# History of Belle and some of its lesser known highlights

Stephen Lars Olsen[1]
*Center for Underground Physics, Institute for Basic Science*
*Yuseong-gu, Daejeon Korea*

I report on the early history of Belle, which was almost entirely focused on testing the Kobayashi Maskawa mechanism for $CP$ violation that predicted large matter-antimatter asymmetries in certain $B$ meson decay modes. Results reported by both BaBar and Belle in the summer of 2001 verified the Kobayashi Maskawa idea and led to their Nobel prizes in 2008. In addition to studies of $CP$ violation, Belle (and BaBar) reported a large number of important results on a wide variety of other subjects, many of which that had nothing to do with $B$ mesons. In this talk I cover three (of many) subjects where Belle measurements have had a significant impact on specific sub-fields of hadron physics but are not generally well know. These include: the discovery of an anomalously large cross sections for double charmonium production in continuum $e^+e^-$ annihilation; sensitive probes of the structure of the low-mass scalar mesons; and first measurements of the Collins spin fragmentation function.

arXiv:1601.01061v1 [hep-ex] 6 Jan 2016

## 1 Introduction

The organizers of this meeting asked me to give a talk with the title "Best Belle results and history of Belle collaboration." A talk about the history of Belle is no problem. The intial motivation of the Belle/KEKB project and essentially all of its early work was the study of $CP$-violation in the $B$-meson sector, and the work done in this area certainly ranks among Belle's "best results." However, while the planing and first few year's of operation were almost completely focused on $CP$-violation measurements, the collaboration subsequently branched out and studied a wide range of physics subjects that included many unexpected discoveries. To the people involved, each of these rank among the "best Belle results," and I could not argue with them. So instead of even attempting to identify "best results," I decided to confine myself to reporting on Belle's early work on $CP$ violation, which covers the early "history of the Belle collaboration," and then discuss a few other results that seem to be not very widely known but have had a huge impact on the specialized areas of physics that they address. First, some history and Belle's early $CPV$ measurements:

## 2 Belle and CP violation

The Belle experiment traces its roots to the 1964 discovery that the long-lived neutral kaon ($K_L$) is not a $CP$ eigenstate, as evidenced by a small but non-zero branching fraction to $\pi^+\pi^-$: $\mathcal{B}(K_L \to \pi^+\pi^-) \simeq 2 \times 10^{-3}$, which demonstrated that $CP$ is violated, probably by the weak interactions [1]. This inspired Sakharov's classic 1967 paper [2] that pointed out that $CP$-violation ($CPV$) is an essential ingredient for explaining the baryon asymmetry of the universe; *i.e.*, how a matter-antimatter-symmetric condition that prevailed right after the Big Bang, evolved into today's matter-dominated universe (see Fig. 1).

[1]solsensnu@gmail.com

Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

*Out of S. Okubo's effect*
*At high temperature*
*A fur coat is sewed for the Universe*
*Shaped for its crooked figure.*

**НАРУШЕНИЕ *CP*-ИНВАРИАНТНОСТИ, *C*-АСИММЕТРИЯ И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ**

*А.Д.Сахаров* Pis'ma Zh. Eksp. Teor. Fis. **5**, 32–35 (1967)
[JETP Lett **5**, 24–27 (1967). Also S7, pp. 85–88]

**Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует**

Figure 1: When Sakharov completed his famous 1967 paper on "Violation of $CP$ invariance, $C$ asymmetry, and baryon asymmetry of the universe," he gave Lev Okun a preprint with a small poem handwritten on it that identifies $CPV$ as "S. Okubo's effect." This refers to a 1958 paper by Okubo that first pointed out that while $CPT$ invariance requires particle and antiparticle lifetimes to be equal, $CP$ violations would allow partial lifetimes to be different [3].

Incorporating $CPV$ into the Standard Model (SM) while preserving $CPT$ was not very easy. Wolfenstein proposed a mechanism that expanded the SM by adding a new, $\Delta S = 2$ "superweak" interaction that produced a $CP$-violating non-diagonal contribution to the neutral kaon mass matrix and nothing else [4]. However, the superweak interaction was ruled out by the observation of direct $CPV$ decays of neutral kaons by the NA31 experiment at CERN [5] and, later, the KTeV experiment at Fermilab [6].

To incorporate $CPV$ into the SM proper, one needs an amplitude that has a complex phase angle $\phi_{CP}$ that has opposite signs for particle and antiparticle processes. Since measureable processes are proportional to the absolute value squared of the amplitude, this $CPV$ phase is unmeasureable unless it interferes with another process that has a non-zero strong, or common phase $\phi_0$, that has the same sign for particle and antiparticle processes [7]. This is illustrated in Fig. 2a, where a $CP$ violating process $X^0 \to \pi^+\pi^-$ ($\overline{X}^0 \to \pi^+\pi^-$) has a complex amplitude $A = |A|\exp(i\phi_{CP})$ ($\overline{A} = |A|\exp(-i\phi_{CP})$). Differences in the decay rates can be be measured if the $CP$-violating amplitude interferes with a $CP$-conserving amplitude for the same process $C = |C|\exp(i\phi_0) = \overline{C}$. In that case the $X^0 \to \pi^+\pi^-$ and $\overline{X}^0 \to \pi^+\pi^-$ rates differ by a term proportional to $2|A||C|\sin\phi_0\sin\phi_{CP}$; note that this interference term is zero if $\phi_0 = 0$.

In 1972, Kobayashi and Maskawa (KM) showed that a non-trivial $CP$-violating phase could be introduced into the weak interaction quark-flavor mixing matrix, but only if there were at least three generations of quark doublets, *i.e.*, at least six quark flavors (see Fig. 2b) [8]. This was remarkable because at that time, only three quark flavors had been established. In a 1980 paper, Carter and Sanda suggested that if the $b$-quark-related flavor mixing parameters were such that $B^0 \leftrightarrow \overline{B}^0$ was substantial and the $B$-meson lifetime was relatively long, large $CP$ violations might be observable in neutral $B$ meson decays and provide conclusive

