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Charm at Belle II – Status and Prospects

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High-precision flavor physics measurements play a complementary role to the direct searches for new physics by CMS and ATLAS experiments at LHC. Such measurements will be performed with the Belle II detector at the upgraded KEKB accelerator (SuperKEKB) in Japan. The physics potential with emphasis on the charm sector, current status and future prospects of the Belle II experiment are presented in these proceedings.

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1 Introduction

With the discovery of a Higgs-like boson [1] by CMS and ATLAS experiments at the LHC, the standard model (SM) of elementary particles is on the verge of completion. However, we still have many compelling reasons to believe that it cannot be the whole story. Notable among them are a ten orders of magnitude difference between the matter-antimatter asymmetry in universe and the *CP* violation content of the SM, and the absence of a suitable candidate to explain dark matter. Therefore, it is imperative to search for new physics (NP) using a diverse and complementary set of probes that include experiments at the energy frontier (CMS and ATLAS), the luminosity frontier (LHCb [2] and Belle II [3]), and the cosmic frontier studying neutrinos, gamma-ray photons and cosmic rays.

Now one could ask, with the LHC running at full swing, whether there is any need for an experiment operating on a low-energy e^+e^- machine (viz., Belle II at SuperKEKB). Moreover, if the goal is to do flavor physics can we not just focus on LHCb alone? Well, we have good reasons on both the counts. First, a flavor factory mostly studies processes that occur at one-loop level in the SM but may be of $\mathcal{O}(1)$ in various NP models. These processes include flavor-changing neutral current (FCNC) decays, neutral meson mixing and *CP* violation in the decays of beauty and charm hadrons. Being mostly associated with quantum loops, they probe energy scales that cannot be directly accessed at the LHC. Further, in case the LHC finds a NP signal, e.g., supersymmetry, the flavor factory can play an essential role on deciphering its nature through a systematic study of various flavor-violating couplings. Back to the question LHCb *vs.* Belle II, thanks to its pristine e^+e^- environment, high trigger efficiency, and excellent photon and π^0 reconstruction capabilities, the latter will have an edge over LHCb in the study of final states comprising neutral particles and missing neutrinos. Indeed, both Belle II (once operational) and LHCb will work in tandem to explore the NP landscape providing a synergy to the energy-frontier experiments.

In these proceedings, we discuss about the Belle II experiment to be located at the SuperKEKB collider of Japan, which aims at collecting 50 times as much the data as Belle [4] did few years ago. A particular emphasis is placed on its scope of studies of charm hadrons as a NP probe.

2 Charm as a NP probe

Charm decays via loop processes provide an interesting test bed for NP as SM footprints for these decays are tiny due to GIM suppression [5] and the lack of a large hierarchy in the down-type quark masses. Possible NP contributions can make their presence felt in FCNC processes that are larger for the up-type than the down-type quarks. Charm decays are thus best suited to reveal potential non-SM dynamics.

An important avenue that will be explored by Belle II in its pursuit of NP is the search for *CP* violation in charm hadron decays. The most obvious candidates here are the singly Cabibbo-suppressed decays [6], where the typical SM value for the *CP* asymmetry (A_{CP}) is in the range of 10^{-3}. Of course, while talking about such a small effect one would need a good control over the SM predictions, something that is in general lacking in this sector because of long-distance effects.

In Table 1 we summarize results on the direct *CP* asymmetry for a number of charm decay modes from Belle. As we have tried to categorize them in two horizontal blocks, LHCb has an upper hand for the final states containing only charged tracks, or neutral mesons that can be reconstructed in charged-track final states *e.g.*, $K_S^0 \to \pi^+\pi^-$. On the other hand, Belle II will be very competitive for the final states containing π^0, η or η'. In fact, for some of the channels such as $D^0 \to \pi^0\pi^0$ it will be the only one able to perform such measurement, thanks to its clean e^+e^- environment.

Table 1: Summary of direct *CP* asymmetry measured by Belle for various charm decay channels together with the size of the data sample used (see the second and third columns) and the corresponding projection for Belle II.

