

The Hunt for Physics Beyond the Standard Model: Dark Matter, Invisible Higgs Boson Decays,
Large Extra Dimensions and Unparticles in pp Collisions at
 $\sqrt{s} = 13 \text{ TeV}$

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Abstract of Dissertation

The standard model of particle physics is a theory that describes the fundamental structure of matter in the universe, as well as providing a classification for all known elementary particles and their quantum properties. While dark matter has not been directly observed, its existence is implied from astrophysical evidence that cannot be explained by our current understanding of gravity unless more matter is present than is observed. This dissertation explores several models that provide a coupling mechanism between dark matter and ordinary matter. These searches are performed using events with a Z boson candidate and large missing transverse momentum. This dissertation is based on proton-proton collision data at a center-of-mass energy of 13 TeV, collected by the CMS experiment at the LHC in 2016–2018, corresponding to an integrated luminosity of 137 fb^{-1} . The search uses the decay channels $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$. No significant excess of events is observed over the background expected from the standard model. Limits are set on dark matter particle production in the context of simplified models with vector, axial-vector, scalar, and pseudoscalar mediators. For the simplified models, the results are translated to provide limits for spin-dependent and spin-independent scattering cross sections and are compared to those from direct-detection experiments. In addition, results are interpreted for the two-Higgs-doublet model with an additional pseudoscalar. An upper limit is set on the branching fraction of invisible decays of the Higgs boson. Outside the context of dark matter, models that invoke large extra dimensions or propose the production of unparticles could contribute to the same signature and the observed limits on the production cross sections are used to constrain the parameters of these models.

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Chapter 1

Theory

This chapter describes the standard model of particle physics and quantum field theory. Section 1.1 gives an overview of the standard model and some the main discoveries associated with the theory.

1.1 Introduction to the Standard Model of Particle Physics

The standard model (SM) of particle physics is the theory describing three of the four fundamental forces in the universe excluding gravitational forces. The SM describes interactions involving the electromagnetic, weak and strong forces as well as providing a classification for all known elementary particles and their quantum properties. In 1961, Glashow showed that the electromagnetic and weak forces could be unified at high energies using the $SU(2) \times U(1)$ symmetry group [37]. 3 years later Brout, Englert and Higgs published the now commonly known Higgs mechanism [38; 39] which gives mass to Gauge Bosons that were originally considered massless in a Yang-Mills theory [40]. By 1968 Weinberg and Salam were able to combine the electroweak theory with the Higgs mechanism to allow for fermion masses without breaking gauge invariance [41; 42]. While this electroweak, also known as the Glashow-Weinberg-Salam (GWS), theory unified the electromagnetic and weak forces and provided a mechanism for the masses of the elementary particles, it was not considered seriously until 1972, when 't Hooft showed that the theory is renormalizable [43; 44; 45].

In order to complete the SM, quantum chromodynamics (QCD) describes the interactions of the strong force. Based on an $SU(3)$ symmetry [46; 47], QCD predicts an additional property analogous with the electric charge called color. There are eight gluons that are the force carriers for this theory, consisting of three separate color charges instead of the two seen in electromagnetism, where the photon is the mediator [47]. Unlike the photon, however, gluons carry color charge themselves, meaning they not only mediate but also participate in strong interactions. These self interactions constrain color fields to string-like objects which exert a constant force when stretched meaning that it becomes energetically favorable for a new quark-antiquark pair to be produced as colored charged pairs separate. This idea, known as color confinement, while not analytically proven, is well established in lattice QCD [48]. In 1973, QCD became the established theory of the strong force when asymptotic freedom, which describes the reduction in the strength of interactions as the energy scale increases, was discovered by Gross, Wilczek and Politzer [49; 50; 51]

Figure 1.1 shows the elementary particles in the SM: quarks (purple), leptons (green), vector gauge bosons (orange) and the scalar Higgs boson (yellow). The quantum properties are shown for each particle including its' mass, charge and spin. All 3 generations of spin-1/2 fermions are shown for both the quarks and leptons. The force mediators in the SM are the spin-1 bosons: the photon (γ) for electromagnetism; the $W^\pm$ and Z^0 bosons for the weak force; and gluons (g) for the strong force. These gauge bosons arise from invariances in the local gauge symmetry, $SU(3) \times SU(2) \times U(1)$, while the Higgs boson originates from spontaneous symmetry breaking, which gives rise to the masses in the SM.

Standard Model of Elementary Particles

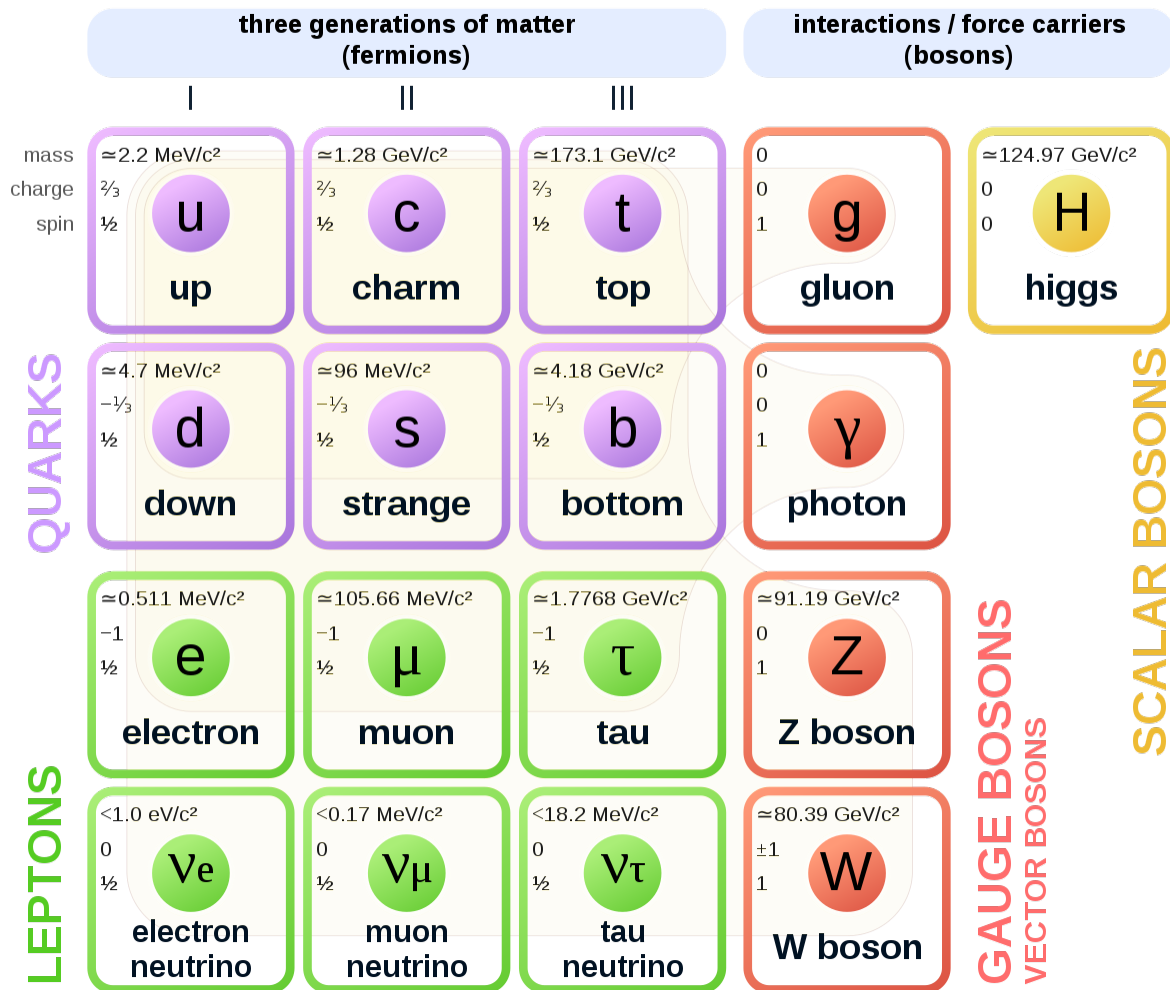


Figure 1.1: The standard model of particle physics. Fermions with half integer spin are shown in the purple for the quarks and green for the leptons. The 3 columns are related to the generations of the fermions. Bosons with integer spin are shown in orange for the vector bosons originating from the gauge groups and in yellow for the Higgs boson.

Chapter 2

Dark Matter

One of the open questions of modern-day physics is related to the properties of DM. This chapter describes the experimental evidence for dark matter as well as the current set of searches for direct observation. Section 2.1 describes the astrophysical evidence implying the existence of DM, introducing galactic rotation curves in Sec. 2.1.1, gravitational lensing in Sec. 2.1.2, and the cosmic microwave background in Sec. 2.1.3. Section 2.2 introduces weakly interacting massive particles as candidates for DM and describes the active experimental program searching for DM, including indirect detection searches in Sec. 2.2.1, direct detection searches in Sec. 2.2.2, and production at particle collider experiments in Sec. 2.2.3. The last 3 subsections focus on specific models that provide a portal to the dark sector, with a simplified model described in 2.3, a two Higgs doublet model in 2.4 and invisible decays of the Higgs boson in 2.5.

2.1 Astrophysical Evidence for Dark Matter

While DM has not been directly observed, its existence is implied from astrophysical evidence that cannot be explained by our current understanding of gravity unless more matter is present than is observed [52]. According to fits based on the Lambda cold dark matter (Λ CDM) model of cosmology [53] to observational data, DM comprises 26.4% of the current matter-energy density of the universe, while baryonic matter accounts for only 4.8% [2].

2.1.1 Galactic Rotation Curves

The rotation curve of a galaxy plots the orbital speed of the visible stars as they traverse around the center of the galaxy. If luminous matter were the only matter in the galaxy, then the rotation curves could be completely determined from Kepler's second law, where the rotation velocities of stars decrease with distance from the center of the galaxy. However, observations of galactic rotation curves do not seem to follow Keplerian dynamics [54]. Instead it was seen that the distribution of mass did not correlate to the distribution of luminous matter [55].

In the 1970s Rubin and Ford provided further measurements of rotation curves showing that stars throughout a spiral galaxy orbit have similar velocities [56; 57]. These results implied that the mass grows linearly with distance from the center of the galaxy, extending beyond the galactic bulge, the central group of stars in a spiral galaxy [58]. This result is in contradiction to the expectation from Kepler's second law, indicating that either there is additional nonluminous mass or that Newton's laws do not fully describe gravity at large scales. Figure 2.1 shows the rotation curve for the spiral galaxy NGC6503 [1]. The contributions are split into effects from halo formed of DM, the luminous matter in the disk and from gas. The presence of DM is implied from the discrepancy between the observed velocities and the predictions from luminous matter.

The velocity distribution based on keplerian mechanics can be seen in equation 2.1 where $M(r) = 4\pi \int \rho(r)r^2 dr$, and $\rho(r)$ is the mass density profile where $M(r) \propto 1/\sqrt{r}$ beyond the optical disk. The observations that show $v(r)$ is approximately constant indicate the existence of a halo with $M(r) \propto r$ and $\rho(r) \propto 1/r^2$ [59].

$$v(r) = \sqrt{\frac{GM(r)}{r}} \quad (2.1)$$

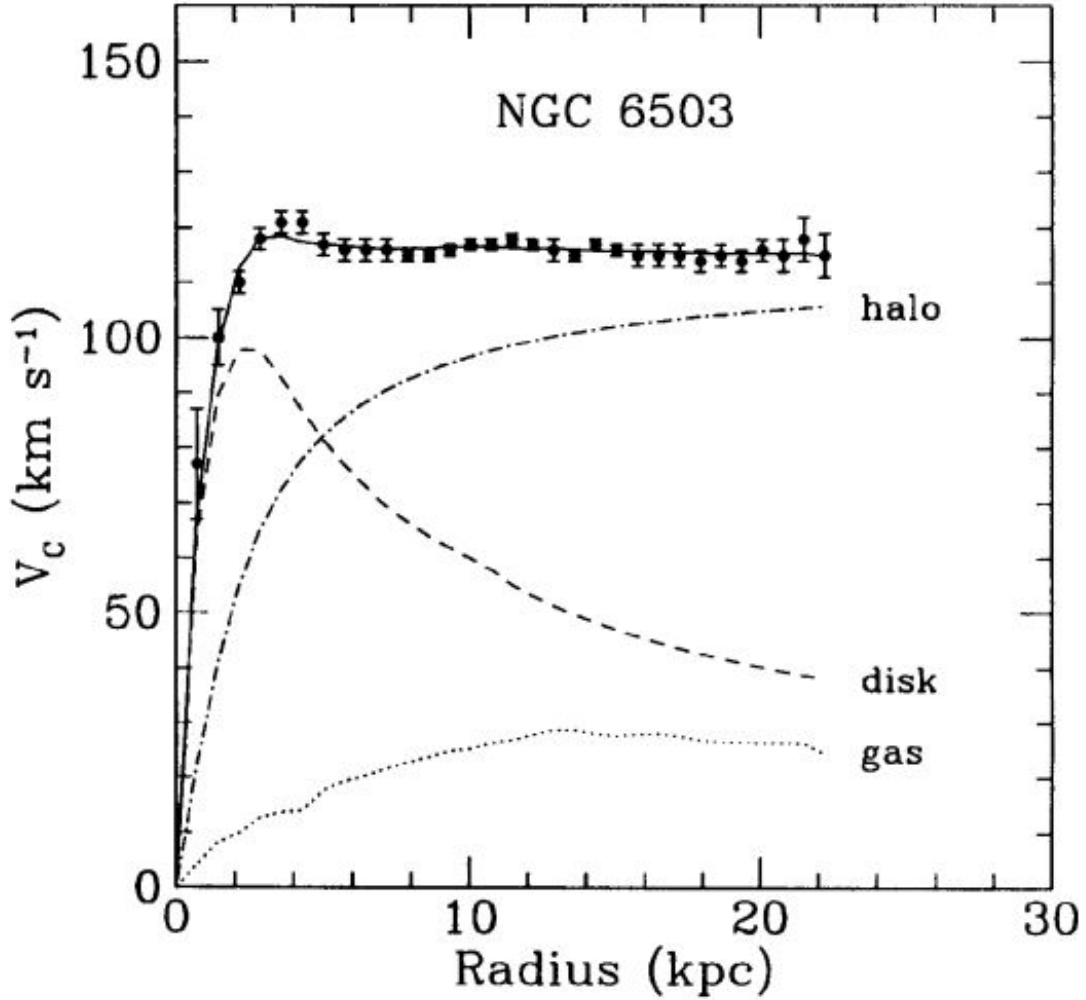


Figure 2.1: The rotation curve showing the velocity of stars in the spiral galaxy NGC6503 [1]. Here, the contributions are split into effects from halo formed of DM (dash-dotted line), the luminous matter in the disk (dashed line) and from gas (dotted line). The velocity predicted from the combination is shown in the solid line strongly indicating the presence of DM.

2.1.2 Gravitational Lensing

In 1915, Einstein published the theory of general relativity (GR) [60], the geometric theory which describes gravity. GR generalizes special relativity and describes gravity in a four-dimensional spacetime where the curvature of this spacetime is determined by the energy and momentum of the present matter. GR also predicts that particles in free motion will follow straight world lines in this curved spacetime, which can be described by geodesics. The consequence of this, is that particles, including light, will appear to bend around massive objects that curve spacetime [61].

In 1919, the first physical evidence for the bending of light was obtained by observing stars near the sun during a solar eclipse [62]. The light from stars near the sun were observed to be slightly out of position indicating that the light was acting in accordance with the predictions of GR. The consequence of light bending around massive objects led to the idea that massive objects in the universe could be used in a similar fashion as an optical lens. This idea, called gravitational lensing, was first considered by Einstein in 1912 [61], however, as he only considered deflection around individual stars, observation was considered impractical. In 1937, this was reconsidered after Zwicky showed that the newly discovered galaxies could act as gravitational lenses [63]. However, even with all the theoretical framework in place, gravitational lensing was not observed until 1979 at the Kitt Peak National Observatory [64], when a quasar appeared as 2 images. Originally named as Twin QSO for the 2 apparent quasistellar objects observed, it was soon identified as a single gravitationally lensed quasar. Figure 2.2 shows a Hubble image of the Twin QSO object originally observed in 1979 showing the gravitationally lensed quasar in the middle of the image as 2 separated quasars.

The observed distortions of background galaxies or galaxy clusters can also provide a measurement of the intermediate mass [65]. These estimations of the intermediate mass clusters as well as the measurement of the spectrum of light observed were seen to correspond to predictions of dark



Figure 2.2: A Hubble image of the Twin QSO object originally observed in 1979. Image courtesy of: <https://www.spacetelescope.org/>

matter clusters [66]. Dark matter subhalos can also be resolved by mapping the lensing-inferred substructure of clusters [67]. This mapping is further evidence for dark matter in the universe. Figure 2.3 shows the effect of lensing indicating the presence of dark matter.



Figure 2.3: An image from the NASA/ESA Hubble Space Telescope. This image shows a galaxy cluster that has gravitational lensing effects. Image courtesy of: <https://www.spacetelescope.org/>

2.1.3 Anisotropies in the Cosmic Microwave Background

The cosmic microwave background (CMB) is electromagnetic radiation remnant from an early stage of the universe. The CMB is an almost uniform background radiation in the microwave region of the radio spectrum observed in all regions of space. The CMB was accidentally discovered

in 1965 by Penzias and Wilson [68], when they observed that the sky had a temperature around 3°K that was isotropic, unpolarized and free from seasonal variations. By the 1970s the established consensus was that the CMB was a thermal black body spectrum remnant from the Big Bang at the early stages of the universe [69].

While, the CMB was originally seen as an isotropic background, further investigations showed microkelvin fluctuations in temperature [70; 71]. These results have been improved upon significantly in recent years with WMAP [52] and more recently Planck [2] mapping out the CMB temperature. Figure 2.4 shows the temperature map of the CMB from the Planck experiment. This map shows the microkelvin fluctuations of the CMB temperature from the nominal value. Here, grey bands mark the regions where residuals from foreground emission are expected to be substantial.

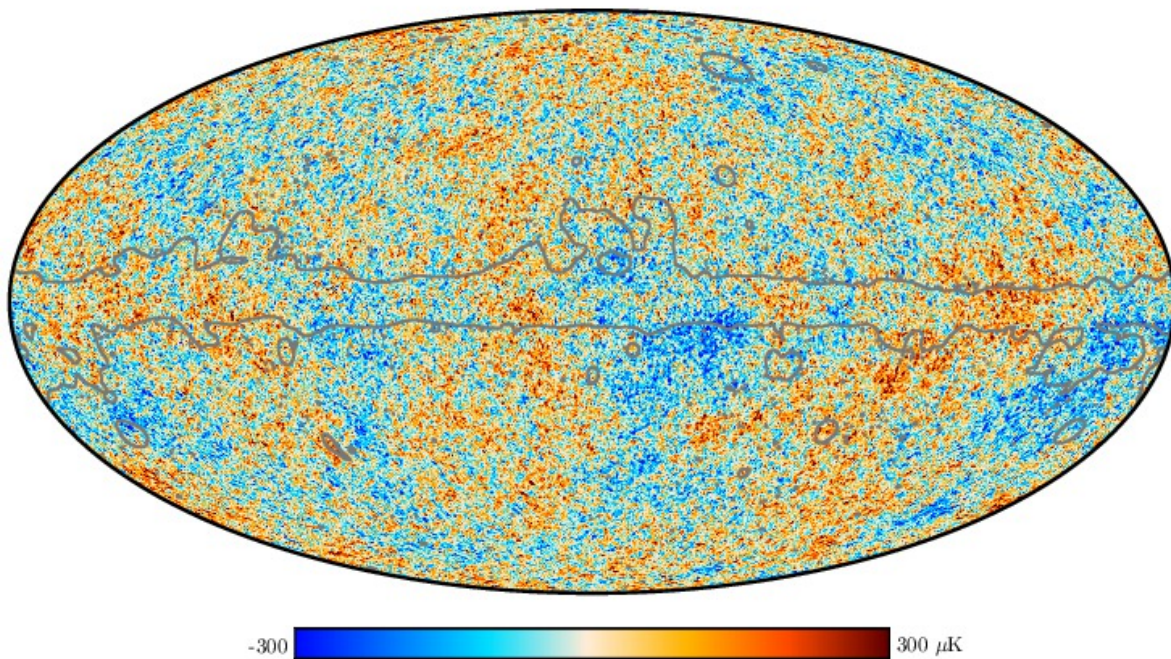


Figure 2.4: The temperature map of the CMB showing the fluctuations in temperature. Grey bands represent the regions where foreground emission is substantial [2].

In the early universe, ordinary matter was ionized and interactions were dominated by radiation from Thomson scattering. Since DM particles do not interact electromagnetically, DM would only affect the CMB through gravitation. The gravitational effects from DM would correspond to changes of the density and velocity of ordinary matter on large scales. The anisotropies shown in figure 2.4 can be decomposed into an angular power spectrum which provides strong evidence for dark matter as the structure is well predicted by Λ CDM [53; 72]. Figure 2.5 shows the Planck [2] CMB power spectra where the best-fitting model for Λ CDM includes pressureless DM that interacts with ordinary matter only gravitationally.

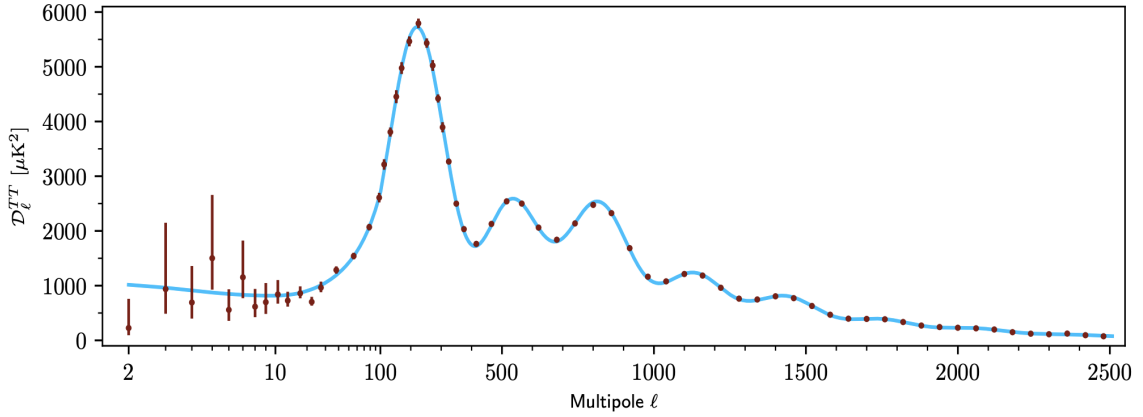


Figure 2.5: The Planck CMB power spectra. This distribution is the foreground-subtracted, frequency-averaged, angular power spectra. The blue lines show the best-fitting model for Λ CDM including pressureless DM that interacts with ordinary matter only gravitationally [2].

2.2 WIMP Dark Matter

Weakly interacting massive particles (WIMPs) are a hypothetical proposed candidate for DM. While there is no rigid definition of what constitutes a WIMP, they are generally new elemental particles that interact with the SM as weak or weaker than the weak nuclear force.

In the early universe, particles were in a state of thermal equilibrium. Given DM particles

(χ) that self-annihilate and sufficiently high temperatures ($T \gg m_\chi$), DM particles and their antiparticles would be constantly forming and subsequently annihilating into lighter particles. As time progressed and the universe expanded, the average thermal energy would decrease, eventually reaching a thermal energy insufficient to produce DM particle pairs. While the DM particle production rate would be reduced, DM self-annihilation would continue, causing an exponential decrease in the number density of DM particles ($n_\chi \propto e^{-m_\chi/T}$) [73; 74]. This decrease in the number density would continue until the number density became so low that DM particle interactions would cease, leaving an approximately constant number density as the universe continued to expand. The period of time to reach this equilibrium or “freeze-out”, would be determined by the self-annihilation cross section, with larger cross sections leading to the DM annihilating for a longer period with a lower remaining relic abundance as a result [75]. Evidence from astrophysical observations give an estimate on the current abundance of DM in the universe. If the DM particle is a relic particle, the self-annihilation cross section is constrained to be as weak or weaker than the weak nuclear force.

The estimate of the DM relic density is shown in Equation 2.2 where, σv is the total annihilation cross section multiplied by the velocity and the brackets indicate the thermal average [59]. This was approximated with a non-relativistic expansion in powers of v^2 and evaluated at the freeze-out temperature.

$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle} \quad (2.2)$$

In spite of the abundance of DM, its nature remains unknown. This mystery is the subject of an active experimental program to search for dark matter particles, including direct-detection experiments that search for interactions of ambient DM with ordinary matter, indirect-detection experiments that search for the products of self-annihilation of DM in outer space, and searches at accelerators and colliders that attempt to create DM in the laboratory. Figure 2.6 shows a diagram showing the different detection techniques used to search for evidence of DM. The arrows indicate

the flow of time for the different interactions, yielding a different combination of SM and DM particles.

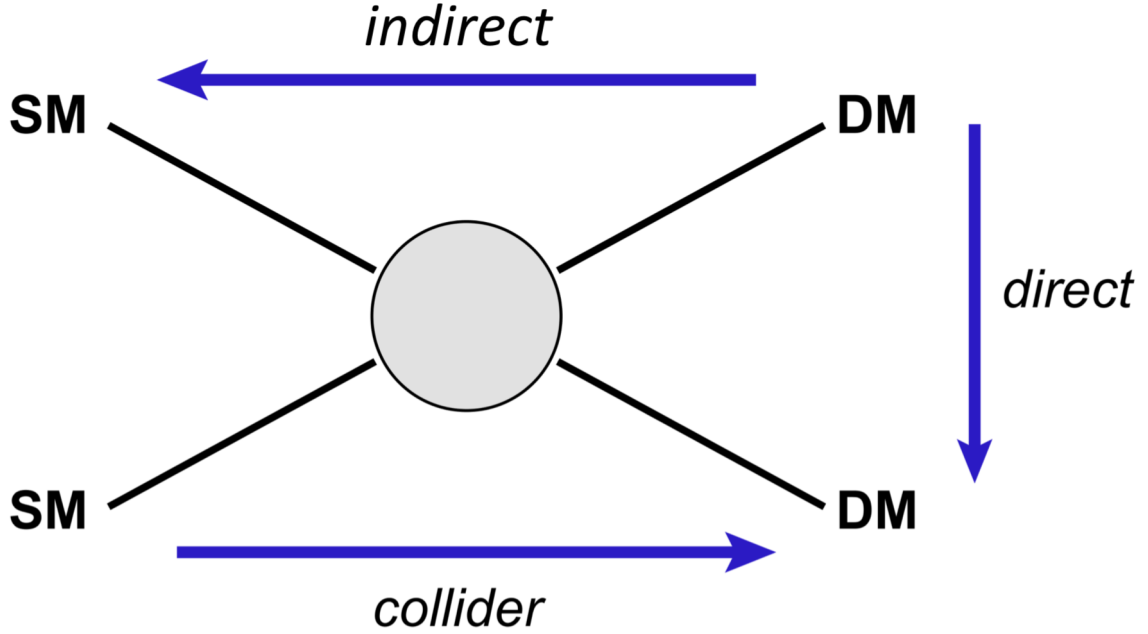


Figure 2.6: A diagram showing the indirect, direct and collider production detection methods for DM particles. Here, the arrows indicate the flow of time for the different interactions, yielding a different combination of SM and DM particles.

2.2.1 Indirect Detection

Indirect detection experiments aim to search for particles originating from the self-annihilation or decay of dark matter particles in the universe. In regions of high dark matter density, DM particles could collide, annihilate and produce SM particles, either in particle-antiparticle pairs or through high energy photons (gamma rays). If the DM particles are inherently unstable, they could also decay into SM particles. Both of these processes have potential to be detected indirectly through observations of excess amounts of gamma rays, antiprotons or positrons [76; 59]. Figure 2.7 shows an example process of DM particle self-annihilation, where the DM particles annihilate and produce SM particles. This type of interaction could be observed through an excess amount of gamma

rays, antiprotons or positrons all associated with pion decays.

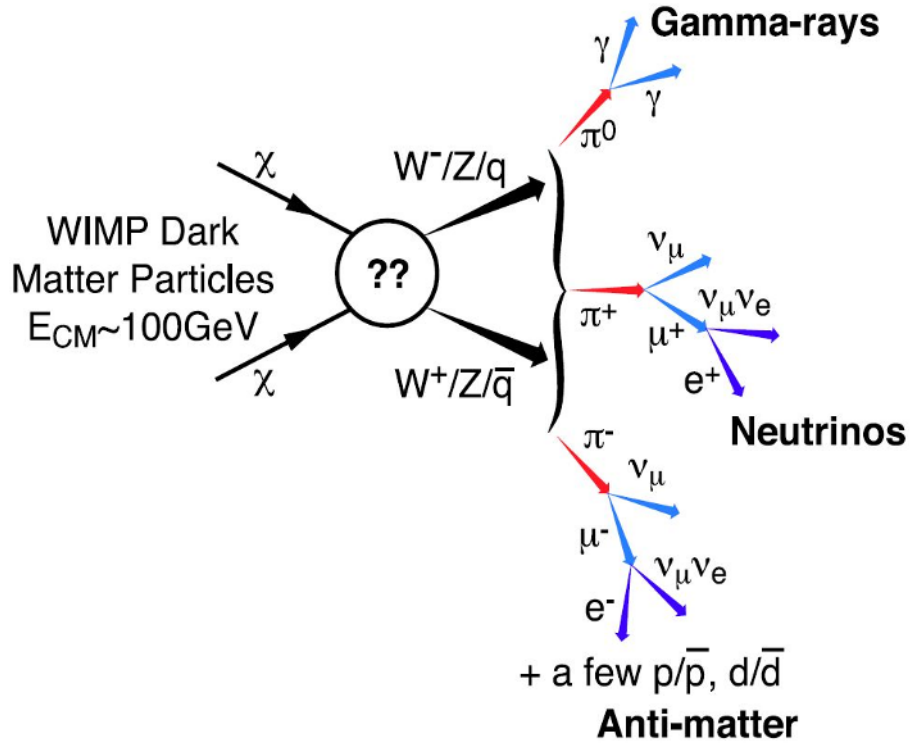


Figure 2.7: A process showing DM particle self-annihilation. Here the DM particles annihilate and produce SM particles which could be observed through an excess amount of gamma rays, antiprotons or positrons.

In addition to self-annihilation in space, excess neutrinos from stars such as our sun may indicate the presence of DM. As DM particles pass through massive objects, they may scatter off SM particles, losing energy. This could cause an accumulation of DM particles at the center of massive objects. If these DM self-annihilate, they could be observed as an excess amount of high energy neutrinos originating from these bodies [77].

Several experiments are already searching for these distinct signatures. The Fermi-LAT [78] looks for excess gamma rays. The PAMELA experiment [79; 80] has observed an excess of positrons, that could be caused from DM particle annihilation or from pulsars. The PAMELA experiment also searched for excess antiprotons but did not observe any excess. The Alpha Mag-

netic Spectrometer (AMS-02) [81], located on the international space station, also indicated an excess of high energy positrons. The IceCube [82] and Super-Kamiokande [33] neutrino observatories have presented constraints on the annihilation cross section from searches for an excess neutrino flux.

2.2.2 Direct Detection

Direct detection experiments attempt to collect direct evidence for the presence of dark matter through the observation of low energy elastic collisions between DM particles and atomic nuclei. As DM particles pass through the Earth, they can collide with a nucleus that will emit energy (on the order of keV) as scintillation light or as phonons as they pass through a sensitive apparatus. These apparatuses are often buried deep underground in order to reduce the background, specifically from cosmic rays. Direct detection experiments primarily use either cryogenic detectors, operating at temperatures below 100 mK, or liquid detector technologies that detect scintillation originating from a collision with a noble liquid or metalloid, such as a xenon, argon or germanium nuclei. Figure 2.8 shows an example diagram of a direct detection apparatus that could measure the recoil energy of a DM particle colliding with a germanium nucleus.

While no evidence for DM has been found from direct detection experiments, several experiments have placed limits on the nucleon cross sections of DM interactions. Some example of recent limits from noble liquid experiments include recently published results from the XENON1T [25], the Large Underground Xenon (LUX) [26], the DarkSide-50 [29] and the PandaX-II [27] experiments. Results from cryogenic detectors include the CRESST-III [28], the CDMS and Super-CDMS [83] experiments, while additional results from bubble chambers include the PICO-60 [30] and PICO-2L [31] experiments.

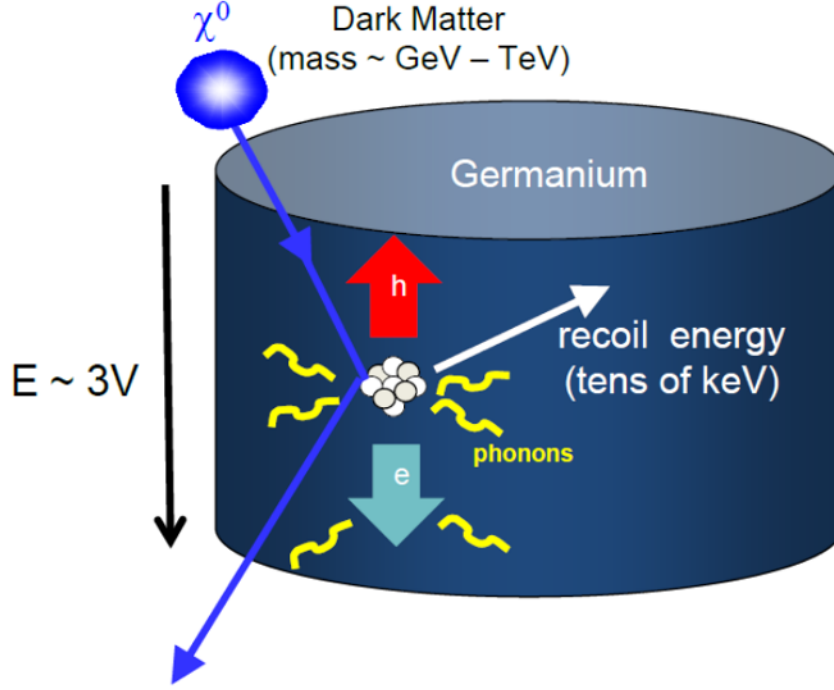


Figure 2.8: A diagram of an example direct detection apparatus designed to measure the recoil energy of a DM particle (χ^0) colliding with a germanium nuclei.

2.2.3 Production in Particle Colliders

If DM is a thermal relic, the relative abundance, as discussed in Sec. 2.2, can be estimated with recent results from Planck yielding $\Omega_\chi h^2 \sim 0.12$ [84; 2]. With this relic abundance and as a consequence of a unitary bound limit on the maximum annihilation cross section (σv), DM particles are assumed to be light ($m_\chi \lesssim 34$ TeV) [59]. With DM particles in the GeV and TeV mass range, experiments at the LHC may be able to detect DM particles produced in the proton-proton (pp) collisions. Because DM will have negligible interactions with the SM, the DM particles would not be detected by typical detector systems, instead appearing as large amounts of missing transverse momentum (p_T^{miss}).

The search presented in this thesis considers a “mono- Z ” scenario where a Z boson, produced in pp collisions, recoils against DM or other beyond the standard model (BSM) invisible particles. The Z boson subsequently decays into two charged leptons ($\ell^+ \ell^-$, where $\ell = e$ or μ) yielding

a dilepton signature, and the accompanying undetected particles contribute to missing transverse momentum. The analysis is based on a data set of pp collisions at a center-of-mass energy of 13 TeV produced at the CERN LHC. The data were recorded with the CMS detector in the years 2016–2018, and correspond to an integrated luminosity of 137 fb^{-1} .

These results extend and supersede a previous search by CMS in the mono- Z channel based on a data set collected at $\sqrt{s} = 13 \text{ TeV}$ corresponding to an integrated luminosity of 36 fb^{-1} [85]. The ATLAS experiment has published searches in this channel as well with the latest result based on a data set corresponding to an integrated luminosity of 36 fb^{-1} [86]. Similar searches for DM use other “mono-X” signatures with missing transverse momentum recoiling against a hadronic jet [87; 88], a photon [89], a heavy-flavor (bottom or top) quark [90; 91; 92], a W or Z boson decaying to hadrons [88; 86; 93], or a Higgs boson [94; 95; 96; 97; 98; 99]. An additional DM interpretation is explored in searches for Higgs boson decays to invisible particles [34; 35].

2.3 Simplified Dark Matter Models

First, we consider a set of simplified models for DM production [100; 101]. These models describe the phenomenology of DM production at the LHC with a small number of parameters and provide a standard for comparing and combining results from different search channels. Four simple ultraviolet-complete models that contain a massive mediator exchanged in the s -channel are considered. For these models, the mediator (either a scalar, psuedoscalar, vector, or axial-vector) couples directly to quarks and the DM particle χ , where χ is assumed to be a Dirac fermion as shown in Fig. 2. Here, the couplings to Standard model quarks, the coupling to dark matter and the mediator mass are all tunable parameters leading to a wide variety of kinematic possibilities. The interaction Lagrangian of the s -channel vector-mediated (axial-vector-mediated) DM model can be written as:

$$\mathcal{L}_{vector} = -g_\chi \mathcal{A}'_\mu \bar{\chi} \gamma^\mu \chi - g_q \sum_{q=u,d,s,c,b,t} \mathcal{A}'_\mu \bar{q} \gamma^\mu q \quad (2.3)$$

$$\mathcal{L}_{axial-vector} = -g_\chi \mathcal{A}'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi - g_q \sum_{q=u,d,s,c,b,t} \mathcal{A}'_\mu \bar{q} \gamma^\mu \gamma^5 q \quad (2.4)$$

Here, $\mathcal{A}'$ is the new vector (axial-vector) mediator, g_q is the coupling between the vector (axial-vector) mediator and the Standard Model quarks and g_χ is the coupling between the vector (axial-vector) mediator and the dark matter particles, χ . The universality of the g_q ensures that the simplified models are minimal flavor violating and avoid constraints from quark flavor physics. The minimal decay width of the mediator can be calculated by a sum of the partial widths which are shown below for the vector mediator:

$$\Gamma_{vector}^{\chi\bar{\chi}} = \frac{g_\chi^2 M_{med}}{12\pi} (1 - 4z_\chi)^{1/2} (1 + 2z_\chi) \quad (2.5)$$

$$\Gamma_{vector}^{q\bar{q}} = \frac{g_q^2 M_{med}}{4\pi} (1 - 4z_q)^{1/2} (1 + 2z_q) \quad (2.6)$$

Here, $z_{\chi,q} = m_{\chi,q}^2/M_{med}^2$ and both types of contributions vanish for $M_{med} < 2m_{\chi,q}$. The partial widths for the axial-vector mediator are:

$$\Gamma_{axial-vector}^{\chi\bar{\chi}} = \frac{g_\chi^2 M_{med}}{12\pi} (1 - 4z_\chi)^{3/2} \quad (2.7)$$

$$\Gamma_{axial-vector}^{q\bar{q}} = \frac{g_q^2 M_{med}}{4\pi} (1 - 4z_q)^{3/2} \quad (2.8)$$

In addition to the vector (axial-vector) models, two spin-0 models are also explored using a scalar (pseudoscalar) mediator. The interaction Lagrangians can be written as:

$$\mathcal{L}_{scalar} = -g_\chi \phi \bar{\chi} \chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} q \quad (2.9)$$

$$\mathcal{L}_{pseudoscalar} = -g_\chi \phi \bar{\chi} \gamma^5 \chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} \gamma^5 q \quad (2.10)$$

Here, $y_q = \sqrt{2}m_q/v$ which represent the SM quark Yukawa couplings with $v \simeq 246$ GeV, the Higgs vacuum expectation value. Again, these models are compatible with the minimal flavor violating hypothesis. In the spin-0 models, an additional contribution arises from loop-induced decays into gluons. The partial widths are shown below for the scalar mediator:

$$\Gamma_{scalar}^{\chi\bar{\chi}} = \frac{g_\chi^2 M_{med}}{8\pi} (1 - 4z_\chi^2)^{3/2} \quad (2.11)$$

$$\Gamma_{scalar}^{q\bar{q}} = \frac{3g_q^2 y_q^2 M_{med}}{16\pi} (1 - 4z_q^2)^{3/2} \quad (2.12)$$

$$\Gamma_{scalar}^{gg} = \frac{\alpha_s^2 g_q^2 M_{med}^3}{32\pi^3 v^2} |f_{scalar}(4z_t)|^2 \quad (2.13)$$

The corresponding pseudoscalar partial widths are:

$$\Gamma_{pseudoscalar}^{\chi\bar{\chi}} = \frac{g_\chi^2 M_{med}}{8\pi} (1 - 4z_\chi^2)^{1/2} \quad (2.14)$$

$$\Gamma_{pseudoscalar}^{q\bar{q}} = \frac{3g_q^2 y_q^2 M_{med}}{16\pi} (1 - 4z_q^2)^{1/2} \quad (2.15)$$

$$\Gamma_{pseudoscalar}^{gg} = \frac{\alpha_s^2 g_q^2 M_{med}^3}{32\pi^3 v^2} |f_{pseudoscalar}(4z_t)|^2 \quad (2.16)$$

Here, the form factors are given by:

$$f_{scalar}(\tau) = \tau \left[1 + (1 - \tau) \arctan^2 \left(\frac{1}{\sqrt{\tau - 1}} \right) \right] \quad (2.17)$$

$$f_{pseudoscalar}(\tau) = \tau \arctan^2 \left(\frac{1}{\sqrt{\tau - 1}} \right) \quad (2.18)$$

Both $f_{scalar}(\tau)$ and $f_{pseudoscalar}(\tau)$ are defined for $\tau < 1$, but are complex. As with the vector and axial-vector models, the total widths of the mediators do not contribute for $M_{med} < 2m_{\chi,q}$. Decays into gluon pairs are relevant for $200 \lesssim M_{med} \lesssim 400$ GeV and if invisible decays are kinematically forbidden.

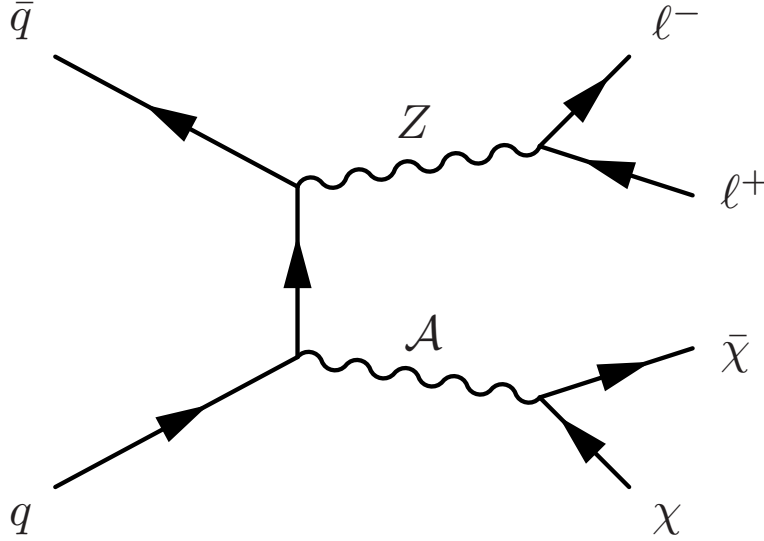


Figure 2.9: Feynman diagram showing dark matter production through the simplified model in the Z boson plus missing p_T^{miss} channel. Here A represents the DM mediator and χ represents a DM particle

The free parameters of each model are the mass of the DM particle m_χ , the mass of the mediator m_{med} , the mediator-quark coupling g_q , and the mediator-DM coupling g_χ . Following the suggestions in Ref. [101], for the vector and axial-vector studies, we fix the couplings to values of $g_q = 0.25$ and $g_\chi = 1$ and vary the values of m_χ and m_{med} , and for the scalar and pseudoscalar studies, we fix the couplings $g_q = 1$ and $g_\chi = 1$, set the dark matter particle mass to $m_\chi = 1$ GeV, and vary the values of m_{med} . The comparison with data is carried out separately for each of the four spin-parity choices for the mediator.

2.4 Two Higgs Doublet Model

We also explore a two-Higgs-doublet model (2HDM) with an additional pseudoscalar boson, $\mathbf{a}$, that serves as the mediator between DM and ordinary matter. This “2HDM+ $\mathbf{a}$ ” model [102; 103] is a gauge-invariant and renormalizable model that contains a Higgs scalar (h) corresponding to the observed 125 GeV Higgs boson, a heavy neutral Higgs scalar (H), a charged Higgs scalar ($H^\pm$), and two pseudoscalars (A , $\mathbf{a}$), where the pseudoscalar bosons couple to the DM particles. For the process studied in this paper, the H boson is produced via gluon fusion and decays into a standard model (SM) Z boson and the pseudoscalar $\mathbf{a}$. These subsequently decay into a pair of leptons and a pair of DM particles, respectively, as shown in Fig. 2.10.

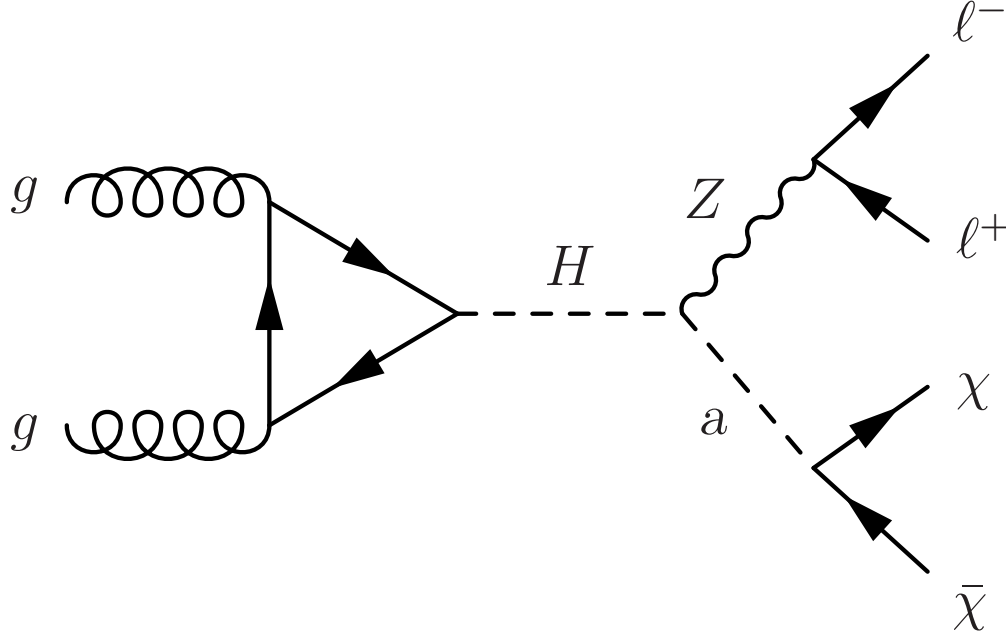


Figure 2.10: Feynman diagram showing dark matter production through the 2HDM+ $\mathbf{a}$ model in the Z boson plus missing p_T^{miss} channel. (H , h) and $\mathbf{a}$ represent the scalar and pseudoscalar Higgs bosons.

The “2HDM+ $\mathbf{a}$ ” model contains 2 Higgs doublets with an additional pseudoscalar singlet P , and is the simplest renormalizable extension of the simplified models with a SM-singlet DM candidate [103]. This model has a gauge symmetry made by coupling the pseudoscalar $\mathbf{a}$ to the DM Dirac fermion χ via:

$$\mathcal{L}_\chi = -iy_\chi P \bar{\chi} \gamma^5 \chi \quad (2.19)$$

The Higgs doublets, H_1 and H_2 , couple to the standard model fermions via:

$$\mathcal{L}_Y = - \sum_{i=1,2} (\bar{Q} Y_u^i \tilde{H}_i u_R + \bar{Q} Y_d^i \tilde{H}_i d_R + \bar{L} Y_l^i \tilde{H}_i l_R + h.c.) \quad (2.20)$$

Here, y_χ is the dark sector Yukawa coupling, Y_f^i are the Yukawa matrices for the generations of the fermion family f , Q and L the left-handed quark and lepton doublets and f_R are the right-handed singlets for each fermion family f . Additionally, $\tilde{H} = \epsilon H_i^*$, where ϵ denotes the asymmetric 2-dimensional tensor.

The particle that acts as a portal between the SM and the dark sector is a superposition of the CP-odd components of the H_1 and H_2 doublets and the P singlet. A Z_2 symmetry is imposed where $H_1 \rightarrow H_1$ and $H_2 \rightarrow -H_2$ such that only one of the Higgs doublets couple to the a fermion in $\mathcal{L}_Y$. This Z_2 symmetry is the minimal condition in order to prevent flavor-changing neutral currents at tree level [104; 105]. The field P is Z_2 -even ($P \rightarrow P$), while the field χ is Z_2 -odd ($\chi \rightarrow -\chi$) and the coupling from Eg. 2.19 is the only DM Yukawa coupling allowed by this symmetry. Additionally, the parameters of the scalar potential are chosen to be real with the CP eigenstates being identified with the mass eigenstates of the 2 scalars h and H , 2 pseudoscalars a and A and the charged scalars $H^\pm$. The renormalizable scalar can be written as:

$$V = V_H + V_{HP} + V_P \quad (2.21)$$

Where the different potentials are defined as:

$$\begin{aligned} V_H = & \mu_1 H_1^\dagger H_1 + \mu_2 H_2^\dagger H_2 + (\mu_3 H_1^\dagger H_2 + h.c.) + \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 \\ & + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + [\lambda_5 H_1^\dagger H_2 + h.c.] \end{aligned} \quad (2.22)$$

$$V_{HP} = P(ib_P H_1^\dagger H_2 + h.c.) + P^2(\lambda_{P1} H_1^\dagger H_1 + \lambda_{P2} H_2^\dagger H_2) \quad (2.23)$$

$$V_P = \frac{1}{2} m_P^2 P^2 \quad (2.24)$$

Here, b_P is the trilinear portal coupling and the terms $\mu_3 H_1^\dagger H_2 + h.c.$ and $P(ib_P H_1^\dagger H_2 + h.c.)$ softly break the Z_2 symmetry. Quartic portal interactions are proportional to λ_{P1} and λ_{P2} while a self coupling P^4 does not lead to any relevant effect on typical observables such as p_T^{miss} . With the rotation to the mass eigenbasis, the 5 parameters with dimensions as well as the 8 dimensionless parameters in the potential are transformed into physical masses, mixing angles and quartic couplings:

$$\left\{ \begin{array}{cccccc} \mu_1, & \mu_2, & \mu_3, & b_P, & m_P, & m_\chi \\ y_\chi, & \lambda_1, & \lambda_2, & \lambda_3, & \lambda_4, & \lambda_5 \\ & & & \lambda_{P1}, & \lambda_{P2} & \end{array} \right\} \longleftrightarrow \left\{ \begin{array}{l} v, M_h, M_A, M_H, M_{H^\pm}, M_a, m_\chi \\ \cos(\beta - \alpha), \tan(\beta), \sin(\theta) \\ y_\chi, \lambda_3, \lambda_{P1}, \lambda_{P2} \end{array} \right\} \quad (2.25)$$

Here, α and θ are the mixing angles between the CP-even and CP-odd weak spin-0 eigenstates, respectively. The ratio of the vacuum expectation values (VEV) of the Higgs doublets is given by $\tan \beta$ with the EW VEV $v \simeq 246$ GeV and the mass of the CP-even mass eigenstate $M_h \simeq 125$ GeV fixed by observations. The sizable couplings of the Z boson to the Higgs bosons makes the mono- Z channel more sensitive to this model than the mono-jet or mono-photon channels. We consider only configurations in which $m_H = m_{H^\pm} = m_A$, and fix the values $\tan \beta = 1$ and $\sin \theta = 0.35$, following the recommendations of Ref. [103].