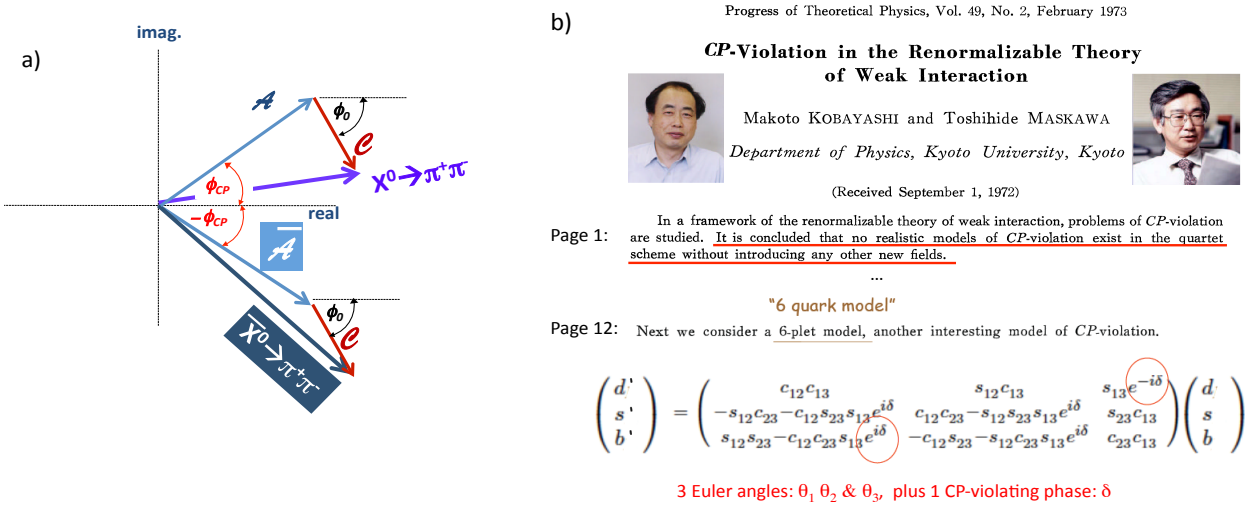


Figure 2: **a)** The amplitude $\mathcal{A}$ represents a $CP$-violating contribution to a hypothetical process $X^0 \to \pi^+$. Differences in the $X^0 \to \pi^+\pi^-$ and $\overline{X}^0 \to \pi^+\pi^-$ decay rates can only be observed if it interferes with a $CP$-conserving process (amplitude = $\mathcal{C}$) that has a non-zero common phase $\phi_0$. **b)** Excerpts from page 1 (above) and page 12 (below) of the classic Kobayashi-Maskawa paper [8].

tests of the KM idea [9]. However, the tests that Carter and Sanda proposed would require data samples the contained several hundreds of exclusive $B^0$ decays to $CP$ eigenstates, such as $B^0 \to K_S J/\psi$ and $B^0 \to K_S \psi'$. In 1983, CLEO reported the world's first sample of exclusive $B$-meson decays shown in Fig. 3a, where there are 18 events in the $B$-meson mass peak, divided equally between neutral and charged $B$-mesons with a background that is estimated to be between 4 and 7 events [10]. No exclusive decays to a $CP$ eigenstate were observed. Thus, in the early1980's, when the state-of-the-art $e^+e^-$ collider luminosity was $\sim 10^{31}\text{cm}^{-2}\text{s}^{-1}$, the possibility for checking the KM idea seemed hopeless, except for a few super-optimists who could foresee luminosities greater than $10^{33}\text{cm}^{-2}\text{s}^{-1}$ by the end of the century.

For the 1973 KM idea to be relevant and testable, there had to be: six quarks instead of three; a relatively long $B$-meson lifetime and sizable $B^0 \leftrightarrow \overline{B}^0$ mixing (corresponding to $|V_{cu}| < |V_{cb}| < 0.1$); and a thousand-fold or more combined improvement in $e^+e^-$ luminosity and detector performance. In 1974, the fourth quark, the $c$-quark, was discovered at Brookhaven [12] and SLAC [13] and the fifth quark, the $b$-quark, was found in 1977 by a Fermilab experiment [14]. Then, in 1983, a long ($\tau_B \simeq 1.5$ ps) $B$-meson lifetime was measured at PEPII [15, 16] and, in 1987, a substantial signal for $B^0 \leftrightarrow \overline{B}^0$ mixing was unexpectedly discovered by the ARGUS experiment at DESY [17]. Taken together, these results indicated that the $CKM$ mixing-angle values were favorable for experimental tests of the KM idea. (The $B^0 \leftrightarrow \overline{B}^0$ mixing frequency is now well measured to be $\omega_0 \simeq 0.5\text{ps}^{-1}$, and not much different than $1/\tau_B$.) In addition, the luminosity of $e^+e^-$ colliders kept increasing in a Moore's-law-like fashion with a doubling time of about 2.5 years (see Fig. 3b). In 2001, less than twenty years after the CLEO report of an 18 event exclusive $B$-meson decay signal with no $CP$ eigenstate modes, the Belle experiment's discovery paper on $CP$-violation in the $B$-meson system used the $\sim 700$ neutral $B$ mesons to $CP$ eigenstate decays with $CP$ eigenvalue $\xi_f = -1$ (mostly $B \to K_S J/\psi$) in the signal peak shown in Fig. 3c [11].

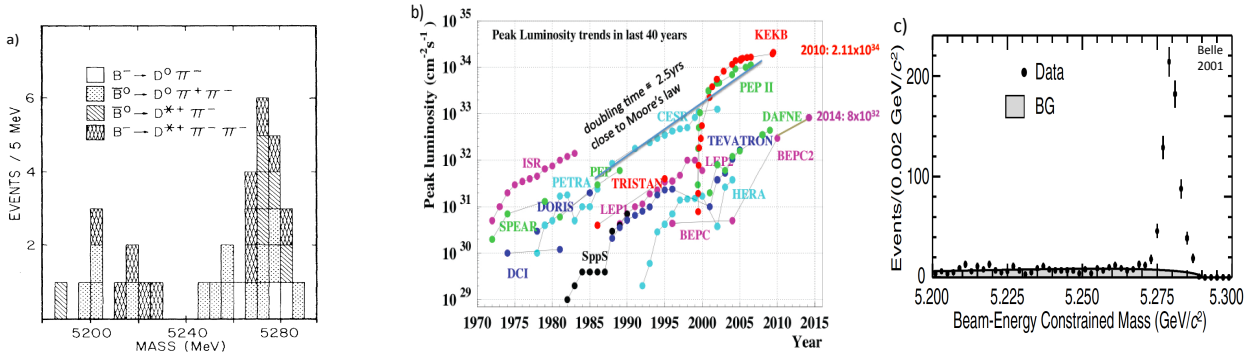


Figure 3: **a)** (Figure 2 from ref. [10].) The first reported signal for exclusive $B$-mesons decays, found by CLEO in a 40 pb$^{-1}$ data sample recorded over a three-year time period. **b)** A "Livingston plot" for $e^+e^-$ luminosities *vs.* year. **c)** (Figure 1 from ref. [11].) The 2001 $B \to K_S(c\bar{c})$, $\xi_f = -1$ $CP$ eigenstate decay signal from a 29 fb−1 Belle data sample, containing ∼700 signal events, mostly $B \to K_S J/\psi$ decays, with a 92% signal purity.

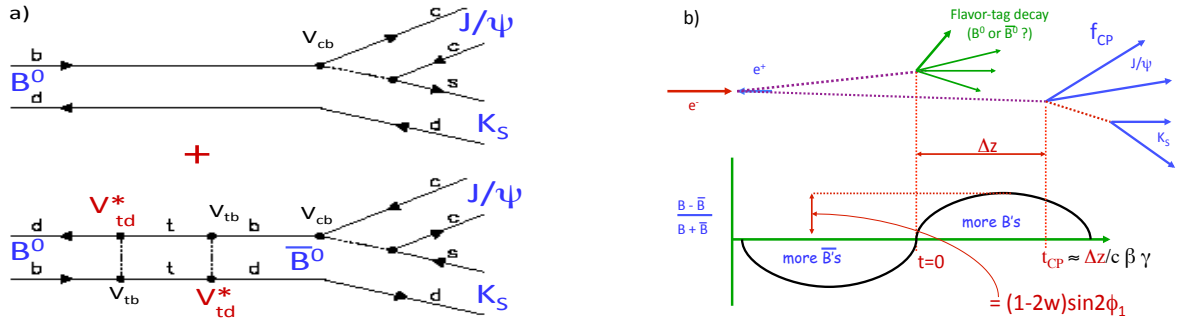


Figure 4: **a)** A $B^0$-meson can decay to a $CP$ eigenstate directly or by first mixing into a $\overline{B}^0$ that in turn decays the same $CP$ eigenstate. The interference between the two processes is $\propto V_{td}^{*2}$ (not $|V_{td}^*|^2$). **b)** A cartoon that illustrates how the $B$-factory experiments measure $\phi_1$, the $CP$-violating phase of $V_{td}^*$.

