Search for TeV Scale Physics in Heavy Flavour Decays

George W.S. Hou
Department of Physics, National Taiwan University, Taipei, Taiwan 10617, R.O.C.

Abstract. The subject of heavy flavour decays as probes for physics at and beyond the TeV scale is covered from the experimental perspective. Emphasis is placed on the more traditional Beyond the Standard Model topics that have potential for impact in the early LHC era, and in anticipation of the B factory upgrade(s). The aim is to explain the physics, without getting too involved in the details, whether experimental or theoretical, to give the interested nonexpert a perspective on the Flavour/TeV link. We cover the forefront topics of CP violation in $b \to s$ transitions involving penguin and box diagrams, and probes of charged Higgs, right-handed and scalar interactions. We touch briefly on $T$ decay, $D^0$ mixing, rare $K$ decays, and lepton flavor violating probes in $\tau$ decay. Our own phenomenology work is often used for illustration.

1 Introduction

As humans we aspire to reach up to the heavens, beyond the veiling clouds of the v.e.v. scale. The conventional high energy approach, such as the LHC, is like the fabled Jack climbing the bean stalk, where impressions are that the Higgs boson may be just floating in a low cloud close by. But then maybe not. It, or the something, may lie up above the darker clouds of the v.e.v. In this direct ascent approach, Jack has to be fearful of the Giant, which in this case could even be the projects like LHC and ILC themselves; the cost is becoming so forbidding, Jack may not be able to return. However, “Jack” may not have to actually climb the bean stalk: quantum physics allows him to stay on Earth, and let virtual “loops” do the work. The virtual Jack has no fear of getting eaten by the Giant. This parable illustrates how flavour physics offers probes of the TeV scale, at much reduced costs. The flavour connection to TeV scale physics is typically through loops.

A further “parable” illustrates the potential for making impact. Let us entertain a hypothetical “What if?” question, by forwarding to the recent past. On July 31, 2000, the BaBar experiment announced at the Osaka conference the low value of $\sin 2\beta \sim 0.12$. The value for the equivalent $\sin 2\phi_1$ from the Belle experiment was slightly higher, but also consistent with zero. Within the same day, a theory paper appeared on the arXiv [1], entertaining the (New Physics) implications of the low $\sin 2\beta$ value. It seems some theorists have power to “wormhole” into the future! A year later, however, both BaBar and Belle claimed the observation of $\sin 2\beta/\phi_1 \sim 1$, which turn out to be consistent with Standard Model (SM) expectations. But, what if it stayed close to zero? Well, it didn’t. Otherwise, you would have heard much more about it: a definite large deviation from the SM has been found! For even in the last century, one expected from indirect data that $\sin 2\beta/\phi_1$ had to be nonzero within SM.

Note that in SM, $\beta/\phi_1 = -\arg V_{td}$ [3]. The measurement of $\sin 2\beta/\phi_1$ is the measurement of the $CP$ violating (CPV) phase in the $B^0\bar{B}^0$ mixing matrix element $M_{12}^d$. We recall that the discovery of $B^0\bar{B}^0$ mixing itself by the ARGUS experiment [4] 20 years ago was the first clear indication that $m_t$ is heavy, a decade before the top quark was actually discovered at the Tevatron. With the $B^0\bar{B}^0$ mixing frequency $\Delta m_{B_d}$ proportional to $|V_{td}|^2 m_t^2$, it is the template of flavour loops as probes into high energy scales. So let us learn from it.

The $B^0\bar{B}^0$ mixing amplitude $M_{12}^d$ is generated by the box diagram involving two internal $W$ bosons and top quarks in the loop. Normally, heavy particles such as the top would decouple in the heavy $m_t \to \infty$ limit. However,
the longitudinal component of the W boson, which is a charged Higgs scalar that got eaten by the W through spontaneous symmetry breaking, couples to the top quark mass. This gives rise to the nondecoupling of the top quark from the box diagram, i.e. $M_W^2 \sim (V_{tb} V_{td}^*)^2 m_t^2$ to first approximation. It illustrates the Higgs affinity of heavy SM-like quarks (called chiral quarks), i.e. $\lambda_t \sim 1$, which brings forth $V_{td}^2$, the CPV phase of which is $\sin 2\beta/\phi_1$, which was measured by the B factories in 1997.

