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Axion-like particle searches at the LHC

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Axion Like Particles (ALPs) are potential dark matter candidates and searches at the LHC are performed in a wide range of masses. It is an active field of research. Several production processes in a variety of final states are explored using the data collected. Advanced analysis techniques are used to improve the search sensitivity. An overview of the analysis strategies and a selected sample of the analyses performed at the LHC are presented. The mass range covered spans from 0.5 GeV to few TeVs.

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1. Introduction

The standard model (SM) of particle physics describes Nature to a good accuracy, however it cannot be considered a complete theory. It does not provide an explanation of gravity nor of the origin of the dark sector of the Universe. Indirect astrophysical observations provide evidence that nearly 30% of the energy content of the Universe consists of dark matter (DM), and offer a strong motivation for the existence of particles beyond the SM (BSM). Axions and axion-like particles (ALPs) are possible candidates in extensions of the SM, and are excellent DM candidates. Axions were postulated as a solution to the CP problem of the strong interactions, and provide an explanation of the CP conservation of strong interactions. Without considering the relation between mass and the coupling, any scalar or pseudoscalar particle could be an axion-like particle (ALP). While axions are expected to be very light (sub-eV), ALPs can be heavy. Couplings and masses of these axions can span many orders of magnitude. ALP masses from MeV to hundreds of GeV are accessible at the LHC. ALPs are neutral pseudo-scalars originating from the spontaneous breaking of a global symmetry. Different production processes and decay final states can be studied. ALPs couple to photons, but they also couple to gluons, Z and Higgs bosons, as well as to leptons and quarks. At the LHC, they can be produced in photon-photon collisions, but also in gluon-gluon collisions which is of interest due to the large cross section. Associated production allows for triggering and is experimentally easier to select.

2. Resonant and non-resonant production

Searches for new high-mass resonances decaying into leptons, quarks or gluons are performed at the LHC. Although no significant discrepancy is observed with respect to SM expectations, the results provide strong constraints for the presence of new physics in several extensions of the SM, for both model-dependent and model-independent resonance production. One example is the search for heavy resonances decaying to ZZ or ZW in events with two charged leptons produced in the decay of a Z boson and two jets produced in the decay of a W or Z boson. This search is sensitive to resonances with masses up to 4500 GeV [1]. Electrons and muons are reconstructed from a combination of calorimeter clusters (for electrons), tracks reconstructed in the tracker, and information provided in the muon spectrometer (for muons). Both merged and resolved jet categories are exploited to maximize the sensitivity. A "jet grooming" technique is used for jets to help identify and discriminate between jets from boosted hadronic V (V=W, Z) decays, which are referred to as “merged jets”, and jets from quarks and gluons. No excess is observed in data and upper limits are derived in the resonance mass.

ALPs can also be searched in non-resonant production at high-energy colliders, where the ALP is an off-shell mediator in the s-channel [2]. In this case, ALP particles with small masses of 1 MeV interacting with SM particles may enhance the cross section at high energies, $\sqrt{s} \gg m_a$. In this regime, the processes include those with two SM bosons in the final state, e.g electroweak gauge bosons (W, Z, γ), gluons and/or the Higgs h. The ALP mediated scattering processes $gg \to a \to VV$ show a larger event invariant mass. The differential cross section for the ALP-mediated process remains dominant at energies much larger than the resonance mass when compared to the SM background processes. Depending on the couplings, the interference with the SM background can be either constructive of destructive. As a consequence, the shape of the s-channel invariant mass distribution from an off-shell ALP of small mass could allow distinguish the presence of a light ALP from SM backgrounds. Furthermore, the angular distribution of the final states could allow to determine its pseudoscalar nature.

At the LHC, possible final states to be considered include gg, ZZ, WW , $Z\gamma$, $\gamma\gamma$ or Zh. Searches were performed for heavy resonances decaying to ZZ or ZW and for ALPs mediating non-resonant ZZ or Zh production, in final states with two light charged leptons produced by the decay of a Z boson, and two quarks produced by the decay of a Z, W, or Higgs boson h [4]. The two quarks can be reconstructed as one single "merged" jet, or as two individually "resolved" jets. The search is sensitive to resonances with masses in the range from 450 to 2000 GeV. A jet grooming technique is used to help identify and discriminate between merged jets from hadronic decays of boosted V and Higgs bosons, and jets from quarks and gluons. Jet substructure variables (subjettiness, τ_{21}, etc.) are applied to define different categories of merged/resolved jets. The products of the boosted hadronic Z decay merge into a single jet, and b-tagged and untagged categories may also be used to provide a further increase in sensitivity. No significant excess is observed in the data and upper limits on nonresonant ALP-mediated ZZ and Zh production cross sections and ALP masses m_a <100 GeV are set for a a new physics energy scale f_a=3 TeV. Non-resonant searches also include a light ALP decaying to $\gamma\gamma$ final states where events at large invariant mass are selected [3].