Carter and Sanda suggested that $\phi_1$, the $CPV$ phase of $V_{td}$, could be measured by the interference between the two $B^0$-meson quark-line processes shown in Fig. 4a. Here the top diagram is the direct $B^0$-meson decay to a $CP$ eigenstate (chosen here as $K_S J/\psi$ for illustration). In the lower diagram, the $B^0$ first mixes into a $\overline{B}^0$ and the $\overline{B}^0$ decays to the same $CP$ eigenstate. The amplitude for the upper diagram is proportional to $V_{cb}$, which has no $CPV$ phase; that for the lower diagram is proportional to $V_{tb}^2 V_{td}^{*2} V_{ub}$, where, in the KM formalism, only $V_{td}^*$ has a $CPV$ violating phase. Thus, the interference term is $\propto V_{td}^{*2} \propto \sin 2\phi_1$.

The way this interference is measured is illustrated in Fig. 4b. An asymmetric energy $e^+e^-$ collison produces a boosted $B^0$ and a $\overline{B}^0$ in a "entangled" $J^{PC} = 1^{--}$ quantum state. After some time, one of the $B$ meson decays to a "flavor specific" final-state, *i.e.* a final state that allows one to distinguish whether the flavor of decaying $B$ meson is a $B^0$ or a $\overline{B}^0$. At that time, which is taken as $t = 0$, the accompanying $B$ meson has to have the opposite flavor. Then this accompanying $B$ meson evolves with time, mixing as it goes along (either forward or backward in time!) into the opposite flavor with a frequency $\omega_{\rm mix}$, and eventually

decays at time $t$ into a $CP$ eigenstate. What is measured, is the asymmetry $\mathcal{A}_{CP}$ as a function of $t$, where

$$\mathcal{A}_{CP} = \frac{N_{\overline{B}^0} - N_{B^0}}{N_{\overline{B}^0} + N_{B^0}} = \xi_f (1 - 2w) \sin 2\phi_1 \sin \omega_B t, \tag{1}$$

$N_{B^0}$ ($N_{\overline{B}^0}$) is the number of times the flavor-tagged $B$ is a $B^0$ ($\overline{B}^0$), $\xi_f$ is the $CP$ eigenvalue of the state being studied (for $B \to K_S J/\psi$, $\xi_f = -1$), $w$ is the probability that the flavor-tagged $B$ meson is assigned the wrong flavor, and $t$ is inferred from $\Delta z$, the measured separation of the two $B$-meson decay vertices: $t = \Delta z/(c\gamma\beta)$. In this measurement, the required common phase that was discussed above in conjunction with Fig. 2a is provided by the mixing term $\exp(i\omega_B t)$, which changes sign at $t = 0$. Thus the time integrated asymmetry is zero and the boost ($\gamma\beta$) provided by the energy asymmetry of the beams is essential.

At the time the flavored-tagged $B$-meson decays, the accompanying $B$ meson is in a pure flavor state, and the interference (and asymmetry) is zero; as this meson propagates, its flavor mixes and, after about 3 ps, the $B^0$ and $\overline{B}^0$ amplitudes are nearly equal and the asymmetry is maximum. However, this 50:50 mixing occurs for a decay-time difference of about two $B^0$ meson lifetimes, and only ∼13% of the $B$ mesons live this long. This, and the small branching fractions for $B^0$ decays to measureable $CP$ eigenstates (typically ∼ 0.1%), explain why such a huge increase in $e^+e^-$ collider luminosity was critical for these measurements.

The $K_L J/\psi$ final state has $\xi_f = +1$ and a $CPV$ asymmetry that is opposite in sign to that for $K_S J/\psi$ final states. Thus, both BaBar and Belle instrumented their magnet return yoke to make it suitable for reconstructing $K_L J/\psi$ final states. A $K_L$ can produce a splash of energy in the instrumented return yoke, either by decaying or interacting in one of the yoke's iron plates, as shown in the top panel of Fig. 5a, that can be used to determine the $K_L$ direction. That, with the assumption of two-body decay dynamics, can be used to infer $p_B^{\rm cms}$, the $B$ meson's three-momentum in the center of mass (c.m.) system. Belle's 2001 $p_B^{\rm cms}$ distribution, shown in the lower panel of Fig. 5a, exhibits a distinct, ∼346-event signal peak for $B \to K_L J/\psi$ decays at $p_B^{\rm cms} \simeq 0.33$ GeV/$c$ (with a 61% signal purity) that were also used for $CPV$ asymmetry measurements.

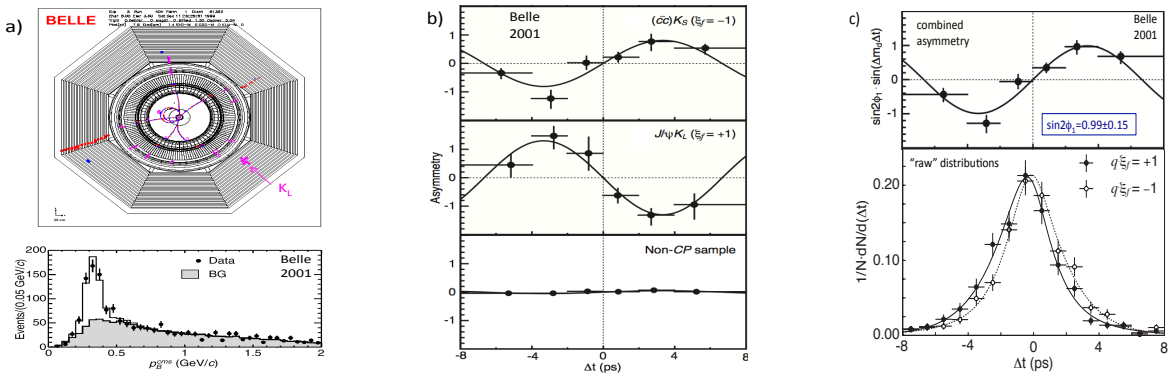


Figure 5: **a)** (top) A computer display of $B \to K_L J/\psi$ events candidate in Belle, where the $J/\psi$ decays into a $\mu^+\mu^-$ pair and the $K_L$ produces an energy cluster in the magnet's instrumented flux return. (bottom) The $p_B^{\rm cms}$ distribution for candidate $K_L J/\psi$ events. **b)** The $t$-dependent $CPV$ asymmetry for $\xi_f = -1$ (top), $\xi_f = +1$ (center) and non-$CP$ eigenstate decays (bottom). **c)** The $t$ dependence of events organized according to $q\xi_f$ values, where $q = +1$ $(-1)$ corresponds to a tagged $B^0$ ($\overline{B}^0$) (bottom). The combined $q\xi_f = -1$ minus $q\xi_f = +1$ asymmetries, together with the fit results (top).

The 2001 Belle result, $\sin 2\phi_1 = 0.99 \pm 0.15$ [11], was $6\sigma$ from zero and conclusively confirmed the KM prediction for a non-zero $CPV$ complex phase in the $V_{td}$ element of the quark-flavor mixing matrix. The

opposite asymmetries for $\xi_f = +1$ and $-1$ decay samples, shown in the center and top panels of Fig. 5b, respectively, provided a check on possible systematic effects on the $\sin 2\phi_1$ measurements. Another validity check is illustrated in the lower panel of Fig. 5b, which shows the results of the same analysis applied to non-$CP$ eigenstate decay modes, where no asymmetry is expected; the fit result for these events is $0.05 \pm 0.04$. At the same time, the BaBar experiment reported a $4\sigma$ non-zero value: $\sin 2\phi_1 = 0.59 \pm 0.15$ [18].

