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Higgs production by heavy ion scattering

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Abstract

We compute the production cross section of the Standard Model Higgs by two photon processes in lead–lead collisions. We investigate several lead form factors and recently proposed impact parameter effects. No approximations are used for the underlying two photon mechanism. We also compare the Higgs signal with its main background, the two photon production of quark pairs.

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Introduction

It is well known that detecting an intermediate mass Higgs ($80\,\mathrm{GeV} < \mathrm{M_{Higgs}} < 2M_W$) at future hadron colliders is severely complicated by the large standard model backgrounds to the $b\bar{b}$ decay modes of the Higgs in this mass range. Recently it has been suggested to search for the Higgs via two photon reactions at a future heavy ion collider by taking advantage of the fact that cross-sections of two photon reactions in collisions of ions with atomic number Z go like $Z^4\alpha^4$ [1, 2].

Drees et al. [3] have estimated that lead–lead collisions in the LHC tunnel at a center of mass energy of 1312 TeV might establish a Higgs signal above backgrounds if the Higgs mass is between about 80 GeV and 160 GeV, given an annual luminosity of $10^{28}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and provided certain stringent experimental requirements can be met. The results in [3] were obtained by folding the cross-section for the process $\gamma\gamma \rightarrow$ Higgs with a Weizsäcker–Williams spectrum obtained by assuming a Gaussian for the elastic form factor of ^{206}Pb.

An essential feature needed for the observability of the signal in a heavy ion experiment is the cleanliness of the reaction, i.e. no hadronic debris from the breakup of the parent nuclei. In order to achieve this, as was first pointed out in [4], the heavy ions must remain well separated in a Higgs production event. Otherwise strong interaction effects will lead to a breakup of the ions thus spoiling the cleanliness of the event. The separation requirement can be simulated e.g. by imposing cuts on the impact parameters of the nuclei [4, 5] and lead to a modification of the effective photon luminosities.

With this separation constraint the Higgs production cross-section is considerably reduced and for the design luminosities suggested in [3] detection for most Higgs masses of interest is not experimentally feasible.

In this paper we extend the calculations of [3] by treating the off shell photons explicitly and by incorporating separation cuts in the spirit of Ref. [4]; i.e. we go beyond the Weizsäcker–Williams approximation and cut against inelastic collisions. As a check we use two independent parametrisations for the elastic form factors of lead. We find that little depends on the choice of the form factors. We also calculate the background due to two photon production of $b\bar{b}$ within the same framework. The size of this irreducible physics background allows to set minimal requirements for the integrated luminosity which is needed to establish a Higgs signal. Results are also presented for Higgs production and background cross sections in elastic lead–lead collisions in the SSC tunnel.

Matrix Elements

The matrix element for Higgs production by two photon scattering can be conveniently parametrised by an effective interaction of the Higgs particle with the electromagnetic field

of the form

$$\frac{\lambda}{4} F_{\mu\nu} F^{\mu\nu} H$$

where λ is some effective coupling constant. The value which the coupling constant takes when all fields are on mass shell is related to the partial width of a physical Higgs decaying into two on shell photons

$$\Gamma(H \rightarrow \gamma\gamma) = \frac{\lambda^2 M^3_{Higgs}}{64\pi} \tag{1}$$

The coupling constant λ varies slowly when the photons are moderately off mass shell, and may be approximated by its on shell value. For the case at hand this is an excellent approximation because the form factors of the nuclei force us into the very small Q^2 region anyway. Thus the effective coupling constant λ is given by the partial $H \rightarrow \gamma\gamma$ decay width, for which we use the results of [6]. This is a deviation from [4] who throughout use an effective coupling constant which is valid only when $\mathrm{M_{Higgs}} < \mathrm{M_W}$.

Since the matrix element for $H \rightarrow \gamma\gamma$ is dominated by the contribution from the W loop, the main uncertainty in λ, which arises from the unknown mass of the top quark in the top loop contribution, is uncritical and amounts to at most a 10% effect when varying the top mass between 90 GeV and 200 GeV.

