Physics Letters B 770 (2017) 507–513

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

NLO predictions for the production of a spin-two particle at the LHC

Goutam Das [a], Céline Degrande [b], Valentin Hirschi [c], Fabio Maltoni [d], Hua-Sheng Shao [e,*]

[a] Theory Division, Saha Institute of Nuclear Physics, 1/AF Bidhan Nagar, Kolkata 700 064, India
[b] Institute for Particle Physics Phenomenology, Department of Physics Durham University, Durham DH1 3LE, United Kingdom
[c] SLAC, National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025-7090, USA
[d] Centre for Cosmology, Particle Physics and Phenomenology (CP3), Université catholique de Louvain, Belgium
[e] Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland

ARTICLE INFO

Article history:
Received 1 June 2016
Received in revised form 7 April 2017
Accepted 2 May 2017
Available online 8 May 2017
Editor: G.F. Giudice

Keywords:
LHC
Spin-two
QCD

ABSTRACT

We obtain predictions accurate at the next-to-leading order in QCD for the production of a generic spin-two particle in the most relevant channels at the LHC: production in association with coloured particles (inclusive, one jet, two jets and $t\bar{t}$), with vector bosons ($Z, W^{\pm}, \gamma$) and with the Higgs boson. We present total and differential cross sections as well as branching ratios as a function of the mass and the collision energy also considering the case of non-universal couplings to standard model particles. We find that the next-to-leading order corrections give rise to sizeable K factors for many channels, in some cases exposing the unitarity-violating behaviour of non-universal couplings scenarios, and in general greatly reduce the theoretical uncertainties. Our predictions are publicly available in the MadGraph5_aMC@NLO framework and can, therefore, be directly used in experimental simulations of spin-two particle production for arbitrary values of the mass and couplings.

1. Introduction

After the discovery of the 125 GeV Higgs boson at the LHC [1,2], the main task of Run II is to explore higher energy scales searching for physics beyond the Standard Model (SM). Evidence for new physics could be gathered via accurate measurements of the interactions among SM particles or from the detection of new particles. The existence of new particles at the TeV scale is widely motivated by both theoretical and experimental issues of the SM. While no significant evidence for new resonances has been reported at the LHC so far, searches are actively pursued by the experimental collaborations with approaches that are as model independent as possible [3,4]. For example, heavy colour-singlet states of arbitrary spins are searched for in several decay channels, including very clean ones (such as dilepton and diphoton) as well as more challenging ones, from diboson (WW, ZZ, HZ, HH) to di-jet (with or without b-tags) and $t\bar{t}$ signatures. Finally, associated production with SM particles are also often considered.

Robust interpretations of the corresponding experimental bounds obtained on rates ($\sigma \cdot$ BR) need model assumptions on the one hand and accurate and precise predictions for the cross sections and decay rates, on the other. Most of the interpretations for spin-0 and spin-1 models are based on next-to-leading and next-to-next-to-leading order predictions, as these can be easily obtained by generalising SM calculations performed for the Higgs boson (in the SM or SUSY) and for the vector bosons.

Interpretations for spin-two resonances, however, are typically performed via leading order computations, which due to their low accuracy and precision lead to a systematic loss in reach. A complementary limitation also exists for dedicated spin-two searches in the context of the many theoretical models predict the presence of massive spin-two resonances. The Kaluza–Klein excitations of the graviton and the composite bound state from strong dynamics are well-known examples of such scenarios. In this case, having accurate predictions can improve the experimental selections and significantly increase the sensitivity of the searches. In addition, having predictions at hand for other production mechanisms or decay modes can provide ideas for new signatures to be looked for, especially in the case of the detection of a signal.

The aim of this Letter is to provide for the first time a complete implementation of the Lagrangian of a generic spin-two particle so that all the relevant production channels for the LHC can be accurately simulated at Next-to-Leading Order (NLO) in QCD. In this context, accurate predictions and in particular event generators at least at NLO in QCD and matched to Parton Showers (PS)

* Corresponding author.
E-mail address: huasheng.shao@cern.ch (H.-S. Shao).

http://dx.doi.org/10.1016/j.physletb.2017.05.007
0370-2693/

are necessary to obtain simulations that can directly be used by the experimental collaborations to allow information to be efficiently extracted from experimental data. While predictions for generic classes of bosonic resonances have become available in the last years, *e.g.* [5] and several results are known in the literature [6–17], a completely general setup for the calculation at NLO in QCD of processes involving a spin-two particle has still been lacking. Especially, NLO results with PS effects are new for almost all processes presented here, where only the inclusive spin-two particle production in the universal coupling case is in exception. Moreover, $2 \to 3$ processes computed here are achieved at NLO accuracy for the first time in this Letter, while other processes like $Y_2 + H/Z/W$ are also first available in the warped dimensional models by taking into account the QCD corrections. We stress that although the discovery itself could not need such an accurate Monte Carlo simulation, the characterisation of a new state, from the determination of its quantum numbers to the form and strength of its couplings, will require the best predictions to be available to the experimental community.