The combined average of the 2001 BaBar and Belle $\phi_1$ results is compared with constraints from other measurements in Fig. 6a [19], where good agreement with expectations is evident. Eventually BaBar and Belle each accumulated a huge amount of additional data and significantly improved the precision on their $\phi_1$ measurements and other quantities that now constrain the 2015 allowed region of the same plane [20] as shown in Fig. 6b, which demonstrates that the consistency of the CKM picture is amazingly good. This success resulted in Kobayahi and Maskawa sharing the 2008 Physics Nobel prize (with Yoichiro Nambu).

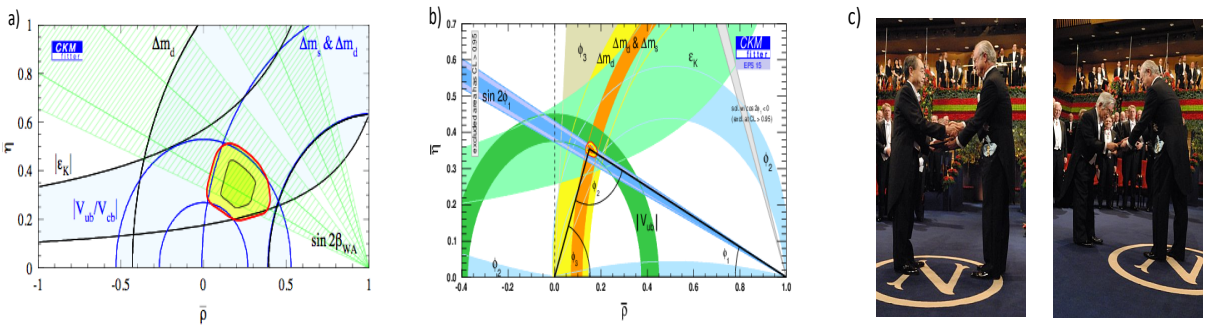


Figure 6: **a)** The unitarity triangle plot from the CKM-fitter group with the average of the 2001 BaBar and Belle $\sin 2\phi_1$ results (labeled as $\sin 2\beta_{WA}$). Here $\overline{\rho}$ and $\overline{\eta}$ are the Wolfenstein $CPV$ parameters [21]. **b)** The 2015 version of the CKM-fitter group's unitary triangle plot. **c)** (left) Kobayashi and (right) Maskawa meeting the King of Sweden in Dec. 2008.

# 3 It wasn't only about CP, or even B mesons

## 3.1 Double $c\bar{c}$ production in $e^+e^-$ annihilation

One of the earliest measurements in Belle was a study of inclusive $J/\psi$ production in continuum $e^+e^-$ annihilation at c.m. energies near 10.6 GeV. Studies of $J/\psi$ production is a common activity for the early stages of an experiment because they are a prolific source of tagged muons and electrons that are useful for calibrating lepton identification systems, validating triggers and tuning up charged particle tracking algorithms. Theoretically, inclusive and exclusive $J/\psi$ production is supposed to be described accurately (and rigorously) by non-relativistic quantum chromodynamics, NRQCD [22].

In 2002, Belle reported a total cross section for the inclusive, continuum annihilation process $e^+e^- \to J/\psi + X$ of $1.47 \pm 0.16$ pb [23]. This was in reasonable agreement with NRQCD [24], which had predicted a $\sim$1.1 pb cross section that is $\sim(1/3)^{\rm rd}$ due to $e^+e^- \to gg(c\bar{c})_1$ and $\sim(2/3)^{\rm rds}$ due to $e^+e^- \to g(c\bar{c})_8$, where $(c\bar{c})_1$ and $(c\bar{c})_8$ refer to color-singlet and color-octet charmed-quark anticharmed-quark configurations, respectively.

However, Belle's measured $J/\psi$ momentum distribution, shown in Fig. 7a, has no significant event signal in the highest kinematically allowed momentum region, 4.5-4.84 GeV/$c$, where the dominant color-octet contribution was expected to be strongest. A MC estimate for the number of expected signal events in this

high momentum region using a special NRQCD-inspired event generator incorporated into PYTHIA [25] predicted a ∼300 event signal in the two highest bins of Fig. 7a, where no signal is seen.

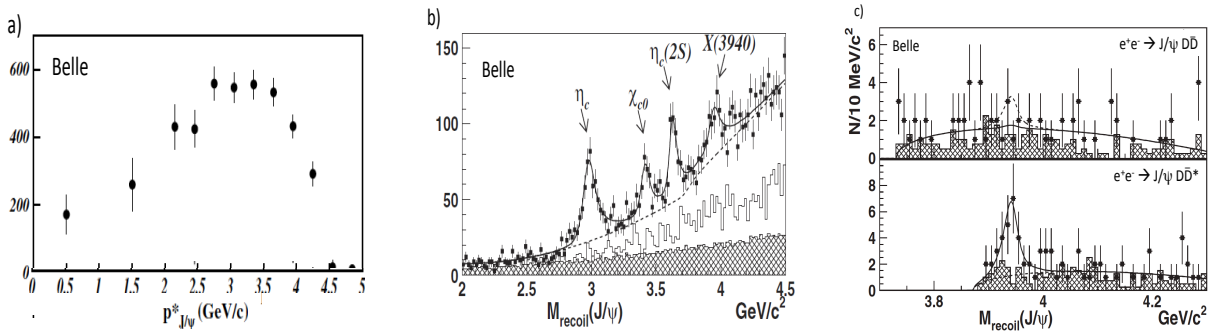


Figure 7: **a)** The $J/\psi$ c.m. three-momentum distribution for inclusive $e^+e^- \to J/\psi X$ reactions near $\sqrt{s} = 10.6$ GeV (from ref. [23]). **b)** The distribution of masses recoiling from the $J/\psi$ in inclusive $e^+e^- \to J/\psi X$ annihilations. The shaded histogram is background estimated from the $J/\psi$ mass side bands; the open histogram is the feed down from $\psi' \to J/\psi + X$ (from ref. [26]). **c)** The $J/\psi$ recoil mass distributions for $e^+e^- \to J/\psi D\overline{D}$ (upper) and $e^+e^- \to J/\psi D\overline{D}^*$ (lower) events (from ref. [26]). The hatched histogram shows the background estimated from the $D$-mass sidebands. (The inclusion of charge-conjugate states is implied.)

A 2007 Belle study of the same process with more data, reported results in terms of the mass recoiling from the detected $J/\psi$ (*i.e.* $M_{\rm recoil}(J/\psi) = \sqrt{(E_{cms} - E^{cms}_{J/\psi})^2 - p^{cms}_{J/\psi}}$ ) shown in Fig. 7b [26]. This distribution has a number noteworthy features:

- there are no obvious signal events below the $\eta_c$ peak, where contributions from color-octet production are expected to be strongest;
- the ∼500 event $\eta_c$ signal corresponds to a cross section for the exclusive process $e^+e^- \to J/\psi\eta_c$ of $25.6 \pm 4.4$ fb [27], more than an order of magnitude higher than NRQCD-based expectations [28, 29];
- the $\sim$ 300 event $\eta_c(2S)$ signal provided the best confirmation of this state at that time;
- the three lower-mass peaks all correspond to established, spin=0 charmonium states;
- there is strong production ($\sigma \simeq 10$ fb) of a previously unknown state with $M \simeq 3940$ MeV.