Similarly, non-resonant ALP-mediated vector boson scattering (VBS) processes can be considered, where the ALP participates as an off-shell mediator [5]. This process occurs when the ALP is too light to be produced resonantly. The production of ZZ, $Z\gamma$, $W\gamma$, WZ and WW pairs with large diboson invariant masses in association with two jets can be studied. Stringent constraints on couplings can be set for ALP masses up to 100 GeV. Non-resonant cross sections and kinematical distributions are found to be independent of the ALP mass up to masses of 100 GeV. Experimentally, the strategy is to look for deviations in the tails of the bosons transverse momenta or diboson mass distributions with respect to SM expectations.

3. The Higgs sector

Properties and decay modes of the Higgs boson are studied as one of the priorities of the LHC experimental program. In particular, the extended Higgs sectors are well motivated theoretically and provide a rich phenomenology. To this end, non-SM Higgs decays and Higgs associated production provide a broad experimental search program. Several searches for exotic decays of the Higgs boson have been performed at the LHC. Such decays occur in the context of the next-to-minimal supersymmetric standard model, NMSSM, and other extensions to two-Higgs doublet models (2HDM) where the existence of a scalar singlet is hypothesised. Searches for $h \to aa$ decays have been performed exploiting various decay modes of the a boson, and probing different ranges of its mass. These searches found no significant deviation from the expectation of the SM background and upper limits were set on the product of the production cross section and the branching fraction for signal resulting in constraints on parameters of the models. Searches for Higgs bosons decaying to ALPs provide an interesting probe of BSM models, either in inclusive or in associated production.

3.1 Exotic Higgs decays

Search for exotic decays of the Higgs boson to a pair of light pseudoscalar particles a was performed under the hypothesis that the two pseudoscalars decay either to two muon pairs, or one decays to a pair of opposite sign muons and the other to $b\bar{b}$. The search selection in the $\mu\mu bb$ final state [6] requires two isolated muons with opposite charge and at least two jets that are likely to originate from b quarks. Assuming the b jets and muons are from the decay of the pseudoscalar a, it is expected that $m_{bb} \simeq m_{\mu\mu} \simeq m_a$ and that the system of muon and b quark jets has an invariant mass close to the Higgs boson mass. An event categorization is developed to enhance the sensitivity. No significant excess of events is found over the SM background predictions and upper limits on the production cross section and branching fraction are set in the range $20 \leq m_a \leq 62.5$ GeV. The upper bound is imposed by the Higgs mass, the lower bound is because a gets boosted and the two b-jets tend to merge. It is interesting to notice that the searches from both ATLAS [7] and CMS [6] collaborations observe a slight excess at similar masses. For ATLAS the local significance is 3.3σ at $m_a = 52$ GeV, while for CMS it shows a fluctuation just above the expected 95% CL limit at $m_a \approx 49$ GeV.

The search for a pair production of light pseudoscalars each decaying into pairs of muons in the $\mu\mu\mu\mu$ final state [8] is model independent. It is required that a pair of identical light bosons are created at a common vertex and each light boson subsequently decays to a pair of muons. The background is expected to be small. The dominant background is from bb production, in events in which both b quarks decay to $\mu\mu + X$ or decay through low-mass resonances. Events passing all the selection criteria and falling in the $m_{\mu\mu(1)} \simeq m_{\mu\mu(2)}$ signal region are consistent with the sum of all SM backgrounds. A model independent 95% CL upper limit on the product of the production cross section times branching fraction to dimuons is set over the mass range $0.25 < m_a < 8.5$ GeV.

Searches also considered final states when at least one of the pseudoscalars decays to a pair of τ leptons. The $2\mu2\tau$ and 4τ final states are used to set limits on the product cross section and branching fraction in the light pseudoscalar mass range between 4 and 15 GeV [9].

In many scenarios, such as fermiophobic a decays, the branching fraction of the pseudoscalar bosons to a pair of photons is close to unity. The final state where pseudoscalar boson pairs from the Higgs boson decay to four isolated photons provides a clean signature with small background. In the absence of a significant deviation, upper limits are set on the production cross section and branching fraction into four photons in the mass range from 15 GeV to 62 GeV [10].

3.2 Associated production

In the case of associated production, triggering the events is easier. This provides an additional handle in lowering the mass range of the candidate. An example is the case of the Higgs boson decaying to ALPs and produced in association with a leptonically decaying Z boson [11]. The final state with multiple b quarks is expected to be large given the ALP is a pseudoscalar that couples to b-quarks via a Yukawa interaction. The Zh associated production was used to search for ALPs with a mass between 15 GeV and 30 GeV. At these mass values the b quark pairs from the ALP are reconstructed as a single jet and identified with dedicated algorithms.

Another interesting case is the Higgs boson decaying into a ALP and a Z boson. The Z boson decays leptonically and can be easily reconstructed while the ALP decays hadronically to a pair of light quarks or gluons. The ALP is reconstructed as single object and neural networks are used to help discriminate between signal and background. The dominant background is from Z boson produced in association with jets. The resonance considered is a light scalar with a mass as low as 0.5 GeV [12].

