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

Searches for invisibly decaying Higgs bosons and semi-visible jets

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.

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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 [61]. Since then, a wealth of independent astrophysical observations have reinforced the existence of this aggregation 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 arise from dark matter, confirmed by its large mass-to-light ratio of $400 M_{\odot}/L_{\odot}$ [87]. Further evidence is that the rotation curves of most galaxies are roughly flat [71], 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 [44] to compensate for the decline expressed by visible matter [25, 49]. 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 [58]. 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 is comprised of dark matter [18, 19, 59]. Though these approximations 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* segment 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 [7]. 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 [23, 56], 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 (see Chpt. 2.3). 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 [86].
- Its interaction with matter and itself is very weak, or even non-existent. The Bullet Cluster — an astronomical object encompassed by two colliding galaxy clusters — 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 [33]. 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 [85], are precise and well-tested [REF]. Even considering the upper limits on neutrino masses [67], 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. 47 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 [39].

Neutrons cannot contribute to dark matter because isolated neutrons are unstable, decaying in a matter of minutes [69]. Transforming 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 [33] 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 [73]. The recoil these SM particles experience could be detected by highly-sensitive, low background experiments such as LUX-ZEPLIN (LZ) [8] 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 [38]. Large ranges of the annihilation cross section and dark matter mass can be probed with telescopes already searching for these characteristic events.
- **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 Chpt. 2.3) reinforcing the idea that 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.

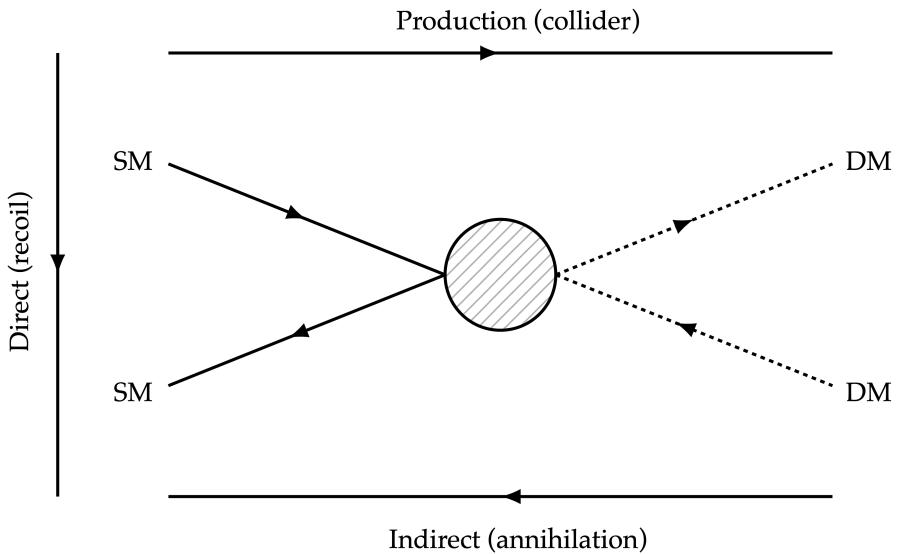


Figure 1.1: A visual representation of the three main types of dark matter detection: direct (dark matter recoiling from standard model particles); indirect (annihilation of dark matter); and production (dark matter created in high energy physics collisions).

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 Chpt. 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 exceptionally 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) [66], sterile neutrinos [43], and Kaluza-Klein states [51] contain dark matter candidates that can be specifically searched for, or indirectly discovered if a theory is experimentally proven. Despite the success of the standard model in explaining the natural world, 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. Weakly Interacting Massive Particles (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. Searches at CMS have been performed for promptly-decaying and “long-lived” supersymmetry in hadronic final states (in which I made contributions) [63, 76]. Searches for specific supersymmetric particles in a variety of decay modes have been conducted by both experiments [28]. In many of these cases, the lightest supersymmetric particle (LSP) is considered to be a dark matter candidate. R -parity conservation is predicted (or even enforced) in many SUSY models [66], which prevents the decay of LSP and any lighter, standard model particles that have been observed to be stable. While supersymmetry is the most popular BSM theory, due in part to its numerous interpretations and approaches for discovery, many others have also been explored at the LHC. From microscopic black holes [64], to [OTHERS], there are many strategies that have the potential to uproot the standard model. The analyses above are usually characterised by large “missing” transverse momentum (explained further in Chpt. 2.4.3), a quantity that represents the momenta of particles invisible to the detector, which include dark matter. In Chpt. 5, I discuss in detail a search for dark matter that utilises this variable.

Precision measurements of standard model parameters is the other method often consulted

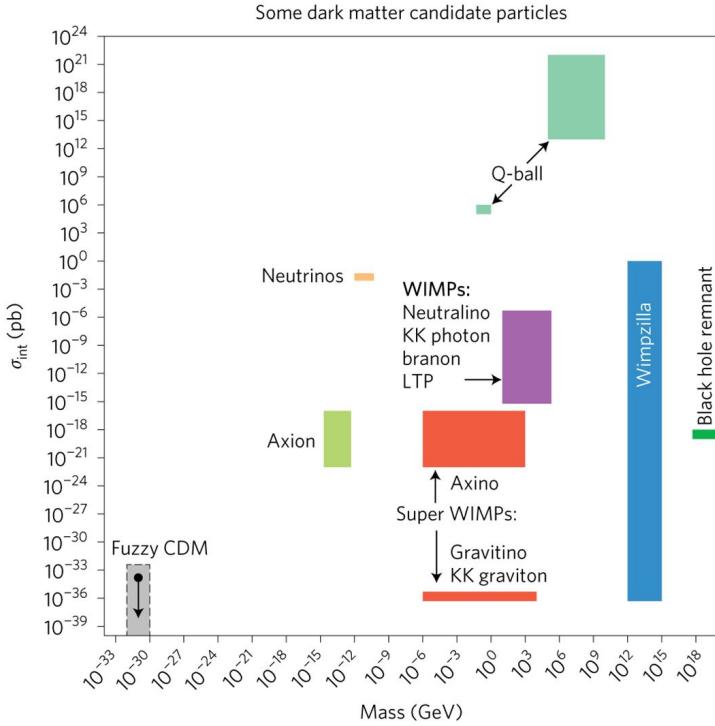


Figure 1.2: The expected masses and interaction cross sections of some dark matter candidates. The centre of mass energy of the LHC is best suited to targeting WIMPs. Figure acquired from Ref. 38.

in the hopes of attributing anomalies to new physics. For example, attempts to explain anomalies in the $b \rightarrow s$ transition include dark matter candidates [29, 84]. In Chpt. 4, I investigate how the measurement of the Higgs boson to invisible state branching ratio can accommodate dark matter.¹

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 $\sqrt{s} = 13 \text{ TeV}$, 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.²

¹Maybe add another example of anomalies in precision measurements

²Add another figure or two somewhere to help separate the text? Maybe an astronomical image of the Bullet Cluster/dark matter distribution in a cosmological object, or a gravitational lensing ring from dark matter

THEORY

This thesis is comprised of experimental searches for dark matter and new physics. The experimental chapters Chpt. 4 and Chpt. 5 delve deeply into the analyses. Before which, the theoretical and phenomenological motivations must be understood to [back up] the need for these searches at the Large Hadron Collider. In this chapter, a brief recap of the standard model will be [presented] along with its shortcomings, i.e., the lack of a dark matter candidate. Theoretical descriptions of dark matter that best fit the relic density and astrophysical observations will then be discussed. Specific interpretations in the form of semi-visible jets and invisibly decaying Higgs bosons are [looked at] that provide the background for the respective analysis chapters.

- 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 the semi-visible jets analysis (main sources from Refs. 34, 35): 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

Despite the standard model providing precise predictions of three of the four fundamental forces and the particles that they interact with, there are many experimental observations that it cannot currently explain. Neutrino masses, dark matter, dark energy, and gravity all escape its description.

2.3 Theoretical motivations for, and descriptions of, dark matter

The universe may have birthed dark matter via one of many possible mechanisms. The most popular is described as a “thermal freeze-out” process. In the hot, early universe when the thermal background allowed spontaneous pair production of particle dark matter, it was produced in abundance. During this period, they may also have frequently annihilated since the cosmos was still small. Inevitably, the universe expanded and cooled; the temperature became too low to allow significant production [16]. Matter was further separated and the dark matter annihilation rate decreased, leaving a behind the “thermal relic” that is observed today. These remaining particles were attracted via gravity, forming filaments throughout the universe. The potential wells they induced allowed the progenitors of galaxies to form within.

2.4 Important observables in collider physics

2.4.1 Transverse momentum (p_T)

In the LHC (or any other collider), the longitudinal momentum of the initial state particles is typically unknown. However, the momentum transverse to the beam is zero before the collision, and therefore must be zero afterward after due to momentum conservation. This is why the transverse momentum of a particle or physics object (\vec{p}_T for the vector quantity, p_T for its magnitude) is a useful variable in an analysis.

2.4.2 H_T

The scalar sum of the transverse momentum of hadronic constituents in an event, i.e., the jets, is symbolised as H_T . It is often used in analyses focused on hadronic objects, such as natural supersymmetry in which a large jet multiplicity is expected. Formally,

$$(2.1) \quad H_T \equiv \sum_{\text{jets}} p_T$$

Typically, a lower limit on p_T is used when calculating the H_T , so jets below this threshold do not factor into the sum. This is to avoid low momentum jets attributed to pileup events (see Chpt. 3.2.3), and those from the primary vertex that can often be mismeasured.