Belle found that the $J/\psi c\bar{c}$ component corresponds to $(59 \pm 0.18)\%$ of the total inclusive $J/\psi$ production cross section [30] in contradiction to NRQCD expectations that it would be $\lesssim$10% of the $J/\psi gg$ component [31, 32]. The cross sections for exclusive double-charmonium processes (such as $J/\psi\eta_c$) are well above lowest-order NRQCD-based predictions [28, 29]. This inspired studies of the corrections due the next-to-leading order (NLO) [33–35], and these were found to be large (large enough to explain the discrepancy), but such large corrections at NLO raise suspicions about the convergence of the NRQCD expansion [36].

Belle's experimental results on double $c\bar{c}$ production have had (and are still having) a huge impact on the development of NRQCD and, although they are not well known outside of this specialty, they are very important to, and highly cited by, practioners in this field. (At the end of 2015, refs. [26], [27] and [30] had 271, 155 and 320 citations, respectively.)

#### 3.1.1 The mass peak at 3940 MeV

In order to study the peak at 3940 MeV in the $J/\psi$ recoil mass spectrum, Belle selected events with a reconstructed $J/\psi$ and $D$ meson [26]. In these events the distribution of masses recoiling from the $J/\psi$-$D$ system exhibit clear and distinct signals for recoil $\overline{D}$ and $\overline{D}^*$ mesons. The $D\overline{D}$ and $D\overline{D}^*$ invariant mass distributions for these events are shown in the upper and lower panels, respectively, of Fig. 7c, where a clear peak at 3.94 GeV is evident in the $D\overline{D}^*$ spectrum but not in the $D\overline{D}$ channel.

The absence of any signals for known spin=1 or spin=2 charmonium states in the $J/\psi$ recoil mass spectrum of Fig. 7b, and the lack of any significant signal for the the 3940 MeV peak in the $D\overline{D}$ mass distribution in Fig. 7C (upper), provide circumstantial evidence that the $J^{PC}$ quantum numbers for this new state are $0^{-+}$, which would make it a candidate for the $\eta_c(3S)$ charmonium state. However, in this case its $3942 \pm 9$ MeV mass would be $\sim$100 MeV below its hyperfine partner, the $\psi(3S) = \psi(4040)$, implying a hyperfine splitting that is about twice as large as the $\psi(2S)$-$\eta_c(2S)$ splitting. This is contrary to expectations from potential models in which the hyperfine splitting decreases with increasing radial quantum number. For states above open charmed thresholds, naïve potential model results are modified by the influence of coupled pairs of open-charmed mesons. The nearest open charmed pair relevant to the $\eta_c(3S)$-$\psi(3S)$ doublet is a $D\overline{D}^*$ system in a relative $P$-wave, and this should not have a very large effect on the hyperfine splitting, which is primarily sensitive to the $c\bar{c}$ wave function at the origin. These issues are discussed in ref. [37].

### 3.2 Probing the $f_0(980)$ and $a_0(980)$scalar mesons

The nature of the scalar mesons with mass below 1 GeV is one of the most long-standing mysteries of hadron physics. Although they have been studied for more than four decades, they continue to remain controversial [38,39]. It has been suggested that they are not "standard" $q\bar{q}$ mesons but, instead, four quark states either of the diquark-diantiquark [40], or meson-meson molecule [41–43] variety.

A way to distinguish between different substructures proposed for the scalar mesons is by the determinations of the two-photon widths ($\Gamma_{\gamma\gamma}$) of the electrically neutral $f_0(980)$ and $a_0^0(980)$ states via measurements of their production cross sections in $\gamma\gamma$ collisions. Figure 8a illustrates how this works for $q\bar{q}$ mesons. Both photons couple to the internal quark pair and the partial-widths are proportional the $e_q^4$. Thus, for example, in the $q\bar{q}$ picture for the isoscalar $f_0(980)$ meson, (where $q = u$ and $d$), the expectation for $\Gamma_{\gamma\gamma}(f_0(980))$ is in the range 1.3 to 1.8 keV [44]; for a four-quark $K\overline{K}$ molecule it is more complicated and much smaller, in the 0.2-0.6 keV range [45]; for $s\bar{s}$ it is expected to be in the range 0.3-0.5 keV [46].

The measurement of $\gamma\gamma \to f_0(980) \to \pi^+\pi^-$ is difficult with Belle because of a huge background from the QED process $\gamma\gamma \to \mu^+\mu^-$. In the $\pi^+\pi^-$ invariant-mass region of interest for this measurement, the pions and muons have low laboratory momenta and do not reach the Belle muon identification system. Nevertheless, the different responses of the CsI crystals in Belle's electromagnetic calorimeter to pions and muons and the huge luminosity of KEKB allow for a mass-bin by mass-bin statistical separation of the pion and muon contributions. The blue triangles and black squares in Fig. 8b show results from previous measurements by Cello [47] and Mark II [48], where there is no sign of any resonance-like behavior in the 980 MeV region. The small red dots in the same figure are not a theoretical curve or the results of MC calculations; these are, instead, Belle measurements with statistical error bars that are about the size as the data points themselves [49]. The upper panel of Fig. 8c provides an expanded view of the Belle results near the $f_0(980)$ mass, where a distinct structure near 980 MeV is evident. This structure does not have a simple Breit Wigner line shape because of strong interference with the helicity=0, non-resonant $\pi^+\pi^-$ background and a distortion caused by the opening of the $f_0(980) \to K\overline{K}$ at the $2m_K$ threshold. The $f_0(980)$ is fit with a coherent Flattè-like lineshape [50,51] using parameters determined by BESII [52] that takes these effects

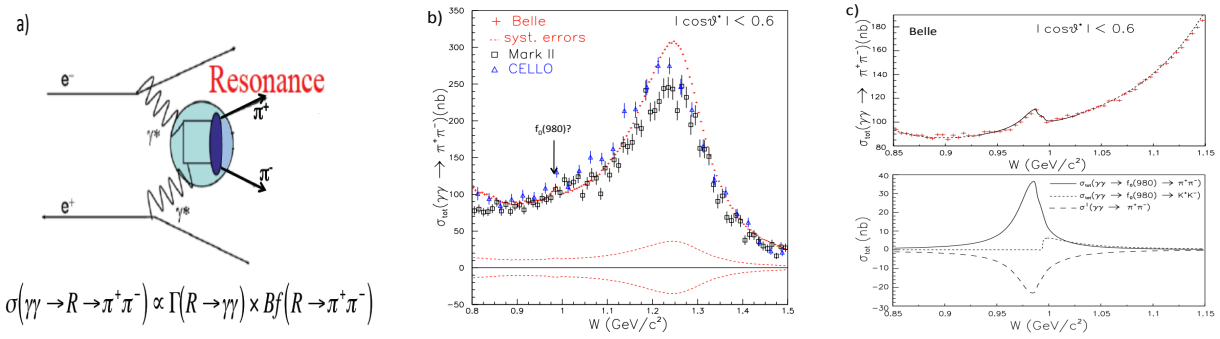


Figure 8: **a)** A cartoon that illustrates the relation between $\gamma\gamma$ production measurements and the internal structure of neutral mesons. **b)** $\sigma(\gamma\gamma \to \pi^+\pi^-)$ measurements from Cello (triangles), Mark II (open squares) and Belle (red dots). The dashed red line indicates the size of Belle's systematic errors **c)** (upper) An expanded view of the Belle measurements in the vicinity of the $f_0(980)$ with fit results shown by the curved line. (lower) The $f_0(980)$ components of the fit: total $f_0(980) \to \pi^+\pi^-$ (solid curve); $f_0(980) \to K\overline{K}$ (short dashes); effect of $f_0(980)$interference of the non-resonant $\pi^+\pi^-$ background (long dashes).

