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$H \to \gamma\gamma$ beyond the Standard Model

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Summary. — We consider the $H \to \gamma\gamma$ decay process and the gluon fusion production of a light Higgs, and provide a general framework for testing models of new physics beyond the Standard Model. We apply our parametrisation to typical models extending the Standard Model in 4 and 5 dimensions, and show how the parametrisation can be used to discriminate between different scenarios of new physics at the Large Hadron Collider and at future Linear Colliders.

PACS `12.60.-i` – Model beyond the standard model.
PACS `12.60.Fr` – Extensions of electroweak Higgs sector.

1. – Introduction

The $H \to \gamma\gamma$ decay is one of the most important discovery channels at the Large Hadron Collider (LHC) if the decay channels into heavy gauge bosons are closed([1]). This mode is also a powerful probe of the electroweak symmetry breaking sector of the theory, because it is a loop-induced process, therefore it is sensitive to any particle with a large coupling to the Higgs; in the SM to the top and the W, and in any extension of the SM, to new particles that do couple strongly to the Higgs. Many models in fact predict the existence of partners of the top and W. Studying this channel will therefore give an indirect access to the mechanism underlying the electroweak symmetry breaking, complementary to the direct discovery of new states at the LHC. At the LHC, we also need to take into account the Higgs production mechanism. In the SM there are four main production mechanisms: gluon fusion ($gg \to H$), which dominates the inclusive production at LHC energies, weak vector boson fusion, weak boson associated production (WH, ZH) and top associated production ($t\bar{t}H$). At low luminosity, we shall therefore consider mainly the inclusive $H \to \gamma\gamma$ process. The interest of performing exclusive studies like the production via vector boson fusion, will be also discussed as it allows to

([1]) Detailed studies, including detector simulations, in the Standard Model (SM) and in its supersymmetric extensions are available [1].

better discriminate the kind of new physics that can be tested in the $H \to \gamma\gamma$ mode, especially when large integrated luminosity is available [2]. The main production process $gg \to H$ is a loop-induced process like the decay $H \to \gamma\gamma$, so it is sensitive to the same particles and physics. By introducing a new parametrisation of these loop processes, we studied the photon channel with the purpose of performing a model-independent analysis, allowing to determine the possibility and the limits for discriminating various scenarios of new physics and using simple formalism to calculate the contribution of the new heavy states given their spectrum. We will assume that the new physics only affects those two processes, and corrections to the other production and decay channels are ignored. In the SM, masses are uniquely generated by the coupling, so the contribution of heavy particles to $H \to \gamma\gamma$ and $H \to gg$ processes does not decouple for particle masses much larger than the Higgs boson one. In general extensions of the SM this is not necessarily the case and decays can therefore be sensitive to the mass scale of the new physics. Finally, the precise determination of the Higgs branching ratios at future Linear Collider will be an even more powerful discrimination tool, even when the new particles are well beyond the direct production threshold at the Linear Collider.

2. – Definitions and notations

To establish our notations, we will briefly review the decay of the Higgs in photons and gluons (the decay width in gluons is directly related to the gluon-fusion production cross-section at hadronic colliders). The decay widths can be written as

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| A_W(\tau_W) + \sum_{\text{fermions}} N_{c,f} Q_f^2 A_F(\tau_f) + \sum_{\text{NP}} N_{c,\text{NP}} Q_{\text{NP}}^2 A_{\text{NP}}(\tau_{\text{NP}}) \right|^2, \tag{1a}$$

$$\Gamma_{gg} = \frac{G_F \alpha_s^2 m_H^3}{16\sqrt{2}\pi^3} \left| \frac{1}{2} \sum_{\text{quarks}} A_F(\tau_f) + \sum_{\text{NP}} C(r_{\text{NP}}) A_{\text{NP}}(\tau_{\text{NP}}) \right|^2,$$

where $\tau_x = \frac{m_H^2}{4m_x^2}$, $N_{c,x}$ is the number of colour states in the colour representation, $C(r)$ is an $SU(3)$ colour factor (defined as $\text{Tr}[t_r^a t_r^b] = C(r)\delta^{ab}$ where t_r^a are the $SU(3)$ generators in the representation r), Q_x is the electric charge of the particle in the loop, and the functions $A_{F,W,S}(\tau)$(2) depend on the spin and couplings to the Higgs of the particle running in the loop. Note that G_F here is a numerical normalization of the widths, defined in terms of the SM Higgs VEV v_{SM} ($\sqrt{2}G_F = 1/v_{\text{SM}}^2$), and not the physical Fermi constant, which may receive corrections from the new physics. For the new physics contribution, we can write the A_{NP} functions for fermions and bosons without loss of generality, as $A_{\text{NP}} = \frac{v_{\text{SM}}}{m_{\text{NP}}} \frac{\partial m_{\text{NP}}}{\partial v} A_{F,W,S}$.