2.4.3 Missing transverse momentum (p_T^{miss})

The missing transverse momentum p_T^{miss} is defined as the negative vector sum of the p_T of all identified particles in an event. It is a term often used interchangeably with missing transverse energy (MET, E_T^{miss}). Undetected particles from neutrinos or dark matter, or mismeasured kinematic properties of identified particles, will introduce an imbalance in the vector sum of the p_T . Hence, the p_T^{miss} will be non-zero. Formally,

$$(2.2) \quad p_T^{\text{miss}} \equiv - \sum_i^{N_{\text{particles}}} \vec{p}_{T,i}$$

The hadronic-only counterpart to this variable, H_T^{miss} , is the negative vector sum of the jet transverse momenta in an event:

$$(2.3) \quad H_T^{\text{miss}} \equiv - \sum_j^{N_{\text{jets}}} \vec{p}_{T,j}$$

As with H_T , the H_T^{miss} is often calculated with a lower limit on the jet p_T .

2.5 Measuring the branching ratio of invisibly decaying Higgs bosons

The Higgs boson has caught the attention of the high energy physics community and even the public eye like no other particle in recent memory. Its discovery in the $H \rightarrow \gamma\gamma$ channel

in 2012 by both CMS [31] and ATLAS [5] independently realised one of the [principal] goals of the LHC’s construction. The particle itself is not necessarily exciting. Rather, it confirms the existence of the Higgs *field* that pervades the universe and gives mass to the elementary particles via the exchange of its namesake boson [45, 50, 57]. [Its discovery], one might think, was the end of the discussion of the Higgs boson. However, it was only the beginning.

Many observations of the Higgs, such as its predominant decay mode $H \rightarrow bb$, were not seen until recently (CMS [74], ATLAS [4]). Constraints on its other properties have also been placed, such as its resonance width and branching ratios \mathcal{B} to other final states. Fully understanding the Higgs boson is important to understanding the Higgs field and the wider standard model. Precision measurements in tension with SM predictions can also be a window to new physics. Measuring the $H \rightarrow \text{inv.}$ branching ratio aims to do just that.

The only SM process in which Higgs boson can decay invisibly is $H \rightarrow ZZ \rightarrow 4\nu$ with a branching ratio of $\mathcal{O}(0.1\%)$ [54]. The leading observed experimental upper limits on this measurement are 19 % from CMS [77] and 26 % from ATLAS [3], far above the predicted value. If undiscovered invisible particles, perhaps dark matter, couple to the Higgs field the branching ratio will be enhanced. Experimental evidence shows the coupling strength to proportionally follow the mass of the particle, as verified in ATLAS and CMS’ latest measurements [78]. A considerably large enhancement may allow for this process to be observed at the LHC. At the very least, a more accurate constraint on the branching ratio is able to exclude some models of dark matter, such as those described in Refs. 42, 60.

There is no reason to assume dark matter does *not* interact with the Higgs field, since it bestows mass to all known elementary particles (a small caveat, perhaps, being neutrinos). Higgs “portal” models have been theorised that connect the visible sector of the standard model to a dark sector where particle dark matter resides [11, 14].

2.6 Searches for semi-visible jets

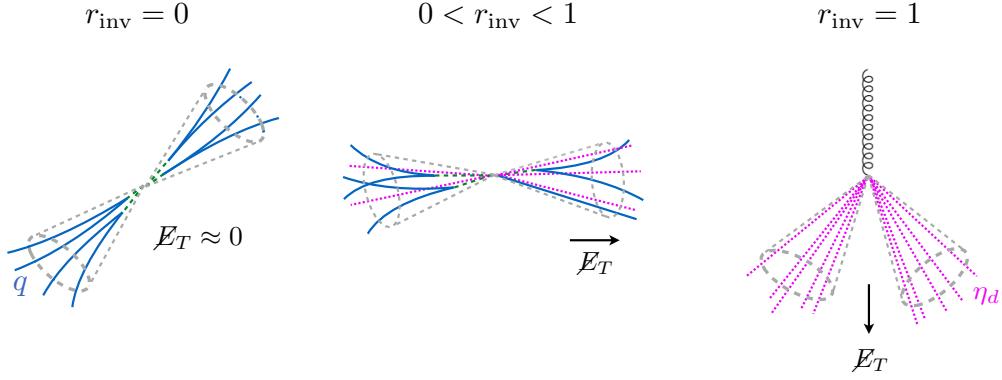


Figure 2.1: The typical direction of the missing transverse energy \cancel{E}_T (or p_T^{miss}) relative to the semi-visible jets as a function of their invisible fraction r_{inv} [35].

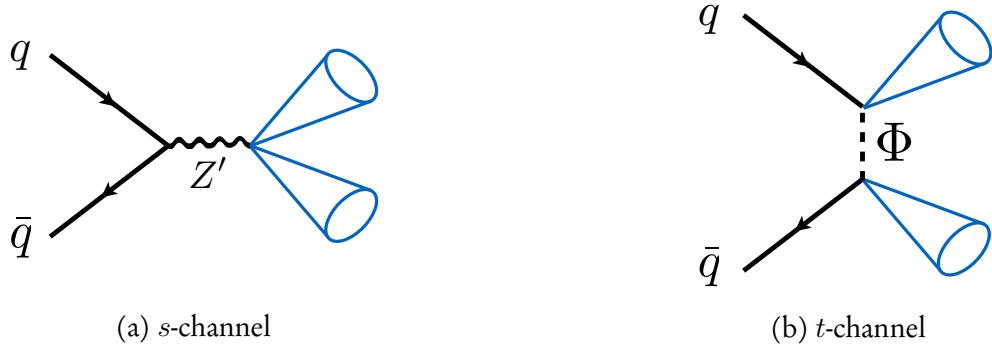


Figure 2.2: Example Feynman diagrams for the two main production modes of semi-visible jets [35]. A Z' boson mediates the s -channel process while a bifundamental Φ mediates the t -channel process.

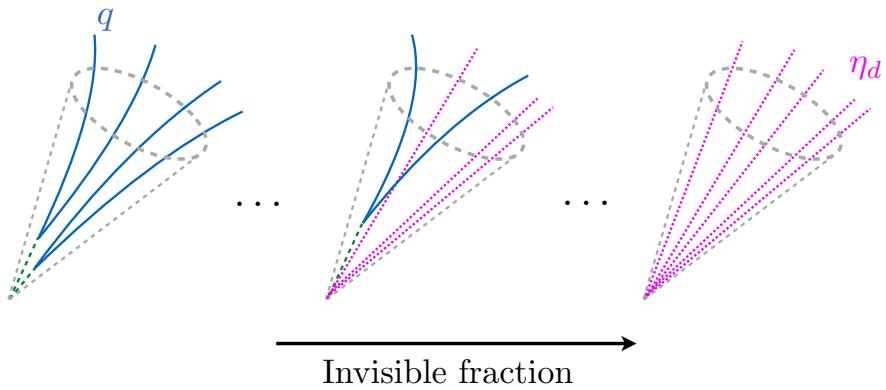


Figure 2.3: The constituents of a semi-visible jet as a function of its invisible fraction r_{inv} [35].

THE LHC AND THE CMS EXPERIMENT

This chapter concerns the experimental setup. CERN is the organisation that manages the machines discussed and is a pioneer in the high energy physics community. As such, it will be given a short overview. The Large Hadron Collider provides the CMS experiment with proton-proton collision data that is then stored, corrected, and then used by physicists for analyses. Ranging from standard model precision measurements, searches for new physics, the development of tools and algorithms to aid the previous two, these and much more are studied by the collaboration.

- Emphasise the jet and energy sum triggers in Level-1 Trigger 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 CERN

CERN, the European Organisation for Nuclear Research (*Organisation Européenne pour la Recherche Nucléaire*), is the body responsible for large scale particle and high energy physics projects in Europe. It was founded in 1954 under the *Conseil Européen pour la Recherche Nucléaire* (European Council for Nuclear Research), from where its acronym derived. CERN's primary site is situated in the canton of Geneva and creeps over the Franco-Swiss border. Its main purpose today is to provide physical and technological infrastructure for particle and high energy physics experiments. From large scale accelerators to extensive computing farms, CERN has grown into the largest laboratory for particle physics in

the world. The organisation also provides a central community for the many researchers, engineers, and technicians to share ideas and collaborate effectively.

The organisation was founded by twelve European member states, the United Kingdom being one of them. It has since expanded to twenty three, encompassing most of western Europe and some of the continent’s east. Many more countries from across the globe are affiliated with CERN in some way, providing researchers, computing resources, and more. The member states and associated members contribute to CERN’s budget, to the tune of 1.2 billion Swiss Francs for the year 2020 [48].

Many important inventions and discoveries can be attributed to CERN and its personnel. Physics [achievements] include observations of weak neutral current interactions in 1973 [52, 53], paving the way for the W [12, 17] and Z [13, 15] boson discoveries with the UA1 and UA2 experiments in 1983. The number of light neutrino generations at the Large Electron-Positron Collider (LEP) in 1989 [83], and direct CP violation with the NA48 experiment in 1999 [46], were also observed. Tim Berners-Lee and Robert Cailliau are credited with inventing the World Wide Web — the ubiquitous service for accessing the internet — in 1989/90.

