Chapter 2
CP Violation in Charmless $b \to s\bar{q}q$ Transitions

With the study of *CP* violation in $b \to d$ transitions seemingly in good agreement with Standard Model (SM) expectations, the subject of CPV studies in charmless $b \to s$ transitions (including $b\bar{s} \leftrightarrow s\bar{b}$) is the current frontier of heavy flavor research. Because there is little CPV weak phase in the controlling product of CKM matrix elements for loop-induced $b \to s$ transitions, $V_{ts}^* V_{tb}$, any observed deviation could indicate New Physics. As transitions between $3 \to 2$ generation quarks, the subject also has $\tau \to \mu$ transition echoes in the lepton sector, an interesting subject covered in Chap. 9. More generally, with the Sakharov conditions [1] that link CPV with the Baryon Asymmetry of the Universe (BAU), i.e., why there is no trace of antimatter in our Universe, we do expect NP sources for CPV. It is well known that the three generation SM falls short by *many orders of magnitude* from the CPV that is needed to generate the observed BAU, a point that we will elaborate in Chap. 10. This certainly has been one of the strongest motivations to search for New Physics in *CP* violation.

In this chapter, we focus on three topics: the $\Delta\mathcal{S}$ problem for mixing- or time-dependent CPV (TCPV) in charmless $b \to s\bar{q}q$ modes vs. $b \to c\bar{c}s$ modes, where we elucidate also how TCPV studies are conducted; the $\Delta\mathcal{A}_{K\pi}$ problem between direct CPV (DCPV) in $B^+ \to K^+\pi^0$ and $B^0 \to K^+\pi^-$ decays; and the DCPV asymmetry $\mathcal{A}_{B^+\to J/\psi K^+}$. We close with an appraisal of New Physics search in hadronic $b \to s$ transitions. The status and prospects for $\sin 2\Phi_{B_s}$ measurement (analogous to $\sin 2\phi_1/\beta$ for B_d system) at the Tevatron and LHC, which is the new forefront, will be discussed in the Chap. 3. Further charmless $b \to s$ probes of different New Physics are covered in subsequent chapters.

2.1 The $\Delta\mathcal{S}$ Problem

The B factories were built to measure mixing- or time-dependent CPV (TCPV) in the $B^0 \to J/\psi K_S$ mode [2]. This is the billion dollar question that started with the ARGUS discovery of large B^0–$\bar{B}^0$ mixing [3]. With the suggestion by Oddone [4] of boosting the $\Upsilon(4S)$, thereby boosting the B^0 and $\bar{B}^0$ mesons, by the late 1980s, both SLAC and KEK initiated feasibility studies for e^+e^- colliders with asymmetric

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beam energies. The push toward asymmetric beam energies also contributed partly to the demise, in 1989, of the proposed machine at Paul Scherrer Institute (PSI), which had a symmetric double ring design. By 1994 or so, both the PEP-II/BaBar and the KEKB/Belle accelerator and detector complexes entered construction phase.

Several miraculous points that aid B factory studies are worthy of note. First, m_B is so close to $m_{\Upsilon(4S)}/2$, such that not only the $\Upsilon(4S)$ decays practically 100% to $B^0\bar{B}^0$ and B^+B^- pairs, the B mesons are produced with rather small momenta. Second, m_{B^+} and m_{B^0} are rather close in mass, such that charged and neutral B mesons are almost equally produced. Their production ratio is of course measured. Third point, which will be immediately discussed in the following, is the "EPR" coherence (or entanglement) of the $B^0\bar{B}^0$ meson pair from $\Upsilon(4S)$ decay. That is, although each meson starts to oscillate between B^0 and $\bar{B}^0$ after being produced, the pair remains in coherence, such that the determination of the B^0 (or $\bar{B}^0$) nature of one meson at time t in the $\Upsilon(4S)$ frame, the other meson starts to oscillate from a $\bar{B}^0$ (or B^0) from time t onward. This quantum coherence has in fact been tested at Belle [5]. Of course, Quantum Mechanics is again affirmed. The fraction of produced B^0 and $\bar{B}^0$ pairs (out of 76M) that disentangle and decay incoherently is measured to be 0.029 ± 0.057, which is consistent with zero.

2.1.1 Measurement of TCPV at the B Factories

At B factories, TCPV measurement utilizes the coherent production of $B^0\bar{B}^0$ pairs from $\Upsilon(4S)$ decay. That is, as the produced B^0 (and vice versa the $\bar{B}^0$) undergoes oscillations back and forth from B^0 to $\bar{B}^0$, the pair remains coherent. As the original B^0 and $\bar{B}^0$ are produced at the same time, if one measures at time t the decay of one B meson, and found that it decays as, say, B^0, we then know from quantum coherence that the other B meson is a $\bar{B}^0$ meson at time t. From then on, this $\bar{B}^0$ meson again oscillates back and forth from $\bar{B}^0$ to B^0, until time Δt later, where it also decays.

Having this picture visualized, we can go further and discuss what is done experimentally to measure TCPV. We repeat (A.9) of Appendix A.3 for TCPV asymmetry,

$$\begin{aligned} A_{\rm CP}(\Delta t) &\equiv \frac{\Gamma(\bar{B}^0(\Delta t) \to f) - \Gamma(B^0(\Delta t) \to f)}{\Gamma(\bar{B}^0(\Delta t) \to f) + \Gamma(B^0(\Delta t) \to f)} \\ &= -\xi_f(\mathcal{S}_f \sin \Delta m \Delta t + \mathcal{A}_f \cos \Delta m \Delta t), \end{aligned} \tag{2.1}$$

where ξ_f is the *CP* eigenvalue of final state f and $\Delta m \equiv \Delta m_{B_d}$. This asymmetry measures, at time Δt, the difference in rate between a state tagged at $t = 0$ as $\bar{B}^0$ vs. B^0. Thus, the Γ's are really shorthands for differential decay rates. With the Δt distribution of $A_{\rm CP}(\Delta t)$, which are actually done by fitting $\Gamma(\bar{B}^0(\Delta t) \to f)$ and $\Gamma(B^0(\Delta t) \to f)$ distributions, the CPV parameters $\mathcal{S}_f$ and $\mathcal{A}_f$ are just the Fourier coefficients of the sine and cosine Δt oscillation terms. Of course, experimentally

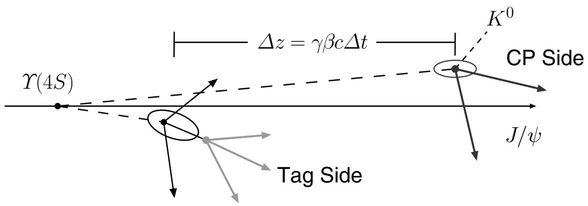

Fig. 2.1 Figure illustrating TCPV measurement. The $\Upsilon(4S)$, which decays into a B^0–$\bar{B}^0$ pair, is boosted in the z-direction. After one B is tagged by its decay, quantum coherence dictates the other B would start evolving from the conjugate of the tagged state. At time $\Delta t = \gamma\beta c\Delta z$ (can be negative), where Δz is the measured difference between the decay vertices, the other B decays into a *CP* eigenstate such as $J/\psi\ K_S$. See text for further discussion

one has to correct for inefficiencies and dilution factors, which we do not go into. As discussed in Chap. 1 and Appendix A, $\mathcal{S}_{J/\psi K^0}$ is just $\sin 2\beta/\phi_1$, the CPV phase of B^0–$\bar{B}^0$ mixing amplitude, while $\mathcal{A}_{J/\psi K^0}$ is the direct CPV for this mode.

To conduct $A_{\text{CP}}(\Delta t)$ measurement, as illustrated in Fig. 2.1, one needs to

(1) *tag* the flavor of one B decay (B^0 or $\bar{B}^0$) at "$t = 0$,"
(2) reconstruct the other B in a *CP eigenstate* (cannot tell B^0 vs. $\bar{B}^0$), and
(3) measure decay *vertices* for both B decays.

