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

FERBER T.[1], SHWARTZ B.[2,3] (for the Belle/Belle Ⅱ collaboration)

(1. *Department of Physics and Astronomy*, *The University of British Columbia*, *Vancouver*, *BC*;
2. *Budker Institute of Nuclear Physics*, *Novosibirsk* 630090, *Russia*; 3. *Novosibirsk State University*, *Novosibirsk* 630090, *Russia*)

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 experiment will provide an opportunity to obtain 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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Belle Ⅱ 上缪子成对产生过程中电荷不对称性精确测量的展望

FERBER T.[1], SHWARTZ B.[2,3] (代表 Belle/Belle Ⅱ 合作组)

(1. 英属哥伦比亚大学天文物理系, 温哥华, 加拿大;
2. 俄罗斯布德克尔核物理研究所, 新西伯利亚 630090, 俄罗斯;
3. 国立新西伯利亚理工大学, 新西伯利亚 630090, 俄罗斯)

摘要: 由于光子和 Z 玻色子在领头阶即已存在干涉, 导致电子-正电子在淹没产生缪子对的过程中前后不对称. 超级 B 工厂对这个不对称值(A_{FB})的精确测量会严格限制新物理学效应. 即使在 B 工厂运行在 10 GeV 质心能量, 测得 $A_{FB}\approx 0.01$. 我们也期待 Belle Ⅱ 实验巨大统计量的高精度结果. 本文简要描述了研究前景以及要得到精确结果面临的困难.

关键词: 正负电子对撞机; 缪子对产生; 前后不对称性; 探测器; 蒙特卡洛模拟

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Biography: FERBER T, PhD. Research field: electro-positron annihilation into hadrons. E-mail: ferber@physics.ubc.ca

Corresponding author: SHWARTZ B, Professor/PhD. E-mail: shwartz@inp.nsk.su

0　Introduction

The standard model (SM) of the electro-weak interactions was tested in many experiments and no clear discrepancies have found. However, at present an intensive quest for such discrepancies which can indicate a new physics are continuing. 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 an angle between positive muon momentum and positron beam direction in the center-of-mass frame and N is a number of events. Experimental measurements of A_{FB} are presented in Fig. 1[1]. The data can be found in the review[2] and references therein. All results are in good agreement with the SM calculation. However, the accuracy of these measurements is not very high and new measurements with a precision of about 1% could be quite useful.

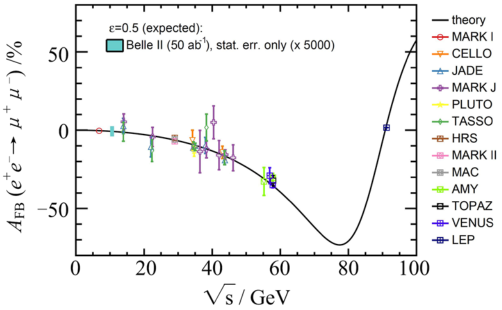

Fig. 1　Measured forward-backward asymmetry

The $\mu^+\mu^-$ production differential cross section is expressed by the formula:

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

where $s=4E_{CM}^2$.

$$\left.\begin{aligned}F_1&=1-2\chi g_V^2\cos\delta_R+\chi^2(g_V^2+g_A^2)\\F_2&=2\chi g_A^2\cos\delta_R+4\chi^2g_V^2g_A^2\\\chi&=\frac{G_F}{2\sqrt{2}\pi\alpha(s)}\frac{sM_Z^2}{\sqrt{(M_Z^2-s)^2+M_Z^2\Gamma_Z^2}}\\\tan\delta_R&=M_Z\Gamma_Z/(M_Z^2-s)\end{aligned}\right\}\qquad(3)$$

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

$$\begin{aligned}g_V&=\sqrt{\rho_l}(T_{3L}^l-2Q_l\sin^2\theta_W)\approx\\&\frac{1}{2}2\sin^2\theta_W g_A=\sqrt{\rho_l}T_{3L}^l\approx\frac{1}{2}\end{aligned}\qquad(4)$$

where $T_{3L}^l=-1/2$ is third component of the charged lepton weak isospin, Q_l is 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 to a search of a New Physics.

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

$$A_{FB}=\frac{3F_2}{4F_1}\approx\frac{3}{16\sqrt{2}}\frac{G_Fs}{\pi\alpha(s)}\qquad(5)$$

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

1　Belle Ⅱ experiment

The KEKB B-factory[3], energy-asymmetric collider with the world′s highest luminosity, 2×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, was in operation from 1999 until 2010. Experiments with the Belle detector[4] 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 quite a difficult task.

At present the new SuperKEKB collider and the Belle Ⅱ detector are under construction at KEK[5]. This new experiment will continue and widen that began at the previous experiments. The instantaneous luminosity of this collider will exceed the previous one by about 40 times, amounting to 8×10^{35} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. However, high luminosity is unavoidably accompanied by high event rate and background. Then the detector should be drastically upgraded. A schematic view of the Belle Ⅱ detector (top half) in comparison to the previous Belle detector (bottom half) is presented in Fig. 2.