The matrix element for the Higgs production process

$$Pb(p_1) + Pb(p_2) \rightarrow Pb(p_3) H(p_4) Pb(p_5)$$

is given by

$$\mathcal{M} = \frac{4e^2 Z^2 \lambda}{t_1 t_2} F(|t_1|) F(|t_2|) \Delta \tag{2}$$

with $t_1 = q_1^2 = (p_1 - p_3)^2$, $t_2 = q_2^2 = (p_2 - p_5)^2$, $\Delta = p_1 \cdot p_2 q_1 \cdot q_2 - p_1 \cdot q_2 p_2 \cdot q_1$, and $F(Q^2)$ is the form factor of the lead nucleus. Because Δ can give rise to big numerical cancellations we evaluate it using the techniques developed in [7]. The decay of the Higgs is just a matter of phase space due to its scalar nature.

For the $b\bar{b}$ background arising from the reaction

$$\mathrm{Pb}(p_1) + \mathrm{Pb}(p_2) \rightarrow \mathrm{Pb}(p_3)\mathrm{Pb}(p_5)\mathrm{b}(p_6)\bar{\mathrm{b}}(p_7)$$

the matrix element squared, averaged over polarisations, is given by

$$|\mathcal{M}|^2 = \frac{e^4 Z^4}{4} \frac{F^2(t_1) F^2(t_2) M_{22}}{(t_1 t_2 ((q_1 \cdot q_2)^2 - (Q \cdot q_1)^2))^2} \tag{3}$$

where $Q = p_6 - p_7$ and

$$M_{22} \;\; = \;\; 512(((q_1 \cdot q_2)^2 - (Q \cdot q_1)^2)((\frac{1}{2}\epsilon^{p_1 q_1 \mu\nu}\epsilon_{p_2 q_2 \mu\nu})^2 - \epsilon^{p_1 q_1 p_2 q_2}\epsilon_{p_1 q_1 p_2 q_2})$$

$$
\begin{aligned}
&-(\epsilon^{p_1q_1Q\mu}\epsilon_{p_2q_2Q\mu}-\frac{1}{2}\epsilon^{p_1q_1\mu\nu}\epsilon_{p_2q_2\mu\nu}(Q^2+q_1\cdot q_2))^2\\
&-\frac{1}{8}\epsilon^{p_1q_1\mu\nu}\epsilon_{p_1q_1\mu\nu}(\epsilon^{p_2q_2\rho\sigma}\epsilon_{q_1Q\rho\sigma})^2\\
&-\frac{1}{8}\epsilon^{p_2q_2\mu\nu}\epsilon_{p_2q_2\mu\nu}(\epsilon^{p_1q_1\rho\sigma}\epsilon_{q_2Q\rho\sigma})^2\\
&-\frac{1}{4}(Q\cdot q_1)^2(\epsilon^{p_1q_1\mu\nu}\epsilon_{p_1q_1\mu\nu})(\epsilon^{p_2q_2\rho\sigma}\epsilon_{p_2q_2\rho\sigma}))
\end{aligned}
$$

Again M_{22} can be evaluated in a numerically stable manner using the techniques of Ref. [7].

In [3] and [4] the form factor of the lead nucleus is approximated by a single gaussian

$$F_{Pb}(Q^2)=e^{-Q^2/2Q_0^2} \tag{4}$$

with $Q_0 = 60\,\mathrm{MeV}$. In order to test the validity of this form factor we also use a direct experimental fit to electron Pb scattering data [8, 9, 10]

$$F_{Pb}(Q^2)=e^{-Q^2\gamma^2/4}\sum_{i=1}^{12}\frac{q_i}{1+2R_i^2/\gamma^2}(cosR_iQ+\frac{2R_i^2}{\gamma^2}\frac{sinR_iQ}{R_iQ}) \tag{5}$$

where $\gamma = 1.7\sqrt{3/2}$ fm and the values of the fit parameters q_i and R_i are given in Ref. [8, 9, 10]. The form factors (4) and (5) behave similarly for small Q^2. For larger Q^2 eq. (5) will be smaller than eq. (4).

In figure 1 we plot the Higgs production cross section using the two form factors (4) and (5) for both the LHC and the SSC. The results using the two form factors usually differ by about 2%. For the LHC, in the W threshold region, the discrepancy increases to about 6%, which is still smaller than the uncertainty in the $H \to \gamma\gamma$ width due to the unknown top quark mass. Hence we use the simple Gaussian ansatz (4) for the form factor in the rest of this paper.