2. Theoretical framework

We consider the effective field theory of a massive spin-two particle Y_2 interacting with the SM fields. The kinetic term of Y_2 can be described by the well-known Fierz–Pauli Lagrangian, with the positive-energy condition $\partial_\mu Y_2^{\mu\nu} = 0$, and the interactions with SM fields are (V is a gauge field, while f are matter fields)

$$\mathcal{L}_{\rm V,f}^{Y_2} = -\frac{\kappa_{V,f}}{\Lambda} T_{\mu\nu}^{V,f} Y_2^{\mu\nu} \, ,$$

where $T_{\mu\nu}^{V}$ ($T_{\mu\nu}^{f}$) are the energy-momentum tensors of V (f), respectively, *i.e.*,

$$\begin{aligned} T_{\mu\nu}^{V} &= -g_{\mu\nu}\Big[-\frac{1}{4}F^{\rho\sigma}F_{\rho\sigma} + \delta_{m_V,0}\big(\left(\partial^\rho\partial^\sigma V_\sigma\right)V_\rho \\ &\quad + \frac{1}{2}\left(\partial^\rho V_\rho\right)^2\big)\Big] - F_\mu^\rho F_{\nu\rho} \\ &\quad + \delta_{m_V,0}\left[\left(\partial_\mu\partial^\rho V_\rho\right)V_\nu + \left(\partial_\nu\partial^\rho V_\rho\right)V_\mu\right], \\ T_{\mu\nu}^{f} &= -g_{\mu\nu}\left[\bar\psi_f\left(i\gamma^\rho D_\rho - m_f\right)\psi_f - \frac{1}{2}\partial^\rho\left(\bar\psi_f i\gamma_\rho\psi_f\right)\right] \\ &\quad + \left[\frac{1}{2}\bar\psi_f i\gamma_\mu D_\nu\psi_f - \frac{1}{4}\partial_\mu\left(\bar\psi_f i\gamma_\nu\psi_f\right) + (\mu\leftrightarrow\nu)\right], \end{aligned}$$

where the indices of other possible quantum numbers (such as colour) are understood and $F_{\mu\nu}$ is the field strength of V. In the SM, the gauge fields V are $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ ElectroWeak (EW) gauge bosons (W, B) or the $\mathrm{SU}(3)_C$ gluon g, while the matter fields f are quarks, leptons and left-handed neutrinos. The gauge-fixed term proportional to the Kronecker delta function $\delta_{m_V,0}$ in $T_{\mu\nu}^{V}$ indicates that it is needed only when V is massless $m_V = 0$ (*i.e.*, $V = g, \gamma$). The Y_2 can also interact with the SM Higgs doublet Φ via

$$\mathcal{L}_{\Phi}^{Y_2} = -\frac{\kappa_H}{\Lambda} T_{\mu\nu}^{\Phi} Y_2^{\mu\nu} \, ,$$

where the energy-momentum tensor $T_{\mu\nu}^{\Phi}$ is

$$T_{\mu\nu}^{\Phi} = D_\mu\Phi^\dagger D_\nu\Phi + D_\nu\Phi^\dagger D_\mu\Phi - g_{\mu\nu}(D^\rho\Phi^\dagger D_\rho\Phi - V(\Phi)) \, .$$

