Efficient, Automatic and Accurate QCD predictions for Higgs (and alike) production at the LHC

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We present a new approach for the determination of the newly discovered resonance at the LHC. This approach is completely generic and model-independent, and it is based on an effective field theory approach. In this approach one can test the different spin and parity hypotheses for the new resonance, with the possibility of including in a consistent manner QCD corrections. We present results at NLO matched with parton shower obtained within the automatic aMC@NLO framework and we compare them with MLM merged samples, showing general good agreement in production and decay related observables.

1 Introduction

After the enthusiasm for the discovery of the new boson at the LHC[1,2], the attention is rapidly shifting towards the measurement of its properties, to assess whether it is or not the Higgs boson as predicted by the Standard Model (SM). These studies consist in systematically testing the various hypotheses and validating them against the data. Any of such hypotheses (e.g. spin and/or parity of this new resonance) needs to be translated into a prediction for the relevant observables. To this aim, two different approaches can be followed: the first approach, implemented e.g. in the JHU code[3,4] consists in introducing all possible couplings, the only constraint being Lorentz symmetry, without any assumption on new physical states. This approach has the limitations of having a large number of free parameters, and, most important, of not allowing the inclusion of higher order corrections in the computation. An alternative approach is the one of building an effective theory, based on the symmetries of the SM, assuming its validity up to a cutoff scale Λ. The number of extra parameters can be therefore reduced by imposing symmetries and by keeping only the lowest dimension operators. This approach has the advantage of providing a theory which is renormalizable order by order in $1/\Lambda$, therefore allowing the inclusion of higher order QCD corrections.

Using the effective theory approach, we will present results for the various spin/parity hypotheses, both at NLO matched to parton shower, employing aMC@NLO, and following the MLM merging prescription[5], as automatically implemented in MadGraph 5[6], to include matrix-element description up to two extra jets. The two approaches are found to reasonably agree for all the studied observables.

2 The Lagrangian

The effective field theory Lagrangian[7] can be written in terms of spin 0, 1 and 2 sectors, corresponding to the possible hypotheses on the nature of the new resonance X, (Higgs boson from now on). Again, we stress that any other new state in the theory is supposed to be heavier than the cutoff Λ.

2.1 Spin 0

The construction of the effective Lagrangian for the spin-0 states is obtained by requiring that the parameterization should i) allow to easily recover the SM case, ii) include 0^- state couplings typical of SUSY or generic 2HDM, iii) allow CP-mixing between 0^+ and 0^- states (parameterized by an angle α, iv) cover the minimal higher dimensional operator beyond the SM for the 0^+ state.
The interaction Lagrangian with fermions and vector-bosons for the spin-0 case is given by

$$\mathcal{L}_0^f = -[c_\alpha \kappa_{Hff} g_{Hff}\, \bar{\psi}_f \psi_f + s_\alpha \kappa_{Aff} g_{Aff}\, \bar{\psi}_f i\gamma_5 \psi_f] X_0, \tag{1}$$

and

$$\begin{aligned}
\mathcal{L}_0^V \;=\;& \Big[c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W^+_\mu W^{-\mu}\big] - \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu}\widetilde{A}^{\mu\nu}\big] \\
&- \frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu}\widetilde{A}^{\mu\nu}\big] - \frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\big] \\
&- \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu}\big] - \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu}\widetilde{W}^{-\mu\nu}\big]\Big] X_0,
\end{aligned} \tag{2}$$

where the (reduced) field strength tensors are

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \quad (V = A, Z, W^\pm), \qquad G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f^{abc} G^b_\mu G^c_\nu, \tag{3}$$

and the dual tensor is

$$\widetilde{V}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} V^{\rho\sigma}. \tag{4}$$

This parametrization allows to describe the mixing between CP-even and CP-odd states via the c_α parameter and correspondingly to give an effective description of a reasonably ample range of CP-violating scenarios, such as those arising in SUSY or in a generic 2HDM.