into account. The components of the resulting fit are shown in the lower panel of Fig. 8c. The fit gives an $f_0(980)$ mass and $\pi\pi$ partial width of $M = 985.6^{+1.2}_{-1.5}\,{}^{+1.1}_{-1.6}$ MeV and $\Gamma_{\pi\pi} = 34.2^{+13.9}_{-11.8}\,{}^{+8.8}_{-2.5}$ MeV and a $\gamma\gamma$ partial width of $\Gamma_{\gamma\gamma} = 205^{+95}_{-83}\,{}^{+147}_{-117}$ eV, where the first errors are statistical and the second systematic. The main systematic error on $\Gamma_{\gamma\gamma}$ is from the cross section normalization that, in turn, is sensitive to the modeling of the non-resonant $\pi^+\pi^-$ background.

Belle also studied $f_0(980)$ production in the $\gamma\gamma \to f_0(980) \to \pi^0\pi^0$ channel, where $\mu^+\mu^-$ and non-resonant $\pi^0\pi^0$ backgrounds are not an issue. In Fig. 9a, Belle results [53] for $\sigma(\gamma\gamma \to \pi^0\pi^0)$ are shown as red diamonds (with invisible statistical error bars) together with previous results from the Crystal Ball experiment [54] shown as black solid circles with error bars. Here again the Belle results represent a huge improvement in statistical precision. The results of Belle fits to the differential cross section measurements are shown in Fig. 9b, where a distinct signal for an $S$-wave resonance near 980 MeV is found with mass $982.2 \pm 1.0^{+8.1}_{-8.0}$ MeV and $\Gamma_{\gamma\gamma}(f_0) = 286 \pm 17^{+211}_{-70}$ eV; these values agree well with Belle's results from the $\pi^+\pi^-$ channel but with different sources of systematic errors.

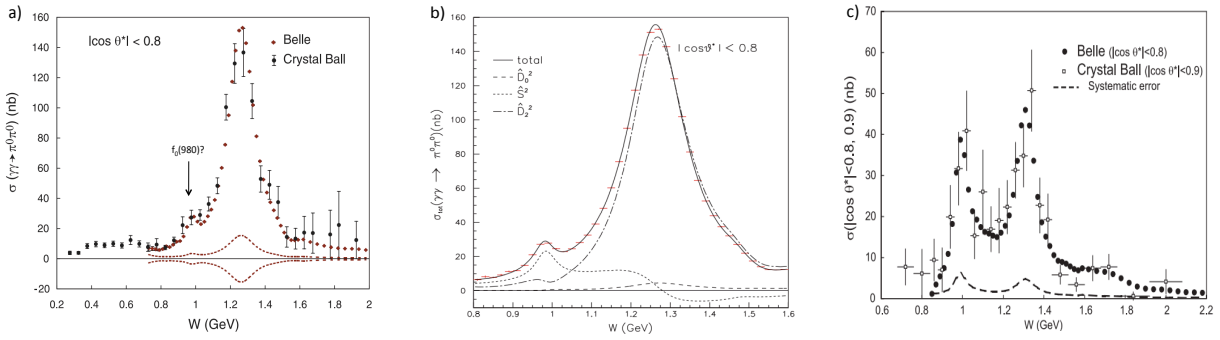


Figure 9: **a)** Belle (red dots) and Crystal Ball (solid circles) results for $\sigma(\gamma\gamma \to \pi^0\pi^0)$. The dashed line indicates the size of Belle's systematic errors. **b)** Belle results for $\sigma(\gamma\gamma \to \pi^0\pi^0)$ with the results of the Belle fit: total fit (solid curve); $S$-wave (short dashes); helicity=2 $D$-wave (dash-dot); helicity=0 $D$-wave (long dashes). **c)** Belle $\sigma(\gamma\gamma \to \eta\pi^0)$ measurements (solid dots) together with previous Crystal Ball results. The dashed curve indicates the size of Belle's systematic errors.

Belle also studied two-photon production of the isovector $a_0^0(980)$ scalar in the $\gamma\gamma \to a_0^0(980) \to \eta\pi^0$ channel [56]. Belle's $\sigma(\gamma\gamma \to \eta\pi^0)$ results are shown as black dots in Fig. 9c with previous measurements from the Crystal Ball shown as open circles with error bars. [57]. Belle results agree well with the previous measurements but with substantially improved precision. The Belle results for the $a_0^0$ mass, total width and $\gamma\gamma$ partial width are: $M = 982.3^{+0.6}_{-0.7}\,{}^{+3.1}_{-4.7}$ MeV; $\Gamma_{\rm tot} = 75.6 \pm 1.6^{+17.4}_{-10.0}$ MeV; and $\Gamma_{\gamma\gamma} \times \mathcal{B}(a_0 \to \eta\pi^0) = 128^{+3}_{-2}\,{}^{+502}_{-43}$ eV. The large positive systematic error on the $\gamma\gamma$ partial width is associated with uncertain interference effects with higher $\eta\pi^0$ resonances, which were not considered in previous measurements.

The Belle $\Gamma_{\gamma\gamma}(f_0)$ results are inconsistent with expectations for a pure $q\bar{q}$ meson and consistent with the four-quark model prediction of 270 eV provided in ref. [55]. The impact of Belle results on the understanding of the light scalar mesons is discussed in refs. [58] and [59].

Belle published ten papers on $\gamma\gamma$ production of six light meson channels: $\pi^+\pi^-$, $\pi^0\pi^0$, $\eta\pi^0$, $\eta\eta$, $K^+K^-$ and $K_SK_S$. These papers all include game-changing improvements in statistical precision over previous work (similar to the examples given above) and include analyses of twenty well identified meson states that include, usually for the first time, consideration of angular distributions and the effects of interference.

### 3.3 Spin polarimetry for quark jets

The strongly interacting particles in the SM are quarks and gluons. The strongly interacting particles in Nature are hadrons. Presumably the transition of quarks and gluons into hadrons is described by long-distance QCD, but calculations of the processes that are involved are hopelessly complicated. Attempts to cope with these difficulties by using "QCD-motivated" models have had only modest success. Usually, the transitions between quarks and hadrons are parameterized by experimentally measured fragmentation functions $D_q^h(z, p_{h\perp}^2)$, which are probability densities for a quark of flavor $q$ to produce a hadron $h$ with a fraction $z$ of the quark's original momentum and with a transverse momentum relative to the quark direction of $|p_{h\perp}|$, as illustrated in the upper part of Fig. 10a. Measuring these fragmentation functions is an important (but unsung) part of the research program of most experiments (see *e.g.*, ref. [60]).