For the last point, one utilizes the boost along the z- or beam direction, and $\Delta z \cong \gamma\beta c\Delta t$ is the measured difference between the two B decay vertices. The $\gamma\beta$ factor is 0.56 and 0.43 for PEP-II and KEKB, respectively. With B lifetime of order picosecond, $\gamma\beta c\tau_B$ is of order 200 μm or so. For the *CP* side, one therefore demands a σ_z resolution of less than 100 μm.

The BaBar and Belle detectors are rather similar to each other. A side view of the Belle detector is given in Fig. 2.2 showing subdetectors. The subdetectors of BaBar and Belle consist of a Silicon Vertex Detector (SVT/SVD), a Central Drift Chamber (DCH/CDC), an Electromagnetic Calorimeter (EMC/ECL) based on CsI(Tℓ), a Particle Identification Detector (PID) system, superconducting solenoid magnet, and an Iron Flux Return that is instrumented (IFR for BaBar) for K_L and muon detection (hence KLM for Belle).

The difference between the two detectors is basically only in the PID system that is crucial for flavor tagging, in particular the task of charged K/π separation at various energies. Note that, even for $B \to J/\psi\ K$ decay, p_K is almost 1.7 GeV/c and rather relativistic, and in addition one has the boost. The Belle PID system consists of Aerogel Cherenkov Counters (ACC), a threshold device with several indices of refraction n for the silica aerogel for different angular coverage, plus a Time of Flight (TOF) counter system. BaBar uses the DIRC, basically a system of quartz bars that generate and guide the Cherenkov photons (by internal reflection) and project them into a water tank at the back end (called the Stand-Off-Box, or SOB) of the detector. It provides more dynamical information, but the large SOB is a little

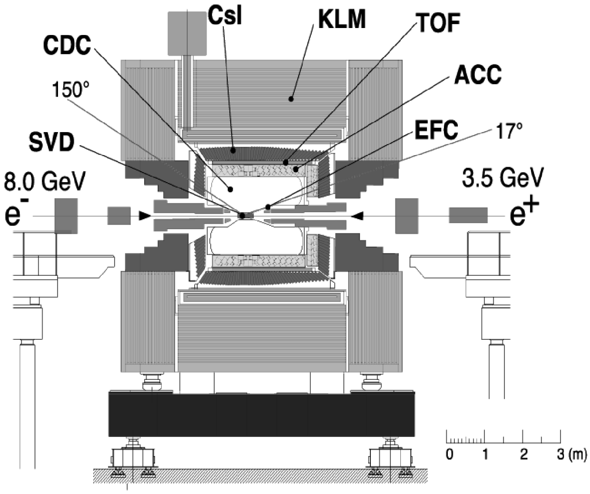

Fig. 2.2 Schematic side view of the Belle detector, with markings of the subdetector systems. (Source: http://belle.kek.jp/belle/transparency/detector1.html.)

unwieldy.[1] One other difference between Belle and BaBar is the Interaction Region (IR), which is at the intersection between detector and accelerator. PEP-II made the conservative choice of zero angle crossing (electrostatic beam separation by permanent magnets), while KEKB used finite angle crossing. This eventually became a main limiting factor for the luminosity reach of PEP-II, although it ensured faster accelerator turn on. In any case, it is truly impressive that both accelerators reached beyond design luminosities, especially since the asymmetric energy design was a new challenge.

The real novelty of the B factories, of course, is the asymmetric beam energies. The $\gamma\beta$ factor for the produced $\Upsilon(4S)$ is 0.56 and 0.43, respectively, for PEP-II and KEKB. Boosting the B^0 and $\bar{B}^0$ mesons allowed the time difference $\Delta t \cong \Delta z/\beta\gamma c$ used in (2.1) to be inferred from the decay vertex difference Δz in the boost direction, while the proximity of $2m_{B^0}$ to $m_{\Upsilon(4S)}$ means rather minimal lateral motion. Both the PEP-II and KEKB accelerators were commissioned in 1999 with a roaring start. By 2001, KEKB outran PEP-II in the instantaneous luminosity and in integrated luminosity as well by the following year (see Fig. 2.3). In April 2008, PEP-II dumped its beam for the last time.

With the good performance of the accelerators and with relatively standard detectors, by 2001, the measurement of the gold-plated mode of $B^0 \to J/\psi K^0$ (including K_L^0) was settled. As can be seen from Fig. 1.3, the mean value between

[1] The aerogel technique was originally developed at BaBar and adopted by Belle when there was insufficient confidence in the original design of a RICH detector system. When BaBar adopted the innovative DIRC, the extra space available, together with budget pressures, led to a slight compromise of the EMC system.

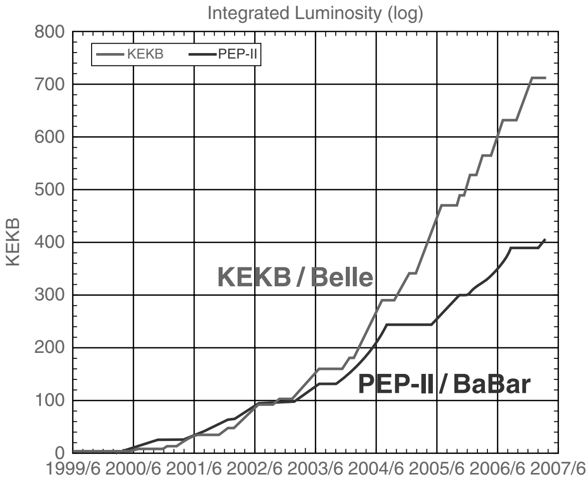

Fig. 2.3 Comparison of integrated luminosities achieved by KEKB/Belle and PEP-II/BaBar, up to early summer 2007

Belle and BaBar remained largely unchanged since then. It would seem that the *raison d'être* of the B factories was accomplished just 2 years after commissioning!

2.1.2 TCPV in Charmless $b \to s\bar{q}q$ Modes

With the measurement of TCPV in $B^0 \to J/\psi K_S$ settled in summer 2001, attention quickly turned to the $b \to s$ penguin modes, where a virtual gluon is emitted from the virtual top quark in the vertex loop.

Let us take $B^0 \to \phi K_S$ as example [6], where, as shown in Fig. 2.4(a), the virtual gluon pops out an $s\bar{s}$ pair. The $b \to s$ penguin amplitude is practically real within SM, just like the tree level $B^0 \to J/\psi K_S$. This is because $V_{us}^* V_{ub}$ is very suppressed, so the c and t contributions carry equal and opposite CKM coefficients $V_{ts}^* V_{tb} \cong -V_{cs}^* V_{cb}$, which is practically real, as can be seen from (A.3). Thus, one has the SM prediction,

$$\mathcal{S}_{\phi K_S} \cong \sin 2\phi_1/\beta \quad \text{(SM)}, \tag{2.2}$$

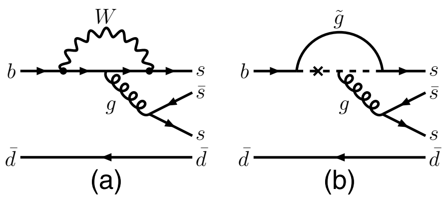

Fig. 2.4 (**a**) Strong penguin (P) diagram for $\bar{B}^0 \to \phi\bar{K}^0$ in SM, and (**b**) a possible diagram in SUSY with $\tilde{b}$–$\tilde{s}$ squark mixing, which is illustrated by the cross on the squark line inside the loop

where $\mathcal{S}_{\phi K_S}$ is the analogous TCPV measure in the $B^0 \to \phi K_S$ mode, following the $\mathcal{S}_f$ notation of (2.1). New physics-induced Flavor-Changing Neutral Current (FCNC) and CPV effects, such as having supersymmetric (SUSY) particles in the loop (for example, $\tilde{b}$-$\tilde{s}$ squark mixing, Fig. 2.4(b)), could break this equality. That is, deviations from (2.2) would indicate New Physics. This prospect prompted the experiments to search vigorously.