CERN is perhaps most widely known as the home of the Large Hadron Collider, the particle accelerator involved in the discovery of the Higgs boson [5, 31]. More is discussed in Chpt. 3.2. But CERN is still involved in many more undertakings. There are many fixed target experiments that use beams from the PS and SPS such as COMPASS (studies hadronic structure) and NA62, investigating rare decays of kaons. Experiments like ALPHA and AEGIS use antiprotons from the Antiproton Decelerator to study antimatter in detail. The ISOLDE facility at CERN delivers beams of radioactive ions to perform many nuclear physics experiments.

Concern is given not just to contemporary science, but also to the physics of tomorrow. The experiments and accelerators are frequently upgraded, for example LHC improvements documented in Chpt. 3.2.4. Future accelerators are also being discussed, such as the Future Circular Collider (FCC). The collider would use the LHC as a booster, with the final ring having a 90–100 km circumference and up to 100 TeV centre of mass energy. Proposals for the injectants are electron-positron beams (FCC-ee, $\sqrt{s} = 90\text{--}350 \text{ GeV}$), and proton-proton beams (FCC-hh, $\sqrt{s} = 100 \text{ TeV}$). Each option boasts its own merits, and in an integrated scenario the former may be used as an intermediate step toward the latter.

3.2 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. As the largest machine in the world, the LHC stands as a testament to the importance of fundamental science and the dedication to which it is pursued. Predominantly a proton collider, lead and xenon ions have also been injected for novel and unique studies. Four primary 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), a counterpart to CMS at the antipode of the LHC ring; 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.

Four additional, smaller experiments are stationed in the LHC ring that are much more specialised than the above mentioned: TOTEM (TOTal Elastic and diffractive cross section Measurement) shares the CMS cavern with three subdetectors positioned near the beam line, performing proton structure and interaction cross section studies; LHCf shares the ATLAS cavern and is concerned with detecting neutral pions in the forward direction to explain the origins of high energy cosmic rays; FASER (ForwArd Search ExpeRiment) is another forward-based detector near ATLAS and searches for light, weakly interacting particles; finally, MoEDAL (Monopole and Exotics Detector at the LHC) is installed in the LHCb cavern and aims to detect magnetic monopoles and other exotic particles.

The technical design report for the LHC can be found at Ref. [26], detailing the ring itself, infrastructure, general services, and the injector chain.

3.2.1 A proton's journey

A proton begins its journey as a hydrogen atom in a little, red bottle. Around 3×10^{14} protons are supplied to each beam in the LHC, with billions of refills available in this single container. Once the hydrogen atoms leave the source, they are stripped of their electrons, and [sent] to the linear accelerator LINAC2.¹ This is the start of a long voyage through the accelerator complex (visualised in Fig. 3.1).

Given a modest boost to 50 MeV (megaelectron volts), the protons are sequentially fed from LINAC2 into the Proton Synchrotron Booster (PSB) that accelerates them further to

¹As of the end of Run-2, LINAC2 has been decommissioned. It has been replaced by LINAC4 in preparation for Run-3.

1.4 GeV. Another upsurge is provided once the protons travel to the Proton Synchrotron (PS), this time to 26 GeV. Then the final energy increase received before entering the LHC comes from the Super Proton Synchrotron (SPS), leaving the protons at 450 GeV. Once injected into the LHC, they are finally accelerated to their peak energy of up to 6.5 TeV from a sequence of radio frequency cavities over the course of twenty minutes. The oscillation frequency of these cavities is precisely tuned and timed to give protons the appropriate kicks and accelerate them to the desired energy. Since there is a distribution of proton energies in the beam, those that enter a cavity slightly out of time with a different energy than expected consequently become sorted into “bunches”. The remainder of the LHC ring is used to steer the beam with the aid of over 1,200 liquid helium-cooled superconducting dipole magnets. It is also focused by almost 400 equivalently-cooled quadrupole magnets to increase the rate of proton collisions.

One beam consists of a “train” of up to 2,808 bunches spaced 25 ns apart, each with 115 billion protons. Using bunches provides an advantage to the experiments at each of the interaction points. Discrete collisions take place between bunches in the opposing beams at 40 MHz as opposed to an almost continuous stream of protons. This allows for estimates of pileup interactions that can be filtered out, and would otherwise introduce miscalculations of sums like p_T^{miss} and H_T . Each proton-proton collision is colloquially known as an “event”, with data recorded by each experiment separated into events.

3.2.2 Luminosity

The *luminosity* of a particle accelerator is, along with centre of mass energy, a quantitative measure of its performance. It also often used to denote the amount of data delivered, or the data collected by the receiving detector. A full derivation of this quantity can be found in Ref. 55, and as such, a summary is given here. The *instantaneous luminosity* \mathcal{L} , typically quoted in $\text{cm}^{-2}\text{s}^{-1}$, is defined as

$$(3.1) \quad \mathcal{L} = \frac{1}{\sigma_p} \frac{dN}{dt}$$

where N is the number of collisions and σ_p is the production cross section. In the LHC, since many final states are possible, σ_p is not generally known. It can be measured, however. A recent paper from LHCb measured the extrapolated inelastic cross section (which is the important component for LHC collisions) to be $75.4 \pm 5.4 \text{ mb}$ at $\sqrt{s} = 13 \text{ TeV}$ [6], allowing an estimate of the collision rate. For two colliding beams split into bunches with the constituents in each bunch distributed according to a gaussian profile,

3.2. THE LARGE HADRON COLLIDER

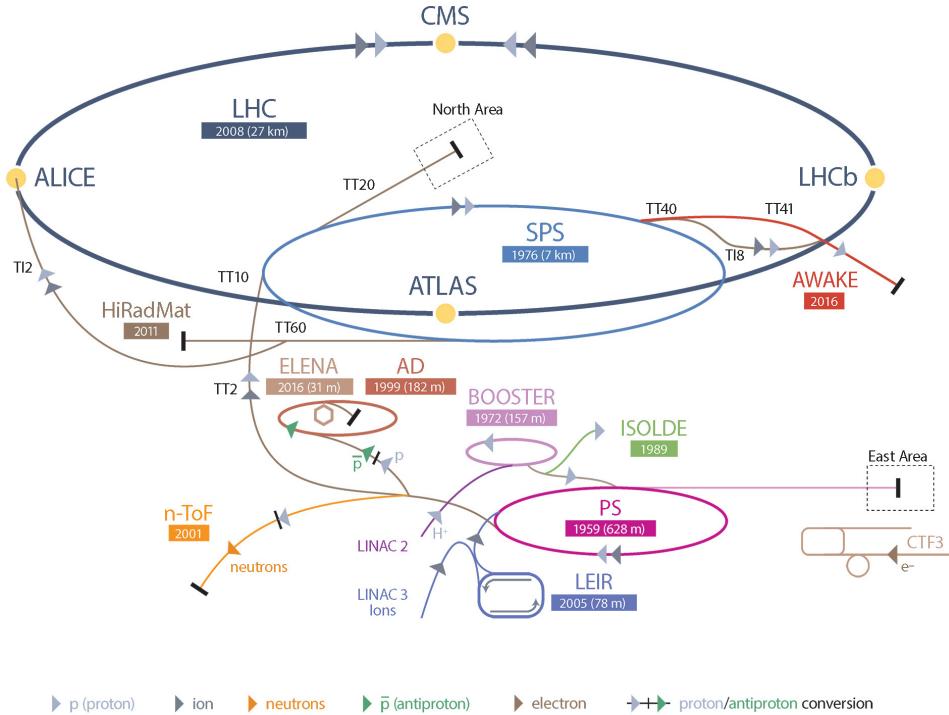


Figure 3.1: A schematic of the CERN accelerator complex. Various particles are shown from their sources to the detectors they are observed at. Figure obtained from Ref. 1.

$$(3.2) \quad \mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} \cdot F$$

where N_1 and N_2 are the number of particles in a bunch in beams 1 and 2, respectively, N_b is the number of bunches in a beam, f is the revolution frequency (11,245 Hz for protons in the LHC), and σ_x and σ_y are the horizontal and vertical sizes of the beam, respectively.²

The geometric reduction factor F is unity for beams colliding head on.³ However, in the LHC, the beams collide at an angle known as the “crossing angle” to reduce the effects of pileup. At the start of a fill when the number of protons in the LHC is at its maximum, the crossing angle at each interaction point is approximately 300 μ rad. As the runs progress, more protons collide and the luminosity decreases. One of measures taken to recover luminosity and keep the LHC as efficient as possible is to reduce the crossing angle. By the end of the fill, it can be as small as 240 μ rad.

The instantaneous luminosity can be increased by the inclusion of more bunches in the beam, decreasing the size of the beam through improved quadrupole magnets, and by reducing

²Add the H factor from the hourglass effect and explain?

³Add mathematical formula for F?

the crossing angle. Tuning these parameters led the LHC to reach its design luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in 2016. It had more than doubled by the end of Run-2.

Integrating the instantaneous luminosity over a period of time yields the *integrated luminosity* $\mathcal{L}_{\text{int.}}$:

$$(3.3) \quad \mathcal{L}_{\text{int.}} = \int \mathcal{L} dt$$

These values are often quoted by experiments in units of “inverse femtobarn” (fb^{-1}) as an indicator of the amount of collision data collected. A “barn” is a unit equal to 10^{-28} m^2 and colloquially used to express cross sectional area in nuclear and particle physics. As such its reciprocal, the same units as integrated luminosity, gives a good sense of scale that relates cross sections of individual processes to the total amount of data. Tab. 3.1 gives the integrated luminosities over Run-2 delivered by the LHC and collected by CMS. Taking 137.19 fb^{-1} from this table, and assuming the inelastic p_T cross section above gives an estimate of 10^{16} collisions recorded by CMS over Run-2 (excluding pileup interactions).

