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Effective theories and measurements at colliders

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ABSTRACT

If the LHC run 2 will not provide conclusive hints for new resonant Physics beyond the Standard Model, dedicated and consistent search strategies at high momentum transfers will become the focus of searches for anticipated deviations from the Standard Model expectation. We discuss the phenomenological importance of QCD and electroweak corrections in bounding higher dimensional operators when analysing energy-dependent differential distributions. In particular, we study the impact of RGE-induced operator running and mixing effects on measurements performed in the context of an Effective Field Theory extension of the SM. Furthermore, we outline a general analysis strategy which allows a RGE-improved formulation of constraints free of theoretical shortcomings that can arise when differential distributions start to probe the new interaction scale. We compare the numerical importance of such a programme against the standard analysis approach which is widely pursued at present.

1. Introduction

After the Higgs discovery in 2012 [1,2], the ATLAS and CMS Collaborations have started to investigate the new particle's properties in further detail [3]. For run 1, the Higgs boson's couplings have been constrained primarily using ratios

$$\kappa = (g_{\rm SM} + \Delta g_{\rm BSM})/g_{\rm SM} \qquad (1)$$

see Ref. [4] for details. These quantities are inclusive with respect to the phase space and are determined by comparing the number of measured events with the Standard Model prediction after subtracting the background for a given process. While this strategy is a reasonable procedure to obtain limits with relatively small statistics and large systematic uncertainties, a larger parameter space will become accessible during run 2, and a more fine-grained picture of constraints on interactions beyond the SM (BSM) can be formulated at higher LHC luminosity and energy.

In the absence of new resonant effects, a common approach to parametrise new physics interactions is to employ effective theory methods [5–8]. Imposing simplifying assumptions, such as *e.g.* the absence of non-trivial BSM flavour structures, one obtains a basis of 59 independent operators that express our lack of knowledge of the underlying new physics model at a high scale [7].

New physics at energy scales larger than the electroweak scale will typically show up as modifications of differential distributions at high transverse momenta. While an increased cross section can be observable in inclusive "$\sigma \times$ BR physics", a proper investigation of differential distributions is not only far more adequate to this particular physics question, but will also provide significantly more insight into the nature of BSM physics if a significant excess over the SM will be observed eventually.

A clear advantage of abandoning the κ prescription of Eq. (1) in favour of an effective field theory approach with a general set of Higgs interaction operators is that information from differential distributions does have a theoretically meaningful interpretation. The presence of dimension 6 operators will not only alter the total rate, but also the shape of measured distributions and new physics searches (in the absence of new kinematically accessible resonances) can be studied in a fairly model-independent way.

However, there are a few caveats. Using differential distributions can also mean a challenge for the effective theory approach. Effective theory, being an expansion in a new physics interaction scale $\Lambda_{\rm NP}$, is strictly speaking only valid when typical interaction scales are distinctively separated, *i.e.* when we have $\Lambda_{\rm NP} \gg \Lambda_{\rm interaction}$ for all relevant scales of the considered process. A well-known example for this is flavour physics, where effective field theories have always been an important tool. When studying rare decays, the weak interaction scale $\Lambda_{\rm NP} = m_W$ is clearly separated from the scale at which B-Mesons decay $\Lambda_{\rm interaction} = m_b$, which acts as the characteristic measurement scale. Corrections

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to the effective theory description are parametrically suppressed by $\mathcal{O}(m_b^2/m_W^2) \sim 0.3\%$. Therefore, applying effective field theory methods provides a well-motivated and theoretically well-controlled approximation.

At collider experiments in general, but at hadron colliders in particular, it is challenging to infer the scale at which the effective operators are probed from the observed final state objects when we want to formulate a limit on the presence of new physics: Different events will always probe the theory prediction at different scales μ. For example, in mono-Higgs production where the Higgs recoils against a hard jet, the transverse momentum of the jet is a relevant scale at which the effective operator $\hat{H}^\dagger \hat{H} \hat{G}^{\mu\nu} \hat{G}_{\mu\nu}/\Lambda_{\text{NP}}^2$ is probed.

On the one hand, a naive constraint on $C_O(v^2/\Lambda_{\text{NP}}^2)$ can always be understood as a limit obtained with $\Lambda \ll \Lambda_{\text{NP}}$ with an appropriate redefinition of the Wilson coefficient's size and we even might be tempted to lower Λ_{NP} to an energy range of a few TeV that is resolved by the LHC for an educated guess of the Wilson coefficient.[1] The reliability and robustness of such a limit is at least questionable as a naive analysis of a Wilson coefficient is performed completely independent of the matching or cut-off scale, which must not be kinematically resolved for the EFT expansion to hold in the first place.

On the other hand, if the effective Lagrangian is defined at a fixed scale Λ_{NP} *outside* the LHC reach or the observable's energy coverage,[2] or at least at the maximum energy probed in a new physics experiment with negative outcome, they mix when evolved from one scale to another as a consequence of electroweak and QCD interactions [10–12]. As a result, different phase space regions do probe different operator combinations. Thus, to infer well-defined constraints from exclusive distributions, the operators probed at different energy scales for different events or bins have to be evolved to a fixed predefined scale to allow a direct interpretation.