The first ever TCPV study in charmless $b \to s\bar{q}q$ modes was performed for $B^0 \to \eta' K_S$ [7] by Belle in 2002 with 45M $B\bar{B}$ pairs [8]. Part of the motivation is the large enhanced rate, which is still not fully understood. But many might remember better the big splash made by Belle in summer 2003, where $\mathcal{S}_{\phi K_S}$ was found to be opposite in sign [9] to $\sin 2\phi_1/\beta$, where the significance of deviation was more than 3σ. But the situation softened by 2004 and is now far less dramatic. What happened was that the Belle value for $\mathcal{S}_{\phi K_S}$ changed by 2.2σ, shifting from $\sim$–1 in 2003 to $\sim$0 in 2004. 123M $B\bar{B}$ pairs were added to the analysis in 2004, but they gave the results with sign opposite to the earlier data of 152M $B\bar{B}$ pairs. The new data was taken with the upgraded SVD2 silicon detector, which was installed in summer 2003. The SVD2 resolution was studied with B lifetime and mixing and was well understood, while $\sin 2\phi_1$ measured in $J/\psi K_S$ and $J/\psi K_L$ modes showed good consistency between SVD2 and SVD1. Many other systematics checks were also done. By Monte Carlo study of pseudoexperiments, Belle concluded [10] that there is 4.1% probability for the 2.2σ shift. This is a sobering and useful reminder, especially when one is conducting New Physics search, that large fluctuations do happen.

The study at Belle and BaBar has expanded to include many charmless $b \to s\bar{q}q$ modes. After several years of vigorous pursuit, some deviation has persisted in an interesting if not nagging kind of way. Let us not dwell on analysis details, except stressing that this is one of the major, concerted efforts at the B factories. Comparing to the average of $\mathcal{S}_{c\bar{c}s} = 0.681 \pm 0.025$ [11] over $b \to c\bar{c}s$ transitions, $\mathcal{S}_f$ is smaller in practically all $b \to s\bar{q}q$ modes measured so far (see Fig. 2.5), with the naive mean[2] of $\mathcal{S}_{s\bar{q}q} = 0.56 \pm 0.05$ [11]. That is,

$$\mathcal{S}_{s\bar{q}q} = 0.56 \pm 0.05 \quad \text{vs.} \quad \mathcal{S}_{c\bar{c}s} = 0.681 \pm 0.025. \tag{2.3}$$

The deviation $\Delta\mathcal{S} \equiv \mathcal{S}_{s\bar{q}q} - \mathcal{S}_{c\bar{c}s} < 0$ is only 2.2σ from zero, and the significance has been slowly diminishing. However, it is worthwhile to stress that the persistence over several years, and in multiple modes, taken together make this "$\Delta\mathcal{S}$ problem" a potential indication for New Physics from the B factories. Despite the lack in significance, it should not be taken lightly. After all, the experiments were not able to "make it go away."[3]

[2] We use the LP2007 update by Heavy Flavor Averaging Group (HFAG) that excludes the new $\mathcal{S}_{f_0(980)K_S}$ result from BaBar. The HFAG itself warns "treat with extreme caution" when using this BaBar result [11]. The value is larger than $\mathcal{S}_{c\bar{c}s}$ and is very precise, with errors three times smaller than the ϕK_S mode. But $f_0(980)K_S$ actually has smaller branching ratio than ϕK_S ! The BaBar result needs confirmation from Belle in $B^0 \to \pi^+\pi^- K_s$ mode.

[3] The Summer 2008 update by HFAG seems to indicate that there is no deviation and the $\Delta\mathcal{S}$ problem now rests in the errors.

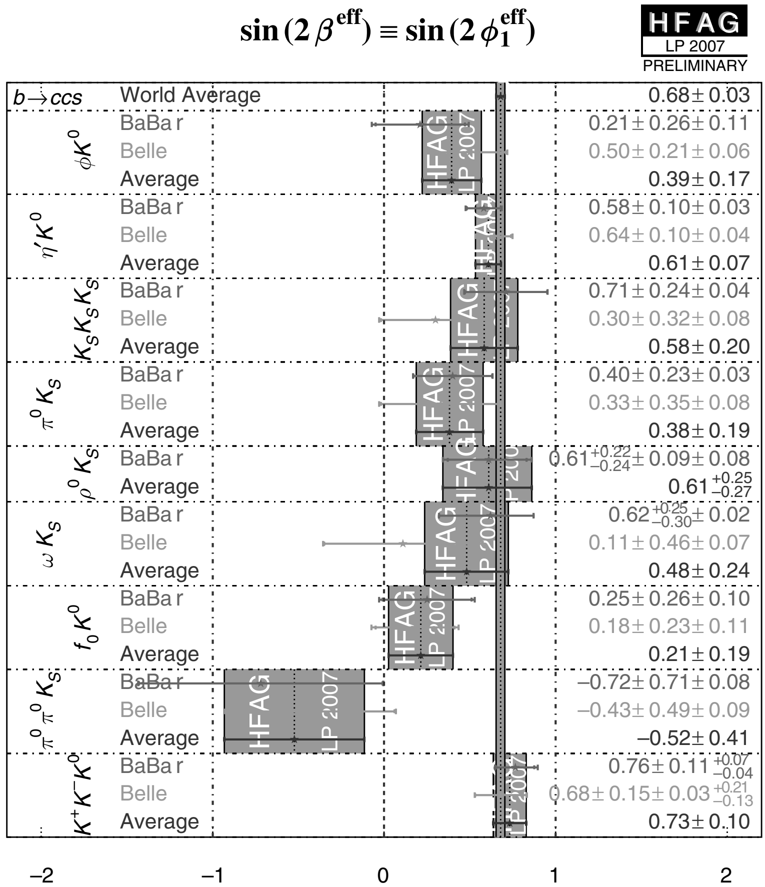

Fig. 2.5 Measurements of $\mathcal{S}_f$ in $b \to s\bar{q}q$ penguin modes [11]. (Summer 2007 results from HFAG, used with permission.) See Footnote 2 for comment on the $B^0 \to f_0(980)K_S$ mode

The point is that theoretical studies, although troubled by hadronic effects, all give $\mathcal{S}_{s\bar{q}q}$ values that are *above* [12–15] $\mathcal{S}_{c\bar{c}s}$, or

$$\Delta\mathcal{S}|^{\mathrm{TH}} > 0. \tag{2.4}$$

This elevates the tension that is already present with the experimental situation, i.e., what lies behind the apparent $\Delta\mathcal{S}|^{\mathrm{EXP}} < 0$.

Is this New Physics? We remark that there are limitations for what one can interpret from deviations in penguin-dominant $b \to s$ hadronic modes. While a large, *definite* effect in a single mode, such as the relatively clean ϕK_S mode, (pure $b \to s\bar{s}s$ penguin) would clearly indicate NP, many of these modes, as well as theoretical approaches, suffer from large hadronic uncertainties, such that the NP effect would vary from mode to mode. So, whether ϕK_S or $\eta' K_S$, or the combined effect in $b \to s\bar{q}q$, one may not gain much more information by averaging over modes. We also note that the mode with the largest branching fraction, and the first mode to be studied [8], i.e. $\eta' K_S$, is now in very good agreement with $b \to c\bar{c}s$. This is not surprising, for it is now believed that the enhancement of $B^0 \to \eta' K^0$ is not due so much to New Physics, but some combination of "hadronic" effects.

It is a bit frustrating for the B factory worker that, after many years of work, this deviation is not much more than 2σ. Clearly, we need more data ! But BaBar has ended its data taking, while Belle would stop for (hopeful) upgrade after reaching 1 ab^{-1}, so the data set for analysis can only double within the present B factory era, which is drawing to an end. As B factory data can at best double, it seems that one would probably need a Super B factory to resolve the issue of $\Delta\mathcal{S}$. In this context, we need a clear litmus test.

