CHAPTER 1

INTRODUCTION

The goal of this analysis is to search for new physics impacting associated top production in multi-lepton final states, using the framework of effective field theory (EFT) to parametrize the potential new physics effects.

While there are many compelling indications that the standard model (SM) of particle physics does not provide a complete description of nature (e.g. the strong evidence for dark matter [7, 8] and dark energy [9]), there is no a priori reason to assume new particles must exist in the energy range that is directly accessible at the LHC. If new physics particles are too heavy to be produced on-shell at the LHC, it may not be possible to identify their signatures with a direct search. However, an approach that indirectly probes higher energy scales may be able to discover these particles via their off-shell effects. The center of mass energy for collisions at the LCH will not significantly increase throughout its remaining years of operation, so indirect approaches may provide an exciting opportunity to extend the discovery reach of the LHC. EFT is an example of such an indirect probe; as a flexible method of systematically describing the off-shell effects of heavy new particles, EFT represents an important part of the search for new physics at the energy frontier.

In general, an effective theory is an approximation, valid under a certain energy range, for a more fundamental underlying theory. In SM effective field theory (SM EFT), the SM is treated as the lowest order term in an expansion of higher dimensional operators; the operators are constructed from products of SM fields that obey the symmetries of the SM. The EFT operators describe new physics interactions at a mass scale Λ. The strengths of the new physics interactions are described by dimensionless parameters known as Wilson Coefficients (WCs). The EFT Lagrangian can thus be expressed as follows:

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^5}{\Lambda} \mathcal{O}_i^5 + \sum_i \frac{c_i^6}{\Lambda^2} \mathcal{O}_i^6 + ..., \tag{1.1}$$

where $\mathcal{L}_{\mathrm{SM}}$ is the SM Lagrangian, $\mathcal{O}_i^d$ are the EFT operators of dimension d, and c_i^d are the WCs for the operators of dimension d. Since each order in the expansion is scaled by an additional power of Λ, the terms in the lowest orders are expected to contribute the most significantly. This analysis therefore focuses on dimension-six operators, as these are the lowest order terms that contribute. The EFT framework will be discussed in more detail in Section 2.2.

While many analyses target a specific signature predicted by a particular new physics model, the EFT approach is more general. Assuming that the SM Lagrangian is the correct and complete description of all physics that is light enough to be probed directly with current experimental capabilities, the EFT Lagrangian provides a systematic description of the off-shell effects of heavy new physics scenarios, allowing for a consistent method of describing these effects across multiple sectors. EFT is thus a complementary approach to dedicated searches; if the off-shell effects of new physics manifest in a variety of signatures across many final states, a global EFT approach may be capable of identifying a statistically significant observation of the combination of effects, even if the effects are not significant when studied individually.

Although the ultimate goal of the EFT paradigm would be a global combination across all sectors of study at the LHC, the first step towards this goal is to begin performing EFT analyses within individual sectors. The analysis described in this thesis focuses on the top sector, targeting processes in which top quarks are produced in association with additional charged leptons. In the SM, these signatures are primarily produced by $t(\bar{t})X$ processes, where the X is a H, W, or Z boson. We refer to these processes as associated top production. Involving multiple heavy particles, the processes are relatively rare, and we are just now reaching the point where we have accumulated enough statistics to study these processes in detail; for these reasons, associated top processes may be an interesting venue in which to stage a search for new physics. In accordance with the global mindset of the EFT approach, this analysis aims to study all dimension-six EFT operators (involving top quarks) that can significantly impact associated top production processes.

The full set of associated top processes studied in this analysis is $t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$, tHq, and $t\bar{t}t\bar{t}$. These processes give rise to a variety of final state signatures; in this analysis, we choose to focus on signatures involving multiple charged leptons. Referred to as multilepton final states, these signatures contain 2 leptons of the same charge or contain 3 or more leptons. Multilepton final states have relatively few backgrounds, clean detector signatures, and efficient triggers. In spite of these experimental benefits, a multilepton EFT analysis also gives rise to several challenges. These challenges primarily stem from the fact that many different processes and effects are capable of contributing to the same final state multilepton signatures. For example, if we consider a final state with two leptons of the same charge, we would expect contributions from both SM $t\bar{t}W$ and SM $t\bar{t}H$ production (as well as a contribution from SM $t\bar{t}Z$ when one of the leptons is lost). Many different dimension-six EFT operators can impact these processes, interfering with each other and with the SM, making this final state a complicated admixture of processes and effects. Other multilepton final states will contain similarly complex admixtures of processes and EFT effects.

Because these effects cannot be isolated from each other, it is important to analyze the effects of all relevant operators across all channels simultaneously. For this reason, it would be difficult to construct this EFT analysis as a reinterpretation of inclusive or differential cross section measurements. Instead, we make use of an approach that directly targets the EFT effects at detector level. First developed in Ref. [10], the key idea of this approach is the parameterization of the predicted yields in terms of the WCs. The procedure through which we obtain this parametrization will be detailed in Section 3.2.2.

Making use of more than three times as much data as was available for [10], the analysis described in this thesis builds on the techniques and tools developed in [10], improving on [10] in several key ways. Since [10] was performed with limited statistics, only inclusive categories defined by the multiplicity of final state objects were studied. With the increased statistics, this analysis leverages differential kinematic distributions within each inclusive bin, allowing additional sensitivity to be gained. An additional signal process ($\mathrm{t\bar{t}t\bar{t}}$) and 10 more dimension-six EFT operators are also included, brining the total number of WCs to 26. These improvements allow more comprehensive limits to be placed on the WCs, resulting in a better understanding of the possibility of heavy new physics effects in the top sector.

The chapters of this thesis are organized in the following order. In Chapter 2, the theoretical concepts of the SM and of the EFT framework are discussed. Chapter 3 describes the simulated samples used in the analysis (including a discussion of the EFT parametrization of the signal samples). In Chapter 4, the CMS detector is described, and Chapter 5 explains how the particle reconstruction is performed. The event selection is detailed in Chapter 6. Chapter 7 describes the data to Monte Carlo corrections for simulated events. The backgrounds for this analysis are discussed in Chapter 8. Chapter 9 enumerates the systematic uncertainties of the analysis. The statistical tools used to extract the confidence intervals for the WCs are explained in Chapter 10. Chapter 11 presents the results of the analysis. A summary is provided in Chapter 12.