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Present and future CKM studies from B physics at e^+e^- colliders

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I will review the main motivations for pursuing the study of B physics at e^+e^- colliders, with a view towards improving the precision of observables that are sensitive to the elements of the CKM matrix. After briefly presenting the Belle II experiment at the SuperKEKB collider, I will focus on the experimental techniques and precision goals for the *sides* and *angles* of the CKM Unitarity Triangle.

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1. Introduction

The past two decades have seen an impressive progress in flavor physics, which saw the spectacular confirmation of the Cabibbo-Kobayashi-Maskawa (CKM) paradigm [1], where the single nontrivial complex phase in the 3×3 quark mixing matrix is responsible for all the CP violating phenomena observed in the hadronic sector of the standard model.

The 2000-2010 decade was dominated by the B-factory experiments BaBar and Belle [2], operating at the high luminosity asymmetric-energy e^+e^- colliders PEP-II and KEKB, respectively. The experiments integrated a combined data set of ~ 1.5 ab^{-1}, mostly taken at a center of mass energy corresponding to the mass of the $\Upsilon(4S)$ resonance, which allowed them to attain milestone achievements, including the discovery of CP violation in B decays.

With the conclusion of data taking for the first generation of B factories, the scene was occupied by the LHCb experiment [3] which, taking advantage of the large cross-section for the production of b-hadrons of the LHC proton-proton collider, was able to quickly match and surpass the sensitivity achieved by the B factories in many key observables related to the CKM matrix.

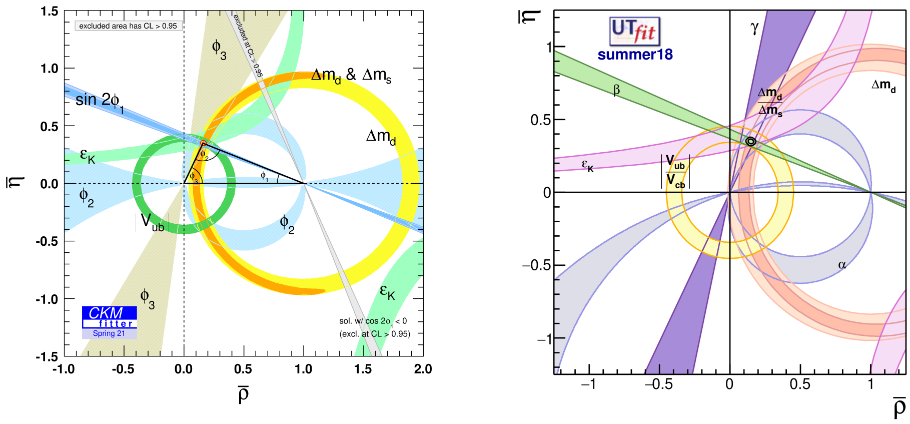

Figure 1: State of the art of the fit of the apex of the CKM Unitarity Triangle, from the CKMfitter [4] (left) and UTfit [5] (right) Collaborations.

Despite the high level of precision that has been currently reached in the standard model fit of the CKM Unitarity Triangle (UT) (see Fig. 1), and the fact that the LHCb experiment will keep improving their determinations of CKM related quantities to a level that will be unreachable to experiments operating at e^+e^- colliders in the foreseeable future, there are strong motivations to extend the program of the first generation of B factories, which rely on the better sensitivity of this type of experiments to final states:

- containing photons, particles decaying to photons (π^0's, $\eta^{(\prime)}$'s, ...) or other neutral particles (K^0_L's, n's, $\overline{n}$'s);
- containing one or more neutrinos;
- affected by *difficult* backgrounds, for which the precise knowledge of the kinematics of the initial state is one of the few (if not the only) tools available to the analysts to control them.

These reasons, in conjunction with the existence of other physics cases not immediately connected with the CKM matrix, led to the construction of the Belle II experiment at the SuperKEKB collider. A complete description of the detector, that will be only sketched in the next section, along with the main physics motivations and physics reach of the experiment, can be found in [6].

