Coherent Processes in Heavy Ion Collisions at the LHC

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Abstract

The strong electromagnetic fields in relativistic heavy ion collisions lead to sizable photon-photon scattering cross sections. We study the production of the intermediate mass Higgs boson, W pairs and new charged particles. For a Higgs search the $\gamma\gamma \to b\bar{b}$ background is important. Higgs production via diffractive collisions is also studied.

1. Introduction

Relativistic heavy ion collisions in the LHC tunnel are being contemplated as a means to study strong interaction thermodynamics [1]. At the same time the very strong electromagnetic fields around the ions provide for high photon fluxes which can be used to study two photon physics. More precisely the coherent coupling of the photons to nuclei of atomic number Z provides for an enhancement factor of Z^4 as compared to equivalent cross sections in proton-proton scattering. It has been suggested to use the resulting large two-photon cross sections to search for new particles, like the Higgs boson or charged superpartners of the known quarks and leptons, or to study W^+W^- pair production [2–13].

In this report we address the question to what extent the discovery potential of the LHC in the high energy domain can be enhanced by two-photon physics in heavy ion scattering. More precisely we have investigated the reach of lead-lead collisions with a center of mass energy of 1312 TeV (3.2 TeV/nucleon for ^{206}Pb), assuming a heavy ion luminosity of $10^{28}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The main emphasis has been on the production of an intermediate mass standard model Higgs boson. If $m_H \leq 80$ GeV, the Higgs will presumably be discovered at LEP. For Higgs masses above ~ 130 GeV Higgs production via gluon fusion at the LHC and/or the SSC will allow the detection of the decay mode $H \to ZZ$ (with one of the Z's possibly being virtual) [14]. This leaves the interesting intermediate mass range between 80 GeV and 130 GeV where a search at a heavy ion collider would have to be performed in the dominant $H \to b\bar{b}$ decay mode. Production cross sections in heavy ion collisions, event characteristics, and irreducible physics backgrounds (from $\gamma\gamma \to b\bar{b}$) to this search will be discussed in Section 2. In Section 3 we discuss production cross sections for heavy charged particles like the W boson or charged superpartners of the quarks, leptons and gauge bosons. Finally in Section 4 diffractive production processes are addressed.

2. Higgs Production

The basic Higgs production and decay process we are interested in here is

$$PbPb \to PbPbH,\ H \to b\bar{b}\,, \tag{1}$$

which proceeds via two-photon collisions and is depicted in Fig. 1. Because of the small production rate one must search for the hadronic decay mode of the Higgs in a background from generic heavy ion collisions, which is many orders of magnitude larger. Clearly one must fully exploit the cleanliness of generic two-photon events, *i.e.* only such events will be useful where the parent nuclei do not break up. At the same time this is a necessary condition for the coherent coupling of the photons to the parent nuclei.

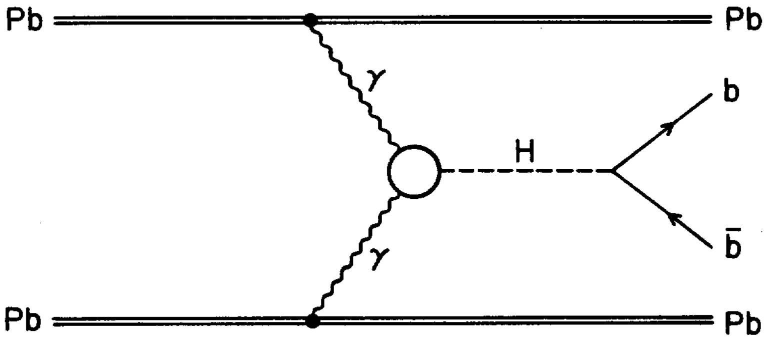

Figure 1: Feynman graph for coherent Higgs production in *Pb Pb* collisions.