As the mass can be a generic function of v, this formula allows to treat a wide range of physical situations beyond the standard model, as long as the particle mass is at least partially generated by the Higgs VEV(3). When the mass of the new physics is not proportional to the Higgs VEV, A_{NP} will decouple for large masses. Note also that

(2) These functions are introduced in [3] for SM particles and given in [4].
(3) Those formulae are valid for a SM Higgs sector; when the Higgs sector is extended, and for scalars which do mix with the Higgs doublet, more general formulae apply [4].

in general $v \neq v_{\rm SM}$, however this difference only introduces higher-order corrections in an expansion for large new physics scale. The new physics can be parametrised by two independent parameters describing the contribution of the new particles to the two decay widths. Here we normalise the new contribution to the top one because the top gives the main contribution to the SM amplitudes, and any new physics, which addresses the problem of the Higgs mass naturalness, will have a tight relation with the top. The widths can be rewritten as

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| A_W(\tau_W) + 3\left(\frac{2}{3}\right)^2 A_t(\tau_t)\,[1+\kappa_{\gamma\gamma}] + \ldots \right|^2, \tag{2a}$$

$$\Gamma_{gg} = \frac{G_F \alpha_s^2 m_H^3}{16\sqrt{2}\pi^3} \left| \frac{1}{2} A_t(\tau_t)\,[1+\kappa_{gg}] + \ldots \right|^2, \tag{2b}$$

where the dots stand for the negligible contribution of the light quarks and leptons, and the coefficients κ can be written as

$$\kappa_{\gamma\gamma} = \sum_{\rm NP} \frac{3}{4} N_{c,{\rm NP}} Q_{\rm NP}^2 \frac{v_{\rm SM}}{m_{\rm NP}} \frac{\partial m_{\rm NP}}{\partial v} \frac{A_{F,W,S}(m_{\rm NP})}{A_t}, \tag{3a}$$

$$\kappa_{gg} = \sum_{\rm NP} 2C(r_{\rm NP}) \frac{v_{\rm SM}}{m_{\rm NP}} \frac{\partial m_{\rm NP}}{\partial v} \frac{A_{F,W,S}(m_{\rm NP})}{A_t}, \tag{3b}$$

where the ratio of A functions depends on the spin and masses of the new particles (and top). In this way, if the experimental data allow to point to a specific quadrant in the $\kappa_{\gamma\gamma}$–κ_{gg} parameter space, we can have a hint of the underlying new physics model. Note also that positive κ's enhance the top contribution, therefore inducing an enhancement in the gluon channel but a suppression in the photon one, where there is a numerical cancellation between the dominant W contribution and the top one. The presence of new physics often modifies the tree level relation between the mass of the SM particles and the Higgs VEV and it is cast also in the κ parameters [4]. Note that the modification of the SM couplings which affect the other production channels and the branching ratio in heavy gauge bosons, will have a minor impact on our analysis. Their inclusion will be necessary in a later model-dependent analysis.

The LHC will measure the inclusive $\gamma\gamma$ Higgs decays and the new physics will modify both the total production cross-section and the branching fraction in photons. At large luminosities, one may also measure the $\gamma\gamma$ decays in a specific production channel, for instance the vector boson fusion one: in this case one may probe directly the branching ratios. Here we will assume that the new physics significantly contributes only to the loop in the gluon fusion channel, while the other cross-sections are unaffected. The total production cross-section normalised with the SM one, that we denote as $\bar{\sigma}$, can be written as

$$\bar{\sigma}(H) \simeq \left(\frac{(1+\kappa_{gg})^2 \sigma_{gg}^{\rm SM} + \sigma_{VBF}^{\rm SM} + \sigma_{VH,\bar{t}tH}^{\rm SM}}{\sigma_{gg}^{\rm SM} + \sigma_{VBF}^{\rm SM} + \sigma_{VH,\bar{t}tH}^{\rm SM}} \right). \tag{4a}$$

