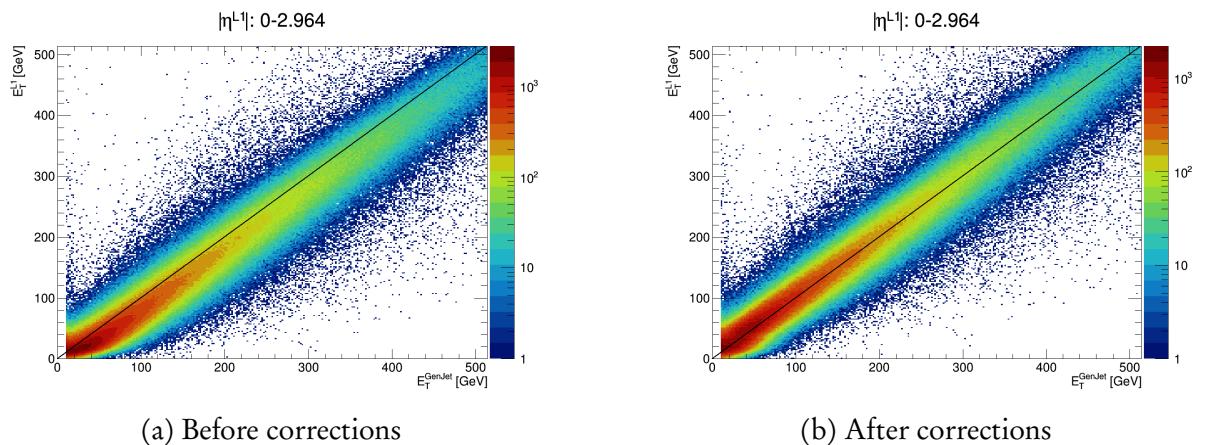


Figure 3.6: The energies of matched pairs of jets in the entire barrel and end cap, before and after jet energy corrections have been applied. After calibrations, the distribution is much more symmetrical. An equivalent plot using jets from LHC data is expected to look similar after applying these calibrations.

COMBINED SEARCH FOR THE INVISIBLE DECAY OF THE HIGGS BOSON IN HADRONIC CHANNELS

This is the analysis chapter on $H \rightarrow \text{inv.}$.

Discuss how the theoretical aspects from the Theory chapter translate into an experimental search.

- Discuss the necessity of including all production modes of Higgs (invisible final state, so characterise events based on initial/additional particles). Also mention how sensitive each production mode is at contributing to the branching ratio limit. Emphasise the non-VBF modes (ggF , $t\bar{t}H$, $VH - W^+H$, W^-H , ZH) in this chapter as that's what I've been working on and another student will be covering VBF.
- Talk about what makes this analysis unique: doing a combination over all production modes from the start instead of separate analyses combined at the end. Means we can share samples, systematics, background methods and workflows, build in orthogonality between the different modes and cover as much phase space as possible (with new final states such as boosted Z bosons with unresolved subjects). This makes the analysis much more cohesive and consistent.
- Include object definitions, overall analysis strategy, triggers, signal production (with each non-VBF mode in detail), event selection, background estimation and results/limit (including comparisons to previous results).
- Emphasise my contributions: control region construction and studies, background estimation, and other studies I will have conducted by the time I write up.

- Current material: no public plots as of yet. Hope to finish analysis by the time I begin writing up. We are preparing a CMS internal analysis note, documenting all aspects of the analysis. I will add all relevant information there which I can subsequently use when writing this chapter.

