Exclusive axionlike particle production by gluon – induced interactions in hadronic collisions

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The exclusive production of axionlike particles (ALPs) by gluon – induced interactions is investigated in this exploratory study considering pp and PbPb collisions for the energies of the next run of the Large Hadron Collider (LHC). Assuming the Durham model, we estimate the associated cross sections for the rapidity ranges probed by central and forward detectors. A comparison with the predictions for the exclusive ALP production by photon – induced interactions is presented. Our results indicate that the contribution of gluon – induced interactions is nonnegligible and can become dominant in pp collisions for small values of the ALP mass.

PACS numbers:
Keywords: Axionlike particles, Durham model, Photon – Photon interactions, Hadronic collisions

Axionlike particles (ALPs) are pseudo – Nambu – Goldstone bosons predicted to occur in many extensions of the Standard Model (SM) due to the spontaneous breaking of a global symmetry and are candidates to constitute the cosmological dark matter. Such particles are expected to be characterized by a small mass $m_a$ and by suppressed couplings to the SM particles. During recent years, several authors have proposed the searching for axionlike particles in $e^+e^-$, $ep$, $vp$, $pp$, $pA$ and $AA$ collisions as well in laser beam experiments (See e.g. Refs. [1–10]). One of the more promising alternatives is the searching for ALPs in ultrarelativistic heavy ion collisions, considering a diphoton system as the final state, as represented in Fig. 1(a). In these collisions, the photon – photon luminosity that scales with $Z^4$, where $Z$ is number of protons in the nucleus, implies a large enhancement of the ALP production cross section. Moreover, the resulting final state is very clean, consisting of the diphoton system, two intact nuclei and two rapidity gaps, i.e. empty regions in pseudo-rapidity that separate the intact very forward nuclei from the $\gamma\gamma$ system. As recently demonstrated in Ref. [11], the backgrounds associated to the Light - by - Light (LbL) scattering and to the diffractive diphoton production can be strongly reduced in PbPb collisions by the exclusivity cuts and that a forward detector, as the LHCb, is ideal to probe an ALP with small mass. Similar study for pp collisions using the proton tagging technique was performed in Ref. [12], which demonstrated that such collisions can constrain ALPs masses in the range $0.5 \leq m_a \leq 2.0$ TeV. All these studies focused in the exclusive diphoton production by photon – induced interactions, characterized by the $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ subprocess. Our goal in this letter is to complement these previous studies, by estimating, for the first time, the exclusive diphoton production in gluon – induced interactions, where the elementary subprocess is the $gg \rightarrow a \rightarrow \gamma\gamma$ reaction. Such process is represented in Fig. 1(b). As the gluons exchanged between the incident particles (protons or nuclei) are in a color singlet configuration, the final state will also be characterized by two rapidity gaps and two intact hadrons. Therefore, such process is an irreducible background for the searching of ALPs in photon – induced interactions. In reality, as we will shown below, the exclusive ALP production in gluon – induced interactions can become dominant in pp collisions for ALPs masses smaller than 100 GeV. In this exploratory study, we will present predictions for fixed values for the ALP couplings to gluons and to photons. We postpone for a future publication a more detailed analysis [13]. Currently, we are implementing the gluon – induced reaction in the Forward Physics Monte Carlo (FPMC) [12], which will allow us to derive the expected excluded regions of the parameter space of the ALP model taking into account of the exclusivity cuts.

Initially, we present a brief review of formalism used to estimate the exclusive ALP production by gluon – induced interactions in pp and PbPb collisions. Such process, represented in Fig. 1(b), will be described using the Durham model [13], proposed many years ago and extensively discussed in the literature (For a review see, e.g. Ref. [16]). In this model, the ALP production occurs by the hard subprocess $gg \rightarrow a$ and a second $t$ – channel gluon is needed to screen the colour flow across the rapidity gap intervals. The decay of the ALP into two photons is described by the branching ratio $\text{BR}(a \rightarrow \gamma\gamma)$. As a consequence, the total cross section can be expressed as follows

$$\sigma (hh \rightarrow h \otimes \gamma\gamma \otimes h; s) = \int dy \int W^2 dW^2 \langle S_{\text{excl}} \rangle \sigma (gg \rightarrow a) \text{BR}(a \rightarrow \gamma\gamma) ,$$

(1)
FIG. 1: Diphoton production in hadronic collisions by the (a) $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ and (b) $gg \rightarrow a \rightarrow \gamma\gamma$ subprocesses.

