

Beyond the Standard Model searches at the LHC

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Summary. — Among the major long-term aims of particle physics are unveiling the form of the Higgs potential and exploring physics at the TeV scale. I will focus on the latter, more timely aim and 1) emphasize the complementarity of Effective Field Theory and Simplified Models; 2) stress why Simplified Models of dark matter are nothing but resonances with exotic BRs. My main purpose here is to help our experimental colleagues to orientate within the jungle of (sometimes misleading) theory literature of the last years.

1. – Introduction

By far the most convincing description of Nature at distances $> 1/\text{TeV}$ is encoded in the Standard Model (SM) with a single Higgs doublet. Yet, we know of at least two missing ingredients: neutrino masses (that require the inclusion of a new mass scale or additional fields, *e.g.*, right-handed neutrinos) and dark matter. Yet, besides this experimental evidence there are a variety of theoretical arguments that independently suggest the existence of Beyond the SM (BSM) physics not far above the weak scale. Because there is at present no reason to prefer a specific extension of the SM compared to another, I will instead focus on the following, more concrete question: *what is the most efficient and model-independent way to look for BSM physics at the LHC?* I feel that reminding ourselves of a few basic points may be useful to both experimental and theoretical communities.

2. – Complementarity of Effective Theories and Simplified Models

There are two popular physical interpretations of the results of a BSM collider search: Effective Field Theory and Simplified Models. These describe different classes of models and are therefore complementary: in order for the LHC to cover as many BSM scenarios as possible, *both interpretations should be carried out.*

2.1. Effective Theories. – In the Effective Field Theory (EFT) approach one studies processes mediated by heavy particles and look for small deviations from SM expectations. A general rate R_{full} may be written as

$$(1) \quad R_{\text{full}}(p^2) = R_{\text{SM}}(p^2) + c_1 \frac{p^2}{\Lambda^2} + c_2 \left(\frac{p^2}{\Lambda^2} \right)^2 + \mathcal{O}(p^6/\Lambda^6)$$

with p^2 the momentum characterizing the process, Λ a mass scale (the UV cutoff of the EFT), and c_i model- and process-dependent numbers. In this language p^2/Λ^2 plays the role of the expansion parameter. This approach is especially useful when the new physics is heavy enough and the experiment sufficiently precise so as to reveal the small corrections of order $p^2/\Lambda^2 \ll 1$. At hadron colliders like the LHC these conditions are hard to meet simultaneously, though, and events occurring in the regime where the parton energy is of order $\sim \Lambda$ may be non-negligible. Nevertheless, the EFT formalism is still extremely useful at the LHC in practice, though for a limited class of scenarios. *EFTs represent in fact our best tool to describe strongly coupled extensions of the SM*, even when they possess potentially accessible light states. This important aspect is better appreciated with the help of explicit examples.

Consider a mono-jet dark-matter signature mediated by the operator

$$(2) \quad \delta\mathcal{L}_{\text{DM}} = \frac{1}{\Lambda^2} \bar{q}\gamma^\mu q \bar{X}\gamma_\mu X,$$

with q a quark and X the dark matter. The rate for $pp \rightarrow j + MET$ can be formally written as in (1) —with $c_1 = 0$ because there is no interference. Current bounds read $\Lambda > \Lambda_*$ with Λ_* a function of the dark-matter mass in the ballpark of a few hundred GeV. This bound should be interpreted with care [1, 2]. Considering the conservative case in which the underlying physics generates the operator (2) via the tree-level exchange of a resonance of mass m_* , one expects $\Lambda = m_*/\sqrt{g_q g_X}$, with g_q, g_X the coupling of the new resonance to quarks and DM, and current bounds translate into $m_* > \sqrt{g_q g_X} \Lambda_*$. We thus see that in a weakly coupled BSM model a resonance that saturates this bound is so light that may be directly produced. In that case a search for di-jet resonances with a non-vanishing branching ratio into missing ET is certainly the most appropriate way to test the model. We will come back to this point in sect. 2.2. On the other hand, for a strong dynamics, say with $g_X^2 > 4\pi$ and/or $g_q^2 > 4\pi$ (see below), the new resonance is either out of kinematical reach or too broad to be directly searched for. In this case the rate for $pp \rightarrow j + MET$ scales again as in (1) (again with $c_1 = 0$) but now with $c_2 = c_2(p^2/m_*^2)$ a “form factor”. The latter is model-dependent and often incalculable, but we know from general field theory arguments that it should be approximately constant for $p^2/m_*^2 < 1$ and vanish as $p^2/m_*^2 \rightarrow \infty$. The momentum dependence of the rate is thus qualitatively captured by taking $c_2 = \text{const}$, which is precisely the same prediction of an EFT with cutoff $\mathcal{O}(\Lambda)$. Since the rate scales as the fourth power of the new physics scale, it is clear that (2) captures the relevant physics even quantitatively. Hence, operators like (2) accurately describe mono-jet processes at the LHC if the physics underlying the EFT is sufficiently strongly coupled.

