Perspectives of a precise measurement of the charge asymmetry in muon pair production at Belle II

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Abstract: Forward-backward asymmetry in the muon pairs production in electron-positron annihilation is caused by the interference of the photon and Z-boson already at leading order. A high precise measurement of the value of this asymmetry, A_{FB}, at the SuperB-factory will provide stringent limitations on the New Physics effects. Even though $A_{FB} \approx 0.01$ at 10 GeV center-of-mass energy of B-factory operation, a huge statistics expected at the Belle II experiments allow to hope on a high precision. This report briefly describes perspectives as well as obstacles on the way to achieve the precise results.

Key words: electron-positron collider, muon pair production, forward-backward asymmetry, detector, Monte-Carlo simulation

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1 Introduction

The Standard Model of the electro-weak interactions (SM) was tested in many experiments and no clear discrepancies was found. However, at present an intensive quests of such discrepancies which can indicate a new physics are continued. One of the SM effects is a forward-backward asymmetry in the process $e^+e^- \to \mu^+\mu^-$ induced by the interference of diagrams with the virtual photon and Z-boson –

$$A_{FB} = \frac{N(\theta^+ > 90^\circ) - N(\theta^+ < 90^\circ)}{N(\theta^+ > 90^\circ) + N(\theta^+ < 90^\circ)}, \qquad (1)$$

where θ^+ is a positron scattering angle in the center-of-mass frame and N is a number of events. Experimental measurements of A_{FB} (see review [1]) are presented in the Fig. 1. All results are in a good agreement with the SM calculation. However, the accuracy of these measurement is not very high and new measurements with a precision of about 1% could be quite useful.

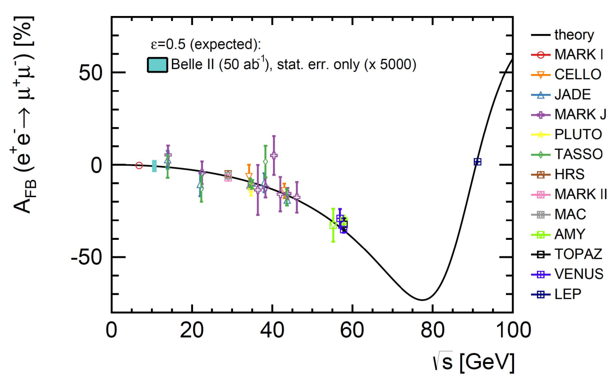

Fig. 1. Measured Forward-backward asymmetry

The $\mu^+\mu^-$ production differential cross section is expressed by the formulae (assuming $\mu - e$ universality):

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2(s)}{2s}[F_1(1+\cos^2\theta) + 2F_2\cos\theta], \qquad (2)$$

where $s = 4E_{CM}^2$ and θ is the scattering angle in CM frame.

$$F_1 = 1 - 2\chi g_V^2 \cos\delta_R + \chi^2(g_V^2 + g_A^2)^2, \qquad (3)$$
$$F_2 = 2\chi g_A^2 \cos\delta_R + 4\chi^2 g_V^2 g_A^2,$$
$$\chi = \frac{G_F}{2\sqrt{2}\pi\alpha(s)} \frac{sM_Z^2}{\sqrt{(M_Z^2 - s)^2 + M_Z^2\Gamma_Z^2}}, \quad \tan\delta_R = \frac{M_Z\Gamma_Z}{M_Z^2 - s},$$

where G_F is the Fermi constant and g_V, g_A are the vector and axial coupling constants of the neutral current weak

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interactions. Then the asymmetry is $A_{FB} = 3F_2/4F_1$. The g_V and g_A constants can be expressed via fundamental parameters of SM as:

$$g_V = \sqrt{\rho_l}(T^l_{3L} – 2Q_l \sin^2\theta_W) \approx \frac{1}{2} – 2\sin^2\theta_W \, g_A = \sqrt{\rho_l} T^l_{3L} \approx \frac{1}{2}, \tag{4}$$

where $T^l_{3L} = -1/2$ – third component of the charged lepton weak isospin, Q_l – lepton charge and θ_W is the weak mixing angle. Parameter ρ_l is close to 1 and summarises the high-order electro-weak corrections and hypothetical New Physics effects. Since for charged leptons $g_V = (1/2 – 2\sin^2\theta_W) \approx 0$ charge asymmetry contribution, F_2, is practically insensitive to the θ_W. However, a precise A_{FB} measurement can be used for a search of a New Physics.

When $s \ll M_Z^2$ the asymmetry (in the Born leading order) can be written as:

$$A_{FB} = \frac{3F_2}{4F_1} \approx -\frac{3}{16\sqrt{2}} \frac{G_F s}{\pi\alpha(s)}. \tag{5}$$

For the Belle II energy range, $\sqrt{s} \approx 10$ GeV, that results in $A_{FB} \approx -0.008$.