where $\sqrt{s}$ is center-of-mass energy of the hadronic collision, $\otimes$ characterizes a rapidity gap in the final state, $y$ the rapidity of the final state, $W$ is the invariant mass of the final state and $(S_{\text{excl}}^2)$ is the gap survival probability. Moreover, $\hat{\sigma}(gg \rightarrow a)$ is the cross section associated to the $gg \rightarrow a$ subprocess, which is given by

$$\hat{\sigma}_{gg\rightarrow a} = \frac{2\pi^2}{m_a^2} (a \rightarrow gg) \times \delta(W^2 - m_a^2),$$

(2)

where $\Gamma(a \rightarrow gg)$ stand for the partial decay width of the ALP in a pair of gluons. The quantity $\mathcal{L}_{\text{excl}}$ is the effective luminosity for exclusive processes, defined by

$$\mathcal{L}_{\text{excl}} = \left[ C \int \frac{dQ_t^2}{Q_t^2} f_g(x_1, x_2', Q_t^2, \mu^2) f_g(x_2, x_2', Q_t^2, \mu^2) \right]^2,$$

(3)

where $C = \pi/(N_c^2 - 1)b$, with $b$ being the t-slope ($b = 4 \text{ GeV}^{-2}$ in what follows), $Q_t^2$ is the virtuality of the soft gluon needed for color screening, $x_1$ and $x_2$ are the longitudinal momentum of the gluons which participate of the hard subprocess and $x_1'$ and $x_2'$ the longitudinal momenta of the spectator gluon. The quantities $f_g$ are the skewed unintegrated gluon distributions $f_g$. At leading logarithmic approximation, it is possible to express $f_g(x, x', Q_t^2, \mu^2)$ in terms of the conventional integral gluon density $g(x)$ and the Sudakov factor $T$, which ensures that the active gluons that participate of the hard process do not radiate in the evolution from $Q_t$ up to the hard scale $\mu \approx m_a/2$. In this letter we will calculate $f_g$ in the proton case considering that the integrated gluon distribution $xg(x, Q_0^2)$ is described by the MMHT2014 parametrization [17]. In the nuclear case we will include the shadowing effects in $f_g$ considering that the nuclear gluon distribution is given by the nCTEQ parametrization [18]. In order to obtain a realistic prediction for the exclusive ALP production, we need to take into account of the soft interactions that are expected to lead to extra production of particles, which will destroy the rapidity gaps in the final state and modify the associated cross sections [19]. In the Durham model, such soft corrections are included in the eikonal factor $(S_{\text{excl}}^2)$. In our study we will assume that the hard process occurs on a short enough timescale such that the physics that generate the additional particles can be factorized and estimated using an soft approach for hadronic interactions constrained by the diffractive data. Following Ref. [15], we will assume that $\langle S_{\text{excl}}^2 \rangle = 3\%$ for $pp$ collisions at the LHC energy. The value of the survival probability for nuclear collisions is still an open question. In what follows, we will consider the conservative estimate proposed in Ref. [20], in which $\langle S_{\text{excl}}^2 \rangle_{A_1 A_2} = \langle S_{\text{excl}}^2 \rangle_{pp}(A_1 \cdot A_2)$. However, it is important to emphasize that smaller values were derived in Refs. [21, 22] using the Glauber model. Consequently, our predictions for the nuclear case can be considered an upper bound for the cross sections.

For completeness of our study, the exclusive ALP production by photon - induced interactions will also be estimated. For the process represented in Fig. 1 (a), the total cross section can be expressed as follows [23, 24]:

$$\sigma(hh \rightarrow h \otimes \gamma\gamma \otimes h; s) = \int d^2r_1d^2r_2dydW \frac{W}{2} N(\omega_1, r_1) N(\omega_2, r_2) S_{\text{sub}}^2(b) \hat{\sigma}(\gamma\gamma \rightarrow a) \text{BR}(a \rightarrow \gamma\gamma),$$

(4)

where $N(\omega_1, r_1)$ is the equivalent photon spectrum, which allows to estimate the number the photons with energy $\omega_1$ at a transverse distance $r_1$ from the center of hadron, defined in the plane transverse to the trajectory. Moreover, the invariant mass is given by $W = \sqrt{4\omega_1\omega_2}$. The cross section for the $\gamma\gamma \rightarrow a$ subprocess is given
by \[25\]

\[
\hat{\sigma}_{\gamma\gamma \to a} = \frac{8\pi^2}{m_a} \Gamma(a \to \gamma\gamma) \times \delta(W^2 - m_a^2),
\]

where \(\Gamma(a \to \gamma\gamma)\) is the partial decay width of the ALP into a pair of photons. The absorptive factor \(S_{abs}^2(b)\), which depends on the impact parameter \(b\) of the hadron collision, insures the dominance of the electromagnetic interaction by excluding the overlap between the colliding hadrons. In our calculations, we will estimate the photon spectrum assuming a pointlike form factor for the hadron. Moreover, the absorptive factor will be estimated using the model proposed by Baur and Ferreira-Filho \[26\], where

\[S_{abs}^2(b) = \Theta(\{|b| - 2R\}) = \Theta(|r_1 - r_2| - 2R)\]

where \(R\) is the hadron radius, being equal to 0.7 fm for a proton and 1.2 \(A^{1/3}\) fm for a nuclei. Such model treats the hadrons as hard spheres with radius \(R\) and assumes that the probability to have a hadronic interaction when \(b > 2R\) is zero. It is important to emphasize that other models can be used to treat the photon flux and the absorptive factor, as discussed in detail in Ref. \[22\]. However, for the values of the ALP masses considered in this letter, the predictions from these different approaches are almost identical.