Similar considerations apply to the SM EFT. For example, consider $\delta\mathcal{L}_{3W} = \text{tr}[W_{\mu\nu} W^{\nu\rho} W_\rho^\mu]/\Lambda^2$. The authors of [3] found that current data imply $\Lambda > 600 \text{ GeV}$ at 95% CL. As above, one should be careful at interpreting this constraint. In a generic weakly coupled UV completion of $\delta\mathcal{L}_{3W}$ one would find $1/\Lambda^2 \sim g^3/(16\pi^2 m_*^2)$, with g the

$SU(2)_L$ gauge coupling and m_* the mass of some electro-weak charged field. If so, the result of [3] would read $m_* \sim 20$ GeV, which is obviously too low to be consistent with collider data. Does this mean that the SM EFT is not useful at the LHC? Of course not! Non-generic, strongly coupled completions of $\delta\mathcal{L}_{3W}$ may violate the expectation $1/\Lambda^2 \sim g^3/(16\pi^2 m_*^2)$, as shown in [4]. For such theories the EFT formalism is again our best tool.

2.2. Simplified Models. – While the EFT formalism should be employed to interpret LHC searches of strongly coupled new physics, Simplified Models should be used to investigate *weakly coupled* extensions of the SM. The necessity of weak coupling is key here. When couplings are $g_*^2 > 4\pi$ (note that this occurs before $g_* \sim 4\pi!$), model-dependent vertex corrections become sizable and the very notion of Breit-Wigner distribution ceases to provide a reliable description of resonant production. In those cases there are incalculable form factors and EFTs are a sufficiently accurate tool!

In Simplified Models one postulates the existence of exotic resonances with specific quantum numbers and couplings. Production of the exotic states at the LHC either occurs in pairs via gauge interactions, or via direct interactions with quarks q (¹). At the renormalizable level there are only a few options available, which can be compactly written as $qq'\Phi'$ (for some scalar Φ'), $\bar{q}\gamma^\mu q Z'_\mu$, $qH\Psi'$, and $q\Phi\Psi$ (where Ψ, Ψ' are fermions, generally with different quantum numbers).

Di-quarks Φ' as well as Z' 's have been extensively studied. Novel interesting model-independent searches have been proposed in [5]. By now, virtually all relevant signatures have been considered. The physics of heavy vector-like fermions and top-partners (that we collectively denoted by Ψ') has also been investigated in detail, and the leading decay channels $\Psi' \rightarrow tH/tZ/bW^+, bH/bZ/tW^-, tW^+, bW^-$ are all covered. The situation for $\delta\mathcal{L}_{\text{BSM}} = \lambda q\Phi\Psi$ is a bit more involved, though. Let me start with a good piece of news. Unless additional interactions are introduced, the model predicts that the lightest between Φ and Ψ is exactly stable. Searches for MET, long-lived charged particles, R -hadrons, etc. are therefore sufficient to probe most of the parameter space of $\delta\mathcal{L}_{\text{BSM}}$, though it is fair to say that existing searches are tailored on SUSY-like topologies —obtained when Ψ is color-neutral. The bad news is that scenarios in which a prompt decay of the light state is triggered by additional, small couplings are far less explored. As a consequence, it is still relatively easy for new colored physics to hide well below the TeV. As a concrete example, assume the coupling λ is small, $m_\Psi > m_\Phi$, and furthermore that $\Phi \rightarrow \text{SM}$ occurs within the detector via unspecified weak interactions (*e.g.*, some higher-dimensional operator that has a negligible impact otherwise). In this scenario the new states are dominantly pair-produced via gluon fusion and the typical signature is $pp \rightarrow \Psi\bar{\Psi} \rightarrow \Phi\bar{\Phi}jj \rightarrow \text{SMSM}jj$. Now, not all such cases are considered; and searches of 3-jet resonances tell us that Ψ can safely live below the TeV. My conclusion is thus that much theoretical and experimental work is still needed to fully cover the parameter space of even the simplest simplified models with sub-TeV colored particles.