3.2.3 Pileup

At the high instantaneous luminosity of the LHC, multiple interactions per bunch crossing (known as *pileup*) are frequent. The expected, or nominal, number of collisions per bunch crossing is one, but because of all the factors that increase the luminosity, many “softer” collisions also take place. Pileup interactions can produce many low- p_T objects, and near-collinear to the beam (detecting particles in this region is essential for some analyses). These additional objects can contaminate the reconstruction of final state from the nominal collision, and as such affect the direction and magnitude of the p_T^{miss} . When one aims to increase the luminosity to collect more data, the more severe pollution from pileup is an inevitable consequence. The distribution of pileup events in CMS during 2015 and Run-2 can be seen in Fig. 3.2.

There are strategies in place in the LHC and the anchored experiments to mitigate pileup. Introducing, or increasing, a crossing angle between the beams reduces the effect. Track reconstruction algorithms are very efficient at connecting particles to their primary vertices, and therefore particles originating from pileup vertices can be identified and removed [2, 30]. At CMS, various methods are available in the calorimeter triggers to subtract the [effects] from pileup.

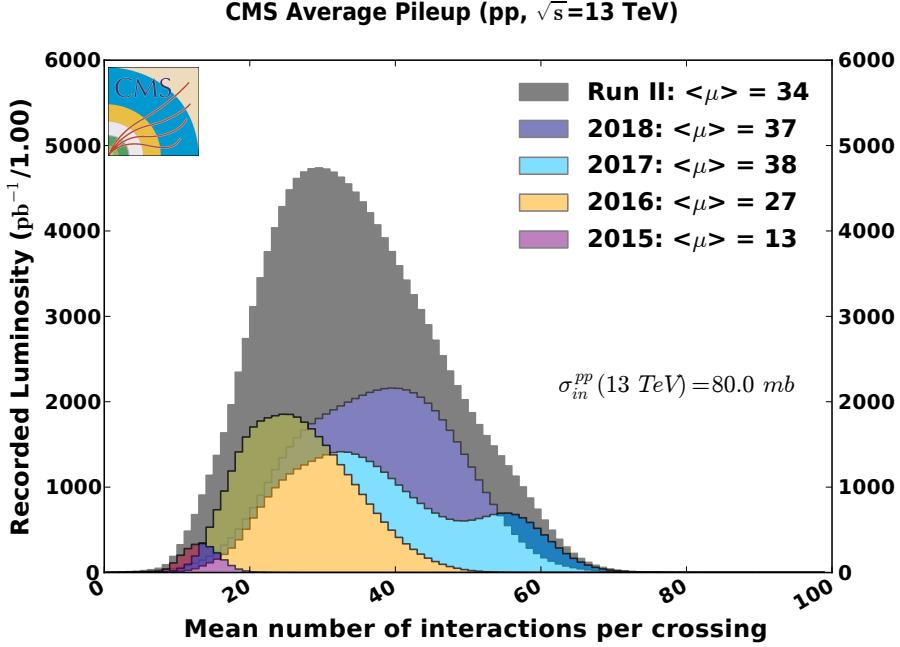


Figure 3.2: The average number of pileup interactions at CMS during 2015 and Run-2 of the LHC. Figure obtained from Ref. 36.

3.2.4 Evolution of the LHC

The LHC began operating in 2010 at a centre of mass energy of $\sqrt{s} = 7$ TeV (teraelectron volts), 3.5 TeV per beam. A modest increase to 8 TeV was achieved by the end of Run-1 in 2013. Long Shutdown 1 then commenced where maintenance work was carried out, and upgrades to the accelerator and experiments were performed. Notably, the superconducting magnets were improved to safely handle much more energetic beams.

The LHC resumed operation in 2015, marking the start of Run-2 and further pushing the frontiers of high energy physics with a centre of mass energy of $\sqrt{s} = 13$ TeV. While valuable data was taken that year, it was not until 2016 when substantial datasets were amassed. As such, when analysts refer to the “full Run-2 dataset”, they typically do not include data from 2015. It requires as much care as the other years with respect to implementing corrections and addressing systematic uncertainties, and so on, for only a very small gain in integrated luminosity. Run-2 ended in 2018 with — omitting the 2015 dataset — 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 [36, 37]. A breakdown by year is presented in Tab. 3.1 with a visual representation in Fig. 3.3.

In addition to the upgrades that have so far been performed, a much grander change is on

	2015	2016	2017	2018	Full Run-2
Integrated luminosity					
Delivered by LHC (fb^{-1})	4.21	40.99	49.79	67.86	162.85
Recorded by CMS (fb^{-1})	3.80	37.80	44.98	63.67	150.25
Certified by CMS (fb^{-1})	2.26	35.92	41.53	59.74	139.45

Table 3.1: The integrated luminosity delivered by the LHC during Run-2 which were recorded and certified by CMS. Typically, only the 2016–18 datasets are analysed since 2015 accrued little data compared to the other years. Numbers obtained from Refs. 36, 37.

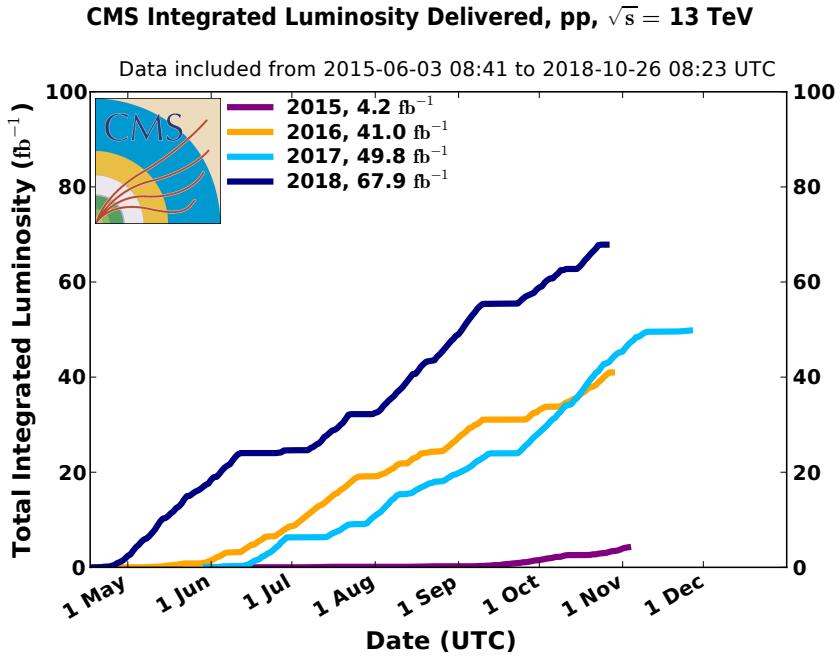


Figure 3.3: The integrated luminosity of pp collision data delivered to CMS during Run-2 of the LHC. Figure obtained from Ref. 36.

the horizon. In 2027, the High Luminosity Large Hadron Collider (HL-LHC) is expected to begin operations. The latest technical design report can be found at Ref. 10. Many [upgrades] are set to be introduced with the primary purpose of increasing the luminosity by up to a factor of ten: more powerful magnets for focusing the beam, crab cavities for increasing the bunch overlap area, shielding and more radiation-resistant components, an upgrade to many of the boosters in the accelerator complex, and much more. A summary of the important parameters at three stages of the LHC’s life is given in Tab. 3.2.

Parameter	End of Run-2	HL-LHC	Design
Beam energy (TeV)	6.5	7	7
Bunches per beam	2,556	2,748	2,808
Protons per bunch	1.5×10^{11}	2.2×10^{11}	1.5×10^{11}
Crossing angle (μrad)	300	590	285
Instantaneous luminosity ($\text{cm}^{-2}\text{s}^{-1}$)	2.1×10^{34}	7.2×10^{34} *	1.0×10^{34}
Integrated luminosity per year (fb^{-1})	68	250	40
Average pileup per bunch crossing	34	140	27

Table 3.2: Some of the important parameters defining the performance of the LHC at the end of Run-2, for the High Luminosity Large Hadron Collider and the design specification. Several values in this table were obtained from Refs. 9, 21.

* Does not account for the large increase to virtual luminosity from the introduction of crab cavities.

3.3 The CMS experiment

The Compact Muon Solenoid (CMS) collaboration was formed in 1992 with a letter of intent circulated to the high energy physics community for a general purpose detector to be built at the LHC [40]. Though its emphasis was the detection of the Higgs boson, the myriad avenues for which physics could be studied was also acknowledged. Just under five hundred people from sixty two institutes were part of the original letter. At the time of writing over five thousand physicists, engineers, technical and administrative staff, and students, spanning over two hundred institutes in fifty countries, comprise the collaboration. Working tirelessly in harmony, with ingenuity, cooperation, and a drive for exploring the frontiers of particle physics, almost one thousand publications have been produced with data collected by the experiment. These range from exotic/BSM searches, standard model precision measurements, B -physics, top quark physics, heavy ions, and more. This wide scope of topics cements CMS as a versatile and world-leading detector, and collaboration as a whole.

