An intermediate-mass Higgs boson in two-photon coherent processes at the LHC

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Abstract

We reexamine the prospects of searching for a neutral Higgs boson in the intermediate-mass range, using the proton- and ion-beam facilities of the LHC to study coherent two-photon processes. Considering realistic design luminosities for the different ion beams, we find that beams of light-to-medium size ions like calcium will give the highest production rates. With a suitable trigger and assuming a $b\bar{b}$ identification efficiency of 30% and a $b\bar{b}$ mass resolution of 10 GeV one could expect to see a Higgs signal in the $b\bar{b}$ channel with a 3-4 $\sigma$ statistical significance in the first phase of operation of the LHC with beams of calcium.
The search for the Higgs particle of the standard model (SM) is one of the major scopes of the LHC. The discovery of such a particle with a mass $M_H$ in the intermediate-mass range $80 - 180$ GeV, i.e. beyond the discovery potential of LEP2, is a challenge for both theory and experiment. Considerations on the stability of the SM Higgs potential suggest a strong correlation between the Higgs mass and the energy scale at which new physics beyond the SM becomes relevant, so $M_H < 100$ GeV implies a scale of $\sim 10$ TeV [1]. In the case of the minimal supersymmetric standard model (MSSM) the lightest neutral Higgs scalar mass should be less than 140 GeV for a top-quark mass of $M_t < 190$ GeV or even less than 120 GeV if $M_t$ is equal to the infrared fixed-point value [2]. Detailed studies have shown that this lower part of the Higgs mass range can be explored in pp collisions at the LHC only through a combination of conventional hard-scattering channels such as $gg \rightarrow H \rightarrow \gamma \gamma$, $gg \rightarrow WH \rightarrow lb\bar{b}$ and $gg \rightarrow t\bar{t}H \rightarrow lbb\bar{b}$ and after three years of operation at a luminosity $L_p \simeq 10^{33}cm^{-2}s^{-1}$ [3]. Even so, to obtain a statistical significance of more than four one would have to wait until the design luminosity $L_p^d \simeq 10^{34}cm^{-2}s^{-1}$ is reached by the year 2008. Additional Higgs production/decay modes would therefore be welcome.

A different kind of Higgs- and SUSY-particle production, which would make use of the ion beam facilities at the LHC, was proposed some time ago [4], namely, the two-photon production in the coherent electromagnetic field of nucleus nucleus collisions in which the nuclei $N_i=1,2$ would “ideally” remain intact:

$$N_1N_2 \rightarrow N_1N_2 + X \quad X = H, \bar{u}u, \bar{\chi}\chi, \ldots.$$  \hspace{1cm} (1)

Triggering on such events would imply cross sections which scale with the nuclear charges as $Z_1^2Z_2^2$ and a signal-to-background ratio (S/B) which is sizably more favourable than in the conventional hard-scattering channels of $pp \rightarrow X + \text{jets}$.  \hspace{1cm} (2)

To illustrate this let us compare the corresponding S/B ratios for $H \rightarrow b\bar{b}$ which would be the predominant SM-Higgs decay mode if $M_H < 140$ GeV. For the processes of eq.(1) and (2) the signal and background cross sections factorise into a flux factor which gives the probability of emitting two photons (gluons) from the nuclei (protons) and the $\gamma\gamma \rightarrow X$ and $gg \rightarrow X$ cross
sections:
\[\sigma(NN \to NNH) = \sigma(\gamma\gamma \to H \to b\bar{b}) \frac{dL_{\gamma\gamma}}{dM_H^2} \quad (3)\]
\[\sigma(pp \to H + jets) = \sigma(gg \to H \to b\bar{b}) \frac{dL_{gg}}{dM_H^2} \quad (4)\]

and
\[\frac{d\sigma}{dW^2}(NN \to NNb\bar{b}) = \sigma(\gamma\gamma \to b\bar{b}) \frac{dL_{\gamma\gamma}}{dW^2} \quad (5)\]
\[\frac{d\sigma}{dW^2}(pp \to b\bar{b} + jets) = \sigma(gg \to b\bar{b}) \frac{dL_{gg}}{dW^2} \quad (6)\]

