Searching for Anomalous Higgs Couplings in Peripheral Heavy Ion Collisions at the LHC.

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Abstract

We investigate the sensitivity of the heavy ion mode of the LHC to anomalous Higgs boson couplings to photons, $H\gamma\gamma$, through the analysis of the processes $\gamma\gamma \rightarrow b\bar{b}$ and $\gamma\gamma \rightarrow \gamma\gamma$ in peripheral heavy ion collisions. We suggest cuts to improve the signal over background ratio and determine the capability of LHC to impose bounds on anomalous couplings by searching for a Higgs boson signal in these modes.

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I. INTRODUCTION

The Higgs boson is the only particle in the Standard Model (SM) that has not yet been confirmed experimentally. It is responsible for the mass generation of fermions and gauge bosons. The search for the Higgs boson is the main priority in high energy experiments and hints of its existence may have been already seen at LEP \cite{1} at around $m_H \sim 115$ GeV. However, once found the detailed study of its couplings could give information on the mass generation mechanism and on physics beyond the Standard Model.

An intermediate-mass Higgs boson could also be produced in peripheral heavy ion collisions through photon-photon interactions \cite{2,3}. This possibility, in the context of the SM, has been explored in detail in the literature \cite{4–6}, with the general conclusion that the chances of finding the standard model Higgs in the photon-photon case are marginal.

However, the Standard Model is only an effective low energy theory of a more complete model and one expects deviations from its predictions. A convenient way to parameterize deviations of the Standard Model predictions is the effective theory approach \cite{7}. In this scenario, we assume that the existence of new physics, associated with a high–energy scale $\Lambda$, can manifest itself at low energies via the process of integrating-out heavy degrees of freedom. These effects are then described by effective operators involving the spectrum of particles belonging to the low–energy theory. At this point we have two possibilities: either the Higgs boson is light and it should be included in the effective operators or the Higgs boson is heavy and should also be integrated out. In this work we will adopt the former possibility, where the gauge group $SU(2)_L \otimes U(1)_Y$ is linearly realized. In this case, the effective lagrangian will generate anomalous Higgs couplings.

In this Letter we explore the capabilities of peripheral heavy ion collisions in constraining anomalous Higgs couplings, which could in principle arise from new physics beyond the SM. We analyse the processes $\gamma\gamma \to b\bar{b}, \gamma\gamma$. After simulating the signal and background, we find optimal cuts to maximize their ratio. We show how to use energy and invariant mass spectra of the final state $b\bar{b}$ or photon pair in order to identify the presence of a Higgs boson and extract information about its couplings. Finally, we compare the bounds on the anomalous couplings that will be possible to extract from our analyses to bounds coming from other processes in different machines.

II. ANOMALOUS HIGGS COUPLINGS AND EFFECTIVE LAGRANGIANS

In the linear representation of the $SU(2)_L \otimes U(1)_Y$ symmetry breaking mechanism, the SM model is the lowest order approximation while the first corrections, which are of dimension six, can be written as

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n,$$

where the operators $\mathcal{O}_n$ involve vector–boson and/or Higgs–boson fields with couplings $f_n$ \cite{8}. This effective Lagrangian describes the phenomenology of models that are somehow close to the SM since a light Higgs scalar doublet is still present at low energies. Of the eleven possible operators $\mathcal{O}_n$ that are $P$ and $C$ even, only three of them modify the Higgs–boson couplings to photons \cite{9,10},

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\[ O_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi , \]
\[ O_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi , \]
\[ O_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi , \]

where \( \Phi \) is the Higgs doublet, \( \hat{B}_{\mu\nu} = i (g'/2) B_{\mu\nu} \), and \( \hat{W}_{\mu\nu} = i (g/2) \sigma^a W^a_{\mu\nu} \), with \( B_{\mu\nu} \) and \( W^a_{\mu\nu} \) being respectively the \( U(1)_Y \) and \( SU(2)_L \) field strength tensors. In the unitary gauge, the anomalous \( H\gamma\gamma \) coupling is given by

\[ L_{\text{eff}}^{HVV} = g H\gamma\gamma H A_{\mu\nu} A^{\mu\nu} , \]

where \( A_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \) and

\[ g_{H\gamma\gamma} = \frac{g M_W^2}{\Lambda^2} \left( s^2 (f_{BB} + f_{WW} - f_{BW}) \right) , \]

with \( g \) being the electroweak coupling constant and \( s \equiv \sin \theta_W \).