2. The Belle II Experiment at the SuperKEKB collider

Significant progress, with respect to the BaBar and Belle experiments, can be achieved only with a large increase in the size of the data set. The SuperKEKB collider [7] is located at the KEK laboratory in Tsukuba, Japan, and re-utilizes most of the infrastructure of KEKB, its predecessor (see Fig. 2). It is an asymmetric energy e^+ (4.0 GeV) e^- (7.0 GeV) collider, designed with the goal of collecting an integrated luminosity of 50 ab^{-1}, a factor $\sim$ 50 larger than the data set collected by Belle. The target instantaneous luminosity is $\sim 6 \times 10^{35}$ cm^{-2} s^{-1} (a factor $\sim$ 30 better than KEKB), mostly thanks to a strong reduction of the transverse size of the colliding electron and positron bunches ($\sim$ 10 μm in the horizontal direction, $\sim$ 50 nm in vertical) and a moderate ($\sim$ 50%) increase in the circulating currents.

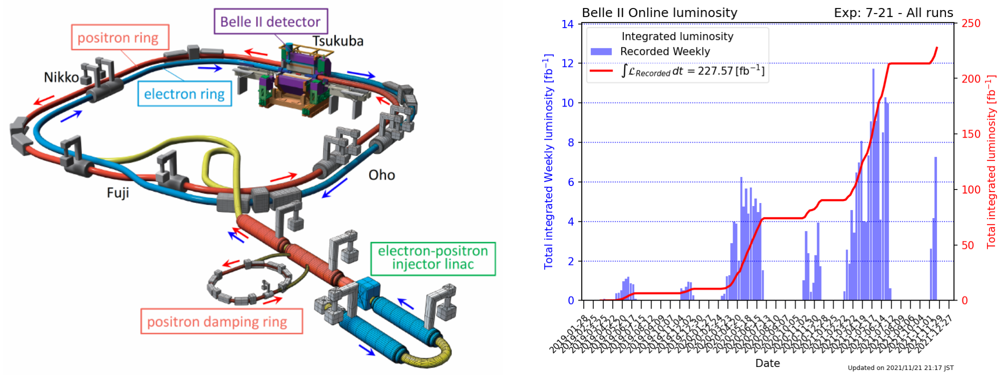

Figure 2: Left: schematic view of the SuperKEKB collider [7]. Right: progress of data taking until the start of the CKM2021 Workshop.

Figure 2 shows also the progress of data taking at SuperKEKB: after a brief commissioning run in 2018, data taking with the complete detector began in Spring 2019. At the time of delivering this presentation, Belle II integrated $\sim$ 228 fb^{-1}; while this is only about one half of the data set of BaBar, and one quarter of Belle's, the record instantaneous luminosity has been 3.12×10^{34} cm^{-2} s^{-1}, a factor 3 and 1.5 higher, respectively, of the records achieved by the PEP-II and KEKB colliders.

The Belle II detector (Fig. 3) re-utilizes the iron structure, superconducting solenoid, and electromagnetic calorimeter crystals of the Belle detector. In brief, the improvements of Belle II over the previous detector consist in a bigger silicon vertex tracker, combining both pixel (for the first two layers) and strip (for the outer four) sensors, with better acceptance for the reconstruction of K_S^0 mesons, and better impact parameter resolution, also thanks to the smaller distance (1.5 cm) of the innermost layer to the interaction point. The tracking system is completed by a large drift chamber,

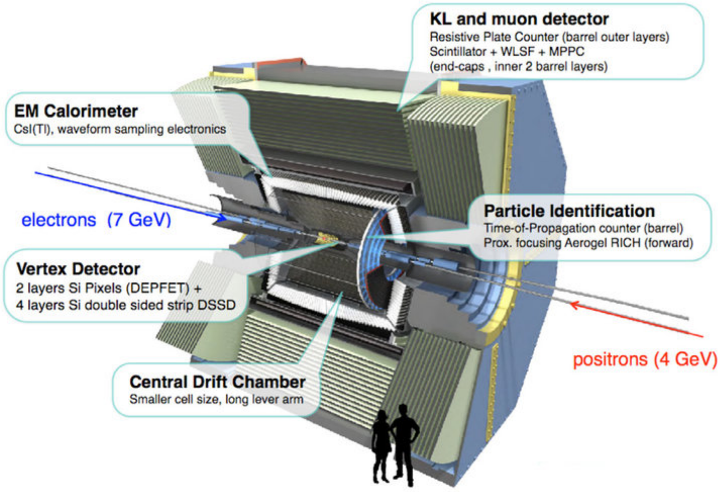

Figure 3: Cartoon of the Belle II detector.