where \(W\) is the invariant mass of the \(b\bar{b}\) system. The SM Higgs couples to the gluons mainly through the top-quark loop \(I_t \simeq 1\) for \(M_t^2 >> M_H^2\) while there is an extra contribution from the vector boson loop \(I_W \simeq -1/2\) when it couples to the photons. Therefore, including the colour factors,

\[\sigma(gg \to H) \simeq \frac{G_F}{288} \frac{\alpha_s^2(M_H^2)}{\sqrt{2\pi}} |I_t|^2 \quad (7)\]

over

\[\sigma(\gamma\gamma \to H) \simeq G_F \frac{\alpha^2}{\sqrt{2\pi}} |(\frac{2}{3})^2 I_t + I_W|^2 \quad (8)\]

is just the ratio of the gauge coupling constants \(\alpha_s^2/\alpha^2\), while

\[\sigma(gg \to b\bar{b}) \simeq \frac{8\pi\alpha_s^2}{3W^2} \quad (9)\]

over

\[\sigma(\gamma\gamma \to b\bar{b}) \simeq \frac{4\pi\alpha^2q^4}{W^2} \quad (10)\]

is enhanced by an extra factor of \(10^2\) due to the electric charge of the \(b\) quark. As a consequence, the signal-to-background ratio in hard-scattering processes \((S/B)_{HS} \sim \mathcal{O}(\infty r^{-3} - \infty r^{-\Delta})\) is by 2-3 orders of magnitude less favourable than in coherent processes where \((S/B)_{COH} \sim \mathcal{O}(\infty r^{-\infty})\), assuming a \(b\bar{b}\) resolution of \(\mathcal{R} \simeq \infty t\) GeV. These ratios can be improved up to a factor of ten by imposing a cut on the transverse momentum of the \(b\) jets, \(p_T \geq 0.4M_H\), which affects mainly the softer background spectrum [5]. This brings \((S/B)_{COH}\) down to 1:3 for 120 GeV < \(M_H\) < 150 GeV and to 1:5 for 100
GeV < \text{\textit{M}}_H < 120 \text{ GeV} \ [6]. \ To \ this, \ one \ should \ add \ the \ large \ coherent \ Higgs-boson \ production \ which \ for \ lead-on-lead \ collisions \ would \ be \ of \ the \ order \ of \ a \ few \ tens \ of \ picobarns \ (\text{Fig.} \ 2) \ and \ comparable \ to \ the \ production \ in \ hard \ pp \ collisions. \ This \ is \ not \ surprising \ because \ the \ coherent \ coupling \ \textit{Z} \alpha \ becomes \ equal \ to \ \alpha_s \ already \ for \ rather \ light \ nuclei.

Now, \ compared \ to \ central \ heavy-ion \ collisions \ where \ one \ will \ study \ the \ quark-gluon-plasma \ signals \ the \ occurrence \ of \ peripheral \ collisions \ is \ rather \ overwhelming. \ The \ total \ cross \ section \ for \ purely \ electromagnetic \ processes \ lies \ in \ the \ kilobarn \ range \ and \ it \ exceeds \ the \ geometric \ cross \ section \ by \ at \ least \ one \ order \ of \ magnitude. \ This \ is \ an \ advantage \ as \ much \ as \ a \ limitation. \ On \ one \ hand, \ in \ collisions \ with \ heavy \ nuclei \ there \ would \ be \ a \ strong \ enhancement \ of \ the \ two-photon \ flux:

$$\frac{dL_{\gamma\gamma}}{dW^2} = \frac{16 Z_1^2 Z_2^2 \alpha^2}{3 \pi^2 W^2} \times F\left(\frac{\gamma}{\sqrt{R_\infty R_\infty W}}\right)$$ \ (11)

with \ respect \ to \ \text{e}^+\text{e}^- \ and \ pp \ collisions, \ in \ particular, \ at \ the \ lower \ end \ of \ the \ mass \ spectrum \ \text{\textit{W}} < \text{\textit{W}}_i,

$$\text{\textit{W}}_i = \frac{\text{\textit{W}}_i}{\sqrt{R_\infty R_\infty}}$$ \ (12)

where

$$F \simeq \ln^3\left(\frac{\text{\textit{W}}_i}{\text{\textit{W}}_i}\right)$$ \ (13)