2.2 Spin 1

The spin-1 X interaction Lagrangian with fermions is

$$\mathcal{L}_1^f = \sum_{f=u,d} \bar{\psi}_f \gamma_\mu (\kappa_{f_a} a_f - \kappa_{f_b} b_f \gamma_5) \psi_f X_1^\mu, \tag{5}$$

where u and d denote the up-type and down-type quarks, respectively. The a_f and b_f are by default set to their SM-like value, i.e.

$$a_u = \frac{g}{2c_W}\Big(\frac{1}{2} - \frac{4}{3}s_W^2\Big), \quad b_u = \frac{g}{2c_W}\frac{1}{2}, \qquad a_d = \frac{g}{2c_W}\Big(-\frac{1}{2} + \frac{2}{3}s_W^2\Big), \quad b_d = -\frac{g}{2c_W}\frac{1}{2}. \tag{6}$$

The XWW interaction at the lowest dimension is in general[8]

$$\begin{aligned}
\mathcal{L}_1^W \;=\;& +i\kappa_{V_1} g_{WWZ}(W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu})X_1^\nu + i\kappa_{V_2} g_{WWZ} W^+_\mu W^-_\nu X_1^{\mu\nu} \\
&- \kappa_{V_3} W^+_\mu W^-_\nu (\partial^\mu X_1^\nu + \partial^\nu X_1^\mu) + i\kappa_{V_4} W^+_\mu W^-_\nu \widetilde{X}_1^{\mu\nu} \\
&- \kappa_{V_5} \epsilon_{\mu\nu\rho\sigma}[W^{+\mu}(\partial^\rho W^{-\nu}) - (\partial^\rho W^{+\mu})W^{-\nu}] X_1^\sigma,
\end{aligned} \tag{7}$$

where $g_{WWZ} = e \cot\theta_W$. Similarly, the XZZ interaction is given by [9]

$$\mathcal{L}_1^Z \;=\; -\kappa_{V_3} X_1^\mu (\partial^\nu Z_\mu) Z_\nu - \kappa_{V_5} \epsilon_{\mu\nu\rho\sigma} X_1^\mu Z^\nu (\partial^\rho Z^\sigma). \tag{8}$$

For the $X_1 = 1^-$ case (in parity-conserving scenarios) the non vanishing κ parameters are:

$$\kappa_{f_a, V_1, V_2, V_3} \neq 0. \tag{9}$$

Conversely, for the $X_1 = 1^+$ case one has:

$$\kappa_{f_b, V_4, V_5} \neq 0. \tag{10}$$

2.3 Spin 2

The spin-2 X interaction Lagrangian starts from the dimension-five terms [10,11,12,13]:

$$\mathcal{L}_2^f = -\frac{1}{\Lambda} \sum_{f=q,\ell} \kappa_f \, T_{\mu\nu}^f X_2^{\mu\nu}, \tag{11}$$

and

$$\mathcal{L}_2^V \;=\; -\;\frac{1}{\Lambda}\kappa_V \, T_{\mu\nu}^V X_2^{\mu\nu} \;-\; \frac{1}{\Lambda}\kappa_\gamma \, T_{\mu\nu}^\gamma X_2^{\mu\nu} \;-\; \frac{1}{\Lambda}\kappa_g \, T_{\mu\nu}^g X_2^{\mu\nu}, \tag{12}$$

where $V = Z, W^\pm$ and $T_{\mu\nu}^i$ is the energy-momentum tensor of the SM fields; see e.g. [14] for the explicit forms. The even higher dimensional terms [4], dimension-seven, are also implemented. In these proceedings we will only consider the lowest dimension $X_2 = 2^+$ case. The common Randall-Sundrum (RS) case corresponds to the graviton coupling universally to the different energy-momentum tensors, i.e.

$$\kappa_f = \kappa_g = \kappa_\gamma = \kappa_V \neq 0\,. \tag{13}$$

In general, there is no real constraint (such as gauge invariance, for example) that enforces this condition, and one may be interested in probing different coupling strengths to the different parts of the energy momentum tensor. We will show and comment these results in Sec. 3.2.

