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LHC Effective Field Theory Working Group [a]

Internal Note

LHC EFT WG Report in Area 3: Experimental Measurements and Observables

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Abstract

In this note we discuss how observables relate to operators, which measurements are important for a given operator or set of operators, differential/fiducial measurements vs. dedicated ones, identification of optimal observables, machine learning, re-interpretation vs. static. We also discuss presentation of results, such as reporting covariance, multi-D likelihood, etc., compatibility with global fits, including assumptions used in deriving measurement and reporting results.

Contents

Chapter 1

Introduction

Within the LHC EFT Working Group, we have identified the so-called Area-3 of the WG activities devoted to experimental measurements and observables. Here we relate EFT operators, defined in Area-1 and modeled in Area-2, to experimentally observable effects. Therefore, we survey the sensitive channels, or physical processes, and the corresponding operators. Once this connection is established, we examine strategies of experimental analysis of the LHC data using the sensitive channels, and determine experimental outputs, or measurements. These measurements become the input to the global EFT fits, further considered in Area-4 of the WG activities.

This note serves as a guide to experimental measurements leading to EFT fits, but does not establish authoritative guidelines how those measurements should be performed. There is a spectrum of experimental approaches, covering differential distributions, optimal observables, including machine learning, dedicated EFT measurements, spin density matrices, EFT-optimized fiducial regions, amplitude analyses, angular distributions, pseudo observables, etc. Each approach has its own stronger and weaker sides, and none of the approaches has been established as the universally best approach to perform the measurements. Therefore, one of the goals of this note is to survey these approaches and identify their key features.

In order to discuss experimental approaches, we will use the following notation. We will denote a *channel* to be a process used to perform a measurement, for example production of a top-antitop pair in association with the Higgs boson $t\bar{t}H$ in pp collisions at the LHC. We will denote an *observable* to be an experimentally defined quantity in such a process, for example transverse momentum of the Higgs boson p_T^H. We will denote a *measurement* to be an experimentally delivered quantitative result, for example differential cross section in bins of p_T^H in the $t\bar{t}H$ process. Experimental *measurements* using the *observables* sensitive to EFT effects in a given set of *channels* at the LHC become the input to EFT fits which would set constraints on the EFT operators.

Chapter 2

Survey of the sensitive channels and corresponding operators

One of the goals of this activity area on Experimental Measurements and Observables is to survey which experimental channels are sensitive to which EFT operators. We aim to establish a map between observables and operators. As a first step we want to determine which operators are relevant and as a second step to examine the amount of information that each process can provide for a given operator, given the accuracy of any given experimental process. The second step can be achieved by considering some appropriate metric such as the Fisher information.

A valuable source of information in this endeavour are the global fits which exist in the literature. The set of operators relevant for each fit is determined by the processes included in the fit as well as the choice of flavour assumption which determines the relevant degrees of freedom. As an example we show a schematic representation of the datasets and their overlapping dependences on the 34 Wilson coefficients included in the global Higgs, top, diboson and EWPO analysis of Ref. [?]. The relevant operators form part of the Warsaw basis, with the ones involving the top quark following the conventions set in the Top Working Group EFT note. We note that such a simple representation can be further refined by considering different channels in each sector, e.g. examining each production and decay channel of the Higgs separately etc

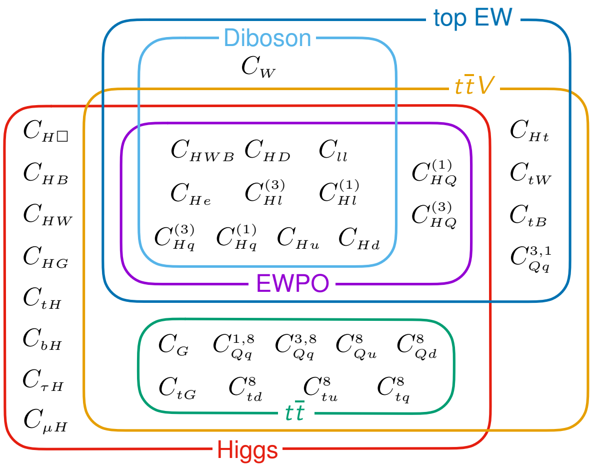

Figure 2.1: Schematic representation of the datasets and their overlapping dependences on the 34 Wilson coefficients included in the analysis of Ref. [?]