At \ the \ LHC \ where \ the \ maximum \ energy \ of \ a \ proton \ beam \ will \ be \ \text{\textit{E}}_p = 7 \ \text{TeV}, \ the \ maximum \ energy \ of \ an \ ion \ beam \ will \ be \ \text{\textit{E}}_{\text{ion}} = \text{\textit{E}}_p Z \ and

$$\gamma \simeq 7.5 \frac{Z, \text{\textit{TeV}}}{A, \text{\textit{n}}}$$ \ (14)

where \ \textit{A} \ is \ the \ atomic \ number. \ This \ implies \ that \ the \ mass \ range \ that \ could \ be \ well \ explored, \ in \ for \ example \ Pb-Pb, \ Ca-Ca \ and \ p-p \ coherent \ collisions \ is \ \text{\textit{M}}_X \leq \text{\textit{W}}_i \simeq 168 \ \text{GeV}, \ 366 \ \text{GeV} \ and \ 3 \ \text{TeV} \ respectively. \ The \ production \ of \ masses \ much \ higher \ than \ \text{\textit{W}}_i \ is \ exponentially \ suppressed. \ Therefore \ using \ heavier \ ions \ is \ not \ necessarily \ more \ advantageous \ for \ exploring \ the \ upper \ part \ of \ the \ mass \ spectrum, \ as \ the \ function \ \textit{F} \ tends \ to \ compensate, \ partially \ or \ fully, \ the \ gain \ from \ a \ higher \ nuclear \ charge \ due \ to \ the \ bigger \ size \ \textit{R} \simeq r_0 A^{1/3} \ (r_0 \simeq 1.2 \ \text{fm}) \ of \ heavier \ nuclei. \ On \ the \ other \ hand, \ the \ maximal \ achievable \ beam \ luminosity \ \textit{L}_b \ is \ limited \ by \ intra \ beam \ effects \ which \ become \ particularly
large for heavy-ion beams. The overall advantage of doing two-photon physics with ion beams depends mainly on $L_b \times dL_{\gamma\gamma}/dW$ and the efficiency to trigger on such events.

When this mechanism was first proposed and studied in the context of an intermediate mass Higgs search it was not known what would be the maximal achievable luminosity at the LHC for different ion species, so it was assumed that lead-on-lead collisions would be the best environment for such searches. In a recent study [7] it was found that while for a beam of lead the luminosity would be only $L_{Pb} \simeq 5 \times 10^{26}$ cm$^{-2}$s$^{-1}$, for medium-size nuclei like calcium it could be four orders of magnitude higher $L_{Ca} \simeq 5 \times 10^{30}$ cm$^{-2}$s$^{-1}$. This gain would not only compensate the loss in the two-photon flux. As will be shown next, it may allow for an intermediate-mass Higgs search which looks impossible with lead beams.

Before presenting the results I would like to remark that knowing precisely the two-photon flux in such collisions requires a definite prescription for implementing the requirement of “coherency” in the calculations as much as in the experimental set-up. So it was found that, for the mass range in question, calculations based on a form factor approach [5] gave results which were by a factor of $2 - 10$ higher than impact-parameter calculations based on a “hard-disc” scattering approach [8-10], the higher masses being more affected by this uncertainty [8]. The presence of the nuclear elastic form factor is namely not sufficient to exclude strong interaction processes taking place after the photons have been emitted from the nuclei. When nuclei and nucleons overlap, elastic scattering is partly the “shadow” of inelastic processes. These can be eliminated by imposing cuts on the impact parameters of the two nuclei:

$$ b_i > R_i \quad \text{and} \quad |b_1^+ - b_2^+| > R_1 + R_2, \quad (15) $$

i.e, treating the nuclei as two nonoverlapping, “hard” and “opaque” discs. The results presented in this paper have been obtained by using this last approach, - the details of which can be found in ref.[8] - and are therefore predictions for experiments with an ion (proton) identification device.