3. – Dark matter at the LHC

Let me start stating the obvious. Any sort of exotic MET signal at the LHC would look like dark matter. The truth, however, is that the latter may come from either new collider-stable neutral particles as well as exotic neutrino interactions [1]. It is not always

(¹) Couplings to the Higgs are neglected here because usually subleading.

easy to distinguish the two. In addition, should some evidence of anomalous MET events be detected, it would not be possible to robustly infer whether such a signal is truly due to the missing matter of the Universe or some other particle. This obvious point entails a number of important implications that I decided to stress explicitly below because, apparently, I profoundly disagree with some of the suggestions made by the Dark Matter LHC working Group in a number of publications.

First, *simplified dark-matter models are nothing but Simplified Models for exotic resonances with branching ratios into invisible energy*. Hence they should be treated as such. Take as an example the so-called s -channel models. These are defined in terms of 5 parameters: the dark-matter and mediator masses ($m_{\text{DM}}, m_{\text{res}}$), the couplings of the new resonance to quarks and dark matter (g_q, g_X), and the resonance width (Γ). As argued above, these models are only fully trustable in the weak-coupling regime $\Gamma \ll m_{\text{res}}$ (here there is already a disagreement with [6]). Hence, the search may be interpreted for “heavy” and “light” mediators depending on whether $m_{\text{res}} > 2m_{\text{DM}}$ or not. In the former case two are the relevant parameters: a familiar plot in the $m_{\text{res}}, \sigma_{\text{res}} \times \text{BR}$ plane is thus not only useful but also the most deontologically correct way to present the results of an experimental search. In the “light” mediator regime the relevant parameters are again just two ($m_{\text{DM}}, g_q \times g_X$), and a 2-dimensional plot is able to capture the entire physics of the model. Unfortunately, ref. [6] (and many other theoretical publications before and after it) prefers to plot in the plane m_{DM} vs. m_{res} . Because this can only be done after g_q, g_X, Γ have been arbitrarily fixed, such plots cannot be translated into constraints on scenarios with different values of the parameters.

Second, the LHC probes very different energy scales and physical processes compared to other dark-matter searches, like underground direct detection experiments. However, ref. [6] suggests to show the LHC results also in a m_{DM} vs. σ_{DM} plot, with σ_{DM} a cross-section for dark-matter scattering off nucleons. This choice is conceptually wrong because, as we have emphasized, the relevant parameters in a collider analysis are different depending on the kinematical regime one considers. But I believe there is a deeper reason why one should avoid such plots: they give the impression that the LHC is bragging to be *better* than direct detection experiments. The truth is of course that *collider searches for dark matter are complementary to direct detection*, they are not competing against them. The LHC Collaborations should therefore present their results as any of the other collider search they perform.

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REFERENCES

- [1] FRIEDLAND A., GRAESSER M. L., SHOEMAKER I. M. and VECCHI L., *Phys. Lett. B*, **714** (2012) 267.
- [2] SHOEMAKER I. M. and VECCHI L., *Phys. Rev. D*, **86** (2012) 015023.
- [3] BUTTER A., BOLI O. J. P., GONZALEZ-FRAILE J., GONZALEZ-GARCIA M. C., PLEHN T. and RAUCH M., *JHEP*, **07** (2016) 152.
- [4] LIU D., POMAROL A., RATTAZZI R. and RIVA F., *JHEP*, **11** (2016) 141.
- [5] KATS Y. and STRASSLER M. J., *JHEP*, **11** (2012) 097.
- [6] BOVEIA A. *et al.*, arXiv:1603.04156 [hep-ex].