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**NEW HUNT FOR AN INTERMEDIATE-MASS HIGGS-BOSON
IN PERIPHERAL ULTRARELATIVISTIC HEAVY-ION
COLLISIONS**

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New hunt for an intermediate-mass Higgs boson in peripheral ultrarelativistic heavy-ion collisions

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Abstract

We reopen the discussion on the two-photon production of the intermediate mass Higgs boson in peripheral ultrarelativistic heavy-ion collisions at LHC. Due to larger expected luminosity, larger collision energy and higher photon energies the Higgs production rate is enlarged by more than a factor of ten in Ca+Ca collisions compared to Pb+Pb collisions. Besides the background of direct $b\bar{b}$ -production via two-photon fusion we also discuss photon-gluon fusion into $b\bar{b}$.

The hunt for the Higgs boson is one of the major challenges in today's physics. Its discovery would represent a complete validation of the Standard Model, which unifies strong and weak interactions. In present e^+e^- colliders, like LEP at CERN, a lower mass bound of the SM-Higgs boson of $m_H \geq 58.4$ GeV has been set [1]. With LEP II the mass regime could be explored up to $m_H \approx 80$ GeV. On the other side, present (Fermilab) and future (LHC) pp colliders will only allow a detection of the Higgs boson for masses larger than $m_H \geq 130$ GeV [2]. This leaves the intermediate mass regime $80 \text{ GeV} \leq m_H \leq 130 \text{ GeV}$ uncovered. To pour even more salt into this open wound, it has been predicted, that the lightest Higgs boson of the minimal supersymmetric extension of the Standard Model should not be heavier than about 110 GeV [3].

In an attempt to overcome this difficulty, it had been suggested to utilize the strong transverse electromagnetic fields prevailing in peripheral ultrarelativistic heavy-ion collisions to produce intermediate mass Higgs bosons in coherent two-photon collisions [4,5]. For the Pb+Pb mode with $E = 3$ TeV/u at the planned LHC the maximum photon frequencies $\omega_{max} = \gamma/R = 80$ GeV to be reached correspond to the reciprocal of the Lorentz contracted nuclear radius R , so that particles with masses up to about $m \approx 2\omega_{max} \approx 160$ GeV could be produced. The cross section for the production of an intermediate mass SM-Higgs boson in such heavy-ion collisions has been calculated to be approximately 40 pb [4–15]. However, these numbers do not suffice to achieve reasonable production rates; with the expected luminosity $L = 1.6 \cdot 10^{27} \text{ cm}^{-2} \text{ sec}^{-1}$ for a Pb beam at LHC and a running time of 10^7 sec ($= 1/3$ year) only 0.6 SM-Higgs bosons could be produced per year.

The luminosity of the lead beam is strongly limited by two electromagnetic processes: The sudden electromagnetic pulse accompanying the fast impinging nucleus may lead to Coulomb dissociation of the collision partner with a cross section of 222 barn [16]. The other process, the creation of an electron-positron pair with successive electron capture, comes with a cross section of 101 barn [17]; this value is controversial since a newer calculation yields 222 barn [18]. Thus the expected luminosity for a Pb beam at LHC energies will not be larger than $L = 1.6 \cdot 10^{27} \text{ cm}^{-2} \text{ sec}^{-1}$ [19]. Therefore, Brandt, Eggert and Morsch proposed

to use lighter heavy ions, as for example Ca, instead of Pb and in this way increase the luminosity. At a first glance this might be misleading because the electromagnetic particle production cross sections are reduced by a factor of $(Z_{Pb}/Z_{Ca})^4 = 283$ in Ca+Ca collisions compared to Pb+Pb collisions. On the other hand, the Coulomb dissociation cross section is reduced to 2 barn and the electron capture cross section to only 0.04 barn for Ca+Ca collisions, which leads to a gain of more than three orders of magnitude in luminosity. For Ca+Ca collisions with a colliding energy of 3.75 TeV/u the expected luminosity will be $L = 4 \cdot 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ [19]. Furthermore, due to the larger collider energy larger photon frequencies of up to $\omega_{max} \approx 180 \text{ GeV}$ can be reached. Altogether, in Ca+Ca collisions particle production is enhanced by considerably more than a factor of ten in contrast to Pb+Pb collisions. Consequently, the electromagnetic production of heavy particles such as the Higgs boson should be reconsidered.

In the framework of the equivalent photon method the cross section for particle production excluding central collisions can be formulated in the following way [20]:

$$\sigma^{red} = \int_{2R}^{\infty} db 2\pi b \int d\omega_1 \int d\omega_2 \left[n_{\parallel}(\omega_1, \omega_2, \vec{b}) \sigma_{\parallel}^{\gamma\gamma}(\omega_1, \omega_2) + n_{\perp}(\omega_1, \omega_2, \vec{b}) \sigma_{\perp}^{\gamma\gamma}(\omega_1, \omega_2) \right], \quad (1)$$

where $\sigma_{\parallel}^{\gamma\gamma}$ and $\sigma_{\perp}^{\gamma\gamma}$ represent the elementary particle production cross sections by two real photons with parallel and perpendicular polarizations to each other. $n_{\parallel}$ and $n_{\perp}$ are the two-photon distribution functions, which also depend on the photon polarizations. In the case of scalar Higgs boson production only the parallel part contributes whereas the perpendicular part vanishes:

$$\sigma_{\parallel}^{\gamma\gamma} = 2 \frac{8\pi^2}{m_H} \Gamma_{H \rightarrow \gamma\gamma} \delta(s - m_H^2) \quad ; \quad (2)$$

$\Gamma_{H \rightarrow \gamma\gamma}$ is the two-photon decay width of the Higgs boson [21], for which we use $m_t = 175 \text{ GeV}$ for the top quark mass.