2.5 Invisible Decays of the Higgs Boson

In the SM, as seen in Fig. 2.11, the only fully invisible decays of the Higgs boson ($H \rightarrow inv$) is through the $H \rightarrow ZZ \rightarrow 4\nu$ process which has a branching fraction, $\mathcal{B}(H \rightarrow inv) \sim 10^{-3}$ [34]. However, the rate of invisible decays could be greatly enhanced in the context of several BSM scenarios, such as “Higgs portal” models [106; 107; 108; 109]. If $m_\chi < m_h/2$, the Higgs boson could decay invisibly into a pair of DM particles. More specifically, for this thesis, the dark matter particle is a fermion singlet that couples to a scalar boson which itself mixes with the Higgs through the following interactions:

$$\mathcal{L} = \mathcal{L}_{SM} - \mu_s s^3 - \lambda_s s^4 - y_\chi \bar{\chi} \chi s - \mu_p s |H|^2 - \lambda_p s^2 |H|^2 \quad (2.26)$$

Where s is the real scalar mediator that couples to dark matter, y_χ is the Yukawa coupling in the dark sector and μ_p is the portal coupling. As a result of the portal coupling, the Higgs and the scalar field s mix yielding two mass eigenstates h_1 and h_2 given by:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix} \quad (2.27)$$

Here h_1 is the mass eigenstate detected in 2012 that matches all Standard Model predictions. As one can see, the dark sector decouples from the Standard Model in the limit $\theta \rightarrow 0$. However, more interestingly, when θ is non-zero, dark matter decays are allowed to be mediated by two separate mass eigenstates.

A primary focus of the Large Hadron Collider (LHC) physics program after the discovery of a Higgs boson [110; 111] by the ATLAS and CMS collaborations is the study of the properties of the new particle. The observation of a sizable branching fraction of the Higgs boson to invisible states [112; 113; 114] would be a strong sign of physics beyond the standard model (BSM). An illustrative Feynman diagram for such a case is shown in Fig. 2.12, while additional gluon-induced

diagrams are also considered.

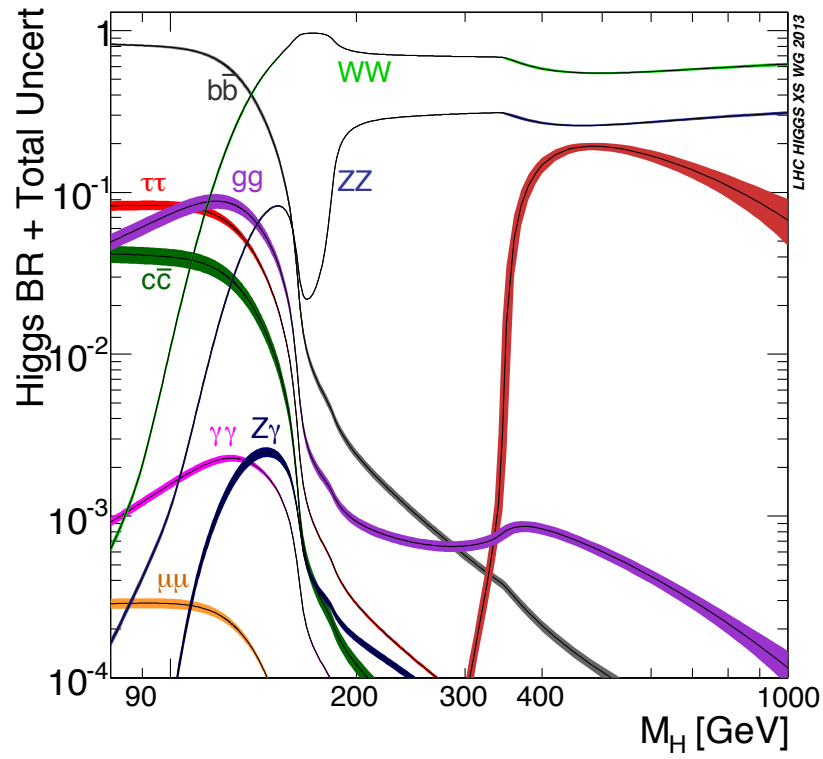


Figure 2.11: The decay branching fractions and uncertainty of the Higgs boson as a function of the Higgs boson mass [3].

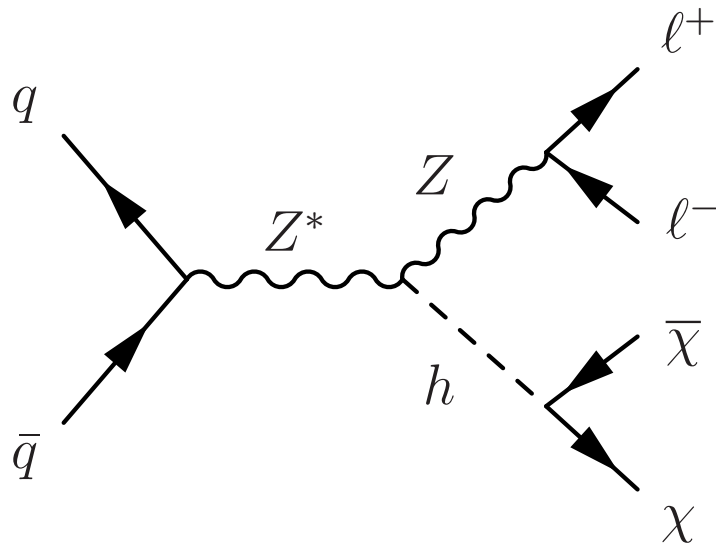


Figure 2.12: Feynman diagram showing dark matter production through invisible decays of the Higgs boson in the Z boson plus missing $p_{\text{T}}^{\text{miss}}$ channel. Here h is identified with the 125 GeV scalar boson.

Chapter 3

Extra Dimensions and Unparticles

An unanswered question in modern day physics, otherwise known as the Hierarchy problem, is why the force of gravity is so small compared to the weak force. The class of models incorporating Supersymmetry answers this question by having "superpartners" provide quantum corrections to the Higgs mass that exactly cancel out the higher order divergences in the SM. Alternatively, the discrepancy in scale could be caused by gravity propagating in additional spatial dimensions that are large compared to the Planck scale. In Kaluza-Klein theory, with appropriate choice of dimensions, the fundamental scale is much lower than the Planck due to a shift in the power law of gravity. Theories like this have been increasingly popular due to the increase in accelerator energies approaching these new theoretical fundamental scales, leading to several interesting new processes. Section 3.1 describes a model with Kaluza-Klein gravitons, while Sec. 3.2 describes a scale invariant theory incorporating unparticles.

3.1 Kaluza-Klein Gravitons

In Large Extra Dimensions (LED) models, graviton particles can propagate in $D = 4 + n$ dimensions, where n is the number of extra spatial dimensions in the theory, while Standard Model particles reside in the typical $(3+1)$ -dimensional space. In the Kaluza-Klein theory of extra dimensions, a massless D -dimensional graviton will appear as several massive Kaluza-Klein gravitons

propagating in $(3 + 1)$ -dimensions. Here the Kaluza-Klein gravitons appear massive due to unobservable harmonic oscillations of the massless graviton in the extra n -dimensions. This means that the new fundamental scale must be associated with the size of the extra dimensions as seen below:

$$M_{Pl}^2 = \frac{2(4\pi)^{-\frac{d}{2}}}{\Gamma(\frac{d}{2})} M_D^{2+n} R^n \quad (3.1)$$

Where $M_{Pl} = 1/\sqrt{G_N}$, G_N is Newton's constant, M_D is the new fundamental scale and $R/2\pi$ is the radius of the compactified dimensions.

The LED model considered here is the Arkani-Hamed–Dimopoulos–Dvali (ADD) model of large extra dimensions [115; 116], which is motivated by the disparity between the electroweak (EW) unification scale ($M_{EW} \sim 100$ GeV) and the Planck scale ($M_{Pl} \sim 10^{19}$ GeV). This model predicts graviton (G) production via the process $q\bar{q} \rightarrow Z + G$, as shown in Fig. 3.3. The graviton escapes detection, leading to a mono- Z signature. In the ADD model, the apparent Planck scale in four spacetime dimensions is given by the form $M_{Pl}^2 \approx M_D^{n+2} R^n$ as shown in Eq. 3.1, where M_D is the fundamental Planck scale in the full $(n+4)$ -dimensional spacetime and R is the compactification length scale of the extra dimensions. Assuming M_D is of the same order as M_{EW} , the observed large value of M_{Pl} suggests values of R much larger than the Planck length. These values are on the order of nm for $n = 3$, decreasing with larger values of n . The consequence of the large compactification scale is that the mass spectrum of the Kaluza–Klein graviton states becomes nearly continuous [115; 116], resulting in a broadened spectrum for the transverse momentum (p_T) of the Z boson.

In order to ensure the validity of the effective theory used in the Graviton model, a truncation method, described in [117], was applied. Perturbative calculations are only valid in cases where the $\hat{s}$ of the process is smaller than the fundamental scale of the theory Λ_U , which in the case of the ADD model, is equivalent to M_D . As such this truncation method suppresses the cross section for events with $\hat{s} > M_D^2$ by a factor of $M_D^4/\hat{s}^2$. This truncated cross section was used for this analysis.

Additionally, in order to get the correct shape-based correction a normalized ratio of this weight was applied to the generated p_T^Z . This will increase the weight of events on the lower end of the mass spectrum while decreasing the weight of events in the high end of the distribution where the EFT approximation is not valid. The effect of this truncation is largest for small M_D as seen in Figure 3.1. The effect also increases with the number of dimensions where additional energy is lost in the extra dimensions as seen in Figure 3.2

3.2 Unparticles

The unparticle physics concept [118; 119] is based on scale invariance, which is anticipated in many BSM physics scenarios [120; 121; 122]. The effects of the scale-invariant sector (“unparticles”) appear as a non-integral number of invisible massless particles. In this scenario, the SM is extended by introducing a scale-invariant Banks–Zaks field, which has a nontrivial infrared fixed point [123]. This field can interact with the SM particles by exchanging heavy particles with a high mass scale M_U [124]. Below this mass scale, where the coupling is nonrenormalizable, the interaction is suppressed by powers of M_U and can be treated within an effective field theory (EFT). The EFT lagrangian used to interpret this model is shown in Eq. 3.2, where the parameters that characterize the unparticle model are the possible noninteger scaling dimension of the unparticle operator d_U , the coupling of the unparticles to SM fields λ , the unparticle operator $\mathcal{O}_{Uq\bar{q}}$ and the cutoff scale of the EFT Λ_U . In order to remain in the EFT regime, the cutoff scale is set to $\Lambda_U = 15 \text{ TeV}$ and to maintain unitarity, only $d_U > 1$ is considered. Figure 3.3 shows the tree-level diagram considered for the production of unparticles associated with a Z boson.

$$\mathcal{L}_U = \frac{\lambda}{\Lambda_U^{d_U-1}} \mathcal{O}_{Uq\bar{q}} \quad (3.2)$$

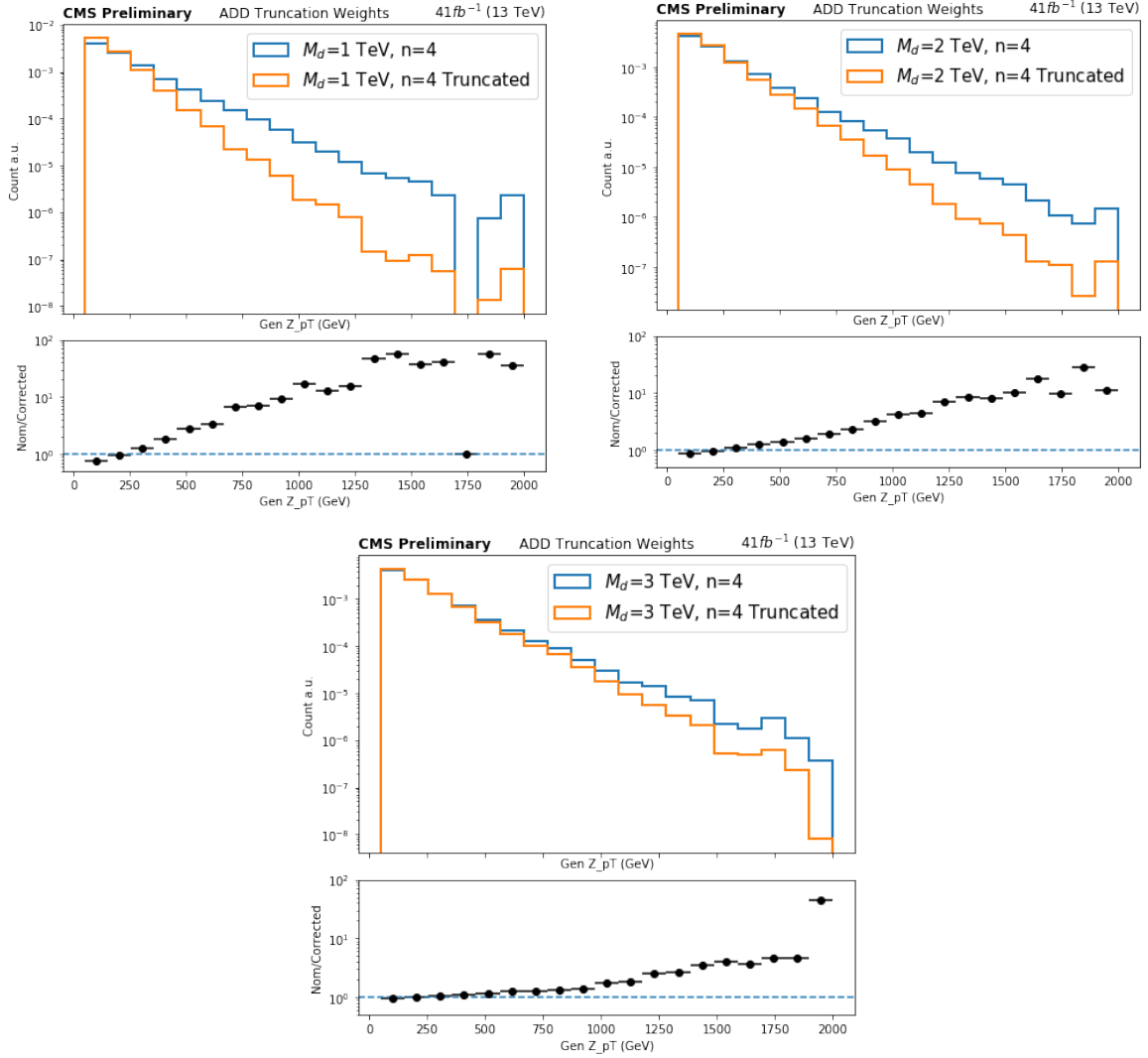


Figure 3.1: The generator level p_T^Z distribution before and after the truncation has been applied for all three M_D values with $n = 4$. The largest effect is seen in the $M_D = 1$ TeV case (left) where there are a larger proportion of events failing the EFT approximation and the distribution is shifted to smaller values of p_T^Z . The $M_D = 2$ TeV case (right) and $M_D = 3$ TeV case (bottom) are also shown for comparison.

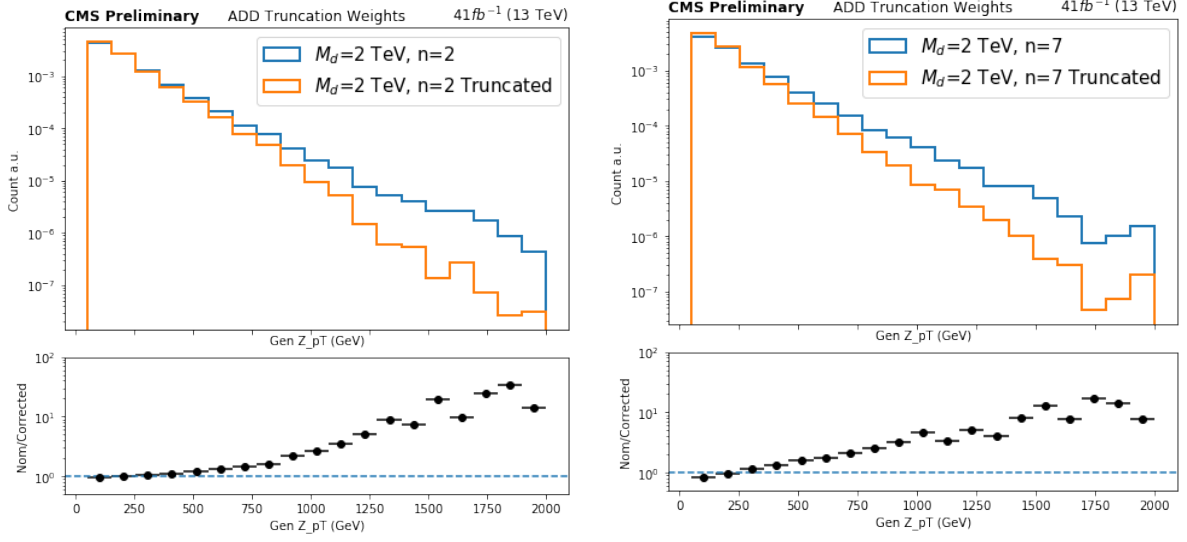


Figure 3.2: The generator level p_T^Z distribution before and after the truncation for $n = 2$ (left) and $n = 7$ (right) for $M_D = 2$ TeV. The effect of truncation is increased with n as more energy is lost in the extra dimensions.

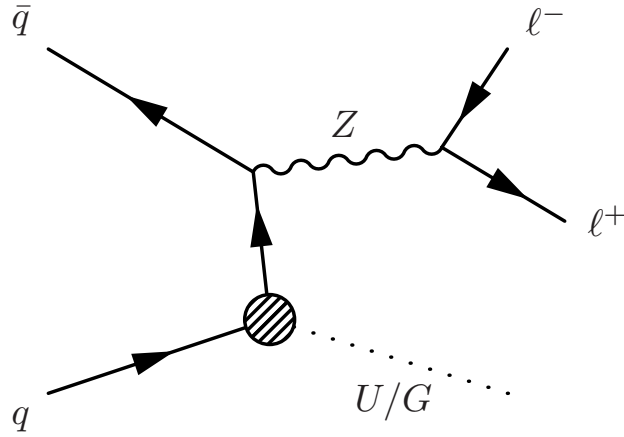


Figure 3.3: Feynman diagram showing graviton (G) production in a model with large extra dimensions or unparticle (U) production. The dotted line represents either an unparticle or a graviton.

Chapter 4

The Large Hadron Collider and the Compact Muon Solenoid experiment

This chapter describes the world's most powerful particle collider, the Large Hadron Collider (LHC). The LHC as well as the associated accelerator complex to create high energy proton beams are described in Sec. 4.1, while the Compact Muon Solenoid detector is introduced in Sec. 4.2. The CMS detector itself is formed of many layers designed to detect and measure the energy and momentum of particles produced in the collisions seen at the LHC. Section 4.3 describes the inner tracker system. The calorimeters are introduced next, with the Electromagnetic Calorimeter and the Hadronic Calorimeter described in Sections 4.4 and 4.5, respectively. The superconducting magnet is described in Sec. 4.6 followed by the muon systems in Sec. 4.7. Finally, the trigger system is explained in section 4.8, while the planned upgrade for Phase-2 is explained in appendix A. A description of one of the trigger systems, the Endcap Muon Track Finder (EMTF), and its developments during Run-2 and the shutdown are in Sec. 4.9.

4.1 LHC

The Large Hadron Collider (LHC) is a two-ring-superconducting-hadron accelerator based in Meyrin, Switzerland at the European Organization for Nuclear Research (Organisation européenne pour la recherche nucléaire or CERN). The LHC is installed in the existing 26.7 km tunnel from 45

up to 170 meters underground that was constructed between 1984 and 1989 for the Large Electron-Positron (LEP) experiment [4]. The tunnel itself is formed of 8 straight sections (octants) and eight arcs that cross at interaction points associated with the different detectors.

The two general purpose high luminosity experiments are located on opposite sides of the ring with ATLAS (A Toroidal LHC ApparatuS) [125] located in the first octant (Point 1) and CMS located in the fifth octant (Point 5). The ALICE (A Large Ion Collider Experiment) [126] and LHCb (LHC Beauty) [127] focus on heavy ion and b-quark physics and are located in caverns originally built for LEP in octant 2 and 8 (Points 2 and 8), respectively. In addition, there are three detectors associated to the LHC: TOTEM (TOTAl Elastic and diffractive cross section Measurement) [128] provides measurements of elastic scattering and diffractive processes and is located on either side of the CMS interaction point; LHCf (Large Hadron Collider forward) [129] studies particles in the forward region of collisions and is located on either side of the ATLAS interaction point; and MoEDAL (Monopole and Exotics Detector at the LHC) [130] which searches for the magnetic monopole and is located at Point 8 with LHCb. As of 2019, the FASER (ForWard Search Experiment) [131] is planned to be added and will be located in a service tunnel 480 meters downstream from the ATLAS interaction point and will search for new light and weakly interacting particles. Figure 4.1 shows the current layout of the LHC.

The LHC accelerator is designed to provide a center-of-mass energy of 14 TeV with an unprecedented instantaneous luminosity up to $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [4]. During Run-2, associated with data taken from 2015 through 2018, the LHC operated at a center-of-mass energy of 13 TeV with a possible increase in energy for future runs. In order to achieve this energy, the proton beams need to be accelerated in multiple separate steps, with each step ramping up the energy of the beam. As seen in figure 4.2 [5], the beam starts in LINAC2 where hydrogen gas at one side of the system is stripped of electrons and then accelerated to 50 MeV. This proton beam is accelerated through 3 synchrotrons, BOOSTER, PS (Proton Synchrotron) and SPS (Super Proton Synchrotron), which

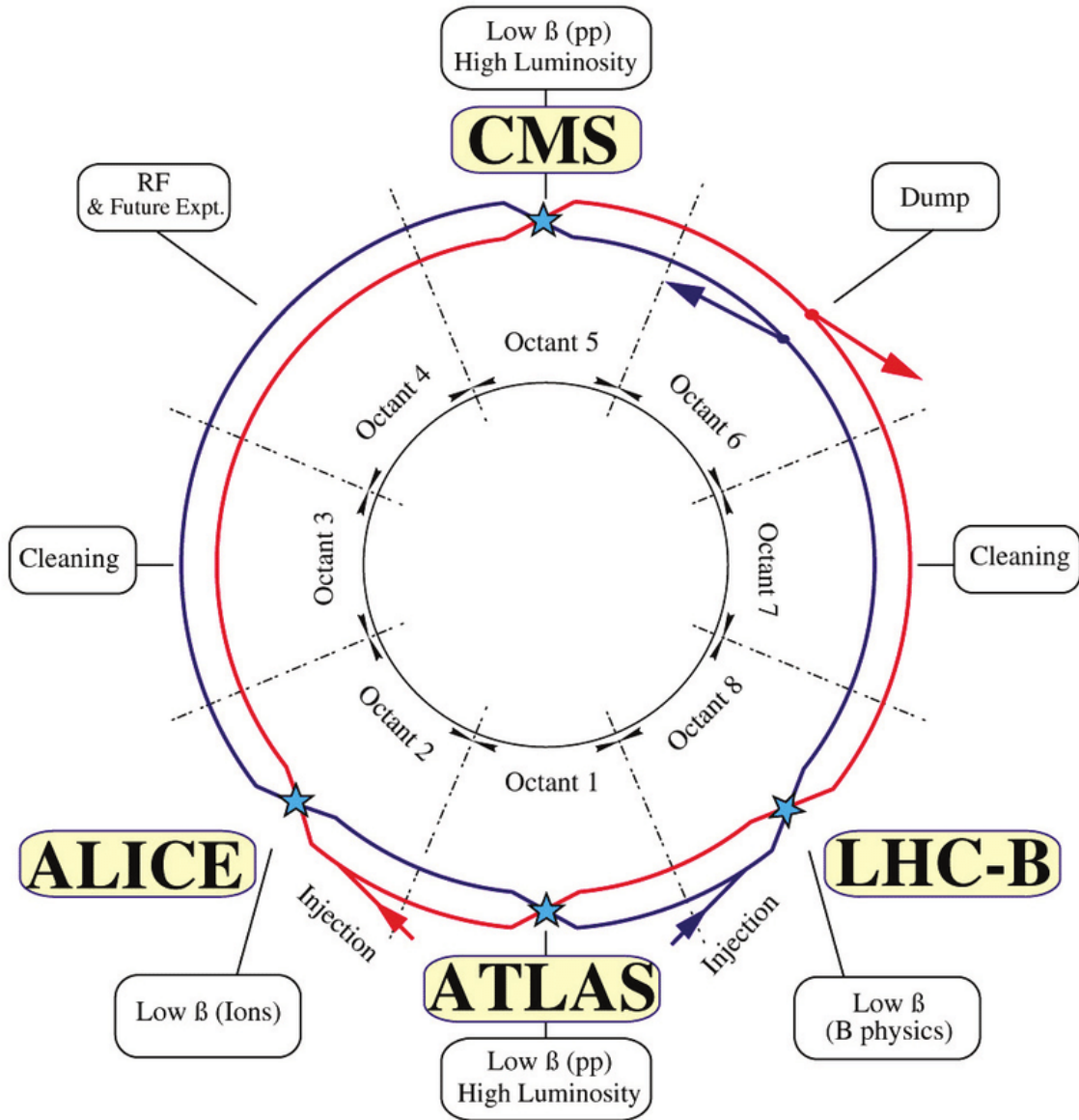


Figure 4.1: The schematic layout of the LHC and the associated experiments [4]. The two largest experiments, ATLAS and CMS, are located at opposite sides of the LHC ring at Point 1 and Point 5, respectively.

bring the beam energy to 1.4 GeV, 28 GeV and 450 GeV, respectively. Once at 450 GeV, the proton beam is split and injected into the LHC ring where both beams are accelerated to 6.5 TeV yielding a center-of-mass energy of 13 TeV for proton-proton collisions.

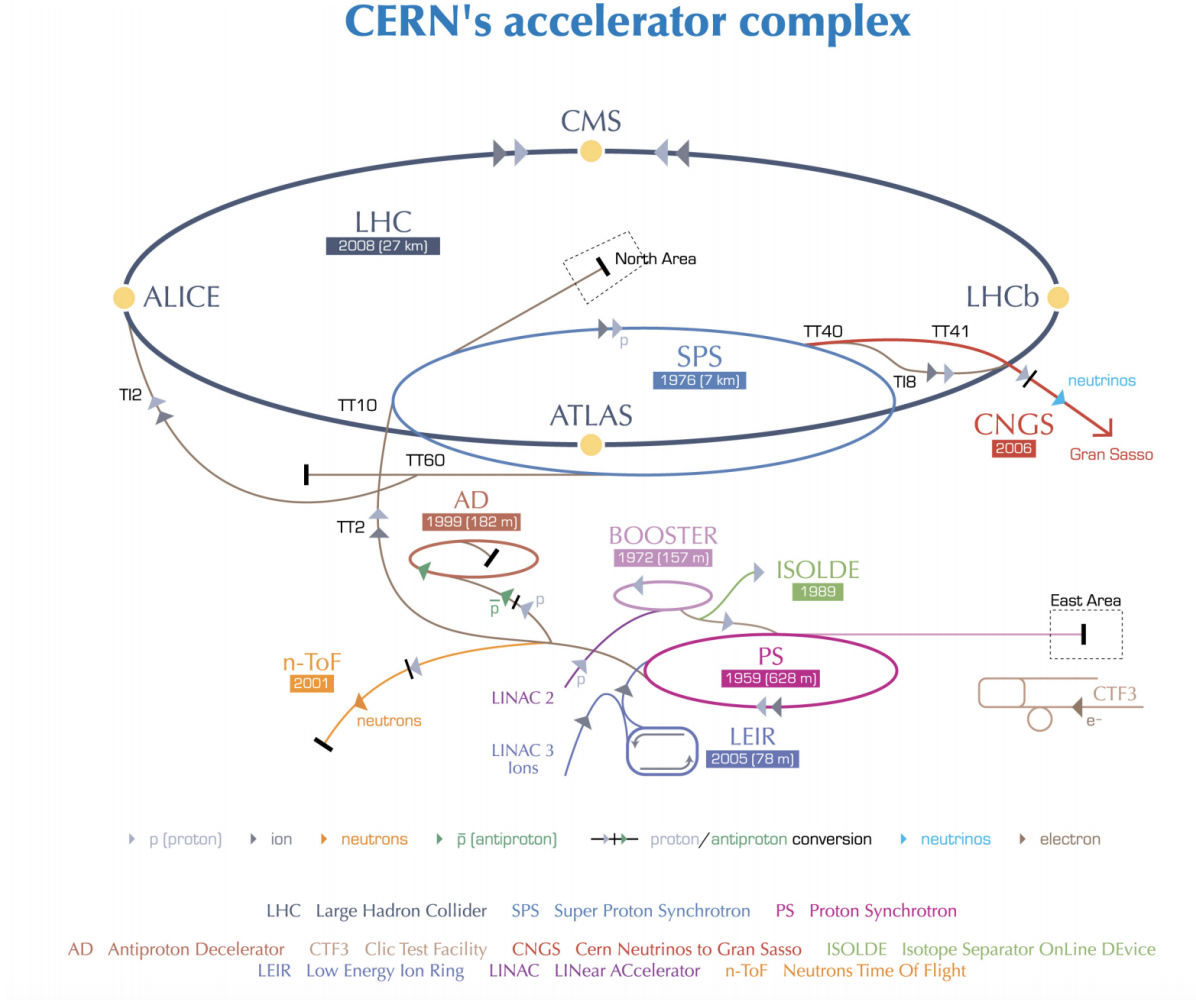


Figure 4.2: The CERN accelerattor complex [5]. The proton beams start in the LINAC2 and are accelerated to 50 MeV. This beam is then accelerated by BOOSTER, PS and SPS to bring the beam energy up to 450 GeV. From there, the beam is split and accelerated by the LHC to a total center-of-mass energy of 13 TeV.

With the aim of revealing any physics beyond the standard model, it is important to understand the backgrounds expected at LHC experiments where the energy, instantaneous luminosity and the time colliding particles play a huge role in the experimental process. The number of events

generated by LHC collisions is given by equation 4.1, where L is the machine luminosity which has been integrated over the time of active collisions, and σ_{event} is the cross section of the event being considered [4].

$$N_{event} = L\sigma_{event} \quad (4.1)$$

This machine luminosity is determined by the parameters of the proton beams where N_b is the number of protons per bunch, n_b is the number of bunches per beam, f_{rev} is the frequency of revolution, γ_r is a lorentz factor, ϵ_n is the normalized transverse beam emittance, $\beta\star$ is the beta function and F is the geometric luminosity reduction factor. Here the star represents that the beta function is at the interaction point (IP).

$$L = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta\star} F \quad (4.2)$$

The geometric luminosity reduction factor reduces the machine luminosity due to the crossing angle of the 2 beams at the interaction point. This factor is given by equation 4.3 where θ_c is the beams crossing angle at the IP, σ_z is the RMS bunch length and $\sigma\star$ is the transverse RMS beam size at the IP. This equation assumes both beams are round with $\sigma_z \ll \beta$ and have equal parameters.

$$F = \left(1 + \left(\frac{\theta_c \sigma_z}{2\sigma\star}\right)^2\right)^{-1/2} \quad (4.3)$$

In order to understand the event rate of SM processes that will be seen at the LHC, we use factorization theorem to calculate the hard scattering cross sections. In 1971 Drell and Yan showed that parton model ideas developed for deep inelastic scattering could be extended to processes in hadron-hadron collisions [132]. The process they studied was the production of a massive lepton pair by quark-antiquark annihilation, now known as the Drell-Yan (DY) process. They postulated that the total hadronic cross section could be calculated by weighting the subprocess cross section with the parton distribution functions (pdfs) extracted from deep inelastic scattering. This assumption is valid in the asymptotic scaling limit ($s \rightarrow \infty$ and the ratio of the dilepton

mass over s is fixed) [6]. Good experimental agreement caused this idea to be extended to other hard scattering processes with problems only arising when perturbative corrections from gluon emission were calculated where large logarithms from gluons emitted collinear with the incoming quarks preventing convergence. These logarithms were then discovered to be the same as those that arise in deep inelastic scattering structure function calculations and could be absorbed using the DGLAP equations [133], allowing us to generalize the cross section calculations for hard scattering processes in hadron-hadron collisions as seen in equation 4.4.

$$\sigma^{AB} = \int dx_a dx_b f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2) \hat{\sigma}_{ab \rightarrow X} \quad (4.4)$$

Where σ^{AB} is the total production cross section for a hadron-hadron collision, $f_{a/A}(x_a, Q^2)$ and $f_{b/B}(x_b, Q^2)$ are the pdfs extracted from deep inelastic scattering with Q^2 as the large momentum scale that characterizes the hard scattering, and $\hat{\sigma}_{ab \rightarrow X}$ is the subprocess cross section. As an example, for the DY process $X = \ell^+ \ell^-$ and $ab = q\bar{q}, \bar{q}q$. Figure 4.3 shows a diagram for a generic hard scattering process. The cross sections and event rates for some example SM processes associated with proton-proton collisions at different center-of-mass energies are shown in figure 4.4.

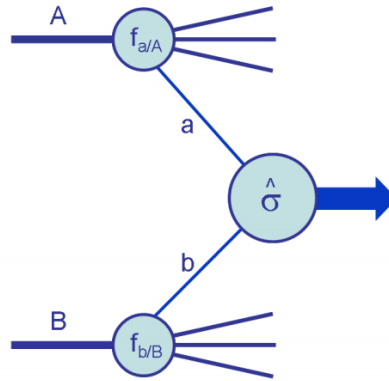


Figure 4.3: Diagram showing the generic structure of a hard scattering process [6].

This thesis is based on proton-proton collision data at a center-of-mass energy of 13 TeV, collected by the CMS experiment at the LHC in 2016–2018, corresponding to an integrated luminos-

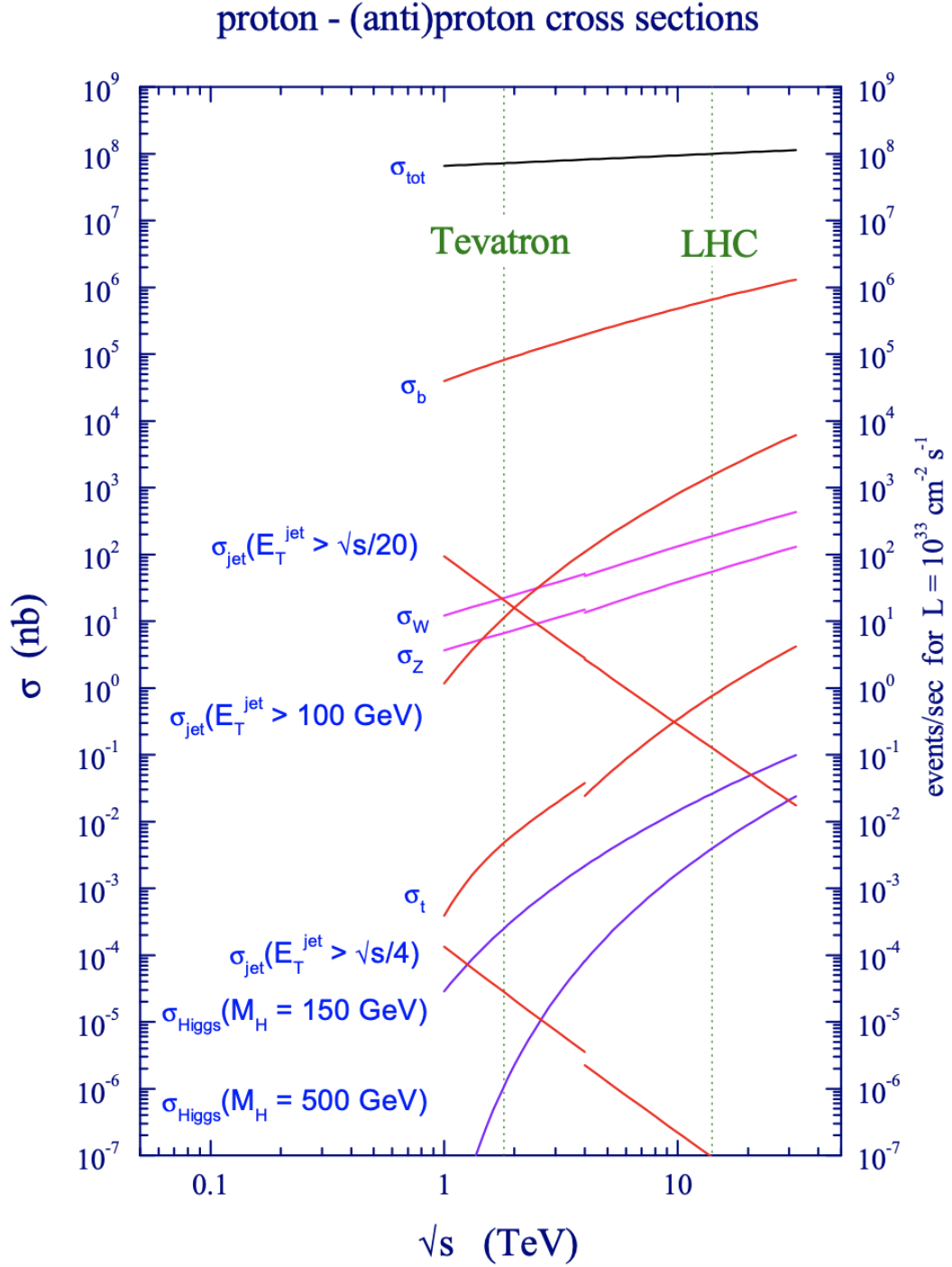


Figure 4.4: The cross sections and rates for SM processes seen at the Tevatron and LHC energies [6].

ity of 137 fb^{-1} . The integrated luminosity collected for each data-taking year is shown in Fig. 4.5 (left), while the cumulative luminosity is shown in Fig. 4.5 (right). The mean number of interactions, also known as pileup, per proton beam crossing is shown in Fig. 4.6 for each data-taking year.

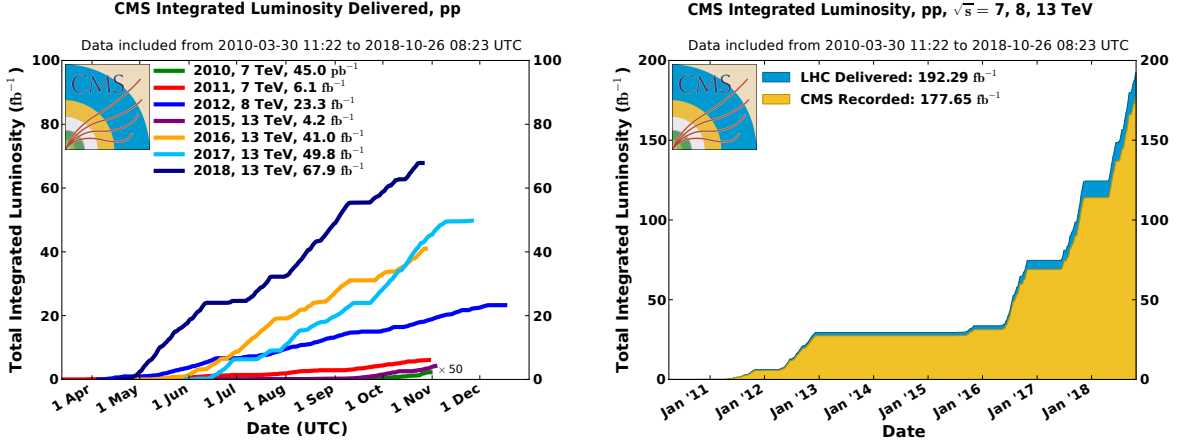


Figure 4.5: The integrated luminosity recorded for each data-taking year is shown on the left while the cumulative integrated luminosity for CMS is shown on the right [7].

4.2 CMS

CMS is one of the two general purpose detectors located at the LHC designed to investigate a wide range of physics searches for BSM physics including dark matter, extra dimensions and supersymmetry. Additionally, precision studies of QCD, electroweak, flavor physics and heavy-ion physics as well as study the properties of the newly discovered Higgs boson are included in the project's goals. The CMS detector itself is 21.6 m long, 14.6 m in diameter and weighs approximately 14,500 tons. It is used to measure the properties of decay products stemming from proton-proton and heavy ion collisions. The detector layout is shown in Figure 4.7. Overall, the CMS has five main subdetectors described below, listed from the inner part of the detector to the outermost muon detectors. Figure 4.8 shows the transverse view of CMS as well as a slice showing each detector technology, where each of these systems are described in further detail in Sections 4.3–4.7.

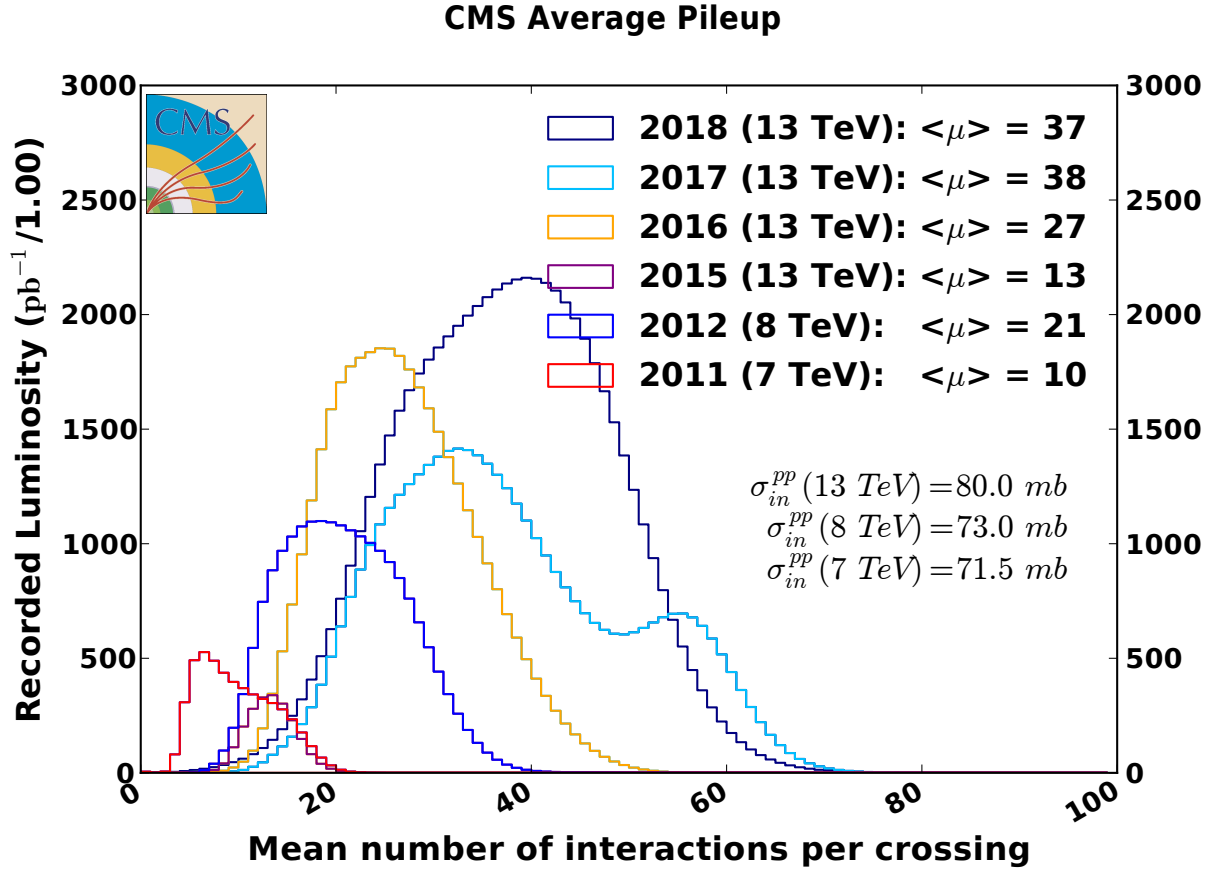


Figure 4.6: The mean number of interactions (pileup) per proton beam crossing for each data-taking year [7].

- **The inner tracking system:** The tracking system is composed of silicon pixel and microstrip detectors that measure charged particles' momenta, direction and interaction vertices.
- **The electromagnetic-calorimeter(ECAL):** The ECAL system is designed to measure the energy of photons, electrons and positrons. The ECAL uses lead tungstate crystals that scintillate when electrons or photons pass through them.
- **The hadronic-calorimeter(HCAL):** The HCAL measures the energy of hadrons (particles made of quarks and gluons) using alternating layers, of absorber and scintillator materials that yield the energy of hadronic showers.
- **The superconducting solenoid magnet:** The CMS magnet is the largest superconducting magnet ever built, creating a 4 Tesla magnetic field which causes charged particles to bend within the CMS detector allowing the momenta to be measured.
- **Muon systems:** The muon systems form the outermost layers of the detector and have multiple stations that will each record a hit when a muon passes through. By tracking the position through multiple stations the momentum can be measured by determining the amount of bend caused by the strong magnetic field present.

CMS has adopted a coordinate system with an origin centered at the nominal collision point inside the experiment [14]. The y-axis points vertically upward while the x-axis points radially inward toward the center of the LHC ring. The z-axis points along the beam direction with the positive direction pointing towards the Jura mountains from LHC Point 5. Figure 4.9 (left) shows the coordinate system with the azimuthal angle (ϕ) defined in the x–y plane, measured from the x-axis, while the polar angle (θ) is measured from the z-axis. However, since θ is not Lorentz invariant, pseudorapidity as defined in equation 4.5 is used, where the translation from the polar angle to pseudorapidity is shown in figure 4.9 (right). The momentum (p_T) and energy (E_T) transverse to the beam direction are computed from the x and y components with the imbalance of energy in the transverse plane denoted by p_T^{miss} .

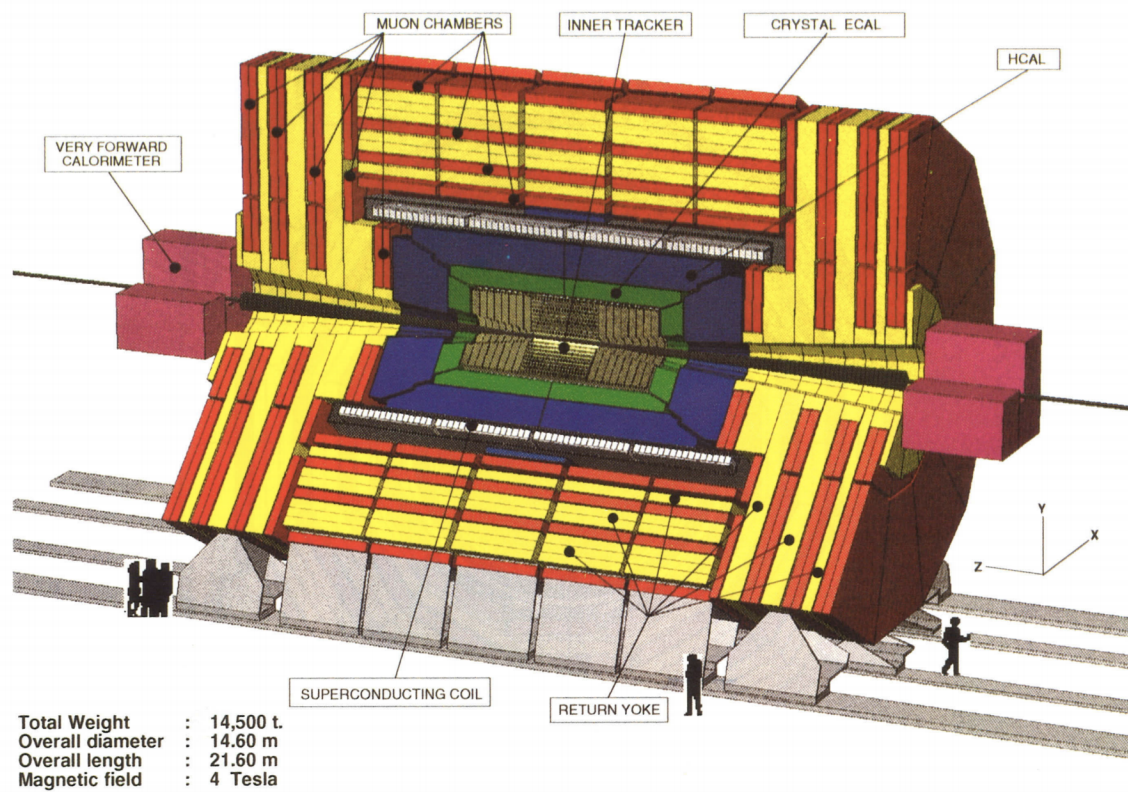


Figure 4.7: A 3-dimensional view of the CMS detector [8].

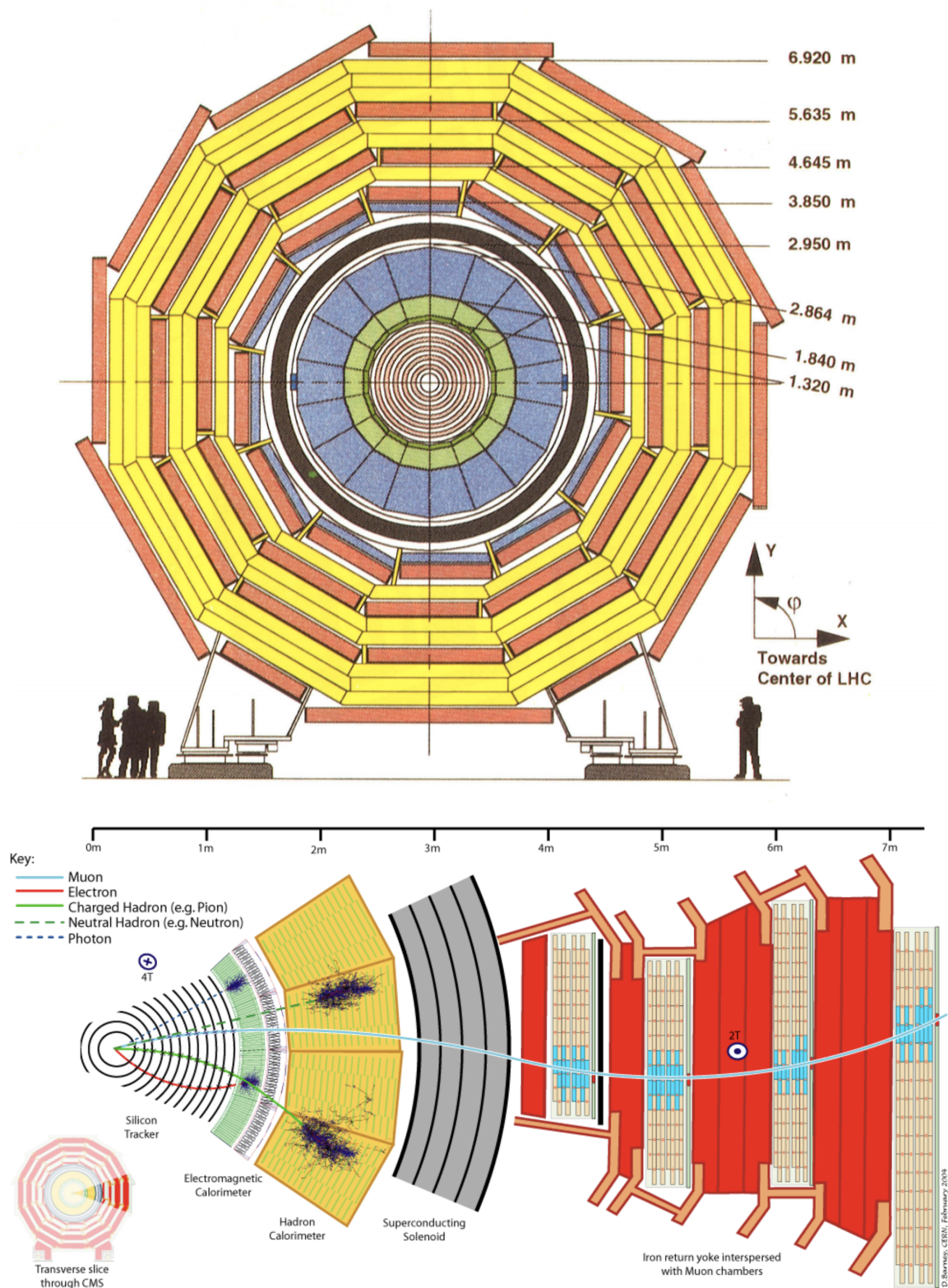


Figure 4.8: The top diagram shows a transverse view of the CMS detector [8], while the bottom shows a transverse slice and the particles each detector technology is sensitive to [9].

$$\eta \equiv -\ln \left[\tan\left(\frac{\theta}{2}\right) \right] \quad (4.5)$$

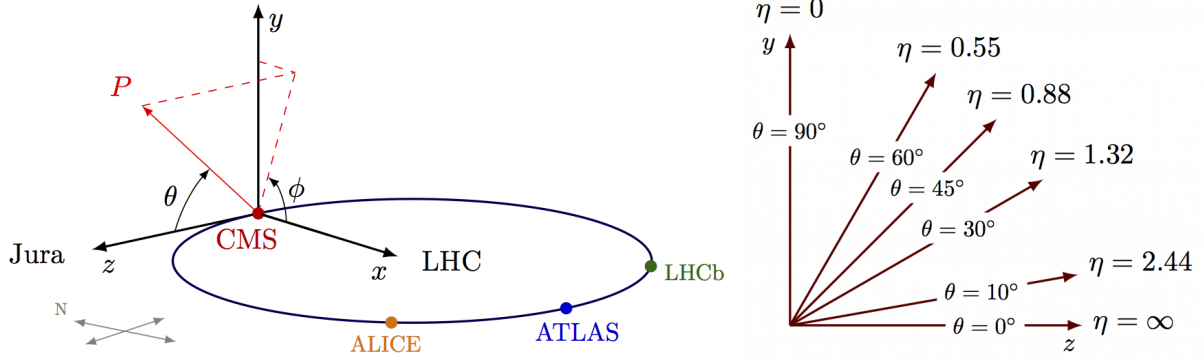


Figure 4.9: A diagram of the coordinate system used at CMS is shown on the left, while the translation from the polar angle (θ) to pseudorapidity (η) is shown on the right.

