Can we Observe the Radion and Higgs Signals in Peripheral Heavy Ion Collisions?

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We investigate the sensitivity of the heavy ion mode of the LHC to Higgs boson and Radion production via photon-photon fusion through the analysis of the processes $\gamma\gamma \to \gamma\gamma$, $\gamma\gamma \to b\bar{b}$, and $\gamma\gamma \to gg$ in peripheral heavy ion collisions. We suggest cuts to improve the Higgs and Radion signal over standard model background ratio and determine the capability of LHC to detect these particles production.

1 Introduction

Collisions at relativistic heavy ion colliders like the Relativistic Heavy Ion Collider RHIC/Brookhaven and the Large Hadron Collider LHC/CERN (operating in its heavy ion mode) are mainly devoted to the search of the Quark Gluon Plasma. In addition to this important feature of heavy-ion colliders, we will also have ultra-peripheral collisions with impact parameter $b > 2R_A$, where R_A is the nuclear radius, and the ions remain intact after the collision.

The interactions will be mostly of electromagnetic origin (two-photon processes). Due to the very strong photon field of each charge Z accelerated ion, the photon luminosity will be quite high. In the case of RHIC final states produced in the two-photon process with an invariant mass up to a few GeV will appear at large rates. Above this scale the photon luminosity drops very fast. At LHC a final state with a mass almost two orders of magnitude larger can still be produced at reasonable rates. The variety of processes that can be studied in heavy ion peripheral collisions have been extensively reviewed recently[1, 2].

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[3] at around $m_H \sim 115$ GeV. Nevertheless, the SM can only be a low energy limit of a more fundamental theory because it cannot explain a number of theoretical issues, one of which is the gauge hierarchy problem between the only two known scales in particle physics – the weak and Planck scales. Recent advances in string theories have revolutionized our perspectives and understanding of the problems, namely, the Planck, grand unification, and string scales can be brought down to a TeV range with the help of extra dimensions, compactified or not. Arkani-Hamed *et al.* [4] proposed that using compactified dimensions of large size (as large as mm) can bring the Planck scale down to TeV range. Randall and Sundrum [5] proposed a 5-dimensional space-time model with a nonfactorizable metric to solve the hierarchy problem. The Randall-Sundrum model (RSM) has a four-dimensional massless scalar, the modulus or Radion. The most important ingredients of the above model are the required size of the Radion field such that it generates the desired weak scale from the scale M ($\approx$ Planck scale) and the stabilization of the Radion field at this value. A stabilization mechanism was proposed by Goldberger and Wise [6]. As a consequence of this stabilization, the mass of the Radion is of order of $O(\mathrm{TeV})$ and the strength of coupling to the SM fields is of order of $O(1/\mathrm{TeV})$. Therefore, the detection of this Radion will be the first signature of the RSM and the stabilization mechanism by Goldberger and Wise.

Higgs and Radion can be produced in various types of accelerators. Several papers have been published in order to study the possibility of detection of the Higgs particle in e^+e^-, $\mu^+\mu^-$, $p\bar{p}$, pp and $\gamma\gamma$ colliders [7]. Recently, the phenomenology of the Radion particle has been also studied for e^+e^-, pp and $\gamma\gamma$ colliders [8]. In this paper we explore the possibility of an intermediate-mass Higgs boson or Radion scalar be produced in peripheral heavy ion collisions through photon-photon interactions [9, 10]. The reason to choose photon-photon fusion in peripheral heavy ion collisions resides in the fact that the production mode is free of any problem caused by strong interactions of the initial state, which make these processes cleaner than pomeron-pomeron or pomeron-photon fusions. In the context of the SM, the Higgs boson has been explored in detail in the literature [2, 11, 12], with the general conclusion that the chances of finding the SM Higgs in the photon-photon case are marginal. On the other hand, a study of Radion production in peripheral heavy ion collisions has not yet been made.

