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Light Higgs pair production in the 2HDM: LHC *vs.* $\gamma\gamma$ collider

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Summary. — We discuss pair production of light CP-even Higgs bosons in the framework of the two-Higgs doublet model in the limit $\sin(\beta - \alpha) = 1$, where this Higgs resembles very much the Standard Model Higgs. Possible measurements of non-decoupling effects at the Large Hadron Collider and at a future $\gamma\gamma$ collider are compared.

PACS `12.60.Fr` – Extensions of electroweak Higgs sector.
PACS `14.80.Cp` – Non-standard-model Higgs bosons.

1. – Introduction

The search for the Higgs boson is about to start at CERN's Large Hadron Collider (LHC) while the Tevatron [1] has recently excluded a 162–166 GeV Standard Model (SM) Higgs at 95% CL. The Higgs mass region probed will obviously grow as data is being collected and a Higgs boson can still be discovered at the Tevatron. If a Higgs boson is found we would like to understand which underlying mechanism gives mass to all known particles by characterizing the Higgs potential. In this work we will focus on one possible extension of the Higgs sector where one more Higgs doublet is added to the potential. This eight-parameter CP-conserving two-Higgs double model (2HDM), has in its spectrum two CP-even scalars, h and H, one CP-odd scalar A and a pair of charged Higgs bosons, $H^\pm$ and has no tree-level flavour changing neutral current (FCNC). Our main purpose is to compare Higgs pair production at the LHC via gluon fusion, $pp(gg) \to hh$, with pair production at a photon collider via $\gamma\gamma \to hh$. We will concentrate on the scenario where the lightest CP-even Higgs boson is similar to the SM Higgs regarding its couplings to gauge bosons, fermions and also the Higgs self-couplings. We will perform a comparative study on the possibility of measuring non-decoupling effects in each collider.

2. – The two-Higgs doublet model

The most general 2HDM is explicitly CP-violating. Even if explicit CP-violating interactions are not allowed in the potential, spontaneous CP-breaking can still occur. However, one can force the CP minimum conditions to have no solution by imposing the exact Z_2 discrete symmetry $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$ [2, 3]. The soft breaking of this symmetry by the dimension two terms $[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}]$ can lead to a CP-conserving or to a spontaneously broken CP potential [4, 5]. In this work we choose to work with a minimum that does not break CP-invariance nor electric charge and that was shown to be stable at tree level [6, 7]. Under these constraints, the most general renormalizable potential which is invariant under $SU(2) \otimes U(1)$ can be written as

$$\text{(1)}\quad V(\Phi_1,\Phi_2) = m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{1}{2}\lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}\right],$$

where Φ_i, $i = 1, 2$ are complex $SU(2)$ doublets with four degrees of freedom each and all m_i^2, λ_i and m_{12}^2 are real. From the initial eight degrees of freedom, if the $SU(2)$ symmetry is broken, we end up with two CP-even Higgs states usually denoted by h and H, one CP-odd state, A, two charged Higgs bosons, $H^\pm$ and three Goldstone bosons. This potential has seven independent parameters which we choose to be the four masses m_h, m_H, m_A, $m_{H^\pm}$, $\tan\beta = v_2/v_1$, α and M^2. The angle β is the rotation angle from the group eigenstates to the mass eigenstates in the CP-odd and charged sector. The angle α is the corresponding rotation angle for the CP-even sector. The parameter M^2 is defined as $M^2 = m_{12}^2/(\sin\beta\cos\beta)$ and is a measure of how the discrete symmetry is broken. The potential with $M^2 = 0$ has an exact Z_2 symmetry and is always CP-conserving [2]. The discrete symmetry imposed to the potential, when extended to the Yukawa Lagrangian guarantees that FCNCs are not present as fermions of a given electric charge couple to no more than one Higgs doublet [8]. There are a total of four possible combinations [9] and therefore four variations of the model. We define as Type I the model where only the doublet ϕ_2 couples to all fermions; Type II is the model where ϕ_2 couples to up-type quarks and ϕ_1 couples to down-type quarks and leptons; a Type III model is built such that ϕ_2 couples to up-type quarks and to leptons and ϕ_1 couples to down-type quarks and finally in a Type IV model, ϕ_2 couples to all quarks and ϕ_1 couples to all leptons.