4.3 Tracker

The inner tracker is located in the innermost region of the CMS detector surrounding the beam pipe and interaction point. The tracker is designed for robust tracking and for detailed vertex reconstruction within the cylindrical tracker volume 5.8 *m* in length and 2.5 *m* in diameter [11]. The entirety of the inner tracker system is immersed in a 3.8 T, homogeneous and co-axial magnetic field provided by the CMS solenoid magnet. The tracking system is composed of microstrip detectors with a silicon pixel tracker inside of it, that measure charged particles' momenta, direction and interaction vertices within a pseudorapidity range of $|\eta| < 2.5$ [36; 134]. As seen in figure 4.10, the pixel tracker consists of 3 co-axial barrel layers between 4.4 *cm* and 10.2 *cm* from the beam line and 10 co-axial strip tracker barrel layers extending to a radius of 110 *cm*. Both subdetectors have additional endcap disks on either side of the barrel, with 2 disks for the pixel tracker, and 12 disks for the tracker composed of 3 small disks and 9 larger ones. The CMS tracker forms a total active area of 200 *m*², making it the largest silicon tracker ever built.

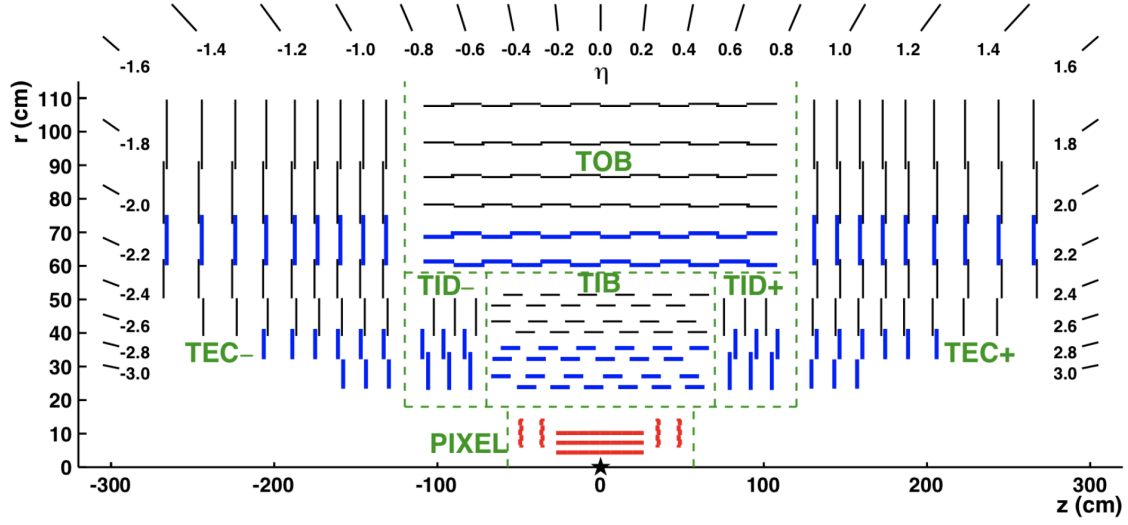


Figure 4.10: A schematic cross section through the CMS tracker in the r - z plane showing the top half of the detector. The interaction point is indicated by a star while green dashed lines and names indicate which modules belong to each of the named tracker subsystems. Strip tracker modules that provide 2D hit information are shown in black while those that provide 3D hit information are colored blue. The red pixel modules also provide 3D hit information [10].

The pixel detector consists of a cylindrical barrel section (BPIX) and 2 endcap disks (FPIX) at $z = \pm 34.5$ and ± 46.5 cm, providing 3D position measurements from hits associated with charged particles originating from the interaction point. The system contains 66 million pixels and has a hit position resolution of approximately $10 \mu\text{m}$, the width of a human hair, in the transverse coordinate and between 20 to $40 \mu\text{m}$ in the longitudinal coordinate [11]. In addition to the pixels, there are inactive structural elements that surround the BPIX: the pixel detector support tube; inner and outer shields; and the beam pipe itself [10]. These support structures as well as the BPIX layers can be seen in figure 4.11 with the top left plot showing an azimuthal cross section of the pixel detector, the top right showing one of the semi-circular halves of the BPIX and the bottom plot showing the number of nuclear interactions that happen within the pixel volume including interactions within the support structures.

The strip tracker system is made of 15148 silicon modules made of 9.3 million strips split into four subsystems: the Tracker Inner Barrel (TIB) which is composed of 4 barrels and the 2 Tracker

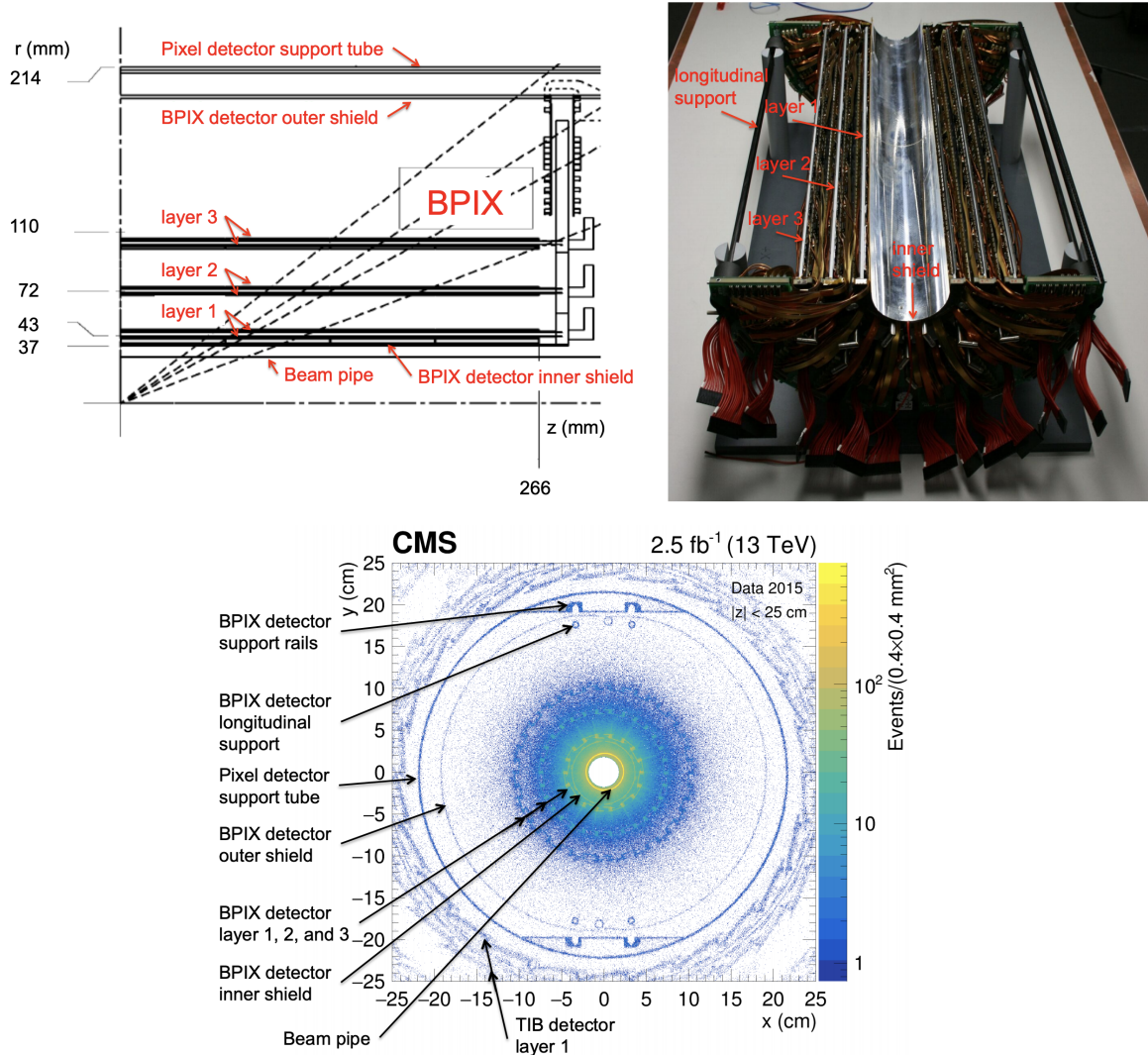


Figure 4.11: The top left plot shows an azimuthal cross section of the BPIX and support structures, the top right shows one of the semi-circular halves of the BPIX and the bottom plot shows the number of nuclear interactions that happen within the pixel volume including interactions within the support structures [10].

Inner Disks (TID) cover $r < 55\text{ cm}$ and $|z| < 118\text{ cm}$ with a resolution between 13 to 38 μm ; a Tacker Outer Barrel (TOB) consists of 6 barrels covering $r > 55\text{ cm}$ and $|z| < 118\text{ cm}$ with a resolution between 18 to 47 μm ; and the Tracker EndCaps (TEC) composed of nine disks, each containing up to seven concentric rings of silicon strip modules covering $124 < |z| < 282\text{ cm}$ with a resolution similar to the TOB [11]. The modules of the pixel detector use silicon of 285 μm thick while the modules in the TIB, TID and the 4 inner rings of the TEC use silicon that is 320 μm thick. The TOB and 3 outer rings of the TEC use silicon 500 μm thick. Table 4.1 summarizes the tracker subsystems and figure 4.12 shows the total thickness of the tracker material traversed by a particle produced at the interaction point as a function of pseudorapidity.

Table 4.1: A summary table of the number of layers, coverage and resolution for the different tracker subsystems [11; 36].

Tracker subsystem	Layers	Radial coverage	Longitudinal coverage	Resolution ($r\phi$)
Pixel tracker barrel (BPIX)	3 barrels	$4.4 < r < 10.2\text{ cm}$	$ z < 32.5\text{ cm}$	10 μm
Strip tracker inner barrel (TIB)	4 barrels	$20 < r < 55\text{ cm}$	$ z < 82\text{ cm}$	13-38 μm
Strip tracker outer barrel (TOB)	6 barrels	$55 < r < 116\text{ cm}$	$ z < 118\text{ cm}$	18-47 μm
Pixel tracker endcap (FPIX)	2 disks	$6 < r < 15\text{ cm}$	$34.5 < z < 46.5\text{ cm}$	10 μm
Strip tracker inner disks (TID)	3 disks	$20 < r < 55\text{ cm}$	$58 < z < 124\text{ cm}$	13-38 μm
Strip tracker endcap (TEC)	9 disks	$20 < r < 116\text{ cm}$	$124 < z < 282\text{ cm}$	18-47 μm

4.4 ECAL

The CMS electromagnetic calorimeter (ECAL) is a hermetic, and homogeneous calorimeter designed for high-resolution measurement of the energy of photons, electrons and positrons. The ECAL system is composed of a cylindrical barrel system (EB) consisting of 61200 crystals, weighing 67.4 tons, and two flat endcaps (EE) each consisting of 7324 crystals and weighing 25.2 tons [12]. In total, the ECAL uses 75,848 lead tungstate (PbWO₄) crystals, chosen because PbWO₄ has a short radiation length (0.89 cm), a small Molière radius (2.19 cm) and is a fast scintillator (99% of the light is collected within 100 ns, consistent with the 40 MHz interaction rate) [135; 13]. These PbWO₄ crystals scintillate (from Compton scattering and the photo-electric

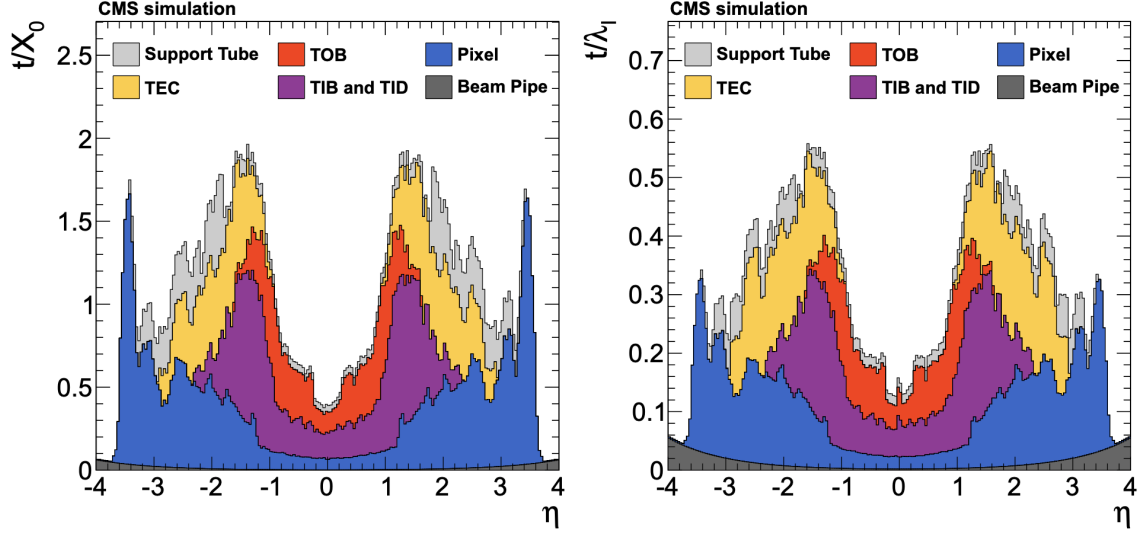


Figure 4.12: Total thickness (t) of the tracker material that a particle produced at the interaction point will traverse. The thickness is shown as a function of pseudorapidity, expressed in units of radiation length X_0 (left) and nuclear interaction length λ_I (right). [11].

effect) when photons, electrons or positrons pass through them. The scintillation light is then picked up at the end of the crystals by precise photodetectors. A preshower detector (ES) is placed in front of the endcap crystals, which uses lead absorbers with silicon strip sensors to enhance the photon identification capabilities [12]. A 3-D layout of the ECAL system is shown in figure 4.13.

The EB covers the pseudorapidity range of $|\eta| < 1.479$ organized into 36 supermodules, with 18 on either side of the beam interaction point [12]. These supermodules each provide a 360-fold granularity in ϕ and an 85-fold granularity in η . These supermodules are formed from 4 modules in eta each containing 425 crystals that are 23 cm long with a front face cross section of around $21.8 \times 21.8 \text{ mm}^2$. The EE extends the pseudorapidity coverage to $|\eta| = 3.0$, with the crystals arranged in a circular shape forming an x-y grid. The EE is made of 4 Dees each containing 5382 crystals that are 22 cm long with a front face cross sections of $24.7 \times 24.7 \text{ mm}^2$. The ES covers the fiducial region of $1.65 < |\eta| < 2.6$ and contains 2 active planes of silicon strip sensors. The sensors cover an area of $61 \times 61 \text{ mm}^2$ and are divided into 32 strips. This geometry yields a granularity in $\Delta\eta \times \Delta\phi$ of 0.0175×0.0175 for the EB and 0.0175×0.0175 to 0.05×0.05 in the

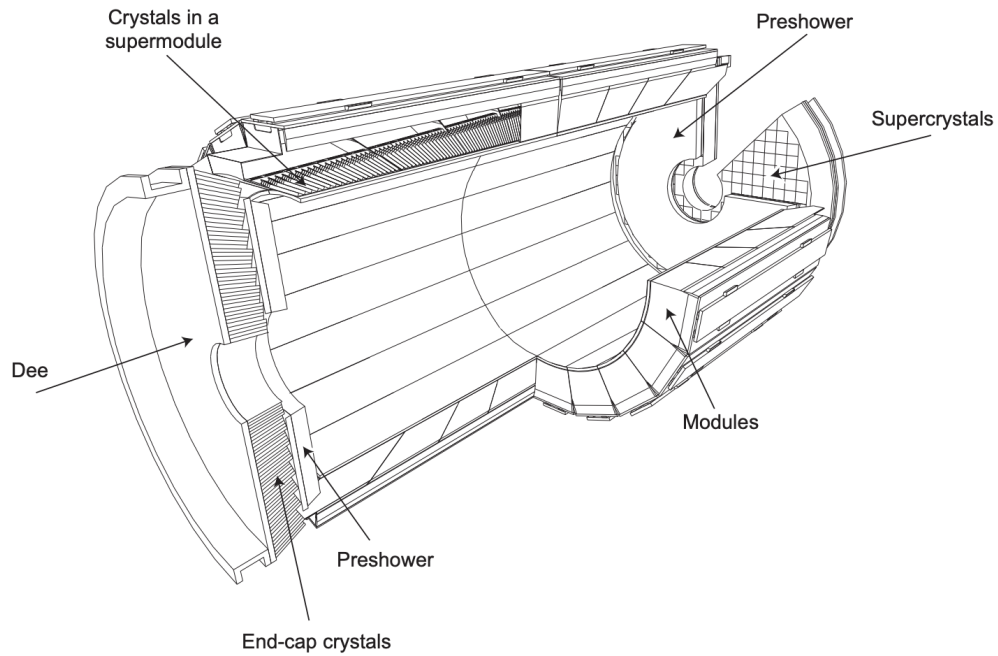


Figure 4.13: A layout of the ECAL system, showing the cylindrical barrel, two flat endcaps and both preshower detectors [12].

EE [135]. A cross section of the ECAL system showing the coverage of the different regions is shown in figure 4.14

Due to the presence of a high transverse magnetic field, the barrel region uses avalanche photodiodes (APD) to collect the scintillation light as they are able to provide the required gain. In the endcap regions, the photodetectors receive a significantly higher radiation dose (50 kGy) and neutron fluence ($7 \times 10^{14} \text{n/cm}^2$) [135]. With this increased radiation, bulk damage to the silicon structure will induce dark currents and would lead to unacceptable amounts of electronic noise for APDs. As such, vacuum phototriodes (VPT) are used in this region instead. Figure 4.15 shows views of a EB supermodule and an EE Dee filled with supercrystals, as well as a barrel crystal with an APD and a endcap crystal with a VPT.

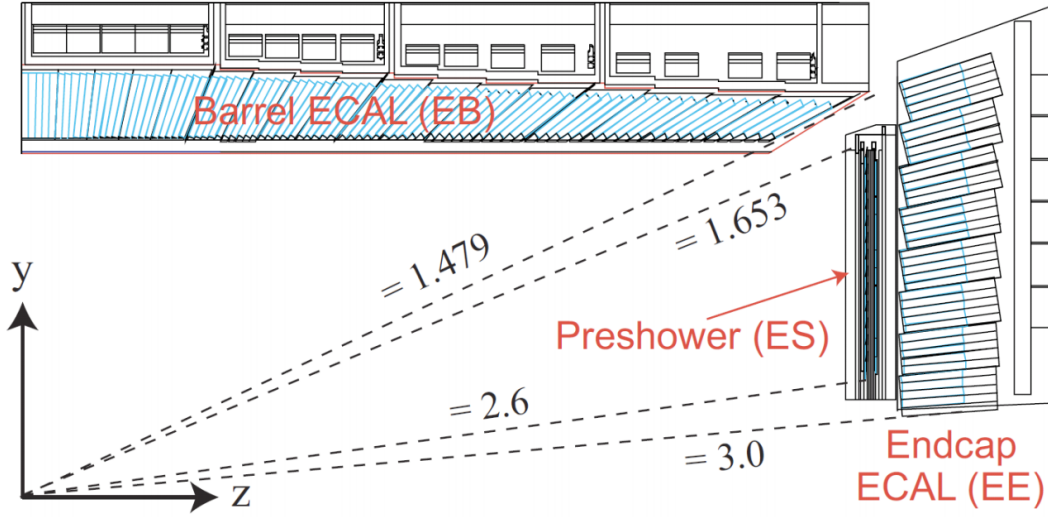


Figure 4.14: A longitudinal cross section of the ECAL system showing the pseudorapidity coverage of the EB, EE and ES [13].

4.5 HCAL

The hadronic calorimeter (HCAL) measures the energy of hadrons (particles made of quarks and gluons) [14; 15; 16]. The HCAL is a sampling calorimeter meaning that it uses alternating layers, of absorber and scintillator materials. The scintillating light is fed into photodetectors that amplify the signal. The signals are summed over many of these layers, designated as towers, which yield the particle energy. The HCAL includes four distinct subsystems: the barrel (HB) and end-cap (HE) calorimeters which are located within the cryostat; the outer (HO) calorimeter located directly outside the magnet coil; and the forward (HF) calorimeters located near the beam line at high pseudorapidity. Figure 4.16 shows the pseudorapidity coverage for each of the four HCAL subsystems.

The HB is a sampling calorimeter composed of brass absorber material and scintillators as the active material. The HB consists of 36 azimuthal wedges, to form 2 half barrels (HB+ and HB-), as

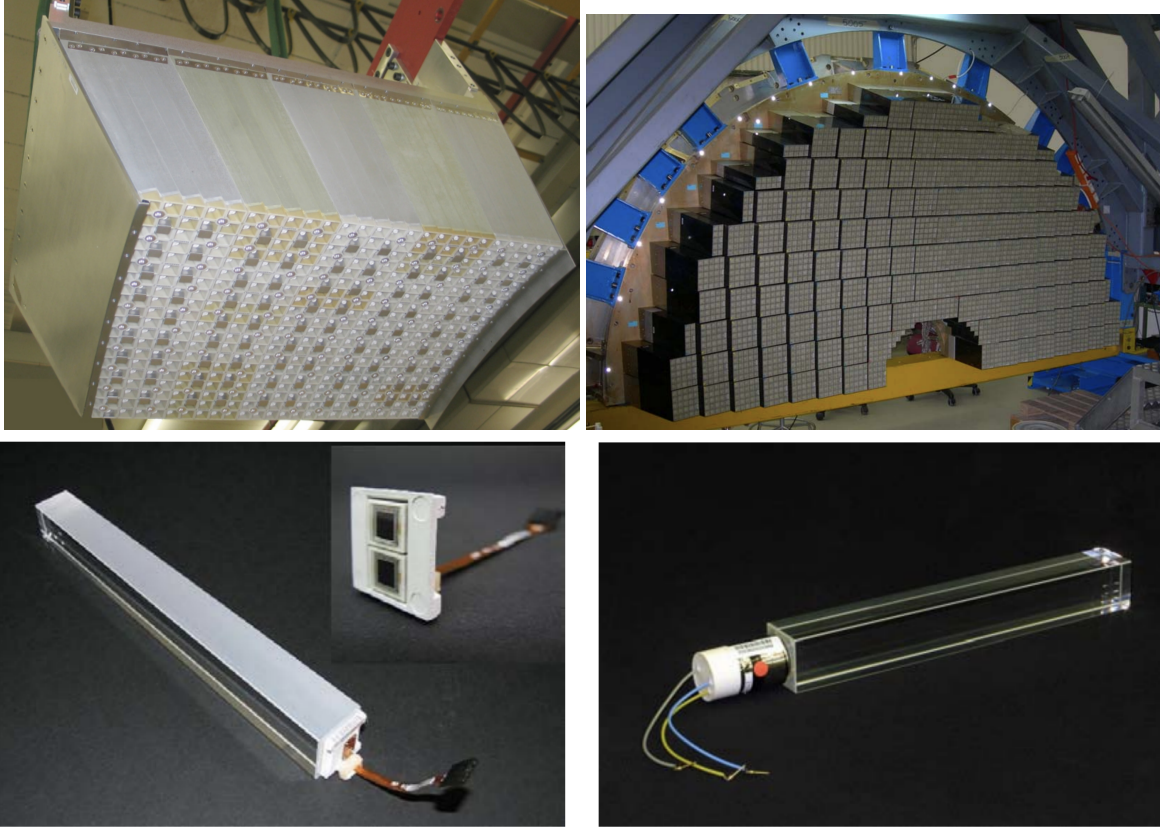


Figure 4.15: A front view of a supermodule used in the EB (top left) and an endcap Dee with supercrystals (top right). PbWO₄ crystals with photodetectors attached are also shown with a barrel crystal with the upper face depolished and the APD capsule attached (bottom left) and an endcap crystal with a VPT attached (bottom right). In the insert in the bottom left, a capsule with two APDs is shown [14].

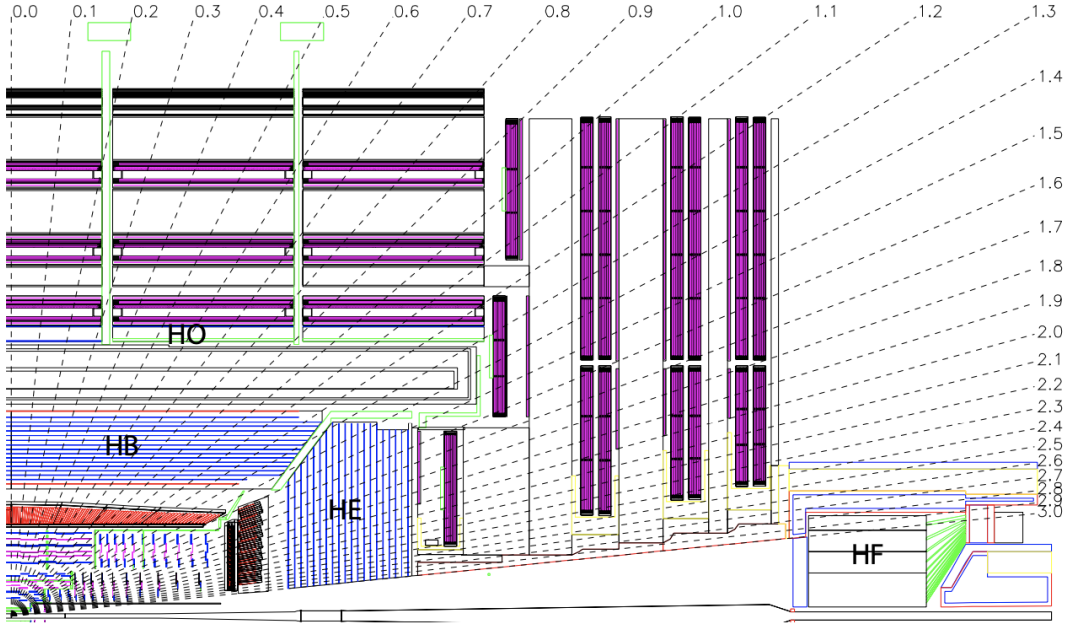


Figure 4.16: [14].

shown in figure 4.17, which each cover 20 degrees in ϕ and are split into 16 η regions covering up to $|\eta| < 1.2$. Due to the magnet cryostat being located directly outside of the barrel calorimeters, the HB thickness is constrained to 5.8 hadronic interaction lengths (16.42 cm) at the center of the subsystem at $\eta = 0$ and increases to 10.6 interaction lengths at the edge for $|\eta| = 1.2$ [14; 15; 16]. The segmentation of the calorimeter towers has a granularity in $\Delta\eta \times \Delta\phi$ of 0.087×0.087 .

The HE is another sampling calorimeter composed of similar materials as the HB and extends the pseudorapidity coverage to $|\eta| < 3.0$. The HE and HB are separated by a gap in range of $1.3 < |\eta| < 1.4$ [15; 16]. This gap does not project to the center of the CMS detector so coverage is shared between the HE and HB. As shown in figure 4.18, the HE is supported in the endcap iron yoke behind EE in a self-supporting hermetic structure containing 79 mm thick brass plates as well as 9 mm gaps for the scintillators, where the total length of the calorimeter, including the electromagnetic crystals is about 10 interaction lengths [16]. The granularity for the HE is $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ except for $|\eta| > 1.74$, where the η segmentation ranges from 0.09 to

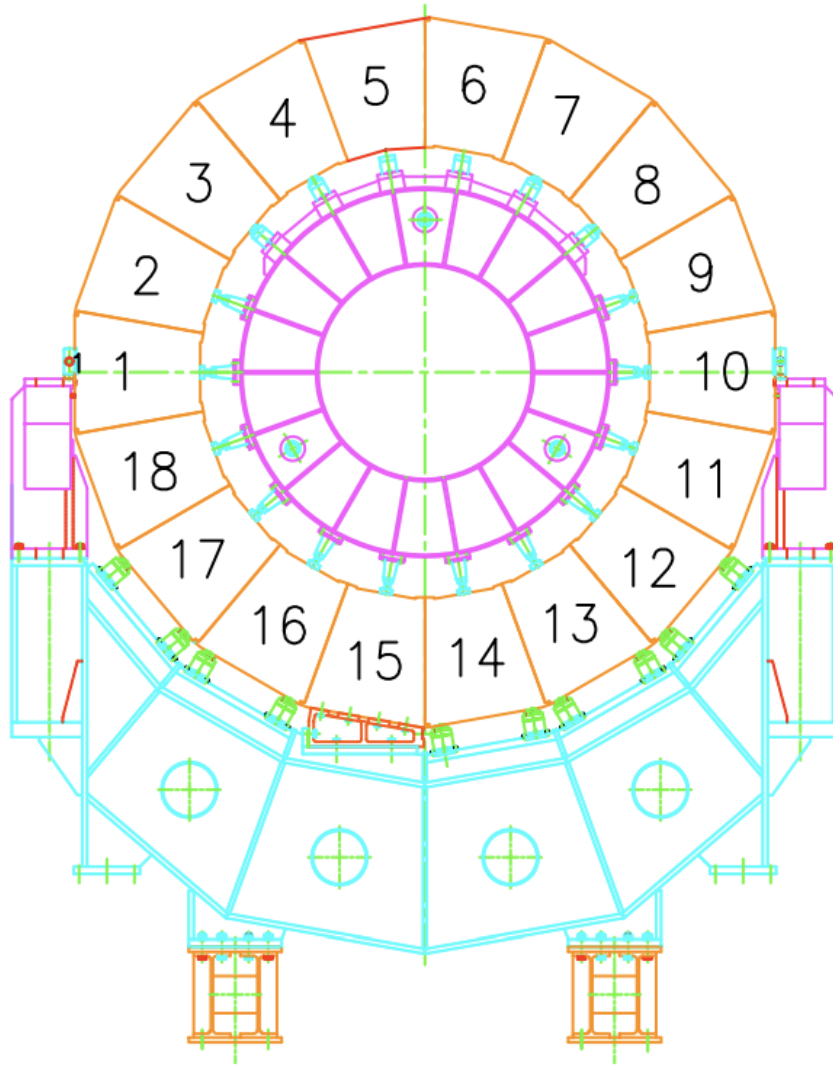


Figure 4.17: Numbering scheme for the HB wedges where wedge 1 is on the inside in the positive x direction of the LHC ring [14].

0.35 and the ϕ segmentation is 0.175.

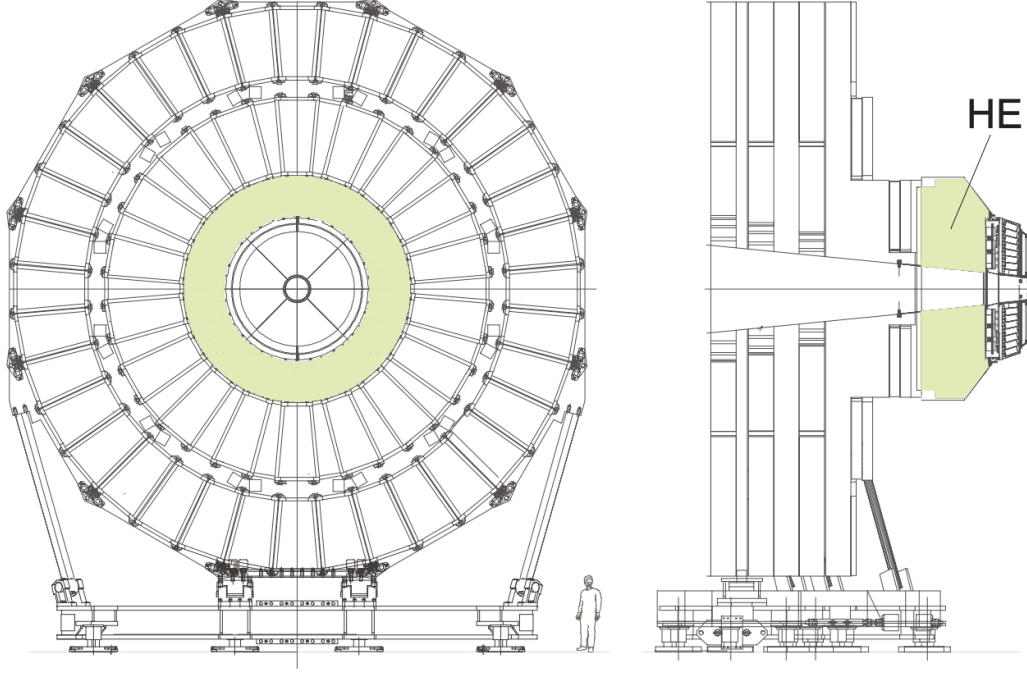


Figure 4.18: The HE calorimeter mounted on the endcap iron yoke behind the EE calorimeter [14].

In order to collect energy that leaked from the HB, layers of scintillators are placed outside of the magnet cryostat. These additional scintillators constitute the HO where about 5% of hadrons with $p > 100$ GeV deposit energy in the HO [15; 16]. The HO has five 2.536 m wide rings which follow the structure of the magnet return yoke as shown in figure 4.19. Each of these rings is split into 12 structures in ϕ , where Ring 0 covers the range of $|\eta| < 0.35$, the rings on either side cover $0.35 < |\eta| < 0.87$ and the outermost rings cover $0.87 < |\eta| < 1.2$ [14]. The granularity for the HO is designed to match the granularity in the HB of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$.

The last component of the HCAL is the HF which is composed of quartz fiber and a steel calorimeter which covers the forward region corresponding to $3.0 < |\eta| < 5.2$. This region re-

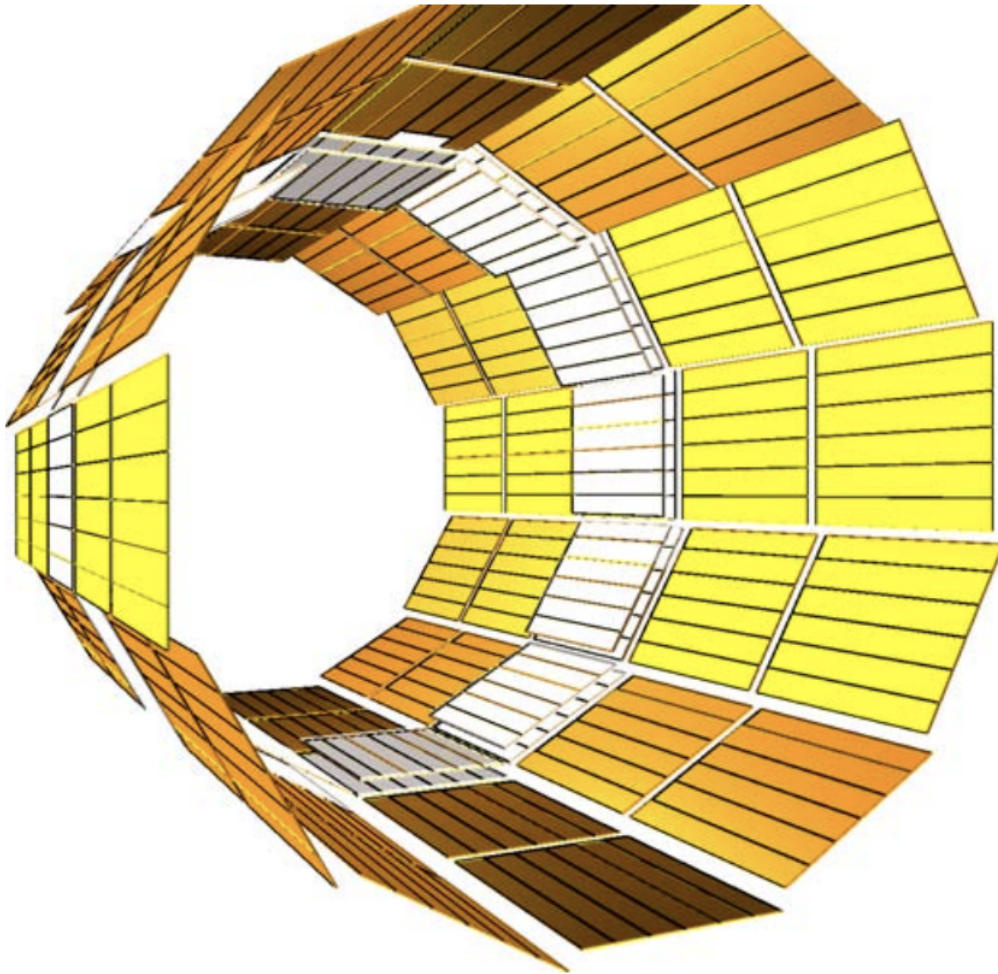


Figure 4.19: The layout of the 5 HO rings outside of the magnet cryostat [14].

carries a large particle flux where, on average, 760 GeV per proton-proton interaction is deposited into the HF while only 100 GeV is deposited in the rest of the detector [14]. The HF has 18 wedges, each containing 2 10 degree sectors, with a granularity of $\Delta\eta \times \Delta\phi = 0.175 \times 0.175$ for $|\eta| < 4.7$ and $\Delta\eta \times \Delta\phi = 0.175 \times 0.35$ for $|\eta| > 4.7$ [14; 15; 16]. The final layout and dimensions of the HCAL system is shown in figure 4.20.

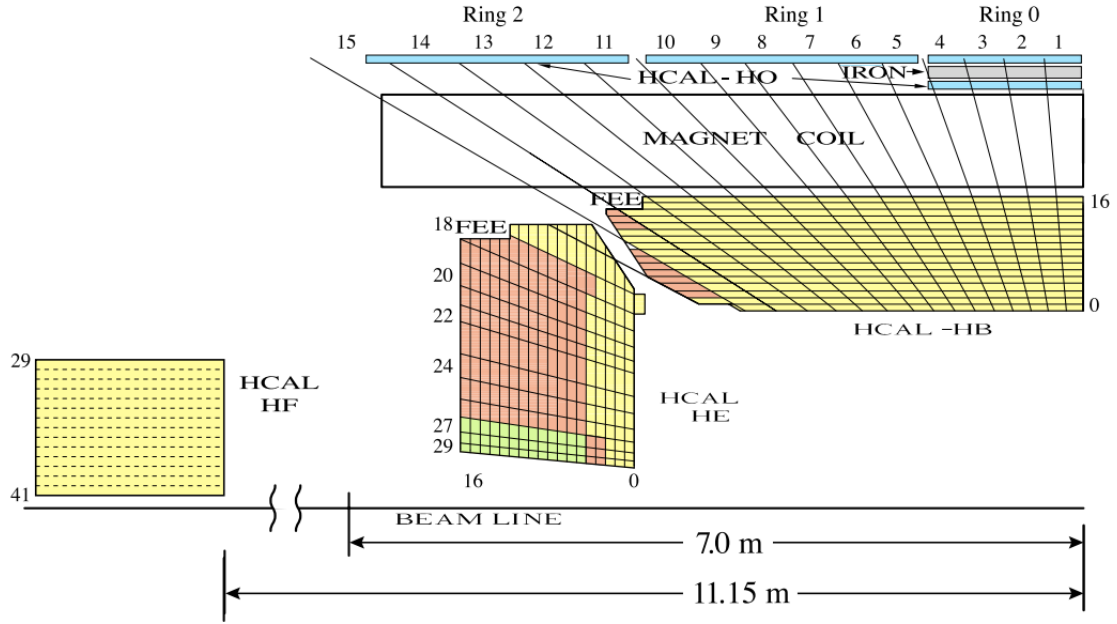


Figure 4.20: An azimuthal cross section of the HCAL system. Here FEE indicates the locations for the front-end electronics. [15; 16].

4.6 Magnet

The superconducting solenoid magnet for CMS is the central structure around which the experiment is built. The solenoid magnet provides a homogeneous magnetic field with a magnetic flux density of $B = 4$ T within the inner detectors [17]. The strong magnetic field, which is approximately 100,000 times stronger than the Earth's magnetic field, significantly bends the paths of charged particles emerging from the collisions seen at the LHC. This bending allows for the precise

measurement of the momentum of these particles as the more momentum a particle has, the less its path is bent by the magnetic field. The superconducting solenoid is the largest superconducting magnet ever built, measuring 12.5 meters in length with an inner diameter of 5.9 meters [17] as shown in figure 4.21.

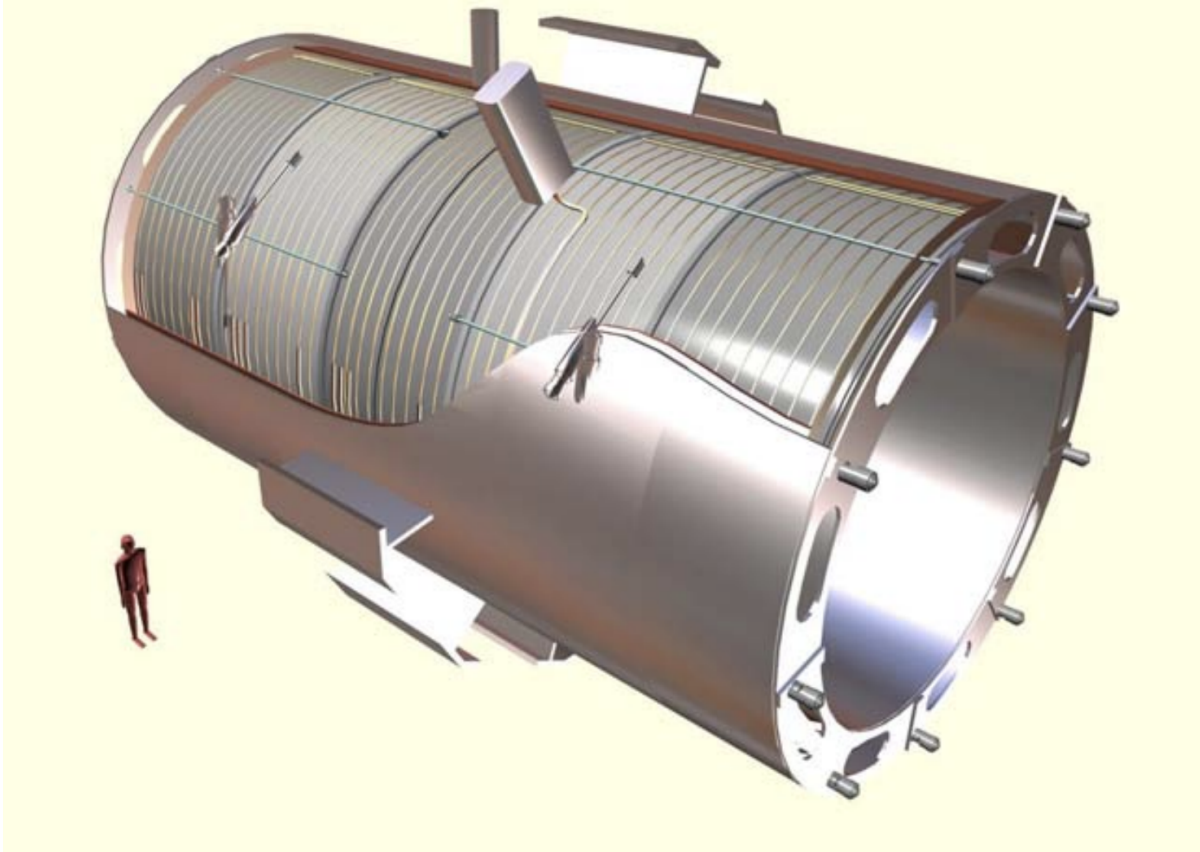


Figure 4.21: An artist's representation of the superconducting solenoid magnet used in CMS [17].

The radial extent of the coil (ΔR) are kept small making the CMS coil a thin coil with $\Delta R/R \sim 0.1$. The E/M ratio, which is directly proportional to the mechanical hoop strain, is distinctly large compared to other detector magnets [14]. Figure 4.22 shows the E/M ratio as a function of the stored energy where the CMS magnet can store the total energy of 2.6 GJ at full current.

In order to provide the necessary hoop strength, the CMS coil must have a structural function.

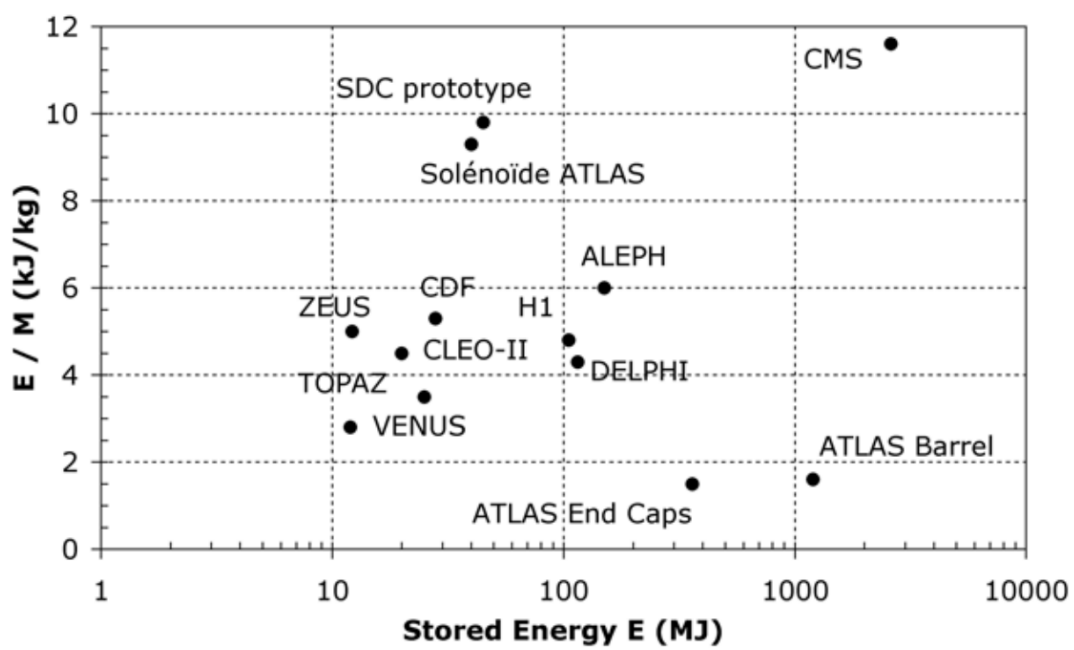


Figure 4.22: The energy-over-mass ratio E/M as a function of the stored energy for several detector magnets [14].

The solenoid encircles the tracker as well as the ECAL and HCAL systems which fit tightly within the magnet coil. Additionally the coil has five modules composing the cold mass in the cryostat which is cooled to 4.6 K with liquid helium. The conductor, made from a Rutherford-type cable co-extruded with pure aluminum, is mechanically reinforced with an aluminum alloy weighing 220 tons in total [14]. A schematic view of the CMS detector showing the placement of the solenoidal magnet and steel yokes in CMS can be seen in figure 4.23.

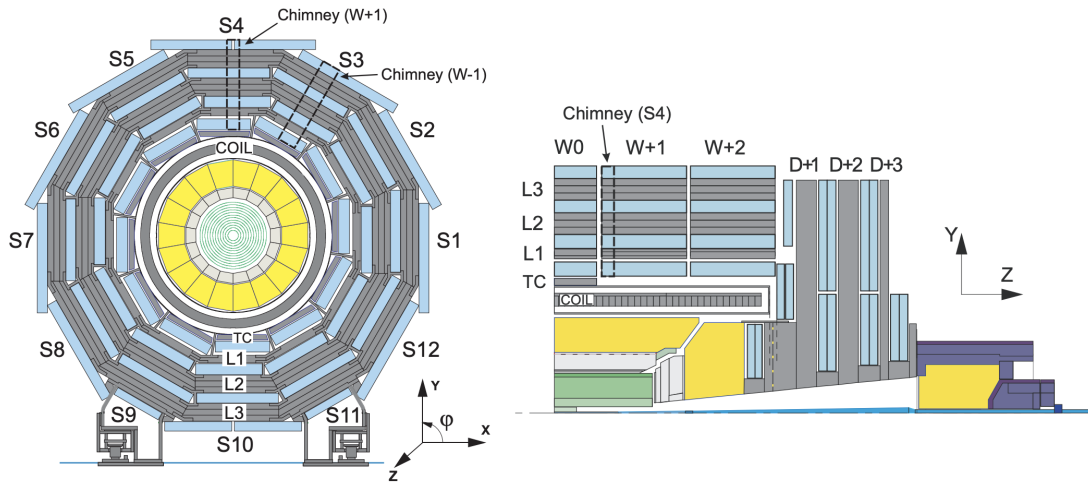


Figure 4.23: A schematic view of the CMS detector. The sectors (S), wheels (W), barrel yoke layers (L) and endcap disks (D) are shown. The tail-catcher (TC) is an additional steel layer present in the central barrel wheel only. Left: A transverse view is shown with $z = 0$. Right: A longitudinal cross sectional view is shown of the positive z and positive y quarter of the detector [18]. Here the tracker is shown in green, the ECAL is light grey, the HCAL is yellow, the muon detectors are blue and the magnet and support structures are dark grey.

The support structure for the outer detector is a 12000 ton steel yoke composed of 5 barrel wheels and 3 endcap disks at each end [14; 18]. In the barrel the yokes vary in thickness with the innermost layer being 295 mm thick and the outermost layers being 630 mm thick. For each endcap the yoke is composed of one 295 mm thick steel layer as the outermost disk and two additional 600 mm thick steel layers as the inner disks. The main role of the steel yoke is maintain the homogeneity of the magnetic field within the tracker volume and to reduce the stray field by returning the magnetic flux. However, the yoke also increases the presence of the central magnetic

flux density by 8%. Figure 4.24 shows the strength of the magnetic field and field lines for a longitudinal cross section of the CMS detector.

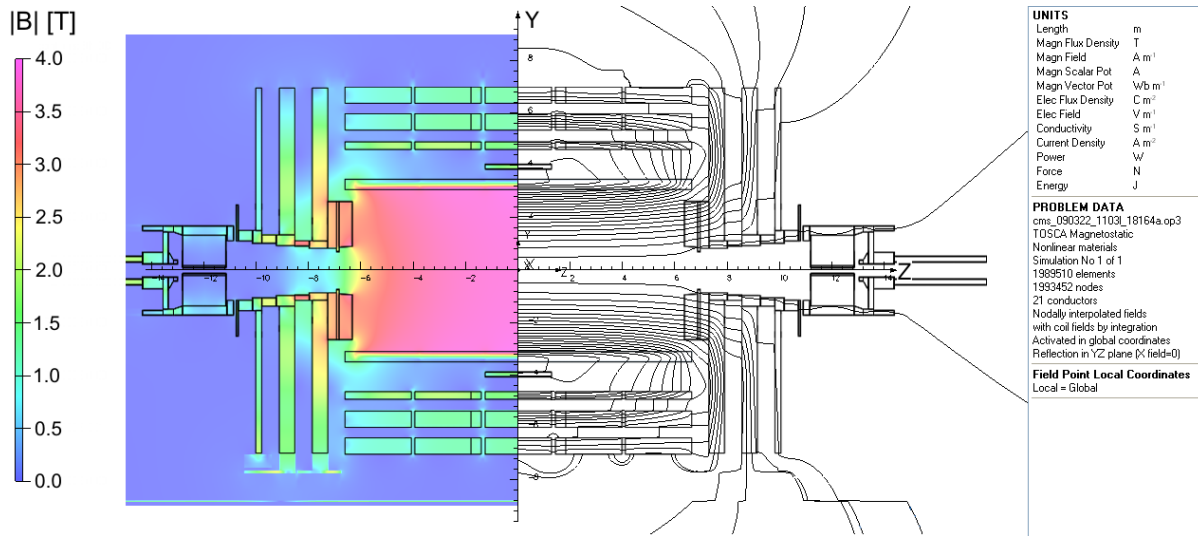


Figure 4.24: A longitudinal cross section of the CMS detector showing the values of the magnetic field (left) and the magnetic flux field lines (right) for a central magnetic flux density of 3.8 T. Each line in the right section represents a magnetic flux increment of 6 Wb. [18].