3.3.1 The CMS detector

The machine, aptly named the “CMS detector”, lives a hundred metres underground at Interaction Point 5, just outside the town of Cessy in France. Constructed over several years, the detector construction of the detector was separated into fifteen sections. Each was built on the surface and lowered into the experimental cavern with an incredibly small tolerance of a few centimetres. Here, they were joined together to assemble the 14,000 tonne goliath. The finished detector is a hermetic cylinder enclosing the LHC beam pipe, measuring 21 m in length (plus a little extra from the smaller, bolt-on forward calorimeters) and 15 m in

diameter. Its etymology stems from how *compact* (relatively speaking) the detector is as it weighs twice as much as ATLAS in only one sixth of the volume, it has a subsystem dedicated to detecting *muons*, and a *solenoid* is used to generate the magnetic field.

CMS is designed to detect all manner of particles as accurately as possible. To accomplish this, the detector can be divided into four subsystems (or subdetectors): the silicon tracker, the electromagnetic calorimeter (ECAL), the hadron calorimeter (HCAL), and the muon chambers. These are each explained in more detail below, with a graphic of the entire detector presented in Fig. 3.4 and a transverse slice through it in Fig. 3.5.

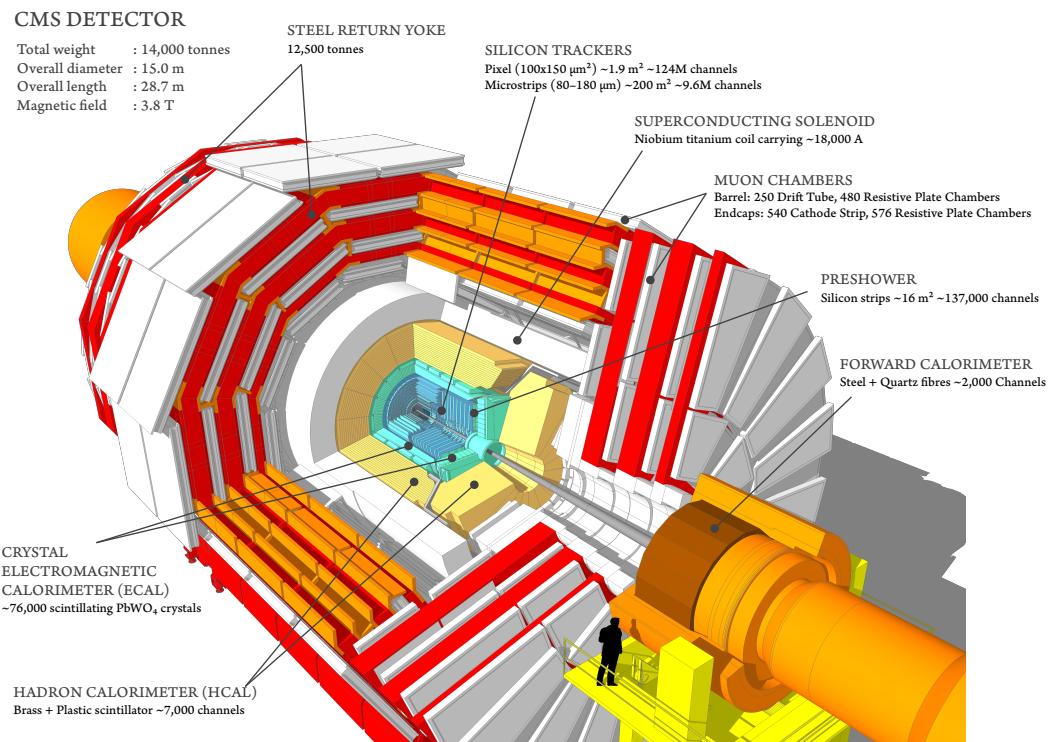


Figure 3.4: A cutaway diagram of the CMS detector with all of the principal components labelled. This detector configuration was used for the 2017–18 data taking years, where the coverage of the pixel detectors in the silicon tracker were upgraded from 1 m^2 (66 million channels) to 1.9 m^2 (124 million channels). Image taken from Ref. 72.

3.3.1.1 Subsystems

When a collision occurs, the ejected particles first encounter the silicon tracker that extends to just under 1 m in radius [62, 82]. Consisting of tens of millions of pixels and microstrips, the positions of particles can be recorded to within $10 \mu\text{m}$. Initially, the pixel detector covered 1 m^2 , consisting of 66 million channels. It was upgraded for the 2017–18 run period to 1.9 m^2

with 124 million channels. Since it is the closest subsystem to the interaction point, the components must be extremely radiation tolerant to withstand the bombardment of particles pummelling them every collision.

After the tracker, the particles can interact with the ECAL [24, 79]. The 76,000 lead-tungstate crystals record energy deposits in the barrel and end cap regions belonging to charged particles. In particular, electrons and photons are identified here, and are usually stopped entirely in the ECAL.

Hadronic particles can propagate further into the HCAL [80]. A brass and plastic scintillator with 7,000 channels, the energies in showers of hadrons are measured. Unlike the ECAL which only covers the barrel and end cap, the HCAL also has a component in the forward region of the detector: the hadron forward calorimeter (HF). Made of quartz fibres and steel, it is designed for particles with trajectories close to the beam line, and serves the additional function of measuring the luminosity delivered to, and collected by, the experiment. Each cell of the HCAL maps onto a given number of ECAL crystals, forming “calorimeter towers” that are important when collecting data (see Chpt. 3.3.2). The towers project mostly radially from the interaction point. Their granularity is greatest perpendicular to the beam line, and decreases closer to it.

These three subsystems are encased in a massive solenoid [81], making up 12,500 of the 14,000 tonne detector. It generates a magnetic field of 3.8 T and $2.4 \times 10^9\text{ J}$ of energy, making it the largest store of energy in the world for a single magnet. The field allows for the transverse momentum of a charged particle to be measured at high resolution, since it deflects the particle into a circular orbit. The magnetic force qvB exerted is equal to the centripetal force mv^2/r , and as such the radius of the orbit is proportional to the momentum.

An iron return yoke interspersed with the muon chambers [65] [make up] the rest of the detector, extending from a radius of around 3 m to 7.5 m. The iron yoke confines the magnetic field to the volume of the detector and provides a 2 T field in the opposite direction to that found further inward. Since muons are much heavier than electrons and have high p_T , they deposit little energy in the ECAL. The final states of several interesting decays, such as the Higgs, that produce muons. As such, constructing a dedicated subdetector is therefore essential. There are four muon “stations”, as can be seen by the orange strips in Fig. 3.5, separated by portions of the return yoke. 480 resistive plate chambers and 250 drift tubes reside in the barrel region, with 540 cathode strip chambers complemented by 576 resistive plate chambers in the end caps.

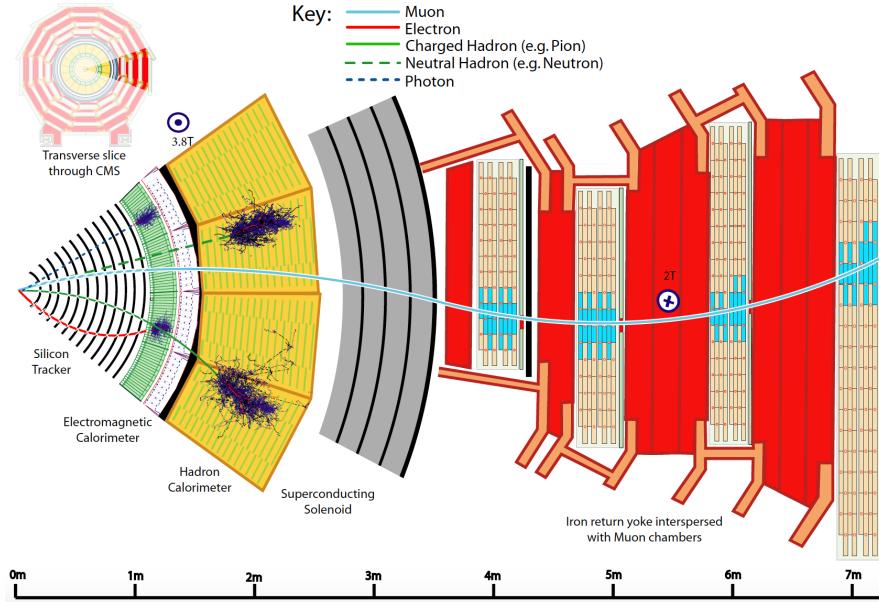


Figure 3.5: A transverse slice through the CMS detector with the main subsystems and components visible (figure obtained from Ref. 75). Several particles produced at the primary vertex and their interactions with the detector are also depicted.

3.3.1.2 Geometry

Collider physics tends to use certain conventions when describing the positions of particles in a detector. The azimuthal angle ϕ is the same variable as in cylindrical coordinates, i.e., the angle between the particle's position and the longitudinal axis of the detector (the beam line). Pseudorapidity, denoted by η , is a coordinate that describes the angle of a particle (after a collision in an accelerator) relative to the beam axis:

$$(3.4) \quad \eta = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right]$$

where θ is the angle between the particle's three-momentum \mathbf{p} and the positive direction of the beam axis. So as $\theta \rightarrow 0^\circ$ (the beam line), $\eta \rightarrow \infty$. Generally, particles with large η escape the detector which is why forward calorimeters are in place. The transverse momentum of a particle can be found with $p_T = |\mathbf{p}| / \cosh \eta$.