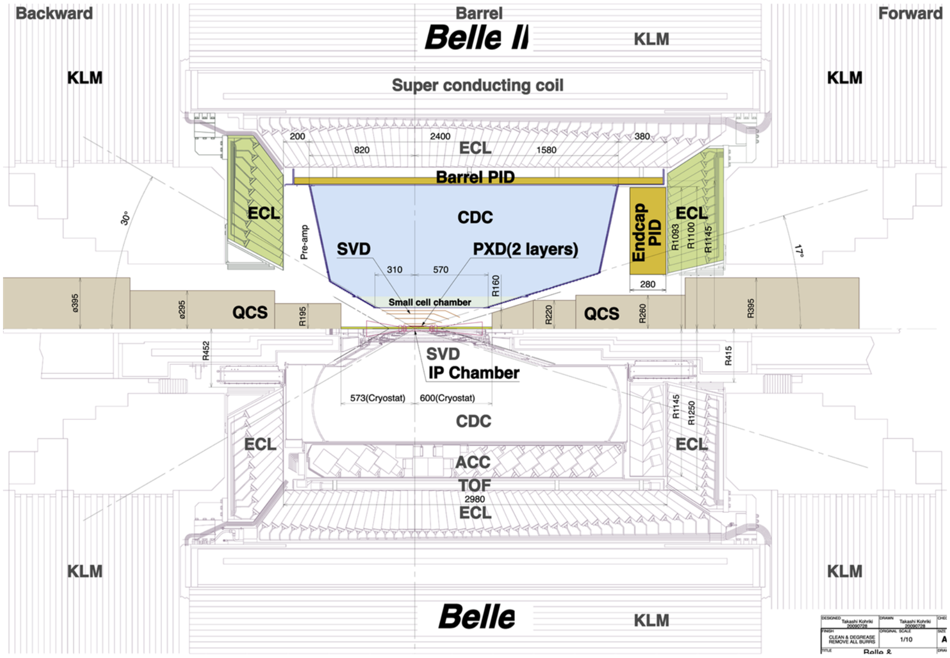

Fig. 2 Schematic view of the Belle Ⅱ detector (top half)

In 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 completely. 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 replaced by a more modern one.

Although the SM was confirmed in the previous A_{FB} measurements, 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.

(Ⅰ) Number of good tracks: 2.

(Ⅱ) Acollinearity: $\psi_{CM} < 10°$.

(Ⅲ) $E_{CM}/(\sqrt{s}/2) > 0.75$ (for both tracks).

(Ⅳ) $|\cos(\theta^{+}_{CM})| < 0.75$.

(Ⅴ) Particle identification.

Here ψ_{CM}, E_{CM}, $\cos(\theta^{+}_{CM})$ are acollinearity, particle energy and positron polar angle respectively.

After these selections 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 $e^+e^-\to e^+e^-\mu^+\mu^-$ ($\sim 1\times10^{-3}$), $e^+e^-\to\tau^+\tau^-\to(\mu^+\bar{\nu}_\tau\nu_\mu)\,(\mu^-\bar{\nu}_\mu\nu_\tau)$ ($\sim 5\times10^{-4}$) 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).

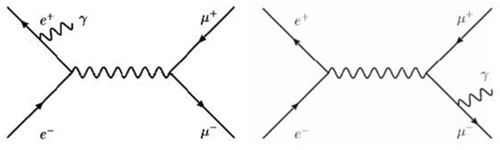

Fig. 3　Feynman diagrams corresponding to the initial and final state radiation

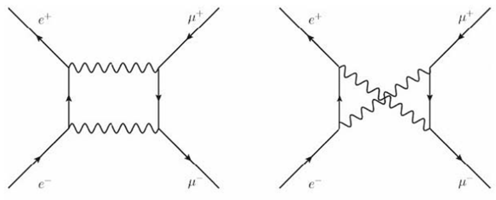

Fig. 4　Box diagrams providing small FB asymmetry

The asymmetry provided by these contributions calculated with the KKMC code is shown in 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.

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 should be calculated with high accuracy. One can expect to achieve a required precision in the QED induced A_{FB} taking into account the detector acceptance using. The QED asymmetry can be studied using the existing MC generators KKMC 4.19[6] and PHOKHARA 9.1[7]. Very large experimental statistics which can be collected at SuperKEKB will provide a possibility of a careful checks on both the QED as well as apparatus asymmetries by detailed fits of the angular distributions for the different cuts on acollinearity. The detector induced asymmetry will be revealed by a study of the other QED processes.

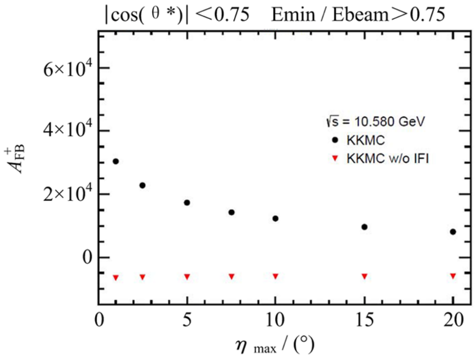

Fig. 5　A_{FB} with and without QED interference contribution

Effects of the New Physics can be described by three parameters[8]: 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 limits on T are obtained independently of other parameters, S and U.

2　Conclusion

(Ⅰ) Belle Ⅱ provides a unique environment for a precision electroweak measurement far from the Z pole

(Ⅱ) The $\mu^+ \mu^-$ FB asymmetry study is complementary to measurements of the parity violation at low energy.

(Ⅲ) For precise calculations of the high order QED contributions to the FB asymmetry the theoretical input is highly needed.

(Ⅳ) 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.

(Ⅴ) The Belle Ⅱ experiment starts data taking in 2017 and 50 ab^{-1} is expected by the end of 2023.

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