When calculating the Higgs production cross section the coherence requirement can be implemented by using form factors for the coupling of the photons as determined from elastic electron nucleus scattering [5]. This form factor is precisely the Fourier transform of the charge distribution of the parent nucleus. For lead nuclei a Gaussian form factor

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

with $Q_0 = 60$ MeV gives a good approximation [12]. The form factor limits the virtuality $q^2 = -Q^2$ of the exchanged photons to very small values compared to the Higgs mass and hence reasonable results are obtained by using a Weizsäcker Willams approximation (WWA). In the WWA the production cross section is given by folding the subprocess cross section $\hat{\sigma} = \hat{\sigma}(\gamma\gamma \to X)$ with the photon flux $f_{\gamma/Pb}(z)$,

$$\sigma(PbPb \to PbPbX) = Z^4 \int dz_1 dz_2 f_{\gamma/Pb}(z_1) f_{\gamma/Pb}(z_2) \hat{\sigma}(z_1 z_2 s) \tag{3}$$

where the photon flux is given in terms of the elastic form factor by

$$f_{\gamma/Pb}(z) = \frac{\alpha}{\pi} \int_{z^2M^2}^{\infty} dQ^2 \frac{|F_{Pb}(Q^2)|^2}{Q^2} \left(\frac{1}{z} - \frac{M^2}{Q^2} z \right) . \tag{4}$$

Here M is the mass of the lead nucleus.

The cross section of Eq. 3 does not correspond to the rate of clean two photon events, as was first noted by Cahn [7]. When producing massive objects X of order

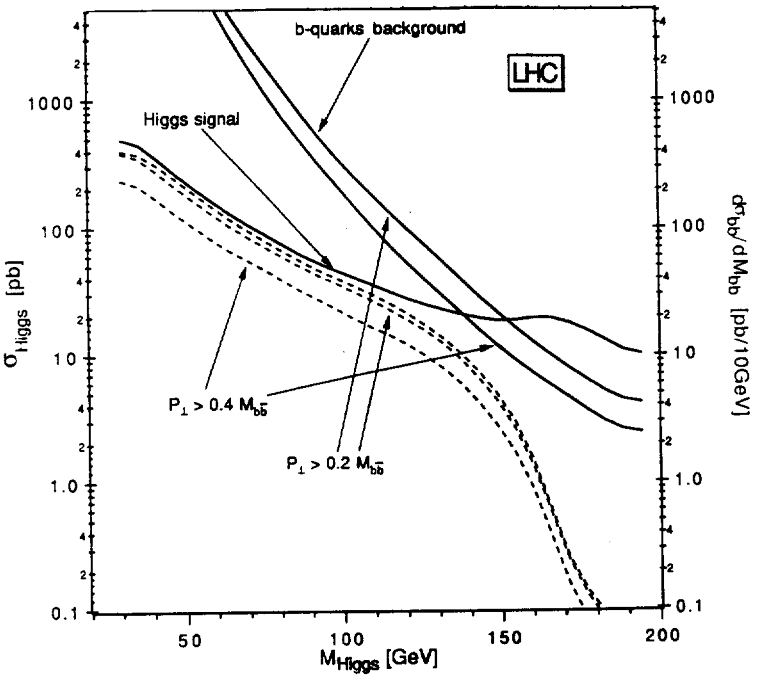

Figure 2: The $b\bar{b}$ rates for Higgs signal and background arising from two photon fusion in Pb Pb scattering at the LHC. An impact parameter cut has been imposed already. Note that the $b\bar{b}$ background is in units of pb/10GeV. From Ref. [12].

100 GeV a substantial fraction of the collisions occurs at small lead-lead impact parameters where the two nuclei overlap and are subject to strong interactions in addition to the two-photon process. The strong interaction effects will almost always lead to a breakup of the parent nuclei thus spoiling the cleanliness of the events.

In a black disk approach to the nuclear interactions the requirement of no residual strong breakup is equivalent to a cut on the relative impact parameters $\vec{b}_1 - \vec{b}_2$ of the two nuclei

$$\left|\vec{b}_1 - \vec{b}_2\right| > 2R \tag{5}$$

with $R \approx 7$ fm the nuclear radius. This cut can either be imposed in the WWA by performing a Fourier transformation of the transverse heavy ion momenta, which implicitly enter in the Q^2 integrals of the photon flux functions $f_{\gamma/Pb}(z)$ in Eq. (3) [8, 10, 11], or it can be imposed in a calculation of the complete $PbPb \to PbPbH$ process [9, 13]. An alternative approach was followed in Ref.[12], where the cut was directly imposed on the relative transverse momenta $q_{1\perp}$ and $q_{2\perp}$ of the final state lead nuclei:

$$\frac{1}{4}(q_1 - q_2)^2_\perp < \frac{1}{4R^2}\,. \tag{6}$$

Depending on the procedure to implement the absence of nuclear scattering on top of Higgs production, one finds reduction factors of 2–5 compared to the Higgs production cross section given by Eq. (3). Using Eq. (6) one finds a reduction factor ≈ 4 and the resulting cross sections at the LHC are plotted in Fig. 2 for both the Higgs signal and the $b\bar{b}$ background.

For the Higgs signal we show both the total Higgs production cross section (solid line) and 3 curves for the signal $b\bar{b}$ 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. As was already noted in [5], the signal to background ratio can be improved substantially by imposing a cut on the transverse momentum, $p_T > \eta m_{b\bar{b}}$, 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 [5].

In Fig. 2 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 usable two photon luminosities 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 $80\,\mathrm{GeV} < m_H < 140\,\mathrm{GeV}$ an integrated luminosity of between 5 and $15\,\mathrm{pb}^{-1}$ is required to obtain a 4σ signal. 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 which arises from gluon gluon fusion events [5, 15].

On the other hand it has been argued that a luminosity in Pb Pb collisions at the LHC beyond $10^{28}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is very difficult if not impossible to achieve [16]. 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 $10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ would be required at the LHC 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.

3. Charged Particle Production within and beyond the Standard Model

Apart from searches for the Standard Model minimal Higgs, efforts at present and future colliders focus on the production and detection mechanisms of the new particles that Supersymmetry and other theories beyond the Standard Model predict.

The production of electrically charged exotic particles in two-photon collisions is interesting because the couplings are fixed to lowest order and thus the production rates of exotic particles with a certain mass are given in a model-independent way. Therefore the first question to be adressed is whether the mass range that heavy-ion collisions at the LHC can cover will exceed that of LEP2. A rough estimate for the maximum two-photon invariant mass yields: $W_{\max} \sim \gamma/R \simeq 200$ GeV assuming a Lorentz contraction factor $\gamma \simeq 3500$ and a nuclear radius $R \simeq 7$ fm, but at a luminosity of $\mathcal{L} = 10^{28}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ the event rate might not be significant. While the cross sections grow mainly with some power of the logarithm of the heavy-ion energy, which is typical for the two-photon subprocesses, light particles are boosted in the direction of the beam and escape detection as the beam energy is increased. Hence detection is easiest at the upper end of the mass spectrum where, however, the usable two-photon flux is most uncertain when one requires exclusion of events with residual strong interactions.

The other interesting point will be to look for the pair-production of W^+W^- via photon-photon collisions. A test of the four-boson vertex via this process would supplement the LEP2-tests of the nonabelian gauge structure of the electroweak theory.

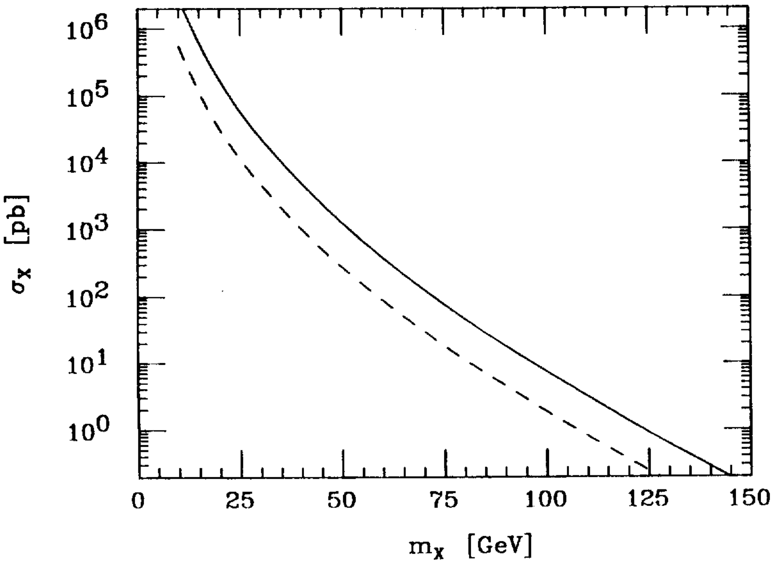

Figure 3: The cross section for the production of a pair of fermions (solid line) and a pair of scalars (dashed line) in lead on lead collisions at the LHC as a function of the particle's mass. Adapted from Ref. [11].

The cross section for the production of a pair of fermions, which can be a pair of quarks, leptons or a pair of winos (the supersymmetric partner of the W-boson), out of two real photons is given by [17]:

$$\sigma(\gamma\gamma \to f\bar{f}) = \frac{4\pi\alpha^2 q_f^4}{W^2}\left[2\left(1+y-\frac{1}{2}y^2\right)\ln\left(\frac{1}{\sqrt{y}}+\sqrt{\frac{1}{y}-1}\right)-(1+y)\sqrt{1-y}\right], \tag{7}$$

where q_f and M_X are the charge and mass of the fermion and $y = 4M_X^2/W^2$. The integration over the two-photon invariant mass W is performed using an equivalent-photon luminosity which excludes nuclear absorption effects in a sharp-cut off model. For particle masses $M_X \geq 100$ GeV the total cross sections are ≤ 10 pb at the LHC operating with lead beams [11], as is shown in Fig. 3. This means that with a luminosity of $10^{28}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ the discovery range of the LHC does not exceed that of LEP2. Earlier results which were obtained by allowing the nuclei to overlap in impact parameter space were enhanced by an overall factor of ten [6], while the low-frequency approximation had pushed the 10 pb mass threshold from 100 GeV down to 50 GeV [4].

For charged scalars like squarks, sleptons, or charged Higgs bosons the total production cross section is given by [18]

$$\sigma(\gamma\gamma \to S^+S^-) = \frac{2\pi\alpha^2}{W^2}\left[(1+y)\sqrt{1-y} - 2y\left(1-\frac{y}{2}\right)\ln\left(\frac{1}{\sqrt{y}}+\sqrt{\frac{1}{y}-1}\right)\right], \quad (8)$$

and is even smaller than the one for fermion pairs [11], Fig. 3.

The two-photon cross section of W^+W^- pairs is given by [19]

$$\sigma(\gamma\gamma \to W^+W^-) = \frac{8\pi\alpha^2}{W^2}\left[\frac{1}{t}\left(1+\frac{3}{4}t+3t^2\right)\beta - 3t(1-2t)\ln\left(\frac{1+\beta}{1-\beta}\right)\right], \quad (9)$$

with

$$t = \frac{M_W^2}{W^2} \quad \text{and} \quad \beta = \sqrt{1-4t}\,. \quad (10)$$

This leads to the production of $\simeq 40$ W^+W^- pairs per year at the LHC operating again with beams of lead at a luminosity of $\mathcal{L} = 10^{28}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The resulting W^+W^- invariant mass spectrum is shown in Fig. 4.

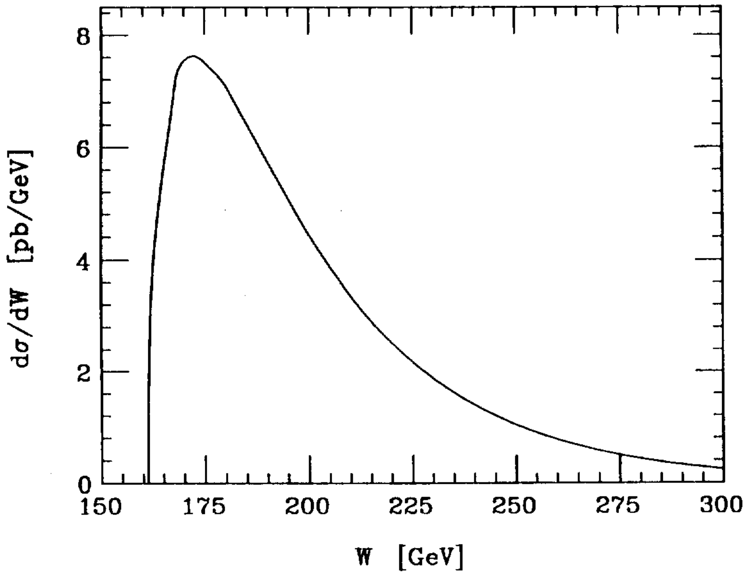

Figure 4: The invariant mass spectrum for the production of W^+W^- pairs in lead-on-lead collisions at the LHC.

Since the number of pairs is small their identification above the four-jet and the two-jet plus lepton background becomes crucial. Assuming that the background originates only from other competing two-photon processes one can try to estimate the order of magnitude of the signal to background ratio. From Fig. 2 one finds that only few $\gamma\gamma \to b\bar{b}$ events with high $p_T(jet)$ and an invariant mass larger than 150 GeV will be produced. Even though the production rate for all light flavors is a factor $\Sigma(e_q/e_b)^4 = 34$ larger, one is still left with a dijet rate which is comparable to the W

pair rate. The rate for 4 well-separated jets is then suppressed by 2 powers of the strong coupling constant $\alpha_s \sim 0.15$ and hence there will be a small background only to the double hadronic decay of the two W's. The two-jet plus lepton plus missing p_T and double leptonic decay signals for W^+W^- will be virtually background-free.

The above remarks assume, however, that a near perfect veto against the presence of beam jets is possible, which occur in all hard QCD background reactions, *i.e.* that it is possible to identify the quiet two-photon events in the huge background of hard QCD processes. Additional studies are needed to assess the validity of this assumption.

4. Production of Higgs particles in diffractive collisions

In order to observe the two-photon processes which we have discussed so far one will have to trigger on soft collisions in which the nuclei stay intact. Such reactions are not distinguishable from diffractive strong interactions, which are described by pomeron exchange. Therefore we have analysed Higgs production via Pomeron exchange as an example for diffractive production processes [20]. We present this analyses for proton proton collisions for which it might be promising. It is then easy to see why it is not of interest for heavy ion collisions.

Two processes can contribute, the inclusive $(p+p \to p+p+H+X)$ and the exclusive $(p+p \to p+p+H)$ one. The inclusive process is fairly straightforward to estimate using the methods developed for 'hard diffraction' [21–23].

The incoming protons produce an equivalent flux of pomerons which in turn produce a flux of gluons (G) which can produce a Higgs by GG fusion. Using the formulae of [23] the differential number of pomerons from the protons is given by

$$dn_{Pom}\left(E_i,\omega_i,|t_i|\right) = \frac{9\beta^2}{4\pi^2}\left[F_1(t_i)\right]^2 \left(\frac{\omega_i}{E_i}\right)^{1-2\alpha(t_i)} d\left(\frac{\omega_i}{E_i}\right) d|t_i| \qquad (11)$$

Here $E_i = p_i^0$, $\omega_i = k_i^0$, $t_i = (p_i - p_i')^2$, $i = 1,2$, $\beta = 1.8\ GeV^{-1}$, $\alpha(t) = 1.085 + \alpha' t$, $\alpha' = 0.25\ GeV^{-2}$, and $F_1(t)$ is the isoscalar electromagnetic nucleon form factor

$$F_1(t) = \frac{4M_N^2 - 2.8t}{4M_N^2 - t}\left(1 - t/0.7\,\mathrm{GeV}^2\right)^{-2} \qquad (12)$$

where M_N is the nucleon mass. According to Ref. [23] Eq. 11 should be valid for $\omega_i/E_i \leq 0.1$. We therefore cut the pomeron spectrum off at $0.1E_i$ by requiring each proton to suffer at most an energy loss of 10 percent.

For the flux of gluons in a pomeron we use the Ingelman-Schlein distribution function [21]

$$G_{Pom}(x) = \frac{6}{x}(1-x)^5 \,. \qquad (13)$$

Putting everything together we find for the total cross section of diffractive Higgs production in the inclusive case :

$$\begin{aligned}\sigma(p+p \to p+p+H+X) &= \frac{\pi^2}{32}\frac{\Gamma(H \to GG)}{m_H}\int dn_G(E_1,\omega_1') \\ &\quad \times \int dn_G(E_2,\omega_2')\,\delta(m_H^2/4 - \omega_1'\omega_2') \qquad (14)\end{aligned}$$

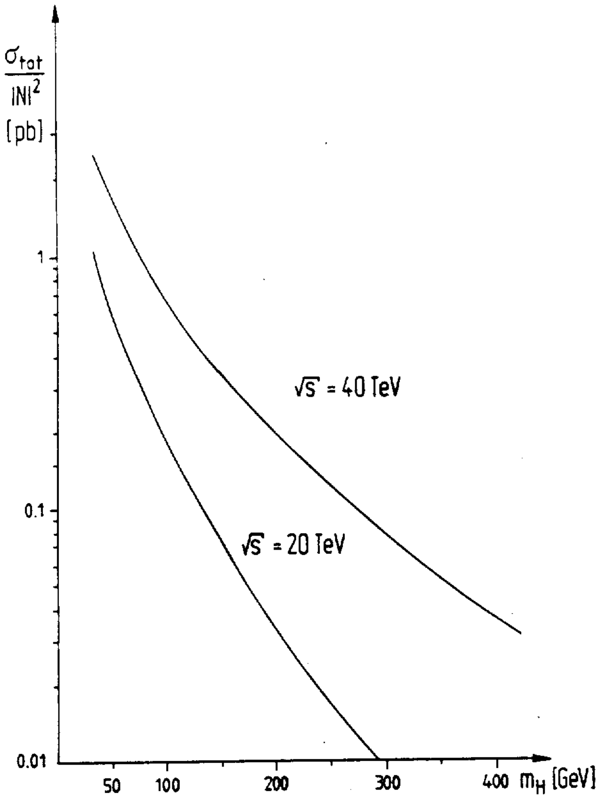

Figure 5: Total diffractive Higgs production cross section modulo $|N|^2$ as a function of the Higgs mass in *pp* collisions of 20 TeV and 40 TeV. From Ref. [20].

Here $\Gamma(H \to GG)$ is the two-gluon width of the Higgs which is dominated by the t quark loop, and thus approximately given by

$$\Gamma(H \to GG) = G_F\sqrt{2}\,\frac{m_H^3\alpha_s^2}{72\pi^3}\,|N|^2 \tag{15}$$

where $|N|^2$ is a numerical factor between 1 and 2 depending on the top mass. In Fig. 5 we show the resulting $\sigma/|N|^2$ as function of m_H for $\sqrt{s}$=20 TeV and 40 TeV. Although the obtained cross sections are very small, the large luminosity expected for the LHC leads to counting rates of $\approx$10 per hour already for $\mathcal{L}$ $=10^{34}\text{cm}^{-2}\text{s}^{-1}$, orders of magnitudes more than what can be expected from heavy ion experiments.

After having discussed the nucleon-nucleon process let us now turn to the problem of Higgs production in heavy ion collisions. Here we have to insert the nucleus formfactor instead of the nucleon and have to multiply with the coherence factor $A^{8/3}$. As the integration over the formfactor leads to a factor $1/R_{\text{nuc}}^4 \sim A^{-4/3}$ the effective gain factor is at most $A^{4/3}$ which is too small to balance the difference in luminosity. Thus if one wants to look for diffractive Higgs production one should do so in proton-proton collisions, not in heavy-ion collisions.

Diffractive processes could, however, produce additional background for heavy-ion collisions. Müller and Schramm [24] concluded that this is no problem if one requires that both heavy ions stay completely intact. For a more realistic trigger this still has to be investigated. An additional, probably much more severe background problem is due to photon-gluon fusion [25]. Thus heavy ion collisions with the presently discussed luminosities are not promising for Higgs searches, neither in the two-photon nor in the diffractive production channel.

The idea of Higgs production by diffractive pomeron-pomeron interactions has been criticised as it uses a proton-proton collider of 16 TeV center of mass energy effectively as a 1 TeV pomeron-pomeron collider with comparable luminosity, which seems like a waste of energy. While this is true it misses the point. The pomeron interactions are a subset of all hadronic interactions, namely the 'silent' ones. Looking for the weak signals of Higgs decays it seems very reasonable to investigate this class of events. What has been done in Ref. [20] is to calculate how many Higgs particles are produced in such events and it appears that this rate is high enough to make such an analyses interesting.

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