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Heavy Ion Interactions at Supercolliders and the Search for the Higgs Particle

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ABSTRACT

We discuss the proposal of detecting an intermediate mass Higgs produced by $\gamma\gamma$ fusion in heavy ion collisions at LHC and SSC. Even if one was able to perfectly discriminate the strong interaction processes, both the signal rate and the signal over background ratio are shown to be discouraging, once still optimistic but conceivable values for mass resolutions, b tagging efficiencies and light quark rejection factors are taken into account. We also quantitatively argue that rejecting the gg background to the required accuracy on the basis of the p_T distributions of the nuclear jets or other similar distributions is not feasible.

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It is well known that the search for and discovery of the standard Higgs boson with an intermediate mass ($m_Z < m_H < 2m_Z$) is a very difficult experimental problem at hadron colliders [1]. It has been recently suggested [2,3] that a possible solution could be the search for Higgs production in $\gamma\gamma$ reactions induced by ion-ion collisions at LHC or SSC. The reasons for this suggestion are first that the signal over background ratios for $\gamma\gamma \rightarrow H \rightarrow b\bar{b}$ and $\gamma\gamma \rightarrow b\bar{b}$ are sizeably more favourable than for $gg \rightarrow H \rightarrow b\bar{b}$ and $gg \rightarrow b\bar{b}$ (the difference is mainly due to the virtual W 's running in the loop for $\gamma\gamma \rightarrow H \rightarrow b\bar{b}$ and to the suppression of $\gamma\gamma \rightarrow b\bar{b}$ from the small b electric charge). Second, the cross section for H production via $\gamma\gamma$ fusion in ion-ion collisions is relatively large because the photon can be coherently emitted by the whole nucleus of charge Ze . The problem is that the $\gamma\gamma$ and the gg mechanisms are both present in ion-ion collisions. Actually, the gg background is orders of magnitude larger than the $\gamma\gamma \rightarrow H$ signal. Clearly one can take advantage of the better signal over background ratio of $\gamma\gamma$ fusion only if the gg fusion mechanism can be discriminated to a very high level of efficiency. More in general the crucial problem is the detection of the small signal from $\gamma\gamma \rightarrow H$ in the huge background of ion-ion inelastic collisions.

A general analysis of the background problem has been recently presented by Drees et al. [4]. The signal from $\gamma\gamma \rightarrow H \rightarrow b\bar{b}$ was compared to the background $\gamma\gamma \rightarrow b\bar{b}$. It was argued that with adequate luminosity, mass resolution, b tagging efficiency and light quark rejection capability the detection of the Higgs signal is in principle possible. However it was assumed that the $\gamma\gamma$ channel could be selected against the gg mechanism by using the fact that the coherent γ emission tends to leave the nucleus unbroken and essentially undeflected.

In the present note we consider the background problem in more detail. We first show that even if one assumes that the gg background can be completely discriminated, the detection of the Higgs signal is essentially impossible once feasible, although still optimistic, values for the luminosity, the mass resolution, the b tagging efficiency and the light quark rejection factors are introduced. Furthermore we argue that the vetoing of the gg channel to the required accuracy on the basis of the distributions of the nuclear jet near the forward direction is completely unrealistic. We conclude that the ion-ion approach to the search for the intermediate mass Higgs is actually more difficult than the ordinary $p-p$ case.

For definiteness we refer to the case of Pb-Pb collisions at LHC (and to some extent also at SSC). For Pb one has $Z = 82$ and $A \simeq 207$. As a consequence, for a completely ionized beam, the expected energy will be at LHC $E_{beam} = Z \times 8 \text{ TeV} = 656 \text{ TeV}$ ($E_{beam} = Z \times 20 \text{ TeV} = 1640 \text{ TeV}$ at SSC) corresponding to a total centre-of-mass energy per nucleon $\sqrt{s} = \frac{2 \times 656}{207} \simeq 6.4 \text{ TeV}$ at LHC ($\simeq 16 \text{ TeV}$ at SSC).