Channel	$\mathcal{L}_{\rm int}[\,{\rm fb}^{-1}]$	$A_{CP}[\%]$	Belle II with $50\,{\rm ab}^{-1}[\%]$
$D^0 \to K_S^0\pi^0$	791	$-0.28 \pm 0.19 \pm 0.10$	± 0.05
$D^0 \to K_S^0\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.10
$D^0 \to K_S^0\eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.10
$D^0 \to \pi^0\pi^0$	976	$\sigma[A_{CP}] \approx 0.6\%$	
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	
$D^0 \to K^+\pi^-\pi^0$	281	-0.6 ± 5.3	
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.20
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.20
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.07
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.05
$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.8 ± 4.4	
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.05
$D^+ \to K_S^0\pi^+$	977	$-0.363 \pm 0.094 \pm 0.067$	± 0.05
$D^+ \to K_S^0K^+$	977	$+0.08 \pm 0.28 \pm 0.14$	± 0.10
$D_s^+ \to K_S^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.30
$D_s^+ \to K_S^0K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.10

Another interesting NP probe for Belle II is the rare FCNC and forbidden decays of charm mesons. Under the first category will be the channels $D^0 \to \gamma\gamma$ and $D^0 \to h\ell^+\ell^-$ ($h = \pi^0, \eta, \omega$ and $\ell = e, \mu$). Going by the SM predictions, even some of them could be observed for the first time. Among the decays that are forbidden in the SM due to lepton-flavor or lepton-number violation, Belle II will have a better sensitivity for $D^0 \to h\ell^{\pm}\ell'^{\mp}$ ($h = \pi^0, \eta, \omega$ and $\ell, \ell' = e, \mu$) compared to LHCb. It can also probe decays with charged-track final state such as $D^0 \to e^{\pm}\mu^{\mp}$.

In addition to having almost two orders of magnitude larger data compared to Belle and *BABAR*, Belle II will see lots of innovation in the data analysis techniques. One such nice idea is the so-called *Charm tagging* where a recoiling charm hadron can be measured in the continuum process $e^+e^- \to c\overline{c} \to \overline{D}_{\rm tag} X_{\rm frag} D^{(*)}_{\rm rec}$ just by reconstructing the tagged D meson $\overline{D}_{\rm tag}$ together with some fragmentation products $X_{\rm frag}$. We have already some good working examples from the current-generation B factories; a recent one being the measurement of absolute branching fractions of lepton and hadron D_s^+ meson decays at Belle [7]. This idea will be explored further at Belle II.

3 KEKB to SuperKEKB

To look for the possible deviation from SM predictions in the flavor sector, at least two orders of magnitude larger data sample in excess of $50\,\mathrm{ab}^{-1}$ is required. Such a rise in the integrated luminosity calls for an equally large increase in the instantaneous luminosity,

$$\mathcal{L} = \frac{\gamma_{e^{\pm}}}{2er_e}\left(1 + \frac{\sigma_y^{\star}}{\sigma_x^{\star}}\right)\frac{I_{e^{\pm}}\xi_y^{e^{\pm}}}{\beta_y^{\star}}\,\frac{R_L}{R_{\xi_y}}, \tag{1}$$

where γ is the Lorentz factor, r_e is the classical electron radius, $\sigma^{\star}_{x,y}$ and $\beta^{\star}_y$ are the transverse beam size and vertical beta function at the interaction point (IP), I is the beam current, ξ_y is the beam-beam parameter, and R_L/R_{ξ_y} is a geometric factor because of finite beam-crossing angle and hour glass effect. The $e^{\pm}$ refers to the product of the corresponding quantities for low-energy positron (LER) and high-energy electron (HER) beams.

KEKB holds the current world record for instantaneous luminosity which is $2.1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. In order to get a value 40 larger than that, one needs to improve on some of the parameters given in Eq. (1). The main contribution comes from a significantly smaller beam size at the IP. The $\beta^{\star}$ values are reduced from 5.9 mm to 0.27/0.30 mm in the y direction and from 1200 mm to 32/25 mm in the x direction for HER/LER. To keep the beam-beam parameter that is proportional to $\sqrt{\beta^{\star}/\epsilon}$ at the similar level as KEKB, the emittance ϵ is reduced from 24/18 nm to 4.6/3.2 nm for HER/LER. This is accomplished by installing a new electron source and a new damping ring and by redesigning the HER arcs. The last contribution to the luminosity gain comes from the higher beam currents. They are increased from 1.64/1.19 A to 3.6/2.6 A by modifying the radio-frequency systems. Among other important changes of the KEKB complex are: installation of TiN-coated beam pipe with antechambers, a completely revamped interaction region having new superconducting/permanent final focusing quads (QCS), and replacement of short dipoles with longer ones for LER.