4.7 Muons

The muon systems form the outermost layers of the detector with drift tubes (DT) and resistive plate chambers (RPC) in the barrel region and cathode strip chambers (CSC) and RPCs in the end-cap regions [21; 20; 19]. Since muons penetrate several meters of iron, the muon systems have multiple stations that will each record a hit when a muon passes through. By tracking the position through multiple stations the momentum can be measured by determining the amount of bend caused by the strong magnetic field present. A cross section showing the positions of the muon subsystems is shown in Fig. 4.25.

The DTs are formed from long segmented drift cells where the position of the traversing muon can be determined by measuring the drift time to the anode wires in the center of each cell. Each

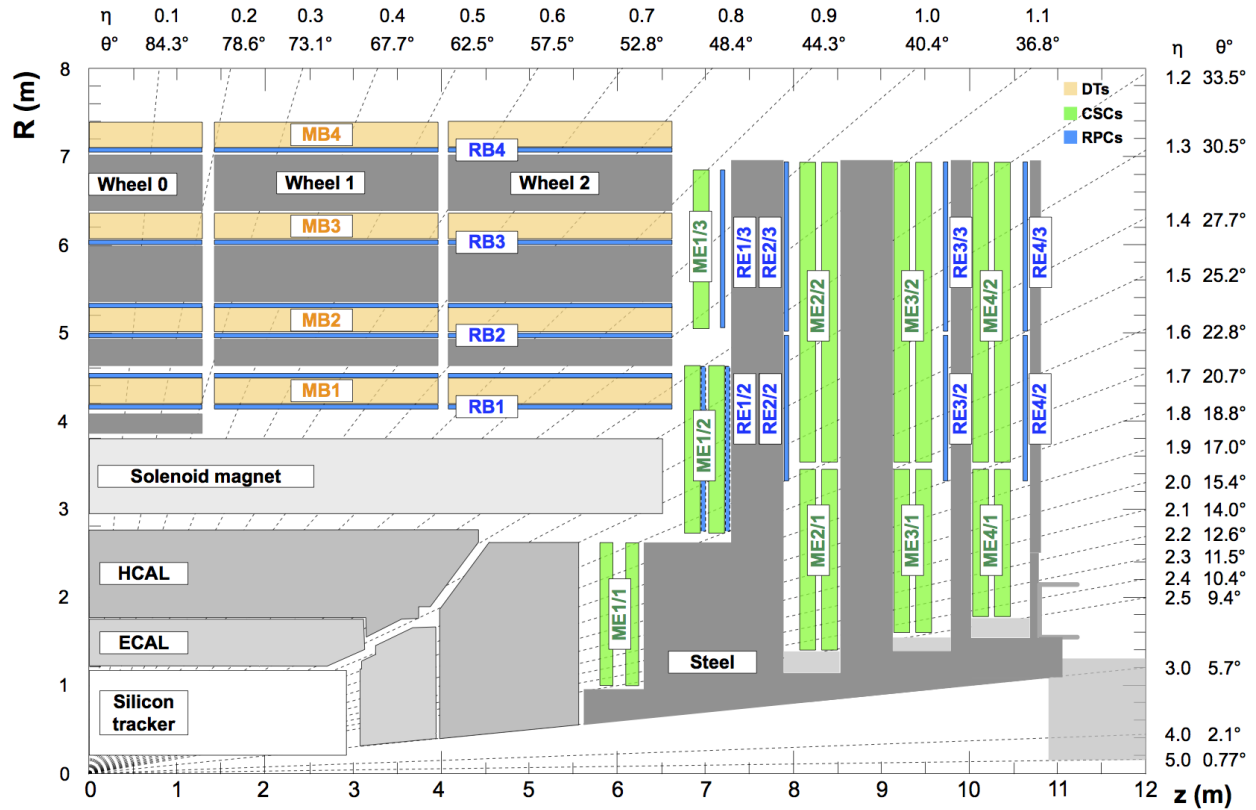


Figure 4.25: A cross section of a quadrant of the CMS detector with the interaction point at the lower left corner. The geometry of the various muon subsystems and the steel yoke (dark areas) are shown. The yellow drift tube stations (DTs) are labeled MB (“Muon Barrel”) and the green cathode strip chambers (CSCs) are labeled ME (“Muon Endcap”). The blue Resistive plate chambers (RPCs) are mounted in both the barrel and endcaps of CMS, where they are labeled RB and RE, respectively [19].

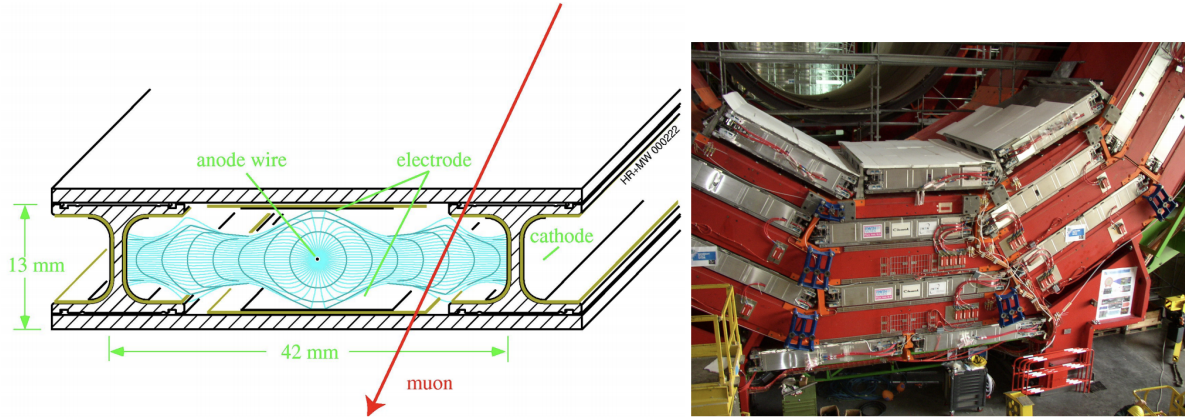


Figure 4.26: A single DT cell is shown on the left and the DT chambers in the steel yoke of the barrel is shown on the right [20].

cell contains an optimally shaped electric field with a spatial resolution of $260 \mu m$ or better. For the 8-layer chambers used, this is increased into a resolution of approximately $100 \mu m$. Each DT chamber consists of 3 superlayers, with each superlayer comprised of 4 staggered layers of parallel drift cells. Wires are oriented such that 2 of the superlayers measure the position in the bending plane ($R-\phi$). The last superlayer measures the position in the longitudinal plane ($R-z$). The DTs consist of 4 stations (MB1–4), in which the outermost chambers of the DT system only have 2 $R-\phi$ superlayers. Since the DT cells measure the drift time, the cell can be relatively large leading to a large detector with a modest number of readout channels with 250 DT chambers covering $18000 m^2$ with 17200 channels. A DT cell as well as the DT detectors installed in the steel yoke can be seen in Fig. 4.26 [20].

The CSCs are standard multi-wire proportional counters with finely segmented cathode strip readout. The strips run radially to measure the position in the bending plane, while the anode wires are orthogonal to the strip (tilted in the innermost station) to measure the position in R . Each trapezoidal chamber is made of 6 anode wire and 6 cathode strip layers and provides a precise measurement of position with a resolution between $50-150 \mu m$ and time with a resolution of $3 ns$. In addition, the CSC technology can handle high particle rates without significant degradation and are able to operate in strong non-uniform magnetic fields that are present in the forward regions. In

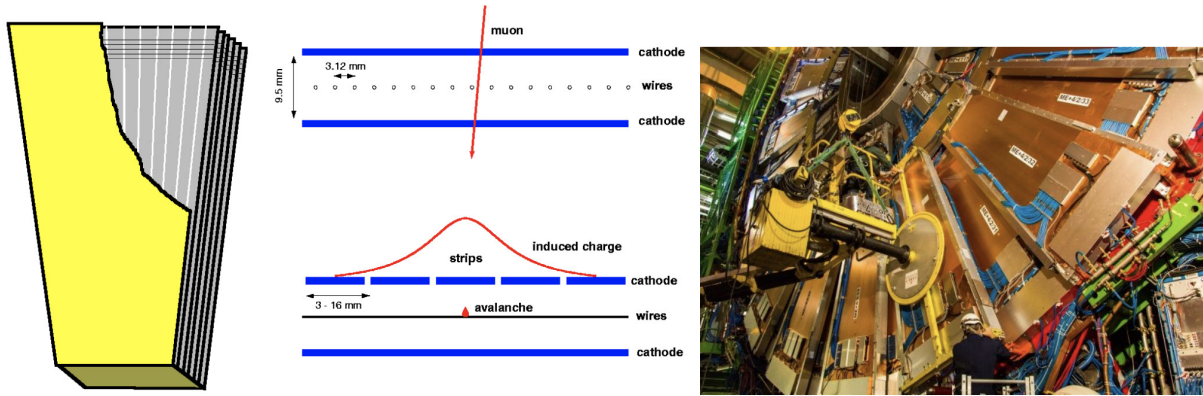


Figure 4.27: A diagram of a 6 layer CSC chamber is shown on the left, while the middle shows the working principle of a CSC. The right shows the ME4/2 chambers during installation [21; 20].

total, there are 4 stations of CSCs (ME1–4) for each endcap, comprised of 540 chambers covering a total area of 700 m^2 . Figure 4.27 shows a diagram of the 6 layer trapezoidal CSC chamber, an illustration of anode wires and cathode strips as well as the outer station chambers during installation [21; 20].

The RPC system uses double-gap chambers operated in avalanche mode using a high electric field. The chambers use a high pressure laminate, known as Bakelite, electrodes with high bulk resistivity. The RPCs are used for fast timing with a resolution of 1.5 ns which is small enough for the identification of the corresponding bunch crossing. The RPCs have 4 stations in the barrel (RB1–4) following the DTs with the 2 innermost stations containing 2 RPC chambers per ϕ sector while the outer stations contain 1 RPC chamber per ϕ sector. There are 4 stations in the endcap (RE1–4) following the outer rings of the CSCs. Figure 4.28 shows a diagram of the double-gap RPC technology as well as the RPC endcap chambers after installation. Table 4.2 summarizes the different muon subsystems [20].

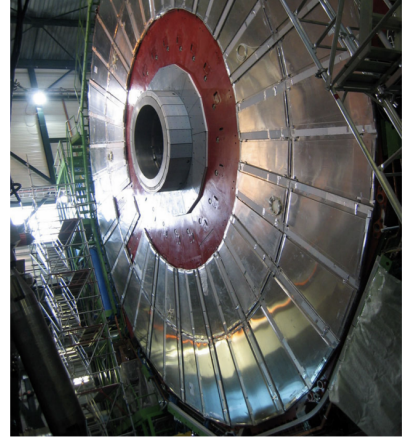
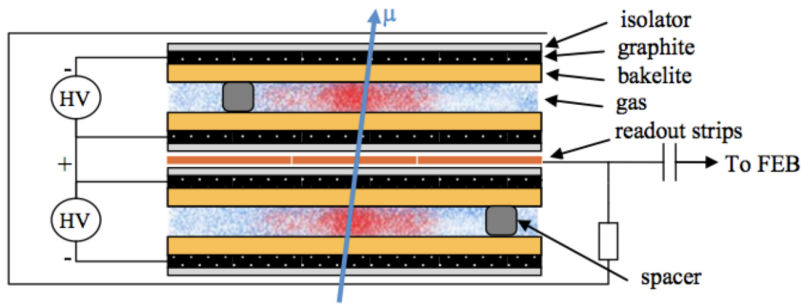


Figure 4.28: The double-gap chamber of the RPC system is shown on the left while the RPC endcap chambers are shown on the right [20].

Table 4.2: Properties of the CMS muon subsystems. The spatial and time resolutions refer to a full chamber [20].

Muon subsystem	Drift Tubes (DT)	Cathode Strip Chambers (CSC)	Resistive Plate Chambers (RPC)
$ \eta $ range	0.0–1.2	0.9–2.4	0.0–1.9
# of chambers	250	540	Barrel 480, Endcap 576
# of layers/chamber	$r-\phi$: 8, z : 4	6	RB1 and RB2: 2, elsewhere: 1
Surface area of layers	18000 m^2	700 m^2	Barrel 2300 m^2 , Endcap 900 m^2
# of channels	172000	Strips 266112, Anodes 210816	Barrel 68136, Endcap 55296
Spatial resolution	$100 \mu\text{m}$	$50\text{--}140 \mu\text{m}$	$0.8\text{--}1.3 \text{ cm}$
Time resolution	2 ns	3 ns	1.5 ns

4.8 Trigger

When the CMS detector is performing at its peak, there are about one billion proton-proton interactions per second inside the detector. As such, it is unrealistic to get usable data from all of these events. In order to reduce this rate, it is important to discriminate against events that have uninteresting final states such as simple proton deflection. This is done using a two level trigger system designed to find physics-wise interesting events. The first part of this trigger, called the level 1 trigger (L1T), is an extremely fast and automatically called set of algorithms that look for simple indications of interesting physics, such as the presence of a high p_T muon, thus reducing the rate to approximately one thousand events per second. The second level of the trigger, named the high level trigger (HLT), then combines information from all of the subdetectors' trigger primitives to further reduce the rate to just a few hundred events per second. This leaves only events that have the potential to lead to new physics discoveries.

The L1 trigger is composed of custom hardware processors that receive and process data at a rate of 40 MHz from front end boards associated with the calorimeter and muon systems. These custom hardware front ends generate a trigger signal in approximately $3.8 \mu s$ with a maximum rate of 100 kHz at the design luminosity of $\mathcal{L} = 10^{34} \text{ cm}^{-2} s^{-1}$ [22]. The HLT hardware consists of a processor farm formed of PCs mounting 2.66 Hz dual quad-core Intel processors and a total 16 GB RAM. HLT algorithms run on this farm and reduce the event rate to approximately 1 kHz. A schematic view of the two level trigger system used at CMS is shown in figure 4.29, while the L1 trigger system used in the muon endcaps is expanded upon in section 4.9 and the planned upgrade to the L1 for Phase-2 is described in appendix A.

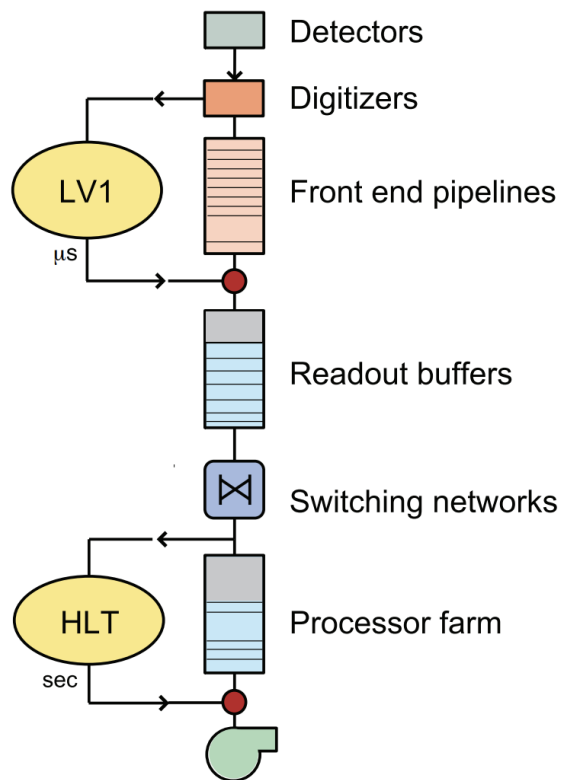


Figure 4.29: Schematic view of the CMS trigger systems showing the approximate latency for both the L1 and HLT systems [22].

4.9 Endcap Muon Track Finder

Due to the large area covered by the muon detectors, the muon trigger responsibilities are split into three regions in pseudorapidity. The first region is the barrel, known as the Barrel Muon Track Finder (BMTF), and consists of DTs and RPCs and covers $|\eta| < 0.8$. The second region is the overlap, known as the Overlap Muon Track Finder (OMTF), which contains information from all muon detectors including DTs, RPCs and CSCs covering $|\eta| > 0.8$ and $|\eta| < 1.2$. The final region, known as the Endcap Muon Track Finder (EMTF), contains CSCs and RPCs and covers $|\eta| > 1.2$. The EMTF system is discussed below, however, information on the RPCs is omitted because it operates similarly to the CSCs, but is used much less frequently by the EMTF due to its smaller area of coverage (see Fig. 4.30) and worse spatial resolution.

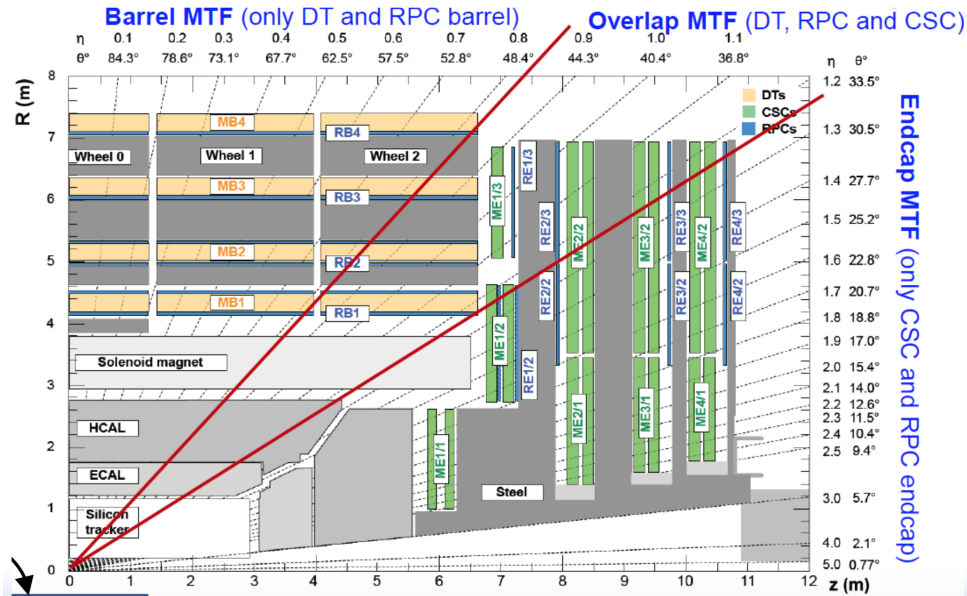


Figure 4.30: The splitting of the muon trigger systems. This image shows a 2-D slice of the detector.

The CSC chambers contain six layers of both radial cathode strips and orthogonal (tilted off orthogonal in some cases) anode wires that provide precise positioning in both ϕ and R coordinates. While running, signals from the cathode strips will be amplified and read by the Cathode

Front End Boards (CFEBs) on the CSC chamber. The positions of hits received by the CFEBs are digitized in units of cathode half-strips and transferred to the Trigger Mother Board (TMB) and the Data Mother Board (DMB) contained in the connected peripheral crate (60 degrees in ϕ for stations 2-4 or 30 degrees for station 1). If the TMB sees that at least four layers of cathodes are fired within the readout window, it will create a Cathode Local Charged Track (CLCT), a trigger primitive (TP) containing basic information of a hit's position in ϕ and timing.

A similar process is done with the anode wires for the radial position and precise timing. Anode Front End Boards (AFEBs) amplify anode signals and transfer them to the CSC chamber's Anode Local Charge Track Board (ALCT Board) where they are time-aligned and create up to two Anode Local Charge Tracks (ALCT). These ALCTs are then transmitted to the TMB and DMB on the peripheral crate. The TMB performs a time coincidence check of ALCTs and CLCTs and builds up to two combined Local Charged Tracks (LCT) which are transferred to the Muon Port Card (MPC) on the same peripheral crate. The MPC collects all of the LCTs from a trigger sector (9 chambers) and selects the three "best" LCTs to send to the EMTF Sector Processors in the service cavern.

Once the LCTs are received by the sector processors, the EMTF's track building algorithms are applied to create multi-station muon tracks. If the EMTF is able to combine multiple LCTs from different stations, the EMTF will trigger and send a Level 1 Accept (L1A) to the Timing and Control Distribution System (TCDS). The TCDS receives information from all subsystems and ensures synchronization and timing alignment between the subdetectors. If the timing between subsystems remains aligned, the TCDS transfers the trigger information to the Clock and Control Boards (CCBs) which assigns a global detector time to the L1As and sends them back to all subdetectors. Upon the subdetectors receiving an L1A from the CCB, data stored on the DMBs buffer is readout through the Data Acquisition (DAQ) system and stored centrally. This workflow can be seen below in Fig. 4.31.

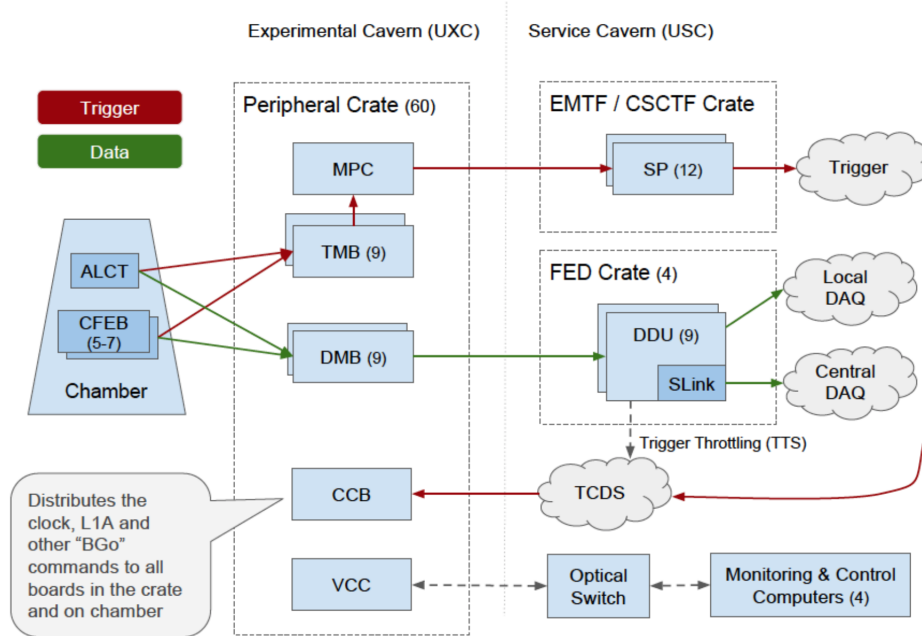


Figure 4.31: The workflow of the EMTF trigger system.

Once the data is readout and passed through the HLT, subsets of the data will be analyzed by the Data Quality Monitoring group (DQM) for monitoring. The DQM serves 3 main purposes by raising alarms if some part of the detector malfunctions, providing quick data certification and aiding in debugging by the subsystem experts by providing detailed information [136]. The DQM group provides several different data types to allow robust monitoring and quick feedback as seen in figure 4.32. A subset of the data is reconstructed and monitored directly at Point 5 and used to fill the Online DQM GUI to allow shifters to give immediate feedback. The data transferred to the Tier0 is split into multiple streams with the express stream being promptly reconstructed within approximately an hour of being taken. The prompt reco stream contains the full set of data and is reconstructed within approximately 48 hours, while the rereco comes significantly after the data but contains better alignment and calibration constants. All of these data streams are reconstructed and create a large number of plots, named monitor elements (ME), which are transferred to an interactive interface named the DQM GUI. This DQM GUI is where shifters and detector experts can browse these MEs and monitor various subsystems. Figure 4.33 shows several MEs summarizing

the strip occupancy for each chamber in various stations and rings while figure 4.34 summarizes the LCT chamber occupancy for the entire CSC system.

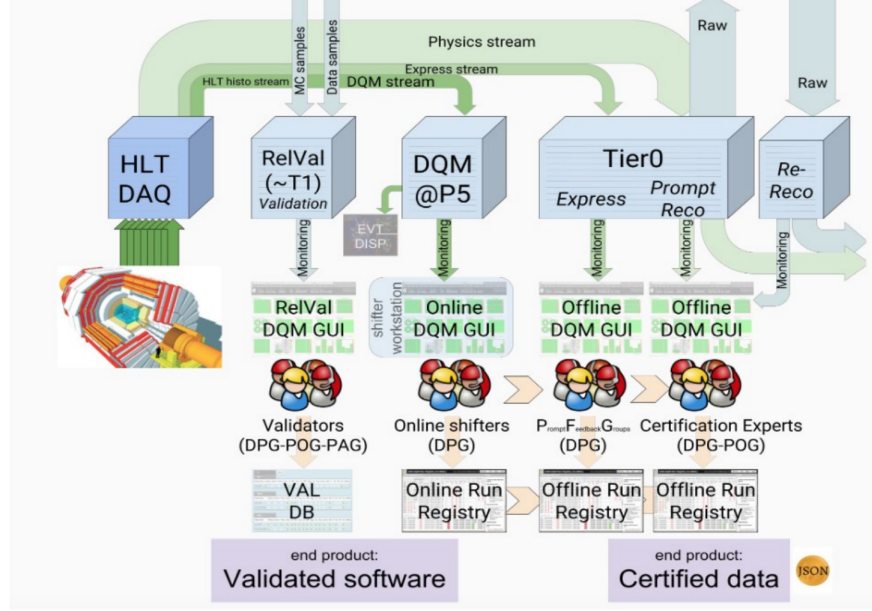


Figure 4.32: The data stream after the HLT DAQ.

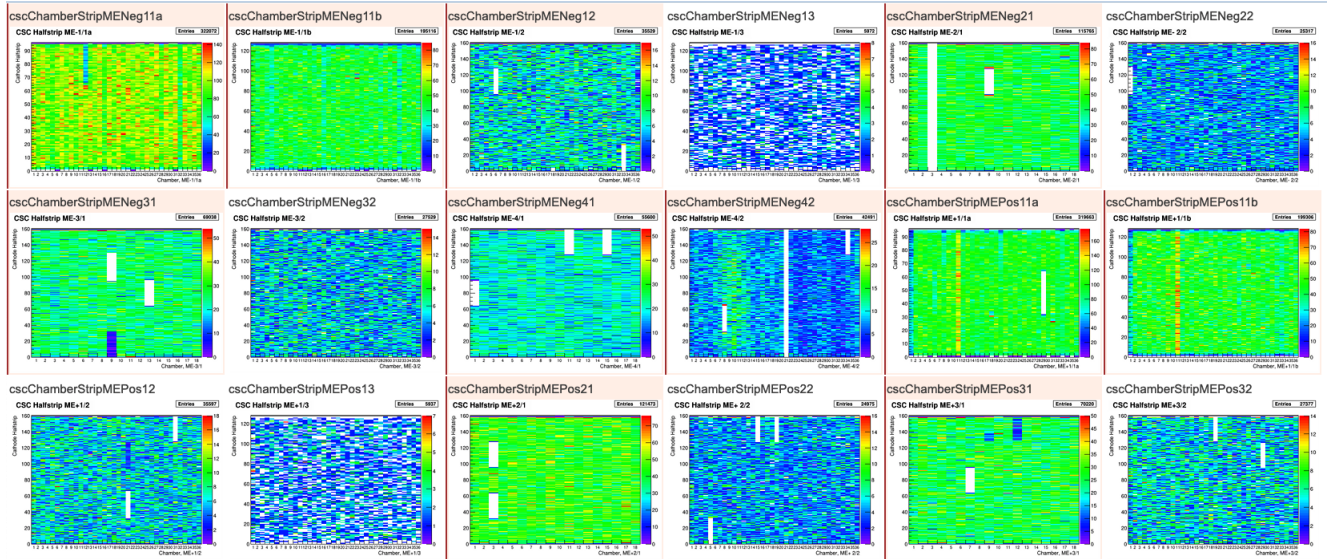


Figure 4.33: Shows several monitor elements from the DQM GUI summarizing the chamber strip occupancy for various stations and rings.

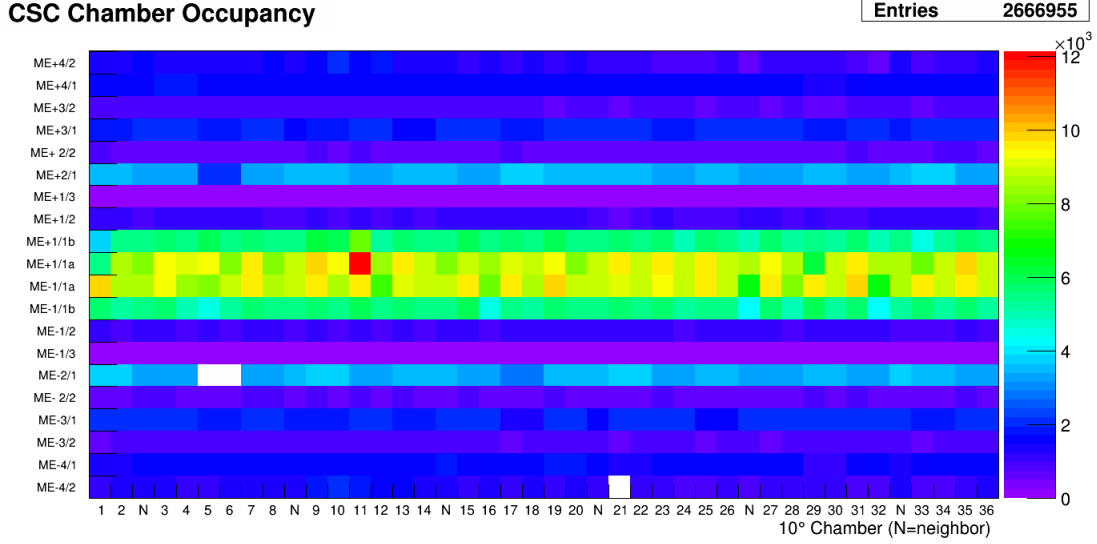


Figure 4.34: Shows a monitor element from the DQM GUI that summarizes the LCT chamber occupancy for the entire CSC subsystem.

During the second half of Run-2 data-taking, the EMTF DQM was expanded to help monitor the system with larger amounts of pileup. With increased pileup, there is a danger of a quadratic increase in trigger rates with respect to the number of pileup vertices. As such, the DQM was expanded to increase the monitoring associated with track information. In addition to basic track information, monitor elements were added that match the requirements for quality and p_T requirements that are used for the L1 trigger. These added plots simulate the lowest p_T unrescaled L1 trigger used by EMTF and were used in 2018 data-taking as well as in future runs to debug issues in EMTF or CSC.

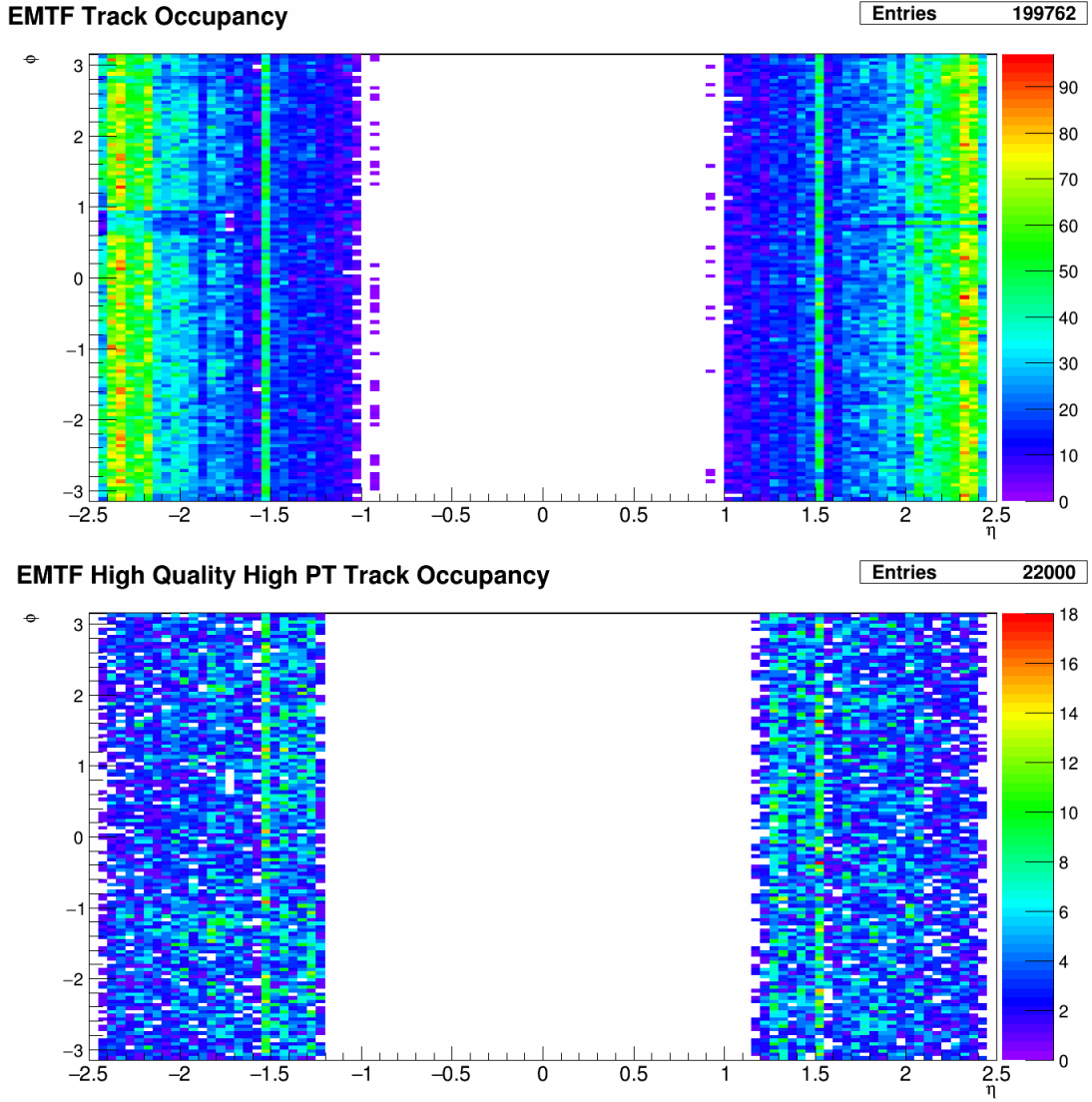


Figure 4.35: The top plot shows the ϕ (y-axis) and η (x-axis) value for each track constructed by EMTF. The bottom plot shows the ϕ (y-axis) and η (x-axis) value for each track constructed by EMTF that have an LCT from the innermost station as well as $p_T > 20$ GeV. These values match the selections applied to the lowest p_T unprescaled L1 trigger used by EMTF.

Chapter 5

Physics Objects

The final state of this analysis is a pair of oppositely charged, same-flavor, high transverse momentum (p_T) isolated leptons that are compatible with decays from a Z boson, large missing transverse momentum associated with undetectable particles and low jet activity. For all models presented, the signal cross sections are orders of magnitude lower than the Standard Model backgrounds. As such several steps are performed to extract the signal from data:

1. Select only events that pass single or double lepton triggers.
2. Select events requiring a high p_T oppositely charged, same-flavor lepton pair (e^+, e^-, μ^+, μ^-) by requiring:
 - Identification and Isolation requirements for both electrons and muons.
 - $p_T > 25(20)$ GeV for leading(trailing) leptons.
3. Apply a loose Z mass constraint for the lepton pair.
4. Veto events with 2 or more jets.
5. A tighter event selection is performed in an exclusive ≤ 1 jet category.

A summary of the objects used in this analysis is shown in Table 5.1. Each object is further detailed in sections 5.1-5.8.

Table 5.1: Objects and their selections.

Object	Selection
Triggers	Single and Double Lepton
Primary Vertices	Largest $\sum_{tracks} p_T^2$
Electrons	“ <i>Medium</i> ” ID and Isolation
Muons	“ <i>Tight</i> ” ID and Isolation with Impact Parameter selections
Taus	Veto via DecayModeFinding
Jets	PF CHS jets using <i>anti</i> - k_T with $\Delta R = 0.4$
B-tagging	“ <i>Medium</i> ” DeepCSV
p_T^{miss}	Type-1 corrected PF p_T^{miss}

5.1 Triggers

A list of signal and control triggers for this analysis is designed individually for each year. These sets combine single and double lepton triggers to give high efficiency ($\sim 99.7\%$) independent of the data-taking conditions. It should be noted that the inclusion of the single lepton triggers adds about 3% larger efficiency, making the analysis more robust under any data to simulation trigger efficiency discrepancy, and making the overall trigger selection almost fully efficient. The signal triggers are shown Tables 5.2-5.4.

To measure the efficiency in data we follow the procedure described here [137], which has also been used in several analyses in the run-II. Events are selected by a set of events that were recorded on a trigger that is uncorrelated with the lepton triggers, in particular events recorded on the MET Primary dataset are used. Then, events with two fully identified leptons are selected on that sample. Finally, the trigger efficiency is measured for the candidate events to pass the logical of triggers being considered. A similar procedure is also followed on simulated events. The trigger

efficiency scale factors between data and simulation as a function of p_T and $|\eta|$ of the leading and trailing leptons is shown in Figures 5.1 to 5.12. The ratio of data and simulation is found to be consistent with unity within 1% for this analysis.

Table 5.2: Triggers for 2016.

Primary Dataset	Trigger Name
MuonEG	Mu17_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL
	Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL
	Mu17_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL
	Mu23_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL
	Mu8_TrkIsoVVL_Ele17_CaloIdL_TrackIdL_IsoVL
	Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL
DoubleMuon	Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ
	Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ
	TkMu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ
DoubleElectron	Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ
SingleMuon	IsoMu22
	IsoTkMu22
	IsoMu24
	IsoTkMu24
SingleElectron	Ele25_eta2p1_WPTight_Gsf
	Ele27_eta2p1_WPLoose_Gsf
	Ele27_WPTight_Gsf
	Ele35_WPLoose_Gsf

5.2 Primary Vertices

The primary vertex (PV), which represents the origin for hard processes, is constructed in a cylindrical volume with a radius of 2 cm and a length of 24 cm surrounding the nominal interaction point. In the case that multiple PVs are formed for one event, the PV with the largest squared sum of track p_T ($\sum_{tracks} p_T^2$) is chosen.

To match the expected number of pileup interactions in simulation with in data, a reweighting is

Table 5.3: Triggers for 2017.

Primary Dataset	Trigger Name
MuonEG	HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ
	HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL
	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ
	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL
	HLT_Mu23_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL_DZ
	HLT_Mu23_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL
	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ
	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL
DoubleMuon	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8
	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass8
	HLT_Mu19_TrkIsoVVL_Mu9_TrkIsoVVL_DZ_Mass3p8
	HLT_Mu19_TrkIsoVVL_Mu9_TrkIsoVVL_DZ_Mass8
DoubleElectron	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ
	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL
	HLT_DiEle27_WPTightCaloOnly_L1DoubleEG
	HLT_DoubleEle33_CaloIdL_MW
	HLT_DoubleEle25_CaloIdL_MW
	HLT_DoublePhoton70
SingleMuon	HLT_IsoMu24
	HLT_IsoMu27
	HLT_IsoMu30
	HLT_Mu50
SingleElectron	HLT_Ele115_CaloIdVT_GsfTrkIdT
	HLT_Ele27_WPTight_Gsf
	HLT_Ele32_WPTight_Gsf
	HLT_Ele35_WPTight_Gsf
	HLT_Ele32_WPTight_Gsf_L1DoubleEG
	HLT_Photon200

performed using the minimum bias cross section of 69 mb with an uncertainty of 5%, as described in [138]. The number of reconstructed vertex distributions in 2016, 2017, and 2018 in $Z \rightarrow \ell\ell$ events are shown in Figure 5.13.

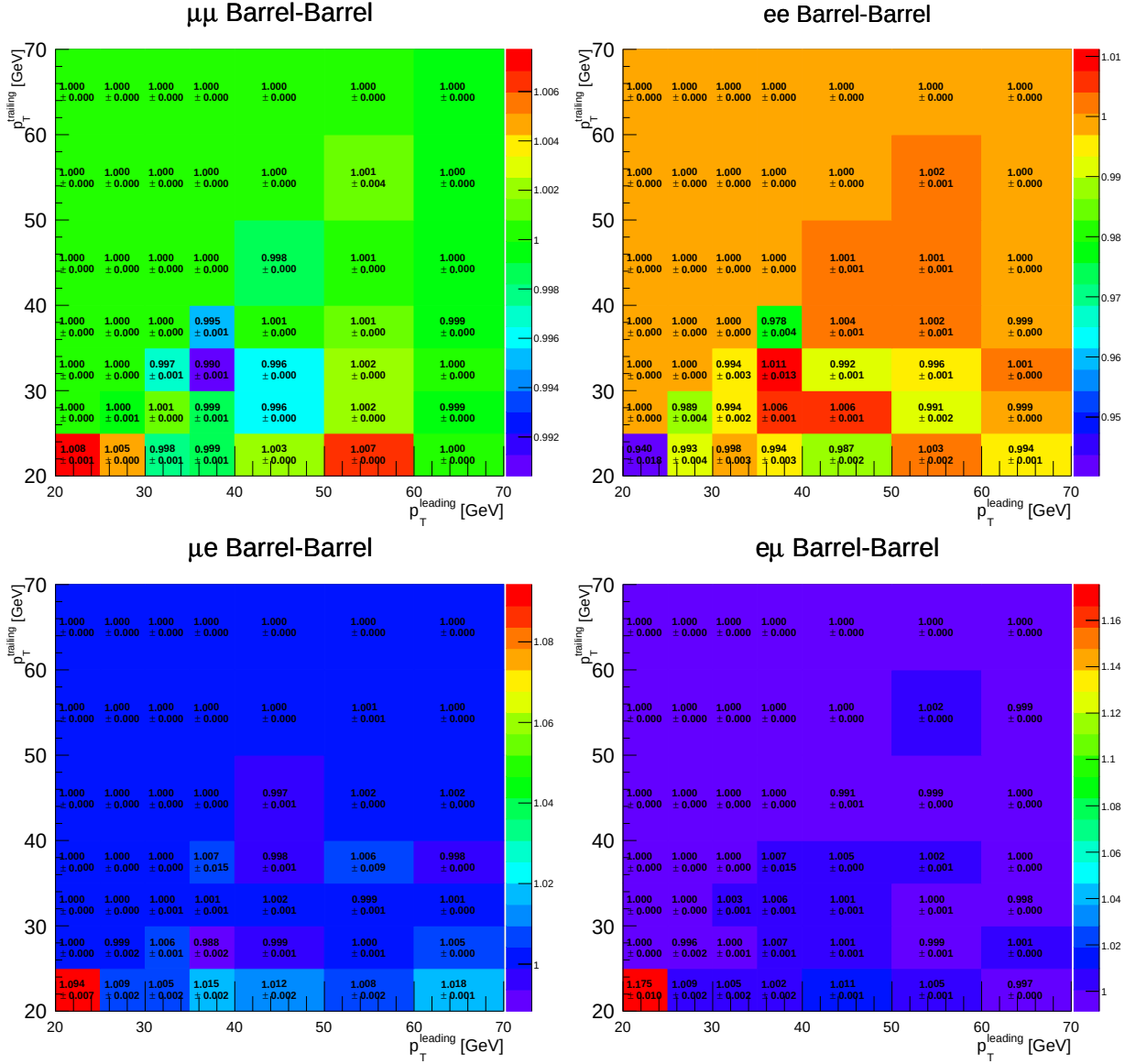
Table 5.4: Triggers for 2018.

Primary Dataset	Trigger Name
MuonEG	HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ
	HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL
	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ
	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL
	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ
	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL
DoubleMuon	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8
	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass8
	HLT_Mu19_TrkIsoVVL_Mu9_TrkIsoVVL_DZ_Mass3p8
	HLT_Mu19_TrkIsoVVL_Mu9_TrkIsoVVL_DZ_Mass8
DoubleElectron	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ
	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL
	HLT_DiEle27_WPTightCaloOnly_L1DoubleEG
	HLT_DoubleEle33_CaloIdL_MW
	HLT_DoubleEle25_CaloIdL_MW
	HLT_DoubleEle27_CaloIdL_MW
	HLT_DoublePhoton70
SingleMuon	HLT_IsoMu24
	HLT_IsoMu27
	HLT_IsoMu30
	HLT_Mu50
SingleElectron	HLT_Ele115_CaloIdVT_GsfTrkIdT
	HLT_Ele27_WPTight_Gsf
	HLT_Ele28_WPTight_Gsf
	HLT_Ele32_WPTight_Gsf
	HLT_Ele35_WPTight_Gsf
	HLT_Ele38_WPTight_Gsf
	HLT_Ele40_WPTight_Gsf
	HLT_Ele32_WPTight_Gsf_L1DoubleEG
	HLT_Photon200

5.3 Jets

Jets are reconstructed using the anti- k_T algorithm [139] on all PF candidates, after rejecting charged hadrons from pileup vertices, i.e. the Charged Hadron Subtraction (CHS) collection is used, within a cone of $\Delta R = 0.4$ implemented in the FASTJET package [140; 141]. Energy of the recon-

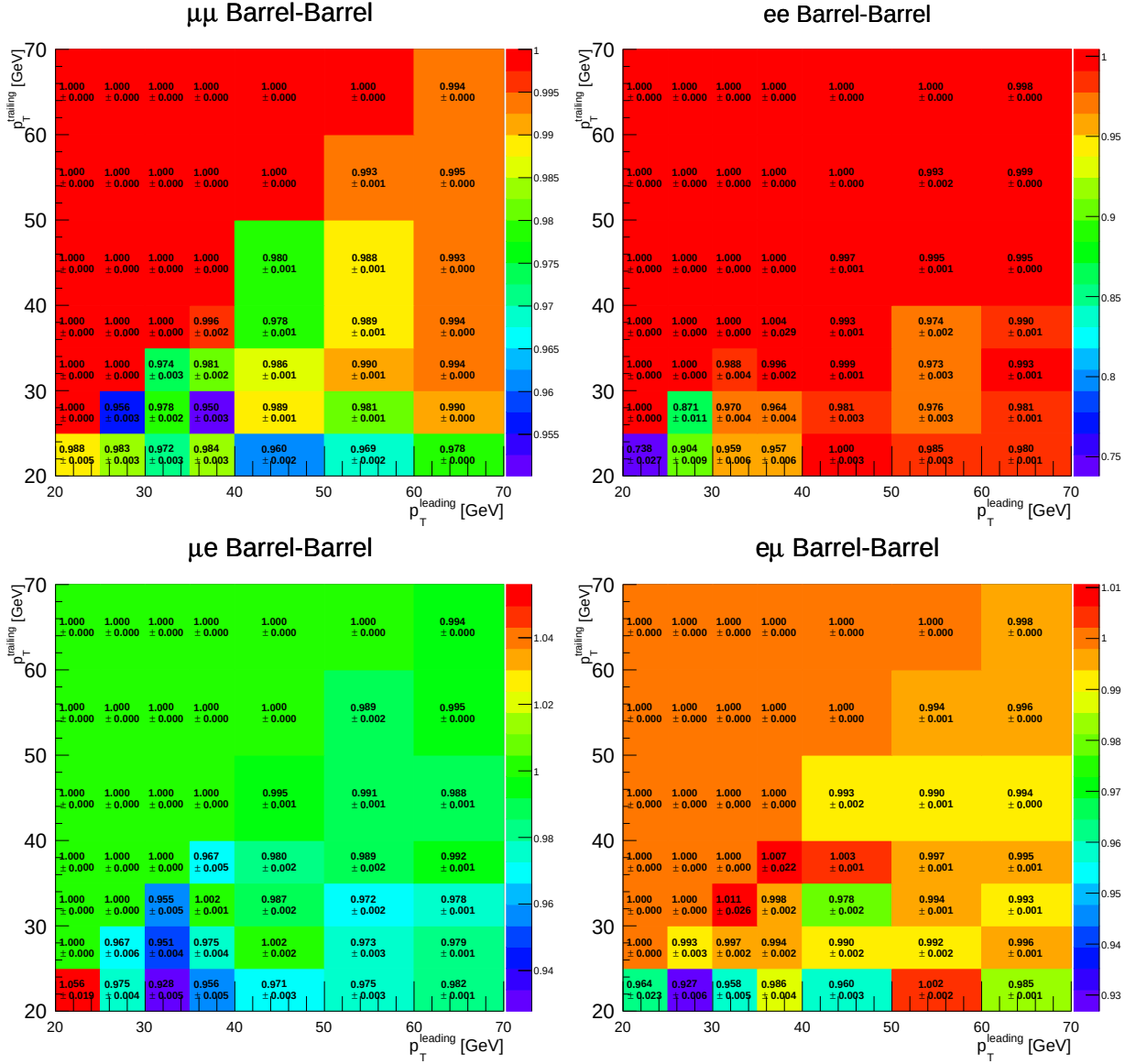
Figure 5.1: Trigger efficiency scale factors for $\mu\mu$ (top left), ee (top right), μe (bottom left), and $e\mu$ (bottom right) events in 2016 with both leptons with $|\eta| < 1.5$.



structured jets is corrected in 3 separate steps:

1. **L1:** A correction is applied to mitigate the effect of pileup events.
2. **L2:** η -dependent corrections are applied to the jet 4-vector.

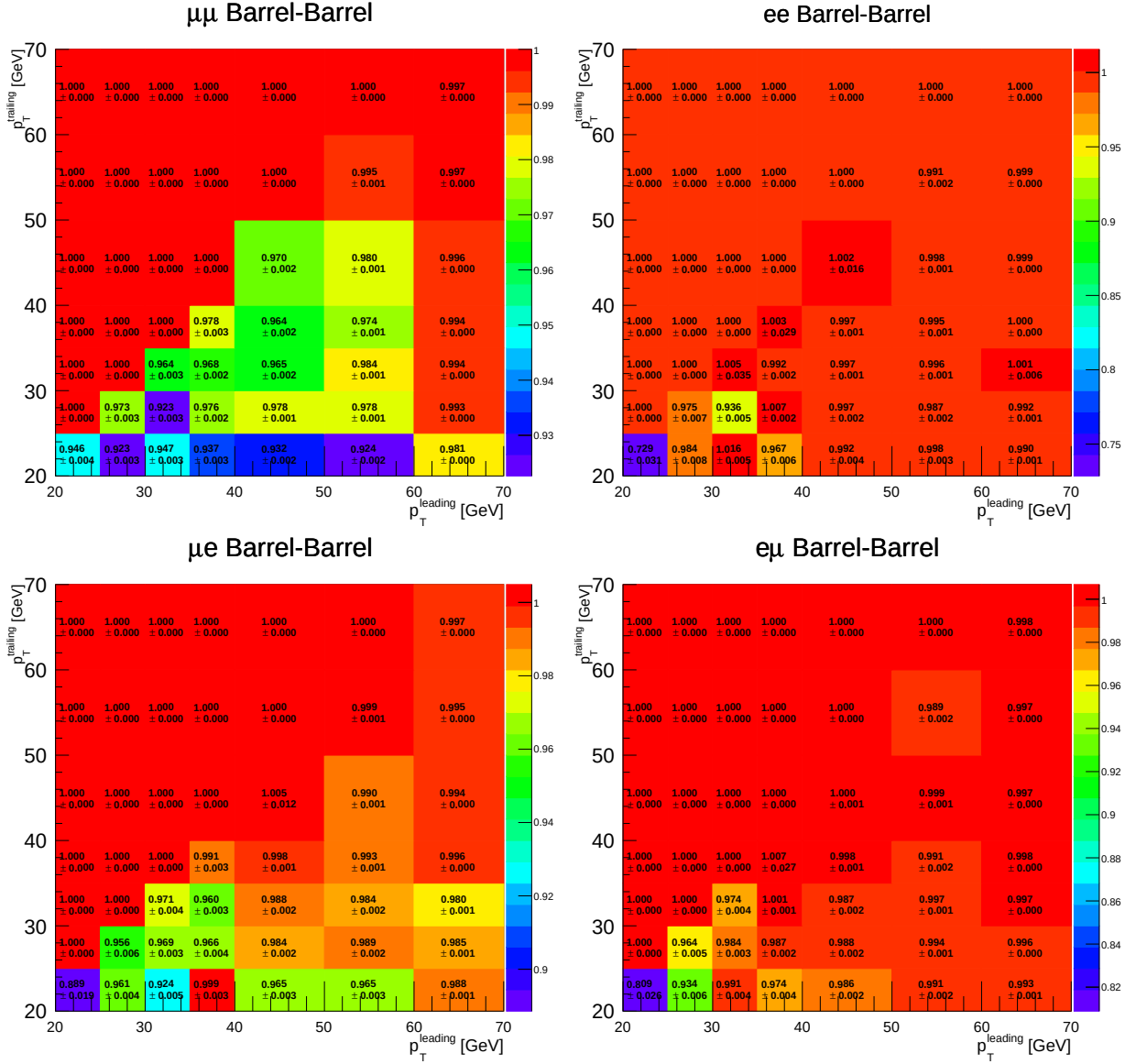
Figure 5.2: Trigger efficiency scale factors for $\mu\mu$ (top left), ee (top right), μe (bottom left), and $e\mu$ (bottom right) events in 2017 with both leptons with $|\eta| < 1.5$.