We start by recalling the conditions for the photon to be soft enough for coherence and yet to be able to produce a Higgs with $m_H \simeq 100 \text{ GeV}$. We can write the initial and final nucleus four-momenta p and p' in the form:

$$p = (p_L + \frac{M^2}{2p_L}, p_L, \vec{0}) \quad (1)$$

$$p' = ((1-z)p_L + \frac{M^2 + p_T^2}{2(1-z)p_L}, (1-z)p_L, \vec{p}_T) \quad (2)$$

where M is the mass of the nucleus, z is the fraction of longitudinal momentum p_L given to the photon and $\vec{p}_T$ is the transverse momentum. The four-momentum of the photon is $q = p - p'$ and

$$-q^2 = +Q^2 = \frac{M^2 z^2 + p_T^2}{(1-z)} \quad (3)$$

For producing the Higgs the relation

$$4z_1 z_2 p_L^2 = m_H^2 \quad (4)$$

must hold, so that for a Higgs nearly at rest $z \sim \frac{m_H}{2p_L}$ (i.e. $z \simeq 10^{-4}$ at LHC). Thus, only a small fraction of the nucleus energy is transferred to the photon. The conditions for complete coherence are that $|\vec{p}_T| < \frac{1}{R_{ph}}$, $z p_L < \frac{1}{R_{ph}}$ or $M z < \frac{1}{R_{ph}}$, where R_{ph} is the nuclear radius ($R_{ph} \simeq 7 \text{ fm}$). We see that while the transverse momentum cannot exceed R_{ph}^{-1} , the longitudinal momentum can be considerably larger because of the Lorentz contraction of the nucleus as seen in the collision frame. Note however that the production of an intermediate mass Higgs at LHC is at the limit of the condition for full coherence. More in general it is the shape of the nucleus form factor $F(Q^2)$ that fixes the effective charge of the emitting process. For small z the equivalent photon approximation leads to the following density of photons inside a nucleus of charge Z :

$$f_{\gamma N}(z) = \frac{Z^2 \alpha}{\pi z} \int_{z M^2}^{\infty} \frac{dQ^2}{Q^2} |F(Q^2)|^2 \left(1 - \frac{z^2 M^2}{Q^2}\right) \quad (5)$$

with $F(0) = 1$. At each Q^2 the effective charge is $ZF(Q^2)$. At small Q^2 , $F(Q^2)$ is approximately Gaussian, $|F(Q^2)|^2 = e^{-\frac{Q^2}{Q_0^2}}$ with $Q_0 \simeq 55 - 60 \text{ MeV} \simeq (3.3 - 3.6 \text{ fm})^{-1}$. We shall use this approximate expression for the form factor in the following. We have checked, following ref. [4], that this approximation is quite adequate in the range of Q^2 values actually probed in the integral. The Higgs cross section is then given by:

$$\sigma_{\gamma\gamma \rightarrow H} = \frac{8\pi^2 \Gamma(H \rightarrow \gamma\gamma) \frac{1}{m_H}}{\int_{\frac{m_H^2}{4}}^{\frac{1}{s}} \frac{dz}{z} f_{\gamma N}(z) f_{\gamma N}(\frac{m_H^2}{zs})} \quad (6)$$

where $\sqrt{s}$ is the total nucleus-nucleus energy in the centre-of-mass. The expression of $\Gamma(H \rightarrow \gamma\gamma)$ is well known [5,6].

A good orientation into the problem is obtained by plotting the relevant cross sections for Pb-Pb collisions at LHC as done in fig. 1. Throughout this paper we assume that the decay $H \rightarrow t\bar{t}$ is kinematically forbidden. The signal cross sections $\gamma\gamma \rightarrow H \rightarrow b\bar{b}$ and $gg \rightarrow H \rightarrow b\bar{b}$ as functions of m_H are compared with the background reactions $\gamma\gamma \rightarrow b\bar{b}$ and $gg \rightarrow b\bar{b}$ for different cuts on the transverse momentum of the $b\bar{b}$ pair. The signal cross sections are computed for $m_t = 110 \text{ GeV}$, but the dependence on m_t of the cross section times branching ratio is very mild for $m_H \leq 2m_W$. We find good agreement with Drees et al. [4] on the values of the $\gamma\gamma$ cross sections. The only difference is that we inserted for the $H \rightarrow b\bar{b}$ branching ratio the value obtained by also taking into account the contribution to Γ_H from the VV^* final state, where $V = W, Z$ and V^* is a virtual V . The $H \rightarrow b\bar{b}$ branching ratio is considerably reduced by this effect even for m_H well below