4 Enter Belle II

The steep increase in luminosity requires a careful design of various detector components. The main issue will be how to mitigate the effect of higher beam backgrounds (by a factor of 10 to 20), leading to an increase in occupancy and radiation damage as well as fake hits and pileup noise in the calorimeter. The higher event rate will also call for a substantial modification in the trigger scheme, DAQ and computing compared to Belle. Furthermore, to fully exploit the physics potential of the experiment an improved hadron and muon (especially at low momentum) identification capability, and a better hermiticity are required.

Belle II – almost a new experiment rather than being a refurbished Belle – will adopt the following solutions. The inner layers of the vertex detector (VXD) will be replaced with a pixel detector, the main tracking device (central drift chamber, CDC) will be augmented by an inner silicon strip detector (SVD), a better charged hadron identification (PID) device will be used, the CsI(Tl) crystals of the endcap calorimeter (ECL) will be eventually replaced by pure CsI, the resistive plate chambers of the endcap muon and K_L^0 detection system (KLM) will be replaced with plastic scintillators read out by silicon photomultipliers, and all detector components will be read-out by fast electronics and an improved computing system. Figure 1 provides a comparison between Belle and Belle II. Below we have picked out two specific systems (tracking and PID), which will play a crucial role in probing NP, for further deliberation.

The VXD will have two pixel layers (PXD) at $r = 14\,\mathrm{mm}$ and $22\,\mathrm{mm}$ around a 10 mm-radius beryllium beam pipe, and four layers of double-sided silicon strip sensors (SVD) at radii of 38 mm, 80 mm, 104 mm, and 135 mm. The PXD detector will be based on DEPFET sensors whereas the SVD will employ a novel chip-on-sensor readout scheme called *Origami* [8] in the outermost three layers. The latter provides a low-mass solution for the double-sided readout (the left plot in Fig. 2 shows a part of the Origami assembly exercise for the SVD). A significant improvement in the vertex resolution, by a factor of two, is expected both for low momentum particles owing to reduced multiple scattering, and for high momentum particles because the high-resolution pixel detector is closer to the IP. Another salient feature is a better K_S^0 reconstruction efficiency (about 30% more) because of a larger volume covered by the VXD system.

The PID device will comprise a time-of-propagation (TOP) counter in the central part and a ring imaging Cherenkov system with a focusing aerogel radiator (ARICH)

