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Dark sector physics with Belle II

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The Belle II detector has recently started data-taking at the SuperKEKB e^+e^- accelerator facility. The experiment is expected to collect around 50 times the dataset of Belle. Dark sector theories provide a particle explanation for dark matter without any direct coupling to Standard Model particles. Even very early Belle II data has good prospects for competitive dark sector searches. In these proceedings, three such searches for dark mediators are described.

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1. The Belle II detector and status

The Belle II detector is located at the interaction point of the SuperKEKB e^+e^- facility at the KEK laboratory in Tsukuba, Japan. The detector and accelerator are described in detail elsewhere [1, 2]. For the purpose of these proceedings, it is sufficient to state that Belle II has a wire drift chamber tracking system, an electromagnetic calorimeter, and the flux return for the magnet consists of iron plates interspersed with scintillator and resistive plate chamber detectors (the so-called K_L^0 and muon detector). The K_L^0 and muon detector is used both as a veto and to provide muon identification information for tracks. There is a relatively flexible trigger, and therefore a higher efficiency for low-multiplicity events than, for example, the BaBar [3, 4] or Belle experiments.

SuperKEKB will provide a significant increase in the instantaneous luminosity (a factor of approximately 40) with respect to the precursor accelerator facility (KEKB). In addition to the higher instantaneous luminosity, the experiment is scheduled to run slightly longer, such that the final dataset will be approximately 50 ab^{-1} of e^+e^- collisions. A large portion of the data will be collected at the nominal collision energy, $\sqrt{s} = 10.58$ GeV, which is the mass of the $\Upsilon(4S)$ resonance[1].

At the time of writing, Belle II has collected two datasets with collisions: approximately 0.5 fb^{-1} of commissioning data (collected in 2018) and approximately 6.5 fb^{-1} of physics data (in 2019). Several preliminary results based on these data were presented at this conference, for example in Ref. [5].

2. Dark sector physics

Dark matter is a persistent problem in modern physics. Despite astronomical evidence [6, 7] for dark matter, no dark matter particles have been observed. There are several extensions to the Standard Model of particle physics (SM) which could explain dark matter. Due to the choice of $\sqrt{s}$, searches at Belle II cover masses up to GeV$/c^2$. This is several orders of magnitude above the typical mass-scale of QCD axion models, but below that of a weakly-interacting massive particle (WIMP) dark matter candidate.

Belle II is therefore sensitive in the realm of *dark-sector* models. In these models, the dark matter does not directly interact with the SM particles but via a new mediator particle[2]. In the minimal case, this requires two new particles: the mediator and the stable dark matter particle. Depending on the relative masses of these two particles, visible or invisible decays of the mediator particle are more or less likely.

3. Visible decay of a pseudoscalar axion-like particle

A scalar axion-like particle (ALP) mediator results in the following additional terms after electroweak-symmetry breaking:

$$\mathscr{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_{a\gamma Z}}{4} a F_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aZZ}}{4} a Z_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aWW}}{4} a W_{\mu\nu}\tilde{W}^{\mu\nu}$$

[1] because it decays with nearly 100% branching fraction to $B\bar{B}$ pairs

[2] also called a "portal" particle in literature

where a is the scalar ALP field; g denotes the relevant coupling; $F_{\mu\nu}$, $Z_{\mu\nu}$, and $W_{\mu\nu}$ are the field strength tensors for the electromagnetic photon, Z and W bosons; and $\tilde{F}_{\mu\nu} \equiv 1/2\,\varepsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$ denote the dual fields. At $\sqrt{s} = 10.58$ GeV$/c^2$, the first term dominates [8]. This implies two production mechanisms: ALP-strahlung and photon-photon fusion.

The ALP-strahlung process with visible decay to two photons (shown to the left of Fig. 1) is experimentally more accessible as it results in a unique final state which is relatively easy to trigger, and does not suffer from undetected final-state particles. Backgrounds can be suppressed by requiring that the three-photon candidates have a combined invariant mass close to the beam energy, and are reconstructed in time with each other. A scan can then be performed in the diphoton invariant mass to search for peaks. Considering only the dominant background, $e^+e^- \to \gamma\gamma$ with additional radiated (or beam background) photons, the expected sensitivity is shown in Fig. 1. This search can be performed with the very first data collected by Belle II during 2018.

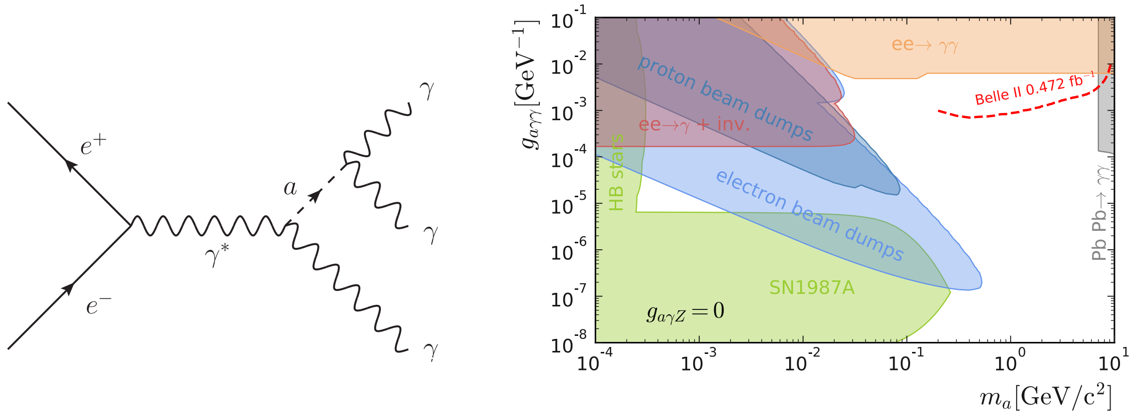

Figure 1: The Feynman diagram for an axion-like particle (ALP) produced by ALP-strahlung and decaying visibly (left), and the Belle II sensitivity of a search for three-photon events in early data (right). The right hand figure contains exclusion regions described in Ref. [8] and the expected sensitivity for the early data set.

4. Invisible decay of a vector dark photon

An additional $U(1)$ vector field [9], could also give rise to a mediator particle. A *dark photon*, A', results in:

$$\mathscr{L} \supset \varepsilon g_D A'_\mu J^\mu_{\mathrm{EM}},$$

if it only interacts via kinetic mixing with the SM electromagnetic photon with mixing strength ε, and some coupling to dark matter g_D.

In the region of parameter space where the dark photon is more massive than twice the mass of the dark matter, it decays invisibly. In this case, the invisible final state can be observed by requiring the presence of an initial-state-radiated (ISR) photon. This monoenergetic photon can be related to the dark photon mass with

$$E_{\gamma\mathrm{ISR}} = \frac{(\sqrt{s})^2 - m_{A'}^2}{2\sqrt{s}}.$$

The diagram for this process is shown in the left-hand side of Fig. 2.

Analyses of *visible* decays of the dark photon are also planned. However these require a larger data set in order to compete with BaBar [10].

The single photon search is conceptually rather straightforward. One searches for events containing a single photon cluster in the electromagnetic calorimeter, and inside the tracking volume where the rest of the detector was quiet. Background processes are $e^+e^- \to \gamma\gamma$, and $e^+e^- \to e^+e^-(\gamma)$ in combination with gaps in the calorimeter, material conversions, and tracking inefficiency. For this analysis, one requires a rather good knowledge of the detector efficiencies, and stable operation of all subdetectors. The single photon search is therefore not able to be performed on the commissioning data collected in 2018. However, with around 20 fb^{-1} of full-detector data, Belle II should be able to set a limit around an order of magnitude lower than the equivalent analysis performed at BaBar [3] and orthogonal to a search performed at NA64 [11]. The improvement with respect to the BaBar search is mainly due to lower trigger thresholds and fewer projective gaps in the calorimeter. This is shown in the right-hand side of Fig. 2.

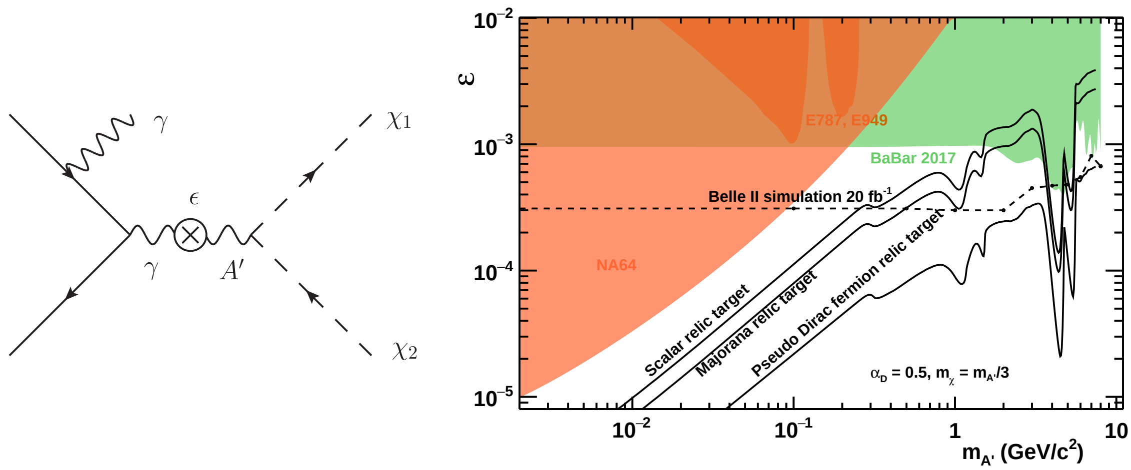

Figure 2: The Feynman diagram for a dark photon produced by kinetic mixing of the SM photon and decaying invisibly (left), and the Belle II sensitivity of a search for single photon events (right). Other constraints come from a BaBar [3] and recently updated NA64 analysis [11].

5. Invisible decay of a lepton-non-universal Z′

An vector portal with more complicated electroweak coupling structure[3] would be a massive Z'. In $L_\mu - L_\tau$ models, the Z' couples to muons and taus but not electrons resulting in:

$$\mathscr{L} \supset g'\bar{\mu}\gamma_\alpha Z'^\alpha \mu - g'\bar{\tau}\gamma_\alpha Z'^\alpha \tau + g'\bar{\nu}_\mu \gamma_\alpha Z'^\alpha P_L \nu_\mu - g'\bar{\nu}_\tau \gamma_\alpha Z'^\alpha P_L \nu_\tau,$$

with coupling g'; where $\gamma_\alpha Z'^\alpha$ is the Pauli matrix contracted with the new Z' current; P_L is the projection operator; and μ, τ, ν_i are the lepton spinors. Such a model may explain the anomalous magnetic moment of the muon [12] and also the recent B-physics anomalies [13, 14, 15].

[3]The distinction between Z' and dark photon, A' is largely one of nomenclature. Here the A' denotes a field which mixes exclusively with the SM photon, hence dark "photon".

The Z' could therefore be produced via $e^+e^- \to \mu^+\mu^- Z'$. As with other mediators, it will decay either visibly or invisibly to a dark matter final state dependent on the relative dark matter mass. A search for a visible decay has been performed by BaBar [4]. However, the parameter-space for the invisible decay is unexplored.

The experimental signature of the invisible decay (shown to the left of Fig. 3) is two muon tracks and missing energy, with no other activity in the detector. The Z' candidate *recoil mass* is then related to the dimuon invariant mass, $m_{\mu\mu}$, and the energy of the dimuon pair in the centre-of-mass frame, $E_{\mu\mu}^{\mathrm{CM}}$, with

$$m_{Z'} = \sqrt{s + m_{\mu\mu}^2 - 2\sqrt{s} \cdot E_{\mu\mu}^{\mathrm{CM}}}.$$

Since the conference and before preparation of these proceedings, a preliminary limit has been set for this process [16]. The search is able to be performed on the 2018 calibration data, but only on 0.276 fb^{-1} due to varying trigger configurations at startup. A scan is performed in the recoil mass, and no excess is observed. Therefore an upper limit is set on the coupling, g'. This is shown to the right-hand side of Fig. 3.

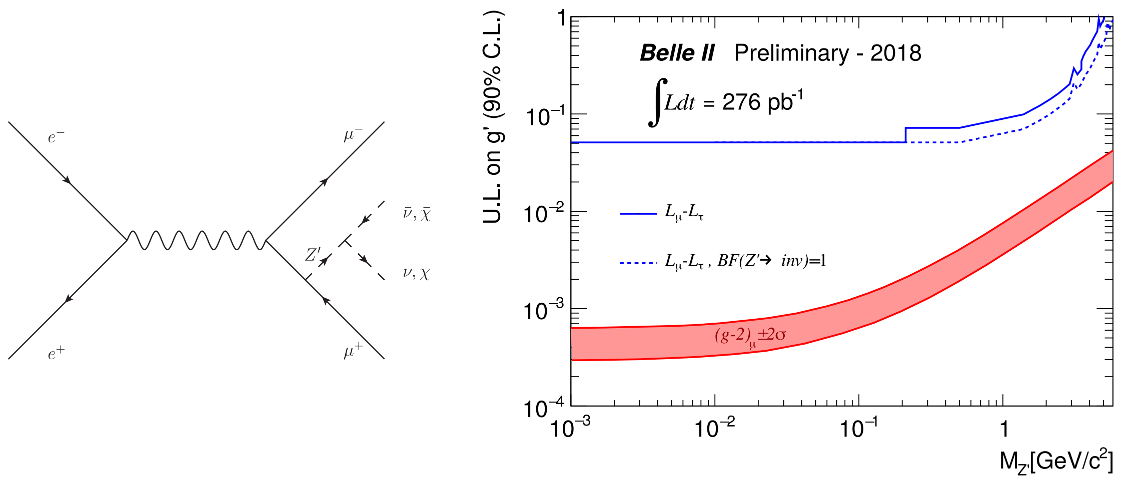

Figure 3: The Feynman diagram for a Z' produced in $e^+e^- \to \mu^+\mu^-$ events and decaying invisibly (left), and the preliminary exclusion limit of a search for such events in early Belle II data (right).

6. Prospects and summary

In summary, the Belle II experiment can set very competitive limits for several dark sector models. This document describes three such analyses that can be performed with early Belle II data. With around 20 fb^{-1} of data, a single photon search for the invisible decay of a dark photon can be performed. However even with 2018 data, collected predominantly for calibration purposes, a search for the production and visible decay of an axion-like particle can be performed. Since the conference, and before the preparation of this document, a preliminary exclusion limit for the production and invisible decay of a lepton-non-universal Z' has been set. Publications for these latter two searches are under preparation and expected soon.

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