which takes advantage of the thinner PID detectors, to increase its lever arm and thus momentum resolution. Outside the tracking volume, two detectors are devoted to particle identification, in particular to the separation of charged pions and kaons. In the barrel region, this is achieved by a detector that measures the time of arrival of the Cherenkov photons emitted by charged particles while traversing quartz bars; in the forward endcap region, a focusing ring imaging Cherenkov detector completes the PID system. The electromagnetic calorimeter has been upgraded with new waveform sampling electronics, while the return yoke of the magnetic field is instrumented with resistive plate chambers and scintillators for the detection of muons and neutral hadrons.

Overall, a re-designed software infrastructure [8], which makes broader use of machine learning, helps improving the reconstruction efficiencies and contrast the degradation caused by the severe accelerator related background conditions that Belle II has to cope with.

3. The UT sides

Two sides of the UT are determined by experimental measurements (the length of the third is 1 by construction). They are typically referred to as:

$$R_t = \left| \frac{V_{\rm td} V_{\rm tb}^*}{V_{\rm cd} V_{\rm cb}^*} \right| \qquad \text{and} \qquad R_u = \left| \frac{V_{\rm ud} V_{\rm ub}^*}{V_{\rm cd} V_{\rm cb}^*} \right| . \tag{1}$$

R_t is determined by the measurement of the oscillation frequencies $\Delta m_{d,s}$ of the B_d and B_s mesons, using crucial input from Lattice QCD. Currently, the uncertainty from the theory is comparable to the experimental one, and the precision is dominated by the LHCb experiment. Belle II will not be able to measure the B_s oscillation frequency, and will not match the precision of the Δm_d measurement of LHCb in the foreseeable future.

On the other hand, the prospects for R_u are much more promising for Belle II. The determination of this side is dominated by the $|V_{\rm ub}|/|V_{\rm cb}|$ ratio, which is derived from measurements of branching ratios of $b \to u\ell\nu$ and $b \to c\ell\nu$ transitions. The great advantage of the B-factory experiments consists in the wide spectrum of *inclusive* and *exclusive* measurements (for which there is a long standing tension in the determinations of both $|V_{\rm ub}|$ and $|V_{\rm cb}|$, see [10]). Particularly important is the possibility of fully or partially reconstructing one of the two B mesons in the event (the so called Full Event Interpretation or FEI technique, see e.g. [9]), so that all the remaining particles in the event can be associated to the decay of the B meson under study. This technique is very powerful for final states containing one or more neutrinos: the loss of efficiency due to the reconstruction of the other meson in the event is more than compensated by the better control over difficult backgrounds. In the following, brief mentions of recent Belle (II) analyses related to measurements of $|V_{\rm cb}|$ and $|V_{\rm ub}|$ will be made.

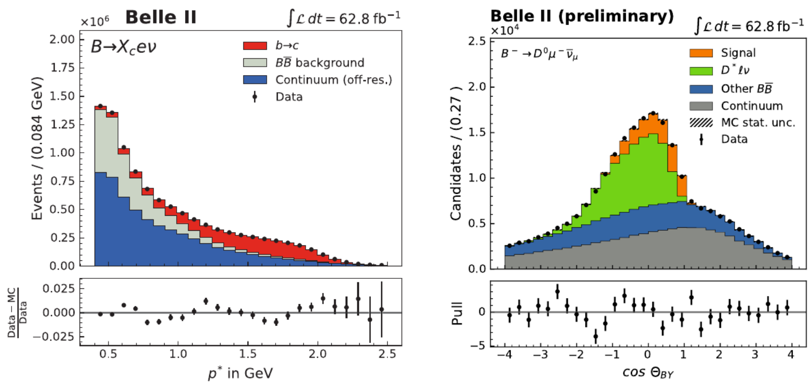

Figure 4: Left plot: CM momentum distribution of the candidates of the inclusive $B \to X_c e\nu$ analysis [11]. Right: distribution of $\cos\theta_{BY}$ for the measurement of the branching ratio of $B^- \to D^0\mu\nu$ [12].