$2m_W$ [7]. Also, in fig. 1 the background differential cross sections $\frac{d\sigma}{dM}$ were integrated in the M range $m_H \pm R$. The resolution energy R was set at the value $R = 0.05m_H$, which we consider as a most optimistic possibility for a $b\bar{b}$ final state (with the tagging efficiencies to be specified later). We see from fig. 1 that the signal over background ratio is indeed much more favourable for $\gamma\gamma$ processes than for gg fusion, but that the $\gamma\gamma$ signal cross section is rather small. Even for $\gamma\gamma$ fusion with the ideal conditions of complete reconstruction of quarks, full rejection of gg fusion and of $\gamma\gamma \rightarrow q\bar{q}$ (q being a light quark), the signal over background ratio is always smaller than one. The background is much increased if the light quarks can be confused with the b quarks at some level [4] because the $\frac{d\sigma}{dM}$ for $\gamma\gamma \rightarrow q\bar{q}$, summed over charm and light flavours, is 34 times larger than $\frac{d\sigma}{dM}$ for $\gamma\gamma \rightarrow b\bar{b}$. One cannot think of applying further cuts because the number of events is already very limited. The signal cross section is between 10-100 pb for $m_Z < m_H < 2m_Z$. The best value one can at present expect for the luminosities in the ion mode at LHC is in the range $\mathcal{L} = 10^{27} - 10^{28} \text{ cm}^{-2} \text{ s}^{-1}$. This means 0.1 to 10 signal events per "year" of 10^7 s. We also see from fig. 1 that the $gg \rightarrow b\bar{b}$ background is $10^6 - 10^7$ times larger than the signal $\gamma\gamma \rightarrow H \rightarrow b\bar{b}$. It is clearly very difficult to imagine a realistic way of vetoing gg processes at this level of accuracy.

Already at this stage we do not find that the prospects of observing the process $\gamma\gamma \rightarrow H \rightarrow b\bar{b}$ are very encouraging. In fact, even keeping for the moment the assumption that all strong interaction backgrounds can be discriminated, the signal over background ratio is further suppressed as soon as reasonable efficiencies for b detection and rejection factors for light quarks are included. Assuming that the presence of a $b\bar{b}$ pair is recognized in 30% of the cases and that a $c\bar{c}$, $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ pair fakes a $b\bar{b}$ pair in 5%, 0.5%, 0.5%, 0.5% of the cases, respectively, the results in fig. 2 are obtained for LHC. We see that the signal for an intermediate mass Higgs is reduced to the level of one event or less in a year even at $\mathcal{L} = 10^{28} \text{ cm}^{-2} \text{ s}^{-1}$ and the background from $\gamma\gamma$ alone is six to ten times larger. Note that achieving a resolution of 5% in the reconstruction of the Higgs mass is very demanding in terms of final states for b decays, so that the assumed 30% efficiency for the detection of a $b\bar{b}$ pair with such a good resolution is really optimistic. Similarly the rejection factors for charm and light quarks used in fig. 2 are at the most optimistic levels expected for LEP experiments [8] with full-fledged vertex detection and flavour tagging by multidimensional analysis. It is really difficult to imagine that flavour tagging can be better in the LHC environment than at LEP. For comparison we show the corresponding plot for SSC in fig. 3. With the same efficiency for $b\bar{b}$ tagging and for light quark rejection factors we obtain a comparable signal to background ratio, although the rates are about a factor of ten larger at SSC.

We now start from the very difficult situation of signal rate and of signal over background ratio shown in figs. 2 and 3 and discuss the problem of rejecting the gg and other strong interaction backgrounds. In principle, according to ref. [4], the discrimination should be attempted on the basis of the fact that the $\gamma\gamma$ events are expected to leave the nuclei unbroken and nearly undeflected (say, with transfer momentum squared of the order Q_0^2) while the typical transverse momentum of the spectator jets in gg processes is expected to be of order $\frac{1}{2}\alpha_s m_H$, i.e. a few GeV. Unfortunately, however, the tails of all conceivable

distributions for gg processes in the phase space regions where the confusion with $\gamma\gamma$ processes is possible are by far too large in comparison with the signal.

Consider for example, the transverse momentum distribution of the recoil nucleus after gluon emission. Neglecting soft radiation from the heavy nucleus the most important contribution is from soft radiation from the emitted gluon which can be resummed by a well-known Sudakov form factor. The resulting expression for the p_T of the recoil nucleus is of the form [9,10]:

$$\frac{1}{\sigma} \frac{d\sigma}{dp_T} = \frac{p_T}{2\pi} \int d^2b e^{-i\vec{b}\vec{p}_T} \exp \left\{ \int_0^{m_H^2} \frac{dk^2}{k^2} c_A \frac{\alpha_s}{2\pi} \log \frac{m_H^2}{k^2} (J_0(kb) - 1) \right\} \quad (7)$$