One promising development is a model-independent geometric approach, which suggests [16] that, once one has enough experimental precision, a deviation as little as a couple of degrees would indicate New Physics. It would be splendid if there is no loophole in this argument, for this is what is needed when we reach the precision of the Super B factory era. However, this approach needs better elucidation, before the commissioning of the upgraded B factory, for people to grasp and appreciate the insight. Other approaches to ascertain at what level a $\Delta\mathcal{S}_{(f)}$ deviation can be called an indication for New Physics should also be developed.

One may think that the LHC, which started first beam in September 2008 (but immediately started facing turn-on pains), and the LHCb experiment in particular should be able to make great progress on the $\Delta\mathcal{S}$ problem. Curiously, because of lack of good vertices or the presence of neutral (π^0, γ) particles (a weakness for LHCb) in the leading channels of $\eta' K_S$, ϕK_S, and $K_S\pi^0$, the situation may not improve greatly with LHCb data. An improved LHCb detector (i.e., after an upgrade), or some different approach, needs to be developed.

The ΔS *problem seems to demand a Super B Factory for its clarification.*

2.2 The $\Delta\mathcal{A}_{K\pi}$ Problem

There is a second possible indication for BSM physics in $b \to s\bar{q}q$ decays. It became widely known through the Belle paper published in *Nature* [17] in March 2008. Unlike the situation with $\Delta\mathcal{S}$, experimentally it is very firm. But for interpretation, opinions still differ.

2.2.1 Measurement of DCPV in $B^0 \to K^+\pi^-$ Decay

Just 3 years after the observation of TCPV in $B^0 \to J/\psi K^0$, Direct CPV (DCPV) in the B system was claimed in 2004 between BaBar and Belle [18, 19]. This attests to the prowess of the B factories, as it took 35 years for the same evolution in the K system [18, 19].

Unlike mixing-dependent CPV, where one needs decay time information and tagging, the experimental study of DCPV is just a counting experiment, hence much simpler. In the self-tagging modes such as $K^{\mp}\pi^{\pm}$, one simply counts the difference between the number of events in $K^-\pi^+$ vs. $K^+\pi^-$. Self-tagging means that a $K^-\pi^+$ would be decaying from a $\bar{B}^0$, while $K^+\pi^-$ comes from a B^0.

Of course, there is the standard rare B reconstruction techniques to reject continuum (from $e^+e^- \to q\bar{q}$, where q is a u, d, s, or c quark) and other backgrounds by some multivariate "filter" methods. We do not go into these technical details. But it is worthwhile to mention a special technique at the B factories that utilizes the kinematics of the $\Upsilon(4S)$ production environment. One reconstructs m_B of a potential candidate, by replacing the measured energy sum with the known center-of-mass beam energy. This trick utilizes the fact that for $\Upsilon(4S) \to B\bar{B}$ two-body production (which has 100% branching fraction), the B meson would carry exactly the CMS beam energy, $E_{\rm CM}/2$. One then checks the signal region around $\Delta E \sim 0$, where the energy difference between the measured energy sum and $E_{\rm CM}/2$ should vanish for a genuine B candidate, but for a background event it would not vanish.

Thus, the two standard variables are the *beam-constrained mass* $M_{\rm bc}$ (called "beam energy-substituted mass" by BaBar, m_{ES}) and the *energy difference* ΔE,

$$M_{\rm bc} = \sqrt{(E_{\rm CM}/2)^2 - \sum(\mathbf{p}_i)^2}, \quad \Delta E = \sum E_i - E_{\rm CM}/2, \tag{2.5}$$

where E_i and $\mathbf{p}_i$ are the measured energy and momentum for particle i, and $E_{\rm CM} = \sqrt{s}$ is precisely known from the accelerator. A correctly reconstructed B meson event would peak in $M_{\rm bc}$ and ΔE, as can be visualized by 1D projection plots illustrated in Fig. 2.6, while background events would not. Note that the $K^{\pm}$ and $\pi^{\pm}$ in $B \to K^{\pm}\pi^{\mp}, \pi^{\pm}\pi^{\mp}$ decays are rather highly boosted, hence PID performance is very critical for the separation of $K^{\pm}\pi^{\mp}$ vs. $\pi^+\pi^-$ events.

With these relatively standard techniques, it was a matter of time and providence (which specific mode) for one to eventually catch the first DCPV measurement, which happened to be the $B^0 \to K^+\pi^-$ mode.

Indications for a negative DCPV in this mode, defined as

$$\mathcal{A}_{K^+\pi^-} \equiv \mathcal{A}_{\rm CP}(B^0 \to K^+\pi^-) = \frac{\Gamma(\bar{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\bar{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)}, \tag{2.6}$$

(basically the same definition as in (A.2)) had been emerging for a couple of years. BaBar announced (using 227M $B\bar{B}$ pairs) a value [20] with 4.2σ significance just before ICHEP 2004, while at that conference, the Belle measurement [21] (using 275M $B\bar{B}$ pairs) was reported with 3.9σ significance. The M_{bc} and ΔE results from Belle are plotted in Fig. 2.6. It is clear by inspection that the number of $\bar{B}^0 \to K^-\pi^+$ events are fewer than $B^0 \to K^+\pi^-$. The combined Belle and BaBar result that year was $\mathcal{A}_{K^+\pi^-} = -0.114 \pm 0.020$, with 5.7σ significance, which established DCPV in the B system. The QCD Factorization (QCDF) approach had predicted the opposite sign [22], while the Perturbative QCD Factorization (PQCD)

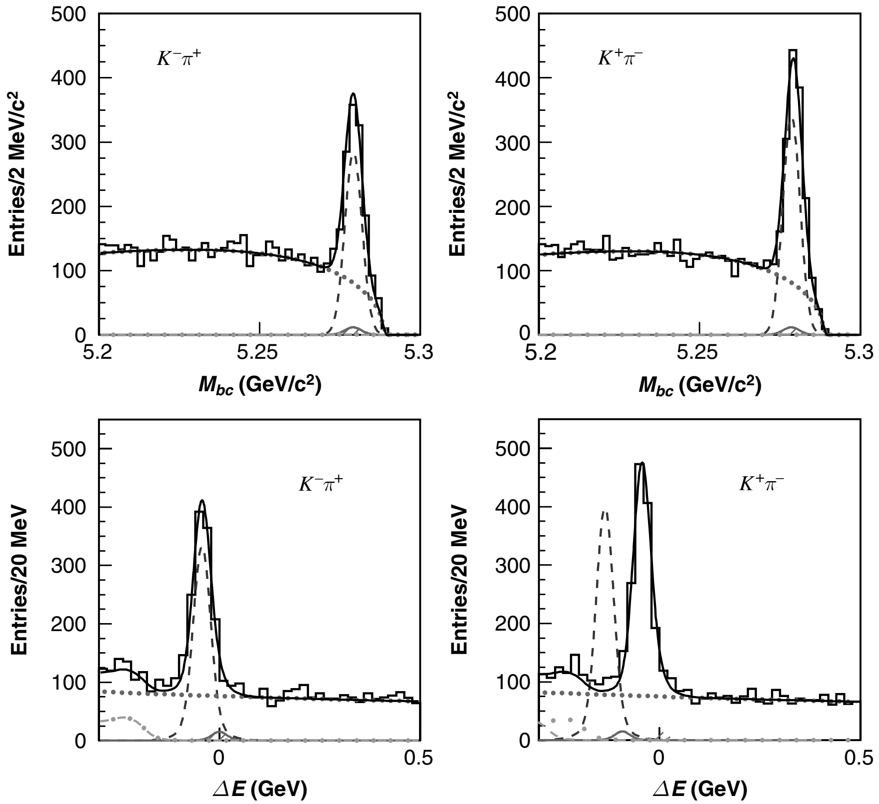

Fig. 2.6 M_{bc} and ΔE projection plots for $B^0 \to K^-\pi^+$ vs. $\bar{B}^0 \to K^+\pi^-$ from Belle [21] based on 275M $B\bar{B}$ pairs. [Copyright (2004) by The American Physical Society.] The CPV asymmetry is apparent, with more $K^+\pi^-$ events than $K^-\pi^+$

approach [23, 24] predicted the correct sign and magnitude. Thus, the measurement has implications for the theory of hadronic B decays.