Chapter 3

Survey of experimental observables and corresponding measurements

Here we survey experimental observables and corresponding measurements in the channels discussed in Chapter 2.

3.1 Experimental observables

The chain of analysis of experimental data is involved and starts with the raw signals in the detector. However, in this note we focus on observable effects sensitive to deviations from the SM due to contributions of EFT operators. Therefore, we focus only on the high-level quantities typically appearing in the final stages of experimental analysis. We group observables sensitive to EFT effects in three categories, without necessarily clear boundaries between those:

- Usual SM observables, such as invariant masses, transverse momenta p_T of reconstructed objets, etc...
- EFT-sensitive observables: angular information, q^2 quantities of the propagators, etc..
- Optimized observables: matrix-element-based calculations, machine learning, special construction, etc..

We note that even if shapes of certain observables may not be sensitive to EFT effects, the rates detected with such observables would still provide such sensitivity, which is certainly the case for the typical SM observables.

The choice of observables in experimental analysis depends on many factors. Ideally there should be a minimal number of observables sensitive to the maximal information contained in a certain process, and with the minimal correlation between these observables. This leads to the idea of the optimized observables targeted to given operators. Such an approach provides better sensitivity. At the same time, generic observables may have wider application and usage, without being tuned to a particular set of operators. Historically many EFT measurements evolved from analyses which did not target EFT operators specifically, and therefore are based on generic observables. It is also possible to describe full kinematic information in a given process with a complete set of observables with a one-to-one map to all four-vector quantities reconstructed in such a process. However, the number of such observables is usually large and additional advanced techniques are needed to analyze them jointly. When more than one observable is considered, correlations of these observables is important to carry forward. Besides the choice of observables, their binning is often an important consideration.

One particular consideration in building EFT-sensitive observables is the fact that higher-dimension operators typically lead to enhancement at the higher values of q^2 distributions of the particles appearing in the propagators. Therefore, observables based on the q^2 calculations or correlated with those quantities become sensitive probes of deviations from the SM. An example of such correlated observable could be transverse momentum of reconstructed objects. At the same time, such generic probes of q^2 may not be sensitive to distinguish multiple operators, all of which lead to the same q^2 enhancement. One example of such a situation is the study of CP-even and CP-odd operators, which may require special CP-sensitive observables to differentiate them.

3.2 Optimized observables

Optimized observables are typically targeted to certain operators, and therefore could be defined when there is a limited set of such operators of interest in a given process. On the other hand, a large number of operators in a process would lead to a large number of optimized observables and would diminish their practical application. Optimized observables can be calculated with the help of matrix-element-based calculations or machine learning techniques.

More to follow ...

3.3 Experimental measurements

Experimental measurements are experimentally delivered quantitative results, which are typically cross sections or related quantities, and can be further used in global fits for EFT operators. These experimental measurements are obtained from analysis of observables in a limited set of processes. We group experimental measurements sensitive to EFT effects in several categories which progress from simple to more involved:

- Single-process cross section.
- Single observable differential distribution affected by a single or multiple processes.
- Multi-observable differential distribution or multiple single-observable differential distributions with correlations.
- Binned sub-process cross sections, such as STXS in Higgs.
- Dedicated EFT measurements, such as amplitude analysis with cross sections per EFT operator.
- Dedicated EFT operator extraction by experiments.

The first three approaches could be generically called differential measurements and may be considered to be the best choices for reinterpretation. The last two approaches could be generically called dedicated measurements and may be considered to be the best choice for their optimality. At the same time they suffer from certain drawbacks. Differential measurements are typically performed with assumptions of the SM kinematic distribution in the unfolding procedure, and therefore only SM simulation is used. Moreover, differential distributions typically carry only limited information about the process, visible only in the given projection of data. The dedicated measurements, on the other hand, are typically limited in application only to the EFT operators chosen in a given analysis at the time of its design, and cannot be easily updated or reinterpreted. They are also often complex in its implementation, which limits their practical application. The binned sub-process cross sections, such as STXS in Higgs, are designed to combine the strengths of the above two approaches, but at the same time they combine their weaknesses as well.

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