The Higgs couplings considered in this paper are given by the usual SM lagrangian while the Radion effects can be described by effective operators involving the spectrum of the SM and the Radion scalar field. In the second section we introduce the photon distribution in the ion that will be used in our calculations. The Radion couplings to the SM particles are similar to the Higgs couplings to the same particles, except from a factor involving the Higgs and the Radion vacuum expectation values (vev's), as can be seen in Section III. In Section IV we present the strategy to evaluate photon-photon fusion processes in peripheral heavy ion collisions and in Section V we explore the capabilities of peripheral heavy ion collisions in detecting Higgs and Radion productions by analyzing the processes $\gamma\gamma \to \gamma\gamma$, $b\bar{b}$, and gg. After simulating the signal and background, we find optimal cuts to maximize their ratio. We show how to use the invariant mass spectra of the final state $\gamma\gamma$, $b\bar{b}$, and gg pairs in order to improve the SM Higgs boson and RMS Radion signals. Finally, in Section VI we draw our final conclusions.

2 Two-photon Processes

The photon distribution in the nucleus can be described using the equivalent-photon or Weizsäcker-Williams approximation in the impact parameter space. Denoting by $F(x)dx$ 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

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

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 of the process $AA \to AA\gamma\gamma$ is

$$\sigma(s) = \int d\tau \frac{dL}{d\tau} \hat{\sigma}(\hat{s}), \tag{2}$$

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

There remains only to determine $F(x)$. In the literature there are several approaches for doing so, and we choose the conservative and more realistic photon distribution of Ref.[12]. Cahn and Jackson [12], using a prescription proposed by Baur [13], obtained a photon distribution which is not factorizable. However, they were able to give a fit for the differential luminosity which is quite useful in practical calculations:

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

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

$$\xi(z) = \sum_{i=1}^{3} A_i e^{-b_i z}, \tag{4}$$

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. [12])

$$\frac{dL}{d\tau} = \left(\frac{Z^2\alpha}{\pi}\right)^2 \frac{16}{3\tau} \left(\ln\left(\frac{1.234}{z}\right)\right)^3. \tag{5}$$

The condition for realistic peripheral collisions ($b_{min} > R_1 + R_2$) is present in the photon distributions showed above.

3 Model and Simulations

The Higgs couplings are given by the usual SM lagrangian while the interactions of the RSM Radion with the SM particles are model-independent and are governed by 4-dimensional general covariance, given by the following Lagrangian

$$\begin{aligned}\mathcal{L}_{\text{int}} = \frac{R}{\Lambda_R} \quad & [\sum_f m_f \bar{f} f - 2m_W^2 W_\mu^+ W^{-\mu} - m_Z^2 Z_\mu Z^\mu \\ + \quad & (2m_H^2 H^2 - \partial_\mu H \partial^\mu H) + ...]\end{aligned}$$

where $\Lambda_R = \langle R \rangle$ is of order TeV. The couplings of the Radion with fermions and W, Z and Higgs bosons are similar to the couplings of the Higgs to these particles, the only difference resides in the coupling constants where v, the vev of the Higgs field, is replaced by Λ_R. The coupling of the Radion to a pair of gluons (photons) is given by contributions from 1-loop diagrams with the top-quark (top-quark and W) in the loop, similar to the Higgs boson couplings to the same pair. However, for the Radion case, there is another contribution coming from the trace anomaly for gauge fields, that is given by $T_\mu^\mu(\text{SM})^{\text{anom}} = \sum_a \frac{\beta_a(g_a)}{2g_a} F_{\mu\nu}^a F^{a\mu\nu}$.

In order to perform the Monte Carlo analysis, we have employed the package MadGraph [14] coupled to HELAS [15]. 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 [16].

We consider electromagnetic processes of peripheral $^{40}_{20}$Ca, $^{40}_{18}$Ar and $^{208}_{82}$Pb collisions in order to produce a Higgs and/or Radion scalar via photon-photon fusion. The center of mass energies are 7, 7 and 5.5 TeV/nucleon, respectively, and the photon-photon luminosity for $m_{\gamma\gamma} = 115$ GeV are, respectively, 6, 0.63 and 0.0025 pbarn^{-1} year^{-1} at LHC.