As we will only be interested in New Physics (NP), we note that extensive studies at the B factories (and elsewhere) indicate that $b \rightarrow d$ transitions are consistent with the SM [5], i.e. no discrepancy is apparent with the CKM (Cabibbo-Kobayashi-Maskawa) triangle [3]

$$V_{td}^*V_{ub} + V_{td} V_{ub} + V_{td}^*V_{ub} = 0,$$  \hspace{1cm} (1)

which is the $db$ element of $V^*V = I$. This is illustrated in Fig. 1. An enormous amount of information and effort has gone into this figure, the phase of $V_{td}^*V_{ub}$ being only one eminent entry. In general, we see no deviation from CKM expectations.

What about $b \rightarrow s$ transitions? This will be our starting point and the main theme.

The outline of this brief review is as follows. In the next section we cover the main subject of CPV search in loop-induced $b \rightarrow s$ transitions: the mixing-dependent CPV difference $\Delta S$ between $b \rightarrow c\bar{s}s$ and $s\bar{q}q$ processes; the direct CPV difference $\Delta A_{K\pi}$ between $B^+ \rightarrow J/\psi K^+$ and $B^0$; the status and prospects for measuring the CPV phase $2\Phi_{B_s}$ involved in $B_s$ mixing, in particular whether it could be large; and direct CPV in $B^+ \rightarrow J/\psi K^+$ decay. In Sec. 3, we turn to $b \rightarrow s\gamma$ and $B^+ \rightarrow \tau^+\nu$ to illustrate forefront probes of the charged Higgs boson $H^+$. In Sec. 4, we use the forward-backward asymmetry in $B \rightarrow K^{(*)}\ell^+\ell^-$ to illustrate how such electroweak penguin processes probe the $bsZ$ vertex and related physics, and $B \rightarrow K^{(*)}\nu\nu$ search as a window on light dark matter. In Sec. 5, we use time-dependent CPV in $B^0 \rightarrow K_S\pi^0\gamma$ to illustrate the probes of right-handed dynamics, and $B_s \rightarrow \mu^+\mu^-$ as probes of the extended Higgs sector. This brings us to a “detour” in Sec. 6, to discuss the utility of the bottomonium system as probes of light dark matter and exotic light Higgs bosons. We then turn briefly to loop effects in $D^0$ mixing and rare $K$ decays in Sec. 7, and lepton flavor violation in $\tau$ decays in Sec. 8, before closing with some discussions, and offering our conclusion. As this is a contribution to a memorial volume dedicated to Julius Wess, a tribute is given as epilogue. In an Appendix, we briefly introduce the mechanism for CPV.

2 CPV in $b \rightarrow s$: On Boxes and Penguins

The subject of CPV studies in charmless $b \rightarrow s$ transitions is the current frontier of heavy flavour research. As $3 \rightarrow 2$ transitions involving quarks, the subject also has $\tau \rightarrow \mu$ echoes in the lepton sector, which will be discussed later. We focus on four topics: $\Delta S$, $\Delta A_{K\pi}$, $\sin 2\Phi_{B_s}$, and $A_{\mu^+\mu^-}\sim J/\psi K^+$. Further charmless $b \rightarrow s$ probes are discussed in subsequent sections.

2.1 The $\Delta S$ Problem

The B factories were built to measure time-dependent CPV (TCPV) in the $B^0 \rightarrow J/\psi K_S$ mode. One utilizes the coherent production of $B^0\bar{B}^0$ pairs from $\Upsilon(4S)$ decay, and

1) reconstruct one $B$ decay to a CP eigenstate,

2) tag the other $B$ meson flavour ($B^0$ or $\bar{B}^0$),

3) measure both the $B$ decay vertices.

The BaBar and Belle (the latter illustrated schematically in Fig. 2) detectors are rather similar, differing basically only in the particle identification detector (PID) used for flavour tagging, the task of charged $K/\pi$ separation at various energies. Belle uses Aerogel Cherenkov Counters, a threshold device, and a TOF system, while BaBar uses the the DIRC, basically a system of quartz bars that guide Cherenkov photons and project them into a water tank at the back end of the detector.

