Minimal matter at the LHC

Roberto Franceschini
ITPP, EPFL, CH-1015, Lausanne, Switzerland
E-mail: roberto.franceschini@epfl.ch

Abstract. A systematic approach for a model independent description of phenomenology at the LHC is presented. The most general linear interaction of scalars and fermions with pairs of standard model fields is considered at the renormalizable level. Searches for the new states are devised and the reach of TeVatron and LHC is discussed. Extensions to more general cases with more complicated spectra and interactions mediated by higher dimensional operators are briefly discussed.

1. Introduction
The experiment at the LHC are taking collision data since 2009 and the accelerator schedule foresees an integrated luminosity of 1/fb collected by the end of 2011. The data from the LHC will come out collisions at the highest energies reached so far in accelerators.

The collisions of the LHC are probing physics at energy scales in the multi-TeV range and are likely to produce the Higgs boson or other particles that appear in beyond the standard model physics scenarios.

The unprecedented complexity of the final states of the collisions and absence of an outstanding model for BSM physics requires to be open minded in terms of the possible observations of the LHC.

Motivated models are a very useful guidance to investigate possible signature for the collider, however it might well be that our model building experience is biasing our analysis in such a way that we are missing some signature of potential interest for an observation at the LHC. Thus we want to investigate what is the generic phenomenology that can be studied at the LHC and we want to do that in a model independent fashion.

The model independent treatment of the LHC phenomenology will give us a rationale to understand the reach of LHC in terms of discovery of different kinds of new physics. Furthermore we will produce a list of the possible signatures for the LHC under mild assumptions on the interaction of the new physics. This will allow to judge how much the model inspired signatures studies for the LHC have actually covered the space of possible signatures. Finally we will discuss how much of the phenomenology can be discussed without specifying a model, that is to say we will address the problem of the model independent characterization of the new physics.

To formulate a model of BSM physics requires to specify the particle content of the model, that is to say the quantum numbers of the states of the theory, and a set of symmetries that we want to impose on top of the Lorentz and gauge invariance of the SM.

The quantum numbers are restricting the possible interactions by the enforcing of the symmetries imposed on the theory. Additional symmetry can involve flavor and thus specify the
flavor structure of the interactions. The actual interactions are the result of the combination of these ingredients.

In this contribution we will describe how the simplest realizations of BSM physics result in set of simple and distinctive signatures for the collider. More complicated scenarios and motivated models of new physics beyond the standard model can in many cases be, at least coarsely, captured by the simple examples that we will discuss. The simplest model that we can imagine has no additional symmetry with respect of the SM and has only one new light state. For concreteness we can assume that the decay of the new state is dominated by renormalizable interactions with bilinears of SM fields. Unless the new physics is very close to strong coupling with the SM the higher dimensional operators that can potentially change the decay phenomenology of the new states are expected to be of little relevance.

Under the specified assumptions our new physics state will have an interaction

\[ \mathcal{L} = \lambda \Phi_{\text{new}} \phi_{\text{SM}} \phi_{\text{SM}}, \]  

where \( \lambda \) is a generic coupling of the new physics to the SM sector. The coupling \( \lambda \) can be rather large in the cases in which the interaction is not constrained by current experiments. However we shall consider the case of nearly vanishing coupling \( \lambda \) in which all the effects on physics at scales lighter than the mass of the new particle \( \Phi_{\text{new}} \) can be neglected. Due to the absence of competing interaction terms the decay of \( \Phi_{\text{new}} \) will be dominated by the coupling \( \lambda \).

The production of new states \( \Phi_{\text{new}} \) with mass \( M \) will occur through pair production via the gauge interactions. Direct production of single resonances through the coupling \( \lambda \) is also possible, but in the cases where \( \lambda \) is taken small this is bringing only a small contribution. The single production can be sizable in the cases where the coupling \( \lambda \) is not constrained to be overly small, however this should be studied in a case-by-case fashion and we decide to deal only with pair production, which will serve as a guaranteed starting point for every analysis.

2. States of minimal matter

Here we shall consider what are the possible signatures of new particles present in BSM scenario. From eq. (1) we can derive the complete list of one particle states that can interact linearly with the SM. The full list of the fermionic and scalar states can be found in [1]. The case of vector is effectively covered, although in a different spirit, in [2] [3].

The list of all the possible fermions that can couple to the SM contains more than ten states and in principle each of them is a separate case for a study of the phenomenology for the collider. Indeed the differences in the quantum numbers of each state are potentially observable in the details of the final states of the collisions. Nonetheless the coarsest features of the final state of the collisions in which these new states are produced are determined basically just by the \( SU(3) \) representation of the new object and by its coupling to heavy flavors. As a matter of fact the new fermions that can couple according to eq. (1) are either colored or not colored, i.e. they are heavy quarks that decay into a jet and a vector of the SM or are heavy leptons that decay to a lepton and a vector of the SM

- heavy quarks \( Q \to j h, j W, j Z \)
- heavy leptons \( L \to \ell h, \ell W, \ell Z \)

where by \( \ell \) we mean either a charged SM lepton or a neutrino, by \( j \) we mean a light quark jet and the vectors are longitudinally polarized. The list of states contains some exotic charge as leptons of charge ++ or quarks of charge 5/3 or 4/3.