In the SM the Higgs branching fraction in photons amounts to $2 \cdot 10^{-3}$. In the presence of new physics, the branching fraction will also be sensitive to the gluon loop via the total width, as the gluon channel is significant: it amounts to 7% of the total for $m_H =$

115 GeV, decreasing to 3% for $m_H = 150\,\text{GeV}$. Also in this case, we define a branching ratio normalised to the SM value, $\overline{BR}$. For instance,

$$\overline{BR}(H \to \gamma\gamma) = \frac{\Gamma^{\rm NP}_{\gamma\gamma}}{\Gamma^{\rm SM}_{\gamma\gamma}} \frac{\Gamma^{\rm SM}_{\rm tot}}{\Gamma^{\rm NP}_{gg} + \Gamma^{\rm NP}_{\gamma\gamma} + \Gamma^{\rm SM}_{\rm others}} \tag{5a}$$

$$\simeq \left(1 + \frac{\kappa_{\gamma\gamma}}{\frac{9}{16}A_W(\tau_W) + 1}\right)^2 \frac{\Gamma^{\rm SM}_{\rm tot}}{(1+\kappa_{gg})^2\Gamma^{\rm SM}_{gg} + (\Gamma^{\rm SM}_{\rm tot} - \Gamma^{\rm SM}_{gg})}\,. \tag{5b}$$

3. – Survey of models of new physics

To illustrate the usefulness of our proposed parametrisation and its impact of new physics on the Higgs search, we studied the values of the two parameters $\kappa_{\gamma\gamma}$ and κ_{gg} in a variety of models of new physics:

- [♦] A fourth generation [5,6] (the result is independent of the masses).
- [♣] Supersymmetry in the MSSM golden region: we only included the contribution of the stops with the spectrum given by the benchmark point in [7]. The result is very sensitive to the parameters in the superpotential and in the SUSY breaking terms, therefore the general MSSM will cover a region of the parameter space.
- [▲] Simplest Little Higgs [8], the result scales with the W' mass (in the plots, $m_{W'} = 2\,\text{TeV}$) and [$*$] Littlest Higgs [9], the result scales with the symmetry breaking scale f: for a model with T-parity we use $f = 500\,\text{GeV}$, without T-parity $f = 5\,\text{TeV}$.
- [■] Colour octet model [10], the result depends on 2 free parameters: for illustration we use in the plots $X_1 = 1/9$ and $X_2 = 1/36$ (see [4]).
- [▶] Lee-Wick Standard Model [11,12], $M_{\widetilde{W}} \sim 1\,\text{TeV}$ for illustration.
- [$\otimes$] Universal Extra Dimension model [13], where only the top and W resonances contribute: here we set $m_{KK} = 500\,\text{GeV}$.
- [★] The model of Gauge Higgs unification in flat space in ref. [14], where only the W and top towers contribute, with the first W resonance at 2 TeV and [•] the Minimal Composite Higgs [15] (Gauge Higgs unification in warped space) with the IR brane at $1/R' = 1\,\text{TeV}$: only W and top towers contribute significantly.
- [▼] A flat (W' at 2 TeV) and [♠] warped ($1/R'$ at 1 TeV) version of brane Higgs models [16], in both cases the hierarchy in the fermionic spectrum is explained by the localisation, and all light fermion towers contribute.

In the numerical results, the value of the mass of the new particles is at or around the lower bound given by precision electroweak tests. In many cases, the result scales like the inverse squared mass (except for the fourth generation) and only depends on one mass scale. It is insensitive to other free parameters present in the model (except for supersymmetry and the colour octet model, where a wide region of the parameter space may be covered). Therefore, if we could measure with enough accuracy the two parameters, we may be able to distinguish between models, displayed in fig. 1. So it is crucial to understand the reach and discrimination power of the LHC in this parameter space. For

