PROCEEDINGS OF SCIENCE

Invisible ALPs at Belle II

Francesca Acanfora[a,b,*]

[a] *Galileo Galilei Institute for Theoretical Physics, Largo Enrico Fermi 2, I-50125 Firenze, Italy*

[b] *Mathematics and Physics department, Università degli Studi and INFN Roma Tre, Via della Vasca Navale 84, I-00146, Rome, Italy*

E-mail: francesca.acanfora@uniroma3.it

We consider an axion-like particle coupled to the Standard Model photons and decaying invisibly at Belle II. We study the e^+e^- + invisible channel and find that it has the potential to ameliorate the reach from the standard γ + invisible channel for the whole ALP mass range. This is due to a significant Standard Model background suppression that we achieve via some dedicated kinematic variables.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

*Speaker

PoS(EPS-HEP2023)049

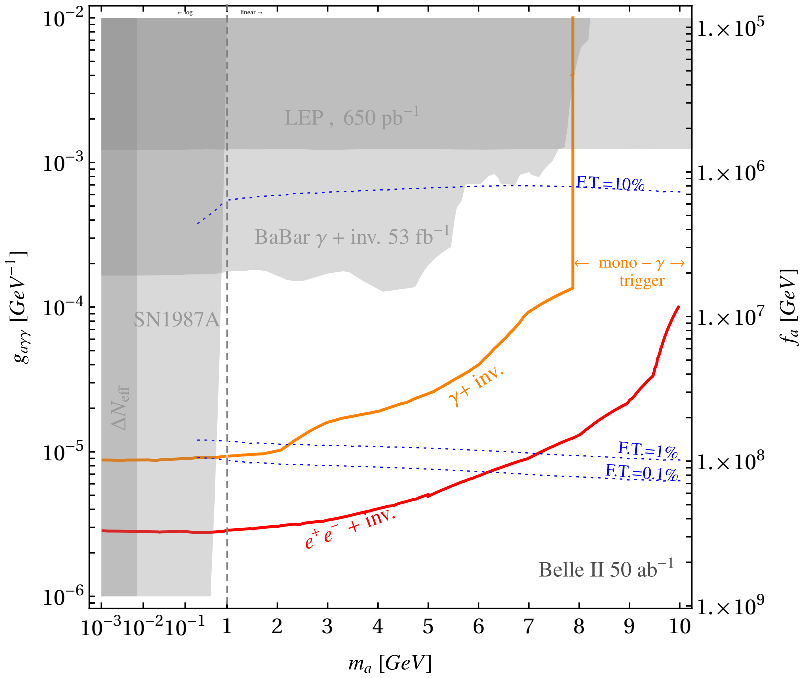

Figure 1: Expected sensitivity of Belle II at 95% C.L. to the ALP coupling to photons $g_{a\gamma\gamma}$ as defined in Eq. (1). The orange line is the expected reach of the γ + invisible channel derived in Ref. [1]. The red line shows the reach of the e^+e^- + invisible channel discussed here. The gray shaded region shows existing constraints from LEP and Babar γ + invisible searches [2–4] and from $\Delta N_{\rm eff}$ constraints from CMB [5]. We also show the expected constraint from SN cooling estimated in Ref. [1]. The dotted blue lines show the freeze-out prediction for resonant DM annihilation with fine tuning (F.T.) 10%, 1% and 0.1% as discussed below Eq. (2).

1. Introduction

In [6] we revisit the sensitivity of the Belle II experiment to DM communicating with the SM through an axion-like particle coupled only to photons. Belle II is high intensity lepton colliding machine and as such gives us the possibility to test directly extremely feebly interactions of Dark Matter (DM) with the Standard Model which would be impossible to probe otherwise. These interactions can be responsible to produce light DM (in the MeV – GeV range) in the early Universe through thermal freeze-out [7]. This simple dark sector scenario was considered in Ref. [1], where the sensitivity of Belle II was derived focusing on the standard mono-photon final state accompanied by missing energy.