3. **L3:** p_T -dependent corrections are applied to the jet 4-vector adjusting the absolute scale of the jet.

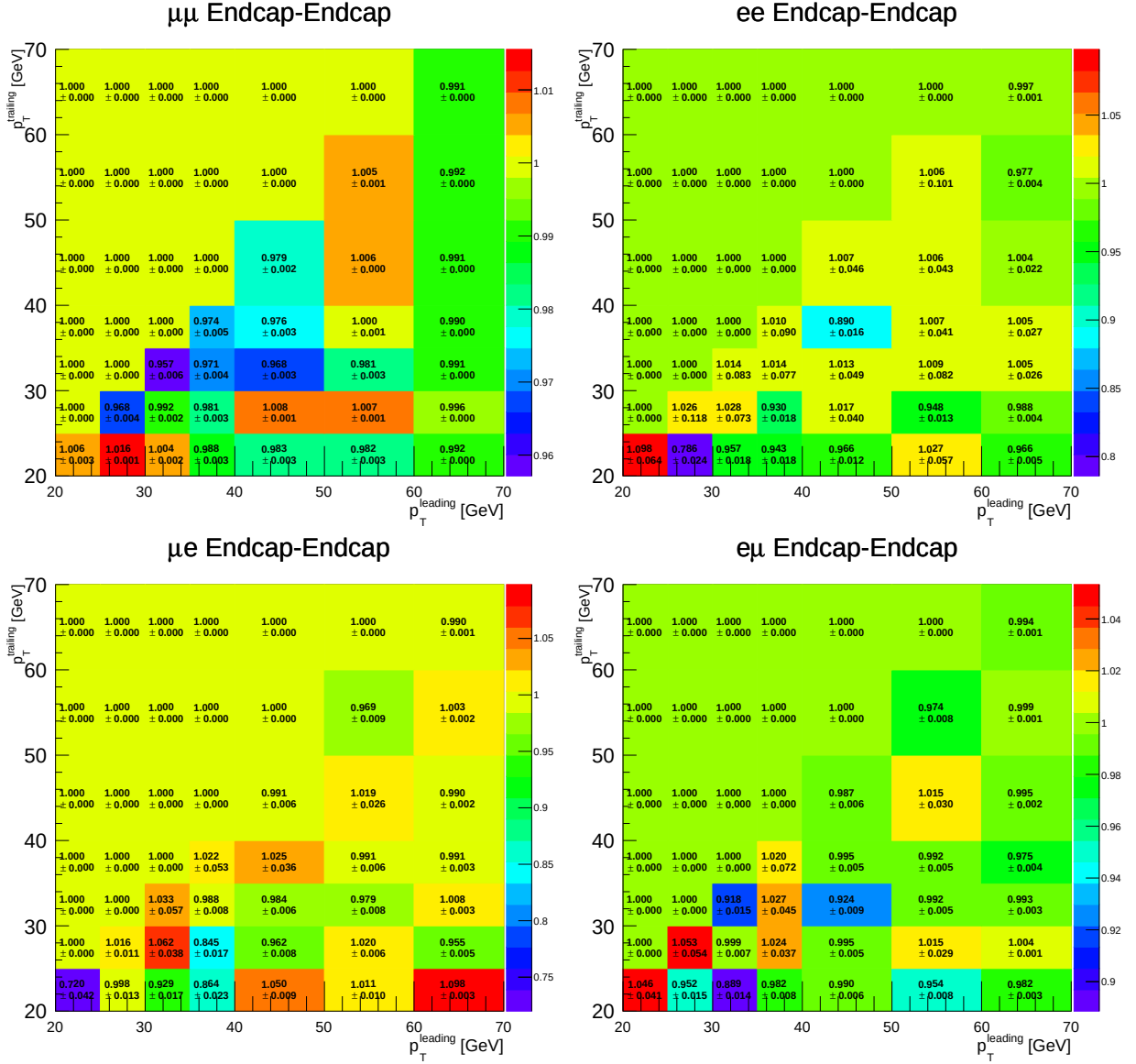
For data, an additional residual correction is included in the absolute scale correction. This analysis considers any jets with $p_T > 30$ GeV and $|\eta| < 4.7$ and passing loose (tight) jet ID requirements [142; 143; 144] for 2016 (2017 and 2018). Any jet that is within a cone of $\Delta R = 0.4$

Figure 5.3: Trigger efficiency scale factors for $\mu\mu$ (top left), ee (top right), μe (bottom left), and $e\mu$ (bottom right) events in 2018 with both leptons with $|\eta| < 1.5$.



of an identified lepton is ignored. Events are rejected with more than one reconstructed jet.

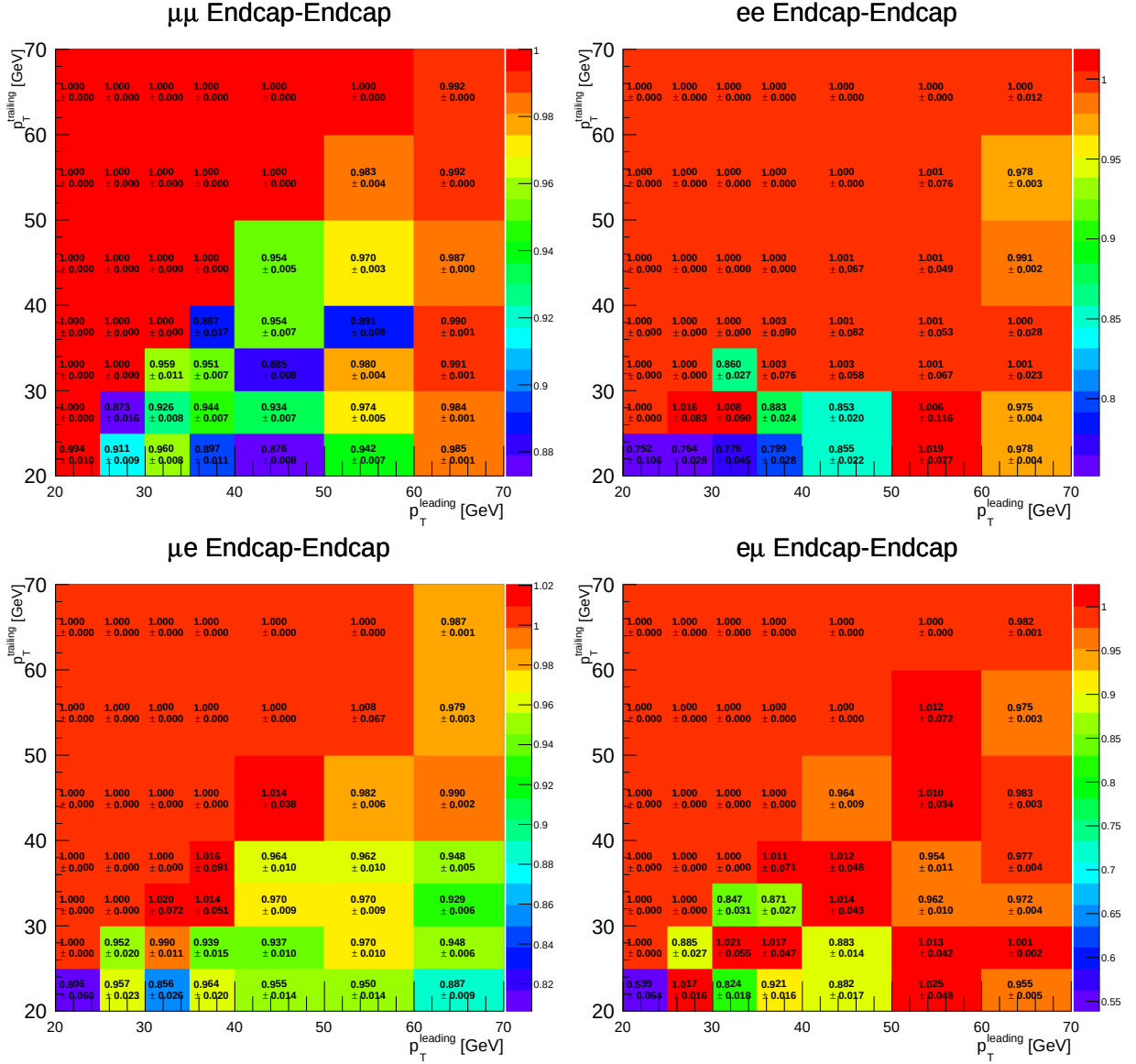
Figure 5.4: Trigger efficiency scale factors for $\mu\mu$ (top left), ee (top right), μe (bottom left), and $e\mu$ (bottom right) events in 2016 with both leptons with $|\eta| > 1.5$.



5.4 B-tagging

Any jet reconstructed within the tracker region of $|\eta| < 2.4$, with $p_T > 20$ GeV, is considered as a potential b-jet candidate. The b-tagging method used in this analysis is based on the DeepCSV algorithm, which expands on older combined secondary vertex (CSV) taggers by incorporating deep

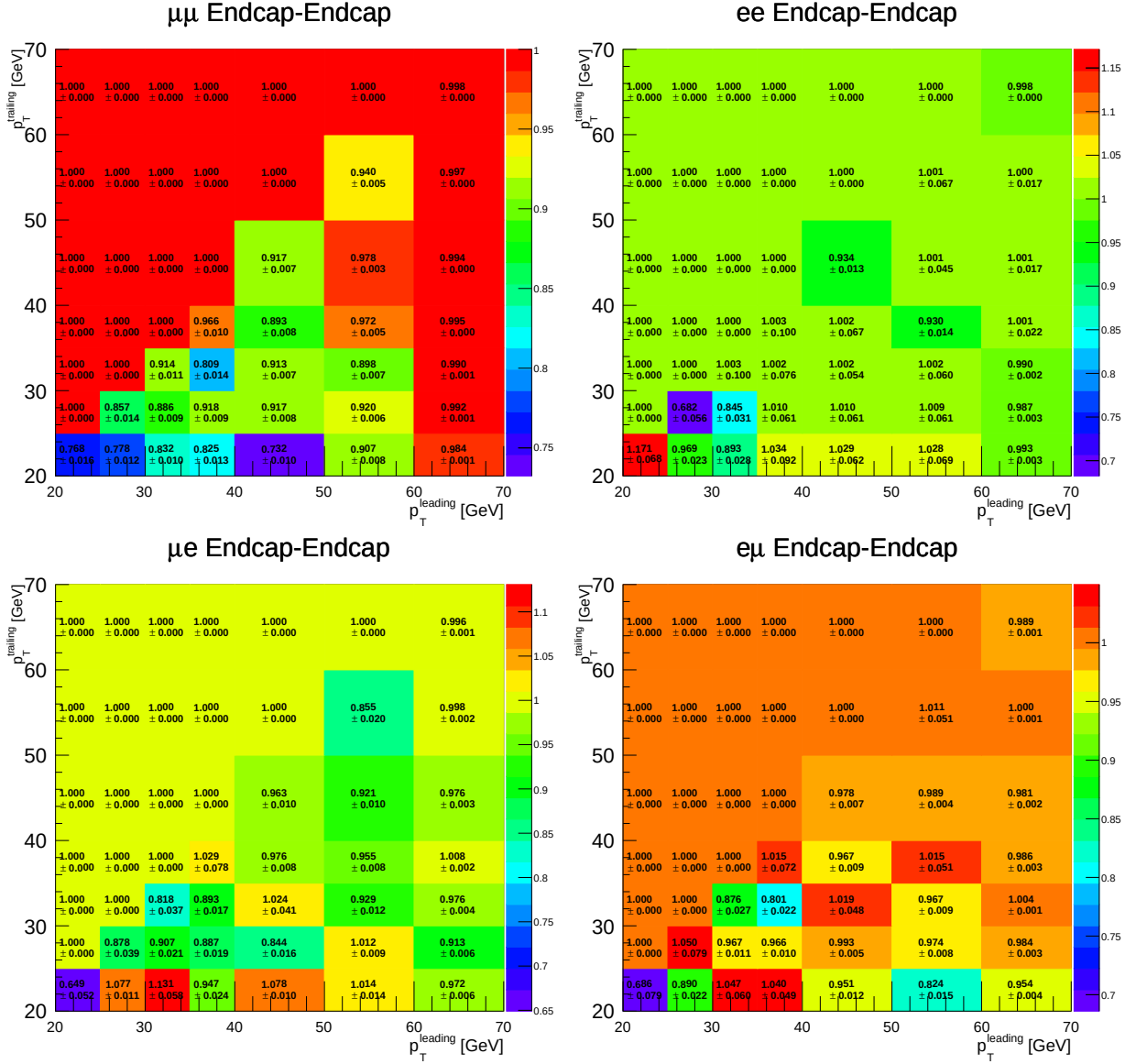
Figure 5.5: Trigger efficiency scale factors for $\mu\mu$ (top left), ee (top right), μe (bottom left), and $e\mu$ (bottom right) events in 2017 with both leptons with $|\eta| > 1.5$.



machine learning [145]. The DeepCSV algorithm was developed using a deep neural that uses track and jet information as inputs and performs a simultaneous training for all jet flavors. A medium working point was used where the efficiency to select b-quark jets is about 70% and the rate for mistagging jets originating from the hadronization of gluons or $u/d/s$ quarks is about 1%.

using the medium working point [146; 147]. The values for the working points for each year

Figure 5.6: Trigger efficiency scale factors for $\mu\mu$ (top left), ee (top right), μe (bottom left), and $e\mu$ (bottom right) events in 2018 with both leptons with $|\eta| > 1.5$.



are shown in table 5.5.

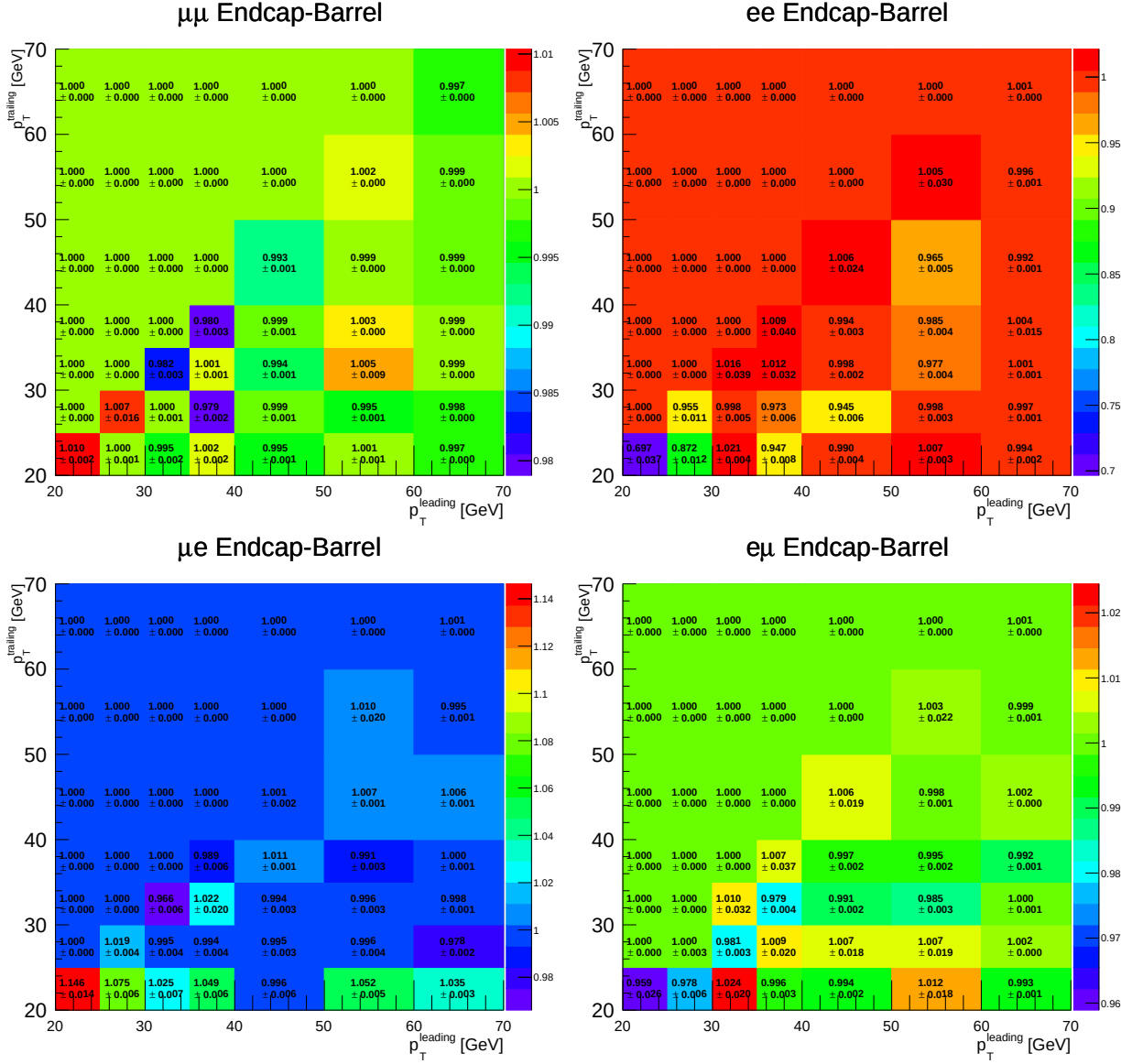
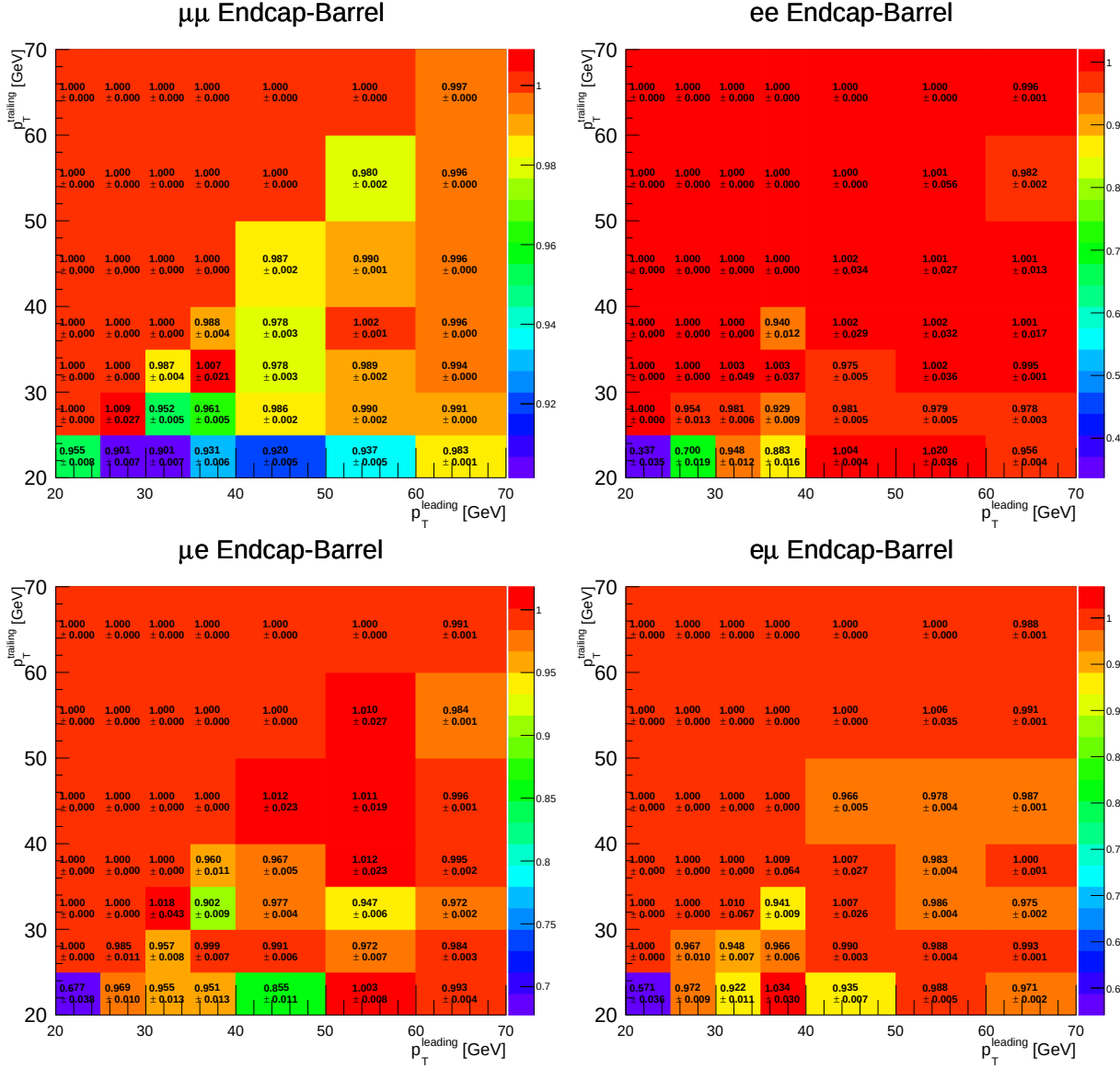


Figure 5.7: Trigger efficiency scale factors for $\mu\mu$ (top left), ee (top right), μe (bottom left), and $e\mu$ (bottom right) events in 2016 with $|\eta^{\text{leading}}| > 1.5$ and $|\eta^{\text{trailing}}| < 1.5$.

5.5 Taus

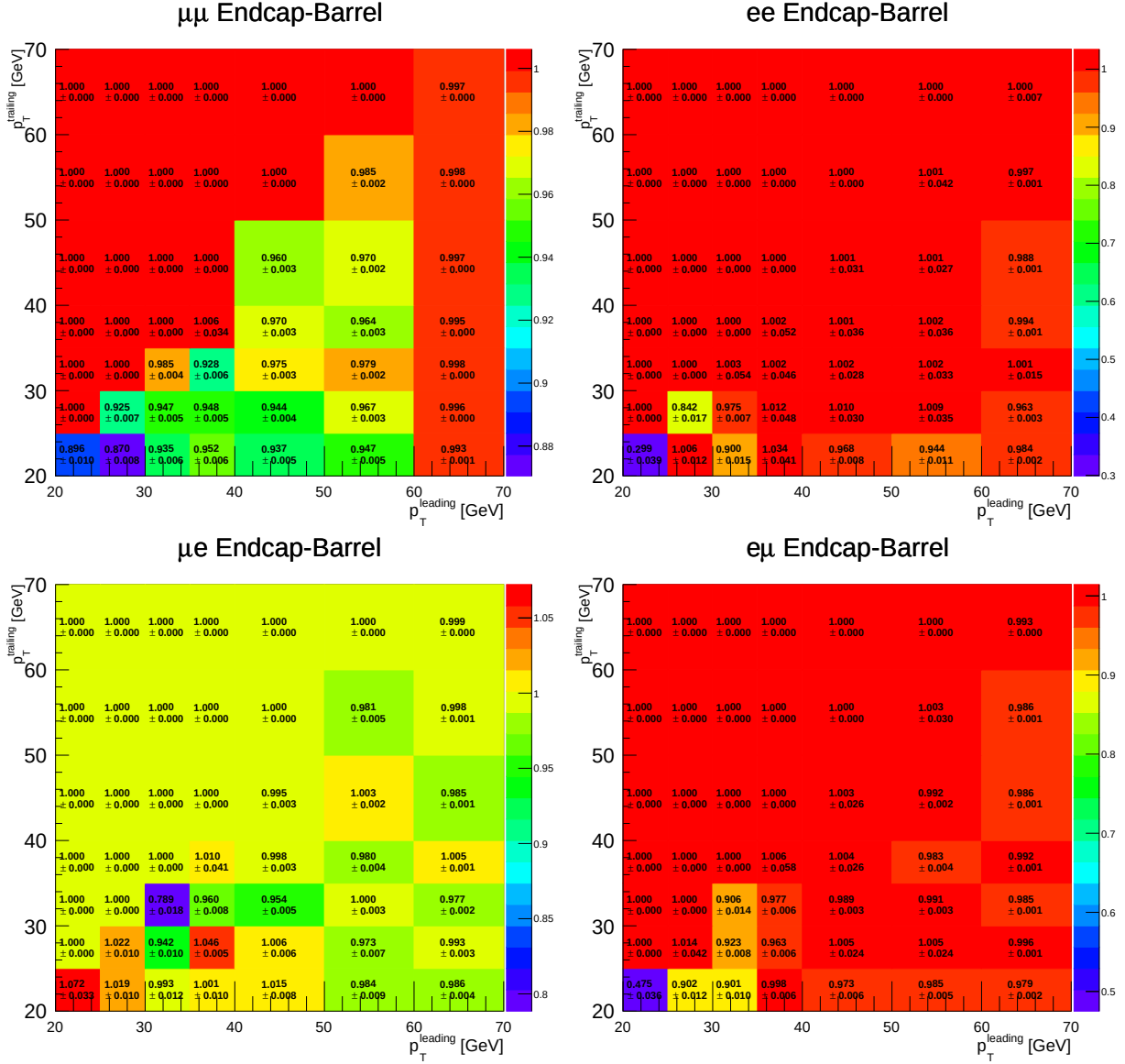
Events with hadronic τ lepton decays are identified and rejected in order to suppress electroweak backgrounds. We identify the τ_h candidates with the hadron-plus-strips algorithm [148], which constructs candidates seeded by jets that are consistent with either a single or triple charged pion

Figure 5.8: Trigger efficiency scale factors for $\mu\mu$ (top left), ee (top right), μe (bottom left), and $e\mu$ (bottom right) events in 2017 with $|\eta^{leading}| > 1.5$ and $|\eta^{trailing}| < 1.5$.



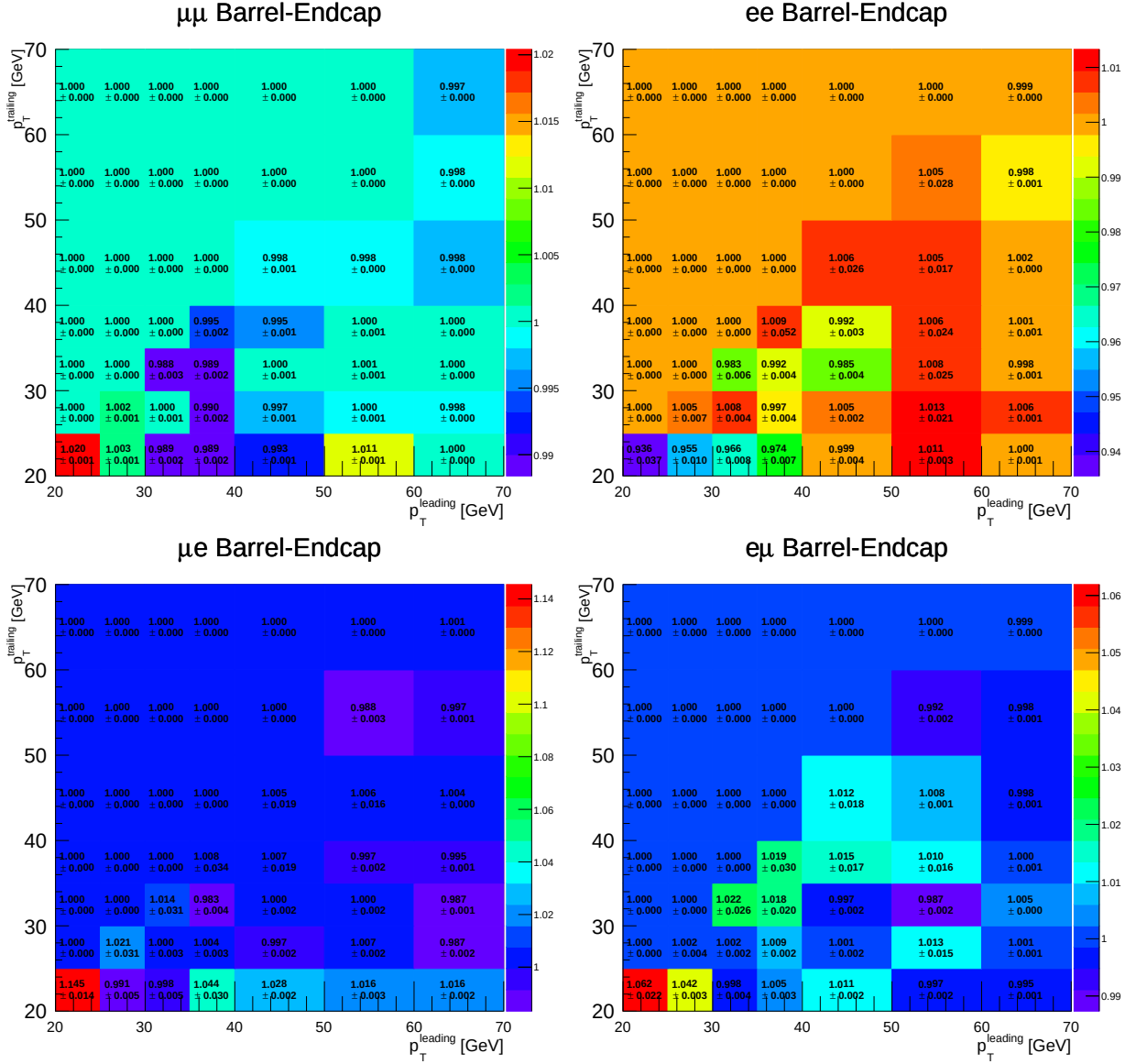
decay of the τ lepton. Jets originating from non- τ decays are rejected by a discriminator that takes into account the pileup contribution to the neutral component of the τ_h decay [148]. The selection for taus is done using the “decayModeFindingOldDMs” method and the “byVLooseIsolationMVARun2v1DBoldDMwLT” working points [149], with the additional requirements of $p_T > 18$ GeV and $|\eta| < 2.3$. Decays that are consistent with production of muons or electrons are rejected by an overlap veto in which any possible τ candidate pointing within a ΔR cone smaller than 0.4

Figure 5.9: Trigger efficiency scale factors for $\mu\mu$ (top left), ee (top right), μe (bottom left), and $e\mu$ (bottom right) events in 2018 with $|\eta^{leading}| > 1.5$ and $|\eta^{trailing}| < 1.5$.



from either the electron or muon candidates is not considered. In all cases, we use the so-called “2017v2” MiniAOD version for the isolation.

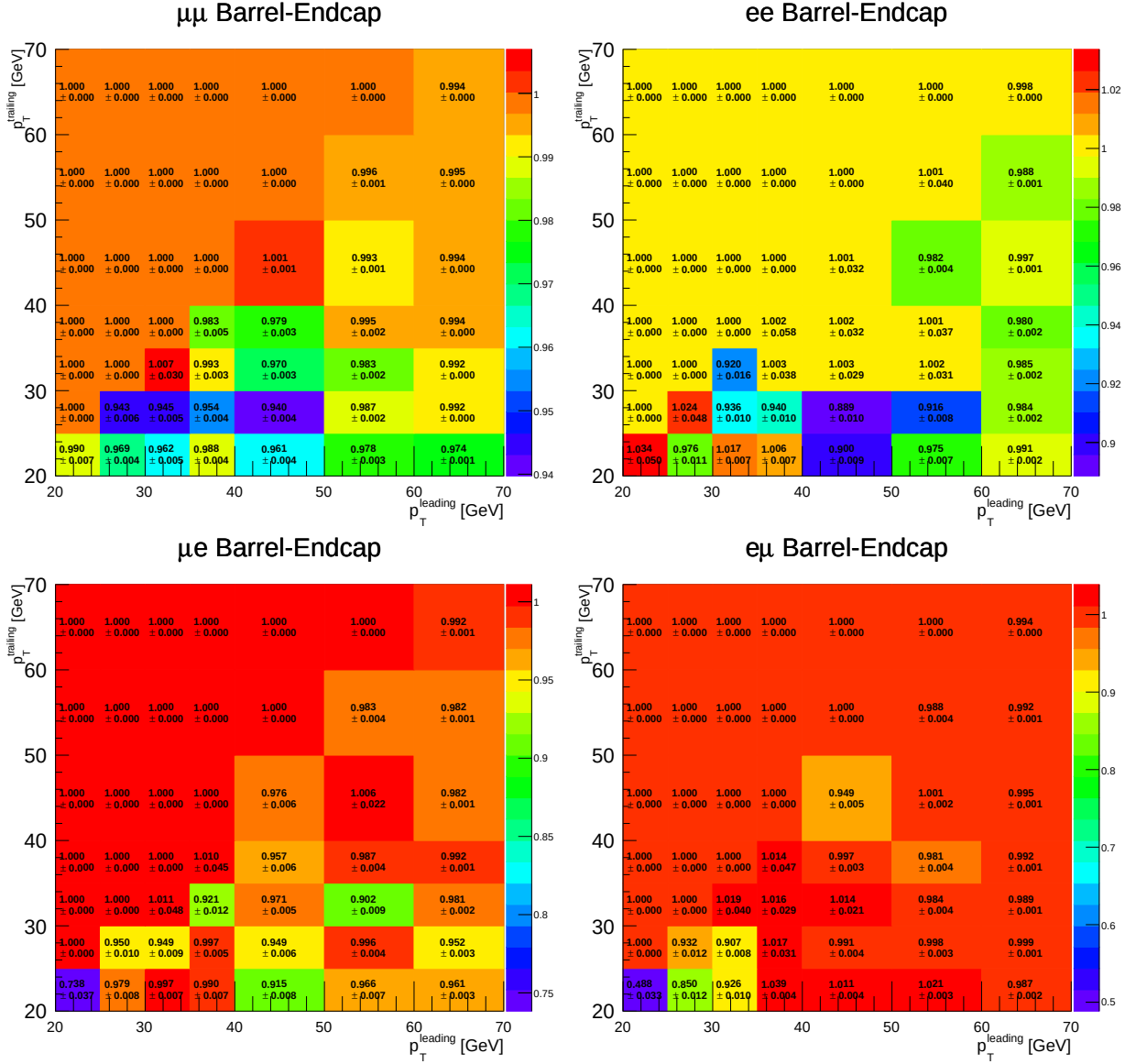
Figure 5.10: Trigger efficiency scale factors for $\mu\mu$ (top left), ee (top right), μe (bottom left), and $e\mu$ (bottom right) events in 2016 with $|\eta^{leading}| < 1.5$ and $|\eta^{trailing}| > 1.5$.



5.6 Electrons

In the CMS detector, electrons are reconstructed through association of energy clusters in the ECAL with tracks in the inner silicon detector. Electromagnetic showers initiated by electrons (photons) deposit most of their energy in a small number of crystals in the ECAL. Two sets of

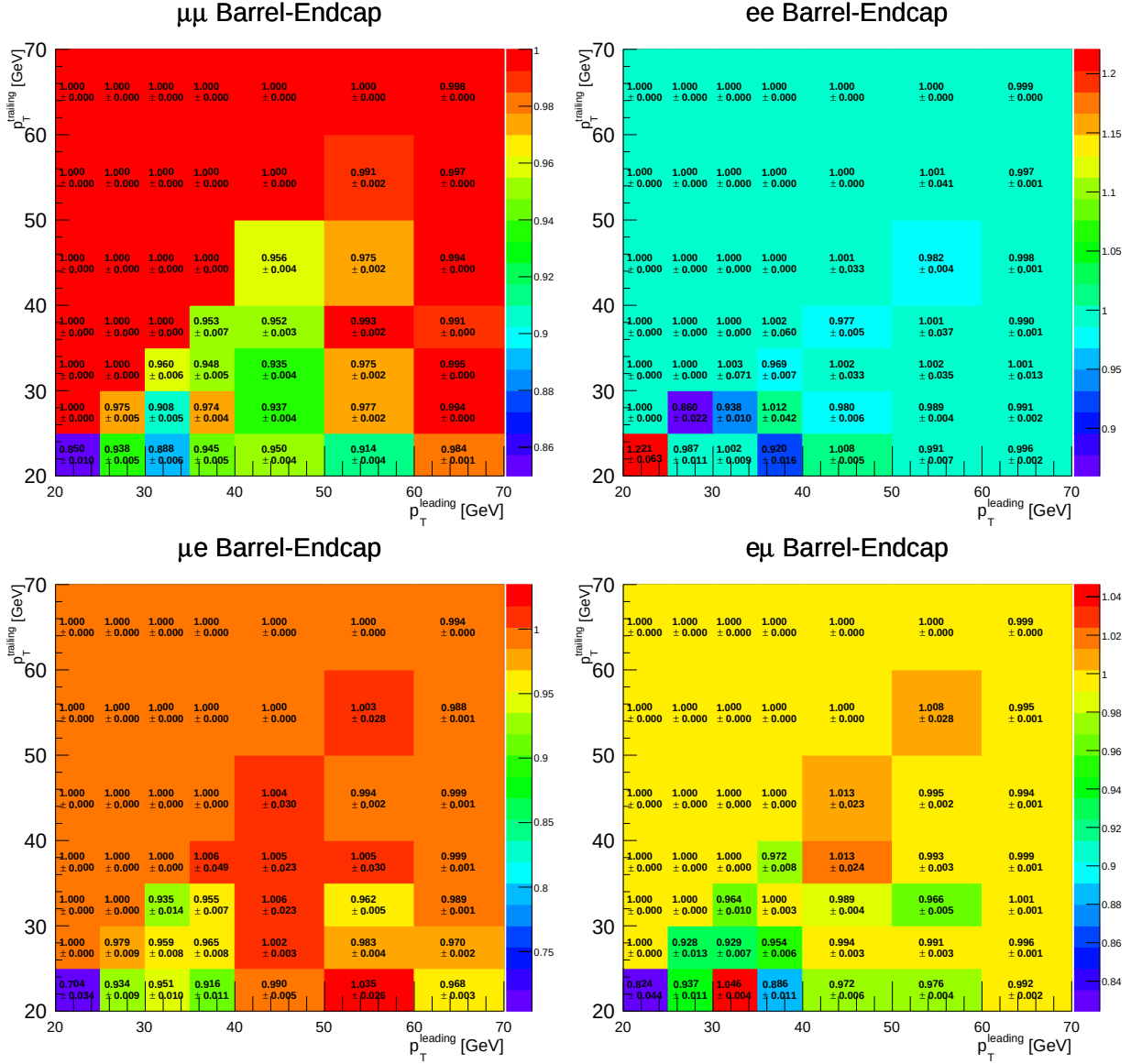
Figure 5.11: Trigger efficiency scale factors for $\mu\mu$ (top left), ee (top right), μe (bottom left), and $e\mu$ (bottom right) events in 2017 with $|\eta^{leading}| < 1.5$ and $|\eta^{trailing}| > 1.5$.



clustering algorithms are performed. In the endcaps small clusters of 3×3 crystals in $\eta \times \phi$ are created that contain approximately 94% of the incident energy of the electron (photon) [150]. Because of the strong magnetic field energy, the energy gets spread in ϕ . As such, a cluster of clusters, called a supercluster, is built which extends the ϕ information of the original cluster. Due to the simplicity of the barrel geometry superclusters can be formed directly.

For electrons superclusters are also matched with tracks from the inner silicon detector to dif-

Figure 5.12: Trigger efficiency scale factors for $\mu\mu$ (top left), ee (top right), μe (bottom left), and $e\mu$ (bottom right) events in 2018 with $|\eta^{leading}| < 1.5$ and $|\eta^{trailing}| > 1.5$.



ferentiate them from photons. Potential tracks are formed from a collection of hits in the silicon tracker that are combined using a combinatorial Kalman filter procedure. Then, a track fitting procedure is performed using a Gaussian Sum Filter (GSF), in which the energy loss in each tracker layer is approximated by a mixture of Gaussian distributions [151]. The combination of the supercluster energy and position matched to a GSF track, form the fully reconstructed electron [152].

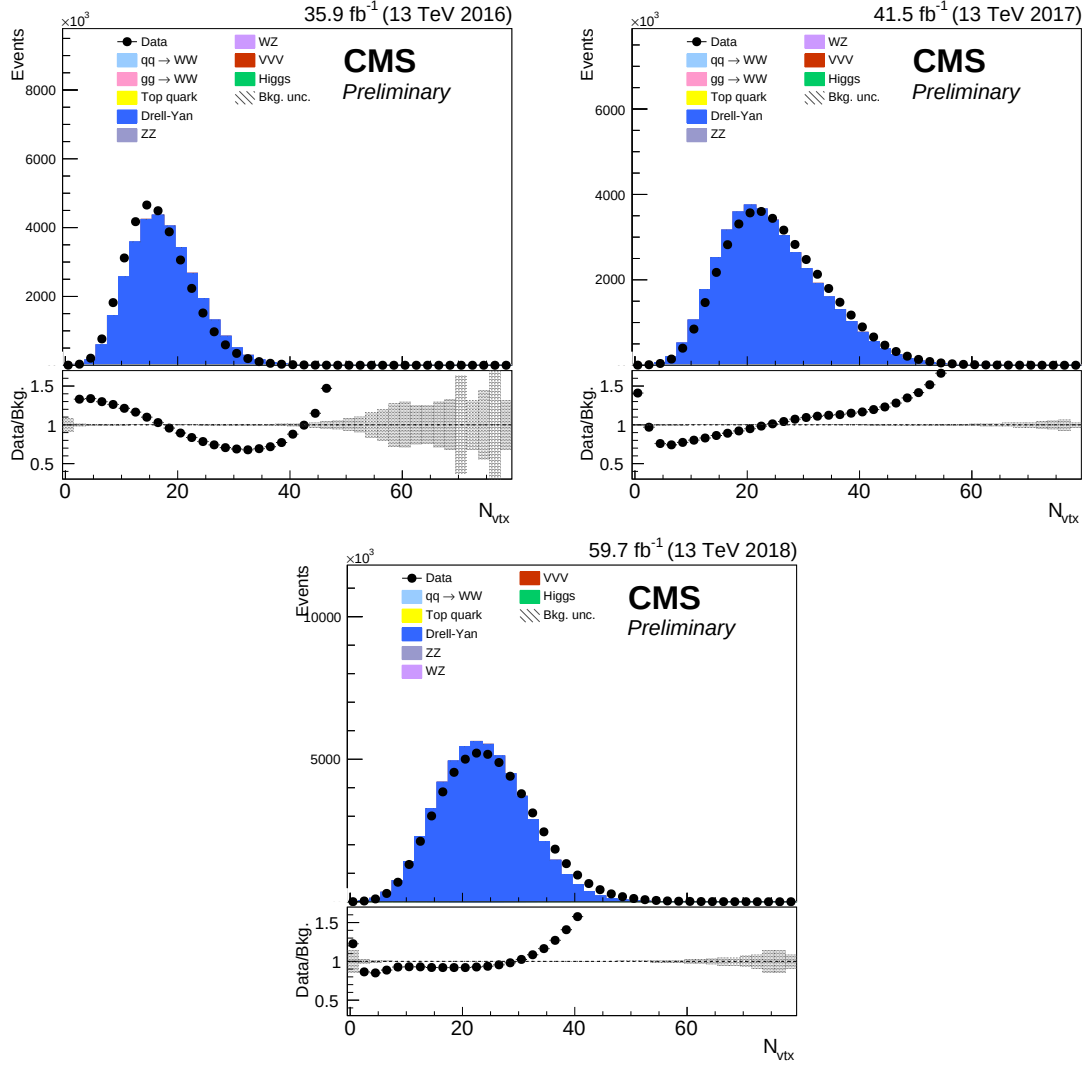


Figure 5.13: Number of reconstructed vertex distributions in 2016 (top left), 2017 (top right), and 2018 (bottom) with basic selections to isolate $Z \rightarrow \ell\ell$ events.

Table 5.5: DeepCSV medium working points for each year. For the medium working point, the efficiency to select b-quark jets is about 70% and the rate for mistagging jets originating from the hadronization of gluons or $u/d/s$ quarks is about 1%

Year	DeepCSV WP
2016	0.6324
2017	0.4941
2018	0.4184

Electron momentum is found using a multivariate regression derived from simulation [153]. Electron energy corrections are then applied to enhance the Z mass peak resolution [154]. Smearing is applied to simulated datasets to match the energy resolution seen in data. Scale factors evaluated using the tag and probe technique are also used to correct for differences in the reconstruction ID and Isolation efficiencies in data and Monte Carlo. The scale factors and the uncertainty prescriptions are provided by the EGamma POG [155; 156].

Electron candidates are flagged using a multivariate identification method [156; 157]. Electrons used in this analysis are found using the medium working point, defined to have an identification efficiency of approximately 85%. In order to reject events with more than two leptons, electron candidates can also be tagged using the loose working point. Additionally, there are requirements on $p_T > 20(10)$ GeV and $|\eta| < 2.5$ for the tight(loose) electrons used in this analysis. This is summarized in Table 5.6.

Table 5.6: Electron working points and requirements.

Requirement	Medium Electron	Loose Electron
ID	wp90V2	wpLooseV2
p_T	20 GeV	10 GeV
$ \eta $	< 2.5	< 2.5
Isolation	Yes	Yes

Lepton isolation is required to distinguish leptons originating prompt decays from leptons

within jets originating from weak decays. The isolation variable evaluates a lepton relative to the sum of p_T of PF candidates within a cone of $\Delta R = 0.4$ around the lepton candidate [158]. Contribution from pileup and from neutral particles is corrected by removing the average energy density per area from $PU(\rho)$ multiplied by the effective area (A_{eff}) from the isolation sum. The effective area is chosen to be independent of the number of pileup interactions. The relative isolation for electrons is defined in eq 5.1:

$$I_{rel}^e = \frac{1}{p_T} [I_{ch} + \max(I_{nh} + I_g - A_{eff} \cdot \rho, 0)] \quad (5.1)$$

The Isolation for the electron candidates has been included in the MVA based IDs shown in Table 5.6 used for this analysis.

5.7 Muons

Muons are reconstructed in the CMS detector from hits in the inner silicon and from outer muon spectrometer. This leads to tracks formed from two reconstruction methods [159]:

1. **Global Muon:** The first step of global muon reconstruction is the formation of a standalone muon which is a multi-segment(a track formed from hits in the DTs, RPCs or CSCs) track formed in the muon systems. This standalone muon is then matched to a tracker track to construct a global muon.
2. **Tracker Muon:** Tracker tracks, with $p_T > 0.5$ GeV and $p > 2.5$ GeV are extrapolated to the outer muon systems. If one muon segment from either the DT or CSC subsystems matches the extrapolated track, the tracker track is considered as a tracker-muon. This extrapolation method includes effects from the magnetic field, energy loss and multiple scatterings. This method of reconstructing muons is more efficient than global muon reconstruction at low

momentum ($p < 5$ GeV) whereas the global muons are more efficient at higher momentum.

The muons used in this analysis are selected only inside the region covered by the muon spectrometer ($|\eta| < 2.4$) with $p_T > 20$ GeV and isolation requirements. Muons used to reconstruct the Z mass peak are required to have a Tight muon ID as suggested by the Muon POG [160], while muons for the third lepton veto use the Soft muon ID and a looser requirement of $p_T > 10$ GeV. The cut-based requirements for the muon IDs used are described in Table 5.7.

Table 5.7: Muon working points and requirements.

Requirement	Tight ID	Soft ID
Muon Type	Global	Tracker or Global
p_T	> 20 GeV	> 10 GeV
$ \eta $	< 2.4	< 2.4
Isolation	≤ 0.15	≤ 0.25
χ^2/dof (global)	< 10	
Valid Pixel Hits	> 0	
Pixel Layers with measurement		> 0
Tracker Layers with Measurement	> 5	> 5
Valid Muon Hits	> 0	
Matched Muon Stations	> 1	
$d_0(vtx)$ (cm)	< 0.2	< 0.3
$d_z(vtx)$ (cm)	< 0.5	< 20

Isolation for muons is performed using the same method as electrons using a cone of $\Delta R = 0.4$ to compute particle flux of PF candidates around the muon candidate [158]. The “delta-beta” correction is applied by computing the sum of charged hadrons originating from pileup vertices, scaling it by a factor of 0.5 and subtracting this value from the neutral hadron and photon sums giving the corrected sum for neutral particles. The 0.5 scale factor is derived from simulations to be approximately the ratio of neutral to charged hadron production in inelastic proton-proton collisions. This corrected energy sum from neutral particles is constrained to be greater than or equal to zero. The relative isolation for muons is defined in eq 5.2:

$$I_{rel}^{\mu} = \frac{1}{p_T} [I_{ch} + \max(I_{nh} + I_g - 0.5 \cdot I_{chPU}, 0)] \quad (5.2)$$

Finally, scale factors are used to correct differences in the reconstruction ID and Isolation efficiencies between data and Monte Carlo. These scale factors and their uncertainties are derived using the tag and probe technique [161; 162].

5.8 Missing Transverse Momentum

Missing transverse momentum is calculated as the negative vectorial sum of the transverse momentum of all reconstructed objects in an event. In order to prevent the degradation of this variable to pileup, corrections are applied in order to remove contributions from pileup vertices through charged hadron subtraction (CHS). Additionally, in order to make a more accurate estimate of invisible particles, corrections are also applied which propagate jet energy corrections to the pileup corrected p_T^{miss} .

In 2017 there was an issue of noise in the ECAL endcap that greatly increase the fake p_T^{miss} tail in 2017 data. As such some jets in the problem region needed to be removed from p_T^{miss} calculations. To implement this correction, jets with $2.65 < |\eta| < 3.139$ and with a raw $p_T < 50$ GeV are not factored in the PF p_T^{miss} calculation. It should be noted that this correction was applied to both simulation and data for consistency.

As a last step to correct the p_T^{miss} , anomalous high- p_T^{miss} events from CMS must be removed. Large p_T^{miss} events in CMS which can be due to a variety of reconstruction failures, detector malfunctions or noncollision backgrounds, such as detector noise, cosmic rays and beam-halo particles. In order to have an accurate representation of the p_T^{miss} , these events containing a fake source of p_T^{miss} must be removed. This is done using MET filters which are a set of algorithms designed to

remove these events [163; 164]. The set of MET filters used in this paper is shown in table 5.8 and are designed to identify more than 85–90% of the spurious high- p_T^{miss} events with a misidentification rate of less than 0.1% [165].

Table 5.8: MET filters applied in each year. Filters not used in 2016 is indicated by a *.

Filter	Name
primary vertex	Flag_goodVertices
Beam halo	Flag_globalSuperTightHalo2016Filter
HBHE noise	Flag_HBHENoiseFilter
HBHEiso noise	Flag_HBHENoiseIsoFilter
ECAL TP	Flag_EcalDeadCellTriggerPrimitiveFilter
Bad PF Muon	Flag_BadPFMuonFilter
Bad Charged Hadron	Flag_BadChargedCandidateFilter
*ECAL bad calibration update	ecalBadCalibReducedMINIAODFilter

In 2018, a significant mismatch between data and MC was noticed in the raw and corrected p_T^{miss} distributions. This issue was traced back to effects from the numbr of vertices in the events. As such, an additional correction was applied to the MC samples to correct for this mismatch.

5.9 Level 1 pre-firing trigger inefficiency

The L1-DPG group discovered that ECAL trigger primitives (TPs), located in the most inner rings of the endcap region ($2.5 < |\eta| < 3.0$), exhibit a timing drift during 2016 and 2017 data-taking, leading to an increase of the Level 1 (L1) pre-firing rate for any calorimeter based trigger (L1-EG seeds).