The Belle II experiment recently produced an inclusive measurement of $|V_{\rm cb}|$ from $B \to X_c\ell\nu$ ($\ell = e, \mu$) events [11]. Candidate electrons and muons are selected on a wide range of momentum, measured in the center of mass (CM) system: $0.4 < p^*_\ell < 2.5$ GeV/c. The signal (shown in red in Fig. 4, left plot) is extracted from a binned fit of the p^*_ℓ distributions, where the background from other B decays is modeled from the simulation, and the $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$ continuum is taken from the data collected slightly below the $\Upsilon(4S)$ resonance. The e and μ samples are fit separately, in order to check for any lepton universality violation. The measured $|V_{\rm cb}|$ is well consistent with the world average [10], although the results are limited by systematic uncertainties that will be reduced in future versions of the analysis.

Analogous results have been obtained in the first Belle II measurements of the branching ratios of $B^- \to D^0\ell^-\nu$, $D^0 \to K^-\pi^+$ [12]. The difficulty of this measurement consists in correctly modeling and estimating the contribution of the more frequent $B \to D^*\ell\nu$ decays, in which the low momentum pion from the D^* decay is not reconstructed. The signal is extracted from a binned fit to the distribution of the variable $\cos\theta_{BY}$, which is widely used in exclusive semileptonic analyses and represents the cosine of the angle (measured in the CM system) between the flight direction of the B meson under study and the *visible* Y system ($D^0\ell^-$ in this case). No deviations from the lepton flavor universality are observed within the precision of the analysis.

Finally, both Belle and Belle II performed a measurement of the q^2 moments (where q^2 is the square of the four-momentum transfer) in $B \to X_c \ell \nu$ transitions [13], [14]. The analyses are performed on the recoil of fully reconstructed B mesons and the results are going to serve as input for an extraction of $|V_{\rm cb}|$ using a novel technique proposed in [15].

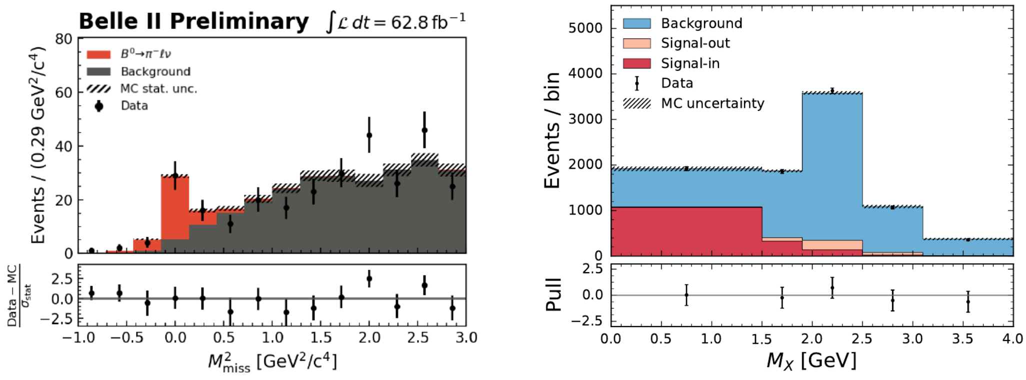

Figure 5: Left plot: missing M^2 distribution of the $B^0 \to \pi^- \ell^+ \nu$ analysis utilizing the FEI technique [16]. Right: M_X distribution of Belle's inclusive $|V_{\rm ub}|$ analysis [17].

The measurement of $|V_{\rm ub}|$ is pursued using a variety of techniques. In [16], Belle II reconstructed the *golden channels* for the exclusive determination: $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \pi^0 \ell^+ \nu$, and further obtained a modest signal excess, consistent with the expectations, for the more difficult channels $B^0 \to \rho^- \ell^+ \nu$ and $B^+ \to \rho^0 \ell^+ \nu$. These measurements were performed utilizing the FEI technique, in which the other B meson in the event is fully reconstructed in hadronic final states. This allows the strong reduction of the backgrounds, mostly originating from $b \to c \ell \nu$ transitions, that are two orders of magnitude more likely than the signal that is searched for. Fig. 5 shows the level of the signal to noise ratio that is achievable with this approach.