The real novelty of the B factories is the asymmetric beam energies. The $\beta\gamma$ factor for the produced $\Upsilon(4S)$ is 0.56 and 0.43, respectively. Boosting the $B^0$ and $\bar{B}^0$ mesons allow the time difference $\Delta t \equiv \Delta z/\beta\gamma c$ to be inferred from the decay vertex difference $\Delta z$ in the boost direction, while the proximity of $2m_{B_s}$ 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 outstrip PEP-II in the instantaneous luminosity, and surpassing in integrated luminosity as well in the following year. In April 2008, PEP-II dumped its beam for the last time.

With the measurement of TCPV in $B^0 \rightarrow J/\psi K_S$ settled in summer 2001, attention quickly turned to the $b \rightarrow s$ penguin modes, where a virtual gluon is emitted from the virtual top quark in the vertex loop. Let us take $B^0 \rightarrow \phi K_S$ as example, where the virtual gluon pops out an $s\bar{s}$ pair. The $b \rightarrow s$ penguin amplitude is practically real within SM, just like the tree level $B^0 \rightarrow J/\psi K_S$. This is because $V_{ts}^*V_{ub}$ is very suppressed. Thus, SM predicts

$$S_{\phi K_S} \equiv \sin 2\phi_1/\beta, \hspace{1cm} (\text{SM})$$  \hspace{1cm} (2)

where $S_{\phi K_S}$ is the analogous TCPV measure in the $B^0 \rightarrow \phi K_S$ mode. New physics induced flavour changing neutral

![Fig. 2. Schematic picture of the Belle detector.](image-url)
current (FCNC) and CPV effects, such as having supersymmetric (SUSY) particles in the loop (for example, $\tilde{b}_R$–$\tilde{s}_R$ squark mixing) could break this equality, prompting the experiments to search vigorously.

Many might remember the big splash made by Belle in summer 2003, where $S_{\phi K_S}$ was found to be opposite in sign [6] to $\sin 2\phi_1/\beta$, where the significance of deviation was more than $3\sigma$. But the situation softened by 2004 and it is now far less dramatic. But some deviation has persisted in an interesting if not nagging kind of way. Comparing to the average of $S_{c\bar{c}K_S} = 0.681 \pm 0.025$ [5] over $b \rightarrow c\bar{c}s$ transitions, $S_f$ is smaller in practically all $b \rightarrow s\bar{q}q$ modes measured so far (see Fig. 3), with the naive mean$^2$ of $S_{c\bar{c}q} = 0.56 \pm 0.05$ [5]. The deviation is only $2.2\sigma$, and the significance has been slowly diminishing. We stress, however, that the persistence over several years, and in multiple modes, together make this “$\Delta S$ problem” a potential indication for New Physics from the B factories, and should be taken seriously.

The point is that theoretical studies, although troubled by hadronic effects, all give $S_{\bar{q}q}$ values that are above $S_{c\bar{c}s}$. A model-independent geometric approach suggests [7] that, with enough precision, a deviation as little as a couple of degrees would indicate New Physics. Alas, BaBar has ended its data taking, while Belle would stop for (hopeful) upgrade after reaching 1 ab$^{-1}$, so the dataset for analysis can only double within the present B factory era, which is coming to an end. One may think that the LHC, which is turning on in 2008, the LHCb experiment in particular, could make great impact. But because of lack of good vertices, presence of neutral ($\pi^0, \gamma$) particles, in the leading channels of $J/\psi K_S, \phi K_S$ and $K_S\pi^0$, the situation may not improve greatly with LHCb data. Thus, the $\Delta S$ problem would need a Super B Factory to clarify.

### 2.2 The $\Delta A_{K\pi}$ Problem

There is a second possible indication for physics beyond SM (BSM) in $b \rightarrow s\bar{q}q$ decays. It is by now widely known because of Belle effort, and, unlike the $\Delta S$ situation, experimentally it is very firm.

Just 3 years after the observation of TCPV in $B^0 \rightarrow J/\psi K^-$, direct CPV (DCPV) in the B system was claimed in 2004 between BaBar and Belle [3]. This attests to the prowess of the B factories, as it took 35 years for the same evolution in the K system. The CDF experiment recently joined the club, with results consistent with the B factories. The current world average [5] is $A_{K^+\pi^-} = -9.7 \pm 1.2\%$. This by itself does not suggest New Physics, but rather, it indicates the presence of a finite strong phase between the strong penguin (P) and tree (T) amplitudes, where the latter provides the weak phase (for a primer on CPV, see the Appendix). Most QCD based factorization approaches failed to predict $A_{K^+\pi^-}$.