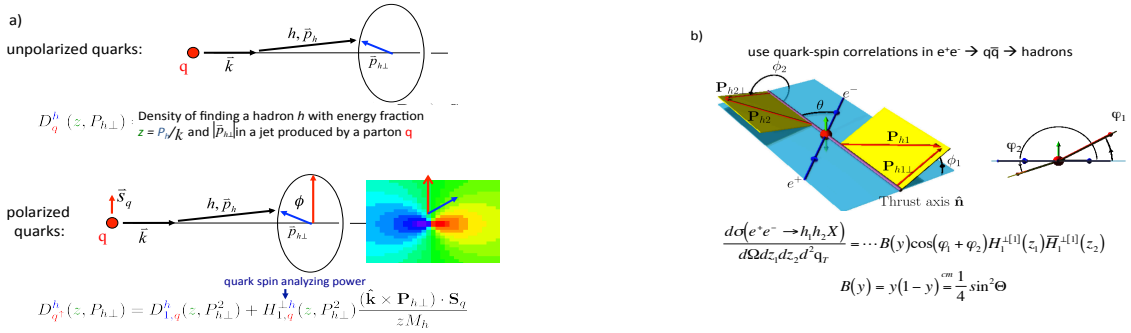


Figure 10: **a)** Illustration of unpolarized (upper) and polarized (lower) quark fragmentation functions. **b)** The principle of measurement of the product of two Collins spin fragmentation functions using $e^+e^- \to q\bar{q}$ annihilations. Here the blue plane is defined by the thrust axis of the event (purple line) and the incoming $e^+e^-$ direction (blue line).

If the quark is polarized, the fragmentation density can also depend on the azimuthal angle around the the quark's initial momentum direction as illustrated in the lower part of Fig. 10a. This was first discussed by Collins [61], who introduced a second term in the fragmentation, $H_{1,q}^{\perp h}(z, p_{h\perp}^2)$, as a first-order characteriza-

tion of this azimuthal modulation. Thus, if $H_{1,q}^{\perp h}$ is known, the azimuthal distribution of hadrons $h$ in a jet can be used as a "polarimeter" to determine the polarization of its parent quark.

There is growing interest in the proton's transverse spin structure and some important observables require measurements of quark spin directions [62]. For this, independent determinations of the Collins function are needed, and this requires sources of quarks with well defined spin orientation.

In $e^+e^- \to q\bar{q}$ annihilations the individual quarks are not polarized. However, since the spin of the $q\bar{q}$ system is aligned as either $|J;J_z\rangle = |1;+1\rangle$ or $|1;-1\rangle$, with no $|1;0\rangle$, the spins of the individual $q$ and $\bar{q}$ are tightly correlated. Because of this, measurements of the azimuthal angles of pairs of particles from opposite quark jets can be used to extract products of two Collins functions as illustrated in Fig. 10b [63].

Belle used this technique to make first measurements of the Collins function [64]. Figure 11a shows the the $2\phi_0$ distribution for a typical $(z_1, z_2)$ bin, where a clear $\cos 2\phi_0$ modulation, with an amplitude that is six standard deviations from zero, is apparent. Distributions for these modulation amplitudes for ten $(z_1, z_2)$ bins, from ref. [65] are shown in Fig. 11b. Here results from 492 fb$^{-1}$ data sample accumulated at the $\Upsilon(4S)$ resonance peak (green points) and a much smaller, 29 fb$^{-1}$ data sample taken at energies below the $\Upsilon(4S)$. (Since this analysis is restricted to high thrust events ($T > 0.8$), contamination of the $\Upsilon(4S)$ data sample results from $B$-mesons is negligibly small.)

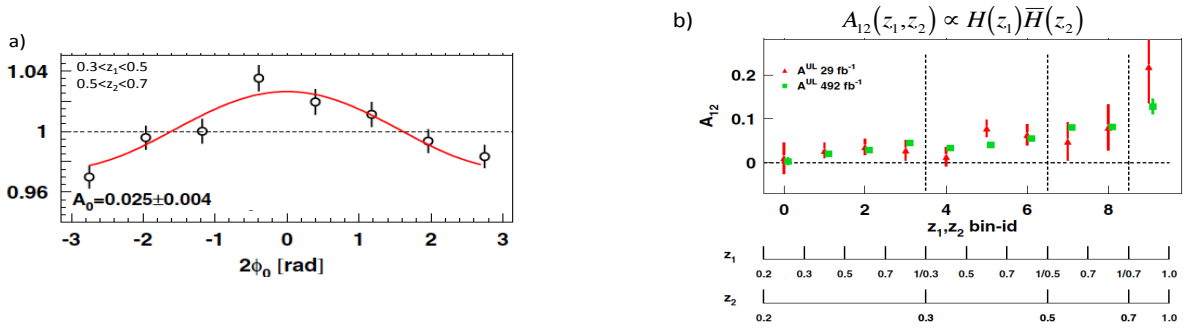


Figure 11: **a)** The $2\phi_0$ distribution for selected events in the $(z_1, z_2) = (0.4, 0.6)$ data bin. Here $\phi_0$ is the azimuthal angle between the $h_1$ and $h_2$ directions (see ref. [64]). **b)** The green points are the measured $\cos(\phi_1 + \phi_2)$ modulation amplitudes at $\sqrt{s} = 10.58$ GeV; the red points are from a small data set taken at a slightly lower c.m. energy (from ref. [65]).

These first measurements of Collins spin fragmentation functions have had a big effect on spin physics experiments. Belle refs. [64] and [65] have been cited 206 and 145 times, respectively. In addition, they have also stimulated measurements by the BaBar [66] amd BESIII [67] experiments.

## 4 Summary and Outlook

In addition to achieving all of its original goals of exploring $CP$ violations in the $B$ meson sector, Belle has had an interesting and diverse program of investigations that cover a wide variety of subjects. While many of these subjects, such as the discoveries of $D^0 \leftrightarrow \overline{D}^0$ mixing and $XYZ$ mesons, are generally well known, there are many others that are less publicized but have had a major impact on their particular specialized field. In this presentation, I only had time to cover three of these subjects.

This broad range of investigation was mostly facilitated by the huge luminosity that was provided by the KEKB collider, which acheived a world-record-breaking instantaneous luminosity in excess of $2 \times$

$10^{34}\text{cm}^{-2}\text{s}^{-1}$, twice the original design value, and that was generally considered to be wildly over optimistic when it was first proposed [68]. This bodes well for BelleII [69] and SuperKEKB [70]. We can look forward to all sorts of interesting surprises and unexpected phenomena from this facility.

# 5 Afterword

While preparing this proceedings article I was saddened to learn of the passing of my close friend and esteemed colleague Susumu Okubo. Susumu was a brilliant theoretical physicist and one of the pioneers in hadron physics, with important input into many of the subjects that I touched on in this summary and memories of him and his deep insights kept recurring to me as I struggled to digest the subject material into some sensible remarks. I am grateful for his friendship and all that he taught me and pray that he now rests in peace.

**Acknowledgments**

I congratulate the organizers of QFTHEP-2015 on their successful and interesting meeting. This work was supported by the Institute for Basic Science (Korea) under project code IBS-R016-D1.

# References

[1] J.H. Christenson, J.W. Cronin, V.L. Fitch and R. Turlay, Phys. Rev. Lett. **13**, 138 (18964).

[2] A.D. Sakharov, Zh. EK. Teor. Fiz. **5**, 32 (1967) (English translation, JETP Lett. **5**, 24 (1967)).

[3] S. Okubo, Phys. Rev. **109**, 984 (1958).

[4] L. Wolfenstein, Phys. Rev. Lett. **13**, 562 (1964).

[5] G.D. Barr *et al.* (NA31 Collaboration), Phys. Lett. **B317**, 233 (1993).

[6] A. Alavi-Harati *et al.* (KTeV Collaboration), Phys. Rev. Lett. **83**, 22 (1999).