2·1. *Experimental and theoretical constraints.* – We will now briefly discuss the main experimental and theoretical constraints which affect the parameter space of the 2HDM (see [10] for a more recent and detailed discussion). The two most restrictive theoretical constraints are the ones arising from demanding tree-level vacuum stability [11] and tree-level unitarity [12] of the potential. We have also imposed perturbativity on the parameters of the potential by choosing $|\lambda_i| < 8\pi$. In fig. 1 we show how vacuum stability and perturbative unitarity constrain the parameter space of the model in the limit $\sin(\beta - \alpha) = 1$. In the left panel, where $M^2 > 0$, it is clear that large values of $\tan\beta$ are allowed. However, if $\tan\beta$ is very large, M has to be very close and below the mass of the heavy CP-even Higgs boson. Although very restrictive, it should be noted that the MSSM lives in such a region. In the right panel we consider the case $M^2 < 0$. Contrary to the previous scenario, now M is much less constrained but $\tan\beta$ has to be rather small. We show the limits for $\tan\beta$ for two values of m_H and the conclusion is that as the masses and/or M grow, the maximum allowed value of $\tan\beta$ becomes smaller. The dependence on the remaining parameters of the 2HDM is much weaker and was discussed in [10]. Regarding the experimental bounds the most restrictive are: new contributions to the ρ parameter stemming from Higgs states [13] have to comply with the current limits from precision measurements [14]: $|\delta\rho| \lesssim 10^{-3}$; values of $\tan\beta$ smaller

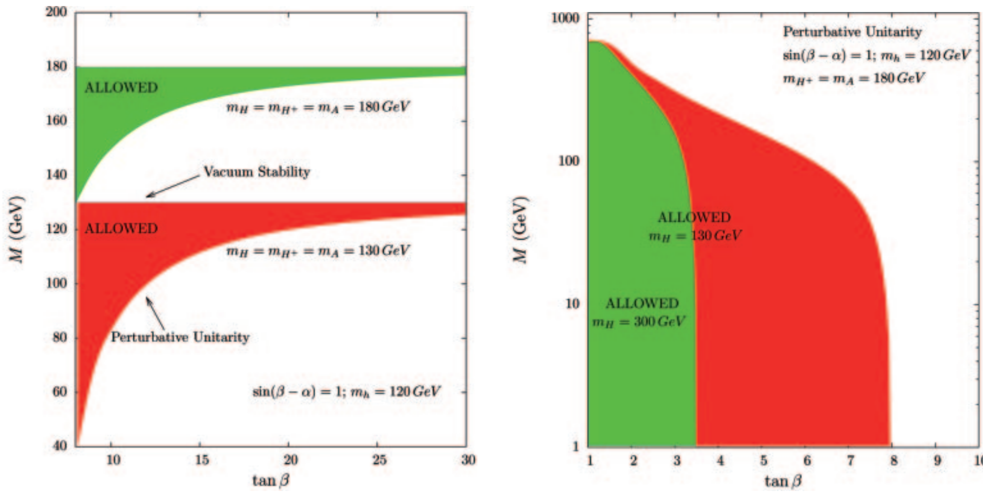

Fig. 1. – Perturbative unitarity and vacuum stability limits for M^2 as a function of $\tan\beta$ with $\sin(\beta-\alpha)=1$. On the left panel $M^2>0$ and on the right panel $M^2<0$.

than ≈ 1 together with a charged Higgs with a mass below 100 GeV are disallowed both by the constraints coming from R_b (the b-jet fraction in $e^+e^- \to Z \to$ jets) [15, 16] and from $B_q\bar{B}_q$ mixing [17] for all Yukawa versions of the model. It has been shown in [18] that data from $B \to X_s\gamma$ impose a lower limit of $m_{H^\pm} \gtrsim 290$ GeV in models where the quarks have type II or type III Yukawa couplings. In models type I and IV charged Higgs bosons as light as 100 GeV are still allowed.

3. – Results and discussion

The tree and one-loop amplitudes were generated and calculated with the packages FeynArts [19] and FormCalc [20]. The scalar integrals were evaluated with LoopTools [21]. NLO QCD corrections to double Higgs production were calculated in [22] for the SM and for the MSSM. The total K factor, in the large top mass limit, was shown to vary between 1.8 and 2 for the SM and for a Higgs mass between 70 and 200 GeV and could be directly applied to the 2HDM in the decoupling limit.