The detector is predominantly separated into three regions dependent on η : the barrel, or central⁴ region ($|\eta| < 1.479$); the end caps ($1.479 < |\eta| < 3.0$); and the forward region ($3.0 < |\eta| < 5.0$). The divisions are due to the locations of the components that make up the calorimeters. The ECAL and HCAL cover the barrel and end caps regions entirely, with the

⁴Is the central region just the barrel, or is it everything that's $|\eta| < 2.4$?

HCAL additionally having a component in the forward region. The muon chambers only reside in the barrel and end caps, but its pseudorapidity range is restricted to $|\eta| < 2.4$, since the steel that surrounds the structure takes up the remainder of the end cap. One quadrant of CMS showing the η divisions can be seen in Fig. 3.6.

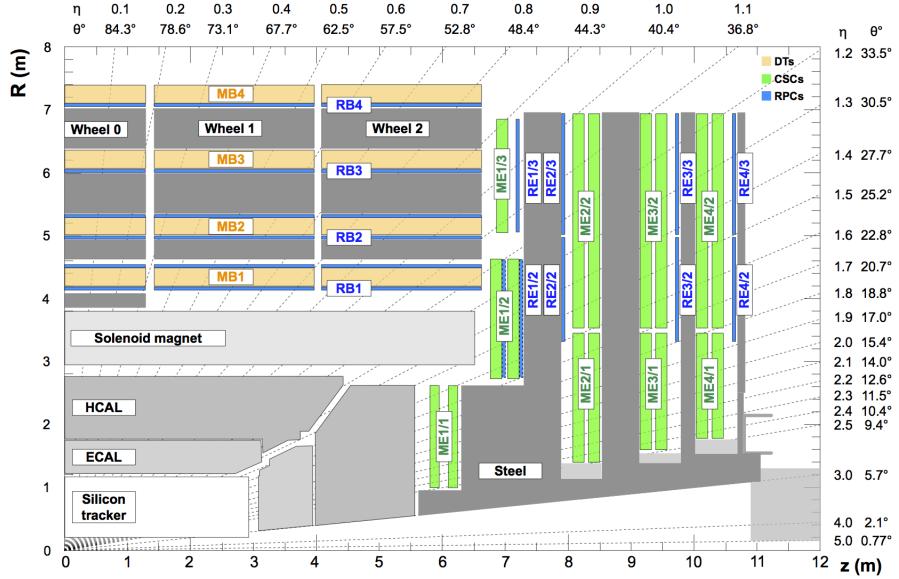


Figure 3.6: A quadrant of the CMS detector showing the main subsystems with their radius R , longitudinal distance z , and pseudorapidity η from the interaction point. The grey box at $3.0 < |\eta| < 5.0$ and $\sim 10.9 < z < 12$ m is the hadron forward calorimeter. Figure taken from Ref. 68.

The distance between two objects can be found with the variable ΔR :

$$(3.5) \quad \Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

It is often used as a distance parameter in jet clustering, or between individual objects in highly-boosted decays.

3.3.2 Data acquisition and triggering

With the enormous collision rate at the CMS interaction point, acquiring data requires some thought and ingenuity. Today’s electronics cannot handle the bandwidth from recording every single collision, $\mathcal{O}(1 \text{ petabyte s}^{-1})$. As such, a “trigger” is used to select the events that may be of use to analysers. In CMS, a two stage trigger [20] is used: the Level-1 Trigger (L1T), implemented in the detector hardware; and the High-Level Trigger (HLT) [32], a

software farm to further reduce the events selected at Level-1. The trigger is part of the larger data acquisition (DAQ) system, an intricate network of custom electronics and commercial processors — a union of hardware, firmware, and software — interconnected by multi-gigabit links to record the products of the highest-energy manmade collisions on Earth.

3.3.2.1 The Level-1 Trigger

The Level-1 Trigger is a set of algorithms (a trigger “menu”)⁵ implemented in custom hardware designed to reduce the event rate from 40 MHz to a maximum of 100 kHz. FPGA and ASIC chips contain the algorithms in firmware, with timing systems synchronised with the LHC clock. When a collision occurs, particles interact with the detector and registered by the components.

Coarsely-segmented data is sent from the ECAL and HCAL through a two-layer Calorimeter Trigger. These are arrays of custom processors located at Point 5. Layer-1 receives data from the calorimeters over upwards of one thousand fibre optic links, each with multi-gigabit bandwidths. The information from the two subsystems are combined into calorimeter towers, and some simple position- and energy-dependent calibrations are applied. The data from Layer-1 is then transmitted to Layer-2, again over many high-bandwidth optical links. Here, physics object candidates are identified (jets, e , γ , τ).⁶ Additional calibrations are applied to them (for example, in Chpt. 3.3.4), and simple pileup subtraction is performed.⁷ Energy sums are also calculated at this stage, such as E_T^{miss} , H_T , and H_T^{miss} .

In parallel, the various subdetectors in the muon chambers pass information through successive stages, notably the Muon Track-Finder Layer (EXPAND), and is then combined with some of the calorimeter information in a sorting/merging/isolation layer. The output from this layer is combined with the remaining information in Layer-2 in the Global Trigger, a series of μ TCA boards with FPGAs. The trigger menu lives here, and all of the information gathered — object candidates, energy sums, beam conditions — is provided to it. These triggers may be dependent on the presence a single object or the number of objects of a single class (e.g., one muon, two jets), multiple classes of object (cross triggers), the energy sums, the topologies of objects, and more. The latency given to make a decision on whether to keep or reject an event is 4 μ s.⁸ A diagram of this data flow is given in Fig. 3.7.

⁵Do I need to say that different menus are used throughout the data-taking periods and for different injectants (heavy ions, etc.)?

⁶An overview of the latest Run-2 algorithms for object identification can be found in Ref. 88.

⁷Do I need to describe in detail how jets are formed? Jet seed, chunky donut PU subtraction, etc... Since it may be relevant for JEC.

⁸Mention pre-scaling of triggers, and that as \mathcal{L} decreases over a fill, the pre-scales change?

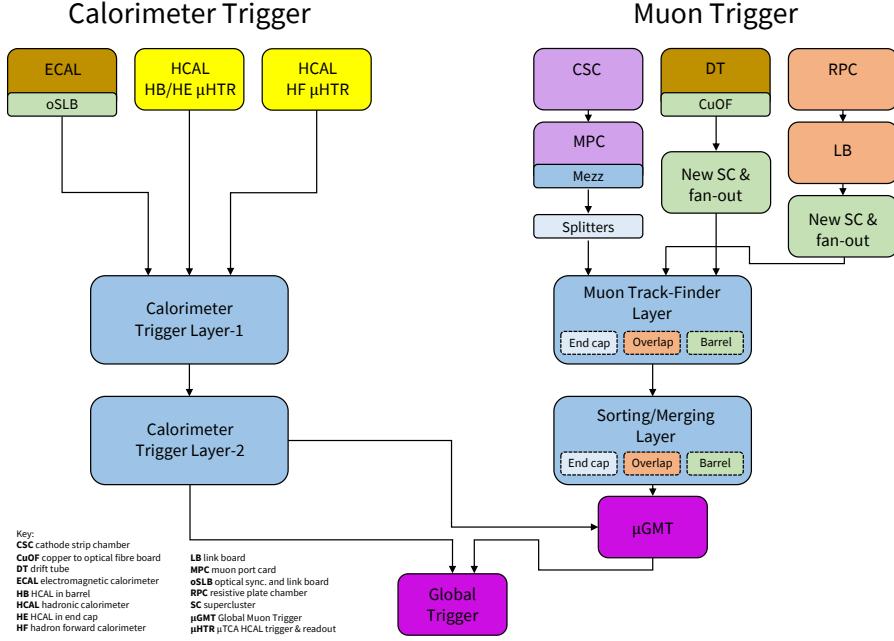


Figure 3.7: A summary of the CMS Level-1 Trigger data flow from the hits recorded by the subsystems to the Global Trigger. Figure reproduced from Ref. [41].

A small subset of data from the L1T is diverted for monitoring purposes. During data taking periods, CMS has a plethora of members that participate in the maintenance and observation of the experiment. At Point 5, shifters monitor the different [areas] collecting information from various sources. Data acquisition, data quality, access to the experimental cavern, the L1T (which I have performed on numerous occasions), and the HLT are among them. Experts in these, and more specific, systems are on call on a rotating period. I, myself, have been an on call for Layer-2 of the Calorimeter Trigger several times.

3.3.2.2 The High-Level Trigger

Events that pass a logical OR of the triggers at Level-1 are transmitted to the HLT. The higher resolution data collected at the point of collision is available, along with information from the tracker. Populated with Intel Xeon processors (high core count CPUs), approximately 22,000 cores are available (by the end of Run-2) to process the data sent from the L1T. In order to avoid a back-log, a 100 kHz input rate allows a HLT node ~ 220 ms to make a decision. High-level software in the cmssw environment (written in C++ and Python, see Chpt. [REF]) is executed. A larger and more complex trigger menu is available, including the possibility analysis-specific triggers (such as those that target VBF topologies in Chpt. 4). Complex variables such as α_T can even be calculated and triggered on.