The Belle experiment recently presented an inclusive measurement of $|V_{\rm ub}|$, in which the reduction of the $B \to X_c \ell \nu$ backgrounds (X_c being any final state originating from the hadronization of the c quark) is performed through an aggressive use of multivariate classifiers that are sensitive to the topological differences with respect to the $B \to X_u \ell \nu$ signal [17]. In this way, the signal to background ratio is amplified to ~ 1 (see Fig. 5). Several alternative approaches are utilized to extract the signal yield, considering a combination of the variables M_X (the mass of the hadronic system), q^2 (square of the four-momentum transfer), and E_ℓ (energy of the lepton candidate). All determinations lead to consistent values of $|V_{\rm ub}|$.

Belle performed also a measurement [18] of the branching ratios of $B^+ \to \eta \ell^+ \nu$ and $B \to \eta' \ell \nu$. While these channels are not of the highest importance for the determination of $|V_{\rm ub}|$, this kind of measurements are still very useful to improve our knowledge on the hadronization processes and reduce the uncertainties in the measurements for which these decays constitute a background. In this case, no reconstruction of the other B meson in the event is performed, so that the reconstruction efficiency is maximized at the cost of higher backgrounds. In order to reduce any model dependence, no restrictions to the investigated q^2 range are applied. The results are compatible with earlier results by Belle (obtained on the recoil of fully reconstructed B mesons) and BaBar, and are limited by statistical uncertainties.

The precision on the UT side R_u is currently $\sim 5\%$, the uncertainty being dominated by the $|V_{\mathrm{ub}}|$ determination. Thanks to the expected progress of Lattice QCD predictions, it is foreseen that the uncertainty on $|V_{\mathrm{ub}}|$ with the full Belle II data set (50 ab^{-1}) will be $\sim 1.5\%$, and the most precise determinations will be provided by the exclusive measurements [6]. The final precision on R_u at the end of Belle II data taking will be around 2%.

4. The UT angles

Belle II will be excellently placed to measure all three angles of the CKM UT triangle, taking advantage of many B decay channels.

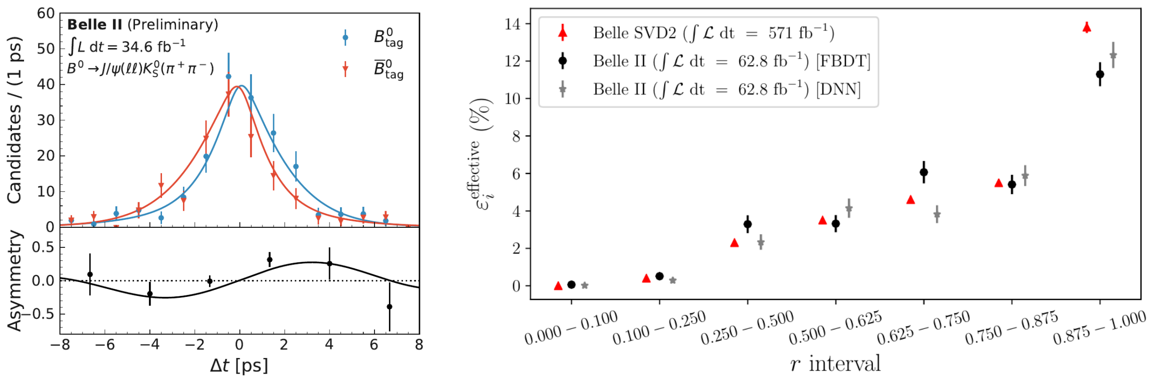

Figure 6: Left plot: first Belle II measurement of the time dependent CP violation on $B \to J/\psi K^0_S$ [19]. Right: comparison between the performance of the Belle II flavor tagger (gray and black points) and Belle's (red), from [21].