3 Results

We now turn to the presentation of some illustrative result. As said, our approach allows to consistently include effects of extra QCD radiation, both by merging different matrix-element multiplicities with the MLM scheme, or by matching NLO computations with parton showers in the aMC@NLO framework.

3.1 aMC@NLO vs. MLM merging

Fig. 1 shows prediction for the transverse momentum of the Higgs boson, in different spin/parity hypotheses: the main frames show curves obtained with the MLM merging procedure, while the lower frames show the ratio of each curve over the corresponding NLO matched to parton shower prediction. The employed parton shower is Pythia 6 (p_T-ordered), and distributions are all normalised to 1. Differences in the main frame can be traced to the different initial state which are probed. At the LO, $0^\pm$ are only gg-initiated, 2^+ receives most of its contribution from gg initial state ($\sim$ 95%), while $1^\pm$ are only $q\bar{q}$-initiated. This turns into harder (more central) transverse momentum (pseudorapidity) distributions for $0^\pm$ and 2^+ with respect to $1^\pm$. The comparison between MLM and aMCatNLO samples shows nice agreement between the two, their ratios always being close to unity, with the exception of the p_T distribution at large values of the transverse momentum, where MLM samples are slightly harder, as a consequence of the inclusion of matrix-elements up to 2 extra jets, multiplicity not covered by the NLO computation.

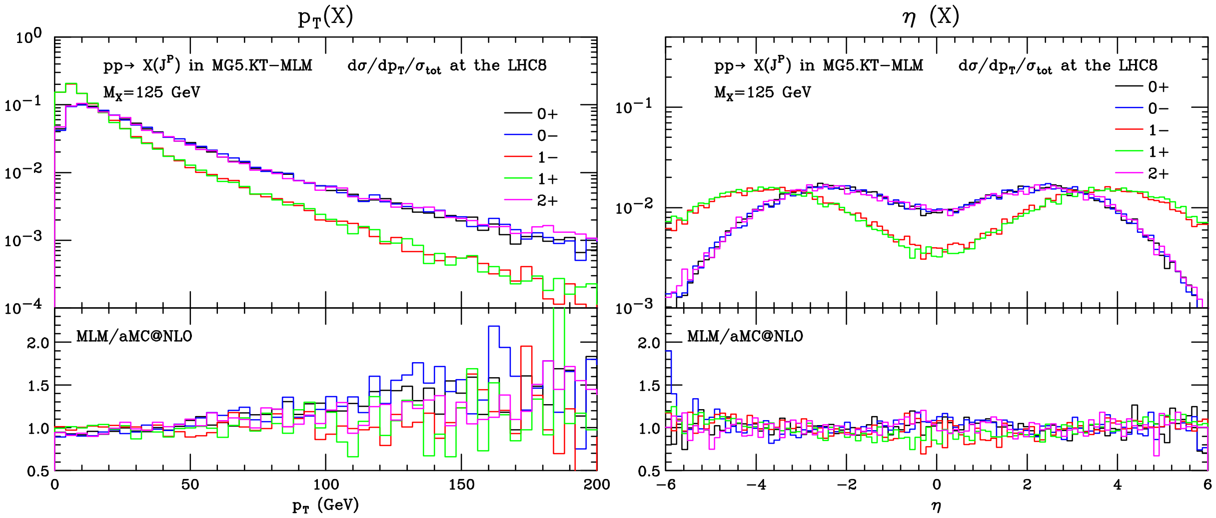

Figure 1: Higgs boson transverse momentum (left) and pseudorapidity(right) distributions for different spin/parity hypotheses. The upper frame shows the MLM-merged curves (including up to two extra jets), whereas the lower plot shows, for each prediction, the ratio of the curve in the upper plot over the corresponding one obtained with aMC@NLO. Events are showered with Pythia 6 (p_T-ordered).