The Higgs production cross sections obtained from our full calculation are about 50% larger than those using the Weizsäcker–Williams approximation. The enhancement factor slightly decreases with energy. Multiplying the results obtained from the Weizsäcker–Williams approximation by a constant factor K = 1.5 will yield agreement to within better than 10% over the entire mass range 30 GeV $< m_H <$ 180 GeV shown in figure 1. The enhancement is presumably due to contributions from longitudinal modes which are neglected in the Weizsäcker–Williams approximation as used in [3]. As pointed out in [11], neglecting these modes may lead to underestimates for total cross sections.

Elimination of Inelastic Events

Cahn and Jackson [4] have pointed out that the use of elastic form factors leads to an overestimate of the useful $\gamma\gamma$ cross sections in heavy ion collisions. Whenever the two

heavy ions get too close to each other the strong interactions between the nuclei will lead to a breakup of the heavy ions. Thus a typical strong interaction event will appear to be superimposed over the two photon interaction. Experimentally it would be impossible to identify these dirty $\gamma\gamma$ events in a hadronic background which is many orders of magnitude larger. In addition the assumption of a coherent photon-nucleus coupling which underlies the Z^4 enhancement factor of the two photon cross sections is not justified any more in this phase space region of inelastic events.

In a classical picture, and treating the nuclei as black disks, one can eliminate these inelastic interactions by putting a cut on the impact parameter of the collision which, following [4], is taken to be

$$b_{min}=2R \tag{6}$$

where R is the radius of the nuclei given by $R = 1.2A^{1/3}$fm. Originally, in [4], this cut was imposed on the photon spectrum of each of the heavy ions, which results in an overestimate of strong absorption effects [12]. Subsequently a number of authors have employed a cut on the relative impact parameter of the two nuclei in order to suppress the inelastic two photon events [5, 13, 14, 15]. This typically results in Higgs production rates which are a factor 2 to 5 smaller than the ones neglecting strong absorption effects.

Requiring the impact parameter to be larger than a cut value b_{min} is related, via a Fourier transformation, to an upper bound on the momentum component of the scattered ions which is transverse to the beam direction. Equivalently, one can cut on the scattering angles of the ions. We denote these transverse momenta by $P_{3\perp}$ and $P_{5\perp}$ in the following. Going beyond the black disk approximation for the heavy nuclei corresponds to folding the matrix elements of the last section with some function which suppresses transverse momenta larger than $1/b_{min}$. Since additional experimental information is needed to specify this function, we use the simplest approach possible, namely we impose a sharp transverse momentum cutoff. Differences compared to a sharp cutoff in impact parameter space do then allow to estimate the uncertainties in the elastic Higgs production cross section.

We have investigated two possible cutoff schemes: i) Strong nuclear effects can be avoided by requiring that at least one of the two nuclei is well separated from the combined system of the Higgs and the second nucleus. In momentum space this corresponds to the requirement $P_{3\perp} < 1/b_{min}$ or $P_{5\perp} < 1/b_{min}$. ii) As a second option we look at the momentum transfer between the lead nuclei. The momentum that is relevant for this transfer is $\frac{1}{2}(q_1 - q_2)$. Hence we have to restrict the transverse component of this quantity. In a reaction without the Higgs (just lead–lead elastic scattering) this would be the momentum transfer between the lead nuclei because then $q_2 = -q_1$. The restriction on this transverse momentum can be rewritten as

$$\frac{1}{4}(q_1-q_2)_\perp^2=\frac{1}{4}(2P_{3\perp}^2+2P_{5\perp}^2-P_{4\perp}^2)<1/b_{min}^2 \tag{7}$$

In Fig. 2 we plot the effect of these transverse momentum cuts on the production rates of a 100 GeV Higgs boson in lead–lead collisions at both the LHC and the SSC as a function of b_{min} in the vicinity of $b_{min} = 2R$. We find suppression factors between 1.5 and 3 at the SSC and between 3 and 6 at the LHC. We believe that the variations of the numbers shown in Fig. 2 are a fair measure of the uncertainties involved. When we use a cut in the sequel of the paper we will use the cut on $\frac{1}{4}(q_1 - q_2)^2_\perp$ and the central value $b_{min} = 2R$. We have checked that the cross sections with the cuts are independent of which of the form factors we consider.