2 Belle II experiment

The KEKB B-factory [2], energy-asymmetric collider with world highest luminosity, $2{\times}10^{34}\text{cm}^{-2}\text{s}^{-1}$, was in operation from 1999 until 2010. Experiments with the Belle detector [3] in the energy range of 10-11 GeV collected an integrated luminosity exceeding 1000 fb^{-1}. This huge data sample provided a number of important results concerning the CP symmetry violation in the quark sector, heavy quarkonium spectroscopy, tau lepton decays and two-photon physics. The total number of $e^+e^- \to \mu^+\mu^-$ events is about 10^9 that can provide a statistical uncertainty of $\sigma A_{FB}/A_{FB} \sim 1\%$. However an achievement of the comparable systematic uncertainties, caused by the apparatus effects as well as background asymmetry, is a quite difficult task.

At present the new SuperKEKB collider and the Belle II detector are under construction at KEK [4]. This new experiment will continue and widen the studies began at the previous experiments. The instantaneous luminosity of this collider will exceed the previous one by about 40 times, amounting to $8 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$. However, high luminosity is unavoidably accompanied by the high event rate and background. Then the detector should be drastically upgraded. Schematic view of the Belle II detector (top half) in comparison to the previous Belle detector (bottom half) is presented in Fig. 2.

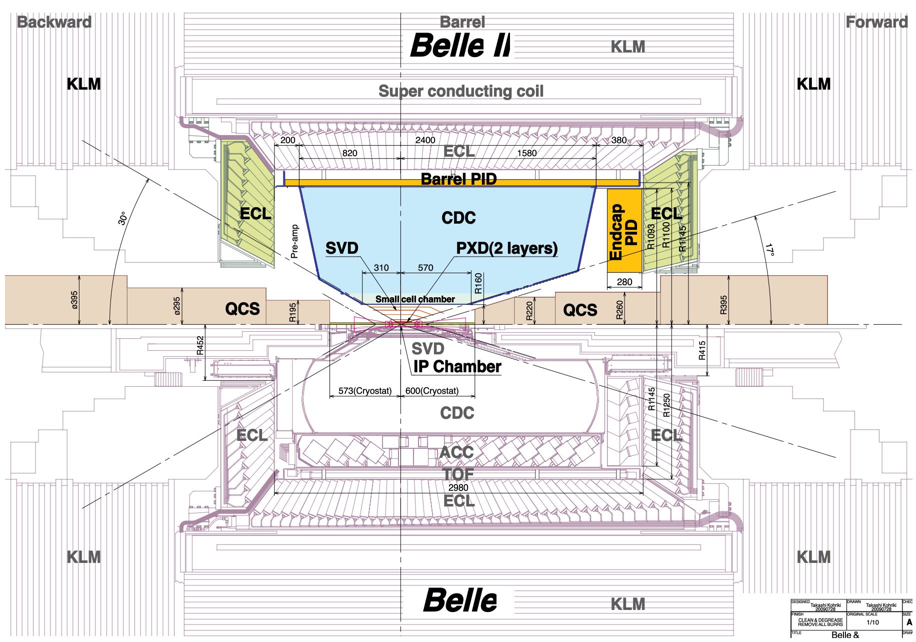

Fig. 2. Schematic view of the Belle II detector (top half) in comparison to the previous Belle detector (bottom half). Belle and Belle II: SVD – silicon vertex detector, CDC – central drift chamber, ECL – electromagnetic crystal calorimeter, KLM – K-long and muon detector; Belle: ACC – aerogel Cherenkov counters, TOF – time-of-flight system; Belle II: PXD – pixel vertex detector, Barrel PID – Cherenkov time-of-propagation counters, Endcap PID – aerogel RICH detector.

The vertex detector, central drift chamber and particle identification system will be replaced by completely new ones. The KLM will be partially upgraded. The ECL scintillation crystals and mechanical structure is kept from the previous experiments. However, the calorimeter electronics will be replace by more modern one.

Although the SM was confirmed in these experiments, achieved accuracies still leave certain room for the New Physics (NP). Thus, a search for NP, i.e. phenomena which are not described by the SM, becomes the most important task for the Belle II experiment. With an integrated luminosity of about 50 ab^{-1}, which should be reached with SuperKEKB, statistical uncertainties in the value A_{FB} reduce to 0.1%. High statistics will help to reduce the systematics uncertainties by the detail study of the $\mu^+\mu^-$ angular distribution, careful study of the background processes and detector asymmetry effects.

To estimate the Belle II capability for the discussed asymmetry a MC simulation of the studied process including the weak interaction contribution was done. The Belle software was used in this study. A set of the straight forward selections were applied to the detected events:

- Number of Good tracks: 2;
- Acollinearity: $\psi_{\rm CM} < 10°$;
- $E_{\rm CM}/\sqrt{s}/2 > 0.75$ (for both tracks);
- $|\cos(\theta^+_{\rm CM})| < 0.75$;
- Particle identification.

Here $\psi_{\rm CM}$, $E_{\rm CM}$, $\cos(\theta^+_{\rm CM}$ are acollinearity, particle energy and positron polar angle respectively. After these selection the tracking acceptance is about 70% and the detection efficiency after particle identification selection becomes about 45%.