Since the coherency condition of eq.(15) implies transverse momenta of the final state nuclei

$$ q_{iT} < \frac{1}{R_i} \quad \text{and} \quad (q_1 - q_2)_T^2 < \frac{1}{(R_1 + R_2)^2} \quad (16) $$
which are limited to a few tens of MeV for heavy nuclei up to a GeV for protons, tagging may be possible only for the latter. Alternatively, one will have to veto spectator jets, coming from diffractive dissociation and/or nucleon fragmentation, in the very forward and backward direction and with a transverse momentum of typically a few GeV. Because in this case one cannot exclude partial or full dissociation of the nuclei, and, electromagnetic and nuclear interactions taking place in the final state, the limits in eq.(15) should be relaxed accordingly. One would then gain back the factor of 2-10 for the two-photon flux, without getting significant contributions to the $b\bar{b}$ background, as most such inelastic processes will either take place below the $b\bar{b}$ threshold or will stem from incoherent electromagnetic processes.

In Fig. 1 the two-photon luminosity function $dL/dW = L_b \times dL_{\gamma\gamma}/dW$ is plotted for collisions of heavy ions (Pb-Pb), of medium-size ions (Ca-Ca) and protons (p-p), using the values of ref.[7] for the ion luminosities and $L_p \simeq 10^{33} cm^{-2}s^{-1}$ for the protons. The upper and lower dotted curves correspond to a nuclear cut-off in eq.(15) of $R \simeq 0.2$ fm, which is the proton radius as determined from elastic electron scattering, and $R \simeq 1$ fm respectively. This is to demonstrate how the absence of a sharp edge for protons and light nuclei (the form factor is an exponential) may affect the two-photon luminosity function by choosing a cut-off at the tail of the distribution to ensure the absence of all strong interaction processes. For invariant masses up to 250 GeV coherent collisions with calcium beams will provide a higher or at least a comparable flux of photons with respect to proton beams (until the upgraded luminosity for protons is reached) while the heavy-ion flux will be two to three orders of magnitude lower.

The total Higgs production cross section for these three type of collisions is shown in Figs. 2-3. The gain of only one order of magnitude -on average- in $\sigma(PbPb \rightarrow PbPbH)$ over $\sigma(CaCa \rightarrow CaCaH)$ multiplied by four orders of magnitude of luminosity loss means a factor of thousand gain in the event rate when going from lead to calcium beams. For $10^7$ sec of running time per year one should expect 20-50 events per year in Ca-Ca collisions for a Higgs with a mass of 80 – 180 GeV. This rate should be compared to the 30 – 70 events from Fig. 3 for coherent p-p collisions after one year of running at the upgraded luminosity of $L_p^d \simeq 10^{34} cm^{-2}s^{-1}$.

The requirements for detecting a Higgs signal in the $b\bar{b}$ channel have been studied in detail in the refs.[5,6,11]. Assuming an efficient trigger for selecting only coherent processes and perfect $b$ identification, the signal-to-
background ratio \((S/B)_{\text{COH}}\) is indeed very favourable, as discussed previously. One should then expect to see a signal with a statistical significance of \(S/\sqrt{S+B} \simeq 2\) in the mass range \(M_H \simeq 100 - 130\) GeV already after one year of running with calcium. On the other hand, assuming realistic values for the b-detection efficiency \(\epsilon = 30\%\) and for the misidentification probabilities for a \(c\bar{c}\), a \(u\bar{u}\), a \(d\bar{d}\) and a \(s\bar{s}\) pair of 5\%, 0.5\%, 0.5\% and 0.5\% respectively, reduces \((S/B)_{\text{COH}}\) to 1 : 5 in the mass range 120 GeV < \(M_H\) < 150 GeV and to 1 : 10 in the mass range 100 GeV < \(M_H\) < 120 GeV [11]. In this case three to four years of running will be needed to reach a statistical significance of 3 – 4. Even so, this is competitive with what one does also expect from the hard-scattering channels [3].