The operator \( O_{BW} \) contributes at tree level to the vector–boson two–point functions, and consequently is severely constrained by low–energy data \[11,9\]. The present 95% CL limits on these operators for \( 90 \text{ GeV} \leq m_H \leq 800 \text{ GeV} \) and \( m_{\text{top}} = 175 \text{ GeV} \) read \[12\],

\[ -1.0 \leq \frac{f_{BW}}{\Lambda^2} \leq 8.6 \text{ TeV}^{-2} . \]

The remaining operators can be indirectly constrained via their one–loop contributions to low–energy observables, which are suppressed by factors \( 1/(16\pi^2) \). Using the “naturalness” assumption that large cancellations do not occur among their contributions, we can consider only the effect of one operator at a time. In this case, the following constraints at 95% CL (in units of \( \text{TeV}^{-2} \)) arise \[12\]

\[ -24 \leq \frac{f_{WW}}{\Lambda^2} \leq 14 , \quad -79 \leq \frac{f_{BB}}{\Lambda^2} \leq 47 . \]

These limits depend in a complex way on the Higgs mass. The values quoted above for the sake of illustration were obtained for \( M_H = 200 \text{ GeV} \).

There are also limits coming from direct Higgs searches at LEP II \[13\], Tevatron \[14\] colliders. The combined analysis \[13\] of these signatures yields the following 95% CL bounds on the anomalous Higgs interactions (in \( \text{TeV}^{-2} \)):

\[ -7.5 \leq \frac{f_{WW(BB)}}{\Lambda^2} \leq 18 \]

for \( m_H \leq 150 \text{ GeV} \). These limits can be improved by a factor 2–3 in the upgraded Tevatron runs. The 95% CL bounds on the anomalous Higgs interactions (in \( \text{TeV}^{-2} \)) coming from direct Higgs searches via gluon gluon fusion at LHC \[16\] collider are

\[ -0.35 \leq \frac{f_{WW} + f_{BB} - f_{BW}}{\Lambda^2} \leq 0.46 \quad \text{and} \quad 2.8 \leq \frac{f_{WW} + f_{BB} - f_{BW}}{\Lambda^2} \leq 3.6 . \]

for \( m_H \leq 150 \text{ GeV} \).

The anomalous Higgs interaction \( f_{BW} \) can also be constrained by their effect on the triple gauge–boson vertices, but this is not the case for \( f_{WW} \) nor \( f_{BB} \).

In the following we will present our limits in terms of the relevant combination \( f = f_{WW} + f_{BB} - f_{BW} \) which is the only combination of anomalous couplings directly measured in the processes we study.
III. SIMULATIONS

In order to perform the Monte Carlo analysis, we have employed the package MadGraph \cite{17} coupled to HELAS \cite{18}. Special subroutines were constructed for the anomalous contribution which enable us to take into account all interference effects between the QED and the anomalous amplitudes. The phase space integration was performed by VEGAS \cite{19}.