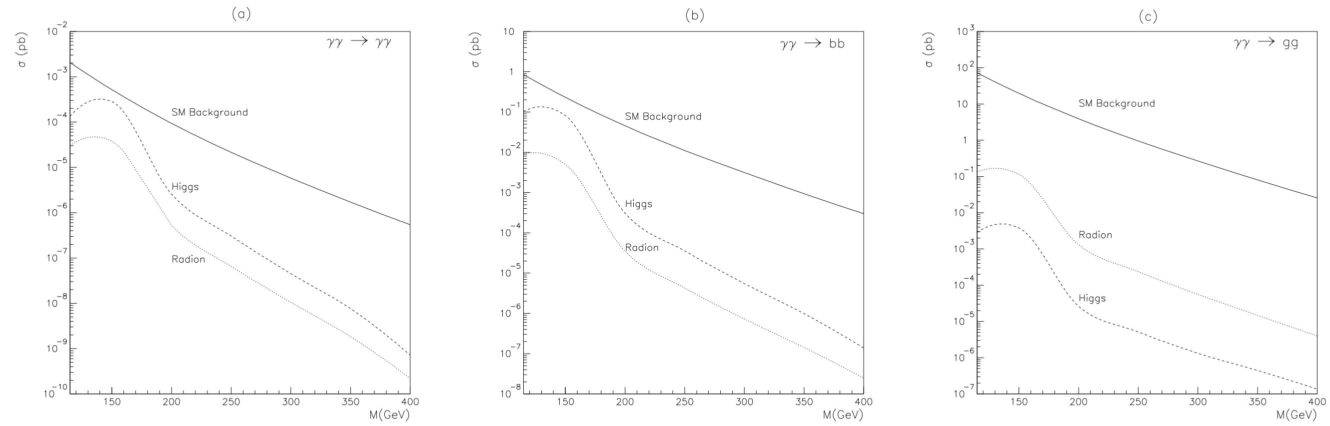

Figure 1. Cross sections for the processes (a) $\gamma\gamma \to \gamma\gamma$, (b) $\gamma\gamma \to b\bar{b}$ and (c) $\gamma\gamma \to gg$, for $\Lambda_R \approx 1$ TeV, considering events whose invariant masses fall in bins of size of 30 GeV around the mass M. The full (dashed) [dotted] line corresponds to the SM background (Higgs) [Radion] contribution.

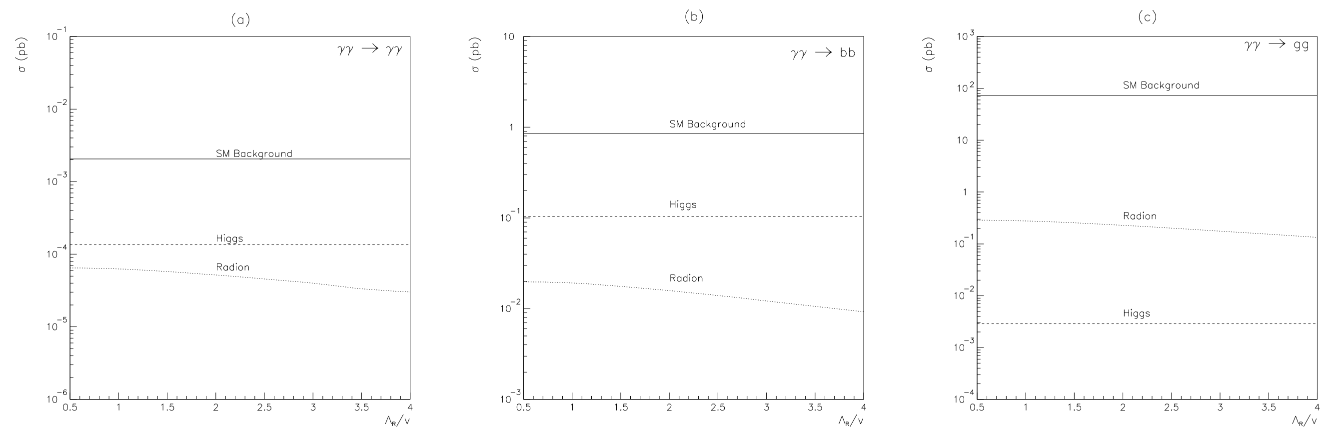

Figure 2. Cross sections for the processes (a) $\gamma\gamma \to \gamma\gamma$, (b) $\gamma\gamma \to b\bar{b}$ and (c) $\gamma\gamma \to gg$, considering events whose invariant masses fall in bins of size 30 GeV around Higgs (Radion) in terms of the ratio of the vev's of the Radion (Λ_R) and the Higgs (v). The full (dashed) [dotted] line corresponds to the SM background (Higgs) [Radion] contribution.