In Fig. 1 the solid line represents the cross section for the Higgs boson production in Ca+Ca collisions. The peak in the reduced Higgs boson cross section σ^{red} at about 160 GeV results from a resonance corresponding to twice the mass of the W boson. For a Higgs

boson mass $m_H = 100$ GeV we compute a cross section of 1.0 pb. This corresponds to 40 SM-Higgs bosons per year assuming an expected luminosity of $4 \cdot 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ and a running time of 10^7 sec ($=1/3 \text{ year}$).

In the intermediate mass regime the Higgs boson predominantly decays into $b\bar{b}$. Above $m_H = 120$ GeV a new decay channel into one real and one virtual W boson becomes more and more important [22]. Thus, the background for the intermediate mass Higgs signal will be the process $\gamma\gamma \rightarrow b\bar{b}$. The invariant mass spectrum $d\sigma/dM_{b\bar{b}}$, where $M_{b\bar{b}} = \sqrt{4\omega_1\omega_2}$ is the invariant mass of the $b\bar{b}$ system, is also calculated from (1) with $m_b = 4.5$ GeV. The corresponding elementary cross sections $\sigma_{\parallel/\perp}^{\gamma\gamma}$ are given in [20] and have to be multiplied with $3 \cdot q^4$ in addition, where $q = -1/3$ is the charge of the b quark. The results for this background process are also presented in Fig. 1 as a function of the invariant mass of the $b\bar{b}$ pair. To compare the differential cross sections of the direct $b\bar{b}$ production with the reduced cross section of the Higgs boson production the former has to be multiplied with the expected mass resolution ΔM . In the case of photon-photon fusion we are showing two curves corresponding to $\Delta M = 1$ GeV and $\Delta M = 10$ GeV, respectively. If one assumes $\Delta M = 1$ GeV, the intermediate-mass Higgs signal is of the same order of magnitude as the two-photon fusion process. For the production of a Higgs boson with $m_H = 100$ GeV the statistical significance is $N_s/\sqrt{N_s + N_b} = 4.5$, where N_s and N_b denote the number of signal and background events. Assuming a larger mass resolution of $\Delta M = 10$ GeV the statistical significance is reduced to 2.0.

With adequate cuts the statistical significance might even be increased. Kinematically the intermediate-mass Higgs boson is produced with small rapidities in the laboratory frame, $|y| < y_{\text{max}} \approx 1.5$ [23], and thus it decays almost isotropically into $b\bar{b}$. This is not the case for the direct background process $\gamma\gamma \rightarrow b\bar{b}$. Therefore a cut in single rapidity or in the single transverse momentum of the quarks might improve the Higgs signal. Furthermore, according to the original design of the ALICE detector at LHC [24], one can only measure charged particles within the polar angle range $45^\circ \leq \Theta \leq 135^\circ$. This automatically leads to a cut in rapidity, which can be introduced with the following condition [23]:

$$\frac{\sinh |y \pm \bar{y}|}{\sqrt{1 - (1 - \beta^2) \cosh \bar{y}}} \leq 1 \quad . \quad (3)$$

Here y stands for the rapidity of the two-photon system in the laboratory frame; $\bar{y}$ is the rapidity of one quark in the c.m. system of the two photons. $\beta = \sqrt{1 - 4m_b^2/s}$ is the velocity of a single quark; in case of Higgs boson production the c.m. energy is $s = m_H^2$.

In Fig. 2 we show the same cross sections as in Fig. 1 but now with rapidity cuts involved. Obviously, the two-photon fusion contribution is reduced by more than one order of magnitude. On the other hand the Higgs signal is reduced only by about a factor of 4. Furthermore, one has to take into account the branching ratio of the Higgs boson into $b\bar{b}$. As one can see in Fig. 2 the Higgs boson decays mostly into $b\bar{b}$ up to a mass of 120 GeV, then the new decay channel into one real and one virtual W boson opens up [22]. The electromagnetic production of a Higgs boson with $m_H = 100$ GeV leads then to about 9 Higgs bosons per year with a statistical significance of 2.8 and 1.7 for $\Delta M = 1$ and $\Delta M = 10$ GeV, respectively. Obviously, both the signal and background rate have become so small, that the statistical significance has decreased somewhat. Running the collider two years thus would increase the statistical significance by a factor $\sqrt{2}$. Still a statistical significance of about 3 should be enough for the SM Higgs detection in peripheral Ca+Ca collisions.