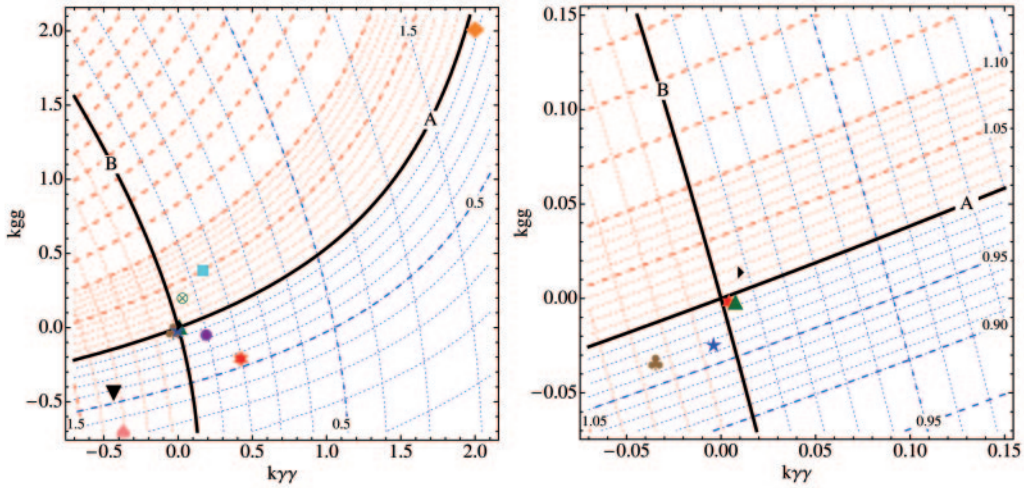

Fig. 1. – $\kappa_{\gamma\gamma}$ and κ_{gg} at the LHC for a light Higgs ($m_H = 120\,\text{GeV}$). The two solid lines correspond to the SM values of the inclusive $\gamma\gamma$ channel (A), and the vector boson fusion production channel (B). On the left panel, the dashed lines are spaced by 0.5, while the dotted ones by 0.1. On the right, we zoomed near the SM point.

an integrated luminosity of $10\,\text{fb}^{-1}$ we can expect to measure the inclusive cross-section $\sigma(pp \to H \to \gamma\gamma)$ with 10% accuracy with respect to the Standard Model [17]. We plotted the inclusive cross-section normalised by the SM value in the $\kappa_{\gamma\gamma}$-κ_{gg} parameter space for a light Higgs ($m_H = 120\,\text{GeV}$) in fig. 1: many models lie very far from such line, and a 10% measurement would allow to probe new physics masses up to few TeV in some cases. Note that many of the models, in the $\kappa_{\gamma\gamma} < \kappa_{gg}$ region, predict a reduction of the inclusive signal: the measurement of an enhancement at the LHC may be a sign of unexpected new physics. Note also that some very different models can accidentally give the same prediction, like the fourth generation case. Therefore, we need to measure another observable at the LHC in order to distinguish such models. For the light Higgs case, in fig. 1 we plotted the vector boson fusion channel, which is sensitive to the $\gamma\gamma$ branching fraction directly. This channel is orthogonal to the inclusive one, and therefore offers the best discrimination power. However a detailed study of this channel, as required for the precise determination of the κ parameters demands a high luminosity [18]. A precise study requires a detailed simulation and will not be given here. For a heavier Higgs near the VV-threshold the decay in massive gauge bosons $H \to V^*V$ (with one virtual) becomes relevant and offers another discovery channel. The Linear Collider will be able to measure directly the branching fractions into gluons and photons and have a much better chance to discriminate between models than the LHC. After $100\,\text{fb}^{-1}$ of data, in the photon channel an accuracy of 5–7% is expected (reduced to 2–3% with the $\gamma\gamma$ collider option), while the gluon channel offers a 2% accuracy (assuming SM values) [19]. We compared the models with the ILC measurements in [4].

4. – Conclusions

We studied the contribution of new physics to the $H \to \gamma\gamma$ and $H \to gg$ decay widths (the latter is proportional to the production cross-section). We propose a convenient parameterisation of the new contributions, by introducing two independent parameters

$\kappa_{\gamma\gamma}$ and κ_{gg}. Such a simple parameterisation neglects contributions to the tree level processes, such as production channels other than gluon fusion and decays, that are generically present in models of new physics. This parameterisation is especially useful in models where such effects are small. They could be taken into account in a later model-dependent analysis once a specific model or class of models is preferred by data. On more general grounds, more parameters can be introduced and the analysis extended in a similar fashion. In order to illustrate the power of a model-independent measurement at the LHC (and at future Linear Colliders) we compiled a necessarily incomplete survey of models of new physics both in 4 and 5 dimensions. Our results show that there are classes of models pointing in different quadrants of the parameter space, and that the deviations from the SM predictions can be as large as 50%. In this parameterisation it would be easy to discover hints of unconventional or unexpected new physics, independently of direct and/or indirect signals in other channels.

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