The photon distribution in the nucleus can be described using the equivalent-photon or Weizsäcker-Williams approximation in the impact parameter space. Denoting the photon distribution function in a nucleus by \( F(x) \), which represents the number of photons carrying a fraction between \( x \) and \( x + dx \) of the total momentum of a nucleus of charge \( Ze \), we can define the two-photon luminosity through

\[
\frac{dL}{d\tau} = \int_{\tau}^{1} \frac{dx}{x} F(x) F(\tau/x), \tag{8}
\]

where \( \tau = \hat{s}/s \), \( \hat{s} \) is the square of the center of mass (c.m.s.) system energy of the two photons and \( s \) of the ion-ion system. The total cross section \( AA \to AA\gamma\gamma \to AX \), where \( X \) are the particles produced by the \( \gamma\gamma \) process, is

\[
\sigma(s) = \int d\tau \frac{dL}{d\tau} \hat{\sigma}(\hat{s}), \tag{9}
\]

where \( \hat{\sigma}(\hat{s}) \) is the cross-section of the subprocess \( \gamma\gamma \to X \).

We choose to use the conservative and more realistic photon distribution of Cahn and Jackson \cite{5}, including a prescription proposed by Baur \cite{3} for realistic peripheral collisions, where we must enforce that the minimum impact parameter \( (b_{\text{min}}) \) should be larger than \( R_1 + R_2 \), where \( R_i \) is the nuclear radius of the ion \( i \). A useful fit for the two-photon luminosity is:

\[
\frac{dL}{d\tau} = \left( \frac{Z^2\alpha}{\pi} \right)^2 \frac{16}{3\tau} \xi(z), \tag{10}
\]

where \( z = 2MR\sqrt{\tau} \), \( M \) is the nucleus mass, \( R \) its radius and \( \xi(z) \) is given by

\[
\xi(z) = \sum_{i=1}^{3} A_i e^{-b_i z}, \tag{11}
\]

which is a fit resulting from the numerical integration of the photon distribution, accurate to 2% or better for 0.05 < \( z \) < 5.0, and where \( A_1 = 1.909 \), \( A_2 = 12.35 \), \( A_3 = 46.28 \), \( b_1 = 2.566 \), \( b_2 = 4.948 \), and \( b_3 = 15.21 \). For \( z \) < 0.05 we use the expression (see Ref. \cite{5})

\[
\frac{dL}{d\tau} = \left( \frac{Z^2\alpha}{\pi} \right)^2 \frac{16}{3\tau} \left[ \ln \left( \frac{1.234}{z} \right) \right]^3. \tag{12}
\]

We consider Ca-Ca collisions since they are the most promising ones to put limits on the anomalous couplings because of the larger luminosity of the Ca beams. The energy for \( ^{40}\text{Ca} \) considered was 140 TeV/beam with a luminosity of \( 5 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1} \) at LHC \cite{20}. Since the collider will run in the heavy ion mode only a few months per year we will consider two possibilities for an integrated luminosity per year, one optimistic of 50 pb\(^{-1}\) year\(^{-1}\) and another more realistic of 10 pb\(^{-1}\) year\(^{-1}\).
IV. RESULTS

In our analyses we computed the SM and anomalous cross sections for the Higgs production via photon-photon fusion in peripheral heavy ion collisions at LHC using similar cuts and efficiencies as the ones ATLAS Collaboration \[21\] applied in their studies of Higgs boson searches.

We begin our analyses imposing the following acceptance cuts

\[ p_T^{(b)} > 25 \text{ GeV} \quad , \quad |\eta^{(b)}| < 2.5 \quad , \quad \Delta R_{\gamma\gamma(b\bar{b})} > 0.7 \quad , \]

and taking into account an efficiency for reconstruction and identification of one photon of 84\% and a b-tagging of 60\% \[21\].

In order to improve our limits on the anomalous couplings, we have studied several kinematical distributions of the final state particles. The most promising one is the invariant mass of the final particles, since the anomalous interactions occur mainly for the Higgs boson produced on-shell.

For instance, the number of SM cross section for the process $\gamma\gamma \rightarrow b\bar{b}$ with $m_H = 115$ GeV falls from $\sim 25.4$ pb to $\sim 4.06$ pb when the cut $|m_{b\bar{b}} - m_H| < 15$ GeV is applied. The pure anomalous cross section for $\gamma\gamma \rightarrow H \rightarrow b\bar{b}$ with $f = 10$ TeV$^{-2}$ falls from 16.2 pb to 15.8 pb, being almost unaffected by the invariant mass cut. The significance of an anomalous signal, given by $S = N_{\text{signal}}/\sqrt{N_{\text{SM}}}$, is enhanced by a factor of 2.4 when the invariant mass cut is used.