Results and Conclusions

Using the procedure described in the last section we are now in a position to calculate the cross sections for "clean" signal and background $b\bar{b}$ events, i.e. after the subtraction of inelastic events. Our results are shown in Fig. 3 for both LHC and SSC energies. For the Higgs signal we show both the total Higgs production cross section (solid line) and 3 curves for the $b\bar{b}$ decay cross sections (dashed lines). The strong suppression of the latter for Higgs masses above 120 GeV arises because the Higgs decay into one real and one virtual W starts to become important. Already at $m_H = 140$ GeV this new channel dominates over the $b\bar{b}$ mode.

For backgrounds we only show the irreducible physics background arising from $\gamma\gamma \to b\bar{b}$, more precisely we show the $b\bar{b}$ invariant mass distribution in units of pb/10 GeV. Assuming a $b\bar{b}$ mass resolution of 10 GeV the signal total cross section and the background mass distribution can thus be compared directly. It is a well known fact from e^+e^- physics that two photon backgrounds can be reduced by $p_\perp$ cuts. This was also noted in [3], hence the signal to background ratio can be improved substantially by imposing a cut on the transverse momentum, $p_\perp > \eta m_{b\bar{b}}$, of the produced b jets. While the signal is produced in a pure s-wave, many partial waves contribute to the background which results in a much softer transverse momentum spectrum for a given $b\bar{b}$ invariant mass. Because the Higgs is produced with essentially zero transverse momentum this cut is equivalent to a cut on the rapidity difference of the two b quark jets [3].

In Fig. 3 both signal and background are plotted for p_T cuts with $\eta = 0.2$ and 0.4 respectively. Even for the last more stringent p_T cut the signal to background ratio is never better than 1 : 3, assuming an experimental mass resolution of 10 GeV. Notice that this statement is unaffected by the uncertainties of our calculation: changing the two photon luminosities at large heavy ion separation will affect signal and background rates in the same manner.

In order to detect the Higgs as a peak in the $b\bar{b}$ invariant mass distribution one would probably like to see at least a 4σ signal. Denoting by N_S and N_B the number of signal and background events and requiring $N_S/\sqrt{N_S + N_B} \geq 4$, we find that in the mass range $80\,\text{GeV} < m_H < 140\,\text{GeV}$ an integrated luminosity of between 5 and $15\,\text{pb}^{-1}$ is required to obtain a 4σ signal. At the SSC the rates are larger by a factor 10 and hence an integrated luminosity of $1\,\text{pb}^{-1}$ would give a signal of the same significance. Note that these estimates are highly optimistic since no efficiency factors have been included for e.g.

i) b quark identification. The background due to $c\bar{c}$ pairs is 16 times larger than the b quark dijet background.
ii) Vetoing against the $b\bar{b}$ background arising from gluon–gluon fusion events [3, 16].

On the other hand it has been argued that a luminosity in Pb Pb collisions at the LHC beyond $10^{28}\text{cm}^{-2}\text{s}^{-1}$ is very difficult if not impossible to achieve [17]. Already at this luminosity the very large electromagnetic dissociation and electron capture cross sections of order 100 barns or more lead to beam life times of only a few hours. Assuming 10^7 sec of running time per year a luminosity in excess of $10^{30}\text{cm}^{-2}\text{s}^{-1}$ would be required at the LHC (and $10^{29}\text{cm}^{-2}\text{s}^{-1}$ at the SCC) in order to establish a Higgs signal in the $b\bar{b}$ decay mode, according to our previous optimistic criteria.

It appears that a Higgs search in the $H \to b\bar{b}$ decay mode is not a feasible experiment in heavy ion collisions in the LHC tunnel. The same statement is probably true for the SSC.

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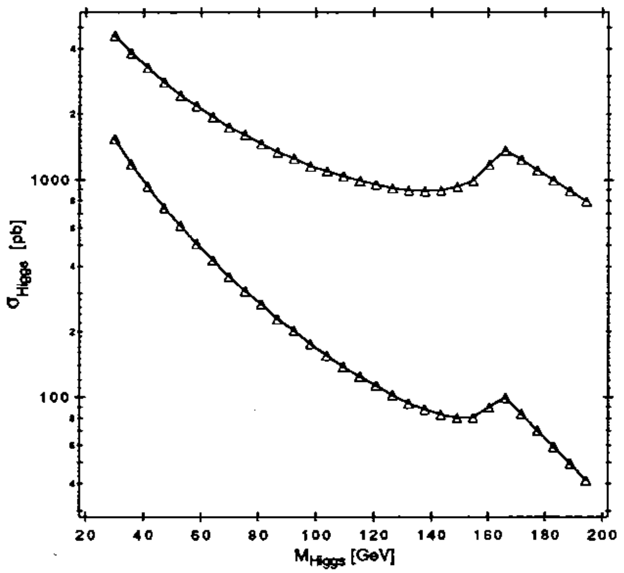