Physics objects are reconstructed further, with algorithms such as anti- k_T algorithm used to cluster jets [27]. Additional classification algorithms are also applied to objects, such as the DEEPCSV neural network to identify b -jets. Some of these algorithms can be computationally expensive. As such, approximations/parameterisations are used at HLT level. A global event reconstruction from the PARTICLE FLOW algorithm (PF) [70, 75] is performed as well. The [fully-fledged] versions of these kind of algorithms are re-run on the retained events in later stages of postprocessing.

The HLT reduces the event rate from the maximum 100 kHz input substantially down to around 1 kHz. The datastream $\mathcal{O}(6 \text{ GB s}^{-1})$ is then subject to further processing before the analysts access it. As well as the data being stored on networked hard drives at sites across the globe, back ups are made to magnetic tape for long term storage. As with the Level-1 Trigger, some data is [diverted] for monitoring, object calibrations, and alignment of detector components.

3.3.3 Simulating CMS data

3.3.4 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 p_T and 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 [27] 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 of the detector $\langle p_T^{\text{L1}} / p_T^{\text{ref.}} \rangle$, 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 (see Eq. 3.5). 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. 3.8). 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. 3.9 are then passed to the Trigger Studies Group to check over and continue the chain of trigger corrections and object calibrations.

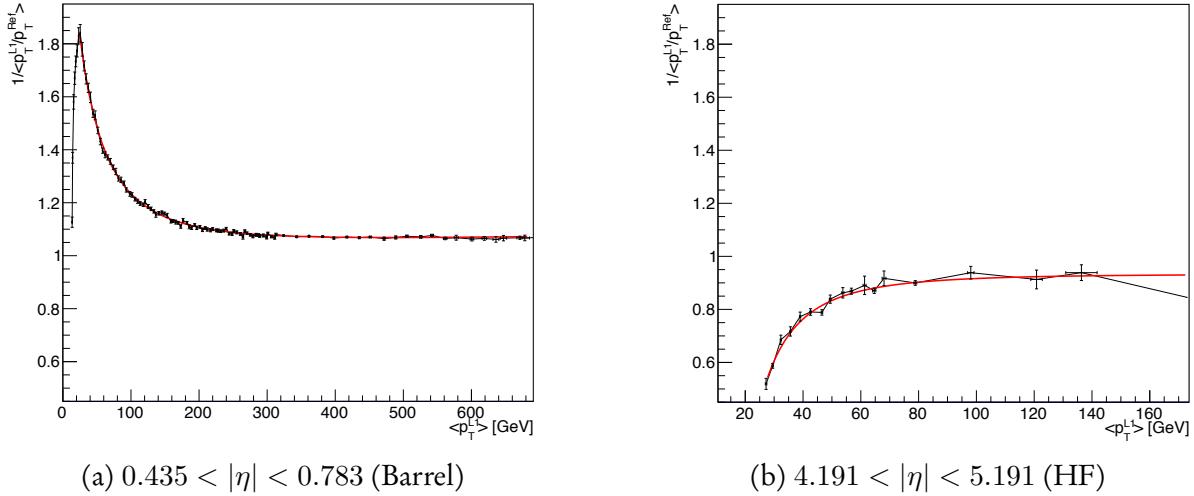


Figure 3.8: Examples of correction curves used to calibrate the jet energies in two $|\eta|$ bins. The response is plotted against the p_T of the Level-1 jet and a complex function produces a fit. These plots are from the jet energy corrections performed on 2018 QCD Monte Carlo.

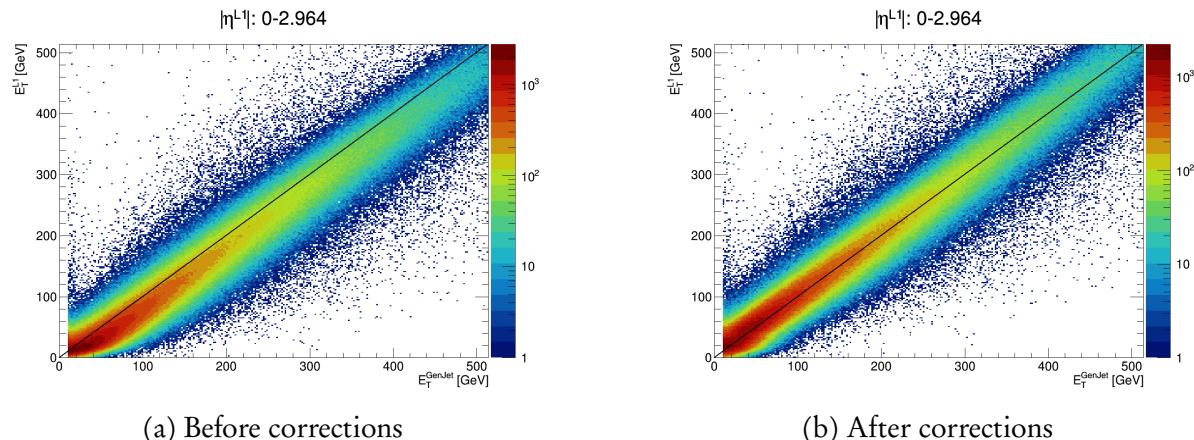


Figure 3.9: The energies of matched pairs of jets in the entire barrel and end cap, before and after jet energy corrections have been applied. After calibrations, the distribution is much more symmetrical. An equivalent plot using jets from LHC data is expected to look similar after applying these calibrations.

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.
- Add a section or subsection somewhere regarding analysis tools. Perhaps add a brief description of ROOT (and how it's entrenched in HEP even though people are tending to move away from ROOT-based analysis onto more industry-standard tools), then lead into the FAST tools and using dataframes, vectorisation, etc., with only small interfaces to ROOT (for I/O) to extract data. Potentially mention how the data tiers work in CMS (RAW, DIGI, RECO, AOD, miniAOD, nanoAOD, etc.)
- 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.
- Since it's my thesis, I can talk about $t\bar{t}H$, VH and $ggF/\text{monojet}$, even though the Bristol contribution to the final, public result would only be $t\bar{t}H$ and resolved VH . Would need to be able to run the fit for all three modes simultaneously, ensuring we have complete (and correct) systematics for ggF .

4.1 Analysis overview

4.1.1 Hadronic production modes of the Higgs boson

4.2 Categorisation of the non-VBF production modes

4.3 Data and simulation

4.3.1 Weights and corrections for simulated processes

In order for simulated events, particularly for background processes, to resemble LHC data as closely as possible, many corrections and weights are applied. These are discussed in more detail in the following sections [REF]. A final event weight w_{event} is the product of the weights from all of the individual sources i that provide a weight:

$$(4.1) \quad w_{\text{event}} = \prod_i w_i$$

When representing these events in histograms, the yield in a given bin $N_{\text{corr.}}$ is the sum of these event weights:

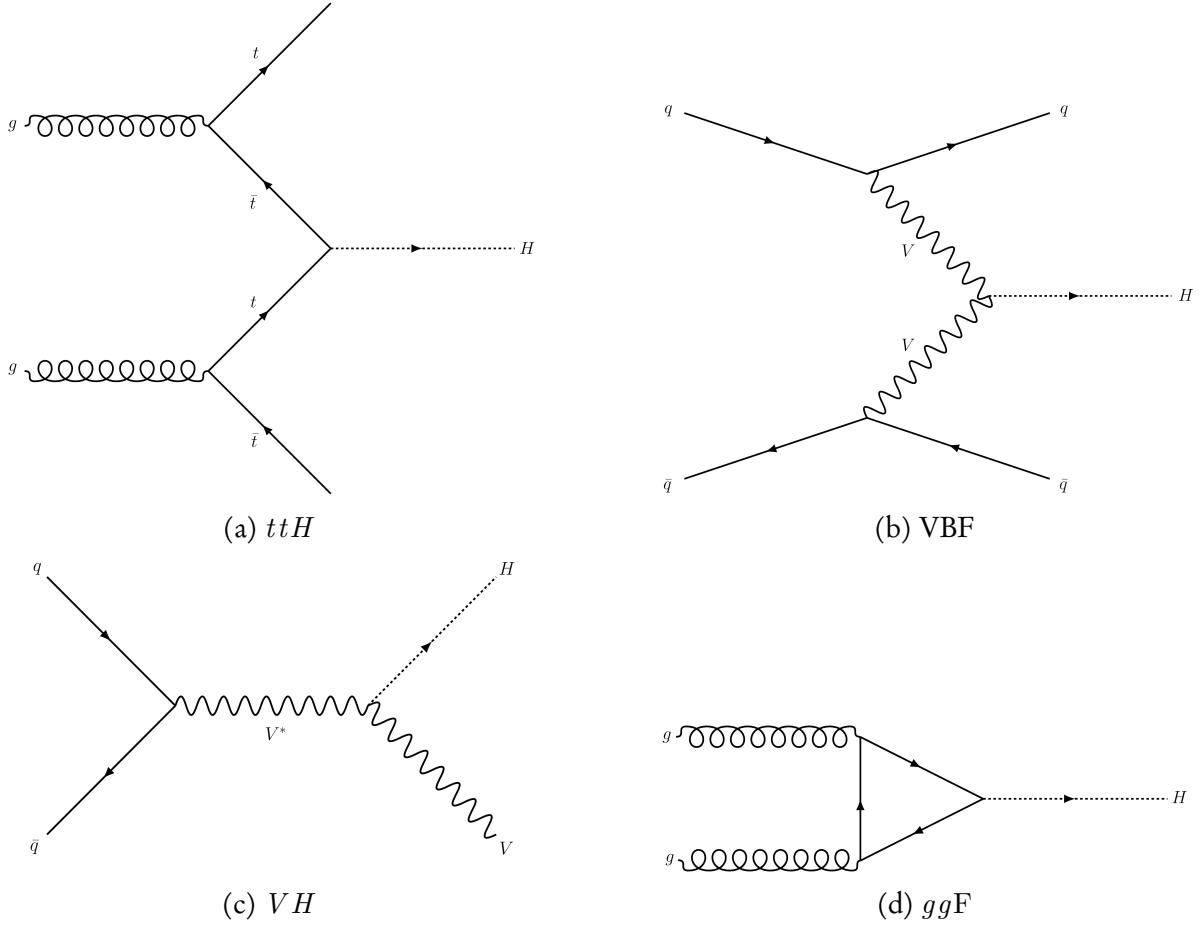


Figure 4.1: The Feynman diagrams for the four main hadronic production modes of the Higgs boson.