Even in 2004, however, there was a whiff of a puzzle [8]. In contrast to the negative value for $B^0 \rightarrow K^+\pi^-$, DCPV in the charged $B^+ \rightarrow K^+\pi^0$ mode was found to be consistent with zero for both Belle and BaBar. The difference between the charged and neutral mode has steadily strengthened, where the current [5] $A_{K^+\pi^0} = +5.0 \pm 2.5\%$ shows some significance for the sign being positive. In a recent paper published in Nature, the Belle collaboration used 535M $B\bar{B}$ pairs to demonstrate a difference [9]

$$\Delta A_{K\pi} \equiv A_{K^+\pi^0} - A_{K^+\pi^-} = +0.164 \pm 0.037,$$

with $4.4\sigma$ significance by a single experiment, and emphasized the possible indication for New Physics. The world average [5],

$$\Delta A_{K\pi} = 0.147 \pm 0.027,$$

is now beyond $5\sigma$.

We plot in Fig. 4 the current status of DCPV in $B$ decays. $A_{K^+\pi^-}$ is clearly established, but no other mode reaches the similar level of significance, and there is a wide scatter in central values. So why is the $\Delta A_{K\pi}$ difference a puzzle, that it might indicate New Physics?

For the $B^0$ decay mode, one has

$$M(B^0 \rightarrow K^+\pi^-) \propto T + P \propto r e^{i\phi_3} + e^{i\delta},$$

where $\phi_3 = \arg V_{ub}^\dagger$, $\delta$ is the strong phase difference between the tree amplitude $T$ and strong penguin amplitude $P$, and $r = |T/P|$. It is the interference between the two kinds of phases (Appendix A) that gives rise to DCPV, i.e. $A_{K^+\pi^-} \equiv A_{CP}(K^+\pi^-)$.

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$^2$ We use the LP2007 update that excludes the new $S_{f_0(980)K_S}$ result from BaBar. The Heavy Flavour Averaging Group (HFAG) itself warns “treat with extreme caution” when using this BaBar result [5]. The value is larger than $S_{c\bar{c}s}$ and is very precise, with errors 3 times smaller than the $\phi K_S$ mode, but $f_0(980)K_S$ actually has smaller branching ratio! The BaBar result needs confirmation from Belle.
experimentally. The difference in a decay amplitude is usually hard to extract and difficult to predict. Although DCPV is one of the simplest hadronic nature of these single amplitude tree dominant processes such as $B^0\rightarrow J/\psi K^0$. One has direct access to the CPV phase of the $B^0\bar{B}^0$ mixing amplitude. In comparison, DCPV relies on the presence of strong interaction phase differences. The hadronic nature of these CP invariant phases make them difficult to predict. Although DCPV is one of the simplest things to measure (counting experiment), the strong phase difference in a decay amplitude is usually hard to extract experimentally.

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

$$\sqrt{2}M_{K^+\pi^0} - M_{K^+\pi^-} \propto C + P_{EW},$$

where $C$ is the colour-suppressed tree amplitude, while $P_{EW}$ is the electroweak penguin (replacing the virtual gluon in $P$ by $Z$ or $\gamma$) amplitude. In the limit that these subleading terms vanish, one expects $\Delta A_{K^+\pi} \approx 0$, which was broadly expected to be the case, but contrary to the experimental result of Eq. (4).

Could $C$ be greatly enhanced? This is the attitude taken by many [11]. Indeed, fitting with data, one finds $|C/T| > 1$ is needed [12], in contrast to the very tiny suggested value of 10 years ago [13]. Furthermore, as the amplitude $C$ has the same weak phase $\phi_3$ as $T$, the enhancement of $C$ has to contrive in its strong phase structure, to cancel the effect of the strong phase difference $\delta$ between $T$ and $P$ that helped induce the sizable $A_{K^+\pi^-}$ in the first place. The amount of finesse needed is therefore considerable.