These results require however a very efficient trigger. Without it the background from hard-scattering processes would be \(A^2\) times the pp background of eq.(6). One can estimate, that

\[
\frac{\sigma(NN \to NNH)}{A^2 \int_{M_H-R}^{M_H+R} dW^2 d\sigma/dW^2(pp \to b\bar{b} + jets)} \simeq \frac{(Z\alpha)^4}{A^2\alpha_s^4} 10^{-3} \mathcal{F}\left(\frac{W}{M_H}\right) \tag{17}
\]

is of order \(O(\infty^{-\infty})\) [11]. Coloured objects like the gluons don’t couple to nuclei or nucleons as such. These processes will always involve dissociation of the nuclei and partial fragmentation of the nucleons, leading in the worst of cases to a final state with all nucleons but one going down the beam pipe and a spectator jet with \(p_T \sim 2 - 5\) GeV. The rejection of low-\(p_T\) jets is therefore vital.

The background from diffractive processes, with or without dissociation of the participating nucleons, has not been yet investigated in detail. Even in deep inelastic scattering at HERA, one percent of all events with a large rapidity gap are of diffractive origin [12]. The pomeron \(\mathcal{P}\), a colour-singlet object, is strongly coupled to nucleons and eventually to nuclei, so that particle production via double-pomeron and photon-pomeron interactions could a priori compete with or even exceed the two-photon production in ion-ion or p-p collisions. Depending on the pomeron structure function, the \(\mathcal{P}\mathcal{P} \to \mathcal{H}\) exclusive/inclusive cross section in p-p collisions at the LHC could be as high as 0.1 pb [13], thus exceeding by three orders of magnitude the two-photon cross section. This looks at first very tempting, but, since the irreducible signal-to-background ratio for \(\mathcal{P}\mathcal{P}\) processes is not expected to be any better than for \(gg\) processes (the pomeron is a multigluon state), a full
analysis is needed, also, because the background from these processes could completely swamp the two-photon signal in p-p collisions [14]. Fortunately, due to nuclear absorption effects, these processes are strongly suppressed for quasi-elastic collisions of nuclei [15]. In fact, it seems that the A dependence is completely eradicated by this effect, so that $\mathcal{PP} \rightarrow \tilde{\tau} \tilde{\tau}$ could not obscure the signal from the electromagnetically produced Higgs bosons.

Taking all this into account it seems that the best place to look for an intermediate-mass Higgs and study new phenomena in genuine coherent processes is in collisions of not too heavy nuclei.

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**Figure Captions**

**Fig. 1** The two-photon luminosity \( dL/dW = L_b \times dL_{\gamma\gamma}/dW \) is plotted as a function of the invariant mass \( W \) for collisions of lead (Pb-Pb), calcium (Ca-Ca) and protons (p-p), with \( L_b = 5 \times 10^{26} cm^{-2}s^{-1} \) for Pb, \( L_b = 5 \times 10^{30} cm^{-2}s^{-1} \) for Ca, as in ref.[7], and \( L_b = 10^{33} cm^{-2}s^{-1} \) for the protons. The upper and lower dotted curves correspond to a nuclear cut-off in eq.(15) of \( R \simeq 0.2 \) fm and \( R \simeq 1 \) fm respectively.

**Fig. 2** The total cross section for the production of the Higgs particle of the Standard Model through two-photon fusion in coherent Pb-Pb and Ca-Ca collisions at the LHC.

**Fig. 3** The total cross section for the production of the Higgs particle of the Standard Model through two-photon fusion in coherent p-p collisions at the LHC.
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pp $\rightarrow$ H pp

\[ \sigma(\text{pb}) \]

$\gamma\gamma \rightarrow H$

$M_H(\text{GeV})$

$10^{-3}$

$10^{-4}$