We develop an alternative strategy based on the

$$e^+e^- \to e^+e^- + \text{invisible}$$

channel, leveraging a more detailed knowledge of the signal kinematics (given the two visible particles) at the price of the reduced production cross section. We will show how it is possible (especially for light ALP masses) to design a search at Belle II where the background rejection is so good to compensate the suppressed production cross section with respect to the γ + invisible

channel. The result is shown in Fig. 1, together with some ALP astrophysical bounds.
One comes from the measurements of the effective number of relativistic species at BBN and CMB [8, 9] and robustly rules out DM masses below roughly 10 MeV. Stronger constraints could be derived by requiring the ALPs produced in the nascent proto-neutron star (PNS) during the supernova (SN) explosion to not substantially modify the canonical neutrino cooling mechanism [10].

The ALP we consider is described by the following Lagrangian

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 - \frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{i}{2}\bar{\chi}\gamma^\mu\partial_\mu\chi + \frac{M_\chi}{2}\bar{\chi}\chi + \frac{g_{a\chi\chi}}{2}M_\chi a\bar{\chi}\gamma_5\chi\,, \tag{1}$$

where χ is a Majorana fermion. If the ALP is the pseudo-Nambu-Golstone boson (pNGB) of a global $U(1)$ symmetry, we can estimate the size of its coupling to photons and DM in terms of the decay constant f_a which controls the UV cutoff of the theory $\Lambda_{\rm UV} = g_* f_a$, where g_* is an $O(1)$ coupling. In this setup, the ALP coupling to photons originates from the ABJ anomaly of the global $U(1)$ symmetry with respect to QED and

$$g_{a\gamma\gamma} \equiv \frac{\alpha_{\rm em} c_{\gamma\gamma}}{2\pi f_a}\,, \tag{2}$$

where the anomaly coefficient $c_{\gamma\gamma} = \sum_E Q_E^2$ is controlled by the charge Q_E of chiral fermions of mass $\Lambda_{\rm UV}$.

The ALP coupling to DM can be generated through explicit breaking of the ALP shift symmetry. As a consequence, the ALP mass is naturally of the same order of the DM one, motivating a mass hierarchy like the one considered in this paper, where the ALP mass is slightly heavier than the DM one. In such a theory, the ALP decays invisibly into DM pairs with a branching ratio close to 1 since the decay into a pair of photons is loop-suppressed. Setting the relic abundance of χ to match the measured DM abundance today [11] generically requires f_a to be around the GeV with a mild dependence on the DM mass. This region is already excluded by existing collider searches.

A simple way to push the freeze-out region at weaker coupling is to make the annihilation resonant by tuning the DM mass to be close to the ALP resonance, i.e. $r \equiv M_\chi/m_a \to 1/2$. The prediction of resonant freeze-out are shown in Fig. 1 for fine-tuned values of r close to the resonance, where F.T. $\equiv 1/2 - r$ can be taken as a measure of the fine-tuning.

2. Signal and background kinematics

Starting from the model in Eq. (1) two possible ALP production mechanisms at a lepton collider are

$$e^+e^- \longrightarrow \gamma_{\rm vis} a\,, \tag{3}$$
$$e^+e^- \longrightarrow e^+_{\rm vis} e^-_{\rm vis} a\,, \tag{4}$$

where the subscript "vis" indicates that we require the photon and the electron-positron pair to be within the geometric acceptance of the detector. The first process is the well studied ALP-strahlung leading to the γ + invisible signal.

The signal cross sections in the acceptance of Belle II with center-of-mass energy $\sqrt{s}$ = 10.58 GeV can be approximated for small enough ALP masses as

$$\begin{aligned}\sigma(e^+e^- \to \gamma a) &\approx 10^{-3}\ \text{pb}\left[\frac{g_{a\gamma\gamma}}{10^{-4}\ \text{GeV}^{-1}}\right]^2 ,\\ \sigma(e^+e^- \to e^+e^- a) &\approx 7\times 10^{-5}\ \text{pb}\left[\frac{g_{a\gamma\gamma}}{10^{-4}\ \text{GeV}^{-1}}\right]^2 .\end{aligned} \tag{5}$$

The ALP-strahlung cross section is larger than the photon-fusion one by roughly a factor of 14 at Belle II . The kinematic varibles that we leverage in the analysis to compensate this difference are the missing mass m_{miss}, the missing energy E_{miss} and the missing pseudo-rapidity η_{miss}.