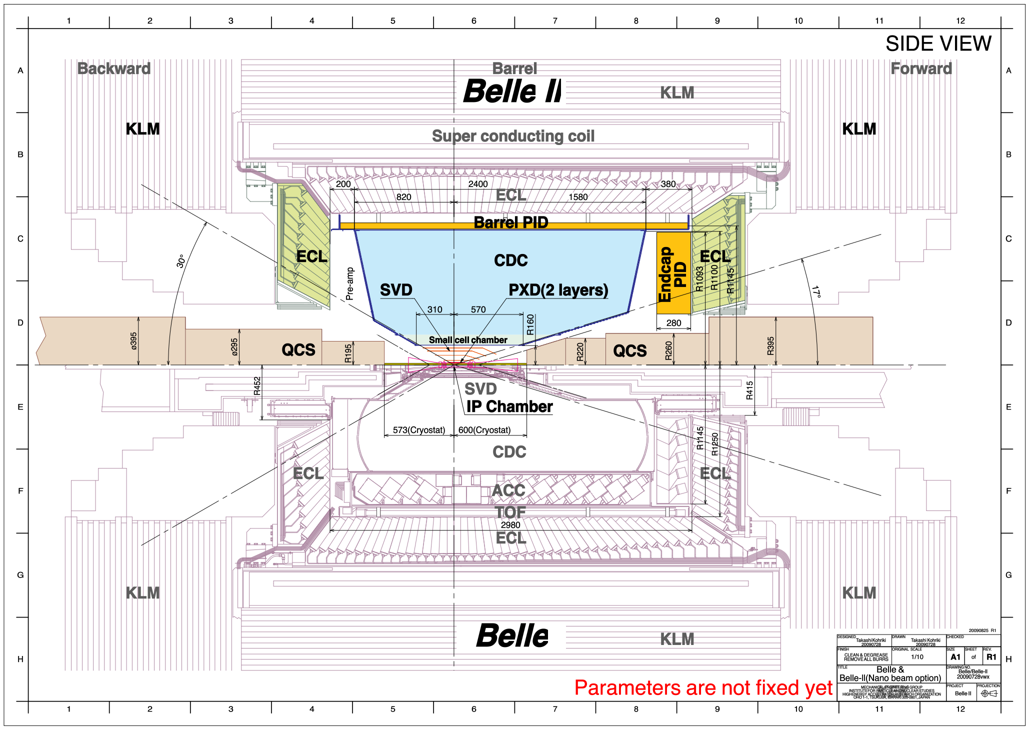

Figure 1: Belle II (top half) compared to its predecessor, Belle (bottom half).

in the forward region of the spectrometer. The TOP with quartz radiator bars yields two-dimensional information from a Cherenkov ring image based on the time of arrival and impact position of Cherenkov photons. At a given momentum, the slower kaon (refer to the right plot in Fig. 2) emits Cherenkov photons at smaller angles than the faster pion; as a result, the former photons also propagate slower along the quartz bar. Both the barrel and endcap PID systems are expected to considerably improve the hadron identification efficiency compared to Belle. For instance, the ARICH alone will provide a 4σ K–π separation up to the kinematic limits while the TOP counter can identify kaons with an efficiency exceeding 90% at a few percent pion misidentification probability.

5 Current Status and Schedule

The SuperKEKB project received initial construction funding in 2010 for the positron damping ring, and a sizable fraction of funds (exceeding 100M US$) under the Japanese 'Very Advanced Research Support Program' during the period 2010-2012 to upgrade the main rings. KEK hopes to obtain additional funding to complete the construction as per schedule, *i.e.*, start the SuperKEKB commissioning in early 2015 and begin

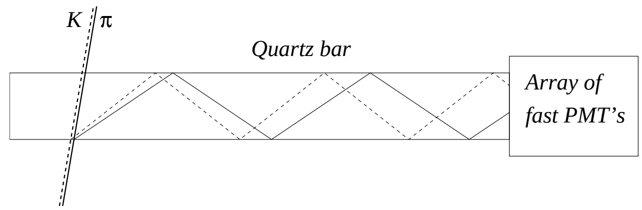

Figure 2: (left) A part of the Origami assembly exercise for the SVD, and (right) the principle of operation of the TOP counter.

the data taking in late 2016. The commissioning itself will take place in three phases: a) without final quads and Belle II detector, b) with final quads and Belle II but no VXD, and c) with QCS and full detector. It is expected that by 2019, the first $5\,\mathrm{ab}^{-1}$ of data will be recorded by Belle II while the full data sample of $50\,\mathrm{ab}^{-1}$ will be reached in 2022-2023.

6 Conclusions and Future Prospect

Time and again, e^+e^- B factories have proven to be an excellent tool for flavor physics producing a wealth of physics results; the most celebrated one being the confirmation of the Kobayashi-Maskawa mechanism [9] for *CP* violation in the SM. The ongoing upgrade of the KEKB accelerator complex to SuperKEKB that plans to accumulate 50 times more data will take this legacy forward by providing a suitable probe for NP. Based on a complementary approach to the energy-frontier experiments at LHC, Belle II will focus on the study of rare decays of beauty and charm hadrons as well as tau leptons. Particularly, a prolific charm physics program will be a key componentof the pursuit of NP at Belle-II; it includes an improved sensitivity to charm mixing and *CP* violation, and search for rare or forbidden charm decays.

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