In case the new object has a preference for third generation couplings the possible decays are

- heavy quarks \( Q_{u,d} \to t, b h \) or \( t, b Z \) or \( b, t W \)
- exotic charged heavy quarks \( Q_{5/3}^u \to t W^+, Q_{4/3}^d \to \bar{b} W^+ \)
heavy leptons \(L^+, L^0 \rightarrow \tau, \nu h\) or \(\tau, \nu W\) or \(\tau, \nu Z\)

For the case of scalars the classes of states that can be used to describe the coarser phenomenology for the LHC are heavy quarks

- heavy quarks that decay into di-jet resonances, \(S_c \rightarrow jj\)
- heavy leptons that decay into leptons \(L \rightarrow \ell \ell\)
- leptoquarks that decay to mixed jet+leptons final states \(LQ \rightarrow j\ell\)

3. Collider phenomenology

Despite the large number of possible combinations of quantum numbers the huge list of states that we can couple to the SM reduces to a rather short list of items to be studied at the collider. Focusing on the signatures without heavy flavors all the possibilities for the pair production of scalars and fermions are

- scalar di-jet resonances that result in 4\(j\) signatures
- scalar di-lepton resonances that result in 4\(\ell\) signatures
- heavy quarks that result in 2\(j2V\) final states
- heavy leptons that result in 2\(\ell2V\) final states
- leptoquarks that result in \(jj\ell\ell\) signatures

where \(V = h, Z, W\).

Detailed searches for each of these final states have been devised in [1] here we will limit to say that interesting signatures emerge in final states with four light jet, four charged leptons, \(l^+l^+l^-l^-jj\) mET, 4\(jl^-l^+\).

Indeed these are the final states that we find to be accessible for a discovery at the LHC in the 2009-2011 run at 7 TeV. The potential of the LHC for the discovery of resonances in these channels is summarized in figure 1. The potential is expressed in the plane of the mass of the new resonance \(M\) and the integrated luminosity of the LHC and compared with the discovery reach of TeVatron under the assumption that 10/fb will be available for the analysis at each experiment of TeVatron. The labels on the vertical dashed lines indicate the number of events produced at TeVatron, while the label on the solid curves corresponds to the number of events produced at the LHC. The region in red corresponds to masses and integrated luminosities for which the TeVatron have more events than the LHC or the LHC has less than one event. The yellow areas correspond to the mass and integrated luminosities where the LHC have more events than TeVatron, in some case in a number sufficient to make a discovery at both the machines. Finally the green area is the region where the TeVatron has a limited reach due to the lack of produced events and the LHC instead can make a discovery.

In general we can see that the LHC must reach 1/fb of integrated luminosity to be competitive with the TeVatron on all the mentioned searches. Furthermore we notice that the discovery regions for the LHC start with luminosity of order a fraction of 1/fb and that the signatures that can be observed over the SM background are either very clean, as the \(l^+l^+l^-l^-\) signature, or rather dirty and ”jettish” as the 4\(j\) signature.

4. Conclusions

In this contribution we discussed the model-independent characterization of new physics in simple set-ups that can capture the coarsest features of the actual model of new physics that the LHC will explore soon. Ignoring the possible flavor structure of the interactions of the new particles and assuming that their decay is mediated by renormalizable interactions we discussed the complete list of final states that can arise in the pair production of the new states by gauge interactions. Our result can simply be generalized to include heavy flavors in the final state.
Figure 1. Discovery reach of LHC at 7 TeV compared with TeVatron with 10/fb of integrated luminosity. The comparison is made as a function of the mass of the resonance and of the integrated luminosity collected at LHC.

The inclusion of higher dimensional operators is less trivial and can give important differences with respect to the scenario discussed here. Indeed higher dimensional operators can arise when the new physics sector experiences some strong coupling. For instance the heavy quarks could have a higher dimensional operator of magnetic moment type

$$\frac{1}{\Lambda} \bar{Q}_{L,R} \sigma^{\mu\nu} V_{\mu\nu} q_{R,L},$$

that can alter significantly the branching fractions and the set of available final states for the decay of the heavy quark $Q$. In other cases the higher dimensional operators can embody the result of having integrated out some heavy state as is for instance the case of four fermions operators

$$\frac{1}{\Lambda^2} \bar{q} \Gamma^{(i)} q \bar{q} \Gamma^{(i)} q,$$

for the decay of a heavy quark $Q \rightarrow jjj$. The cases in which we can integrate out states and obtain effective operators for the decay of the lightest states represent a simple case in which a
spectrum with several levels can be discussed in terms of a finite simple set of possibilities that can be categorized in terms of the properties of the objects appearing in the interaction.

More complicated spectra, as those that admit long decay chains, can result in a signature that is mainly determined by the properties of the lowest lying state of the chain rather than by the properties of the originating objects. In this cases a systematic discussion of the phenomenology of the lightest states is still doable, but a complete classification of the phenomenology of the parents seems overly rich to be enclosed in few representative cases. The full discussion of the phenomenology resulting from spectra with more than one state requires a more complex discussion that we leave for further works.

References
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