The CDF experiment at the Tevatron has also measured $\mathcal{A}_{K^+\pi^-}$ with 1 fb^{-1} data [25] at 3.5σ significance, and the result is consistent with the B factories. Let us give a very brief account of the CDF study. Two opposite-charged track events from a common displaced vertex were selected. But there is not enough invariant mass resolution to separate different contributions clearly. Nor does CDF have sufficient PID capability to separate $K^\pm$ from $\pi^\pm$ in B decay (which is more boosted than at B factories). Using tagged $D^{*\pm}$ decays, charged K, π separation with dE/dx from tracker response is only at 1.4σ. But by combining kinematic and PID information into an unbinned maximum likelihood fit, CDF obtained $\mathcal{A}_{K^+\pi^-} = -0.086 \pm 0.023 \pm 0.029$, based on 1 fb^{-1} data. This should be compared with the latest values from BaBar [26], $-0.107 \pm 0.018^{+0.007}_{-0.004}$ (383M $B\bar{B}$), and Belle [17], $-0.094 \pm 0.018 \pm 0.008$ (535M $B\bar{B}$).

Comparing the BaBar and Belle studies, one can see that the analysis philosophy is slightly different, and in any case, the 5.5σ significance for BaBar vs. 4.8σ for Belle largely reflects a stronger central value for BaBar. Comparing CDF vs. the B factory results, one can see the effect of lack of PID on the systematic error. A statistical power of 1.6 fb^{-1} at CDF could already be comparable to current B factories. However, without improvement in systematic error, which is not likely to happen, CDF cannot be competitive in this study. The advent of LHCb should change the situation, since it has active RICH systems.

We have spent some effort describing how DCPV studies are done, at B factory vs. hadronic environment, largely for sake of comparison. Incorporating even the CLEO measurement [18, 19] done in 2000 (with just 9.7M $B\bar{B}$), the current world average [11] is

$$\mathcal{A}_{B^0\to K^+\pi^-} = -9.7 \pm 1.2\ \%. \tag{2.7}$$

This by itself does not suggest New Physics, but rather, it indicates the presence of a finite strong phase δ between the strong penguin (P) and tree (T) amplitudes, where the latter provides the weak phase via $V_{us}^* V_{ub}$. See Appendix A for a discussion. Most QCD-based factorization approaches failed to predict $\mathcal{A}_{K^+\pi^-}$, largely because of lack of control over how to properly generate δ.

Even in 2004, however, there was a whiff of a puzzle [21]. With large errors, $\mathcal{A}_{\rm CP}(B^+ \to K^+\pi^0)$ was found to be consistent with zero for both Belle and BaBar, and the mean was $\mathcal{A}_{K^+\pi^0} = +0.049 \pm 0.040$. We plot the M_{bc} and ΔE results from Belle in Fig. 2.7. Comparing with the 2004 mean value of -0.114 ± 0.020 for $\mathcal{A}_{K^+\pi^-}$ (see Fig. 2.6 for the corresponding Belle plot), there seemed to be a difference[4] between DCPV in $B^+ \to K^+\pi^0$ and $B^0 \to K^+\pi^-$, a point which was emphasized already in the Belle paper [21].

The difference between the charged and neutral mode has steadily strengthened since 2004, and the current [11] average of

$$\mathcal{A}_{B^+\to K^+\pi^0} = +5.0 \pm 2.5\ \% \tag{2.8}$$

shows some significance for the sign being *positive*, i.e., opposite to the sign of $\mathcal{A}_{K^+\pi^-}$ in (2.7).

2.2.2 $\Delta\mathcal{A}_{K\pi}$ and New Physics

In a recent paper published in *Nature*, the Belle collaboration used 535M $B\bar{B}$ pairs to demonstrate the difference [17]

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[4] Actually, the 2003 value by BaBar, with 88M $B\bar{B}$ pairs, was $\mathcal{A}_{K^+\pi^0} = -0.09 \pm 0.09 \pm 0.01$. But with 227M $B\bar{B}$ pairs, the 2004 value by BaBar changed sign [27], becoming $\mathcal{A}_{K^+\pi^0} = +0.06 \pm 0.06 \pm 0.01$. Combining with the positive value of Belle, $\mathcal{A}_{K^+\pi^0} = +0.04 \pm 0.05 \pm 0.02$ (based on 275M $B\bar{B}$), this made the difference between $\mathcal{A}_{K^+\pi^0}$ and $\mathcal{A}_{K^+\pi^-}$ stand out already in 2004.

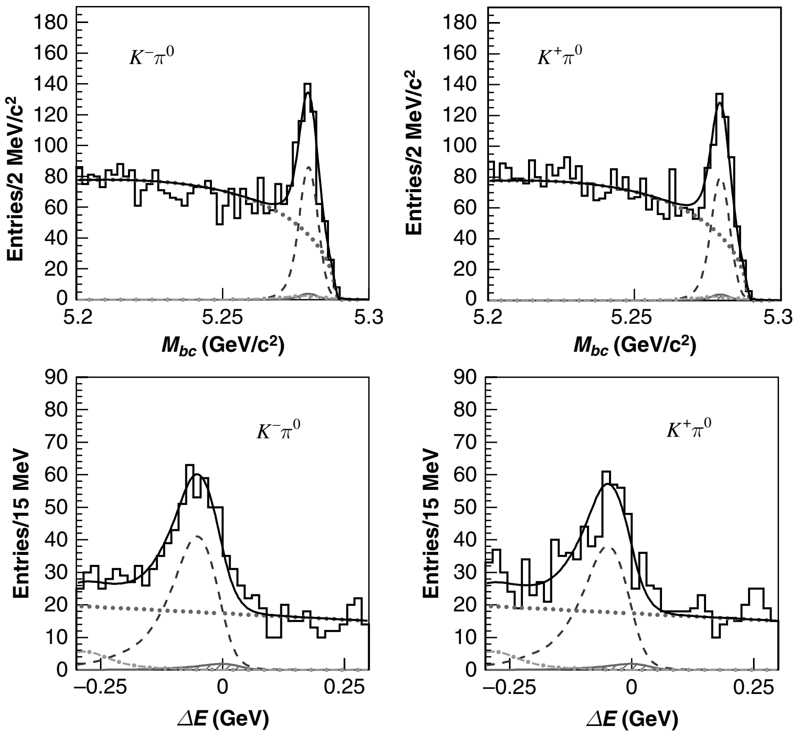

Fig. 2.7 M_{bc} and ΔE projection plots for $B^+ \to K^+\pi^0$ vs. $B^- \to K^-\pi^0$ from Belle [21], based on 275M $B\bar{B}$ pairs. [Copyright (2004) by The American Physical Society.] The CPV asymmetry is consistent with zero, with a slight hint for more $K^-\pi^0$ events

$$\Delta\mathcal{A}_{K\pi} \equiv \mathcal{A}_{K^+\pi^0} - \mathcal{A}_{K^+\pi^-} = +0.164 \pm 0.037, \tag{2.9}$$

with 4.4σ significance by a single experiment, and emphasized the possible indication for New Physics. As mentioned, the Belle effort traces back to the 2004 paper [21], where the difference was already noted. One difference with BaBar is that, even in 2004, the Belle paper covered both $B^+ \to K^+\pi^0$ and $B^0 \to K^+\pi^-$ studies. The comparison, and potential implications of a difference, was already emphasized. Noticing the curiosity, Belle conducted a meticulous study with a data set that is twice as large, which resulted in the *Nature* paper. BaBar, however, published the $B^+ \to K^+\pi^0$ mode [28] separately from the $B^0 \to K^+\pi^-$ [26], bundling it together with the $\pi\pi^0$ modes. The approach and physics emphasis was therefore very different from those of Belle's.