4 Results and Conclusions

We begin our analyses using similar cuts and efficiencies as the ones ATLAS Collaboration [20] applied in their studies of Higgs boson searches. Our initial results are obtained imposing the following acceptance set of cuts:

$$p_T^{\gamma(b)[g]} > 25 \text{ GeV}, \quad |\eta_{\gamma(b)[g]}| < 2.5, \quad \Delta R_{\gamma\gamma(bb)[\bar{g}g]} > 0.4,$$

taking into account a total efficiency factor of 70(32)[80]% for the decay H or $R \to \gamma\gamma(b\bar{b})[gg]$. In order to improve the Higgs and Radion signal over SM background we collected final states $\gamma\gamma$, $b\bar{b}$ and gg events whose invariant masses fall in bins of size of 30(10) GeV around the Higgs (Radion) mass

$$m_{H(R)} - 15 \text{ GeV} < m_{\gamma\gamma(b\bar{b})[gg]} < m_{H(R)} + 15 \text{ GeV}.$$

The behaviour of the cross sections for different values of the Higgs (Radion) mass, considering $\lambda_R = 4v \approx 1$ TeV, and the behaviour of the cross sections for a Higgs (Radion) mass of 115 GeV, varying λ_R/v, where evaluated and presented in Figs. 1 and 2, respectively. The total integrated luminosity needed for a 95% C.L. Higgs signal and for a Higgs plus Radion signal are evaluated and presented in Table I. It was also presented the number of years needed for a 95% C.L. signal considering a luminosity of 0.63(6) pbarn^{-1} year^{-1} for the Ar-Ar (Ca-Ca) mode.

In conclusion, the chances of finding the SM Higgs boson (or the RMS Radion) are marginal for high values of the Higgs (Radion) mass. For lower masses the situation is still critical, but there is some hope left. We have considered $M_H = M_R = 115$ GeV in our analysis according to the recent LEP hints on the Higgs mass. The best place to search the Higgs boson is in the Ca-Ca ion mode of the LHC

TABLE I. Total Integrated Luminosity, in pb^{-1}, (and Years) needed for a 95% C.L. Higgs (H) and Higgs plus Radion (H+R) signals for photon fusion processes with $m_{H,R} = 115$ GeV and $\Lambda_R \approx 1$ TeV in heavy ion collisions at LHC (considering a luminosity of 6 pbarn^{-1} year^{-1} for the Ca-Ca mode).

Signal	Final State	Integrated Luminosity	Years
H	$\gamma\gamma$	1.082×10^{5}	1.804×10^{4}
H	$b\bar{b}$	8.731×10^{1}	1.455×10^{1}
H	gg	6.922×10^{6}	1.154×10^{6}
H + R	$\gamma\gamma$	7.496×10^{4}	1.249×10^{4}
H + R	$b\bar{b}$	7.541×10^{1}	1.257×10^{1}
H + R	gg	3.097×10^{3}	5.161×10^{2}

accelerator through the analysis of the process $\gamma\gamma \to b\bar{b}$. In this case, considering the luminosities presented in the literature, a 95% C. L. signal can be established in 15 years of run. If the Radion scalar of the RSM is taken into account, a 95% C. L. signal would be established in 12.5 years. On the other hand, the best place to search the Radion of the RSM is in the Ca-Ca ion mode of the LHC accelerator through the analysis of the process $\gamma\gamma \to gg$. In this case, the experiments would have to improve their luminosity prediction by a factor of twenty in order to establish a 95% C. L. Radion signal in less than three years of run. In conclusion, SM Higgs and RMS Radion observation in the heavy ion mode of the LHC accelerator is improbable, unless the expected luminosity of the experiment could be enhanced by a factor of 10–20.

References

[1] G. Baur, K. Hencken, D. Trautmann, S. Sadovsky, and Y. Kharlov, hep-ph/0112211 Phys. Rep., in press; G. Baur, hep-ph/0112239; C. A. Bertulani and G. Baur, Phys. Rep.**163**, 299 (1988); G. Baur, J. Phys. G**24**, 1657 (1998); S. Klein and E. Scannapieco, hep-ph/9706358 (LBNL-40457); J.Nystrand and S. Klein, hep-ex/9811997 (LBNL-42524); C. A. Bertulani, nucl-th/0011065, nucl-th/0104059; J. Rau, b. Müller, W. Greiner, and G. Soff, J. Phys. G: Nucl. Part. Phys. **16**, 211 (1990); M. Vidović, M. Greiner, C. Best, and G. Soff, *Phys. Rev.* C**47**, 2308 (1993); M. Greiner, M. Vidović, G. Soff, *Phys. Rev.* C**47**, 2288 (1993). Sigma-meson 2000), Kyoto (June, 2000), hep-ph/0008136.