4.1 Analysis overview

4.1.1 Hadronic production modes of the Higgs boson

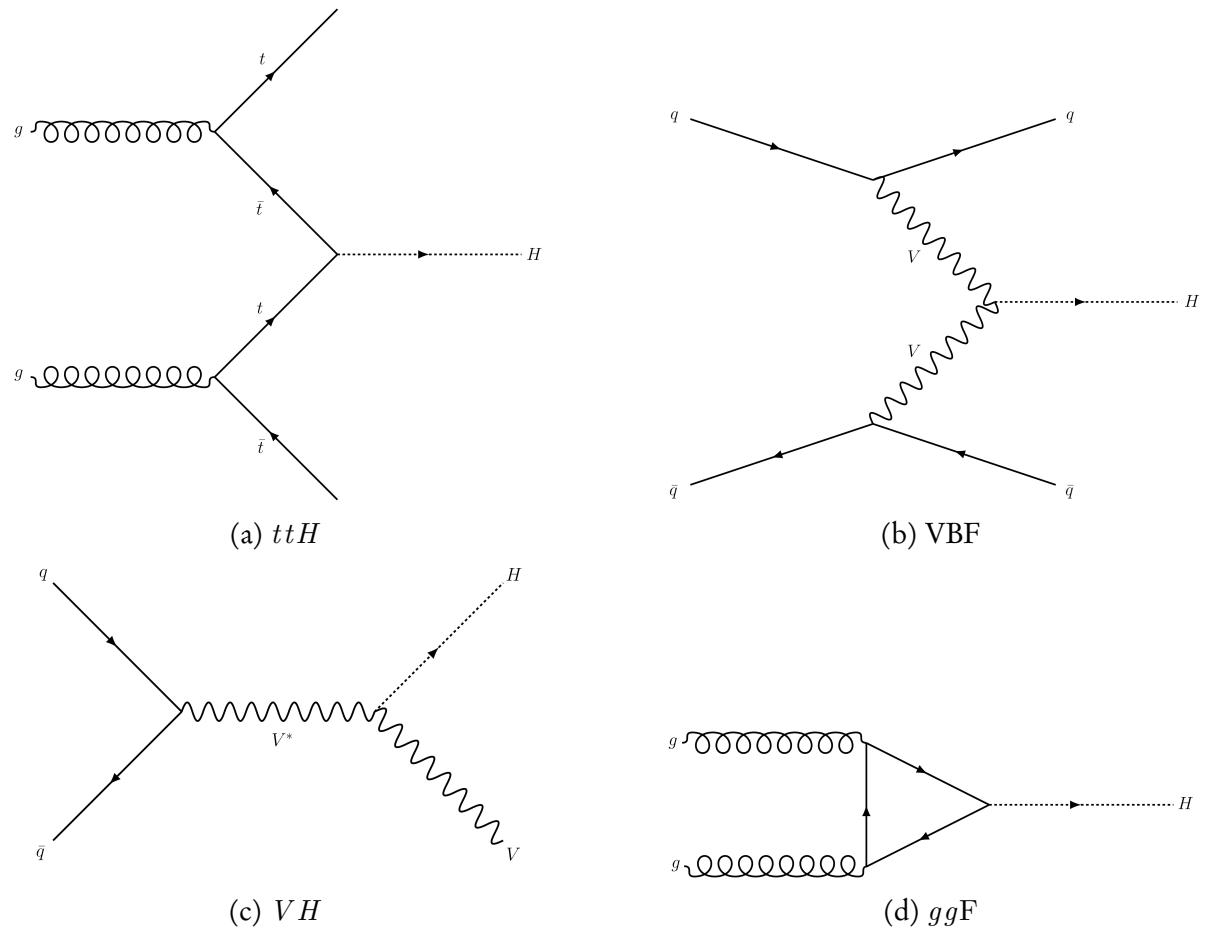


Figure 4.1: The Feynman diagrams for the four main hadronic production modes of the Higgs boson.

4.2 Data and simulation

4.3 Triggers

4.4 Categorisation of the non-VBF production modes

4.5 Background estimation

4.5.1 Control regions

4.5.2 Background estimation methods

SEARCH FOR DARK MATTER THROUGH THE PRODUCTION OF SEMI-VISIBLE JETS

This is the analysis chapter on semi-visible jets.

- Discuss how the theoretical aspects from the Theory chapter translate into an experimental search.
- Include object definitions, triggers, overall analysis strategy, signal production, event selection, background estimation and results/limit (including comparisons to similar searches – monojet/dijet exotic searches).
- Emphasise my contributions: s - and t -channel signal model production and understanding. Angular variable study for QCD background rejection (if used).
- Current material: no public plots as of yet. Hope to finish s -channel analysis soon (see previous section for caveats regarding inclusion), no timeline on t -channel analysis.

5.1 Analysis overview

5.2 Data and simulation

5.2.1 Generating signal samples in PYTHIA

5.2.2 Generating signal samples in MADGRAPH

5.2.3 Triggers

5.3 Background estimation

CHAPTER



CONCLUSIONS

This is the conclusion.

- Include a summary of thesis and work done over the course of my PhD with emphasis on the most important results/contributions.

- Mention the direction the semi-visible jet and Higgs to invisible analyses can take (sharing ideas/strategies I have, potential improvements with more LHC data and future prospects from potential future experiments).

Begins an appendix

A P P E N D I X



APPENDIX A

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GLOSSARY

***b*-jet** A jet identified by a given algorithm or classifier as originating from a *b* quark.

anti- k_{T} algorithm .

semi-visible jet A shower of standard model and dark hadrons from the decay of a leptophobic Z' or Φ mediator that couples the hidden sector to the standard model.

ACRONYMS

ALICE A Large Ion Collider Experiment.

ATLAS A Toroidal LHC ApparatuS.

BSM beyond the standard model.

CERN Organisation Européenne pour la Recherche Nucléaire/European Organisation for Nuclear Research.

CMS Compact Muon Solenoid.

JEC jet energy corrections.

LHC Large Hadron Collider.

LZ LUX-ZEPLIN.

MOND modified Newtonian dynamics.

QCD Quantum Chromodynamics.

SM standard model.

SUSY supersymmetry.

TeV teraelectron volt.

VBF vector boson fusion.

WIMP Weakly Interacting Massive Particle.