The world average [11] for the direct CPV difference is

$$\Delta\mathcal{A}_{K\pi} = 0.147 \pm 0.027, \tag{2.10}$$

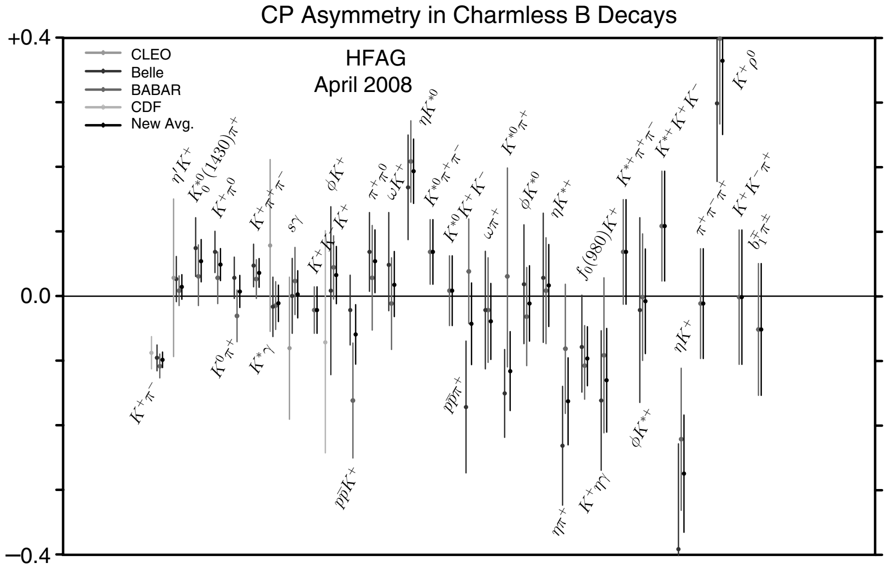

Fig. 2.8 HFAG plot for DCPV measurements in various charmless B decay modes. (Winter 2008 results from HFAG, used with permission.) The difference between $\mathcal{A}_{K^+\pi^0}$ and $\mathcal{A}_{K^+\pi^-}$ could indicate [17, 29] New Physics

which has more than 5σ significance. That there is a real difference is now an experimental fact. We plot in Fig. 2.8 the current status of DCPV in B decays. We see that $\mathcal{A}_{K^+\pi^-}$ is clearly established, while no other mode reaches a similar level of significance, and there is a wide scatter in central values. So why is the $\Delta\mathcal{A}_{K\pi}$ difference a puzzle, that it might indicate New Physics [17, 29]?

For the B^0 decay mode, one has the amplitude (see Fig. A.3)

$$\mathcal{M}(B^0 \to K^+\pi^-) = T + P \;\propto\; r\,e^{i\phi_3} + e^{i\delta}, \tag{2.11}$$

where $\phi_3 = \arg V_{ub}^*$, δ is the strong phase difference between the tree amplitude T and strong penguin amplitude P, and $r \equiv |T/P|$ is the ratio of tree vs. penguin amplitude strength. It is the interference between the two kinds of phases (Appendix A) that generates DCPV, i.e., $\mathcal{A}_{K^+\pi^-} \equiv \mathcal{A}_{\rm CP}(K^+\pi^-)$.

We remark that for TCPV, the equivalent to the strong phase is $\delta = \Delta m_B \Delta t$, where Δm_B is the already well-measured B^0–$\bar{B}^0$ oscillation frequency, and Δt is part of the time-dependent measurement. This is the beauty [2] of mixing-dependent CPV studies, that it is much less susceptible to hadronic effects, especially in single amplitude processes such as the tree-dominant $B^0 \to J/\psi K^0$ mode. One has *direct access* to the CPV phase of the B^0–$\bar{B}^0$ mixing amplitude, which is the equivalent of ϕ_3 in (2.11). In comparison, DCPV relies on the presence of strong interaction phase differences. The hadronic nature of these *CP* invariant phases makes them difficult

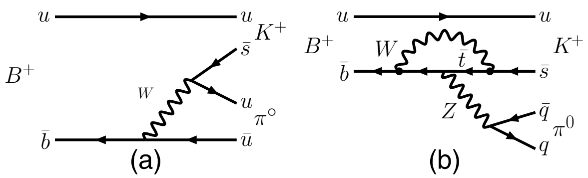

Fig. 2.9 (**a**) Color-suppressed tree diagram (C) and (**b**) electroweak penguin diagram ($P_{\rm EW}$) for $B^+ \to K^+\pi^0$

to predict. Although DCPV is one of the simplest things to measure experimentally, the strong phase difference in a decay amplitude is usually hard to extract.

The $B^+ \to K^+\pi^0$ decay amplitude is similar to the $B^0 \to K^+\pi^-$ one, up to subleading corrections, that is

$$\sqrt{2}\mathcal{M}_{K^+\pi^0} - \mathcal{M}_{K^+\pi^-} = C + P_{\rm EW}, \tag{2.12}$$

where C is the color-suppressed tree amplitude, while $P_{\rm EW}$ is the electroweak penguin (replacing the virtual gluon in P by Z or γ) amplitude. These diagrams are illustrated in Fig. 2.9. In the limit that these subleading terms vanish, one expects $\Delta\mathcal{A}_{K\pi} \sim 0$. For a very long time before the experimental advent, this was broadly expected to be the case. But, eventually, it turned out contrary to the experimental result of (2.10). We therefore understand why something like this was not predicted by any calculations.

Large *C*? Need Large "Finesse"!

Could C be greatly enhanced? This is certainly an option, and it is the attitude taken by many [30]. Indeed, fitting with data, one finds $|C/T| > 1$ is needed [31], in strong contrast to the very tiny value for C suggested 10 years ago [32]. Note that from the usual nonperturbative large N_C expansion perspective, one expects color suppression to be stronger than $1/N_C$. There is further difficulty for an enhanced C amplitude. As this amplitude has the same weak phase ϕ_3 as T, the enhancement of C has to contrive in its strong phase structure to cancel the effect of the strong phase difference δ between T and P that helped induce the sizable $\mathcal{A}_{K^+\pi^-}$ of (2.7) in the first place. The amount of "finesse" needed is therefore quite considerable. This point seems to have been deemphasized by the casual attitude taken by many across the Atlantic Ocean.

It should be stressed that the difference $\Delta\mathcal{A}_{K\pi}$ was *not* anticipated by any calculations beforehand, and theories that do possess calculational capabilities[5] have

[5] For the noncalculational approaches of fitting data with T, P, C, and $P_{\rm EW}$, etc., we stress that they are just that, fitting to data. Without being able to compute these contributions, they are saying nothing more than "Data implies a large C," which is a tautological statement in essence, or a mere translation of data. For example, in the pre-B factory era, by *assuming* $|C| \ll |T|$, there was the suggestion [33] to combine $\mathcal{A}_{\rm CP}(K^+\pi^0)$ with $\mathcal{A}_{\rm CP}(K^+\pi^-)$ for sake of increasing statistics. With

only played catching up, after the experimental fact. In Perturbative QCD (PQCD) Factorization calculations at Next to Leading Order (NLO) [34], taking cue from data, C does move in the right direction. But the central value is insufficient to account for experiment, and the claim to consistency with data is actually hiding behind large errors. For QCD Factorization (QCDF), it has been declared [35] that $\Delta\mathcal{A}_{K\pi}$ is difficult to explain, that it would need very large and *imaginary* C (or electroweak penguin) compared to T, which is "Not possible in SM plus factorization [approach]." In the Soft Colinear Effective Theory (SCET) approach [36], which is rather sophisticated, $\mathcal{A}_{K^+\pi^0}$ is actually predicted, in 2005, to be even more negative than $\mathcal{A}_{K^+\pi^-}$, where the latter has been taken as input. In a way, the SCET proponents were wishing the $\Delta\mathcal{A}_{K\pi}$ to go away. But the $\Delta\mathcal{A}_{K\pi}$ problem has persisted, and SCET people have now admitted to the problem [37]. On whether it could be New Physics, SCET needs to "see a coherent pattern of deviations," before it can be convinced about the need for New Physics. Perhaps we will have more convincing information emerging (soon), as discussed in the next section. In any case, the problem appears to be with SCET itself, rather than with experiment.