where $c_A = 3$ is present because the radiation is from the gluon. In the corresponding formula for the p_T of the state of mass m_H obtained from gg fusion the Sudakov exponential is squared as a result of the convolution of the radiation from both fusing gluons. This model of the p_T distributions is certainly adequate for our indicative purposes. The results are shown in fig. 4. It is apparent from this figure (note the linear scale and the fact that the area under each curve is normalized to 1) that there is a probability of order 1% to find a spectator jet with a few hundred MeV of transverse momentum. This confirms that it is impossible to overcome a factor $10^6 - 10^7$ in the gg background by a cut on p_T or in any other similar variable (even applying it to both the forward and backward jets). Note that we have neglected additional backgrounds from other strong interaction processes with misidentification of jets (as for example $gg \rightarrow gg$ with the final gg misidentified) or from fluctuations of the huge background of minimum bias Pb-Pb collisions.

There is also another point to consider. Although the emission of the photons does not much perturb the incoming nuclei, there is always the possibility that the two nuclei interact with each other during the process of emission. As a consequence the most likely configuration of the final state should be one similar to that of minimum bias Pb-Pb interaction (apart from the presence of a central $b\bar{b}$ pair). Thus the appropriate p_T cut is not of order Q_0 but rather of order 1 GeV. This makes the discrimination of gg processes by their p_T distribution even more impossible. It was argued in ref. [11] that if one wants to impose the constraint that the two nuclei do not interact (e.g. by requiring that for the impact parameter b one has $b > 2R_P$) the result is a drastic suppression of the number of $\gamma\gamma$ events that indeed appear as exceptionally quiet and with the unbroken nucleus in the forward direction.

In conclusion we think that it is not possible to discover an intermediate mass Higgs by colliding heavy ions at LHC or SSC. This is because too many miraculous improvements should take place at the same time (luminosity, $b\bar{b}$ resolution and tagging efficiency, rejection of light quarks, discrimination of strong interaction processes). The proposed method based on $\gamma\gamma$ processes in nucleus-nucleus collisions when analyzed in detail appears completely unrealistic and in any case is certainly more difficult than the search for the Higgs in $p-p$ collisions by using rare decays like $H \rightarrow \gamma\gamma$ (for example in $pp \rightarrow HW \rightarrow \gamma\gamma l\nu$), $H \rightarrow \tau^+\tau^-$ or $H \rightarrow VV^*$ [12].

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Figure captions

- Fig. 1. $\sigma(\gamma\gamma \rightarrow H \rightarrow b\bar{b})$, $\sigma(gg \rightarrow H \rightarrow b\bar{b})$, $\int_{m_H-R}^{m_H+R} dm_{\gamma\gamma} \frac{d\sigma}{dm_{\gamma\gamma}}(\gamma\gamma \rightarrow b\bar{b})$ and $\int_{m_H-R}^{m_H+R} dm_{gg} \frac{d\sigma}{dm_{gg}}(gg \rightarrow b\bar{b})$ for Pb-Pb collisions at LHC ($\sqrt{s} = 6.4 \text{ TeV}$) with an assumed resolution R for the $b\bar{b}$ invariant mass given by $R = 0.05m_H$ and with the transverse momentum of the $b\bar{b}$ pair satisfying the relation $p_T > am_H$ ($a = 0, 0.25, 0.40$). The top mass is fixed at the value $m_t = 110 \text{ GeV}$.
- Fig. 2. Signal ($\sigma(\gamma\gamma \rightarrow H \rightarrow b\bar{b})$) and background ($\int_{m_H-R}^{m_H+R} dm_{\gamma\gamma} \frac{d\sigma}{dm_{\gamma\gamma}}(\gamma\gamma \rightarrow b\bar{b}, q\bar{q})$ where $q\bar{q}$ stands for a light quark pair misidentified as a beauty pair) for Pb-Pb collisions at LHC ($\sqrt{s} = 6.4 \text{ TeV}$) with $R = 0.05m_H$ and $p_T > am_H$ ($a = 0.40$). The detection efficiency for a $b\bar{b}$ was assumed to be $\epsilon_{b\bar{b}} = 30\%$ and the misidentification probabilities for a $c\bar{c}$ and $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ were taken as 5%, 0.5%, 0.5%, 0.5% respectively.
- Fig. 3. Same as fig. 2. for the SSC case ($\sqrt{s} = 16 \text{ TeV}$).
- Fig. 4. Normalized p_T distributions for the spectator jets (solid) and for the produced system of mass $m_H \simeq 100 \text{ GeV}$ (dashed) in processes originated by gg fusion for Pb-Pb collisions.

Fig. 1

Fig. 2

Fig. 3

Fig. 4