There is a limit in 2HDM where the lightest CP-even Higgs resembles very much the SM Higgs boson. In fact, by simply choosing $\cos(\beta-\alpha) \to 0$ we enforce the following conditions on the Higgs couplings: $g^{\rm SM}_{VVh} = g^{\rm 2HDM}_{VVh}$, $g^{\rm SM}_{\bar{f}fh} = g^{\rm 2HDM}_{\bar{f}fh}$, $g^{\rm SM}_{hhh} = g^{\rm 2HDM}_{hhh}$ and $g^{\rm 2HDM}_{Hhh} = 0$, where V is a gauge boson and f is a fermion. Therefore, if h is indeed the lightest scalar of the model, most Higgs production modes as well as its signature do not differ from the SM, except for marginal contributions like for instance the charged Higgs loop contributions to $h \to \gamma\gamma$ which could modify the Higgs branching ratio into photons. When working in an actual decoupling limit [23], where all other Higgs masses are at least well above M_Z, the loop contribution from the heavy states becomes negligible. In our discussion we will consider that H, A and $H^\pm$ are heavy and mass-degenerate with a common mass M_Φ.

Several studies have been carried out looking for non-decoupling effects in Higgs boson decays and Higgs self-interactions. Large loop effects were calculated in the framework of 2HDM [24] and may give indirect information on Higgs masses and the involved triple

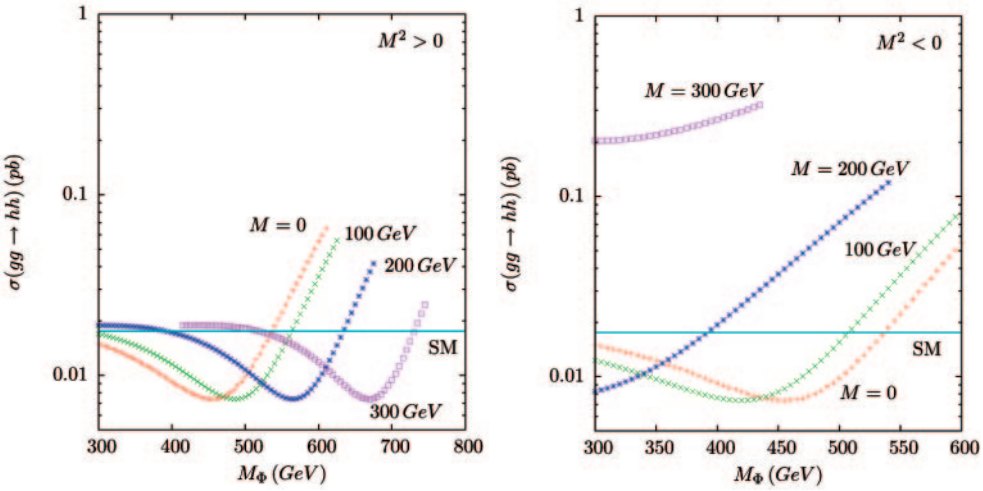

Fig. 2. – Cross-section for Higgs pair production via gluon fusion at the LHC as a function of the common mass M_ϕ, for a Higgs mass of 115 GeV. We take $\sin(\beta - \alpha) = 1$. In this limit, the cross-section is independent of $\tan\beta$. On the left panel $M^2 > 0$ and on the right panel $M^2 < 0$.

Higgs couplings. In this limit of 2HDM, Higgs pair production at the LHC via gluon fusion, $pp(gg) \to hh$, would give exactly the same results in 2HDM and in the SM [25]. At a $\gamma\gamma$ collider, the process $\gamma\gamma \to hh$ proceeds via charged Higgs loops and therefore non-decoupling effects could appear [26, 27] due to the hH^+H^- interaction. However, non-decoupling effects could still be revealed in the gluon fusion process. It was shown in [28] that there is a non-decoupling contribution to the triple Higgs self-coupling hhh. As shown in [28], the one-loop leading contributions from all heavy Higgs boson loops and also from top quark loops to the effective hhh coupling, can be written as