Large $P_{\rm EW}$? Then New Physics!

The other option is to have a large CPV contribution from the electroweak penguin [29, 31, 38] amplitude, $P_{\rm EW}$. The interesting point is that *this calls for a New Physics CPV phase*, as it is known that $P_{\rm EW}$ carries practically no weak phase within SM ($V_{ts}^*V_{tb}$ is practically real, see (A.4)) and has almost the same strong phase as T [39].

— So, what New Physics can this be? —

Note that this would not so easily arise from SUSY, since SUSY effects tend to be of the "decoupling" kind, compared to the *nondecoupling* of the top quark effect already present, in fact dominating, in the Z penguin loop.[6] The latter is very analogous to what happens in box diagrams.

So, can there be more *nondecoupled* quarks beyond the top in the Z penguin loop? This is the so-called (sequential) fourth generation. It would naturally bring into the $b \to s\bar{q}q$ electroweak penguin amplitude $P_{\rm EW}$ (but not so much in the strong penguin amplitude P) a new CPV phase, in the new CKM product $V_{t's}^*V_{t'b}$.

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experimental indication that $|C/T|$ is finite, the same mentality flips over [30] to allow C/T, both in strength and (strong) phase, to be free parameters.

[6] In Fig. 2.4, we compared the gluonic penguin P for $b \to s\bar{s}s$ in SM with a possible SUSY effect through $\tilde{b}$–$\tilde{s}$ mixing. This is possible in SUSY. Unlike the Z penguin, the top quark mass effect in the gluonic penguin largely decouples, as it is weaker than logarithmic dependence [40]. The usual image of top dominance in the strong penguin loop is somewhat misplaced. It really is just due to operator running from W scale, rather than a genuine heavy top mass effect. It does rely on m_t being heavier than M_W, but QCD running between m_t and M_W is rather mild.

It was shown [38] that (2.9) can be accounted for in this extension of SM. We will look further into this, after we discuss NP prospects in B_s mixing.

With the two hints for New Physics in $b \to s$ penguin modes, i.e., the ΔS (TCPV) and $\Delta\mathcal{A}_{K\pi}$ (DCPV) problems, one might expect possible NP in B_s mixing. Note that recent results for Δm_{B_s} and $\Delta\Gamma_{B_s}$ are SM-like. However, the real test clearly should be in the CPV measurables, $\sin 2\Phi_{B_s}$ and $\cos 2\Phi_{B_s}$, as the NP hints all involve CPV. This is the subject of the next section.

2.3 $\mathcal{A}_{\rm CP}(B^+ \to J/\psi K^+)$

If the $\Delta\mathcal{A}_{K\pi}$ problem is genuinely rooted in the electroweak penguin amplitude $P_{\rm EW}$, one can infer a corollary to be checked relatively quickly as a confirmation. Rather than becoming a π^0, the Z^* from the effective bsZ^* vertex could produce a J/ψ. If there is New Physics in the $B^+ \to K^+\pi^0$ electroweak penguin, one can then contemplate DCPV in $B^+ \to J/\psi K^+$ as a probe of NP.

$B^+ \to J/\psi K^+$ decay is of course dominated by the color-suppressed $b \to c\bar{c}s$ amplitude (Fig. 2.10(a)), which is proportional to the CKM element product $V_{cs}^* V_{cb}$ that is real to very good approximation. At the loop level, the penguin amplitudes are proportional to $V_{ts}^* V_{tb}$ in the SM. Because $V_{us}^* V_{ub}$ is very suppressed, $V_{ts}^* V_{tb} \cong -V_{cs}^* V_{cb}$ is not only practically real (see (3.5) in Chap. 3), it has the same phase as the tree amplitude and can be absorbed into it, as far as the CKM factor is concerned. Hence, it is commonly argued that DCPV is less than 10^{-3} in this mode, and $B^+ \to J/\psi K^+$ has often been viewed as a calibration mode in search for DCPV. However, because of possible hadronic effects, there is no firm prediction that can stand scrutiny. A recent calculation [41] of $B^0 \to J/\psi K_S$ that combines QCDF-improved factorization and the PQCD approach confirms the three generation SM expectation that $\mathcal{A}_{\rm CP}(B^+ \to J/\psi K^+)$ should be at the 10^{-3} level. Thus, if % level asymmetry is observed in the next few years, it would support the scenario of New Physics in $b \to s$ transitions, in particular, stimulating theoretical efforts to compute the strong phase difference between C and $P_{\rm EW}$.

We shall argue that, in the fourth-generation scenario, DCPV in $B^+ \to J/\psi K^+$ decay could be at the % level. We give the electroweak penguin amplitude in SM in Fig. 2.10(b). Within SM, the same remark as before holds, and little CPV is generated. But, as we have seen for $B \to K\pi$ decay, if $P_{\rm EW}$ picks up a sizable New

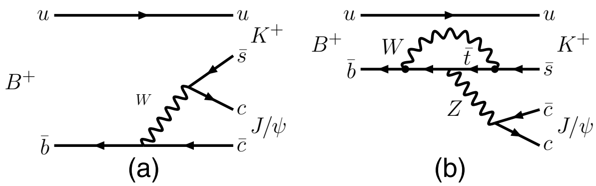

Fig. 2.10 (**a**) Color-suppressed tree diagram (C) and (**b**) electroweak penguin diagram ($P_{\rm EW}$) for $B^+ \to K^+ J/\psi$

Physics CPV phase, then it can interfere with the C amplitude and generate DCPV, if there is a strong phase difference. More generally, one can view the $P_{\text{EW}}(b \to s\bar{c}c)$ amplitude as a four-quark operator (e.g., Z' models). Then the CPV phase of this amplitude is not constrained by the effect in $B \to K^+\pi^0$.

The experiment so far is consistent with zero, but has a somewhat checkered history [18]. Belle has not updated from their 2003 study based on a mere 32M $B\bar{B}$ pairs, although they now have more than 25× the data. BaBar's study flipped sign from the 2004 study based on 89M to the 2005 study based on 124M, which seemed dubious at best. However, the sign was flipped back in PDG 2007, simply because it was found that the 2005 paper used the opposite convention to the (standard) one used for 2004. The opposite sign between Belle and BaBar suppresses the central value, but the error is at 2% level. This already rules out, for example, the suggestion [42] of enhanced H^+ effect at 10% level.