Pre-firing of L1 triggers represents a problem because of the unfortunate CMS trigger rules, which were developed to prevent buffer overflows. Trigger rules are enforced by the TCDS system right after the final decision of the Global Trigger (GT). The pre-fired trigger occupies the buffer

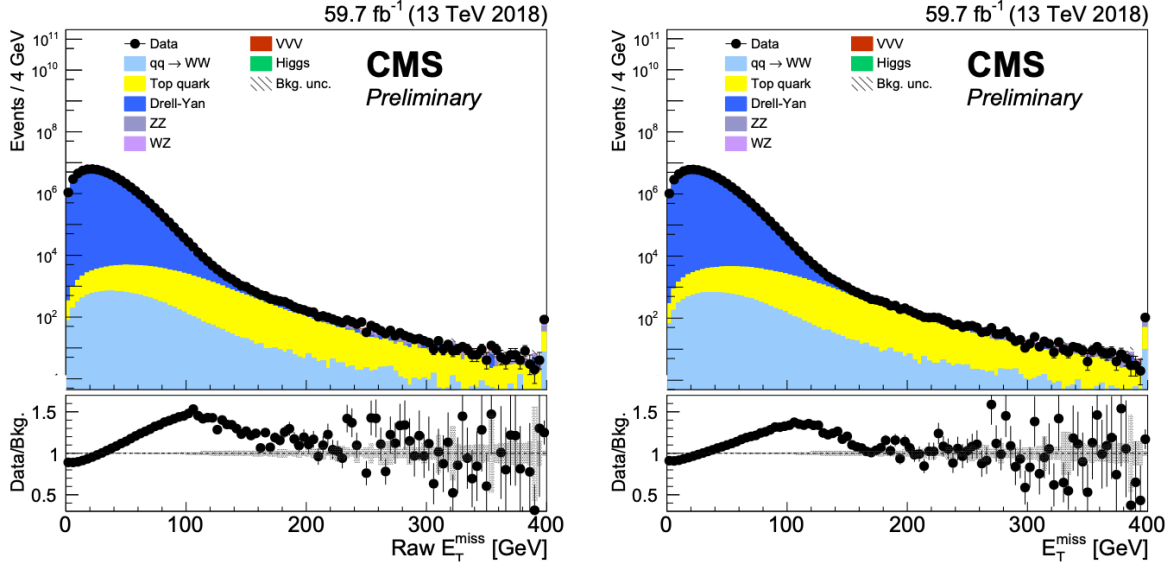


Figure 5.14: Distributions for the Raw (left) and the corrected (right) p_T^{miss} before N_{vtx} corrections.

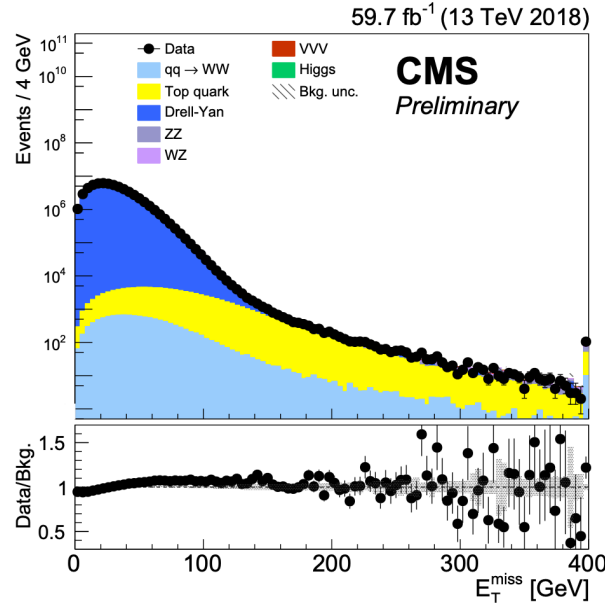


Figure 5.15: Distribution for the corrected p_T^{miss} after N_{vtx} correction.

and prevents the real trigger on the subsequent beam crossing from creating triggers. In addition, the readout event from the pre-fired event will likely be rejected by the HLT. Therefore, the main consequence of the pre-firing is an inefficiency in recording potentially interesting event by the L1 trigger system.

The pre-firing rate cannot be measured with standard techniques because, even if a pre-fired event passes the HLT decision, it is not possible to know whether it has been selected because of a pre-firing or because it is a genuine interesting event. To estimate the pre-firing rate, the standard technique is to use the trigger rules to collect a set of un-prefirable events, which are used as a denominator in the pre-firing measurement. An event in BX0 is called “un-prefirable” when the event in BX-3 was already accepted by the L1 trigger. In fact, because of the trigger rules, BX-2 and BX-1 are vetoed by the TCDS system and cannot prevent the acquisition of BX0. Therefore, even if a mis-timed TP in BX0 pre-fires, BX-1 will not be readout. In addition, for every interesting event accepted by L1 trigger, all L1-objects and GT decision bits are stored in a window of ± 2 BX. Therefore, from a set of selected un-prefirable events, the pre-firing probability can be computed for a specific analysis selection. This set of events can be used to estimate the probability of wrong BX assignment by performing a standard tag-and-probe method making sure that the tag candidate is not responsible for the prefiring.

The pre-firing probabilities are measured as a function of the p_T and η of a given object. In this analysis, two sets of pre-firing probability maps are used: one for photon objects and a second one for jet objects. First, the photon pre-firing probability is applied, and then the jet pre-firing probability is applied to objects not matching the above used photons.

For the photon related measurements, events from the SingleElectron dataset are used. The event selection requires a tag electron with $|\eta| < 1.75$ and matched to *HLT_Ele32_WPTight*. This ensures that the tag is not responsible for the prefiring. The probe is a generic photon passing the cut based medium selection. The tag and probe pairs should have a mass consistent with a Z boson.

For the jet related measurements, events from the SingleMuon dataset are used. The event

selection requires exactly one muon matched to *HLT_IsoMu24/27*. An electron veto is also required. The probed jet is requested to pass the tight identification requirements and is required to be the only jet with $p_T > 40$ GeV found in the $1.75 < |\eta| < 3.5$ region. This ensures that the probe is the object responsible for the possible prefiring. The photon and jet prefiring probability maps for 2016 and 2017 are shown in Figures 5.16 and 5.17, respectively.

Figure 5.16: Photon (top) and jet (bottom) prefiring probability maps for 2016.

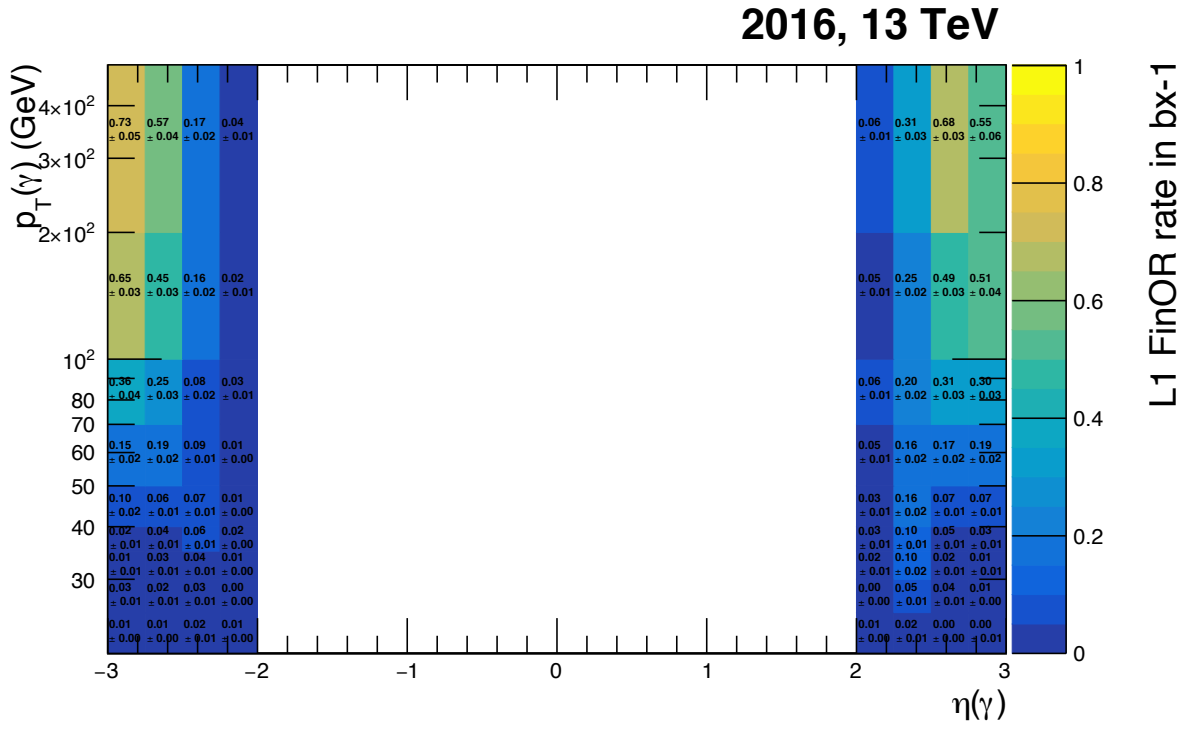
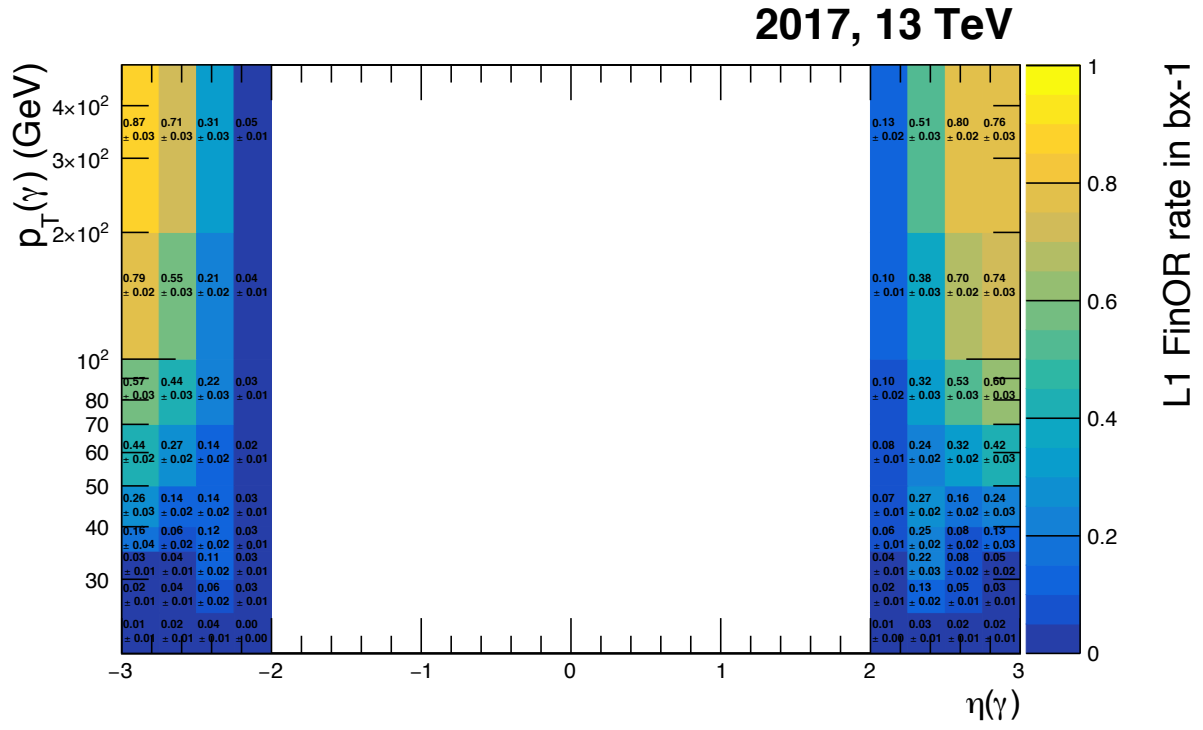


Figure 5.17: Photon (top) and jet (bottom) prefiring probability maps for 2017.



Chapter 6

Searches

This chapter describes the search methods used for interpreting the various BSM models discussed in this thesis following the results recently published by CMS [166]. A description of the data and simulated samples used as well as a description of the event reconstruction is presented in Sec. 6.1. The event selection used to define the signal region is detailed in Sec. 6.2, while the control regions and background estimation is described in Sec. 6.3. The fitting method is presented in Sec. 6.4 and the systematic uncertainties are described in Sec. 6.5.

6.1 Data samples and event reconstruction

This search uses pp collision events collected with the CMS detector during 2016, 2017, and 2018 corresponding to a total integrated luminosity of 137 fb^{-1} . The data sets from the three different years are analyzed independently with appropriate calibrations and corrections to take into account the different LHC running conditions and CMS detector performance.

Several SM processes can contribute to the mono-Z signature. The most important backgrounds come from diboson processes: $WZ \rightarrow \ell \nu \ell \ell$ where one lepton escapes detection, $ZZ \rightarrow \ell \ell \nu \nu$, and $W^+W^- \rightarrow \ell \ell \nu \nu$. There can also be contributions where energetic leptons are produced by decays of top quarks in $t\bar{t}$ or tW events. Smaller contributions may come from triple boson processes, $t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}\gamma$, referred to collectively as VVV due to the similar decay products. Drell–Yan

(DY) production of lepton pairs, $Z/\gamma^* \rightarrow \ell\ell$, has no intrinsic source of missing transverse momentum but can still mimic a mono- Z signature when the momentum of the recoiling system is poorly measured.

Monte Carlo (MC) simulated events are used to model the expected signal and background yields. Three sets of simulated events for each process are used in order to match the different data taking conditions. The samples for DM production are generated using the DMSIMP package [167; 168] interfaced with MADGRAPH5_aMC@NLO 2.4.2 [169; 170; 171; 172]. The vector and axial-vector model samples are generated at NLO in QCD, while the pseudoscalar and scalar model samples are generated at leading order (LO) in QCD. The next-to-leading-order (NLO) POWHEG v2 [173; 174; 175; 176; 177] generator is used to simulate the invisible Higgs Zh signal process at NLO in quantum chromodynamics (QCD), as well as the $t\bar{t}$, tW , and diboson processes. The BSM Higgs boson production cross sections, as a function of the Higgs boson mass for the Zh process are taken from Refs. [178]. Samples for the 2HDM+a model are generated at NLO with MADGRAPH5_aMC@NLO 2.6.0. Events for both the ADD and unparticle models are generated at LO using an EFT implementation in PYTHIA 8.205 in 2016 (8.230 in 2017 and 2018) [179; 180]. In order to ensure the validity of the effective theory used in the ADD model, a truncation method, described in Ref. [117], is applied. Perturbative calculations are only valid in cases where the center-of-mass energy squared of the incoming partons $\hat{s}$ is smaller than the fundamental scale of the theory M_D^2 . As such, this truncation method suppresses the cross section for events with $\hat{s} > M_D^2$ by a factor of $M_D^4/\hat{s}^2$. The effect of this truncation is largest for small values of M_D , but also increases with the number of dimensions n as more energy is lost in extra dimensions. The MADGRAPH5_aMC@NLO 2.2.2 (2.4.2) generator in 2016 (2017 and 2018) is used for the simulation of the VVV and DY samples, at NLO accuracy in QCD.

The NNPDF 3.0 NLO [181] (NNPDF 3.1 NNLO) parton distribution functions (PDFs) are used for simulating all 2016 (2017 and 2018) samples. For all processes, the parton showering and

hadronization are simulated using PYTHIA 8.226 in 2016 (8.230 in 2017 and 2018). The modeling of the underlying event is generated using the CUETP8M1 [182] (CP5 [183]) for simulated samples corresponding to the 2016 (2017 and 2018) data sets. The only exceptions to this are the 2016 top quark sample, which uses CUETP8M2 [182] and the simplified DM (2HDM+a) samples, that uses CP3 [183] (CP5) tunes for all years. All events are processed through a simulation of the CMS detector based on GEANT4 [184] and are reconstructed with the same algorithms as used for data. Simultaneous pp collisions in the same or nearby bunch crossings, referred to as pileup, are also simulated. The distribution of the number of such interactions in the simulation is adjusted to match the data [185]. The average number of pileup interactions was 23 for the 2016 data and 32 for the 2017 and 2018 data.

The diboson MC samples are generated in electroweak leading-order. For the ZZ background, a higher order electroweak correction is applied following [186; 187]. An event-by-event reweighting is performed with correction weights binned in the generator-level p_T of the trailing boson. This correction results in a net reduction of the overall ZZ yield of about 10%, although with a strong dependence on the trailing-boson p_T . Overall, the p_T^{miss} spectrum becomes softer, with a correction of down to 40% for a trailing- p_T^Z of 700 GeV. Following [188], the corresponding NLO EWK correction to WZ production is small. Furthermore, for the $qq \rightarrow ZZ$ process, a QCD NLO to NNLO correction factor is applied as a function of generator-level invariant mass of the two Z bosons [189; 190; 191]. In the case of the WZ process, a NLO to NNLO correction factor of 1.109 is applied [192]. The effect of these corrections is shown in figure 6.1.

Information from all subdetectors is combined and used by the CMS particle-flow (PF) algorithm [193] for particle reconstruction and identification. The PF algorithm aims to reconstruct and identify each individual particle in an event, with an optimized combination of information from the various elements of the CMS detector. The energies of photons are obtained from the ECAL measurement. The energies of electrons are determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy from the

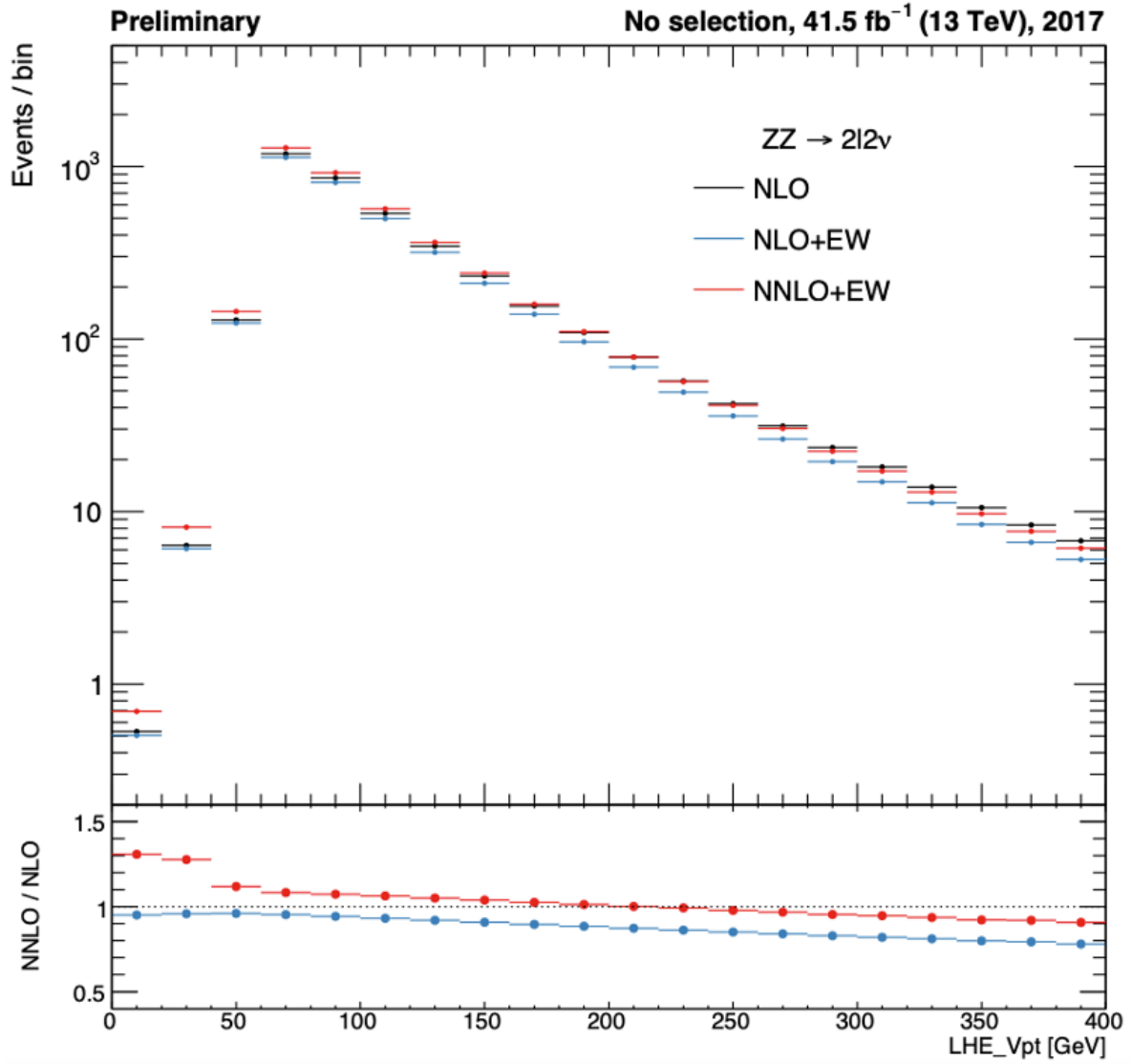


Figure 6.1: The effect of the correction factors applied to the diboson sample are shown here as a function of the generated p_T of the Z boson. Here, a ZZ sample is shown for MC simulated for 2017.

corresponding ECAL cluster, and the energy sum from all bremsstrahlung photons spatially compatible with originating from the electron track. The momentum of muons is obtained from the curvature of the corresponding track in the tracker detector in combination with information from the muon stations. The energies of charged hadrons are determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energies of neutral hadrons are obtained from the corresponding corrected ECAL and HCAL energies.

The candidate vertex with the largest value of summed physics-object p_T^2 is taken to be the primary pp interaction vertex. The physics objects are the jets, clustered using the jet finding algorithm [139; 194] with the tracks assigned to candidate vertices as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the p_T of those jets.

Both electron and muon candidates must pass certain identification criteria to be further selected in the analysis. At a loose level, they must satisfy requirements on the transverse momentum and pseudorapidity: $p_T > 10$ GeV and $|\eta| < 2.5$ (2.4) for electrons (muons). At the final level, a medium working point [195; 19] is chosen for the identification criteria, including requirements on the impact parameter of the candidates with respect to the primary vertex and their isolation with respect to other particles in the event. The efficiency for this selection is about 85 and 90% for each electron and muon, respectively.

In the signal models considered in this paper, the amount of hadronic activity tends to be small, so events with multiple clustered jets are vetoed. For each event, hadronic jets are clustered from these reconstructed particles using the infrared and collinear safe anti- k_T algorithm [139; 194] with a distance parameter of 0.4. Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5 to 10% of the true momentum over the entire spectrum and detector acceptance. Pileup interactions can contribute

additional tracks and calorimetric energy depositions to the jet momentum. To mitigate this effect, charged particles identified to be originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions [196]. Jet energy corrections are derived from simulation to bring the measured response of jets to the average of simulated jets clustered from the generated final-state particles. In situ measurements of the momentum balance in dijet, photon + jet, Z + jet, and multijet events are used to determine corrections for residual differences in jet energy scale in data and simulation [196]. The jet energy resolution amounts typically to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV. Additional selection criteria are applied to each jet to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures [197]. Jets with $p_T > 30$ GeV and $|\eta| < 4.7$ are considered for the analysis.

In order to reduce the top quark background, events containing quarks are vetoed. To veto events with jets that originated from quarks, we use the medium working point of the DeepCSV algorithm [198]. For this working point, the efficiency to select b-quark jets is about 70% and the rate for mistagging jets originating from the hadronization of gluons or $u/d/s$ quarks is about 1%.

To veto hadronically decaying τ leptons (τ_h), we identify the τ_h candidates with the hadron-plus-strips algorithm [148]. This algorithm constructs candidates seeded by PF jets that are consistent with either a single or triple charged pion decay of the τ lepton. In the single charged pion decay mode, the presence of neutral pions is detected by reconstructing their photonic decays. Decays that are consistent with production of muons or electrons are rejected by an overlap veto. Jets originating from non- τ decays are rejected by a discriminator that takes into account the pileup contribution to the neutral component of the τ_h decay [148].

This analysis is performed with the full Run 2 dataset including pp collisions collected in 2016, 2017 and 2018 with the CMS experiment at the LHC with $\sqrt{s} = 13$ TeV. For 2016 and 2017, five

primary datasets are used: MuonEG, DoubleMuon, DoubleElectron, SingleMuon and SingleElectron. In 2018 SingleElectron, DoubleElectron and MuonEG were merged into the EGamma dataset reducing the primary datasets used to three for that year. All data analyzed is selected using only centrally approved luminosity sections using the following certification files:

- **2016** (35.9 fb^{-1}):

`Cert_271036-284044_13TeV_23Sep2016ReReco_Collisions16_JSON.txt`

- **2017** (40.5 fb^{-1}):

`Cert_294927-306462_13TeV_EOY2017ReReco_Collisions17_JSON_v1.txt`

- **2018** (60.0 fb^{-1}):

`Cert_314472-325175_13TeV_17SeptEarlyReReco2018ABC_PromptEraD_Collisions18_JSON`

The processed dataset names and cross sections for the main processes considered in the analysis are shown in Table 6.1 for 2016, Table 6.2 for 2017 and Table 6.3 for 2018. Simulated datasets from the RunIISummer16NanoAODv5 campaign are used for 2016, RunIIFall17NanoAODv5 for 2017 and RunIIAutumn18NanoAODv5 for 2018.

6.2 Event selection

The final state of this analysis is a pair of oppositely charged, same-flavor, high transverse momentum (p_T) isolated leptons that are compatible with decays from a Z boson, large missing transverse momentum associated with undetectable particles and low jet activity. For all models presented, the signal cross sections are orders of magnitude lower than the Standard Model backgrounds. As such several steps are performed to extract the signal from data:

1. Select only events that pass single or double lepton triggers.
2. Select events requiring a high p_T oppositely charged, same-flavor lepton pair (e^+, e^-, μ^+, μ^-) by requiring:

Table 6.1: Simulated 2016 dataset names and corresponding cross sections.

Process	Dataset Name	Cross Section [pb ⁻¹]
$Z/\gamma^* \rightarrow l^+ l^-$ (50)	DYJetsToLL_Pt-50To100_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	354.6 * (1921.8 * 3/5938)
$Z/\gamma^* \rightarrow l^+ l^-$ (50)	DYJetsToLL_Pt-100To250_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	83.05 * (1921.8 * 3/5938)
$Z/\gamma^* \rightarrow l^+ l^-$ (50)	DYJetsToLL_Pt-250To400_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	3.043 * (1921.8 * 3/5938)
$Z/\gamma^* \rightarrow l^+ l^-$ (50)	DYJetsToLL_Pt-400To650_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	0.3921 * (1921.8 * 3/5938)
$Z/\gamma^* \rightarrow l^+ l^-$ (50)	DYJetsToLL_Pt-650ToInf_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	0.03823 * (1921.8 * 3/5938)
$Z/\gamma^* \rightarrow l^+ l^-$ (50)	DYJetsToLL_M-50_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	4958 * (1921.8 * 3/4958)
$ZZ \rightarrow 2l2\nu$	ZZTo2L2Nu_13TeV_powheg_pythia8	0.564
$ZZ \rightarrow 4l$	ZZTo4L_13TeV_powheg_pythia8	1.256
$ZZ \rightarrow 2l2q$	ZZTo2L2Q_13TeV-amcatnloFXFX_madspin_pythia8	3.220
$qq \rightarrow WW \rightarrow 2l2\nu$	WWTo2L2Nu_13TeV_powheg	(118.7 - 3.974) * 0.1086 * 0.1086 * 9
$gg \rightarrow WW \rightarrow 2l2\nu$	GluGluWWTo2L2Nu_MCFM_13TeV	(3.974 * 0.1086 * 0.1086 * 9 * 1.4
$WZ \rightarrow 3l\nu$	WZTo3LNU_TuneCUETP8M1_13TeV_powheg_pythia8	4.42965 * 1.109
$WZ \rightarrow 2l2q$	WZTo2L2Q_13TeV-amcatnloFXFX_madspin_pythia8	5.595 * 1.109
$t\bar{t} \rightarrow 2l2\nu2b$	TTTo2L2Nu_TuneCUETP8M2_ttHtranche3_13TeV_powheg_pythia8	831.76 * 0.1086 * 0.1086 * 9
$t\bar{t}Z(qq)$	TTZToQQ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.5297
$t\bar{t}Z(l\bar{l})$	TTZToLLNuNu_M-10_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.2529
$t\bar{t}W(l\nu)$	TTWJetsToLNU_TuneCUETP8M1_13TeV-amcatnloFXFX_madspin-pythia8	0.2043
$t\bar{t}W(qq)$	TTWJetsToQQ_TuneCUETP8M1_13TeV-amcatnloFXFX_madspin-pythia8	0.4062
tW	ST_tW_top_5f_inclusiveDecays_13TeV_powheg_pythia8_TuneCUETP8M1	35.6
$\bar{t}W$	ST_tW_antitop_5f_inclusiveDecays_13TeV_powheg_pythia8_TuneCUETP8M1	35.6
$gg \rightarrow ZZ \rightarrow 2e2\mu$	GluGluToContInToZZTo2e2mu_13TeV_MCFM701_pythia8	0.003194 * 2.3
$gg \rightarrow ZZ \rightarrow 2e2\nu$	GluGluToContInToZZTo2e2nu_13TeV_MCFM701_pythia8	0.001720 * 2.3
$gg \rightarrow ZZ \rightarrow 2e2\tau$	GluGluToContInToZZTo2e2tau_13TeV_MCFM701_pythia8	0.003194 * 2.3
$gg \rightarrow ZZ \rightarrow 2\mu2\nu$	GluGluToContInToZZTo2mu2nu_13TeV_MCFM701_pythia8	0.001720 * 2.3
$gg \rightarrow ZZ \rightarrow 2\mu2\tau$	GluGluToContInToZZTo2mu2tau_13TeV_MCFM701_pythia8	0.003194 * 2.3
$gg \rightarrow ZZ \rightarrow 4e$	GluGluToContInToZZTo4e_13TeV_MCFM701_pythia8	0.001586 * 2.3
$gg \rightarrow ZZ \rightarrow 4\mu$	GluGluToContInToZZTo4mu_13TeV_MCFM701_pythia8	0.001586 * 2.3
$gg \rightarrow ZZ \rightarrow 4\tau$	GluGluToContInToZZTo4tau_13TeV_MCFM701_pythia8	0.001586 * 2.3
ZZZ	ZZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.01398
WZZ	WZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.05565
WWZ	WWZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.16510

Table 6.2: Simulated 2017 dataset names and corresponding cross sections.

Process	Dataset Name	Cross Section [pb ⁻¹]
$Z/\gamma^* \rightarrow l^+ l^-$ (50)	DY1JetsToLL_M-50_LHEZpT_50-150_TuneCP5_13TeV-amcnloFXFX-pythia8	316.6
$Z/\gamma^* \rightarrow l^+ l^-$ (50)	DY1JetsToLL_M-50_LHEZpT_150-250_TuneCP5_13TeV-amcnloFXFX-pythia8	9.543
$Z/\gamma^* \rightarrow l^+ l^-$ (50)	DY1JetsToLL_M-50_LHEZpT_250-400_TuneCP5_13TeV-amcnloFXFX-pythia8	1.098
$Z/\gamma^* \rightarrow l^+ l^-$ (50)	DY1JetsToLL_M-50_LHEZpT_400-inf_TuneCP5_13TeV-amcnloFXFX-pythia8	0.1193
$Z/\gamma^* \rightarrow l^+ l^-$ (50)	DY2JetsToLL_M-50_LHEZpT_50-150_TuneCP5_13TeV-amcnloFXFX-pythia8	169.6
$Z/\gamma^* \rightarrow l^+ l^-$ (50)	DY2JetsToLL_M-50_LHEZpT_150-250_TuneCP5_13TeV-amcnloFXFX-pythia8	15.65
$Z/\gamma^* \rightarrow l^+ l^-$ (50)	DY2JetsToLL_M-50_LHEZpT_250-400_TuneCP5_13TeV-amcnloFXFX-pythia8	2.737
$Z/\gamma^* \rightarrow l^+ l^-$ (50)	DY2JetsToLL_M-50_LHEZpT_400-inf_TuneCP5_13TeV-amcnloFXFX-pythia8	0.4477
$Z/\gamma^* \rightarrow l^+ l^-$ (50)	DYJetsToLL_M-50_TuneCP5_13TeV-amcatnloFXFX-pythia8	6529.0
$ZZ \rightarrow 2l2\nu$	ZZTo2L2Nu_13TeV_powheg_pythia8	0.5644
$ZZ \rightarrow 4l$	ZZTo4L_13TeV_powheg_pythia8	1.256
$ZZ \rightarrow 2l2q$	ZZTo2L2Q_13TeV-amcatnloFXFX_madspin_pythia8	3.688
$qq \rightarrow WW \rightarrow 2l2\nu$	WWTo2L2Nu_NNPDF31_TuneCP5_PWeights_13TeV_powheg_pythia8	12.178
$gg \rightarrow WW \rightarrow 2l2\nu$	GluGluWWTo2L2Nu_MCFM_13TeV	0.5905
$WZ \rightarrow 3l\nu$	WZTo3LNU_TuneCP5_13TeV-amcatnloFXFX-pythia8	5.052
$WZ \rightarrow 2l2q$	WZTo2L2Q_13TeV-amcatnloFXFX_madspin_pythia8	6.331
$t\bar{t} \rightarrow 2l2\nu2b$	TTTo2L2Nu_TuneCP5_PWeights_13TeV_powheg_pythia8	88.29
$t\bar{t}Z(qq)$	TTZToQQ_TuneCP5_13TeV-amcatnlo-pythia8	0.5104
$t\bar{t}Z(l\bar{l})$	TTZToLLNuNu_M-10_TuneCP5_13TeV-amcatnlo-pythia8	0.2432
$t\bar{t}W(l\nu)$	TTWJetsToLNU_TuneCP5_13TeV-amcatnloFXFX_madspin-pythia8	0.2149
$t\bar{t}W(qq)$	TTWJetsToQQ_TuneCP5_13TeV-amcatnloFXFX_madspin-pythia8	0.4316
tW	ST_tW_top_5f_inclusiveDecays_TuneCP5_13TeV_powheg_pythia8	34.91
$\bar{t}W$	ST_tW_antitop_5f_inclusiveDecays_TuneCP5_13TeV_powheg_pythia8	34.97
$gg \rightarrow ZZ \rightarrow 2e2\mu$	GluGluToContInToZZTo2e2mu_13TeV_MCFM701_pythia8	0.003291
$gg \rightarrow ZZ \rightarrow 2e2\nu$	GluGluToContInToZZTo2e2nu_13TeV_MCFM701_pythia8	0.001772
$gg \rightarrow ZZ \rightarrow 2e2\tau$	GluGluToContInToZZTo2e2tau_13TeV_MCFM701_pythia8	0.00329
$gg \rightarrow ZZ \rightarrow 2\mu2\nu$	GluGluToContInToZZTo2mu2nu_13TeV_MCFM701_pythia8	0.001772
$gg \rightarrow ZZ \rightarrow 2\mu2\tau$	GluGluToContInToZZTo2mu2tau_13TeV_MCFM701_pythia8	0.003289
$gg \rightarrow ZZ \rightarrow 4e$	GluGluToContInToZZTo4e_13TeV_MCFM701_pythia8	0.001405
$gg \rightarrow ZZ \rightarrow 4\mu$	GluGluToContInToZZTo4mu_13TeV_MCFM701_pythia8	0.001402
$gg \rightarrow ZZ \rightarrow 4\tau$	GluGluToContInToZZTo4tau_13TeV_MCFM701_pythia8	0.001407
ZZZ	ZZZ_TuneCP5_13TeV-amcatnlo-pythia8	0.01398
WZZ	WZZ_TuneCP5_13TeV-amcatnlo-pythia8	0.05565
WWZ	WWZ_TuneCP5_13TeV-amcatnlo-pythia8	0.16510

Table 6.3: Simulated 2018 dataset names and corresponding cross sections.

Process	Dataset Name	Cross Section [pb ⁻¹]
$Z/\gamma^* \rightarrow l^+l^-$ (50)	DY1JetsToLL_M-50_LHEZpT_50-150_TuneCP5_13TeV-amcnloFXFX-pythia8	316.6
$Z/\gamma^* \rightarrow l^+l^-$ (50)	DY1JetsToLL_M-50_LHEZpT_150-250_TuneCP5_13TeV-amcnloFXFX-pythia8	9.543
$Z/\gamma^* \rightarrow l^+l^-$ (50)	DY1JetsToLL_M-50_LHEZpT_250-400_TuneCP5_13TeV-amcnloFXFX-pythia8	1.098
$Z/\gamma^* \rightarrow l^+l^-$ (50)	DY1JetsToLL_M-50_LHEZpT_400-inf_TuneCP5_13TeV-amcnloFXFX-pythia8	0.1193
$Z/\gamma^* \rightarrow l^+l^-$ (50)	DY2JetsToLL_M-50_LHEZpT_50-150_TuneCP5_13TeV-amcnloFXFX-pythia8	169.6
$Z/\gamma^* \rightarrow l^+l^-$ (50)	DY2JetsToLL_M-50_LHEZpT_150-250_TuneCP5_13TeV-amcnloFXFX-pythia8	15.65
$Z/\gamma^* \rightarrow l^+l^-$ (50)	DY2JetsToLL_M-50_LHEZpT_250-400_TuneCP5_13TeV-amcnloFXFX-pythia8	2.737
$Z/\gamma^* \rightarrow l^+l^-$ (50)	DY2JetsToLL_M-50_LHEZpT_400-inf_TuneCP5_13TeV-amcnloFXFX-pythia8	0.4477
$Z/\gamma^* \rightarrow l^+l^-$ (50)	DYJetsToLL_M-50_TuneCP5_13TeV-amcatnloFXFX-pythia8	6529.0
$ZZ \rightarrow 2l2\nu$	ZZTo2L2Nu_TuneCP5_13TeV-powheg_pythia8	0.5644
$ZZ \rightarrow 4l$	ZZTo4L_TuneCP5_13TeV-powheg_pythia8	1.256
$ZZ \rightarrow 2l2q$	ZZTo2L2Q_13TeV-amcatnloFXFX_madspin_pythia8	3.688
$q\bar{q} \rightarrow WW \rightarrow 2l2\nu$	WWTo2L2Nu_NNPDF31_TuneCP5_PWeights_13TeV-powheg-pythia8	12.178
$g\bar{g} \rightarrow WW \rightarrow 2l2\nu$	GluGluWWTo2L2Nu_MCFM_13TeV	0.5905
$WZ \rightarrow 3l\nu$	WZTo3LNu_TuneCP5_13TeV-powheg-pythia8	5.052
$WZ \rightarrow 2l2q$	WZTo2L2Q_13TeV-amcatnloFXFX_madspin_pythia8	6.331
$t\bar{t} \rightarrow 2l2\nu2b$	TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8	88.29
$t\bar{t}Z(qq)$	TTZToQQ_TuneCP5_13TeV-amcatnlo-pythia8	0.5104
$t\bar{t}Z(l\bar{l})$	TTZToLLNuNu_M-10_TuneCP5_13TeV-amcatnlo-pythia8	0.2432
$t\bar{t}W(l\nu)$	TTWJetsToLNU_TuneCP5_13TeV-amcatnloFXFX_madspin-pythia8	0.2149
$t\bar{t}W(qq)$	TTWJetsToQQ_TuneCP5_13TeV-amcatnloFXFX_madspin-pythia8	0.4316
tW	ST_tW_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	34.91
$\bar{t}W$	ST_tW_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	34.97
$g\bar{g} \rightarrow ZZ \rightarrow 2e2\mu$	GluGluToContintToZZTo2e2mu_13TeV_MCFM701_pythia8	0.003291
$g\bar{g} \rightarrow ZZ \rightarrow 2e2\nu$	GluGluToContintToZZTo2e2nu_13TeV_MCFM701_pythia8	0.001772
$g\bar{g} \rightarrow ZZ \rightarrow 2e2\tau$	GluGluToContintToZZTo2e2tau_13TeV_MCFM701_pythia8	0.00329
$g\bar{g} \rightarrow ZZ \rightarrow 2\mu2\nu$	GluGluToContintToZZTo2mu2nu_13TeV_MCFM701_pythia8	0.001772
$g\bar{g} \rightarrow ZZ \rightarrow 2\mu2\tau$	GluGluToContintToZZTo2mu2tau_13TeV_MCFM701_pythia8	0.003289
$g\bar{g} \rightarrow ZZ \rightarrow 4e$	GluGluToContintToZZTo4e_13TeV_MCFM701_pythia8	0.001405
$g\bar{g} \rightarrow ZZ \rightarrow 4\mu$	GluGluToContintToZZTo4mu_13TeV_MCFM701_pythia8	0.001402
$g\bar{g} \rightarrow ZZ \rightarrow 4\tau$	GluGluToContintToZZTo4tau_13TeV_MCFM701_pythia8	0.001407
ZZZ	ZZZ_TuneCP5_13TeV-amcatnlo-pythia8	0.01398
WZZ	WZZ_TuneCP5_13TeV-amcatnlo-pythia8	0.05565
WWZ	WWZ_TuneCP5_13TeV-amcatnlo-pythia8	0.16510

- Identification and Isolation requirements for both electrons and muons.
- $p_T > 25(20)$ GeV for leading(trailing) leptons.

3. Apply a loose Z mass constraint for the lepton pair and veto events with 2 or more jets.

4. The tighter event selection shown in table 6.4 is applied in an exclusive ≤ 1 jet category.

Events with electrons (muons) are collected using dielectron (dimuon) triggers, with thresholds of $p_T > 23$ (17) GeV and $p_T > 12$ (8) GeV for the electron (muon) with the highest and second-highest measured p_T . Single-electron and single-muon triggers with p_T thresholds of 25 (27) and 20 (24) GeV, respectively for 2016 (2017–2018) are used to recover residual inefficiencies, ensuring a trigger efficiency above 99% for events passing the offline selection.

In the signal region (SR), events are required to have two ($N_\ell = 2$) well-identified, isolated electrons or muons with the same flavor and opposite charge (e^+e^- or $\mu^+\mu^-$). At least one electron or muon of the pair must have $p_T > 25$ GeV, while the second must have $p_T > 20$ GeV. In

order to reduce nonresonant background, the dilepton invariant mass is required to be within 15 GeV of the world-average Z boson mass m_Z [84]. Additionally, we require the transverse momentum of the dilepton system $p_T^{\ell\ell}$ to be larger than 60 GeV to reject the bulk of the DY background. Since little hadronic activity is expected for the signal, we reject events having more than one jet with $p_T > 30$ GeV within $|\eta| < 4.7$. The top quark background is further suppressed by rejecting events containing any b-tagged jet with $p_T > 30$ GeV reconstructed within the tracker acceptance of $|\eta| < 2.4$. To reduce the WZ background in which both bosons decay leptonically, we remove events containing additional electrons or muons with loose identification and with $p_T > 10$ GeV. Events containing a loosely identified τ_h candidate with $p_T > 18$ GeV and $|\eta| < 2.3$ are also rejected.

In addition to the above criteria, there are several selections designed to further reduce the SM background. The main discriminating variables are: the missing transverse momentum, p_T^{miss} ; the azimuthal angle formed between the dilepton p_T and the $\vec{p}_T^{\text{miss}}$, $\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{p}_T^{\text{miss}})$; and the balance ratio, $|p_T^{\text{miss}} - p_T^{\ell\ell}|/p_T^{\ell\ell}$. The latter two variables are especially powerful in rejecting DY and top quark processes. Selection criteria are optimized to obtain the best signal sensitivity, defined as $(s/\sqrt{s+b})$, for the range of DM mediator masses considered. The final selection requirements are: $p_T^{\text{miss}} > 100$ GeV, $\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{p}_T^{\text{miss}}) > 2.6$ radians, and $|p_T^{\text{miss}} - p_T^{\ell\ell}|/p_T^{\ell\ell} < 0.4$.

In order to avoid biases in the p_T^{miss} calculation due to jet mismeasurement, events with one jet are required to have the azimuthal angle between this jet and the missing transverse momentum, $\Delta\phi(\vec{p}_T^j, \vec{p}_T^{\text{miss}})$, be larger than 0.5 radians. To reduce the contribution from backgrounds such as W^+W^- and $t\bar{t}$, we apply a requirement on the distance between the two leptons in the (η, ϕ) plane, $\Delta R_{\ell\ell} < 1.8$.

Additionally, in the case of the 2HDM model, where both the Z boson and the invisibly decaying pseudoscalar originate from a single mediator, the m_T , shown below, is used as a discriminatory

variable instead of the p_T^{miss} variable. In this case there is a gain in sensitivity by switching to the m_T variable as shown in fig 6.2. The sensitivity using the m_T as the discriminatory variable is increased in all but the low mass points where the p_T of the Z boson dominates and the signal remains in the bulk of the background. However, even at these low mass points, the m_T variable has approximately the same sensitivity as the p_T^{miss} . As such, the choice was made to switch to using the m_T as the fitting variable for all mass points of the 2HDM model. We make a less stringent requirement on the missing transverse momentum, $p_T^{\text{miss}} > 80$ GeV, and require the transverse mass, $m_T = \sqrt{2p_{\ell\ell}^T p_T^{\text{miss}} (1 - \cos \Delta\phi(\vec{p}_T^{\ell\ell}, \vec{p}_T^{\text{miss}}))}$ to be greater than 200 GeV.

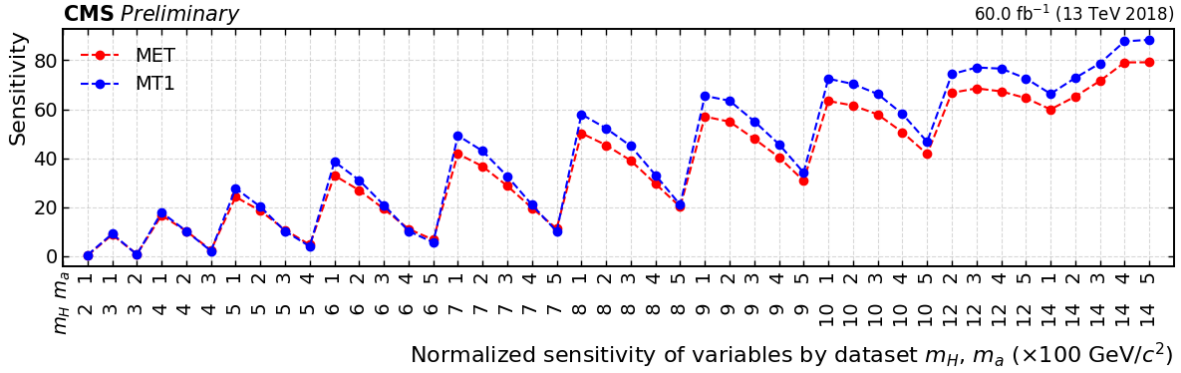


Figure 6.2: A comparison of the signal over square root of the background for m_T variable versus the p_T^{miss} variable. The sensitivity is shown for each mass point simulated for the 2HDM model. This study was done using 2018 Monte Carlo. Here, MET represents the p_T^{miss} and MT1 represents the m_T .

The binning was chosen to increase the bin size at large values without increasing the statistical uncertainties. For the p_T^{miss} regions, 11 bins were chosen: [100,125,150,175,200,250,300,350,400,500,600, ∞], while for the m_T regions 10 bins were chosen: [100,200,250,300,350,400,500,600,700,1000, ∞]. A full optimization was not done due to the number of signal models, but in this way, we have sensitivity to high mass mediators, while for the low mass mediators the fine bins at the lower values are optimal.

A summary of the selection criteria for the SR is given in Table 6.4.

Table 6.4: Summary of the kinematic selections for the signal region.

Quantity	Requirement	Target backgrounds
N_ℓ	=2 with additional lepton veto	WZ, VVV
p_T^ℓ	>25/20 GeV for leading/subleading	multijet
dilepton mass	$ m_{\ell\ell} - m_Z < 15$ GeV	W^+W^- , top quark
number of jets	≤ 1 jet with $p_T^j > 30$ GeV	DY, top quark, VVV
$p_T^{\ell\ell}$	>60 GeV	DY
b-tagging veto	DeepCSV Medium WP	Top quark, VVV
τ_h lepton veto	0 τ_h cand. with $p_T^\tau > 18$ GeV	WZ
$\Delta\phi(\vec{p}_T^j, \vec{p}_T^{\text{miss}})$	>0.5	DY, WZ
$\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{p}_T^{\text{miss}})$	>2.6	DY
$ p_T^{\text{miss}} - p_T^{\ell\ell} /p_T^{\ell\ell}$	<0.4	DY
$\Delta R_{\ell\ell}$	<1.8	W^+W^- , top quark
p_T^{miss} (all but 2HDM+a)	>100 GeV	DY, W^+W^- , top quark
p_T^{miss} (2HDM+a only)	>80 GeV	DY, W^+W^- , top quark
m_T (2HDM+a only)	>200 GeV	DY, W^+W^- , ZZ, top quark

6.3 Background estimation

We estimate the background contributions using combined information from simulation and control regions (CRs) in data. A simultaneous maximum likelihood fit to the p_T^{miss} or m_T distributions in the SR and CRs constrains the background normalizations and their uncertainties. Specific CRs target different categories of background processes, as described below.

6.3.1 The three-lepton control region

The $WZ \rightarrow \ell' \nu \ell \ell$ decay mode can contribute to the signal region when the third lepton ($\ell' = e$ or μ) escapes detection, and this same process can be monitored in an orthogonal CR, where the third lepton is identified and then removed. The construction of the three-lepton (3ℓ) CR is based on events with three well-reconstructed charged leptons. A Z boson candidate is selected in the same

manner as for the SR, while an additional electron or muon with identical quality and isolation is required. To enhance the purity of the WZ selection, p_T^{miss} of at least 30 GeV is required and the invariant mass of three leptons is required to be larger than 100 GeV. The selections are summarized in table 6.5. All background estimates for this CR are taken from simulation.

Selections for 3ℓ control region
OSSF lepton 1 and 2 with $p_T > 25/20$ GeV for leading/subleading and tight (medium) ID
lepton 3 with $p_T > 20$ GeV and tight (medium) ID
dilepton $p_T > 60$ GeV
$ m_{ll} - m_Z < 15$ GeV
$m_{3\ell} > 100$ GeV
$p_T^{\text{miss}} > 80$ GeV
$ p_T^{ll} - p_T^{\text{miss}}(\text{emulated}) /p_T^{ll} < 0.4$
$\Delta\phi_{ll-p_T^{\text{miss}}(\text{emulated})} > 2.8$
≤ 1 jet with $p_T > 30$ GeV
b-jet veto

Table 6.5: Summary of definitions for the 3ℓ CR. Selections shown for muons (electrons).

To simulate the consequences of not detecting the third lepton, the “emulated p_T^{miss} ” is estimated from the vectorial sum of the $\vec{p}_T^{\text{miss}}$ vector and the transverse momentum vector ($\vec{p}_T$) of the additional lepton. The emulated p_T^{miss} is then used in place of the reconstructed p_T^{miss} and the same selection is applied as for the SR. Since there is negligible contamination from $WZ \rightarrow \tau\nu\ell\ell$ and top quark backgrounds in this CR, no veto is applied on additional τ_h or bjet candidates. The resulting emulated p_T^{miss} spectrum is shown in Fig. 6.3. For the 2HDM+a case, the “emulated m_T ” is used instead of “emulated p_T^{miss} ” with the same selections. For this case, the bin widths are doubled to match the corresponding SR.

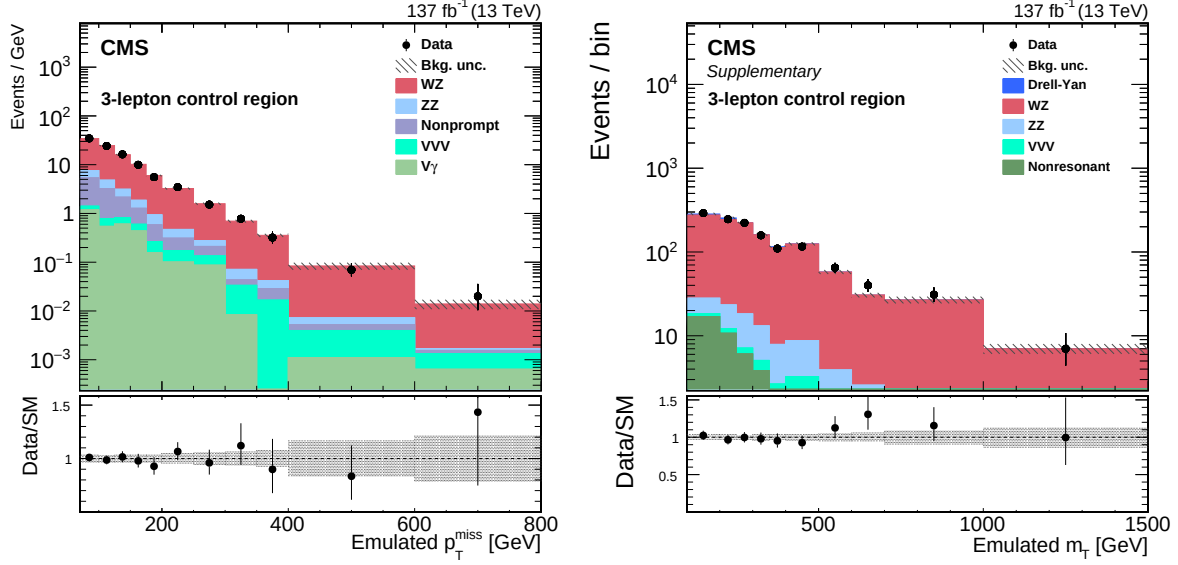


Figure 6.3: Distribution in data and simulation for the 3ℓ CR showing the emulated p_T^{miss} (left) and emulated m_T (right) CRs. Uncertainty bands correspond to the postfit combined statistical and systematic components.