[7] T. Brown, S. Pakvasa and S.F. Tuan, Phys. Rev. Lett. **51**, 1823 (1983).

[8] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[9] A.B. Carter and A.I. Sanda, Phys. Rev. Lett. **45**, 952 (1980).

[10] Phys. Rev. Lett. **50**, 881 (1983).

[11] K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **87**, 091802 (2001).

[12] J.J. Aubert *et al.*, Phys. Rev. Lett. **33**, 1404 (1974).

[13] J.E. Augustin *et al.* (Mark I Collaboration), Phys. Rev. Lett. **33**, 1406 (1974).

[14] S.W. Herb *et al.*, Phys. Rev. Lett. **39**, 252 (1977).

[15] E. Fernandez *et al.* (MAC Collaboration), Phys. Rev. Lett. **51**, 1022 (1983).

[16] N. Lockyer *et al.* (Mark II Collaboration), Phys. Rev. Lett. **51**, 1316 (1983).

[17] H. Albrecht *et al.* (ARGUS Collaboration), Phys. Lett. B **192**, 245 (1987).

[18] B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. Lett. **87**, 091801 (2001).

[19] J. Charles *al.* (CKM-Fitter Group), Eur. Phys. J. C**41**, 1 (2005).

[20] Ed. A.J. Bevan, B. Golob, Th. Mannel, S. Prell and B.D. Yabsley, Eur. Phys. J. C**74**, 3026 (2014).

[21] L. Wolfenstein, Phys. Rev. Lett. **51**, 1945 (1983).

[22] G.T. Bodwin, E. Braaten and G.P. Lepage, Phys. Rev. D **51**, 1125 (1995).

[23] K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **88**, 052001 (2002).

[24] G.A. Schuler, Eur. Phys. J. C **8**, 273 (1999).

[25] T. Sjöstrand, Comput. Phys. Commun. **82**, 74 (1994).

[26] P. Pakhlov *et al.* (Belle Collaboration), Phys. Rev. Lett. **98**, 082001 (2007).

[27] P. Pakhlov *et al.* (Belle Collaboration), Phys. Rev. D **70**, 071102(R), (2004).

[28] E. Braaten and J. Lee, Phys. Rev. D **67**, 054007 (2003); **72**, 099901 (2005).

[29] K.-Y. Liu, Z.-G. He and K.T. Chao, Phys. Lett. B **557**, 45 (2003).

[30] K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **89**, 142001 (2002).

[31] V.V. Kiselev, A.K. Likhoded and M.V. Shevlyagin, Phys. Lett. B **332**, 411 (1994).

[32] A.V. Berezhnoy and A.K. Likhoded. Yad. Fiz. **67**, 778 (2004); Phys. At. Nucl. **67**, 757 (2004).

[33] X.J. Zhang, Y.-J. Gao and K.-T. Cha0, Phys. Rev. Lett. **96**, 092001 (2006).

[34] B. Gong and J.-X. Wang, Phys. Rev. D **77**, 054028 (2008).

[35] G.T. Bodwin, J. Lee and C.Yu, Phys. Rev. D **77**, 094018 (2008).

[36] G.T. Bodwin, H.S. Chung and J. Lee, Phys. Rev. D **90**, 074028 (2014).

[37] E.J. Eichten, K. Lane and C. Quigg, Phys. Rev. D **73**, 014014 (2006).

[38] C. Amsler and N.A. Törnqvist, Phys. Rep. **389**, 61 (2004).

[39] N.N. Achasov, A.V. Kiselev and G.N. Shestakov, Nucl. Phys. Proc. Suppl. **181-182**, 169 (2008); arXix:806.0521 [hep-ph].

[40] R.L. Jaffe, Phys. Rev. D **15**, 267 (1977).

[41] M.B. Voloshin and L.B. Okun, JETP Lett. **23**, 33 (1976).

[42] K. Maltman and N. Isgur, Phys. Rev. Lett. **50**, 1827 (1983).

[43] N.A. Törnqvist, Phys. Rev. Lett. **67**, 556 (1992).

[44] C.R. Münz, Nucl. Phys. A **609**, 364 (1996).

[45] T. Barnes, *IXth International Workshop on Photon-Photon Collisions 1992*, p. 263 (World Scientific, Singapore).

[46] J.A. Oller and E. Oset, *Hadron Spectroscopy 1997*, p. 413, AIP Conf. Proc. No. 432 (AIP, New York).

[47] H.-J. Behrend *et al.* (Cello Collaboration), Z. Phys. C **56**, 381 (1992).

[48] J. Boyer *et al.* (Mark II Collaboration), Phys. Rev. D **42**, 1350 (1990).

[49] T. Mori *et al.* (Belle Collaboration), Phys. Rev. D **75**, 051101(R) (2007).

[50] S.M. Flattè, Phys. Lett. B **63**, 224 (1976).

[51] N.N. Achasov and G.N. Shestakov, Phys. Rev. D **72**, 013006 (2005).

[52] M. Ablikim *et al.* (BES II Collaboration), Phys. Lett. B **607**, 243 (2005).

[53] S. Uehara *et al.* (Belle Collaboration), Phys. Rev. D **78**, 052004 (2008).

[54] H. Marsiske *et al.* (Crystal Ball Collaboration), Phys. Rev. D **41**, 3324 (1990).

[55] N.N. Achasov, S.A. Devyanin and G.N. Shestakov, Phys. Lett. B **108**, 134 (1982).

[56] S. Uehara *et al.* (Belle Collaboration), Phys. ReV. D **80**, 032001 (2009).

[57] D. Antreasyan *et al.* (Crystal Ball Collaboration), Phys. ReV. D **33**, 1847 (1986).

[58] N.N. Achasov and G.N. Shestakov, Phys. Rev. D **77**, 074020 (2008).

[59] L.-Y. Dai and M.R. Pennington, Phys. Rev. D **90**, 036004 (2014).

[60] R. Seuster *et al.* (Belle Collaboration), Phys. Rev. D **73**, 032002 (2006).

[61] J.C. Collins, Nucl. Phys. B **396**, 161 (1993).

[62] A. Airapetian *et al.* (HERMES Collaboration), Phys. Rev. Lett. **94**, 012002 (2005); E.S. Ageev *et al.* (COMPASS Collaboration), Nucl. Phys. B **765**, 31 (2007); D.L. Adams *et al.* (FNAL-E704 Collaboration), Phys. Lett. B **264**, 462 (1991); J. Adams *et al.* (STAR Collaboration), Phys. Rev. Lett. **92**, 1171801 (2004); F. Videback *et al.* (BRAHMS Collaboration), AIP Conf. Proc. **842**, 401 (2006); S.S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **95**, 202001 (2005).

[63] D. Boer Nucl. Phys. B **806**, 23 (2009).

[64] R. Seidl *et al.* (Belle Collaboration), Phys. Rev. Lett. **96**, 232002 (2006).

[65] R. Seidl *et al.* (Belle Collaboration), Phys. Rev. D **78**, 032011 (2008).

[66] J.P. Lees *et al.* (BaBar Collaboration), Phys. Rev. D **90**, 052003 (2014).

[67] M. Ablikim *et al.* (BESIII Collaboration), arXiv:15007.06824 [hep-ex].

[68] See, for example, C. Macilwain, Nature **403**, 586 (2000).

[69] T. Aushev *et al.* (BelleII Collaboration), arXiv:1002.5012 [hep-ex].

[70] www-superkekb.kek.jp/index.html