One impediment to the further study of the available higher statistics at the B factories is the control of the systematic error. It seems formidable to break the 1% barrier. Recent progress has been made, however, by the DØ experiment at the Tevatron. Based on 2.8 fb^{-1} data, DØ reconstructed around 40000 $B^\pm \to J/\psi K^\pm$ events, together with $\sim$1600 $B^\pm \to J/\psi\pi^\pm$. The $M(J/\psi K)$ distribution is shown in Fig. 2.11. Of course, the more important issue is systematics control. DØ measures [43]

$$\mathcal{A}_{B^+\to J/\psi K^+} = 0.75 \pm 0.61 \pm 0.27\ \% \quad (\text{DØ}). \tag{2.13}$$

We should note that there is a correction twice as large as the central value in (2.13) for the $K^\pm$ asymmetry due to detector effects, because the detector is made of *matter*. This is because the K^-N cross section is different from K^+N cross section, especially for lower p_K, because of the $\bar{u}$ quark. This leads to lower reconstruction

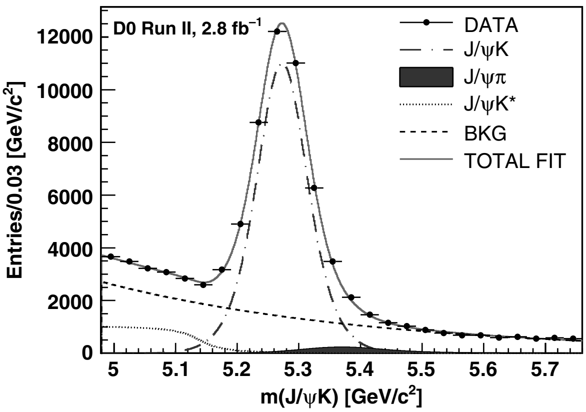

Fig. 2.11 $M(J/\psi K)$ distribution for $B^\pm \to J/\psi\ K^\pm$ events by DØ [43] with 2.8 fb^{-1} data [Copyright (2008) by The American Physical Society], where there is a rather small component for $B^\pm \to J/\psi\pi^\pm$

efficiency for K^-. This "kaon asymmetry" from detector effect is directly measured in the same data. One enjoys a larger control sample in hadronic production, as compared with B factories. DØ compares $D^* \to D^0\pi^+$ ($D^0 \to \mu^+\nu K^-$) with the charge conjugate process, and the kaon asymmetry is measured for different kaon momentum and convoluted with $B \to J/\psi K$ decay. It was found that the detector-matter-induced asymmetry for $B \to J/\psi K$ is of order -0.0145. Correcting the measured one at order -0.007 gives (2.13). One other crucial aspect of the DØ analysis is the cancellation of reconstruction efficiency differences between positive and negative particles. For these purposes, DØ periodically reverses the magnet polarity for equivalent periods.

Overall, in comparison to the challenge at the B factories, of special note is the rather small (roughly a quarter % !) systematic error of the DØ measurement. Thus, even scaling up to 6–8 fb^{-1}, one is still statistics limited, and 2σ sensitivity for % level asymmetries could be attainable. CDF should have similar sensitivity (except the issue of magnet polarity flip), and the situation can drastically improve with LHCb data once it becomes available.

The Tevatron measurement was in fact inspired by a theoretical fourth-generation study [44], which followed the lines that have already been presented in the previous sections. The fourth-generation parameters are taken from the $\Delta\mathcal{A}_{K\pi}$ study [38]. By making analogy with what is observed in $B \to D\pi$ modes, and especially between different helicity components in $B \to J/\psi K^*$ decay, the dominant color-suppressed amplitude C for $B^+ \to J/\psi K^+$ would likely possess a strong phase of order 30°. The $P_{\rm EW}$ amplitude is assumed to factorize and hence does not pick up a strong phase. Heuristically, this is because the Z^* produces a small, color singlet $c\bar{c}$ that penetrates and leaves the hadronic "muck" without much interaction, subsequently projecting into a J/ψ meson. With a strong phase in C and a weak phase in $P_{\rm EW}$, one then finds $\mathcal{A}_{B^+\to J/\psi K^+} \simeq \pm 1\%$.

We plot $\mathcal{A}_{B^+\to J/\psi K^+}$ vs. strong phase difference δ in Fig. 2.12, with weak phase ϕ_{sb} fixed to the range corresponding to (3.25), and the notation is as in Fig. 3.11 (we refrain until Chap. 3, when the motivation is further strengthened, for a more

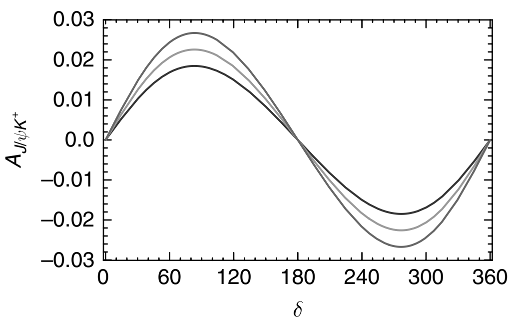

Fig. 2.12 $\mathcal{A}_{B^+\to J/\psi K^+}$ vs. strong phase difference δ between C and $P_{\rm EW}$ in the fourth-generation model [44]. A nominal $\delta \sim 30°$ is expected from strong phases in $J/\psi K^*$ mode. Negative asymmetries are ruled out by the DØ result given in (2.13)

detailed discussion of the fourth-generation scenario). The negative sign is ruled out by the DØ result (2.13). But, of course, DCPV is directly proportional to the strong phase difference, which is not predicted, so $\mathcal{A}_{B^+\to J/\psi K^+} \sim +1\%$ is consistent with the DØ result and can be probed further.

We remark that other exotic models like Z' with FCNC couplings could also generate various effects we have discussed. For example, with $\delta \sim 30^\circ$, $\mathcal{A}_{B^+\to J/\psi K^+}$ could be considerably larger than a percent. With the DØ result of (2.13), however, only % level asymmetries are allowed, ruling out a large (and in any case quite arbitrary) region of parameter space for possible Z' effects.

2.4 An Appraisal

In Chap. 1, we teased with the earlier possible hint that $\sin 2\phi_1/\beta$ could be much smaller than expected. However, the SM expectation was subsequently rather quickly affirmed. It is remarkable that the studies so far confirm the three-generation CKM unitarity triangle for $b \to d$ transitions (1.6).

With unprecedented luminosities (see Fig. 1.2), there were high hopes for the B factories to uncover some Beyond the Standard Model physics, in particular in CPV in $b \to s\bar{q}q$ decays. There were indeed ups and downs, excitements and disappointments. The $B^0 \to \phi K_S$ TCPV splash, gradually faded with more data and more modes, though it has never fully gone away. The ΔS problem is indeed a nagging one: experimentally it is not even established, while theoretically it is hampered by hadronic uncertainties, which further vary from mode to mode, making the combination of modes dubious.

For the $\mathcal{A}_{B^+\to K^+\pi^0}$ vs. $\mathcal{A}_{B^0\to K^+\pi^-}$ DCPV difference, experimentally it is genuine. But the presence of a possible C amplitude, though rather demanding on factorization calculations, has seemingly made the majority so far carry the doubt that this $\Delta\mathcal{A}_{K\pi}$ problem is yet another hadronic effect. Perhaps people suffer from the "cry wolf" syndrome due to the long-suffering ΔS saga. But *remember, the wolf did come eventually.*

Personally, we believe there is a rather good possibility that the $\Delta\mathcal{A}_{K\pi}$ problem is a genuine harbinger for New Physics in CPV $b \to s\bar{q}q$ transitions. We will continue to discuss this in the Chap. 3, on the implications for $\sin 2\Phi_{B_s}$ measurement. However, the problem of hadronic uncertainties for hadronic $b \to s\bar{q}q$ transitions cannot be taken lightly. Even for DCPV in $B^+ \to J/\psi K^+$, although it has often been used as a calibration mode, if it emerges experimentally at the 1% level, as discussed in the previous section, people would still question what is the genuine value within SM, whether it cannot reach subpercent level, i.e., again attributing it to "hadronic uncertainty."

To top it off, and in comparison, we mention briefly the surprisingly large transverse polarization in several charmless $B \to VV$ final states that emerged around 2004. When this emerged experimentally [18], e.g., f_L or the longitudinal polarization fraction, in $B \to \phi K^*$ was only 50%, it was suggested [45] that this could be due to New Physics. However, this is now widely believed to be due to hadronic physics, maybe due to [46] our unfamiliarity with the $B \to K^*$ form factor A_0. What convinced us that this is likely not New Physics is from the polarization and triple-product correlation measurements [47].

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