[2] M. Greiner, M. Vidovic, J. Rau, and G. Soff, J. Phys. G**17**, L45 (1991).

[3] See: `http://delphiwww.cern.ch/~offline/physics_links/lepc.html`.

[4] N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, Phys. Lett. B**429**, 263 (1998); I. Antoniadis *et al.*, Phys. Lett. B**436**, 257 (1998).

[5] L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999); *ibid.* **83**, 4690 (1999).

[6] W. Goldberger and M. Wise, Phys. Rev. Lett. **83**, 4922 (1999); W. Goldberger and M. Wise, Phys. Lett. B**475**, 275 (2000).

[7] A. Sopczak, "Complete LEP data: Status of Higgs boson searches," hep-ph/0112082; M. S. Berger, "Higgs bosons at muon colliders," in *Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001)* ed. R. Davidson and C. Quigg, hep-ph/0110390; M. Carena *et al.*, "Report of the Tevatron Higgs working group," hep-ph/0010338; D. Zeppenfeld, "Higgs Physics At The Lhc," Int. J. Mod. Phys. A **16S1B**, 831 (2001); D. M. Asner, J. B. Gronberg, and J. F. Gunion, "Detecting and studying Higgs bosons in two-photon collisions at a linear collider," hep-ph/0110320.

[8] K. Cheung, Phys. Rev. D **63**, 056007 (2001).

[9] G. Baur, J. Phys. G**24**, 1657 (1998).

[10] G. Baur, K. Hencken, and D. Trautmann, hep-ph/9810418; C. A. Bertulani and G. Baur, Phys. Reports **163**, 299 (1988); G. Baur, in *Proceedings of the CBPF International Workshop on Relativistic Aspects of Nuclear Physics*, Rio de Janeiro, 1989, edited by T. Kodama *et al.* (World Scientific, Singapore, 1990), p. 127; G. Baur and C. A. Bertulani, Nucl. Phys. A**505**, 835 (1989).

[11] E. Papageorgiu, Phys. Rev. **D40** (1989) 92; Nucl. Phys. A**498**, 593c (1989); M. Grabiak *et al.*, J. Phys. G**15**, L25 (1989); M. Drees, J. Ellis, and D. Zeppenfeld, Phys. Lett. B**223**, 454 (1989); B. Müller and A. J. Schramm, Phys. Rev. D**42**, 3699 (1990); B. Müller and A. J. Schramm, Nucl. Phys. A**523**, 677 (1991); J. S. Wu, C. Bottcher, M. R. Strayer, and A. K. Kerman, Ann. Phys. **210**, 402 (1991).

[12] R. N. Cahn and J. D. Jackson, Phys. Rev. D**42**, 3690 (1990).

[13] G. Baur, in *Proc. CBPF Intern. Workshop on Relativistic Aspects of Nuclear Physics*, Rio de Janeiro, 1989, edited by T. Kodama et al. (World Scientific, Singapore, 1990).

[14] T. Stelzer and W. F. Long, Comput. Phys. Commun. **81**, 357 (1994).

[15] H. Murayama, I. Watanabe, and K. Hagiwara, KEK Report 91-11 (unpublished).

[16] G. P. Lepage, J. Comp. Phys. **27** 192 (1978), and "Vegas: An Adaptive Multidimensional Integration Program", CLNS-80/447, 1980 (unpublished).

[17] G. Baur, K. Hencken, D. Trautmann, S. Sadovsky, and Y. Kharlov, hep-ph/0112211.

[18] E. Papageorgiu, "Searching for an intermediate-mass Higgs and new physics in two-photon coherent processes at the LHC," hep-ph/9507221.

[19] S. M. Lietti, A. A. Natale, C. G. Roldao, and R. Rosenfeld, Phys. Lett. B **497**, 243 (2001).

[20] Atlas Detector and Physics Performance Technical Design Report, `http://press.web.cern.ch/Atlas/GROUPS/PHYSICS/TDR/access.html`.

[21] C. Csaki, M. L. Graesser, and G. D. Kribs, Phys. Rev. D **63**, 065002 (2001).