The impact of operator running is parametrically $\mathcal{O}(g_i \gamma_i \log[\Lambda_{\text{NP}}/\Lambda_{\text{meas}}])$, with coupling g_i and the anomalous dimension γ_i of the operator $\hat{O}_i$, the new physics scale Λ_{NP} and the measurement scale Λ_{meas}. For B-decay observables with $\Lambda_{\text{NP}} \simeq m_W$ and $\Lambda_{\text{meas}} \simeq m_b$, the resummation of these large logarithms can provide an important theoretical improvement for the interpretation of the measurement. A priori, when studying Higgs boson properties and assuming no New Physics particles up to several TeV, the hierarchy of electroweak and New Physics scale (*e.g.* $\Lambda_{\text{NP}} \simeq 2$ TeV) can be of similar order. Hence a resummation of these large logarithms can be crucial for a detailed understanding of the impact of Higgs-boson measurements on New Physics models.

In this paper, we study the impact of operator running and mixing on coupling measurements using differential distributions. We focus on three illustrative examples ranging from multi-jet to Higgs physics. To our knowledge these effects have not been discussed in a fully differential fashion at the LHC in the context of effective field theory measurements. We also provide a first step towards a general prescription of how measurements based on differential distributions can be used to constrain an effective Lagrangian, and how to give those constraints an interpretation in terms of a UV scale model, including higher-order corrections in a well-defined and practical way. As we will see, due to the momentum dependence of many of the higher-dimensional operators and their impact being most relevant when probed at large invariant masses, *i.e.* $\Lambda_{\text{meas}} \simeq \sqrt{\hat{s}}$, the characteristic logarithms $\log(\Lambda_{\text{NP}}/\sqrt{\hat{s}})$, depending on the assumed new physics scale Λ_{NP}, are fairly small and the contributions of operator running is of $\lesssim 10\%$.

To make this work self-contained we review the (flavour physics) language relevant to this problem in Section 2 before we apply it to di-jet final states at the LHC. In Sections 5.1 and 5.2 we discuss the impact on Higgs phenomenology in $H+$jet and HZ production before we give our conclusions in Section 6.

2. Effective field theory approach: a quick review

In general an effective Hamiltonian in Operator Product Expansion is given by

$$\hat{\mathcal{H}}_{\text{eff}} = \sum_i C_i(\mu) \hat{O}_i(\mu), \tag{2}$$

where $\hat{O}_i$ are the operators defined at the factorisation scale μ and C_i are the so-called Wilson coefficients. Note that as a consequence of factorisation, both the Wilson coefficient as well as the operators are scale-dependent. This dependence cancels for $\hat{\mathcal{H}}_{\text{eff}}$. Eq. (2) separates the physics into a long-range behaviour of matrix elements $\langle \hat{O}(\mu) \rangle$ and short-range behaviour of Wilson coefficients $C_i(\mu)$ relative to the factorisation scale μ. The ignorance of physics with respect to this arbitrary separation at this stage leads to renormalisation group equations (RGEs). If we focus on a particular model, the coefficients of Eq. (2) can be obtained by a matching calculation. Only assuming SM particle content and gauge symmetries, the lowest order effective operator extension consists of dimension 6 operators documented in Ref. [7]. Relying on this language, we are fairly unprejudiced about the particular UV dynamics at a new physics scale Λ_{NP} (a well-motivated guess on the Wilson coefficients' hierarchies are possible when we consider composite Higgs scenarios [8]).

Approximating general amplitudes and eventually exclusive cross sections in terms of effective operators is only valid if the new physics scale Λ_{NP}, the scale of the masses of the heavy degrees of freedom of the full theory, is much larger than the scale at which the effective operator is probed (see [13–16] for a discussion in the context of Higgs physics).

For example, in the Standard Model process $c\bar{s} \to u\bar{d}$ the leading-order amplitude is given by (we suppress the CKM matrix elements for convenience)

$$\begin{aligned} \mathcal{M} &= i \frac{G_F}{\sqrt{2}} \frac{M_W^2}{\hat{s} - M_W^2} (\bar{s}_a c_a)_{V-A} (\bar{u}_b d_b)_{V-A} \\ &= -i \frac{G_F}{\sqrt{2}} (\bar{s}_a c_a)_{V-A} (\bar{u}_b d_b)_{V-A} + \mathcal{O}\left(\frac{\hat{s}}{M_W^2}\right), \end{aligned} \tag{3}$$

assuming a diagonal CKM matrix and $(V-A)$ referring to the Lorentz structure $\gamma_\mu(1-\gamma_5)$ (we have made the colour indices a and b of the spinors explicit). Physics based on the effective operator $\hat{O}_2 = (\hat{\bar{s}}_a \hat{c}_a)_{V-A} (\hat{\bar{u}}_b \hat{d}_b)_{V-A}$ in Eq. (3) is clearly only valid for scales $\hat{s} = (p_{\bar{s}} + p_c)^2 \ll M_W^2$.

The EFT approach to matrix elements like Eq. (3) has been studied in detail and is well covered in flavor physics reviews and we refer the reader to [17] for details while we only quote the results in the following. The matching procedure at NLO QCD induces two operator structures

$$i\mathcal{M} = C_1 \langle \hat{O}_1 \rangle + C_2 \langle \hat{O}_2 \rangle. \tag{4}$$

As we perform a calculation in EFT with higher dimensional bare interactions $\sim C_i^{(0)} \hat{O}_i(\hat{\bar{u}}^{(0)} \hat{d}^{(0)} \hat{\bar{s}}^{(0)} \hat{c}^{(0)})$, there is an additional multiplicative renormalisation of the Wilson coefficients necessary

[1] This procedure has typically been applied in searches for Dark Matter at the LHC and has been left without criticism for quite some time [9].

[2] This situation is similar to electroweak fits after LEP2, which assumed a Higgs mass at the kinematic endpoint of $m_H \simeq 114$ GeV.