It should be noted that this difference was not anticipated in any calculations beforehand. In perturbative QCD factorization (PQCD) calculations at next to leading order [14], taking cue from data (i.e. after the experimental fact), $C$ does move in the right direction, but insufficiently so. For QCD factorization (QCDF), it has been declared [15] that $\Delta A_{CP}$ is difficult to explain, that it would need very large and imaginary $C$ (or electroweak penguin), which is “Not possible in SM plus factorization [approach].” In the rather sophisticated Soft Colinear Effective Theory (SCET) approach [16], $A_{K^+\pi}$ is actually predicted to be even more negative than $A_{K^+\pi^-}$, where the latter has been taken as input. But this is a problem for SCET itself, rather than with experiment.

The other option is to have a large CPV contribution from the electroweak penguin [12, 17, 18]. The interesting point is that this calls for a New Physics CPV phase, as it is known that $P_{EW}$ carries practically no weak phase within SM, and has almost the same strong phase as $T$ [19]. So what NP 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 the $Z$ penguin loop. 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 sequential fourth generation, which would naturally bring into $b \rightarrow s$ electroweak penguin $P_{EW}$ (but not so much in the strong penguin $P$) a new CPV phase, in the new CKM product $V_{ts}V_{tb}$. It was shown [17] that Eq. (3) 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 NP in $b \rightarrow s$ penguin modes, i.e. $\Delta S$ (TCPV) and $\Delta A_{K^+\pi}$ (DCPV), one might expect possible NP in $B_s$ mixing. Note that recent results for $\Delta m_{B_s}$ and $\Delta \Gamma_{B_s}$ are SM-like, but 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.

### 2.3 $B_s$ Mixing and $\sin 2\phi_{B_s}$

The oscillation between $B_s^0$ and $\bar{B}_s^0$ mesons is too fast for B factories. This brings us to the hadronic collider environment, which enjoys a large boost for produced $B$ mesons. After a slow start of the Tevatron Run II, the CDF and D0 experiments have recently reached $\sim 4$ fb$^{-1}$ integrated luminosity per experiment, and expect to accumulate an overall of 6-8 fb$^{-1}$ per experiment throughout the Tevatron Run II lifetime.

Despite the earlier announcement made by D0 in Winter 2006, the CDF experiment had the advantage of a special two-track trigger. By Summer 2006, based on 1 fb$^{-1}$ data, $B_s$ mixing became a precision measurement [20],

$$\Delta m_{B_s} = 17.77 \pm 0.10 \pm 0.07 \text{ ps}^{-1}.\quad (7)$$

We remark that, if one takes the current nominal values for $f_{B_s}$, e.g. from lattice studies, the result of Eq. (7) seems a bit on the small side. Recall that, before the experimental measurement precipitated, fitting to data and information other than $\Delta m_{B_s}$ itself, the fitted values from the CKMFitter and UTfit groups tended to be larger than 20 ps$^{-1}$. The situation may be even more serious. CLEO [21] and Belle [22] have measured $f_{B_s}$ by
measuring $D^+_s \rightarrow \ell^+\nu$ decays, and the measured values are considerably higher than current lattice results. If this carries over to $f_{B_s}$, the SM expectation for $\Delta m_{B_s}$ would definitely be above $20 \text{ ps}^{-1}$, and one may need some “New Physics” to bring it down to the level of Eq. (7). Unfortunately, because of the large hadronic uncertainties in $f^2_{B_s} B_s$, one cannot take this as a hint for New Physics. One has to turn to CPV that is less prone to hadronic physics.

Analogous to the case for $B_d$ oscillations, the amplitude for $B_s$ mixing in SM behaves as $M^\ast_{L2} \propto (V_{ts}V_{cb})^2 m^2_{ts}$ to first approximation, and CPV in $B_s$ mixing is controlled by the phase of $V_{ts}$. Since $|V_{ts}V_{ub}|$ is rather small, unlike the analogous Eq. (1) for $b \rightarrow d$ transitions, the triangle relation