After spontaneous symmetry breaking, one gets the mass eigenstates of EW bosons ($Z, W^\pm, \gamma$) and SM Higgs boson H. In addition, when working in the Feynman gauge and at 1-loop level, the extra interaction of Y_2 and Fadeev–Popov (FP) ghost fields is necessary (*e.g.* Refs. [18,19]),

$$\mathcal{L}_{\rm FP}^{Y_2} = -\frac{\kappa_V}{\Lambda} T_{\mu\nu}^{\rm FP} Y_2^{\mu\nu} \, ,$$

where

$$\begin{aligned} T_{\mu\nu}^{\rm FP} &= -g_{\mu\nu}\left[\left(\partial^\rho\bar\omega^a\right)\left(\partial_\rho\omega^a\right) - g_s f^{abc}\left(\partial^\rho\bar\omega^a\right)\omega^b V_\rho^c\right] \\ &\quad + \left[\left(\partial_\mu\bar\omega^a\right)\left(\partial_\nu\omega^a\right) - g_s f^{abc}\left(\partial_\mu\bar\omega^a\right)\omega^b V_\nu^c + (\mu\leftrightarrow\nu)\right], \end{aligned}$$

ω being the FP ghost of the gluon field $V = g$ and g_s the strong coupling constant.

Our implementation builds upon the FeynRules package [20,21] and the NLoCT program [22] which are used to generate the UFO model [23] as well as the counterterms for the renormalisation and the rational term R_2. Some extended functionalities have been implemented in NLoCT to handle the effective Lagrangian of a spin-two particle. A point worth of stressing concerns the renormalisation. With universal couplings, *e.g.*, $\kappa_g = \kappa_q$ no extra renormalisation procedure is needed beyond the usual ones of the SM as the spin-two current is conserved. On the contrary, for non-universal couplings, the spin-two current is not conserved and specific renormalisation constants need to be introduced to cancel left-over ultraviolet divergences [5]. These extra couplings are renormalised as

$$\delta\kappa_g = \frac{\alpha_s}{3\pi} T_F \sum_q \left(\kappa_g - \kappa_q\right)\left(\frac{1}{\epsilon} - \gamma_E + \log 4\pi + \log\frac{\mu_R^2}{m_{Y_2}^2}\right),$$

$$\delta\kappa_q = \frac{2\alpha_s}{3\pi} C_F \left(\kappa_q - \kappa_g\right)\left(\frac{1}{\epsilon} - \gamma_E + \log 4\pi + \log\frac{\mu_R^2}{m_{Y_2}^2}\right),$$

by NLoCT, where $C_F = \frac{4}{3}, T_F = \frac{1}{2}$. Our implementation is general and allows for models with non-universal couplings case to be studied at NLO accuracy. The finite part of these counterterms identifies the renormalisation scheme where the couplings $\kappa_{g,q}$ are defined as $\kappa_{g,q}(m_{Y_2})$ and it is chosen so that these couplings do not run at this order in perturbation theory.

The corresponding spin-two UFO model [24] is directly employable in the MadGraph5_aMC@NLO framework [25] to perform phenomenological studies at NLO QCD accuracy including matching to PS. One-loop contributions are calculated numerically by the MadLoop module [26] with the tensor integrand-level reduction method [27,28] that was implemented in Ninja [29,30]. The real emission contributions are calculated with the Frixione–Kuntz–Signer (FKS) subtraction method [31,32] implemented in MadFKS [33]. Finally, the MC@NLO formalism [34] is employed to perform the matching between fixed-order NLO calculations and PS, hence making event generation possible.

3. Production at LHC

We now present predictions for the production of a spin-two particle Y_2 as a function of mass as well centre-of-mass energy at a hadron collider, for a wide range of production channels. We will then focus on the LHC with a centre-of-mass energy of $\sqrt{s}$ =13 TeV. The (N)LO total cross sections of various Y_2 production processes in the universal coupling case (*i.e.* $\frac{\kappa_i}{\Lambda} = 1\ \mathrm{TeV}^{-1}$) are given in Table 1 for 500 GeV, 750 GeV and 1 TeV resonance masses and summarised in Fig. 1. We also consider the minimal "basis" of predictions, the universal couplings $((\frac{\kappa_1}{\Lambda}, \frac{\kappa_2}{\Lambda}) = (1,1)\ \mathrm{TeV}^{-1})$. The non-universal couplings cases $((\frac{\kappa_1}{\Lambda}, \frac{\kappa_2}{\Lambda}) = (1,0), (0,1)\ \mathrm{TeV}^{-1})$, where the definition of κ_1 and κ_2 are given in Table 2, are discussed later for the intermediate reference mass point of 750 GeV, see Fig. 2.

We have employed NLO PDF4LHC15 [35–41] set with 30+2 members to estimate the PDF and α_s uncertainties. Missing higher-order QCD corrections are estimated by independently varying