The missing mass

$$m^2_{\text{miss}} = E^2_{\text{miss}} - |\vec{p}_{\text{miss}}|^2 = m_a^2 , \tag{6}$$

is equal to the ALP mass up to the experimental resolution. A missing pseudo-rapidity can be defined from the initial and final state electrons and positrons:

$$\eta_{\text{miss}} = \frac{1}{2}\log\left[\frac{|\vec{p}_{\text{miss}}| + p^L_{\text{miss}}}{|\vec{p}_{\text{miss}}| - p^L_{\text{miss}}}\right] = -\log\left[\tan\frac{\theta_{\text{miss}}}{2}\right]. \tag{7}$$

Besides the fixed missing mass, the ALP signal is expected to be central (i.e. small η_{miss}) as confirmed by the distribution in Fig. 2 left. Moreover, requiring the electron-positron pair within the Belle II acceptance favors a kinematics where the ALP is not produced at rest resulting in a large E^*_{miss}, even for a very light ALP. For example, for an effectively massless ALP we find that more than 90% of the signal has $E^*_{\text{miss}} \gtrsim 2$ GeV.
Conversely, it is very difficult for any SM background to have a *large* E_{miss} together with a *small* $|\eta_{\text{miss}}|$ and a *small* m_{miss}. Let us show why.

SM processes that give the same final state as the signal in Eq. (4) are

$$e^+e^- \to e^+e^- + n\gamma_{\text{inv}} , \tag{8}$$

$$e^+e^- \to \tau^-\tau^+, \tau^\pm \to e^\pm\nu\nu , \tag{9}$$

where γ_{inv} indicates a "missed photon" that cannot be detected at Belle II because either its energy is below the ECAL energy threshold, or it is emitted in the region not covered by the calorimeter

$$\theta^*_{\text{min}} = 22^\circ , \qquad E^*_{\text{min}} = 0.25\ \text{GeV} . \tag{10}$$

We will refer to Eq. (8) as QED^n background, and to. Eq. (9) as the $\tau\tau$ background. Both of them are *reducible* thanks to the fact that their kinematics does not resemble at all the one of the signal. However, both background processes have a huge cross section compared to the signal Eq. (5). In particular, given the Belle II acceptance, the $\tau\tau$ background cross-section is around 75.4 pb and the QED^2 background is of 1.66 nb. These numbers set the challenge of the photon-fusion search which needs to achieve a background rejection at the level of 10^{-8} to be sensitive to $g_{a\gamma\gamma} \simeq 10^{-5}$ GeV^{-1}, where the target for resonant ALP-mediated freeze-out lies.

As to the QED^n background, the $n = 1$ case is easily reduced as it always has $m_{\text{miss}} = 0$; the $n \geq 4$ cases have a negligible cross section with respect to the signal; then the leading order QED