$$V_{ts}^\ast V_{ub} + V_{cb}^\ast V_{ts} + V_{ub}^\ast V_{cb} = 0 \quad (8)$$

$$\Rightarrow V_{ts}^\ast V_{cb} \approx -V_{cb} \quad (9)$$

i.e. collapsing to approximately a line, and $V_{ts}^\ast V_{cb}$ is practically real (in the standard phase convention [3] that $V_{cb}$ is real). In practice, $\Phi_{B_s} \equiv -\arg V_{ts} \sim 0.02 \text{ rad}$ in SM (the actual definition being $2\Phi_{B_s} = \arg M^\ast_{L2}$, if one ignores absorptive parts), is tiny compared to $\Phi_{B_d} \equiv -\arg V_{td} = \beta/\phi_1 \sim 0.37 \text{ rad}$. With $\Phi_{B_s}$ at the percent level, only the LHCb experiment, which is designed for $B_s$ physics studies at the LHC, would have enough sensitivity to probe it. Thus, it is well known that $\sin 2\Phi_{B_s}$, the analogue of $\sin 2\phi_1/\beta$ for $B_d$, is an excellent window on BSM. That is, any observation that deviates from

$$\sin 2\Phi_{B_s}^{\text{SM}} \equiv -0.04, \quad (10)$$

would be indication for New Physics. In SUSY, this could be squark-glino loops with $\tilde{s}-\tilde{b}$ mixing.

### 2.3.1 $\Delta\Gamma_{B_s}$ approach to $\phi_{B_s}$

Let us first briefly comment on the approach through width mixing, i.e. $\Delta\Gamma_{B_s}$ and $\phi_{B_s}$ from untagged $B_s^0 \rightarrow J/\psi\phi$ and other lifetime studies. Here, the $D\Phi$ experiment has made a concerted effort on dimuon charge asymmetry $A_{SL}$, the untagged single muon charge asymmetry $A'_{SL}$, and the lifetime difference in untagged $B_s \rightarrow J/\psi\phi$ decay (hence does not involve oscillations), using a dataset of $1.1 \text{ fb}^{-1}$. $D\Phi$ holds the advantage in periodically flipping magnet polarity to reduce the systematic error on $A_{SL}$. Combining the three studies, they probe the CPV phase

$$\Delta\Gamma_{B_s} = \Delta\Gamma_{B_s}^{\text{CP}} \cos 2\Phi_{B_s}, \quad (11)$$

where $\Delta\Gamma_{B_s}^{\text{CP}} \approx \Delta\Gamma_{B_s}^{\text{SM}}$. The main result of interest is given in Fig. 5, where $\phi_{B_s} = \Phi_{B_s}$ and $\Delta\Gamma_s = \Delta\Gamma_{B_s}^{\text{CP}}$. The fitted width difference of $0.13 \pm 0.09 \text{ ps}^{-1}$ is still larger than the SM expectation [23] of

$$\Delta\Gamma_{B_s}^{\text{SM}} = 0.096 \pm 0.039 \text{ ps}^{-1}, \quad (12)$$

but certainly not inconsistent. The extracted “first” measurement of $|\Phi_{B_s}| = 0.70^{+0.39}_{-0.47}$ is slightly off zero. Given the large errors, it is both consistent with SM expectation but certainly allows for NP. The details can be found in Ref. [24], which is somewhat technical. For a phenomenological digest, see Ref. [25]. A more recent CDF study [26] of $B_s \rightarrow J/\psi\phi$ using $1.7 \text{ fb}^{-1}$ data finds $\Delta\Gamma_{B_s} = 0.076^{+0.065}_{-0.066} \pm 0.006 \text{ ps}^{-1}$, assuming $CP$ conservation, which is consistent with the SM expectation of Eq. (12). Overall, our comment is that the cos $2\Phi_{B_s}$ approach is somewhat a “blunt instrument”.

#### 2.3.2 Prospects for sin $2\Phi_{B_s}$ Measurement

The more direct approach to measuring sin $2\Phi_{B_s}$ is via tagged TCPV study of $B_s \rightarrow J/\psi\phi$. Let us focus on the shorter term prospects.