Main background processes and corresponding contaminations to $\mu^+\mu^-$ are $e^+e^- \to e^+e^-\mu^+\mu^-$ ($\sim 1\cdot 10^{-3}$), $e^+e^- \to \tau^+\tau^- \to (\mu^+\overline{\nu}_\tau\nu_\mu)(\mu^-\overline{\nu}_\mu\nu_\tau)$ ($\sim 5\cdot 10^{-4}$) and Bhabha scattering, $e^+e^- \to e^+e^-$, due to electron misidentification ($\lesssim 10^{-4}$). Backgrounds from the cosmic rays as well as from the $e^+e^- \to uu/dd/ss/cc$ and $e^+e^- \to e^+e^-e^+e^-$ are negligible.

The main theoretical uncertainty comes from the higher order contributions: an interference of the initial state and final state radiation (see Fig. 3) as well as two double internal photon lines diagrams (see Fig. 4).

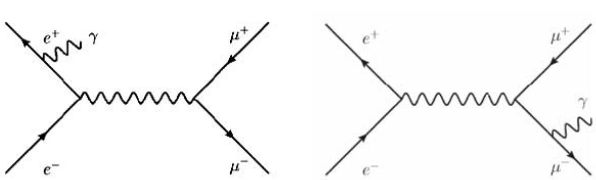

Fig. 3. Feynman diagrams corresponding to the initial and final state radiation.

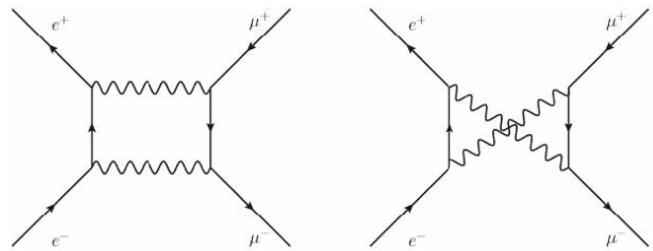

Fig. 4. Box diagrams providing small FB asymmetry.

The asymmetry provided by these contributions calculated with the KKMC code is shown in the Fig. 5. As seen from the figure the main contribution comes from the interference of the initial and final state radiation diagrams. It decreases with the increase of the acollinearity angle and has the opposite sign in comparison with the electro-weak induced asymmetry.

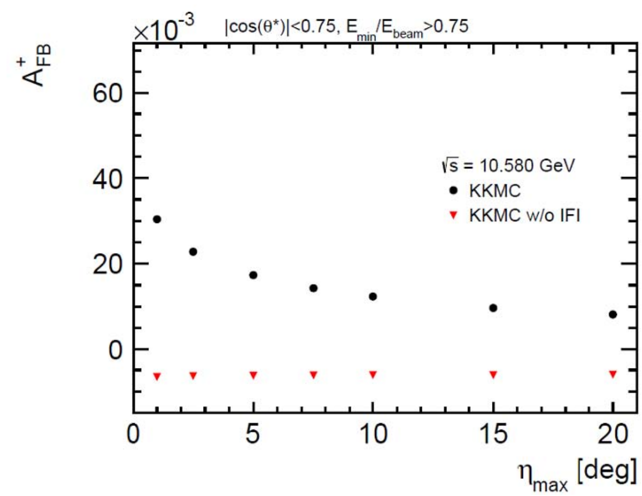

Fig. 5. A_{FB} with and without QED interference contribution.

The value of this QED FB asymmetry is about 10^{-2} at the accolinearity cut of 10° that is approximately the same as that induced by electroweak interactions. Then the QED asymmetry The QED asymmetry can be studied using the existing MC generators KKMC 4.19 [5] and PHOKHARA 9.1 [6]. Very large experimental statistics which can be collected at SuperKEKB will provide a possibility of a careful checks both QED as well as apparatus asymmetries by detail fits of the angular distributions at the different cuts on acollinearity. The detector induced asymmetry will be revealed by a study of the other QED processes.

Effects of the New Physics can be described by three parameters[7]: S, T and U. A difference between measured and theoretical values of the ρ parameter obtained from low energy asymmetry measurements can be expressed as $\Delta\rho = \alpha(M_Z^2)T$ where $\alpha(M_Z^2) = 1/128.945$ is the running electromagnetic coupling constant at Z-boson mass. At the accuracy in $\sigma(A_{FB})/A_{FB} \sim 10^{-3}$ T parameter uncertainty becomes ~ 0.1 which is comparable to the existing accuracy obtained from other experiment. It should be noted that in this case the limitations on T are obtained independently of other parameters, S and U.

3 conclusion

- Belle II provides unique environment for a precision electroweak measurement far from the Z pole.
- The $\mu^+\mu^-$ FB asymmetry study is complementary to measurements of the parity violation at low energy.
- For precise calculations of the high order QED contributions to the FB asymmetry the theory input is highly needed.
- Existing Belle data is used now to study detector related uncertainties as well as to optimize Belle II triggers and Belle II Monte Carlo simulation.
- The Belle II experiment starts data taking at 2017 and 50 ab^{-1} is expected by the end of 2023.

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