This general good agreement between the two methods is also confirmed when one studies the decay products (decay to $\gamma\gamma$, $4l$, $2l2\nu$ final states can be included keeping all spin-correlation effects). For the sake of brevity, we will not show plots relative to decay products here.

3.2 Different coupling strength for the spin-2 case

After the presentation of the results for the different spin/parity cases, we turn to discuss the possibility of changing, in the spin-2 case, the strength of the coupling to the different parts of the energy-momentum tensor. Since, as said in Sec. 3.1, the spin-2 case is almost entirely gluon-initiated, one would expect, at least at the LO, almost no change when the coupling to quarks, κ_q, is suppressed. In the other extreme case, when instead the coupling to gluons (κ_g) is suppressed, one would expect a behaviour similar to that of the quark-initiated spin-1 cases. Even if this is correct at LO, NLO corrections completely change the picture, as shown by Fig. 2 (where the aMC@NLO predictions, matched with Herwig 6[15,16], are shown): as soon as one moves away from the equal-coupling case, the transverse momentum distribution shows a very hard tail. This tail is the consequence of a unitarity-violating behaviour of the real-emission matrix-elements (to which terms proportional to both κ_q and κ_g contribute, arising when $\kappa_q \neq \kappa_g$. In this case, the LO (+PS) prediction does not catch this feature.

4 Conclusion

We have outlined a new approach to study the properties of the Higgs boson, within an effective theory approach. Our approach is generic and model independent, the only assumption being the possible new states of the theory to be heavier than our theory cutoff Λ. We have shown predictions for the different spin/parity cases, finding good agreement between MLM merging and aMC@NLO matching procedures.Due to the lack of space, we have not presented in these proceedings any plot relative to observables related with the decay products. Nevertheless the decay of the Higgs boson can be included in the computation keeping full spin-correlations. MLM matched samples can be generated automatically by MadGraph 5 and special aMC@NLO codes have been prepared and made available, for the different spin/parity cases and with different decays of the Higgs boson, on the aMC@NLO website[17].

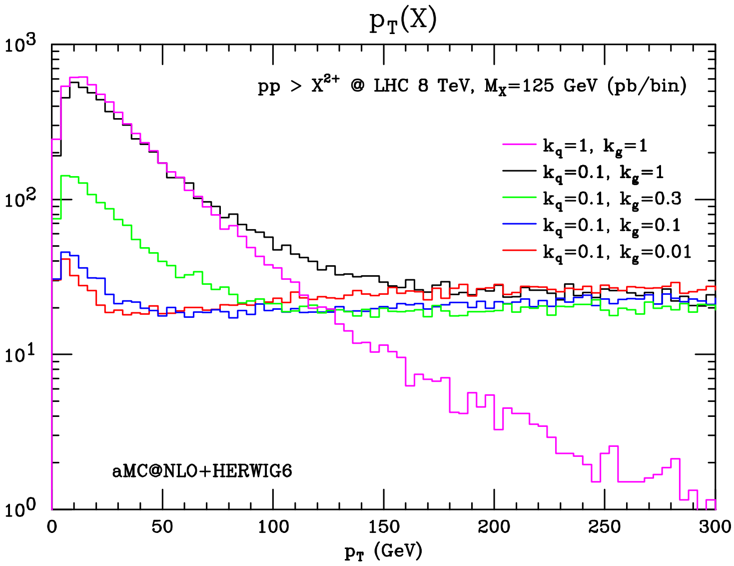

Figure 2: Transverse momentum distribution for a spin-2 Higgs boson, with various values of the coupling strength to quarks and gluons. Distributions are obtained with aMC@NLO and showered with Herwig 6.

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