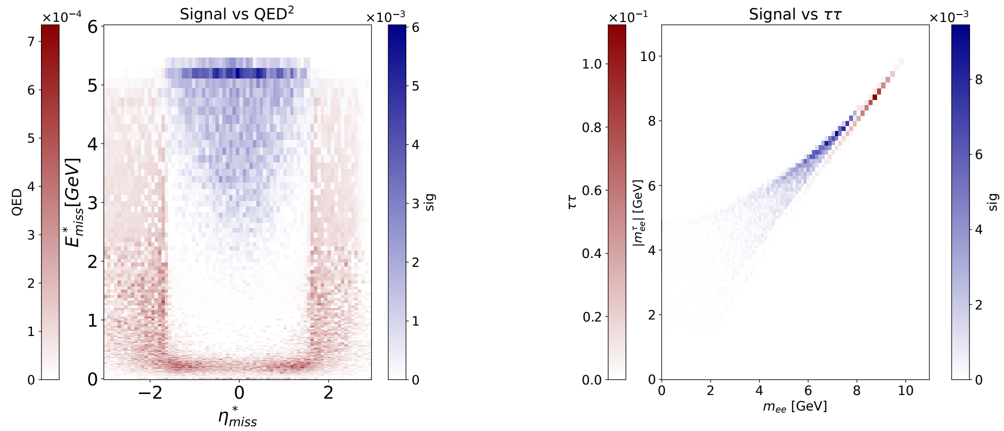

Figure 2: Distributions of the signal $m_a = 1$ GeV and the backgrounds (**red**) with respect to the discriminating variables. In both panels we ask for the final electrons to be within Belle II acceptance and we select $|m^2_{\rm miss} - m^2_a| \leq \kappa \delta m^2_{\rm miss}$ with κ chosen to maximize the sensitivity as described in Sec. 3. In the **left** panel we compare the signal to the QED^2 distribution with respect to $\eta^*_{\rm miss}$ and $E^*_{\rm miss}$ with uniform binning. In the **right** panel we compare the signal to the $\tau\tau$ distribution with respect to m_{ee} and $|m^\tau_{ee}|$ as defined in Sec. 2. The binning is such that $\delta E^*_{\rm miss}/E^*_{\rm miss} = 2\%$, $\delta m_{ee}/m_{ee} = 2\%$ and $\delta\eta^*_{\rm miss} = 0.075$ even though the experimental resolution at Belle II can be better [12].

in perturbation theory corresponds to $n = 2$. It can be showed that there is a region of phase space that contains most of the signal where the QED^n background is forbidden for kinematic reasons. If we ask for a missing energy lower bound of the order of the GeV, the QED^n background can only be realised by hard photons. If we ask for a central missing rapidity, they will have to fly in opposite directions. This will bound the missing mass to be big. Hence the forbidden region is given by central rapidity and small missing mass.

For the $\tau\tau$ background we take advantage of the peculiar kinematics of the electron-positron pair which originates from the two τ leptons being on-shell resonances and flying back-to-back. As much as for the QED case, for the $\tau\tau$ background too we can identify a broad unpopulated phase space.

In the $\tau^\pm$ decays in Eq. 9, consider the neutrino pair as a body $N_\pm$ of mass $m_{N_\pm} = 2p_{\nu_e} \cdot p_{\nu_\mu}$, changing event by event. The energies in the rest frame of the decaying τ^- are

$$\begin{aligned} E^{\tau^\pm}_{e^-} &= \frac{m^2_\tau + m^2_e - m^2_{N_\pm}}{2m_\tau}\,, \\ E^{\tau^\pm}_{N_\pm} &= \frac{m^2_\tau - m^2_e + m^2_{N_\pm}}{2m_\tau}\,. \end{aligned} \tag{11}$$

The first step to find the $\tau\tau$ low rate region is neglecting m_N. In general it is non negligible with respect to $\sqrt{s}$, but the size of phase space accessible to invisible bodies is maximised onto $m_{N_-} = m_{N_+} = 0$. Thus, in this approximation the region of inaccessible phase-space that we find is smaller than the one resulting from an exact computation [1].

[1]On top of that, we neglect m_e as it is small with respect to $\sqrt{s}$.

Within this approximation, the kinematics of the $e^\pm$ and the $N_\pm$ can be written in the Belle II CoM frame as function of just 3 quantities: the angles $\theta_\pm$ of the $e^\pm$ with respect to the direction of flight of the respective parent τ lepton and the angle ϕ between the planes of the decay products of the $\tau^\pm$. Polar angles can be traded with $e^\pm$ energies like

$$E^*_{e^\pm} = \frac{\sqrt{s} \mp c_\pm \sqrt{s - 4m_\tau^2}}{4}. \tag{12}$$

In this system (denoted by a τ superscript) we can compute the invariant mass of the final electrons [2]:

$$(m^\tau_{ee})^2 = \frac{2}{s - 4m_\tau^2}\left[m_\tau^4 - \sqrt{s} m_\tau^2 (E^*_+ + E^*_-) + 2E^*_- E^*_+ (s - 2m_\tau^2) + m_\tau^2 c_\phi \mathcal{M}_- \mathcal{M}_+\right], \tag{13}$$

where we defined $\mathcal{M}_\pm = \sqrt{m_\tau^2 - 2E^*_\pm \sqrt{s} + 4E^{*2}_\pm}$.

As apparent from Fig. 2 right, the $\tau\tau$ background lives along a line of the space $m_{ee} - m^\tau_{ee}$. Up to possible mis-measurements of the electron and positron momenta the $\tau\tau$ background can be removed by filtering out events for which $m_{ee} = m^\tau_{ee}$. As the signal populates the upper part of the plane above the line $m_{ee} = m^\tau_{ee}$, it is possible to obtain high rejection of $\tau\tau$ while keeping a substantial amount of signal.

Further backgrounds may come from quarks or lost photons.
The process

$$e^+e^- \longrightarrow q\bar{q} \longrightarrow \text{hadrons} \longrightarrow e^+e^- + \text{inv.},$$

can be a background if the leading hadron that appears from the color charge of the quark carries the vast majority of the quark momentum and decays semi-leptonically. However, these backgrounds can be assimilated to the $\tau\tau$ background and would simply amount to a variation of the total rate of the $\tau\tau$ process after our selection.

Losses of central photons around small non-instrumented regions of the detector are a potential source of very large backgrounds for our signal. Such configuration leads naturally to a small m_{miss}, due to the small physical photon mass, and small $|\eta^*_{\text{miss}}|$. In principle such background can be removed if η^*_{miss} is well measured by vetoing events for which the missing momentum falls in dead or not covered areas of the detector.

3. Event selection and Sensitivity

A first discrimination between signal and backgrounds can be obtained from a selection on the *missing mass* defined in Eq. (6) which we want to fix around the ALP mass m_a under examination up to the experimental resolution. The missing mass is obtained from a cancellation of two positive terms, E_{miss} and $|p_{\text{miss}}|$, thus it is expected that when m_{miss} tends to zero its experimental uncertainty gets large. After detector effects are included, a good fit for the resolution on m_{miss} is

$$\delta m^2_{\text{miss}} \simeq \left[1 - \left(\frac{m_{\text{miss}}}{10\text{ GeV}}\right)^4\right] \text{GeV}^2. \tag{14}$$

[2]Since for the QED and the signal it can happen that $m_\tau^2 - 2E^*_\pm\sqrt{s} + 4\left(E^*_\pm\right)^2 < 0$ we use the $|m^{(\tau)}_{ee}|$ in our selection described Sec. 3.

In our selection we require

$$|m^2_{\rm miss} - m^2_a| \leq \kappa \cdot \delta m^2_{\rm miss}\,, \tag{15}$$

where the parameter κ controls the width of the missing mass window which has been optimized to maximize the sensitivity.

We further characterize the signal kinematics demanding a large *missing energy* $E^*_{\rm miss}$ and a small *missing rapidity* $\eta^*_{\rm miss}$. In practice we require

$$E^*_{\rm miss} \in \left[E^{\rm low}_{\rm miss}, \frac{s+m_a^2}{2\sqrt{s}}\right]\,, \qquad |\eta^*_{\rm miss}| \leq \eta^{\rm high}_{\rm miss}\,, \tag{16}$$

where both $E^{\rm low}_{\rm miss}$ and $\eta^{\rm high}_{\rm miss}$ are chosen for each ALP mass in order to maximize the sensitivity.

The cuts in Eq. (15) and Eq. (16) are chosen to optimize $S/\sqrt{B}$ in the cut-and-count scheme where $S, (B)$ indicates the number of signal (background) events. As an extra requirement we demand these cuts to keep at least 90% of the signal.

As shown in Fig. 2 left the combination of Eq. (15) and Eq. (16) is enough to suppress most of the QED background. In addition, given the three-body nature of the signal, we can find a fourth selection variable to further improve the sensitivity. We find that the invariant mass of the visible e^+e^- final state is very effective to remove the background from $\tau\tau$ or any of its “look-alike” backgrounds described earlier.

In practice, we construct a log-likelihood using the expected signal and background counts for 50 ab^{-1} at Belle II

$$\Lambda = -2\sum_{i,j} \ln \frac{L(S_{i,j}, B_{i,j})}{L(0, B_{i,j})}\,, \tag{17}$$

where i and j run on the bins of the plane $(m_{ee}, |m^\tau_{ee}|)$ as drawn in Fig. 2. For the computation of the likelihood we define bins of width $\delta m/m = 2\%$ motivated by the expected Belle II resolution. In each bin we compute the Poisson factor

$$L(S, B) = \frac{(S+B)^B}{B!} e^{-(S+B)}\,. \tag{18}$$

The sensitivity shown in Fig. 1 corresponds to 95% C.L. and it is obtained by requiring $\Lambda < 4$.

Our separation of the $\tau\tau$ background from the signal does not rely on a overly fine measurement of m_{ee} and m^τ_{ee}. To ensure the robustness of our sensitivity, we estimate the uncertainty due to finite MC sample performing several independent generations of our background MC. The variation of the sensitivity over these replicas is negligible on the log-scale of our Fig. 1.

4. Conclusions

In this work we derived the expected sensitivity on an ALP decaying invisibly at Belle II in the channel e^+e^- + invisible for a 50 ab^{-1} luminosity. We could demonstrate that there is potential to improve significantly over the results based on the γ + invisible final state [1, 2, 12–14] over the whole mass range, as Fig. 1 shows. The expected improvement on the reach can cover most of the allowed parameter space for DM freeze-out through ALP-mediated annihilations in the resonant regime.

This result could be obtained because signal and background can be told apart very efficiently thanks to the interplay between low *missing mass* and large central *missing energy* for light ALP masses. Thanks to the excellent resolution of the Belle II invariant mass measurements, we could set up a competitive analysis for heavy ALP masses too, that also fills the gap where the γ + invisible search encounters trigger issues related to the very large rate of single photon events at low photon energies.

References

[1] M. J. Dolan, T. Ferber, C. Hearty, F. Kahlhoefer and K. Schmidt-Hoberg, *Revised constraints and Belle II sensitivity for visible and invisible axion-like particles*, *JHEP* **12** (2017) 094, [1709.00009].

[2] BaBar collaboration, J. P. Lees et al., *Search for Invisible Decays of a Dark Photon Produced in e^+e^- Collisions at BaBar*, *Phys. Rev. Lett.* **119** (2017) 131804, [1702.03327].

[3] P. J. Fox, R. Harnik, J. Kopp and Y. Tsai, *LEP Shines Light on Dark Matter*, *Phys. Rev. D* **84** (2011) 014028, [1103.0240].

[4] DELPHI collaboration, J. Abdallah et al., *Search for one large extra dimension with the DELPHI detector at LEP*, *Eur. Phys. J. C* **60** (2009) 17–23, [0901.4486].

[5] C. Boehm, M. J. Dolan and C. McCabe, *A Lower Bound on the Mass of Cold Thermal Dark Matter from Planck*, *JCAP* **08** (2013) 041, [1303.6270].

[6] F. Acanfora, R. Franceschini, A. Mastroddi and D. Redigolo, *Fusing photons into nothing, a new search for invisible ALPs and Dark Matter at Belle II*, 2307.06369.

[7] G. Krnjaic et al., *A Snowmass Whitepaper: Dark Matter Production at Intensity-Frontier Experiments*, 2207.00597.

[8] C. Boehm, M. J. Dolan and C. McCabe, *Increasing Neff with particles in thermal equilibrium with neutrinos*, *JCAP* **12** (2012) 027, [1207.0497].

[9] X. Chu, J.-L. Kuo and J. Pradler, *Toward a full description of MeV dark matter decoupling: A self-consistent determination of relic abundance and Neff*, *Phys. Rev. D* **106** (2022) 055022, [2205.05714].

[10] G. G. Raffelt, *Astrophysical methods to constrain axions and other novel particle phenomena*, *Phys. Rept.* **198** (1990) 1–113.

[11] G. Steigman, B. Dasgupta and J. F. Beacom, *Precise Relic WIMP Abundance and its Impact on Searches for Dark Matter Annihilation*, *Phys. Rev. D* **86** (2012) 023506, [1204.3622].

[12] Belle-II collaboration, W. Altmannshofer et al., *The Belle II Physics Book*, *PTEP* **2019** (2019) 123C01, [1808.10567].

[13] BaBar collaboration, B. Aubert et al., *Search for Invisible Decays of a Light Scalar in Radiative Transitions* $\upsilon_{3S} \rightarrow \gamma$ *A0*, in *34th International Conference on High Energy Physics*, 7, 2008. 0808.0017.

[14] BaBar collaboration, P. del Amo Sanchez et al., *Search for Production of Invisible Final States in Single-Photon Decays of* $\Upsilon(1S)$, *Phys. Rev. Lett.* **107** (2011) 021804, [1007.4646].