6.3.2 The four-lepton control region

The ZZ process contributes to the SR through the $ZZ \rightarrow \ell\ell\nu\nu$ decay mode, and the same production process can be monitored via the decay mode $ZZ \rightarrow 4\ell$. The four-lepton (4ℓ) CR is based on events with two pairs of charged leptons. Each pair comprises two leptons of opposite charge and the same flavor and corresponds to a Z candidate. Two of the four leptons must fulfill the same requirements on the leptons as in the SR, while, in order to increase the yield, the other two leptons need only pass relaxed lepton quality requirements. This choice reflects the very high purity of the four-lepton selection. The highest p_T Z boson candidate is required to have an invariant mass within 35 GeV of the established Z boson mass m_Z [84]. Additionally, we require the transverse momentum of this Z boson candidate to be larger than 60 GeV. The selections are summarized in table 6.6. Backgrounds to the ZZ final state, dominated by triboson processes, are almost negligible in this CR and are taken from simulation.

For these four-lepton events, the emulated p_T^{miss} is calculated as the vectorial sum of the $\vec{p}_T^{\text{miss}}$

Selections for 4ℓ control region	
OSSF lepton 1 and 2 with $p_T > 25/20$ GeV for leading/subleading and tight (medium) ID	
OSSF lepton 3 and 4 with $p_T > 10$ GeV and loose (loose) ID	
dilepton $p_T > 60$ GeV	
$ m_{ll} - m_Z < 30$ GeV	
$\Delta\phi_{ll-p_T^{\text{miss}}(\text{emulated})} > 2.5$	
≤ 1 jet with $p_T > 30$ GeV	

Table 6.6: Summary of definitions for the 4ℓ control region.

and the $\vec{p}_T$ of the Z boson candidate with the larger absolute mass difference to the nominal value of m_Z of the two identified in the event. The choice of which Z boson to use as a proxy for an invisibly decaying boson negligibly alters the emulated p_T^{miss} spectrum. The same selection as the SR is then applied using the emulated p_T^{miss} in place of the reconstructed p_T^{miss} , with the exception of the τ_h and bjet candidate vetoes. The resulting emulated p_T^{miss} spectrum is shown in Fig. 6.4. Similarly to the three-lepton CR, the “emulated m_T ” is used instead of “emulated p_T^{miss} ” for the 2HDM+a case and the distribution is well described by the SM background estimations.

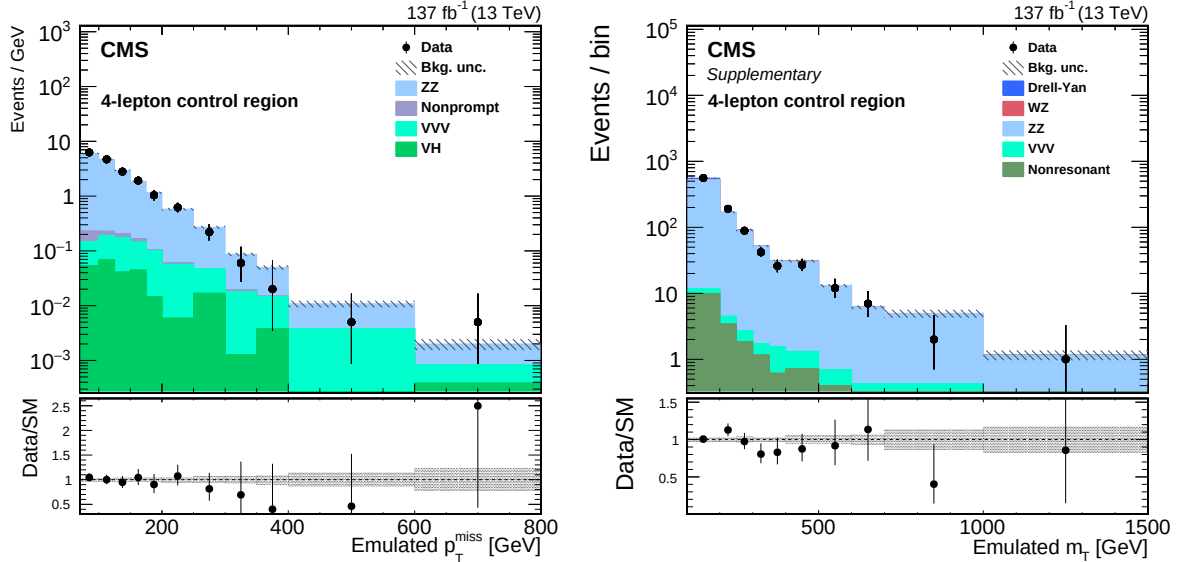


Figure 6.4: Distribution in data and simulation for the 4ℓ CR showing the emulated p_T^{miss} (left) and emulated m_T (right) CRs. Uncertainty bands correspond to the postfit combined statistical and systematic components.

6.3.3 The electron-muon control region

We estimate the contribution of the flavor-symmetric backgrounds from an $e\mu$ CR based on events with two leptons of different flavor and opposite charge ($e^\pm\mu^\mp$) that pass all other analysis selections. This CR is largely populated by nonresonant backgrounds (NRB) consisting mainly of leptonic W boson decays in $t\bar{t}$, tW , and WW events, where the dilepton mass happens to fall inside the Z boson mass window. Small contributions from single top quark events produced via s - and t -channel processes, and $Z \rightarrow \tau\tau$ events in which τ leptons decay into light leptons and neutrinos, are also considered in the NRB estimation. The selections are summarized in table 6.7.

Selections for NRB control region
OSOF lepton 1 and 2 with $p_T > 25/20$ GeV for leading/subleading and tight (medium) ID
third lepton veto
dilepton $p_T > 60$ GeV
$ m_{ll} - m_Z < 15$ GeV
$p_T^{\text{miss}} > 50$ GeV
≤ 1 jet with $p_T > 30$ GeV
b-jet veto

Table 6.7: Summary of definitions for the NRB control region.

In addition to the 3 lepton and 4 lepton control regions, the ratio of WZ and ZZ processes can be used to further validate the samples. Since there should be no significant difference in the shape of the emulated p_T^{miss} between the 2 processes, the ratio of WZ to ZZ was plotted using the emulated p_T^{miss} distribution for all years as shown in Figure 6.5. This ratio was created for both simulation and for data from the respective control regions.

6.3.4 The DY control region

The DY background is dominant in the region of low p_T^{miss} . This process does not produce undetectable particles. Therefore, any nonzero p_T^{miss} arises from mismeasurement or limitations in the

CMS

137.4 fb⁻¹ (13 TeV)

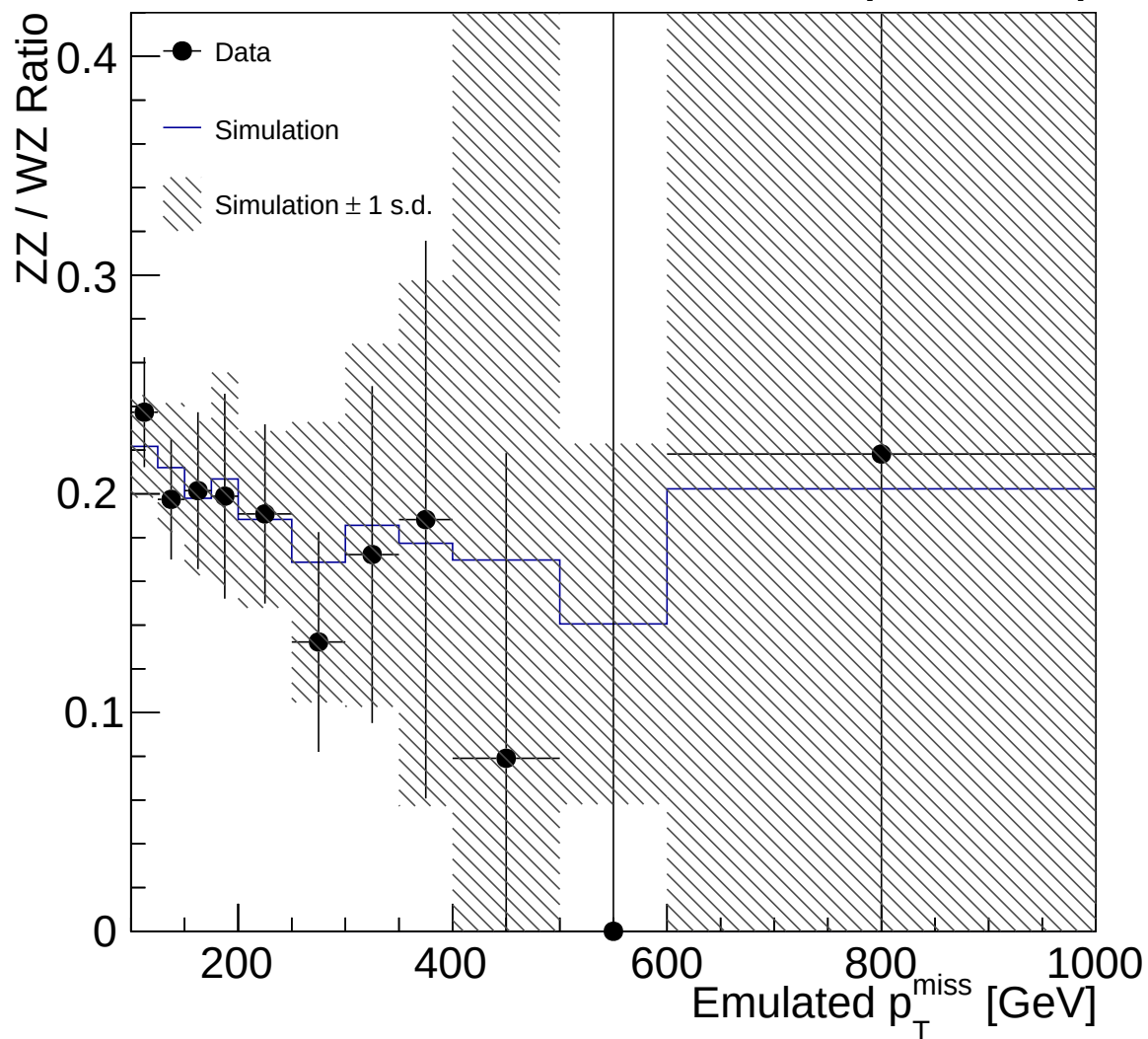


Figure 6.5: Ratio of the WZ and ZZ processes as a function of emulated p_T^{miss} for both simulation and data.

detector acceptance. The estimation of this background uses simulated DY events, for which the normalization is taken from data in a sideband CR of $80 < p_{\text{T}}^{\text{miss}} < 100$ GeV where the signal contamination is negligible, with all other selections applied. For the 2HDM+a analysis, a similar approach is taken with relaxed $p_{\text{T}}^{\text{miss}}$ selection of $50 < p_{\text{T}}^{\text{miss}} < 100$ GeV and an additional selection of $m_{\text{T}} < 100$ GeV applied. The selections are summarized in table 6.8. The sideband CR is included in the maximum likelihood fit and a 100% uncertainty is assigned to the extrapolation from this CR to the SR. This uncertainty has little effect on the results because of the smallness of the overall contribution from the DY process in the SR.

Table 6.8: Selection for the Drell-Yan control region.

Selections for the DY sideband region
$n_l = 2$
$p_{\text{T}}^l > 25/20$ GeV for leading/subleading
$ m_{ll} - m_Z < 15$ GeV
≤ 1 jet with $p_{\text{T}} > 30$ GeV
$p_{\text{T}}^{ll} > 60$ GeV
0 τ candidates with $p_{\text{T}}^\tau > 18$ GeV
$p_{\text{T}}^{\text{miss}} > 80$ GeV
Signal region veto applied

6.4 Fitting method

After applying the selection, we perform a binned maximum likelihood fit to discriminate between the potential signal and the remaining background processes. The data sets for each data-taking year are kept separate in the fit. This yields a better expected significance than combining them into a single set because the signal-to-background ratios are different for the three years due to

the different data-taking conditions. The electron and muon channels have comparable signal-to-background ratios, and are combined in the fit, while the contributions, corrections and systematic uncertainties are calculated individually.

The p_T^{miss} distribution of events passing the selection is used as the discriminating variable in the fit for all of the signal hypotheses except for the 2HDM+a model. For this model, the m_T distribution is used since a Jacobian peak around the pseudoscalar Higgs boson mass is expected. Events in the SR are split into 0-jet and 1-jet categories to take into account the different signal-to-background ratios. In addition, for the CRs defined in Section 6.3, events with 0-jet and 1-jet are included as a single category in the fit. The $e\mu$ and DY CRs are each included as a single bin corresponding to the total yield. The p_T^{miss} or m_T spectra in the 3ℓ and 4ℓ CRs are included in the fit with the same binning as in the SR, where these spectra are based upon the emulated p_T^{miss} . To allow for further freedom in the ZZ and WZ background estimation, the p_T^{miss} and emulated p_T^{miss} distributions are split into three regions with independent normalization parameters: low (<200 GeV), medium (200–400 GeV), and high (>400 GeV), with uncertainties of 10, 20, and 30%, respectively. These values are based on the magnitudes of the theoretical uncertainties as described in Section 6.5. For fits to the 2HDM+a model, three similar m_T regions are chosen with the same uncertainties: low (<400 GeV), medium (400–800 GeV), and high (>800 GeV). To make the best use of the statistical power in the CRs and to take advantage of the similarities of the production processes, we take the normalization factors to be correlated for the ZZ and the WZ backgrounds in each p_T^{miss} region.

For each individual bin, a Poisson likelihood term describes the fluctuation of the data around the expected central value, which is given by the sum of the contributions from signal and background processes. Systematic uncertainties are represented by nuisance parameters θ with log-normal probability density functions used for normalization uncertainties and Gaussian functions used for shape-based uncertainties, with the functions centered on their nominal values $\hat{\theta}$. The uncertainties affect the overall normalizations of the signal and background templates, as well as the

shapes of the predictions across the distributions of observables. Correlations among systematic uncertainties in different categories are taken into account as discussed in Section 6.5. The total likelihood is defined as the product of the likelihoods of the individual bins and the probability density functions for the nuisance parameters:

$$\mathcal{L} = \mathcal{L}_{\text{SR}} \mathcal{L}_{3\ell} \mathcal{L}_{4\ell} \mathcal{L}_{e\mu} \mathcal{L}_{\text{DY}} f_{\text{NP}}(\theta | \hat{\theta}) \quad (6.1)$$

The factors of the likelihood can be written more explicitly as:

$$\begin{aligned} \mathcal{L}_{\text{SR}} = \prod_{i,j} \mathcal{P} \Big(& N_{\text{obs},i,j}^{\text{SR}} \mid \mu_{\text{DY}} N_{\text{DY},i,j}^{\text{SR}}(\theta) \\ & + \mu_{\text{NRB}} N_{\text{NRB},i,j}^{\text{SR}}(\theta) + N_{\text{other},i,j}^{\text{SR}}(\theta) \\ & + \mu_{\text{VV},r(i)} (N_{\text{ZZ},i,j}^{2\ell}(\theta) + N_{\text{WZ},i,j}^{\text{SR}}(\theta)) \\ & + \mu N_{\text{Sig},i,j}^{\text{SR}}(\theta) \Big), \end{aligned} \quad (6.2)$$

$$\mathcal{L}_{3\ell} = \prod_i \mathcal{P} \Big(N_{\text{obs},i}^{3\ell} \mid N_{\text{other},i}^{3\ell}(\theta) + \mu_{\text{VV},r(i)} N_{\text{WZ},i}^{3\ell}(\theta) \Big), \quad (6.3)$$

$$\mathcal{L}_{4\ell} = \prod_i \mathcal{P} \Big(N_{\text{obs},i}^{4\ell} \mid N_{\text{other},i}^{4\ell}(\theta) + \mu_{\text{VV},r(i)} N_{\text{ZZ},i}^{4\ell}(\theta) \Big), \quad (6.4)$$

$$\mathcal{L}_{e\mu} = \mathcal{P} \Big(N_{\text{obs}}^{e\mu} \mid \mu_{\text{NRB}} N_{\text{NRB}}^{e\mu}(\theta) + N_{\text{other}}^{e\mu}(\theta) \Big), \quad (6.5)$$

$$\begin{aligned} \mathcal{L}_{\text{DY}} = \mathcal{P} \Big(& N_{\text{obs}}^{\text{DY}} \mid \mu_{\text{DY}} N_{\text{DY}}^{\text{DY}}(\theta) + \mu_{\text{NRB}} N_{\text{NRB}}^{\text{DY}}(\theta) \\ & + N_{\text{other}}^{\text{DY}}(\theta) + N_{\text{ZZ}}^{\text{DY}}(\theta) + N_{\text{WZ}}^{\text{DY}}(\theta) + \mu N_{\text{Sig}}^{\text{DY}}(\theta) \Big). \end{aligned} \quad (6.6)$$

The purpose of the fit is to determine the confidence interval for the signal strengths μ . Here $\mathcal{P}(N \mid \lambda)$ is the Poisson probability to observe N events for an expected value of λ , and $f_{\text{NP}}(\theta \mid \hat{\theta})$ describes the nuisance parameters with log-normal probability density functions used for normalization uncertainties and Gaussian functions used for shape-based uncertainties. The index i indicates the bin of the $p_{\text{T}}^{\text{miss}}$ or m_{T} distribution, $r(i)$ corresponds to the region (low, medium, high) of bin i , and the index j indicates either the 0-jet or 1-jet selection. The diboson process normalization in the region $r(i)$ is $\mu_{\text{VV},r(i)}$, while μ_{DY} is the DY background normalization and μ_{NRB} is the

normalization for the nonresonant background. The yield prediction from simulation for process x in region y is noted as N_x^y . The smaller backgrounds in each region are merged together and are indicated collectively as "other". The method above for constructing likelihood functions follows that of Ref. [199], where a more detailed mathematical description may be found.

6.5 Systematic uncertainties

In the following, we describe all of the uncertainties that are taken into account in the maximum likelihood fit. We consider the systematic effects on both the overall normalization and on the shape of the distribution of p_T^{miss} or m_T for all applicable uncertainties. We evaluate the impacts by performing the full analysis with the value of the relevant parameters shifted up and down by one standard deviation. The final varied distributions of p_T^{miss} or m_T are used for signal extraction and as input to the fit. For each source of uncertainty, the impact in different bins of these distributions is thus considered fully correlated, while independent sources of uncertainty are treated as uncorrelated. Except where noted otherwise, the systematic uncertainties for the three different years of data taking are treated as correlated.

The assigned uncertainties in the integrated luminosity are 2.5%, 2.3%, and 2.5% for the 2016, 2017, and 2018 data samples [200; 201; 202], respectively, and they are treated as uncorrelated across the different years.

We apply scale factors to all MC samples to correct for discrepancies in the lepton reconstruction and identification efficiencies between data and simulation. These factors are measured using DY events in the Z boson peak region [19; 203; 204] that are recorded with unbiased triggers. The factors depend on the lepton p_T and η and are within a few percent of unity for electrons and muons. The uncertainty in the determination of the trigger efficiency leads to an uncertainty

smaller than 1% in the expected signal yield.

For the kinematic regions used in this analysis, the lepton momentum scale uncertainty for both electrons and muons is well represented by a constant value of 0.5%. The uncertainty in the calibration of the jet energy scale and resolution directly affects the p_T^{miss} computation and all the selection requirements related to jets. The estimate of the jet energy scale uncertainty is performed varying the jet energy scale. The variation corresponds to a re-scaling of the jet four-momentum as $P \rightarrow P \cdot (1 \pm \delta p_T^{\text{JES}}/p_T)$, where δp_T^{JES} is the absolute uncertainty in the jet energy scale which is parameterized as function of the p_T and η of the jet. In order to account for the systematic uncertainty from the jet resolution smearing procedure, the resolution scale factors are also varied within their uncertainty. Since the uncertainties in the jet energy scale are not consistent in the three data sets, they are treated as uncorrelated across the three data sets.

The signal processes are expected to produce very few events containing b-jets, and we reject events with any jets that satisfy a b-tagging algorithm. In order to account for b-tagging efficiencies observed in data, an event-by-event reweighting using b-tag scale factors and efficiencies is applied to simulated events. The uncertainty is obtained by varying the event-by-event weight by ± 1 standard deviation. Since the uncertainties in the b-tagging are not consistent in the three data sets, they are treated as uncorrelated across the three data sets. The variation of the final yields induced by this procedure is less than 1%.

Simulated samples are reweighted to reproduce the pileup conditions observed in data. We evaluate the uncertainty related to pileup by recalculating these weights for variations in the minimum-bias cross section by 5% around the nominal value [205]. The resulting shift in weights is propagated through the analysis and the corresponding p_T^{miss} and m_T spectra are used as input to the maximum likelihood fit. The variation of the final yields induced by this procedure is less than 1%.

Shape-based uncertainties for the ZZ and WZ backgrounds, referred to jointly as VV, and signal processes are derived from variations of the renormalization and factorization scales, the strong coupling constant α_s , and PDFs [206; 207; 208]. The scales are varied up and down by a factor of two. Variations of the PDF set and α_s are used to estimate the corresponding uncertainties in the yields of the signal and background processes following Ref. [181]. The missing higher-order EW terms in the event generation for the VV processes yield another source of theoretical uncertainty [186; 187]. The following additional higher-order corrections are applied: a constant (approximately 10%) correction for the WZ cross section from NLO to NNLO in QCD calculations [209]; a constant (approximately 3%) correction for the WZ cross section from LO to NLO in EW calculations, according to Ref. [210]; a $\Delta\phi(Z, Z)$ -dependent correction to the ZZ production cross section from NLO to next-to-next-to-leading order (NNLO) in QCD calculations [211]; a p_T -dependent correction to the ZZ cross section from LO to NLO in EW calculations, following Refs. [210; 186; 187], which is the dominant correction in the signal region. We use the product of the above NLO EW corrections and the inclusive NLO QCD corrections [212] as an estimate of the missing NLO EW $\times$ NLO QCD contribution, which is not used as a correction, but rather assigned as an uncertainty. The resulting variations in the p_T^{miss} and m_T distribution are used as a shape uncertainty in the likelihood fit.

Higher order terms purely in α_{EW} are expected to be negligible. A significant uncertainty, instead, stems from missing QCD-EW combined corrections, e.g. involving two-loop terms of order $\alpha_s\alpha_{\text{EW}}$. The resulting variations in the p_T^{miss} and m_T distribution are used as a shape uncertainty in the likelihood fit.

The shapes of the p_T^{miss} and m_T distributions are needed for each of the background processes. For the DY and nonresonant processes, we take the shape directly from simulation. The shapes for the WZ and ZZ processes are obtained from a combination of simulation and CR data. In all cases, the limited number of simulated events in any given bin gives rise to a systematic uncertainty. For each bin and process, this uncertainty is treated as fully uncorrelated.

The post-fit pulls and the impacts of the top 30 uncertainties fixing the branching fraction of invisible Higgs boson decays to 1 and 0, ordered by decreasing importance, are shown in Figure 6.6. The post-fit pulls and the impacts of the top 30 uncertainties on data for the invisible Higgs boson case and for a dimension 4 with $m_D = 3$ TeV ADD case are shown in Figure 6.7.

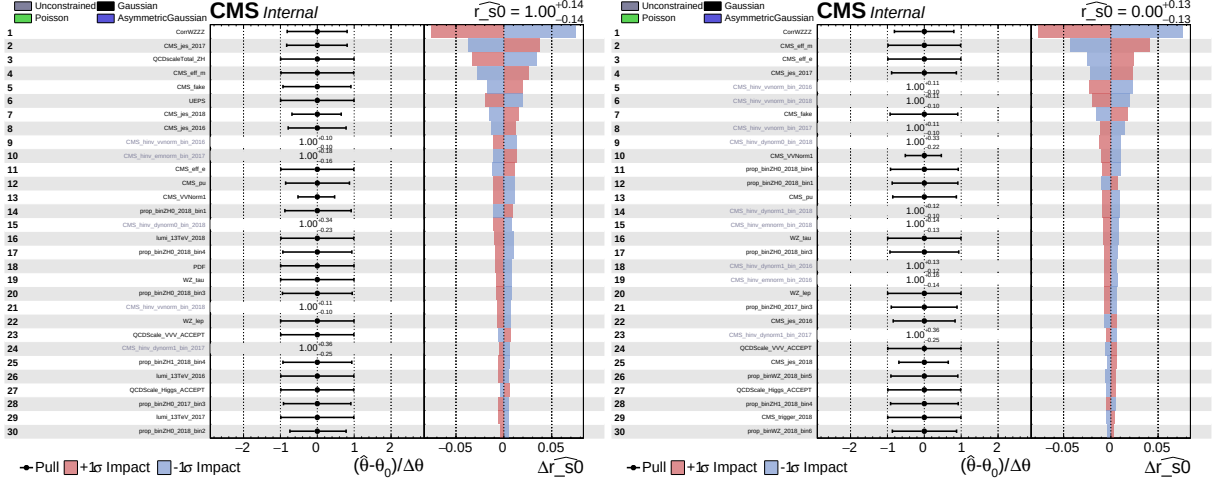


Figure 6.6: Post-fit nuisance parameters fixing the branching fraction of invisible Higgs boson decays to 1 (left) and to 0 (right), ranked by decreasing importance.

A summary of the impact of the systematic uncertainties is shown in Table 6.9. The $Zh(\text{invisible})$ model is used as an example to illustrate the size of the uncertainties, both for the presence of a signal ($\mathcal{B}(h \rightarrow \text{invisible}) = 1$) and the absence ($\mathcal{B}(h \rightarrow \text{invisible}) = 0$). These two paradigms are used to generate Asimov data sets that are then fit to give the uncertainty estimates shown in Table 6.9. The systematic uncertainties are dominated by the theoretical uncertainty in the ZZ and WZ normalization.

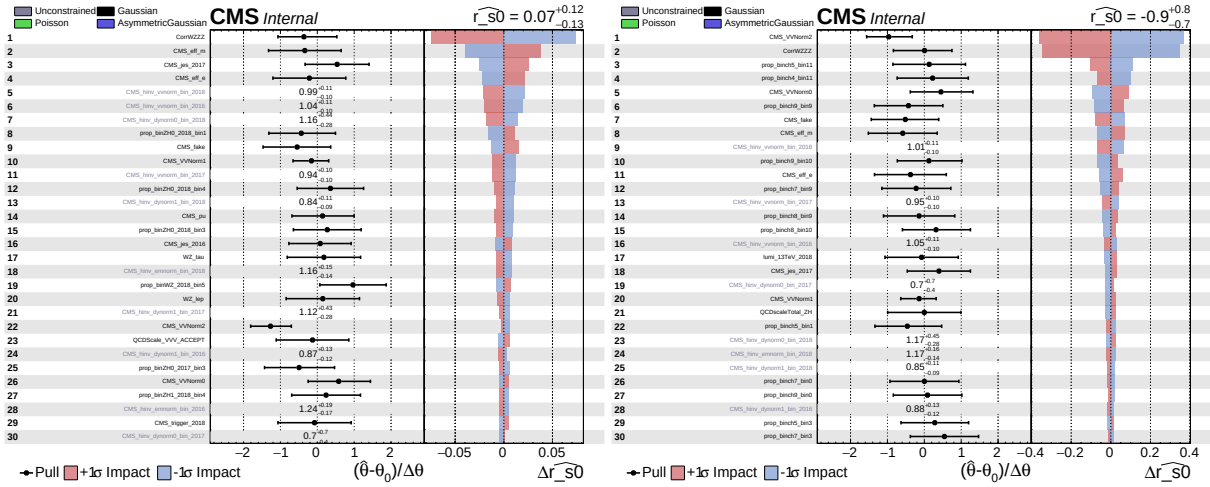


Figure 6.7: Post-fit nuisance parameters on the observed data for the invisible Higgs boson case (left) and for a dimension 4 with $m_D = 3$ TeV ADD case (right), ranked by decreasing importance.

Table 6.9: Summary of impact of the systematic uncertainties considered in the $Zh(\text{invisible})$ model assuming $\mathcal{B}(h \rightarrow \text{invisible}) = 1$ (signal) and $\mathcal{B}(h \rightarrow \text{invisible}) = 0$ (no signal). Here, lepton measurement refers to the combined trigger, lepton reconstruction and identification efficiencies, and the lepton momentum and electron energy scale systematics.

Source of uncertainty	Impact assuming signal (%)	Impact assuming no signal (%)
Luminosity	1.3	0.2
Lepton Measurement	3.2	5.0
Jet energy scale and resolution	4.2	2.4
Pileup	1.2	0.9
b-tagging efficiency	0.4	0.2
Theory	8.8	8.5
Simulation sample size	2.4	2.3
Total systematic uncertainty	11	11
Statistical uncertainty	8.9	7.3
Total uncertainty	14	13

Chapter 7

Results

This chapter presents the results for the models investigated in this thesis following the results recently published by CMS [166]. The unblinded signal region as well as the associated yields are presented in section 7.1. The interpretation for the simplified dark matter models and the comparison with direct detection experiments are shown in Sec. 7.2. An additional dark matter interpretation from the 2HDM+a model is described in Sec. 7.3, while the the upper limit on the branching fraction of invisible Higgs boson decays is described in Sec. 7.4. Finally, extra dimensional models are presented for the Arkani-Hamed–Dimopoulos–Dvali model in Sec. 7.5 and the Unparticle model is presented in Sec. 7.6.

7.1 Yields

The number of observed and expected events in the SR after the final selection is given in Table 7.1, where the values of the expected yields and their uncertainties are obtained from the maximum likelihood fit. The observed numbers of events are compatible with the background predictions. The expected yields and the product of acceptance and efficiency for several signal models used in the analysis are shown in Table 7.2. The post-fit $p_{\text{T}}^{\text{miss}}$ distributions for events in the signal region in the 0-jet and 1-jet categories are shown in Fig. 7.1. The final m_{T} distributions used for the 2HDM+a model are shown in Fig. 7.2.

Table 7.1: Observed number of events and post-fit background estimates in the two jet multiplicity categories of the SR. The reported uncertainty represents the sum in quadrature of the statistical and systematic components.

Process	0 jet category	1 jet category
$WZ \rightarrow 3l\nu$	1479 ± 53	389 ± 16
ZZ	670 ± 27	282 ± 13
Nonresonant background	384 ± 31	263 ± 22
DY	502 ± 94	1179 ± 64
Other background	6.3 ± 0.7	6.8 ± 0.8
Total background	3040 ± 110	2120 ± 76
Data	3053	2142

Table 7.2: Expected yields and the product of acceptance and efficiency for several models probed in the analysis. The quoted values correspond to the Z to $\ell\ell$ decays. The reported uncertainty represents the sum in quadrature of the statistical and systematic components.

Model	Yields	Product of acceptance and efficiency (%)
$Zh(125)$	864 ± 64	10.6 ± 0.8
ADD $M_D = 3 \text{ TeV}, d = 4$	35.1 ± 2.4	18.6 ± 1.3
Unparticle $S_U = 0, d_U = 1.50$	221 ± 16	8.2 ± 0.6
2HDM+a $m_H = 1000 \text{ GeV}, m_a = 400 \text{ GeV}$	14.1 ± 4.0	12.7 ± 2.7
DM Vector $m_{\text{med}} = 1000 \text{ GeV}, m_\chi = 1 \text{ GeV}$	64.8 ± 6.1	17.6 ± 1.7

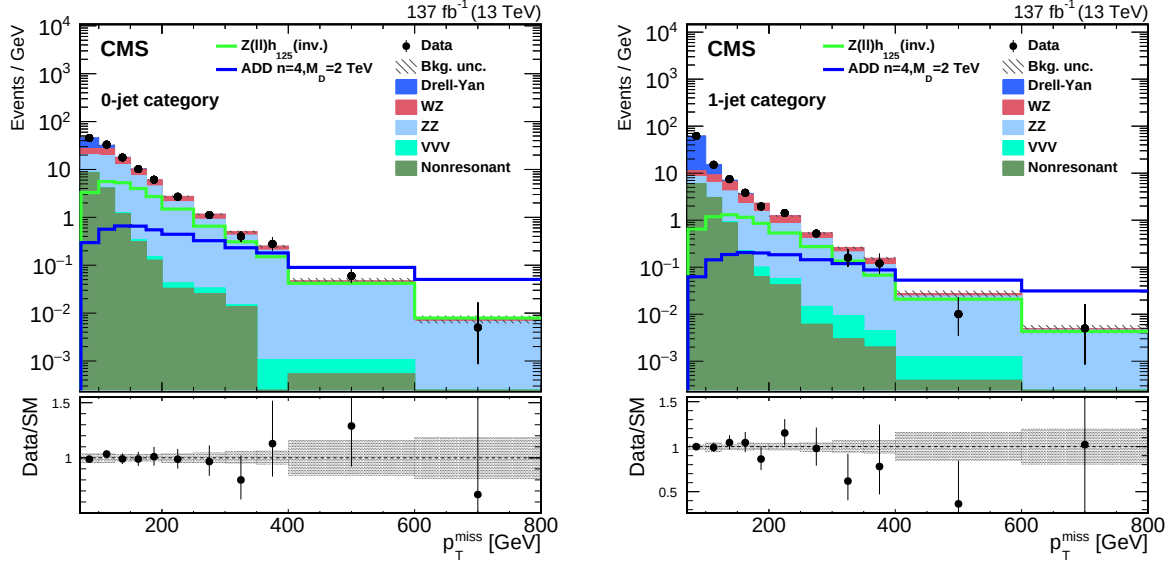


Figure 7.1: The p_T^{miss} distributions for events in the signal region in the 0-jet (left) and 1-jet (right) categories. The rightmost bin also includes events with $p_T^{\text{miss}} > 1000$ GeV. The uncertainty band includes both statistical and systematic components. The $Zh(\text{invisible})$ signal normalization assumes SM production rates and the branching fraction $\mathcal{B}(h \rightarrow \text{invisible}) = 1$.

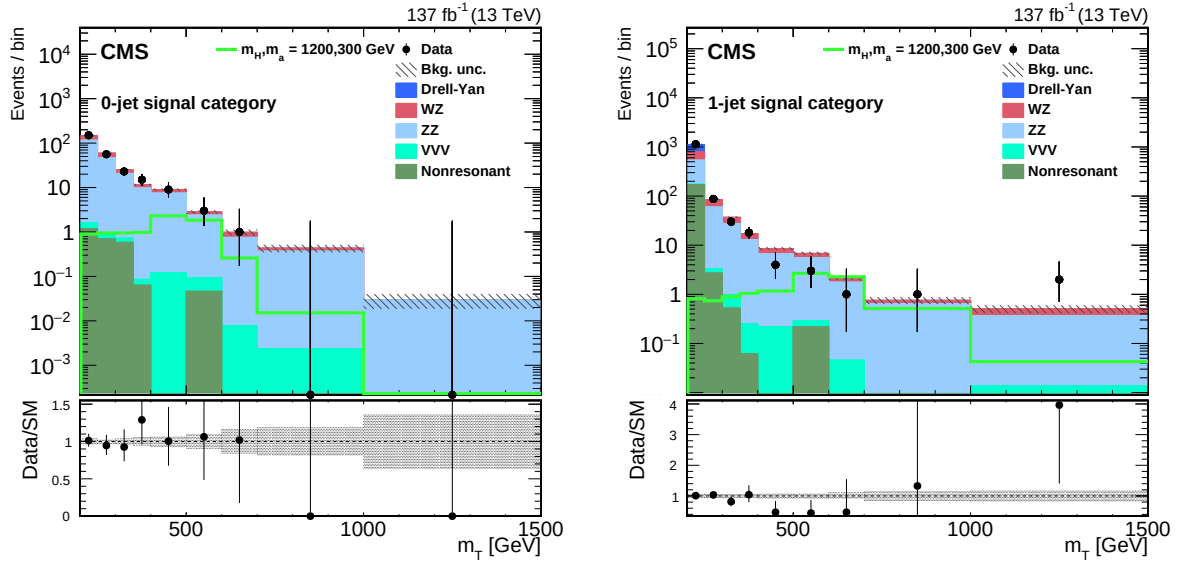


Figure 7.2: The m_T distributions for events in the signal region in the 0-jet (left) and 1-jet (right) categories. The rightmost bin also includes events with $m_T > 1000$ GeV. The uncertainty band includes both statistical and systematic components. The signal normalization assumes the expected values for $(m_H, m_a) = (1200, 300)$ GeV within the 2HDM+a framework.

For each of the models considered, simulated signal samples are generated for relevant sets of model parameters. The modified frequentist construction CL_s [213; 199; 214] is used in the asymptotic approximation [215] to compute 95% confidence level (CL) upper limits on the relevant parameters of each signal model.

7.2 Simplified dark matter model interpretation

In the framework of the simplified models of DM, the signal production is sensitive to the mass, spin, and parity of the mediator as well as the coupling strengths of the mediator to quarks and to DM. The p_T^{miss} distribution is used as an input to the fit. Figure 7.3 gives the 95% CL exclusion contours for vector and axial-vector mediators as a function of the mediator mass m_{med} and DM particle mass m_χ . Cosmological constraints on the DM abundance [216] are added to Fig. 7.3 where the shaded area represents the disallowed region. For vector mediators, we observe a limit around $m_{\text{med}} > 870 \text{ GeV}$ for most values of m_χ less than $m_{\text{med}}/2$. For axial-vector mediators the highest limit reached in the allowed region is about $m_{\text{med}} > 800 \text{ GeV}$. In both cases, the previous limits from this channel are extended by about 150 GeV, but the limits are still less restrictive than those from published mono-jet results [88]. Previous results from CMS and ATLAS are shown for vector mediators in figure 7.4 and for axial-vector mediators in figure 7.5.

The limits for the vector and axial-vector mediators are also translated onto limit plots from direct detection experiments searching for the recoil of a nucleus scattering off a DM particle passing through the detector. Since, the DM is non-relativistic, the dominant interactions can be described by the spin-independent (SI) and spin-dependent (SD) DM-nucleon cross sections [101]. The simplified model with a vector mediator lead to a SI interactions where the DM-nucleon scattering cross section is shown below:

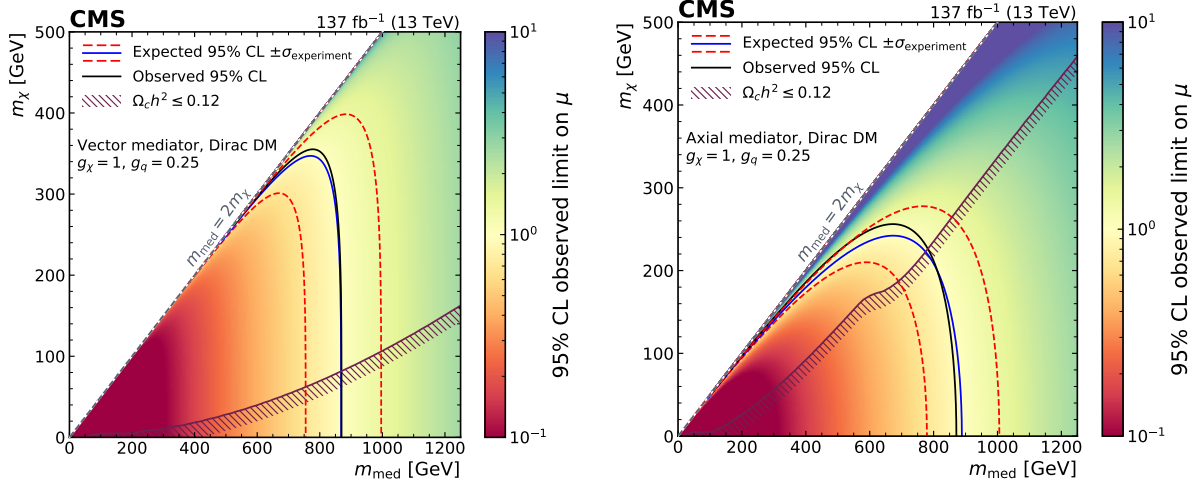


Figure 7.3: The 95% CL exclusion limits for the vector (left) and the axial-vector (right) simplified models. The limits are shown as a function of the mediator and DM particle masses. The coupling top quarks is fixed to $g_q = 0.25$ and the coupling to DM is set to $g_\chi = 1$.

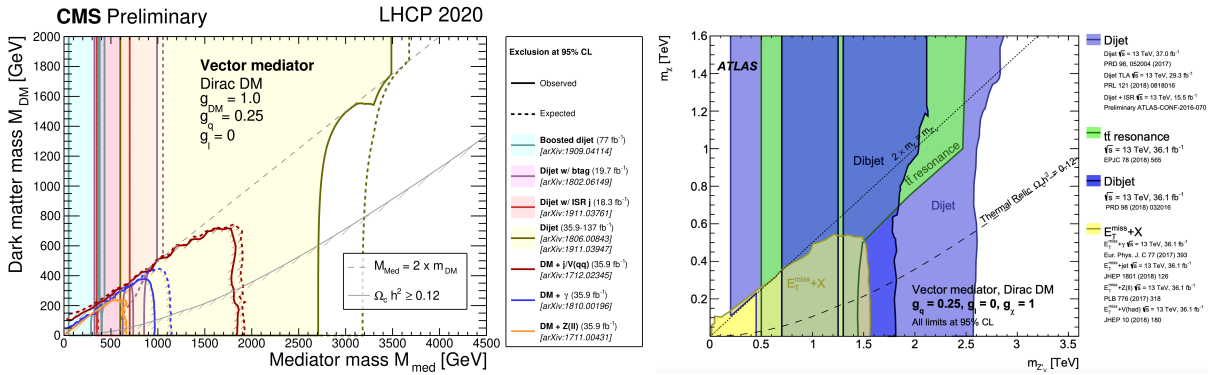


Figure 7.4: Previous results for the vector mediator showing results from CMS (left) [23] and ATLAS (right) [24]. The coupling top quarks is fixed to $g_q = 0.25$ and the coupling to DM is set to $g_\chi = 1$. The limits are shown as a function of the mediator mass.

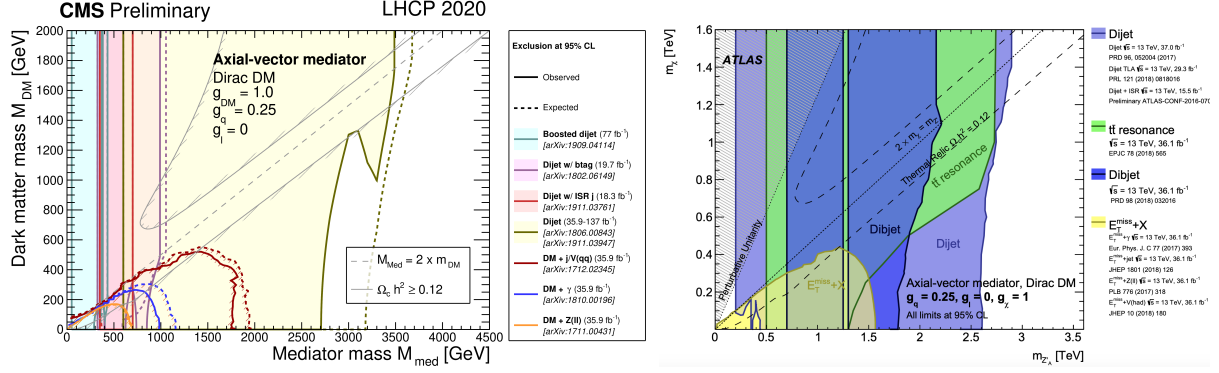


Figure 7.5: Previous results for the axial-vector mediator showing results from CMS (left) [23] and ATLAS (right) [24]. The coupling top quarks is fixed to $g_q = 0.25$ and the coupling to DM is set to $g_\chi = 1$. The limits are shown as a function of the mediator mass.

$$\sigma_{SI} \simeq 6.9 \times 10^{-41} \text{cm}^2 \left(\frac{g_q g_\chi}{0.25} \right)^2 \left(\frac{1 \text{ TeV}}{M_{med}} \right)^4 \left(\frac{\mu_{n\chi}}{1 \text{ GeV}} \right)^2 \quad (7.1)$$

Here, $\mu_{n\chi} = m_n m_\chi / (m_n + m_\chi)$ is the reduced mass with the nucleus mass of $m_n \simeq 0.939 \text{ GeV}$.

It is important to note that this translation is dependent on the choice of mediator mass as well as the mediator-quark couplings. The axial-vector can also be translated and lead to SD interactions with the DM-nucleon scattering cross section below:

$$\sigma_{SD} \simeq 2.4 \times 10^{-42} \text{cm}^2 \left(\frac{g_q g_\chi}{0.25} \right)^2 \left(\frac{1 \text{ TeV}}{M_{med}} \right)^4 \left(\frac{\mu_{n\chi}}{1 \text{ GeV}} \right)^2 \quad (7.2)$$

Figure 7.6 shows the 90% CL limits on the DM-nucleon cross sections calculated following the suggestions in Ref. [101] described above. Limits are shown as a function of the DM particle mass for both the spin-independent and spin-dependent cases and compared to selected results from direct-detection experiments.

In addition to vector and axial-vector mediators, scalar and pseudoscalar mediators are also tested. For these models, we fix both couplings to quarks and to DM particles: $g_q = 1$ and $g_\chi = 1$ as suggested in Ref. [101]. Since the DM particle mass is shown to have negligible effects on the kinematic distributions of the detected particles, we set it to the constant value of $m_\chi = 1 \text{ GeV}$.

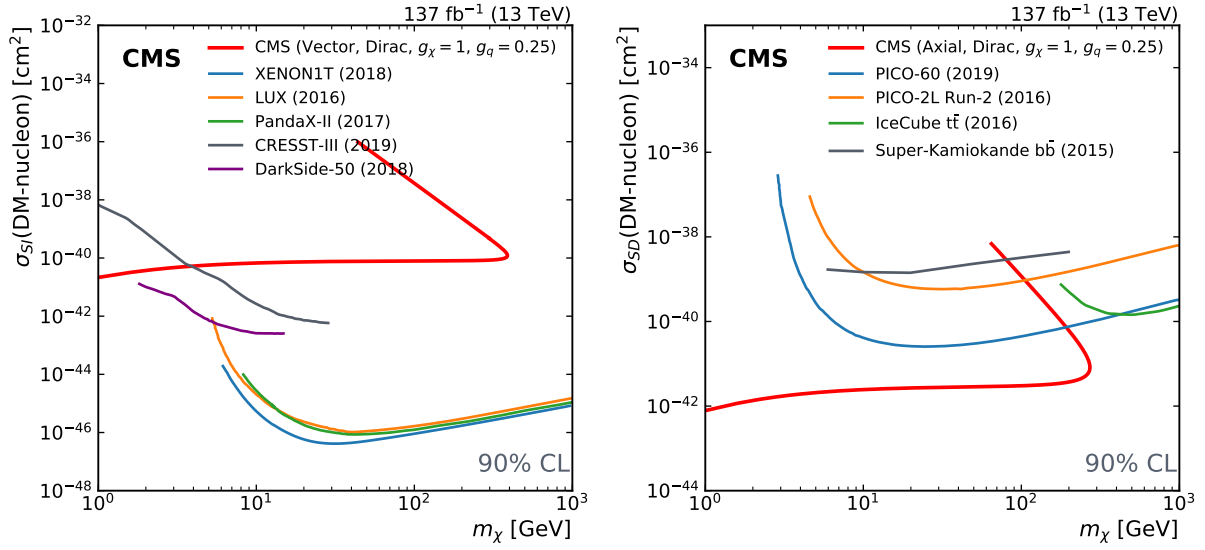


Figure 7.6: The 90% CL DM-nucleon upper limits on the cross section for simplified DM in the spin-independent (left) and spin-dependent (right) cases. The coupling to quarks is set to $g_q = 0.25$ and the coupling to DM is set to $g_\chi = 1$. Limits from the XENON1T [25], LUX [26], PandaX-II [27], CRESST-III [28], and DarkSide-50 [29] experiments are shown for the spin-independent case with vector couplings. Limits from the PICO-60 [30], PICO-2L [31], IceCube [32], and Super-Kamiokande [33] experiments are shown for the spin-dependent case with axial-vector couplings.

Figure 7.7 gives the 95% CL exclusion limits on the production cross section over the predicted cross section as a function the mediator mass m_{med} . The expected limits are about 25% better than the previous results in this channel [85], but are not yet sensitive enough to exclude any value of m_{med} . The best limits obtained on the cross section are about 1.5 times larger than the predicted values for low values of m_{med} . Previous results from CMS and ATLAS are shown for scalar mediators in figure 7.8 and for pseudoscalar mediators in figure 7.9.

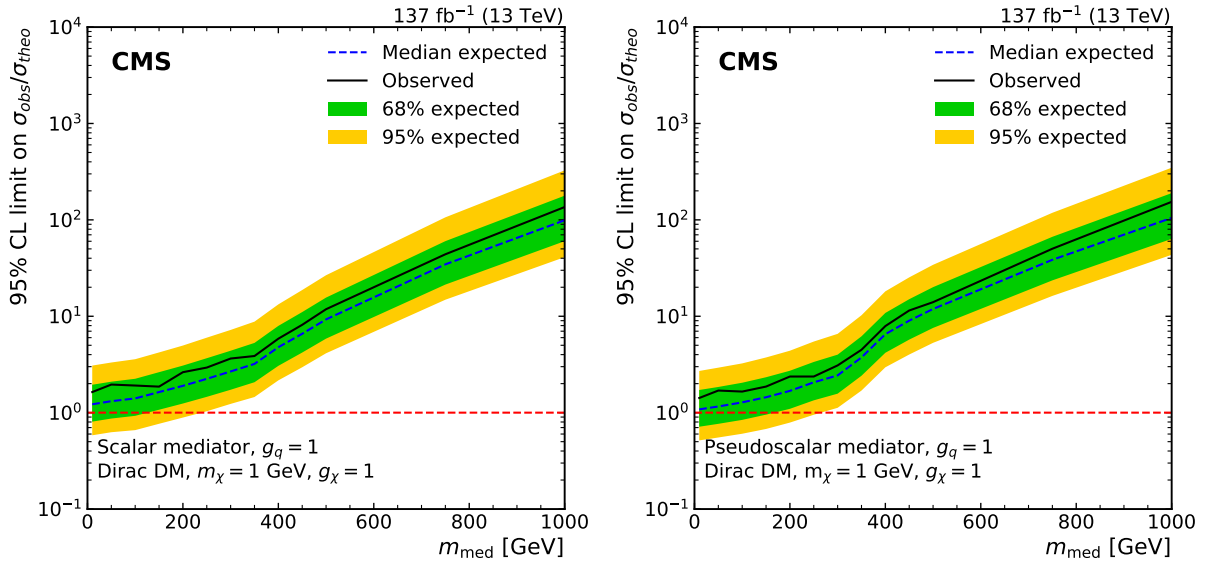


Figure 7.7: The 95% CL upper limits on the cross section for simplified DM with scalar (left) and pseudoscalar (right) mediators. The coupling to quarks is set to $g_q = 1$, the coupling to DM is set to $g_\chi = 1$ and the DM mass is $m_\chi = 1$ GeV.

7.3 Two Higgs doublet model interpretation

For the 2HDM+a model, the signal production is sensitive to the heavy Higgs boson and the pseudoscalar a mass. As discussed in Section 6.4, the m_T distribution is used in the fit rather than p_T^{miss} . The limits on both the heavy Higgs and additional pseudoscalar mediator a are shown in Fig. 7.10. The mixing angles are set to $\tan(\beta) = 1$ and $\sin(\theta) = 0.35$ with a DM mass of $m_\chi = 10$ GeV. The mediator mass with the most sensitivity is $m_H = 1000$ GeV, where the observed (expected)

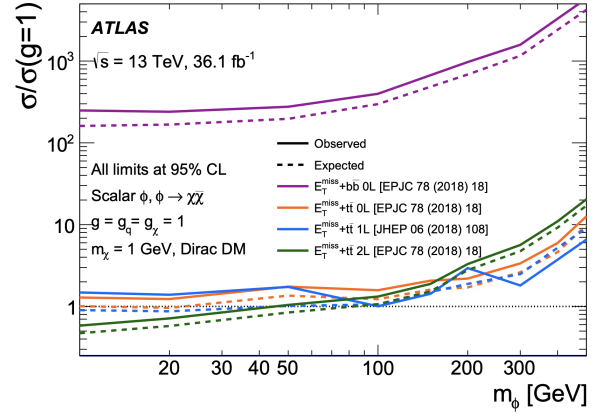
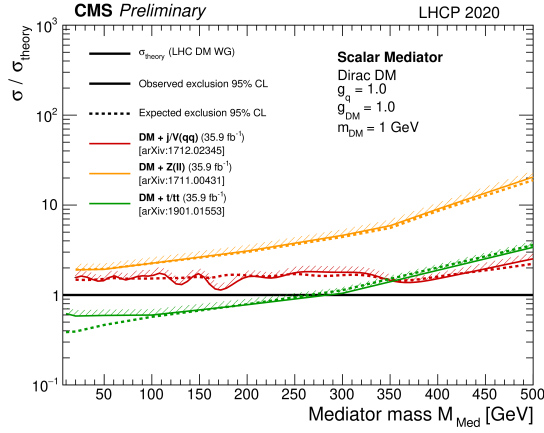


Figure 7.8: Previous results for the scalar mediator showing results from CMS (left) [23] and ATLAS (right) [24]. The coupling to quarks is set to $g_q = 1$, the coupling to DM is set to $g_\chi = 1$ and the DM mass is $m_\chi = 1$ GeV. The limits are shown as a function of the mediator mass.