$B_s \rightarrow J/\psi\phi$ decay is analogous to $B_d \rightarrow J/\psi K_s$, except it is a $VV$ final state. Thus, besides measuring the decay vertices, one also needs to perform an angular analysis to separate the $CP$ even and odd components. As $J/\psi$ is reconstructed in say the dimuon final state, CDF and D0 should have comparable sensitivity. Assuming $8 \text{ fb}^{-1}$ per experiment (which may be questionable), the Tevatron could reach an ultimate sensitivity of

$$\sigma(\sin 2\Phi_{B_s}) \sim 0.2/\sqrt{2}. \quad \text{(Tevatron combined)} \quad (13)$$

However, just now the LHC magnets are cooling down towards running. How fast can LHC turn on and produce physics results? We will have to wait and see, but some training period is expected. I will adopt a conservative estimate [27] for the “first year” (a floating concept in actual calendar terms) running of LHC: $2.5 \text{ fb}^{-1}$ for ATLAS and CMS, and $0.5 \text{ fb}^{-1}$ for LHCb. Assuming this, the projection for ATLAS is $\sigma(\sin 2\Phi_{B_s}) \sim 0.16$, not better than the Tevatron, while for LHCb one has $\sigma(\sin 2\Phi_{B_s}) \sim 0.04$. While the situation would be rather volatile, these sensitivities, listed side by side in Table 1, can be viewed as reference values for 2009, perhaps even Winter conferences for 2010 or beyond.

If SM again holds sway, LHCb would clearly be the winner, since $\sigma(\sin 2\Phi_{B_s}) \sim 0.04$ starts to probe the SM
Table 1. Rough sensitivity to $\sin 2\Phi_{B_s}$, ca. 2009.

| CDF/D0 | ATLAS/CMS | LHCb |
|--------|-----------|------|
| $\sigma(\sin 2\Phi_{B_s})$ | 0.2/0.16 | 0.04 |
| $\int L dt$ | (8 fb$^{-1}$) | (2.5 fb$^{-1}$) | (0.5 fb$^{-1}$) |

expectation of Eq. (10). This is not surprising, as the LHCb detector (see Fig. 6) has a forward design for the purpose of $B$ physics. It takes advantage of the large collider cross section for $b\bar{b}$ production, while implementing a fixed-target-like detector configuration that allows more space for devices such as RICH detectors for PID. We wish to stress, however, that 2009 looks rather interesting — Tevatron could get really lucky: it could glimpse the value of $\sin 2\Phi_{B_s}$ only if its strength is large; but if $|\sin 2\Phi_{B_s}|$ is large, it would definitely indicate New Physics. Thus, the Tevatron has the chance to preempt LHCb and carry away the glory of discovering physics beyond the Standard Model in $\sin 2\Phi_{B_s}$ (publicly stressed since early 2007). Maybe the Tevatron should even run longer, especially if LHC dangles. This can add to the existing competition on Higgs search between Tevatron and the LHC.

2.3.3 Can $|\sin 2\Phi_{B_s}| > 0.5$?

The answer should clearly be in the positive. We provide some phenomenological insight as an existence proof, at the same time attempting to link with the hints for New Physics discussed in the two previous subsections. That is, it is of interest to explore whether the $\Delta B = 1 b \to s$ processes of Secs. 2.1 and 2.2 have implications for the $\Delta B = 2 b\bar{s} \to s\bar{b}$ process.

One can of course resort to squark-gluino box diagrams. Note, however, that squark-gluino loops, while possibly generating $\Delta S$, cannot really move $\Delta A_{K\pi}$, because their effects are decoupled in $P_{\text{EW}}$. If one wishes to have contact with both hints for NP in $b \to s$ transitions from the B factories, then one should pay attention to some common nature between $b \to s$ electroweak penguin and the $B_s$ mixing box diagram. If there are new nondecoupled quarks in the loop, then both $\Delta A_{K\pi}$ and $\Delta S$ could be touched. It also affects $B_s$ mixing, as it is well known that the top quark effect in electroweak penguin and box diagrams are rather similar. Such new nondecoupled quarks are traditionally called the 4th generation quarks $t'$ and $b'$. The $t'$ quark in the loop adds a term $V_{ts}^* V_{tb} \equiv r_{sb} e^{i\phi_{sb}}$ to Eq. (8), bringing in the additional NP CPV phase $\arg(V_{ts}^* V_{tb}) \equiv \phi_{sb}$ with even larger Higgs affinity, $\lambda_{t'} > \lambda_t \simeq 1$. