Vol. 46 (2015) *ACTA PHYSICA POLONICA B* No 11

TOWARDS FIRST PHYSICS AT BELLE II[*]

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(Received October 16, 2015)

The next-generation B-factory Belle II at the upgraded KEKB accelerator, SuperKEKB, is aiming to start physics data taking in 2018. The broad physics program covers *e.g.* physics with B and D mesons, μ and τ leptons as well as measurements using the method of radiative returns and direct searches for New Physics. Among these analyses, there is the search for a Dark Photon decaying into light dark matter or leptons, and the precision measurement of the muon pair asymmetry that both have demanding requirements for the trigger system and the latter also for precision QED theory.

DOI:10.5506/APhysPolB.46.2285
PACS numbers: 12.15.–y, 12.20.–m, 14.60.–z

1. Introduction

The expected data set of $50\,\mathrm{ab}^{-1}$ at Belle II will exceed the one collected by the predecessor Belle by a factor of 50. The bulk of the data will be collected at the $\Upsilon(4S)$ resonance, but it is planned to collect sizable data sets also off-resonance, and at energies around the narrow resonances $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ as well as the $\Upsilon(5S)$. The Belle II physics program will extend to low multiplicity final states that will be accessible due to an improved trigger system.

2. Triggers for low multiplicity physics

The Belle II trigger system will consist of two stages, one fast hardware based trigger (L1) and one high level trigger (HLT) based on offline reconstructed data objects. The requirements of the L1 trigger include a maximum average trigger rate of 30 kHz, a fixed latency of about $5\,\mu$s, a

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[*] Presented at the XXXIX International Conference of Theoretical Physics "Matter to the Deepest", Ustroń, Poland, September 13–18, 2015.

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timing precision of less than 10 ns and a trigger efficiency for $\Upsilon(4S) \to B\bar{B}$ of $> 99\%$. The wider physics program of Belle II requires triggers that are efficient for low multiplicity final states as well that have been partially absent at Belle and are currently under study: Radiative two-track processes like $ee \to \pi\pi(\gamma)$ will be triggered by a single calorimeter cluster and at least one non-electron track in the opposite direction. Non-radiative two-track processes like $ee \to \mu\mu$ will be triggered by two-track triggers based on only one detector subsystem, and also by single track triggers for high energetic muons that penetrate through the muon detectors. Instead of a simplistic polar angle dependent Bhabha-veto that limited various Belle analyses, a very pure veto, based on both the polar and the azimuthal angle, will be used to reject Bhabha events. On the other hand, an efficient Bhabha accept trigger for *e.g.* luminosity measurements or calibration purposes will make use of charge information to apply a polar angle dependent prescale resulting in an approximately flat Bhabha spectrum after L1. A 'single photon' trigger will be used to trigger on isolated energy depositions in the calorimeter.

3. Search for a Dark Photon

Astronomical observations indicate the existence of Dark Matter which makes up most of the matter in the universe. Particles of this so-called Dark Sector interact gravitationally with Standard Model (SM) matter, but do not interact via the electroweak or strong forces. One possible extension of the SM is the existence of new U(1) gauge bosons, so-called Dark Photons A', that couple via kinetic mixing to the SM photon γ [1]. The mixing strength is usually expressed via the parameter ε which can be understood as suppression factor relative to the electron charge e. At Belle II, a Dark Photon A' could be produced in the initial state radiation (ISR) accompanied reaction $e^+e^- \to A'\gamma_{\mathrm{ISR}}$, where the cross section is proportional to $\varepsilon^2\alpha^2/E^2_{\mathrm{CM}}$ [2] and α is the electromagnetic coupling.

If the A' is the lightest dark sector particle, it would decay into SM particles with branching ratios as a virtual photon of mass $M_{A'}$. Several experiments have published results of A' searches and even more results are to come in the next years. The results of the BaBar experiment for the decays of an A' in the e^+e^- and $\mu^+\mu^-$ final states have been used to extract expected limits for the Belle II experiment. Their analysis is based on a search for a narrow peak in the dilepton mass spectrum on top of a large — and apart from the proximity of narrow resonances smooth — QED SM background. Taking into account the better invariant mass resolution ($\sim$ factor 2) of Belle II due to the larger drift chamber radius that improves the possible signal peak resolution and a better trigger efficiency for both muons ($\sim$ factor 1.1) and electrons ($\sim$ factor 2), the projected upper limits for different values of integrated luminosity are shown in Fig. 1.

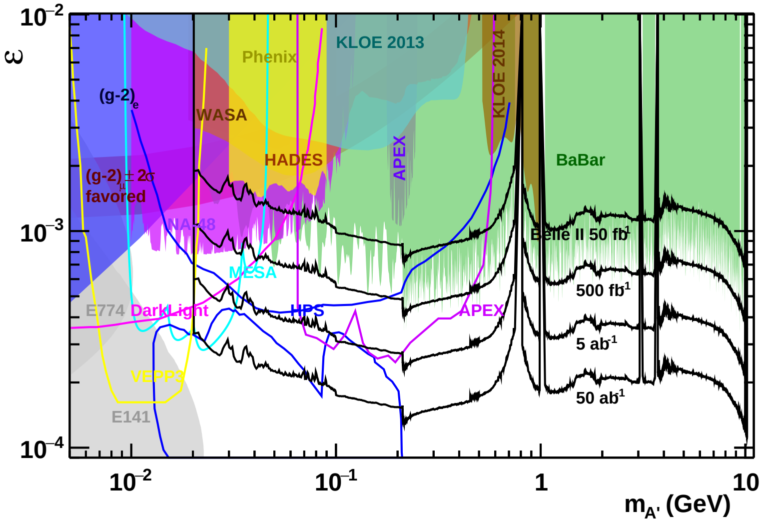

Fig. 1. Existing exclusion regions (90% C.L.) on the dark photon mixing parameter ε and mass $M_{A'}$ (solid regions) for $A' \to \ell\ell$, with projected limits for Belle II and other future experiments (lines). Data for current limits and extrapolations other than Belle II from [4]. (Figure courtesy of Chris Hearty.)

If the A' is not the lightest dark sector particle, it will dominantly decay into light dark matter via $A' \to \chi\bar{\chi}$. Since the interaction probability of dark matter with the detector is negligible, the experimental signature of such a decay will be a mono-energetic ISR photon $\gamma_{\rm ISR}$ with energy $E_\gamma = (E^2_{\rm CM} - M^2_{A'})/(2E_{\rm CM})$. This search would require a L1 trigger that is sensitive to single photons. While the irreducible SM background $e^+e^- \to \nu\nu\gamma$ is negligible, there is a large background from $e^+e^- \to \gamma\gamma$ and $e^+e^- \to e^+e^-\gamma$. $e^+e^- \to \gamma\gamma$ gives a peaking background at $M_{A'} = 0$ when one of the two photons does neither interact in the calorimeter nor in the muon system. $e^+e^- \to e^+e^-\gamma$ is a background when both charged track miss the detector acceptance. A full simulation of the radiative Bhabha background for this analysis is currently under study using the event generators `TEEGG` [6] if one or both electrons scatter under small angles ($< 1^\circ$) and `BHWIDE` [7] or `BabaYaga@NLO` [8] if both electrons scatter under large angles. The possible projected Belle II upper limits for different values of integrated luminosity are shown in Fig. 2. This projection is based on a similar BaBar analysis based on a small data set [3] and assuming that Belle II will have a single photon trigger with an effective energy threshold of $(E_\gamma)_{\rm CM} > 2.2$ GeV and, furthermore, that the systematic uncertainty due to the time stability of the muon system is negligible. This search may be possible during the first phase of Belle II running without a vertex detector.

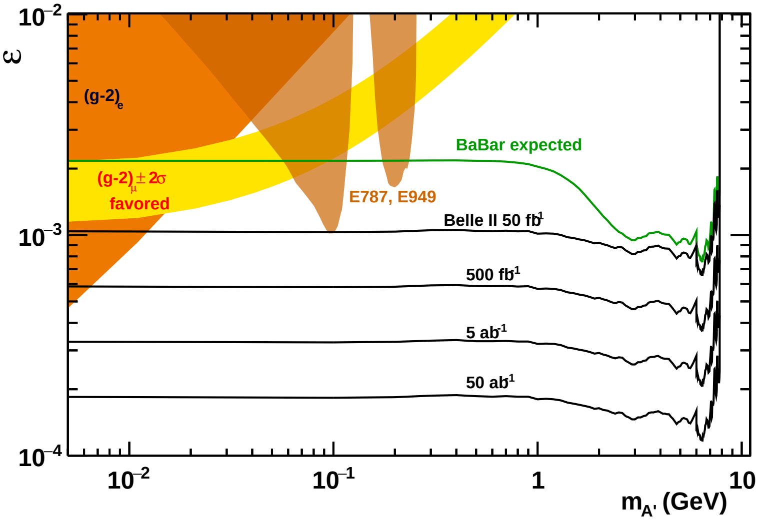

Fig. 2. Projected limits for Belle II for a search for dark photons decaying invisibly, assuming massless daughters. The expected BaBar region is an interpretation of the preliminary result from Ref. [3] in terms of a Dark Photon search. The Belle II limits are based on an extrapolation of the BaBar interpretation assuming negligible systematic uncertainties but no improvement of the mass resolution. Data for current limits and extrapolations other than BaBar and Belle II from [5]. (Figure courtesy of Chris Hearty.)

4. Muon pair asymmetry

The process $e^+e^- \to \mu^+\mu^-$ is among the simplest reactions of the SM where both QED and electroweak (EW) predictions can be tested. The distribution of the polar angle θ_{CM} of the outgoing leptons in the center-of-mass system, defined as the angle between the e^+ and the μ^+, is expected to be asymmetric in the SM at Born level, caused by the interference of γ and Z exchange even at energies well below the Z pole, whereas lowest-order QED predicts a symmetric angular distribution. The forward–backward asymmetry is defined as

$$A^+_{\mathrm{FB}} \equiv \frac{N^+\left(\cos(\theta_{\mathrm{CM}}) \geq 0\right) - N^+\left(\cos(\theta_{\mathrm{CM}}) < 0\right)}{N^+\left(\cos(\theta_{\mathrm{CM}}) \geq 0\right) + N^+\left(\cos(\theta_{\mathrm{CM}}) < 0\right)}\,, \tag{1}$$

where $N^+(\cos(\theta_{\mathrm{CM}}))$ is the number of μ^+ detected under the angle $\cos(\theta_{\mathrm{CM}})$. At lowest order and neglecting initial and final state masses, the forward–backward asymmetry for $s \ll M_Z^2$ can be approximated as

$$A^+_{\mathrm{FB}}(s) = A_{\mathrm{FB}}(s) \approx \frac{3G_{\mathrm{F}}}{4\sqrt{2}\pi\alpha}\frac{sM_Z^2}{s - M_Z^2}g^e_{\mathrm{A}}g^\mu_{\mathrm{A}}\,, \tag{2}$$

where s is the squared center-of-mass energy, G_{F} is the Fermi constant, α is the QED coupling constant, M_Z is the Z boson mass, and g_{A}^{e} and g_{A}^{μ} are the axial couplings of the electron and the muon. The forward–backward asymmetry A_{FB} is proportional to the ρ parameter via $g_{\mathrm{A}}^{f} = \sqrt{\rho_{\mathrm{f}}}\, T_3^f$, where $T_3^f = 1/2$ is the third component of the weak isospin and $f = e, \mu$. The ρ parameter is a measure of the deviation from the vector boson mass relation $\rho = m_{\mathrm{W}}^2/(m_Z^2 \cos^2(\theta_{\mathrm{W}}))$, which is unity in the SM at tree level, and where $\cos(\theta_{\mathrm{W}})$ is the weak mixing angle [9]. Deviation of the extracted $\rho = \sqrt{\rho_e \rho_\mu}$ parameter and its SM expectation after applying flavour-universal (u) and flavour-specific (f) virtual corrections

$$\rho_{\mathrm{f}} = 1 + \Delta\rho_{\mathrm{u}} + \Delta\rho_{\mathrm{f}} + \Delta\rho_{\mathrm{new}} \tag{3}$$

can, *e.g.*, be related to the isospin violating New Physics through the oblique parameter T [10]. The contribution to the low energy ($s \ll M_Z^2$) ρ parameter is approximately given by $\Delta\rho_{\mathrm{new}} \approx \alpha_Z T$, where $\alpha_Z \approx 1/128.945$ is the electromagnetic coupling at the Z pole [11]. This measurement is unique in the sense that it probes axial–axial operators and allows an extraction of the oblique parameter T that is independent of the oblique parameter S. A measurement of A_{FB} can also be used to set limits on four-lepton contact interactions.

The expected statistical uncertainty at Belle II is about $\sigma(A_{\mathrm{FB}}) \approx 10^{-5}$ where the Born-level SM prediction is $A_{\mathrm{FB}} \approx -10^{-2}$. While backgrounds are small and under control, the two largest corrections and systematic uncertainties arise from detector charge asymmetries and from one-loop (and beyond) QED corrections. The detector charge asymmetries are mainly related to the trigger, particle identification and tracking and will be studied using dimuon events triggered by a single track trigger and using large statistics control samples with different SM asymmetries like $e^+e^- \to e^+e^-\mu^+\mu^-$ and $e^+e^- \to \pi^+\pi^-\gamma$. QED asymmetries are of $\mathcal{O}(10^{-2})$, and arise mainly from the interference of initial and final state radiation and box diagrams interference with the Born-level process. Current MC tools and theory packages like KKMC [12] or ZFITTER [13] include only incomplete two-loop QED corrections and additional theoretical work is needed to include the full two-loop QED corrections for the asymmetric part.

5. Summary

The Belle II experiment is expected to start data taking in 2018 and will collect an integrated luminosity of $50\,\mathrm{ab}^{-1}$ at and near the $\Upsilon(4S)$. An improved trigger system will allow a much wider low multiplicity physics program than at Belle which includes searches for a Dark Photon and a precision measurement of the muon pair asymmetry. The search for invisible decays of a Dark Photon is under study for the first phase of Belle II running even before the nominal start with an incomplete detector. The measurement of the muon pair asymmetry at an energy far below the Z pole would offer the unique possibility to determine the SM ρ parameter if both detector systematics and theory calculations match the demanding precision requirements.

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