The main input in our calculations are the ALP mass \(m_a\) and the partial decay widths \(\Gamma(a \to gg)\) and \(\Gamma(a \to \gamma\gamma)\). At leading order, the decay rates of an ALP into two gluons and two photons can be written as

(See e.g. Ref. \[28\])

\[
\Gamma(a \to gg) = 8 \times \left(\frac{c_{gg}}{f_a}\right)^2 \frac{m_a^3}{4\pi}
\]

and

\[
\Gamma(a \to \gamma\gamma) = \left(\frac{c_{\gamma\gamma}}{f_a}\right)^2 \frac{m_a^3}{4\pi}.
\]

In what follows we will estimate the cross sections for the ALP production in gluon and photon-induced interactions as a function of the ALP mass \(m_a\) considering \(pp\) collisions at \(\sqrt{s} = 14\) TeV and \(PbPb\) collisions at \(\sqrt{s} = 5.5\) TeV, which are the energies of the next run of the LHC. We will present predictions considering the typical rapidity ranges probed by central detectors (\(|y| \leq 2.0\)) as well as by a forward detector (\(2.0 \leq y \leq 4.5\)), as the LHCb one. In order to illustrate how important can be the gluon-induced process, we will assume in this exploratory study that \(c_{gg}/f_a = c_{\gamma\gamma}/f_a = 10^{-4}\) GeV\(^{-1}\). Moreover, as in previous studies \[3, 5, 11\], we will estimate the cross sections under the assumption that \(BR(a \to \gamma\gamma) = 1\) and, therefore, our results are a upper limit for the cross section. As pointed out before, a detailed analysis of the ALP production considering the full parameter space \((m_a, c_{gg}/f_a)\), obtained using the FPMC event generator and taking into account of the exclusivity cuts, will be presented in a future publication \[13\]. Our predictions are presented in Fig. 2 for \(PbPb\) (left panel) and \(pp\) (right panel) collisions. For \(PbPb\) collisions, the ALP production by photon-induced interactions is dominant for a large range of ALP masses. Such behaviour is directly associated to the \(Z^4\) enhancement of the cross section in \(\gamma\gamma\) interactions. Our
results indicate that the gluon – and photon – induced interactions become similar for large values of $m_a$ in the kinematical range probed by a forward detector. For a central detector, the gluon – induced contribution is almost two orders of magnitude smaller than the photon – induced one for the mass range considered. In contrast, for $pp$ collisions and $m_a \lesssim 70$ GeV, the gluon – induced interactions dominate the exclusive ALP production, being $\approx 3$ orders of magnitude larger than the photon – induced one for $m_a \approx 5$ GeV. However, both contributions become similar for $m_a \approx 100$ GeV and the photon – induced interactions dominate for larger masses. In particular, our results indicate that for the mass range that can be probed in $pp$ collisions using the proton tagging detectors ($m_a \geq 200$ GeV), the gluon – induced contribution is small for the coupling considered. The dominance of the gluon – induced interactions for the production of ALPs with small mass is directly associated to the large number of gluons in the incident protons at small values of the Bjorken - $x$ variable. At high energies and small mass, the main contribution comes from small - $x$, which implies a very large effective luminosity [See Eq. (3)]. The decreasing of the cross section with the ALP mass is associated to the rapid decreasing of the gluon distribution at large values of $x$. In contrast, the decreasing of the effective $\gamma\gamma$ luminosity is slowly in comparison to $L_{\text{excl}}$ due to behaviour of the equivalent photon flux with the photon energy, which is almost flat in the energy range considered.

As a summary, in this letter we have performed, for the first time, an exploratory study of the exclusive ALP production by gluon – induced interactions in hadronic collisions. Our results indicate that the contribution of such process can be nonnegligible in $pp$ collisions, which motivates a more detailed analysis to determine if this channel can be used to searching for the axionlike particles and to constrain its main properties.

Acknowledgments

VPG acknowledge very useful discussions about ALP production in photon - induced interactions with D. E. Martins and M. S. Rangel. This work was partially financed by the Brazilian funding agencies CNPq, FAPERGS and INCT-FNA (processes number 464898/2014-5).

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