$$(4.2) \quad N_{\text{corr.}} = \sum_j^{N_{\text{MC}}} w_{\text{event } j}$$

where N_{MC} is the number of unweighted simulated events in the bin. The statistical uncertainty ascribed to the yield in a bin is given as

$$(4.3) \quad \Delta N_{\text{corr.}} = \pm \frac{N_{\text{corr.}}}{\sqrt{N_{\text{MC}}}}$$

The statistical uncertainty for the number of events in data is simply the Poissonian error

$$(4.4) \quad \Delta N_{\text{data}} = \pm \frac{N_{\text{data}}}{\sqrt{N_{\text{data}}}}$$

The standard prescription for error propagation is to approximate the uncertainty as the square root of the sum of the weights squared [22]:

$$(4.5) \quad \Delta N_{\text{corr.}} = \pm \left(\sum_j^{N_{\text{MC}}} w_{\text{event } j}^2 \right)^{1/2}$$

Our reasoning for using Eq. 4.3 instead of Eq. 4.5 is that the error should be determined purely from the integer number of events we select (k in a Poisson statistical treatment), regardless of whether they are weighted or not. This often reduces the uncertainty for MC compared to Eq. 4.5 since many more events are generated to predict a given equivalent luminosity. Further justification is that it is a good approximation in our assumed regime where we expect a large number of events from our MC samples before any cuts are applied (say N), and a large enough number of events after the cuts such that we do not encounter the low- k or low- N limits of Poissonian error propagation.

4.3.1.1 Cross section reweighting

Since an arbitrary number of events can be generated for simulation, and a larger number of events gives higher statistical power, events in these datasets need to be reweighted to normalise their contribution to a given region or category. To first order, the weight applied is

$$(4.6) \quad w_\sigma = \frac{\sigma \mathcal{L}_{\text{int.}}}{N \varepsilon}$$

where σ is the cross section of the process at the order it was generated (e.g., on DAS/XSDB for public datasets), $\mathcal{L}_{\text{int.}}$ is the integrated luminosity of the LHC data it is being compared to, N is the number of events in the dataset before any skimming (or the sum of the generator weights), and ε is the filter efficiency (assumed to be unity for all datasets since no generator-level cuts are applied). If a dataset is generated at leading order, higher order corrections are usually applied on an event-by-event basis that changes the shapes of distributions (see [SEC ON NLO CORRECTIONS]). In some circumstances, “flat” k-factors can be applied to a dataset that only alters the normalisation (i.e., its cross section).

4.3.1.2 Pileup

Pileup interactions at the LHC are frequent (see Chpt. 3.2.3) and must be modelled appropriately in simulation. Simulated samples are generated with a certain distribution of the

number of pileup interactions which usually does not match the data recorded by CMS. This is due to changing conditions in the beam over a period of data taking. In order to make them comparable, the simulated events are reweighted; in this context it is known as *pileup reweighting*. ROOT files containing histograms of the number of pileup interactions from short runs in the LHC are available centrally and are used as the reference for which to reweight the simulated events.

In the trees of the simulated samples, the branch `Pileup_nTrueInt` is the mean of the Poisson distribution from which random numbers are drawn. In each simulated event, these random numbers (all from the same distribution) are used to set the number of in-time pileup interactions as well as the number of the interactions in each neighbouring bunch crossing to simulate the out-of-time pileup. In data, the same branch gives the average number of pileup interactions for a colliding bunch pair in a lumi section. The distribution of `Pileup_nTrueInt` in the data is derived from the measured instantaneous luminosity for each colliding bunch pair in each lumi section and the cross section of the total inelastic pp interaction.

The nominal pileup weight, as well as the up and down systematic variations, for each simulated event are derived in nanoAOD-tools.

4.3.1.3 Veto and selection weights

In an analysis, events are often rejected by placing kinematic or object-based requirements. This type of selection strictly removes an event from the analysis if the requirement is not met. While kinematic requirements are either fulfilled or not, a different approach can be used when selecting the number of objects, i.e., when defining control regions. For a set of objects, the selection weight at event level is defined as

$$(4.7) \quad w_{\text{sel.}} = \prod_i^{N_{\text{objects}}} \epsilon_i$$

where ϵ_i is the efficiency/scale factor applied to object i . Only reconstructed (“reco” level) objects that have been matched to a generator level object are considered. For leptons (e, μ, τ) and photons, these scale factors are typically from the reconstruction efficiency, identification efficiency, and p_T - or η -dependent energy corrections. In the case of b -tagged jets, it is the data-MC scale factor at the given working point of the algorithm used to identify them. These weights are calculated individually for each type of object in an event, and individually for each source since they also introduce systematic variations that cannot be trivially aggregated. A veto weight is defined as

$$(4.8) \quad w_{\text{veto}} = \prod_i^{N_{\text{objects}}} 1 - \epsilon_i$$

The uncertainties/systematic variations follow the same prescription. With these quantities defined, an event that meets the object criteria is given the selection weight, otherwise it is given the veto weight. For example, if an event with one muon that meets the criteria for the $\mu + \text{jets}$ region will enter that region with its selection weight. That same event can also enter the signal region or one of the sidebands (depending on the event kinematics) with the veto weights. This “migration” of events, where they are able to contribute to more than one region, and the fact that weights are applied instead of event rejection, provides a noticeable decrease to the Monte Carlo statistical uncertainty in a given bin of a given distribution.

One thing must be noted about the migration of events, since we have many different regions of phase space in the analysis. The signal region and the sidebands have orthogonal kinematic requirements, so an event cannot enter the signal region *and* one of the sidebands. The same is true amongst the control regions, i.e., an event cannot enter more than one of them due to the designed orthogonality. An event *is* able to enter the signal region or a sideband with w_{veto} , and also one of the control regions with w_{sel} . Since events in data are not weighted, they may only enter a single region.

4.4 Triggers

4.5 Background estimation

4.5.1 Control regions

4.5.2 Sidebands to the signal region

4.5.3 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.

PARTICLE FLOW algorithm An event reconstruction algorithm used in CMS. Information from all subdetectors is combined so that all stable particles can be identified. Jets are clustered, and complex objects such as *b*-jets are classified..

anti- k_{T} algorithm A sequential clustering algorithm designed to group hadronic particles into jets with a radius parameter (R). The transverse momentum is symbolised as k_{T} instead of p_{T} . In CMS, standard radius parameters are $R = 0.4$ and $R = 0.8$, referred to as AK4 and AK8 jets, respectively..

jet A collimated shower of hadronic particles. High momentum quarks and gluons fragment due to colour confinement; the resulting particles deposit energy in the detector very close to each other and is reconstructed as a single physics object called a jet.

luminosity Instantaneous luminosity is a measure of the collision rate in a particle accelerator (given in units of area per unit time). The integrated luminosity is the instantaneous luminosity integrated over time and is a metric for the total amount of data delivered by an accelerator or collected by a detector.

missing transverse energy The negative vector sum of the transverse momentum of all particles in a collider event. It is sometimes abbreviate to “MET”, and also referred to in literature as “missing transverse momentum” ($p_{\mathrm{T}}^{\mathrm{miss}}$).

pileup The term ascribed to additional proton-proton collisions during a bunch crossing. Pileup interactions typically produce a large number of low-momentum particles.

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

CMSSW CMS SoftWare.

AEGIS Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy.

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.

DAQ data acquisition.

ECAL electromagnetic calorimeter.

FASER ForwArd Search ExpeRiment.

FCC Future Circular Collider.

HCAL hadron calorimeter.

HF hadron forward calorimeter.

HL-LHC High Luminosity Large Hadron Collider.

HLT High-Level Trigger.

ISOLDE Isotope Separator On Line DEvice.

ACRONYMS

JEC jet energy corrections.

L1 Level-1.

L1T Level-1 Trigger.

LEP Large Electron-Positron Collider.

LHC Large Hadron Collider.

LSP lightest supersymmetric particle.

LZ LUX-ZEPLIN.

MC Monte Carlo.

MeV megaelectron volt.

MoEDAL Monopole and Exotics Detector at the LHC.

MOND modified Newtonian dynamics.

PF Particle Flow.

PS Proton Synchrotron.

PSB Proton Synchrotron Booster.

QCD Quantum Chromodynamics.

SM standard model.

SPS Super Proton Synchrotron.

SUSY supersymmetry.

TeV teraelectron volt.

TOTEM TOTal Elastic and diffractive cross section Measurement.

VBF vector boson fusion.

WIMP Weakly Interacting Massive Particle.