Therefore, for the photon-photon initial state, we collected the final state $\gamma\gamma$ and/or $b\bar{b}$ events whose invariant masses fall in bins of size of 15 GeV around the Higgs mass

\[ m_H - 15 \text{ GeV} < m_{\gamma\gamma(b\bar{b})} < m_H + 15 \text{ GeV} \]

in order to evaluate our results.

Considering the set of cuts \[13\] and \[14\], the luminosity and efficiencies discussed above, and a Higgs mass in the range (115–180) GeV, the number of Standard Model events for the process $\gamma\gamma \rightarrow \gamma\gamma$ is smaller than one since the highest Standard Model cross section is smaller than 3 fb. Since we expect nearly zero events for this process, a 95\% CL limit for the anomalous couplings is obtained when its contribution generates 3 events.

In Table I we present the Standard Model cross section for the process $\gamma\gamma \rightarrow b\bar{b}$ considering a Higgs mass in the range (115–180) GeV. For example, for a Higgs mass of 115 GeV, the number of Standard Model events is $\sim 73(15)$ in one year when we consider a luminosity of 50(10) pb$^{-1}$year$^{-1}$, including b-tagging efficiency. In this case, a 95\% CL signal is obtained when the number of SM events ($N_{SM}$) is changed by a value of $2\times \sqrt{N_{SM}}$ if $N_{SM}$ is greater than 10 units, otherwise we apply Poisson statistics for few background events.

In Tables II and III we present the limits for $f$ considering the same range of Higgs masses. The limits are more stringent in the $\gamma\gamma \rightarrow b\bar{b}$ case, where the number of events is larger. The limits get worse for $m_H > 160$ GeV because the total Higgs width increases due to the opening of $W^+W^-$ decay channel.

The pure anomalous contribution to the process $\gamma\gamma \rightarrow b\bar{b}$ is quadratic in the anomalous coupling because there is only one anomalous vertex in this case. In Figs. I(a) and I(b) the number of $b\bar{b}$ events in the LHC heavy ion mode as a function of the anomalous coupling $f$
is shown together with the SM 95% CL region for $m_H = 115$ GeV and a luminosity of 50 and 10 pb$^{-1}$year$^{-1}$, respectively.

On the other hand, for the process $\gamma\gamma \to \gamma\gamma$, the pure anomalous contribution is proportional to the fourth power in the anomalous coupling because there are two anomalous vertices in this case, as shown in Figs. 2(a) and 2(b).

V. CONCLUSIONS

In this work we have studied the sensitivity of the heavy ion mode of the LHC to anomalous Higgs boson couplings to photons, $H\gamma\gamma$, through the analysis of the processes $\gamma\gamma \to b\bar{b}, \gamma\gamma$ in peripheral heavy ion collisions.

Our best limits for the photon-photon initial state are (in TeV$^{-2}$),

$$-1.1(-2.0) \leq \frac{f}{\Lambda^2} \leq 3.7(4.6) \text{, for } \gamma\gamma \to b\bar{b}$$

and

$$-4.4(-7.3) \leq \frac{f}{\Lambda^2} \leq 7.3(9.9) \text{, for } \gamma\gamma \to \gamma\gamma$$

for an integrated luminosity 50 (10) pb$^{-1}$ year$^{-1}$, including $\gamma$ identification and b-tagging efficiencies.

These results are more stringent than the limits coming from the proton–antiproton mode of the Tevatron 2. We have also studied Higgs production via pomeron-pomeron fusion and found it negligible.