Figure 1: Higgs production as function of the Higgs mass. The upper curve is for a beam energy of 8 TeV/nucleon (SSC) and a single gaussian form factor. The lower curve is for a beam energy of 3.2 TeV/nucleon (LHC) and a single gaussian form factor. The triangles show the results obtained with the form factor representation of eq.(5).

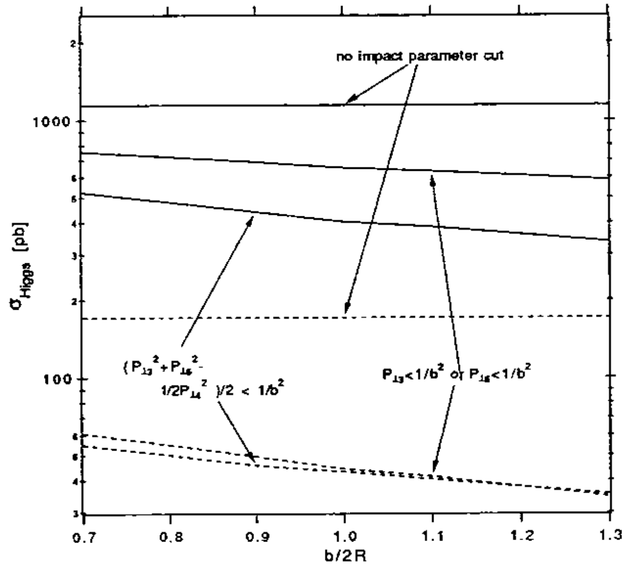

Figure 2: Effect of different cuts for a 100GeV Higgs particle. The solid curves are for a beam energy of 8 TeV/nucleon (SSC) and the dashed curves are for a beam energy of 3.2 TeV/nucleon (LHC). On the horizontal axis we show the minimal impact parameter $1/b_{min}$ in the range 0.7 to 1.3 in units of $1/2R$.

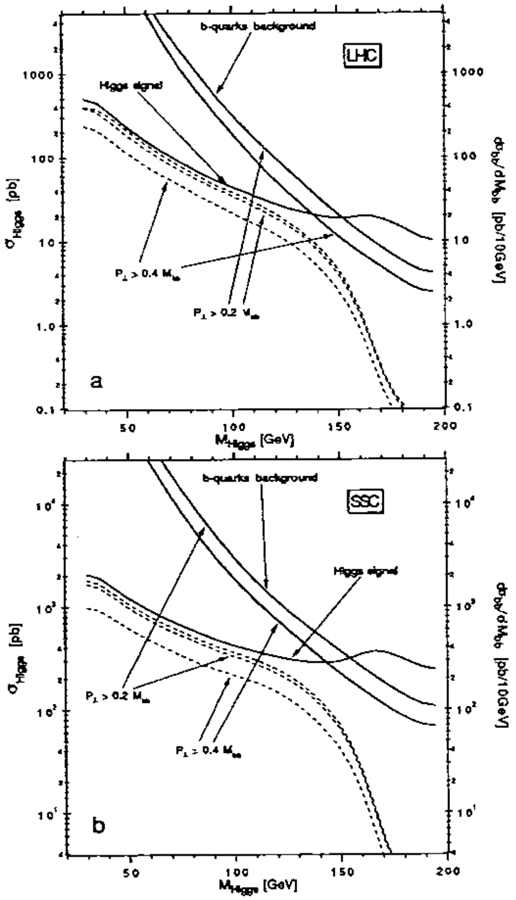

Figure 3: The $b\bar{b}$ rates for Higgs signal and background arising from two photon fusion in ^{206}Pb ^{206}Pb scattering at (a) 3.2 TeV/nucleon (LHC) and (b) 8 TeV/nucleon (SSC) with an impact parameter cut. Note that the $b\bar{b}$ background is in units of pb/10GeV.

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