An additional background results from photon-gluon fusion into $b\bar{b}$ [25]. A photon accompanying the one nucleus might penetrate directly into the other nucleus and fuse with with one of its gluons. The corresponding cross section is also obtained from (1), but instead of the two-photon distribution functions $n_{\parallel}$ and $n_{\perp}$ we have to use the photon-gluon distribution functions $\tilde{n}_{\parallel}$ and $\tilde{n}_{\perp}$ as stated in ref. [26]. The results for photon-gluon fusion into $b\bar{b}$ are also displayed in Fig. 1 taking $\Delta M = 1$ GeV. This process apparently overwhelms the production signal of the intermediate mass Higgs boson by about three orders of magnitude. Taking rapidity cuts into account the difference is reduced by about an order of magnitude as one can see from Fig. 2, but the photon-gluon contribution still seems to be about two orders of magnitude larger than the Higgs signal. In ref. [25] it was argued that for Pb+Pb collisions the processes $\gamma\gamma \rightarrow b\bar{b}$ and $\gamma g \rightarrow b\bar{b}$ are nearly impossible to distinguish. This will

not be the case any longer for Ca+Ca collisions.

In principle photon-gluon fusion processes could be distinguished from two-photon fusion processes since the former automatically leads to the disintegration of that nucleus where the gluon is coming from. The color, which is mediated by the incoming gluon, has to be radiated by the two outgoing b jets in the form of another gluon. This gluon will be absorbed again by the remaining nucleus and, due to the energy scale involved, will lead to its disintegration. Unfortunately for Pb+Pb collisions the probability for Coulomb dissociation for close impact parameters ($b \approx 2R$) is about one [16], so that it can not be distinguished from the gluon initiated dissociation. However, for Ca+Ca collisions the probability of Coulomb dissociation is about a factor 1/100 smaller than for Pb+Pb collisions. Therefore a trigger on intact nuclei should be a good tool to distinguish between both processes. Furthermore, the $b\bar{b}$ pair resulting from the Higgs decay will have a total transverse momentum of up to $\Delta p_t \approx 2/R \approx 100$ MeV in contrast to the pair obtained from photon-gluon process with $\Delta p_t \approx 1/R + 1/r \approx 250$ MeV (r denotes the radius of a nucleon), which is further enlarged by gluon bremsstrahlung. Of course, this deserves a more elaborated investigation. At present we may start from the hypothesis, that the γg -background to the Higgs signal can be ruled out for Ca+Ca collisions.

It should also be mentioned that the electromagnetic production of intermediate mass Higgs bosons of the minimal supersymmetric extension of the standard model (MSSM) may be enhanced over the standard model Higgs boson production by a factor of about 10 for certain choices of the free model parameters [27]. As the number of signal $b\bar{b}$ increases with the enhanced production of the intermediate MSSM Higgs boson with respect to the SM Higgs boson case, the background of directly produced $b\bar{b}$ pairs remains unaffected. Assuming an enhancement factor of 10, about 109 MSSM Higgs bosons with a mass of $m_H = 100$ GeV could be produced per year with rapidity cuts involved. This would lead to statistical significance of 10.3 and 9.5 for $\Delta M = 1$ GeV and $\Delta M = 10$ GeV, respectively.

Another interesting point is the electromagnetic production of supersymmetric particles in Ca+Ca collisions. We obtain cross sections of 17 pb, 7 pb, and 3.3 pb for the production

of a sfermion with a mass of 50 GeV, 60 GeV, and 70 GeV. Taking experimental cuts into account, the cross sections are reduced to 2.8 pb, 1.2 pb, and 0.59 pb, respectively. Due to the larger phase space the production of sbosons leads to somewhat larger cross sections of 89 pb, 36 pb, 16 pb, and 7.8 pb with masses of 50 GeV, 60 GeV, 70 GeV, and 80 GeV, respectively. With rapidity cuts involved the cross sections are 15 pb, 6.5 pb, 3.1 pb, and 1.5 pb. These cross sections correspond to production rates of 60, 26, 12, and 6 per 10^6 sec of beam time (1/30 year) and thus might be large enough to be measurable at LHC.

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Figure caption:

Fig. 1: The cross section σ^{red} for the electromagnetic production of the Higgs boson is shown in dependence on the mass m_H . Also displayed are the differential cross sections $d\sigma^{red}/dM \cdot \Delta M$ of the two contributing background processes $\gamma\gamma \rightarrow b\bar{b}$ and $\gamma g \rightarrow b\bar{b}$. $M_{b\bar{b}}$ is the invariant mass of the $b\bar{b}$ pair and ΔM is the mass resolution. For $\gamma g \rightarrow b\bar{b}$ we consider only $\Delta M = 1$ GeV. The index 'red' reflects the calculation where the central collision region $0 \leq b \leq 2R$ has not been taken into account.

Fig. 2: Same as in Fig. 1, but now with the inclusion of rapidity cuts. The long-dashed line shows the results for the Higgs boson production with subsequent decay into $b\bar{b}$, i.e., the production cross section multiplied with the branching ratio of the Higgs boson into $b\bar{b}$.

Figure 1

Figure 2