$$\lambda^{\text{eff}}_{hhh}(2HDM) = -\frac{3m_h^2}{\sqrt{2}v}\left\{1 + \frac{m_H^4}{12\pi^2 m_h^2 v^2}\left(1 - \frac{M^2}{m_H^2}\right)^3 + \frac{m_A^4}{12\pi^2 m_h^2 v^2}\left(1 - \frac{M^2}{m_A^2}\right)^3 + \frac{m_{H^\pm}^4}{6\pi^2 m_h^2 v^2}\left(1 - \frac{M^2}{m_{H^\pm}^2}\right)^3 - \frac{N_c M_t^4}{3\pi^2 m_h^2 v^2}\right\}, \tag{2}$$

where M_Φ and p_i represent the mass of the H, A or $H^\pm$ bosons and the momenta of the external Higgs lines, respectively. We note that in eq. (2) m_h is the renormalized physical mass of the lightest CP-even Higgs boson h. In our calculation of the cross-section of $pp \to hh$ in the decoupling limit, we ignore one-loop effects due to the $hb\bar{b}$ coupling and replace the hhh coupling by its effective coupling given in eq. (2).

In fig. 2 we present the cross-section for Higgs pair production via gluon fusion at the LHC as a function of the common mass M_ϕ, for a Higgs mass of 120 GeV and $\sin(\beta - \alpha) = 1$. In this limit, the only diference relative to the SM cross-section has its origin in the effective hhh vertex. Hence, for a fixed light Higgs mass the cross-section depends only on M^2 and M_ϕ. The abrupt cuts in the cross-section are due to the theoretical bounds. In the left panel we show the cross-section for $M^2 > 0$. The non-decoupling effects only appear for M_Φ above 500 GeV—they could go up to eight

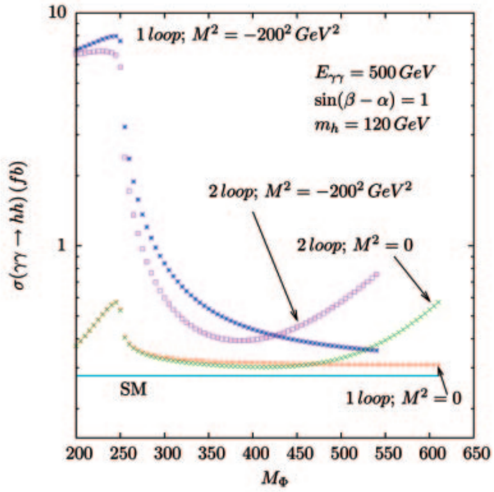

Fig. 3. – Total cross-section for Higgs pair production at a 500 GeV $\gamma\gamma$ collider, for a 120 GeV Higgs. We take $\sin(\beta-\alpha)=1$ and several values of M^2 with and without the hhh effective vertex.

times the SM cross-section but only in small intervals of M_Φ. In the right plot we show the results for $M^2 < 0$. In this case the enhancement can reach more than ten times the SM cross-section and it could happen for small values of M_Φ. Therefore, for all positive M^2 and for negative M^2 below $\approx |200|$ GeV, non-decoupling effects show only for M_Φ above ≈ 500 GeV. Only for very large and negative M^2 the effects occur for smaller values of M_Φ.

Higgs pair production in a photon-photon collider in the decoupling limit of the 2HDM was first studied in [26]. Those studies were combined and extended in [27] to the general 2HDM scenario. In fig. 3 we present the total cross-section for Higgs pair production at a 500 GeV $\gamma\gamma$ collider, for a 120 GeV Higgs and $\sin(\beta-\alpha)=1$. Several values of M^2 with and without the hhh effective vertex are shown. It is well known that a measurement of the triple Higgs coupling is possible at a $\gamma\gamma$ collider [29]. Hence, fig. 3 shows that for $M^2 \le 0$ non-decoupling effects can be detected in a 500 GeV $\gamma\gamma$ collider (except perhaps in some small intervals of M_ϕ). Contrary to what happens in gluon fusion, taking into account all bounds on the parameter space, it will not be easy to detect non-decoupling effects for positive M^2. The most important difference is however that the biggest enhancement in this case is due to the charged Higgs loop contribution that, in turn, depends heavily on the collider energy—as the energy decreases it becomes harder to measure non-decoupling effects. In a photon collider, it is not the absolute value of M_Φ that determines the capability of measuring non-decoupling effects but rather the relation between M_Φ and the collider energy. Therefore, with a tuneable center-of-mass energy, a scan could be performed looking for non-decoupling effects that would exclude a significant region of the 2HDM parameter space.

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