The determination of the angle ϕ_1 (β) is dominated by the measurement of the time dependent CP violation in the *golden mode* $B^0 \to J/\psi K^0$. Belle II performed a very preliminary test of the main ingredients of the analysis by presenting a plot of the proper decay time difference Δt separately for B^0 and $\overline{B}^0$ tagged events [19], see Fig. 6 (left). In fact, one of the crucial ingredients for all time dependent analysis is the ability to determine (*tag*) the flavor of the meson that is not reconstructed in the CP eigenstate. This task is performed by the *flavor tagger*, a tool that analyzes all the particles not associated to the reconstructed B and computes the probability that they originated from a B^0 or a $\overline{B}^0$. Compared to its predecessor, the complexity of the Belle II flavor tagger has been significantly increased, with the use of two successive layers of multivariate discriminators [21]. Figure 6 (right) compares the performance of the Belle and Belle II flavor taggers as a function of r, a variable expressing the probability that the identification of the algorithm is correct. The performance of the two taggers is roughly the same, despite the fact that Belle II has not yet reached its expected PID efficiencies.

The measurement of $\sin 2\phi_1$ ($\sin 2\beta$) will soon be limited by systematics, the most important of which are those arising from the alignment of the vertex detector, and those related to the effects of Doubly Cabibbo Suppressed decays on the tag side [6]; overall, it is expected a factor ~ 4 improvement over the current precision.

On the other hand, measurements of channels that are sensitive to the same CKM angle, but dominantly proceed through *penguin* loop amplitudes, will not be limited by systematics until the end of data taking. These measurements are sensitive probes to physics beyond the standard model: a significant shift of the measured value of the time dependent CP asymmetry from what is determined in $B^0 \to J/\psi K^0$, would be a clear sign of new physics. For many of these channels Belle II will have better sensitivity, compared to LHCb. For the most important channel, $B^0 \to \eta' K^0_S$, Belle II recently performed a measurement [22] of its branching fraction, see Fig. 7 (left).

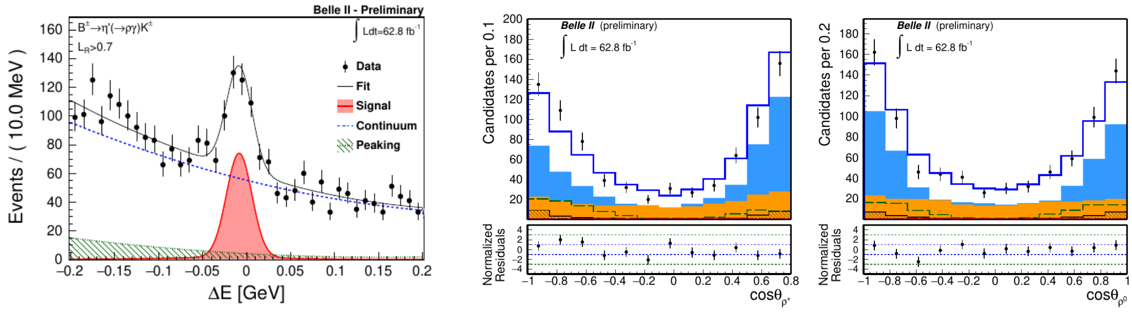

Figure 7: Left plot: ΔE distribution for one of the $B^0 \to \eta' K^0_S$ reconstructed in [22]. Center and left plots: distributions of the two helicity angles reconstructed in the $B^+ \to \rho^+\rho^-$ analysis [24].

The angle ϕ_2 (α) can be determined through an isospin analysis of the $B \to \pi\pi$ or $B \to \rho\rho$ decays, or through a Dalitz plot analysis of $B^0 \to \rho\pi$. On this angle Belle II will have a decisive advantage over LHCb, since π^0's appear in many of the final states that need to be considered. Belle II performed already a number of measurements on B mesons decaying to charmless two-body final states [23]. While these measurements are not yet competitive with the world averages, they confirm the expected sensitivity of the experiment, and the ability to control detector related effects in the measurement of direct CP asymmetries. The analysis of $B^+ \to \rho^+\rho^0$ [24] is an example of a complex analysis that will be needed for the extraction of ϕ_2: in order to obtain an unbiased result of the branching ratios and CP asymmetries, the longitudinal polarization fraction f_L needs to be measured from the distributions of the helicity angles, see Fig. 7 (center and right).

It should also be briefly mentioned that Belle II will be in a position of measuring the time dependent CP asymmetry of $B^0 \to \pi^0\pi^0$, by exploiting the $\pi^0 \to e^+e^-\gamma$ Dalitz decays and the photon conversions in the detector material in proximity of the interaction region. With the full data set, Belle II aims at reconstructing ~ 250 signal decays, enough to obtain a nontrivial measurement of the time dependent CP violation that would reduce the number of ambiguities that are inherent to the isospin analysis.