In conclusion, the limits for anomalous Higgs couplings that can be obtained in peripheral heavy ion collisions at the LHC via electromagnetic processes are a factor of five tighter than the limits that can be obtained in the upgraded Tevatron. However the proton-proton mode of the LHC will be able to put stronger constraints due to its higher luminosity.

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### TABLE I. Standard Model cross sections in pb for the process $\gamma\gamma \to b\bar{b}$ for different Higgs boson masses considerin the set of cuts (13) and (14).

| Higgs Mass (GeV) | $\sigma(\gamma\gamma \to b\bar{b})$ (pb) |
|-----------------|--------------------------------------|
| 115             | 4.06                                 |
| 120             | 3.41                                 |
| 130             | 2.44                                 |
| 140             | 1.78                                 |
| 150             | 1.34                                 |
| 160             | 1.13                                 |
| 170             | 0.53                                 |
| 180             | 0.38                                 |

### TABLE II. 95 % CL allowed regions for $f$ in TeV$^{-2}$ for different Higgs boson masses in the process $\gamma\gamma \to H \to \gamma\gamma$.

| Higgs Mass (GeV) | $\mathcal{L} = 50 \text{ pb}^{-1}$ | $\mathcal{L} = 10 \text{ pb}^{-1}$ |
|-----------------|-----------------------------------|-----------------------------------|
| 115             | $(-4.42, 7.04)$                   | $(-7.28, 9.90)$                   |
| 120             | $(-4.41, 7.09)$                   | $(-7.28, 9.97)$                   |
| 130             | $(-4.41, 7.24)$                   | $(-7.31, 10.2)$                   |
| 140             | $(-4.39, 7.44)$                   | $(-7.36, 10.4)$                   |
| 150             | $(-4.34, 7.73)$                   | $(-7.36, 10.8)$                   |
| 160             | $(-4.04, 8.40)$                   | $(-7.14, 11.5)$                   |
| 170             | $(-13.0, 16.9)$                   | $(-20.4, 24.3)$                   |
| 180             | $(-15.0, 18.7)$                   | $(-23.3, 27.0)$                   |

### TABLE III. 95 % CL allowed regions for $f$ in TeV$^{-2}$ for different Higgs boson masses in the process $\gamma\gamma \to H \to b\bar{b}$.

| Higgs Mass (GeV) | $\mathcal{L} = 50 \text{ pb}^{-1}$ | $\mathcal{L} = 10 \text{ pb}^{-1}$ |
|-----------------|-----------------------------------|-----------------------------------|
| 115             | $(-1.08, 3.69)$                   | $(-1.96, 4.57)$                   |
| 120             | $(-1.08, 3.74)$                   | $(-1.95, 4.63)$                   |
| 130             | $(-1.07, 3.87)$                   | $(-2.17, 4.99)$                   |
| 140             | $(-1.06, 4.06)$                   | $(-2.20, 5.23)$                   |
| 150             | $(-1.05, 4.38)$                   | $(-2.34, 5.73)$                   |
| 160             | $(-1.01, 5.22)$                   | $(-2.35, 6.66)$                   |
| 170             | $(-10.9, 29.2)$                   | $(-19.2, 34.8)$                   |
| 180             | $(-14.7, 26.8)$                   | $(-51.5, 32.5)$                   |
FIG. 1. Number of $b\bar{b}$ events in the LHC heavy ion mode with a luminosity of (a) 50 and (b) 10 pb$^{-1} \cdot $year$^{-1}$ as a function of the anomalous coupling $f$ for $m_H = 115$ GeV. The solid horizontal line is the number of events in the SM and the dashed horizontal line give the 95% CL region. The solid part of the parabola represents the allowed region.
FIG. 2. Number of $\gamma\gamma$ events in the LHC heavy ion mode with a luminosity of (a) 50 and (b) 10 pb$^{-1}$year$^{-1}$ as a function of the anomalous coupling $f$ for $m_H = 115$ GeV. The solid horizontal line is the number of events in the SM and the dashed horizontal line give the 95% CL region. The solid part of the curve represents the allowed region.