3.3 Invisible decays

Another class of studies focuses on searches for invisible ALP decays. In order for these searches to be experimentally viable, ALPs must be produced in association with a visible SM particle. Due to the lack of electric charge and weak interaction cross section, these searches involve missing transverse momentum ($p_{\rm miss}^{\rm T}$) where a SM particle, X, is produced against the missing transverse momentum, associated with the DM particles escaping the detector, in the so called "mono-X" final states. Some of the processes studied and that could be sensitive to couplings to the ALP are $Z \to a\gamma$ [13], $h \to aZ$ [14], $gg \to ag$. The searches explore events with large missing transverse momentum, e.g. typically larger than 200 GeV. No significant excess of events is observed above the predicted SM background and results are interpreted in terms of specific model or limits on effective field theory operators.

4. Photon-photon collisions

The search for ALPs in photon-photon collisions is interesting as it provides a clean signature in the $\gamma\gamma \to a \to \gamma\gamma$. The diphoton final state would produce a resonant peak distribution at the ALP mass over a continuous background. At leading order, the $\gamma\gamma \to \gamma\gamma$, usually referred to as light-by-light scattering, is a rare SM process and is allowed at one-loop level via a virtual box diagram involving charged fermions (leptons and quarks) or W bosons. In various extensions of the SM, additional contributions are possible, making the light-by-light scattering measurement sensitive to new physics. Photon-photon collisions are produced in pp and PbPb collisions.

4.1 Tagging the leading proton with a forward detector

In proton-proton (pp) collisions when protons interact electromagnetically, the final state can be a neutral system produced exclusively in the central detector while the two outgoing protons remain intact. By tagging the leading proton from the hard interaction, the Precision Proton Spectrometer (PPS) [15] provides an increased sensitivity to select central exclusive processes (CEPs) and study the four-photon interactions at the TeV energy scale. Exclusive production of two photons in a photon fusion process allows probing several BSM processes including ALP production. By reconstructing the proton(s) kinematics it is possible to correlate the protons with the events in the central CMS detector. CEP of an object X may occur in the process $pp \to p+X+p$, where '+" indicates the "rapidity gaps" adjacent to the state X. Rapidity gaps are regions without primary particle production. It is worth noticing that the SM predicts the photon-photon production happens through a QCD process via gluon-exchange or QED process via photon-exchange. For a diphoton invariant mass $m_{\gamma\gamma} \geq 100$ GeV, i.e. the region accessible to PPS, the latter dominates. Events are selected with a diphoton invariant mass above 350 GeV and with both protons intact in the final state, to reduce backgrounds from strong interactions. The events of interest are those where the invariant mass and rapidity calculated from the momentum losses of the forward-moving protons match the mass and rapidity of the central, two-photon system. One exclusive diphoton candidate is observed consistent with background-only expectations, and limits are derived on the four-photon anomalous coupling parameters. The process is parameterized as a function of the ALP mass, m_a, and its photon coupling, f^{-1}, and limits are set over the mass range from 500 to 2000 GeV [16].

4.2 Heavy Ion collisions

The $\gamma\gamma \to \gamma\gamma$ process was observed in heavy ion collisions at the LHC by exploiting the very large fluxes of quasi-real photons emitted by the nuclei accelerated at TeV energies. Exclusive light-by-light scattering can occur in these collisions at impact parameters larger than about twice the radius of the ions where the strong interaction becomes less significant and the electromagnetic interaction becomes dominant. Heavy ion beams are an intense source of photons as the flux scales with the fourth power of the beam particle charge, while the low-luminosity of the PbPb collisions mitigate the pileup effects, thus allowing a clean source of ultra-peripheral collisions. Events are selected by requiring two photons above a low energy threshold and vetoing any additional activity. The photons are required to be back-to-back to suppress background from gluon-gluon fusion events as well as from electron-positron pairs misidentified as photons. The observed excess of events over the expected background allows measuring the cross section of this process and used to extract limits on the coupling of ALPs to photons in the mass range from 5 GeV to 90 GeV [17, 18].

5. Summary

Convincing and direct evidence for dark matter comes from astrophysical observation of the rotation of galaxies. Searches for dark matter at particle colliders involve the production of neutral and weakly interacting particles. Axion-like particles provide an elegant explanation of dark matter and could be mediators to a dark sector. Despite its success, the standard model (SM) may be considered a low energy approximation of a fundamental theory that would manifest at higher energies. Several attempts have been made but no sign of new physics has been detected at the LHC. At the LHC, depending on the ALP production and decay mechanism, it is possible to probe a wide range of masses and couplings. An overview of the analysis strategies and a sample of the analyses performed at the LHC are presented. The mass range covered spans from 0.5 GeV to a few TeVs. No clear discrepancy from SM expectations is found. Large data samples are expected to be collected in Run 3 that started in 2022, and in the following Run 4 data-taking period at the High-Luminosity LHC Phase 2 to start in 2029.

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