The CKM angle ϕ_3 (γ) is the one in which Belle II will suffer the most the competition posed by LHCb, which takes advantage of the very large cross section for the production of b hadrons, and can also perform time dependent CP violation measurements of the B_s system.

The highlight from Belle II is the first measurement that combines the Belle and Belle II data sets [25], to obtain a new determination of ϕ_3 utilizing the BPGGSZ method (see e.g. [26]). The analysis exploits the interference of the $B^- \to (D^0/\overline{D}^0)h^-$ decays, where the $D^0/\overline{D}^0$ decay to $K^0_S\pi^+\pi^-$ or $K^0_S K^+K^-$. A binned Dalitz plot analysis is performed, in order to avoid the large

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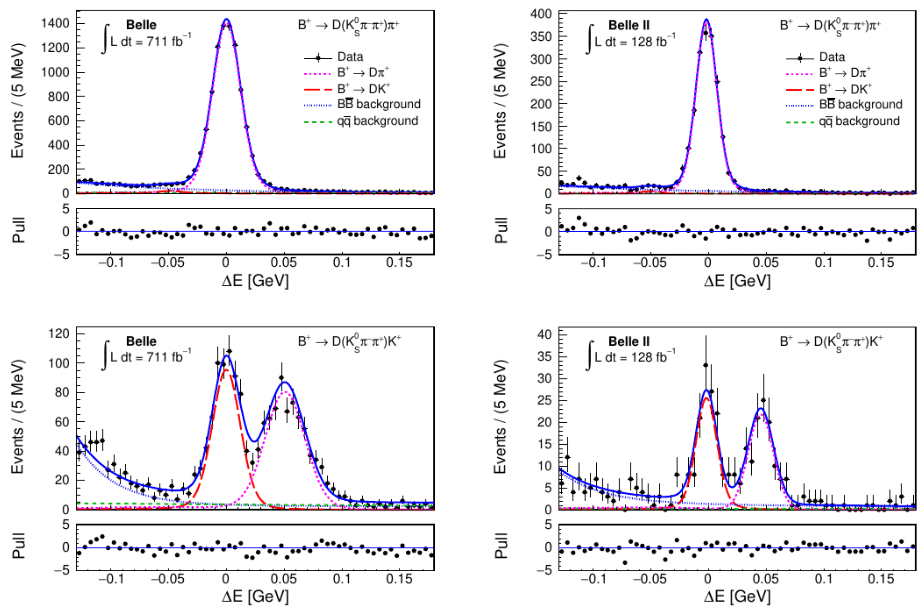

Figure 8: ΔE distributions for the $B^+ \to D^0 h^+$, $D^0 \to K_S^0 \pi^+ \pi^-$ analysis [25]. The left plots have been obtained on the Belle data set, those on the right on Belle II data; the PID selection enhances the $B^+ \to D^0 \pi^+$ component on the top plots, while the reverse selection is applied on the bottom plots, to enhance $B^+ \to D^0 K^+$.

systematic uncertainties related to the choice of a model for the D^0 decay, and information on the D^0 decay strong phase is taken from the CLEO and BESIII experiments.

From the technical point of view, the Belle data have been converted to the format used by Belle II, so that the same software tools can be utilized. Several improvements have been added to the analysis chain, including a high performance multivariate discriminator for the reduction of the continuum background. Figure 8 shows the level of purity and separation between the $D\pi$ and the DK components that are taken into consideration. Compared to the previous analysis on the full Belle data set, the combined analysis, with an increase in the integrated luminosity by only $\sim 18\%$, achieves a reduction on the uncertainty on the ϕ_3 angle from 15° to 11°.

The precision on the angles ϕ_1 (β), ϕ_2 (α), and ϕ_3 (γ) is currently of $\sim 0.7°$, $\sim 4.5°$, and $\sim 3.5°$, respectively. Thanks to the contributions from Belle II alone with its final data set, the precision on the angles is expected to come down to $\sim 0.2°$, $\sim 0.8°$, and $\sim 1.0°$.

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