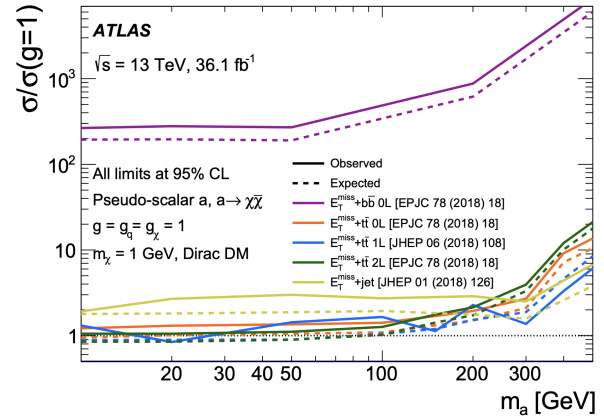
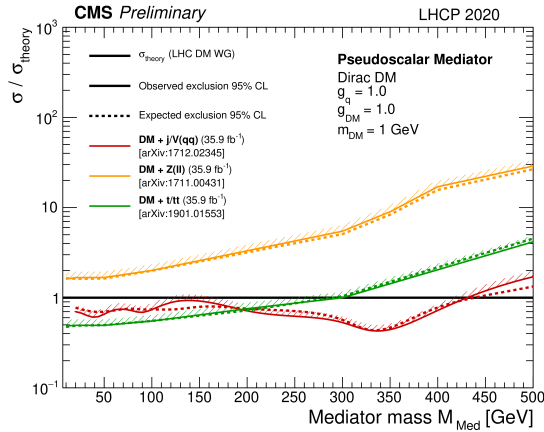


Figure 7.9: Previous results for the pseudoscalar mediator showing results from CMS (left) [23] and ATLAS (right) [24]. The coupling to quarks is set to $g_q = 1$, the coupling to DM is set to $g_\chi = 1$ and the DM mass is $m_\chi = 1$ GeV. The limits are shown as a function of the mediator mass.

limit on m_a is 440 (340) GeV. For small values of m_a , the limit on m_H is about 1200 GeV. Previous CMS results excludes $m_a = 150$ GeV for heavy boson masses between 500 and 900 GeV based on a $\sqrt{s} = 13$ TeV data set corresponding to an integrated luminosity of 36 fb^{-1} [97]. These can be compared with the observed (expected) limits from ATLAS of $m_a > 340(340)$ GeV and $m_H > 1050(1000)$ GeV based on a $\sqrt{s} = 13$ TeV data set corresponding to an integrated luminosity of 36 fb^{-1} [24] as seen in figure 7.11.

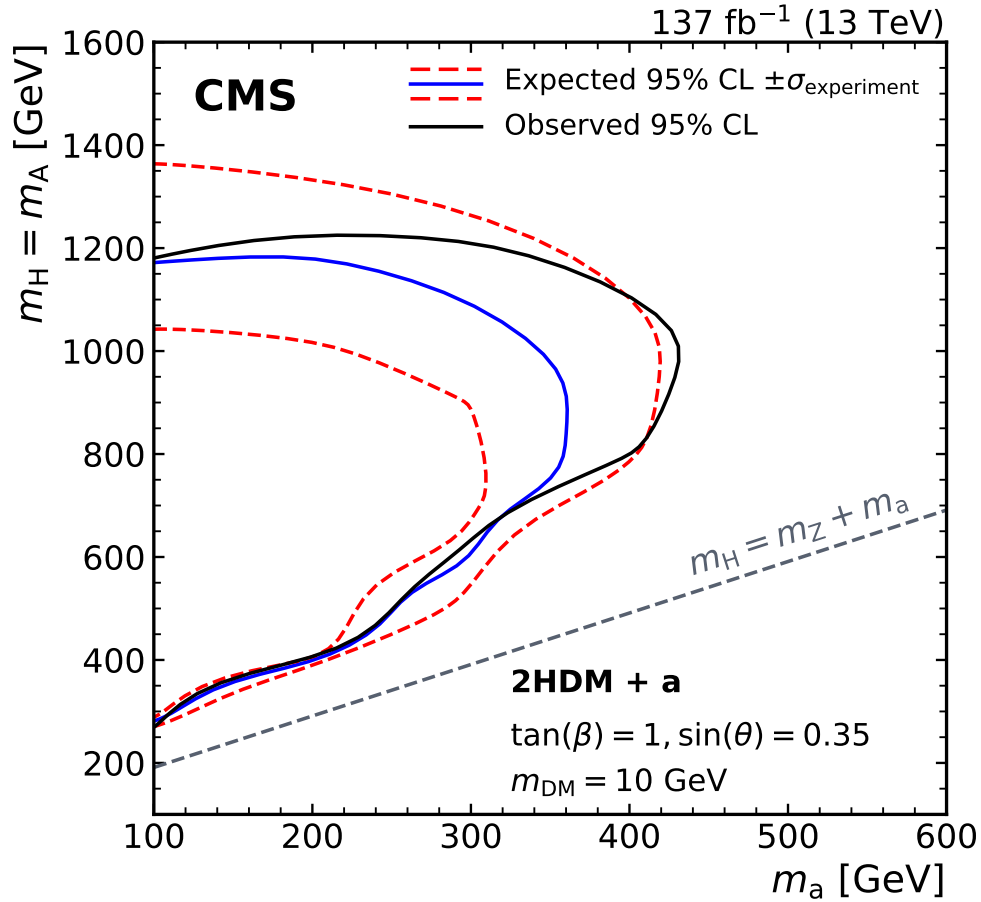


Figure 7.10: The 95% CL upper limits on the 2HDM+a model with the mixing angles set to $\tan(\beta) = 1$ and $\sin(\theta) = 0.35$ and with a DM particle mass of $m_\chi = 10$ GeV. The limits are shown as a function of the heavy Higgs boson and the pseudoscalar masses.

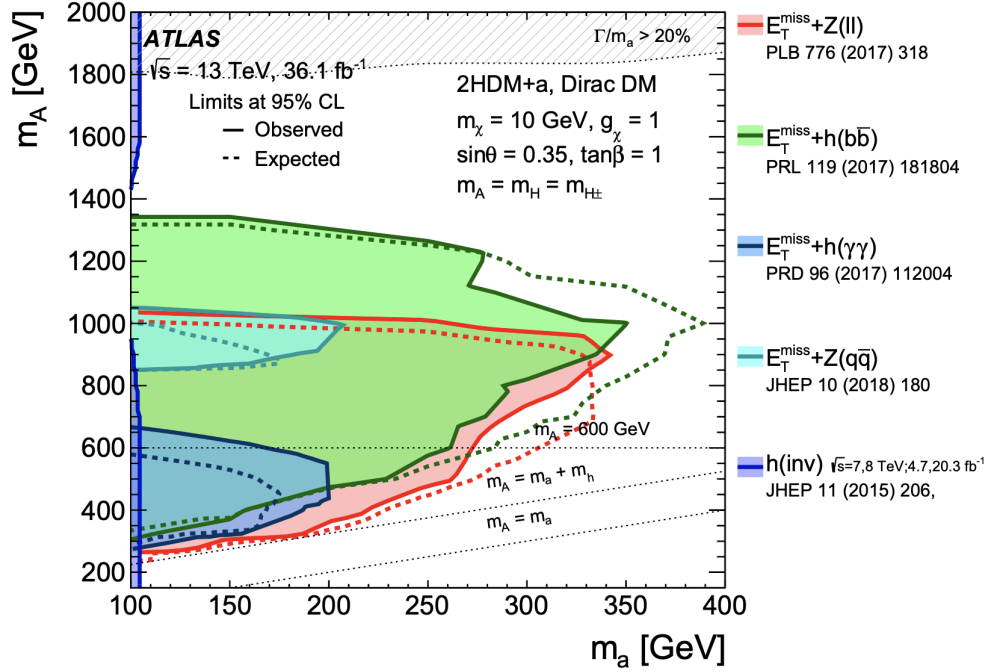


Figure 7.11: The 95% CL upper limits on the 2HDM+a model from the ATLAS experiment. The mixing angles are set to $\tan(\beta) = 1$ and $\sin(\theta) = 0.35$ with a DM particle mass of $m_\chi = 10$ GeV. The limits are shown as a function of the heavy Higgs boson and the pseudoscalar masses.

7.4 Invisible Higgs boson interpretation

For a search for invisible decays of the Higgs boson, we use the p_T^{miss} distribution as input to the fit. We obtain upper limits on the product of the Higgs boson production cross section and branching fraction to invisible particles $\sigma_{Zh}\mathcal{B}(h \rightarrow \text{invisible})$. This can be interpreted as an upper limit on $\mathcal{B}(h \rightarrow \text{invisible})$ by assuming the production rate [217; 178; 218] for a SM Higgs boson at $m_h = 125$ GeV. The observed (expected) 95% CL upper limit at $m_h = 125$ GeV on $\mathcal{B}(h \rightarrow \text{invisible})$ is 29% ($25^{+9}_{-7}\%$) as shown in Fig. 7.12. The observed (expected) limit from the previous CMS result in this channel was $\mathcal{B}(h \rightarrow \text{invisible}) < 45(44)\%$. As seen in figure 7.13, the combinations of all earlier results yields an observed (expected) limit of 19 (15)% from CMS [34] and 26% ($17^{+5}_{-5}\%$) from ATLAS [35].

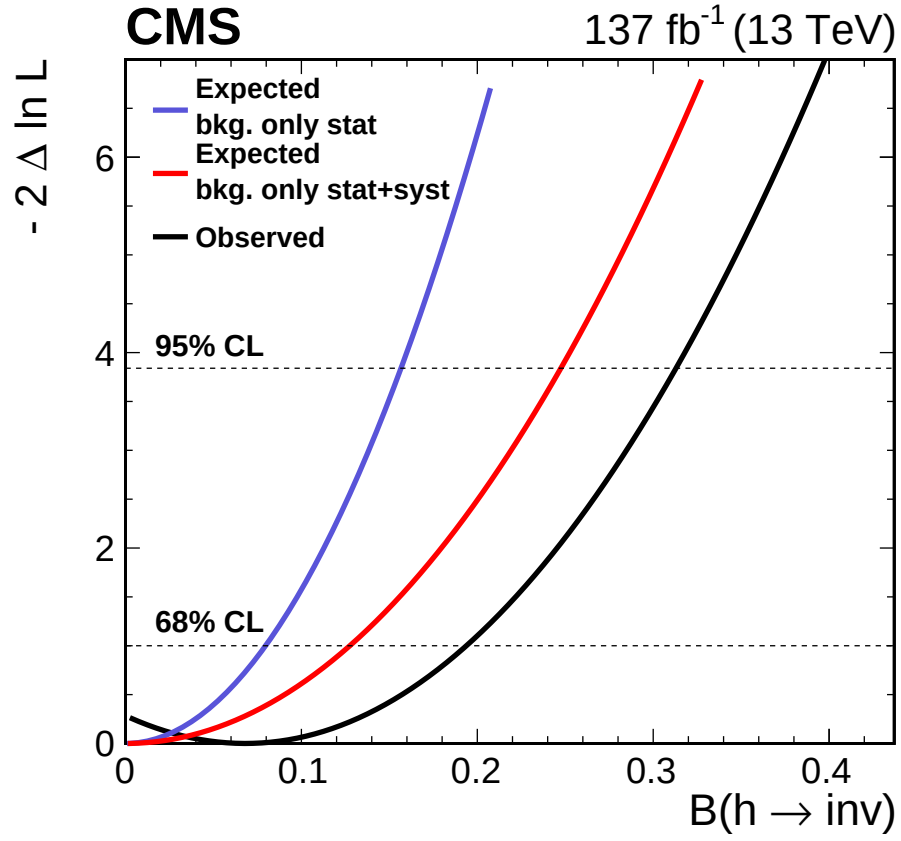


Figure 7.12: Scan of the negative log-likelihood, $-2\Delta\ln\mathcal{L}$, as a function of the branching fraction of the Higgs boson decaying to invisible particles.

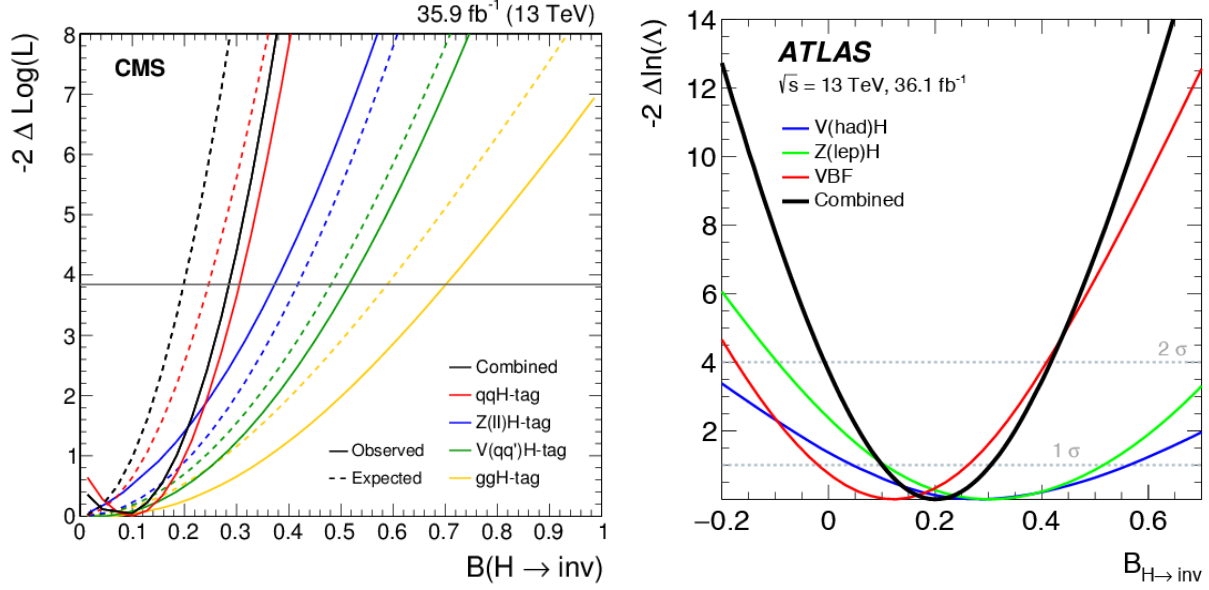


Figure 7.13: Previous combination results showing the scan of the negative log-likelihood as a function of the branching fraction of the Higgs boson decaying to invisible particles for CMS (left) [34] and ATLAS (right) [35].

7.5 The ADD Interpretation

In the framework of the ADD model of extra dimensions, we use the fits to the p_T^{miss} distribution to calculate limits on the number of extra dimensions n and the fundamental Planck scale M_D . The cross section limit calculated as a function of M_D for the case where $n = 2, 3, 4, 6, 7$ is shown in Fig. 7.14. By finding the intersection of the theory cross section with the observed and expected excluded cross sections and projecting that point onto the M_D axis, the limits on M_D as a function of n are shown in Fig. 7.15. The observed (expected) 95% CL exclusion limit on the mass M_D is 2.9–3.0 (2.7–2.8) TeV compared to earlier results of 2.3–2.5 (2.3–2.5) TeV [85].

7.6 Unparticle interpretation

In the unparticle scenario, the same analysis of the p_T^{miss} spectrum is performed. At 95% CL, upper limits are set on the cross section with $\Lambda_U = 15$ TeV. A fixed coupling $\lambda = 1$ is assumed for the

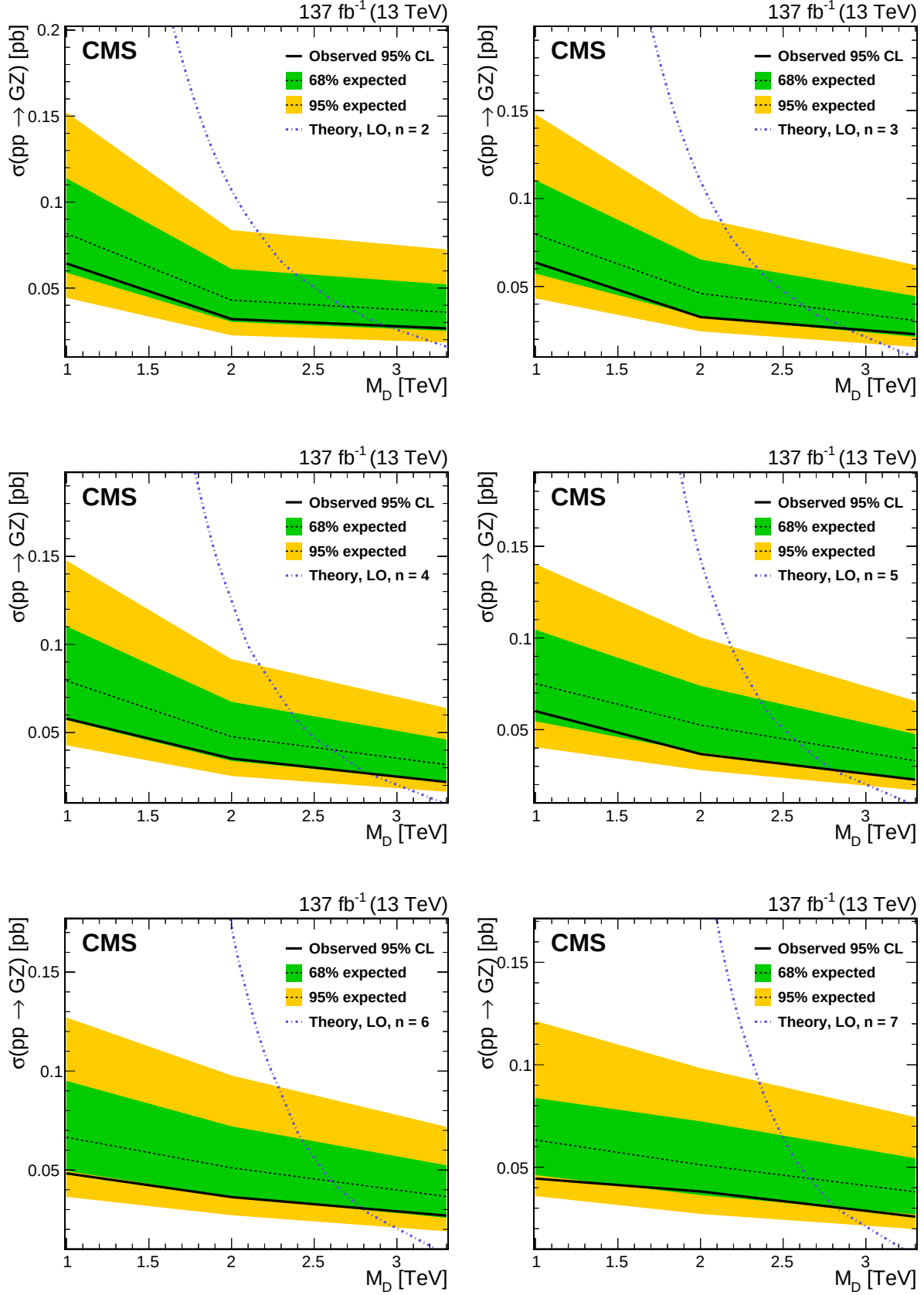


Figure 7.14: The 95% CL cross section limit in the ADD scenario as a function of M_D for $n = 2, 3, 4, 6, 7$.

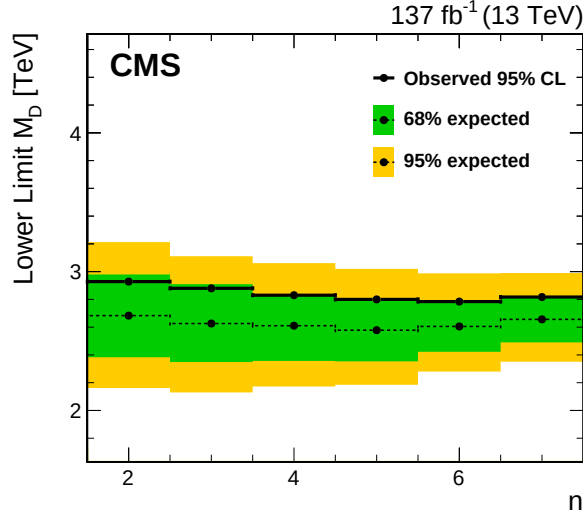


Figure 7.15: The 95% CL expected and observed exclusion limits on M_D as a function of the number of extra dimensions n .

highest sensitivity. The limits are shown in Fig. 7.16 as a function of the scaling dimension d_U . The observed (expected) limits are 0.5 (0.7) pb, 0.24 (0.26) pb, and 0.09 (0.07) pb for $d_U = 1$, $d_U = 1.5$, and $d_U = 2$ respectively, compared to 1.0 (1.0) pb, 0.4 (0.4) pb, and 0.15 (0.15) pb for the earlier result [85]. These limits depend on the choice of λ and Λ_U , as the cross section scales with the Wilson coefficient λ/Λ_U [118].

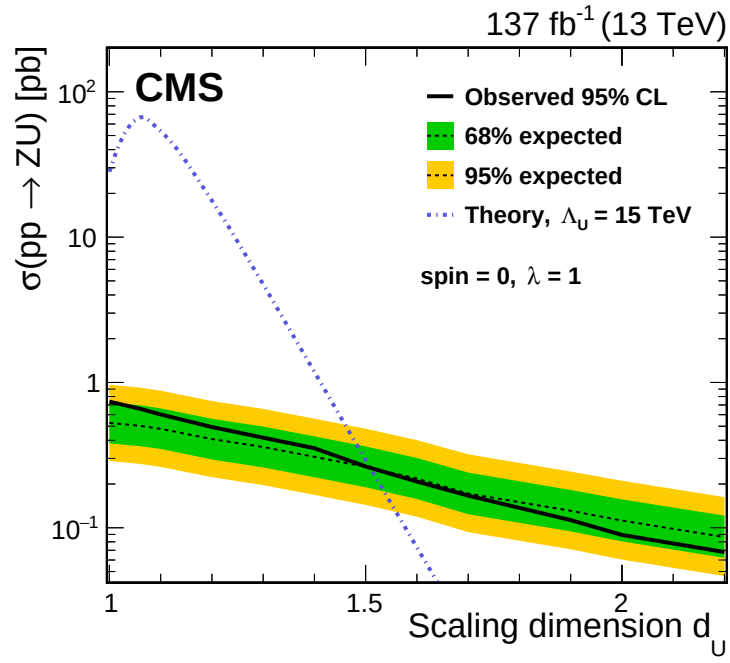


Figure 7.16: The 95% CL upper limits on unparticle+ Z production cross section, as a function of the scaling dimension d_U . These limits apply to fixed values of the effective cutoff scale $\Lambda_U = 15$ TeV and coupling $\lambda = 1$.

Chapter 8

Summary

Table 8.1 gives a summary of the limits expected and observed for a selection of relevant parameters in all of the models considered.

Events with a Z boson recoiling against missing transverse momentum in proton-proton collisions at the LHC are used to search for physics beyond the standard model. The results are interpreted in the context of several different models of the coupling mechanism between dark matter and ordinary matter: simplified models of dark matter with vector, axial-vector, scalar, and pseudoscalar mediators; invisible decays of a 125 GeV scalar Higgs boson; and a two-Higgs-doublet model with an extra pseudoscalar. Outside the context of dark matter, models that invoke large extra dimensions or propose the production of unparticles could contribute to the same signature and are also considered. The observed limits on the production cross sections are used to constrain parameters of each of these models. The search utilizes a data set collected by the CMS experiment in 2016–2018, corresponding to an integrated luminosity of 137 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$. No evidence of physics beyond the standard model is observed. Table 8.1 gives a summary of the limits expected and observed for a selection of relevant parameters in all of the models considered. Comparing to the previous results in this channel based on a partial data sample collected at $\sqrt{s} = 13 \text{ TeV}$ in 2016, corresponding to an integrated luminosity of approximately 36 fb^{-1} for CMS [85] and for ATLAS [86], the exclusion limits for simplified dark matter mediators, gravitons and unparticles are significantly extended. For the case of a 125 GeV scalar boson, an upper limit of 29% is set for the branching fraction to fully invisible decays at 95% confidence level. Results

Table 8.1: Observed and expected 95% CL limits on parameters for the simplified DM models, invisible decays of the Higgs boson, two-Higgs-doublet model, large extra dimensions in the ADD scenario, and unparticle model. For the scalar and pseudoscalar mediators, the limits are dependent on the mediator mass, so the lowest values for the ratio of observed to theoretical cross sections are presented. For the vector and axial-vector mediators, the limits are dependent on the DM particle mass, so the limits are shown for $m_\chi < 300$ GeV for the vector mediator and $m_\chi = 240$ GeV for the axial-vector mediator.

Model	Parameter	Observed	Expected
DM - vector $g_\chi = 1$ $g_q = 0.25$	m_{med}	870 GeV	870 GeV
DM - axial-vector $g_\chi = 1$ $g_q = 0.25$	m_{med}	800 GeV	800 GeV
DM - scalar $g_\chi = 1$ $g_q = 1$ $m_\chi = 1$ GeV	$\sigma_{\text{obs}}/\sigma_{\text{theo}}$	1.8	1.5
DM - pseudoscalar $g_\chi = 1$ $g_q = 1$ $m_\chi = 1$ GeV	$\sigma_{\text{obs}}/\sigma_{\text{theo}}$	1.8	1.4
2HDM+a $\tan(\beta) = 1$ $m_\chi = 1$ GeV $\sin(\theta) = 0.35$ $m_H = m_A = 1$ TeV	m_a	330 GeV	440 GeV
2HDM+a $\tan(\beta) = 1$ $m_\chi = 1$ GeV $\sin(\theta) = 0.35$ $m_a = 100$ GeV	m_H	1200 GeV	1200 GeV
Invisible Higgs boson	$\mathcal{B}(h \rightarrow \text{invisible})$	0.29	0.25
ADD $n = 2-7$	M_D	2.8–2.9 TeV	2.6–2.7 TeV
Unparticles Scaling dimension $d_U=1.5$	σ	0.26 pb	0.24 pb

for the two-Higgs-doublet model with an additional pseudoscalar are presented in this final state and probe masses of the pseudoscalar mediator up to 440 GeV and of the heavy Higgs boson up to 1200 GeV when the other model parameters are set to specific benchmark values.

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APPENDIX A

Phase-2 Upgrades to the Level-1 Trigger

The LHC will remain the most powerful particle accelerator in the world for the next several decades. As such, its full exploitation is integral to the advancement of particle physics as a whole. Part of this exploitation is the extension of the LHC's discovery potential by increasing the luminosity beyond its original design values [219]. In order to attain the increased collision rate required to achieve this increased luminosity the LHC requires major upgrades by the early 2020s as shown in Figure A.1.

Continuing to efficiently collect information-rich datasets will be a challenging task, given the harsh pileup environment of 200 proton-proton interactions per LHC bunch crossing. In order to continue to provide datasets with statistical power matching the high luminosity provided by the Phase-2 upgrade of the LHC, the trigger systems used at the Compact Muon Solenoid (CMS) experiment [220] will need to be upgraded.

The current CMS trigger comprises of two levels; the Level 1 (L1) trigger and the High-Level trigger (HLT) [221]. The L1 trigger is composed of custom hardware processors that receive data from calorimeter and muon systems generating a trigger signal in approximately $3.8 \mu\text{s}$ with a maximum rate of 100 kHz while the HLT is a software based trigger further reducing the rate to approximately 1 kHz. This two-level strategy will remain through Phase-2, however, the trigger and Data Acquisition (DAQ) systems will be replaced with the goal of increasing the physics reach

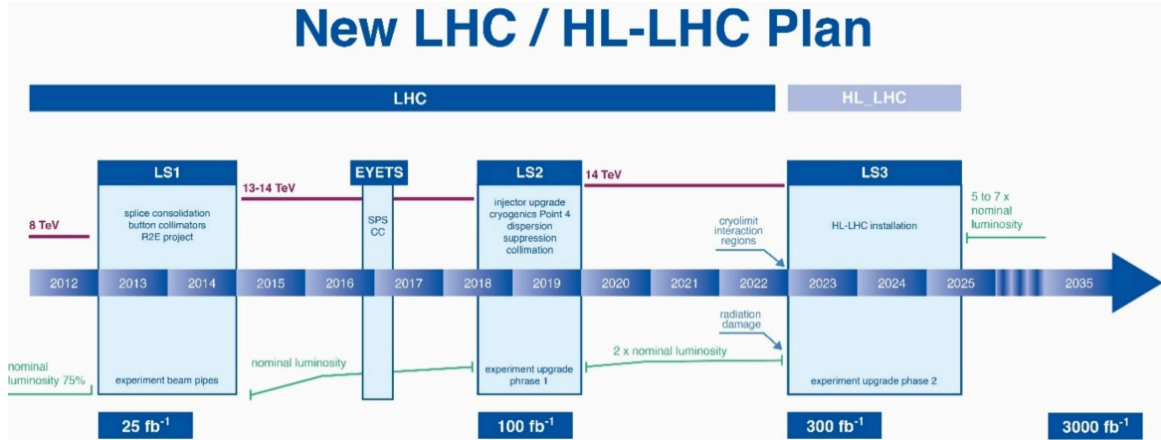


Figure A.1: Schedule of the Phase-2 upgrade for the HL-LHC.

by expanding the physics menu to a maximum L1 trigger rate of 750 kHz (~ 7.5 kHz HLT rate). Additionally, the L1 trigger will incorporate tracking information and high-granularity calorimeter (HGCal) information [222] increasing the latency to $12.5 \mu\text{s}$ (or 500 LHC bunch crossings). An overview of the Phase-2 trigger system is shown in Figure A.2.

A.1 Tracker

A major new functionality of the trigger for the HL-LHC is the inclusion of the Outer Tracker in the L1 trigger at a 40 MHz rate. The raw data rate of data from the tracker is enormous but has been reduced by a two step process designed to reduce the data rate caused by soft p_T tracks. The first step is a rough local p_T measurement using individual p_T modules [223]. For each hit in the inner layer of a module, a window corresponding to a high momentum track is opened in the outer layer. If a hit is found within this window, a stub containing the position and a rough p_T estimation is generated. After the stubs have been generated, tracks are then created from multiple modules giving a more precise p_T estimation.

The addition of tracking information ($|\eta| < 2.4$) allows for numerous improvements to the L1 system, such as the ability to add vertex information as well as upgrades to several L1 algorithms. In order to attain these improvements, full track reconstruction is required. At pileup of 200, approximately 15,000 stubs will be sent to the Track Finder (TF) Trigger Primitive Generator (TPG). The TF must be able to reconstruct tracks within approximately $5 \mu\text{s}$ including $1 \mu\text{s}$ for transmission from the front-end boards. An average of 200 tracks will then be sent to the L1 trigger Correlator Trigger (CT) where trigger objects must be reconstructed and received by the Global Trigger (GT) in another $2.5 \mu\text{s}$. A Level 1 Accept (L1A) is sent back and received by the front-end boards in a further $2 \mu\text{s}$. The target L1 latencies are summarized in Table A.1 with a total target L1 latency of $9.5 \mu\text{s}$, well below the design capacity of $12.5 \mu\text{s}$.

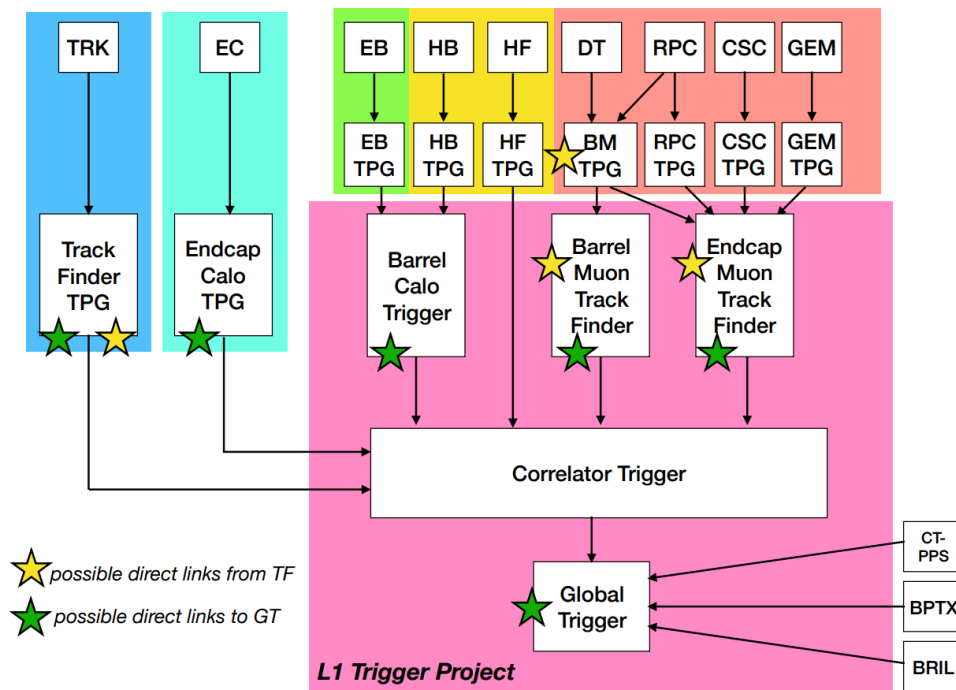


Figure A.2: High-level view of the Phase-2 L1 trigger. The main data flow is shown with solid lines. Shown in the diagram are the Outer Tracking Detector (TRK), the Endcap Calorimeter (EC) System, the ECAL Barrel (EB), the HCAL Barrel (HB), the HCAL Forward Detector (HF), the Muon Drift Tube Detectors (DT), the Resistive Plate Chambers (RPC), the Cathode Strip Chambers (CSC), the Gas Electron Multiplier Chambers (GEM). All muon systems are denoted in orange and feed into region specific muon track finders.

Processing Step	Time (μs)
Input data received by CT	5
Trigger objects received by GT	7.5
L1A received by front-ends	9.5

Table A.1: Targets for L1 Latency.

A.2 Calorimeters

In order to meet the increased trigger latency and rate requirements of the Phase-2 upgrade, several of the calorimeter front-end boards, and in some cases, scintillators will need to be upgraded or replaced. This section describes these changes as well as the replacement of the endcap calorimeters with the HGAL.

The Phase-1 ECAL Barrel (EB) TPG is located on-detector and produces trigger tower sums using 5 X 5 arrays of crystals. Phase-2 will move the EB TPG to back-end electronics. With this migration off-detector, the baseline EB TP will include a single crystal primitive word greatly increasing the spatial resolution with an option for a cluster primitive word. In either case, the EB TPG will continue to include calibration information, as well as digital filtering of input pulses to calculate the transverse energy (E_T) and timing information.

The Phase-2 upgrade of the HCAL Barrel (HB) calorimeter replaces the back-end electronics. Additionally, Phase-2 TPs will include depth information from the HCAL[224]. The Phase-2 HB TPG electronics will use the same hardware that is being developed for the EB.

The hadronic forward (HF) detector will continue operation with Phase-1 front-end and back-end electronics. However, in its current configuration the back-end electronics cannot sustain the

necessary rate. As such, the replaced back-end boards from the HB will be used in conjunction with the HF back-ends to augment the existing back-end system. This addition will allow the system to maintain the target L1 thresholds while maintaining the same HF TP definition as was used in Phase-1.

For Phase-2, the endcap calorimeter (EC) will be replaced by the new HGICAL [225]. The HGICAL is a sampling calorimeter using both silicon and scintillator technology for detection. In total there are 28 layers in the electromagnetic section and 24 layers in the hadronic section for a total of 52 layers per endcap. Due to the important bandwidth expected from the detector, only half of electromagnetic layers will be used, however, performance of precise matching between clusters and tracks is maintained.

The Endcap Calorimeter TPG (ECT) is processed in two stages for the HGICAL. The first stage will form two-dimensional (2D) clusters for each layer of HGICAL by summing tower data into a single grid in ϕ and η . The second stage of reconstruction is to form three-dimensional (3D) clusters from multiple layers associating the trigger cell to the closest seed. There is a large amount of data associated with these 3D clusters but the rate can be significantly reduced with simple E_T cuts as shown in Figure A.3

A.3 L1 Electron and Photon algorithms

Electron and Photon trigger algorithms use data from both electromagnetic and hadronic calorimeters as well as tracking detectors. The rate and efficiency projections for HL-LHC conditions are shown in Figure A.4 for the barrel region. With single crystal granularity projected at Phase-2, the efficiency is near 100 while the rate is also decreased compared to the Phase-1 algorithm. Additionally, with the addition of the tracker information at L1, electron and photon triggers can be

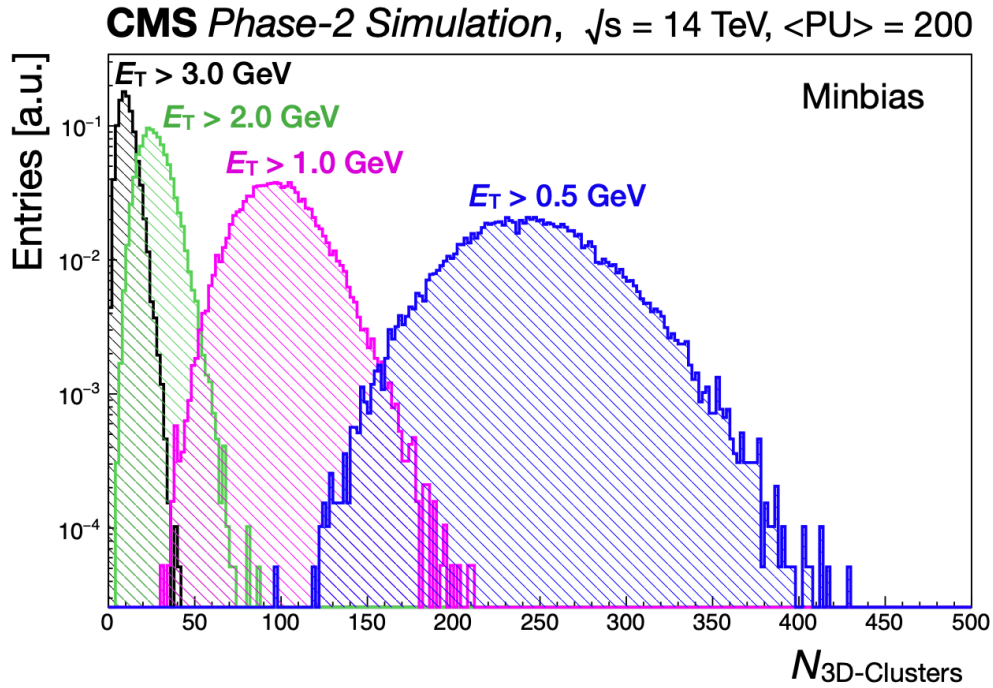


Figure A.3: The number of reconstructed 3D clusters per endcap for simulated $t\bar{t}$ events with 200 pileup.

separated for the trigger. Projections for these electron and photon specific triggers are shown in Figure A.4.

A.4 Muon Upgrades

Similarly to the calorimeter systems, the muon systems in the forward region need to be augmented in order to handle the increased rate and latency required for Phase-2. For the barrel region, in addition to a planned upgrade of the back-end electronics, there has been significant progress on trigger algorithms that have sensitivity to displaced particles. This section describes the upgrades to the endcap region as well as the work being done on increasing the physics sensitivity to long-lived

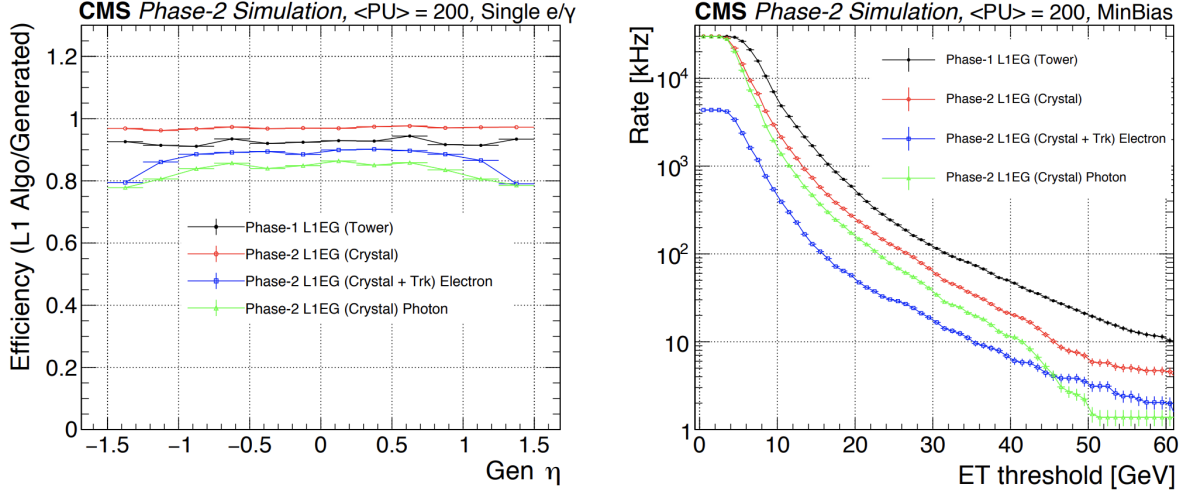


Figure A.4: (Left) Expected efficiency of the single electron trigger for the barrel region: calorimeter only, calorimeter photon tuned trigger, and calorimeter matched to the track, compared to the current trigger efficiency as a function of simulated η of the electrons/photons for a trigger threshold of 20 GeV. (Right) Expected rate for minimum-bias events using the single electron calorimeter trigger (for the barrel region only) as a function of trigger threshold.

particles.

The main change for the endcap region will be the addition of several new detectors to help mitigate the pileup effects expected in this region. The current endcap muon system comprises Cathode strip chambers (CSC) and Resistive Plate Chambers (RPC). By the time of HL-LHC, three additional muon systems will be added; Gas Electron Multiplier (GEM), improved RPC (iRPC) and an additional station (ME0) based on the GEM technology [226]. These additions extend the coverage of the muon system to higher values of η ($|\eta| < 2.8$) as well as extra redundancy to mitigate pileup effects. In particular the combination of GEMs and CSCs in the inner station provides greatly increased resolution in the bend angle due to the longer lever arm. The geometry of the system can be seen in Figure A.5 while the efficiency and rate with the additional detectors can be seen in Figure A.6.

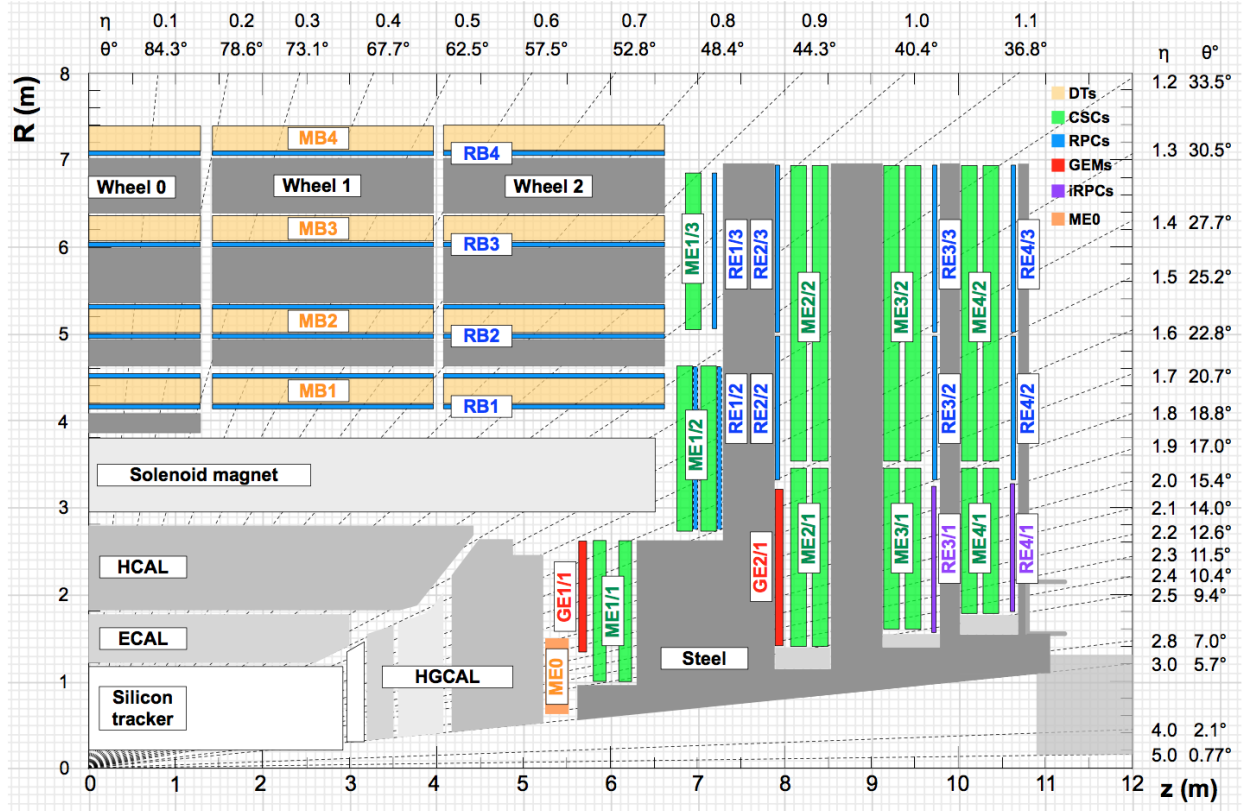


Figure A.5: A cross section of a quadrant of the CMS detector, including the Phase-2 upgrades (RE3/1, RE4/1, GE1/1, GE2/1, ME0). The interaction point is at the lower left corner while the magnet yoke is shaded dark grey. The locations of the various muon stations are shown in color (MB = Drift Tubes, ME = CSC, RB and RE = RPC, GE and ME0= GEM).

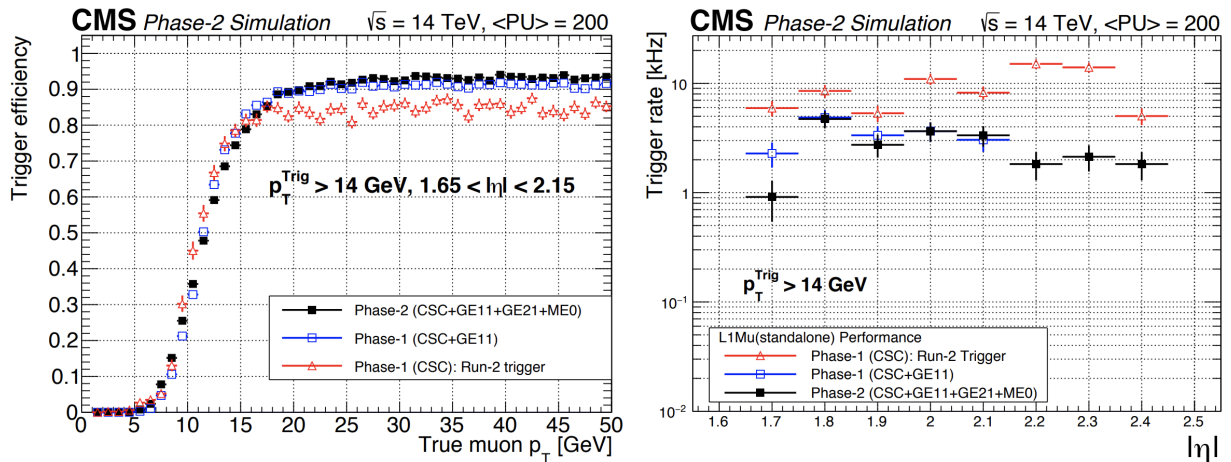


Figure A.6: The rate and efficiency comparisons between Phase-1 and Phase-2.

A.5 Displaced Particle Trigger Algorithms

Significant effort has been placed on expanding the physics capabilities of the trigger system. Part of this effort has been the development of triggers that are sensitive to displaced particles. The first of these algorithms is the Kalman filter that was fully commissioned in late 2018 for the barrel region. In the Kalman filter algorithm, muon tracks are built from the outer station inwards. This method has shown similar efficiencies and rates as the traditional Phase-1 algorithm but does not constrain the interaction point. The unconstrained vertex greatly increases the efficiency as a function of the transverse impact parameter used in many long-lived searches.

Some theoretical models predict the existence of Heavy Stable Charged Particles (HSCP). These slow moving particles can be identified using time-of-flight measurements from RPC chambers. Phase-2 upgrades of the RPC back-end electronics will increase the timing resolution of hits to approximately 1.5 ns to the L1 trigger. This in conjunction with the extended coverage of RPCs in the endcap to $|\eta| < 2.4$ allows for dedicated HSCP triggers at the L1 level.

A.6 Summary and L1 Menu

Developing in parallel to the implementation of the upgrades listed above is the design of the Phase-2 L1 Menu. For the menu, two scenarios of 140 and 200 pileup are assumed. A simplified menu consisting of 20 major trigger paths that encapsulate the main trigger objects used in physics analyses is considered. The menu shown in Figure A.7 covers approximately 70% of the total L1 Rate that would be needed for a fully operational menu.

Of particular note is the consistency of thresholds between Phase-1 and Phase-2 triggers. Here, the increased rate and pileup at HL-LHC are offset by the upgrades planned for Phase-2, particularly the inclusion of the tracker. With the addition of tracking information at the L1 trigger, L1

$L = 5.6 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}, \langle PU \rangle = 140$ $L = 8.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}, \langle PU \rangle = 200$		L1 trigger with L1 tracks	
Trigger algorithm	Rate [kHz]		Offline threshold(s) [GeV]
$\langle PU \rangle$	140	200	
Single Mu (tk)	14	27	18
Double Mu (tk)	1.1	1.2	14 10
Ele* (iso tk) + Mu (tk)	0.7	0.2	19 10.5
Single Ele* (tk)	16	38	31
Single iso Ele* (tk)	13	27	27
Single γ^* (tk-iso)	31	19	31
Ele* (iso tk) + e/ γ^*	11	7.3	22 16
Double γ^* (tk-iso)	17	5	22 16
Single Tau (tk)	13	38	88
Tau (tk) + Tau	32	55	56 56
Ele* (iso tk) + Tau	7.4	23	19 50
Tau (tk) + Mu (tk)	5.4	6	45 14
Single Jet	42	69	173
Double Jet (tk)	26	43	2@136
Quad Jet (tk)	12	45	4@72
Single ele* (tk) + Jet	15	15	23 66
Single Mu (tk) + Jet	8.8	12	16 66
Single ele* (tk) + H_T^{miss} (tk)	10	45	23 95
Single Mu (tk) + H_T^{miss} (tk)	2.7	8	16 95
H_T (tk)	13	24	350
Rate for above triggers*	180	305	
Est. rate (full EG eta range)		390	
Est. total L1 menu rate ($\times 1.3$)	260	500	

Figure A.7: Simplified L1 Trigger Menu for Phase-2. Rates are shown for two separate pileup conditions of 140 and 200 with an extra factor of 1.3 for projections to a fully operational L1 Menu. Triggers associated with tracker tracks will be denoted with (tk), triggers isolated away from tracker tracks will be denoted with (tk-iso) while triggers isolated with a track are denoted by (iso tk).

Phase-2 algorithms can be made to more closely match algorithms running in the software of the HLT. By combining the complete detector information together (tracking matched to calorimeter and/or muon information), a list of individually reconstructed particle candidates can be created using the CMS particle flow (PF) algorithm [227] significantly increasing the overall CMS trigger performance. This increase in performance corresponds to consistent thresholds for several triggers, in particular the Muon and EGamma triggers, as well as the capability to create future triggers to expand the physics coverage of the L1 Menu.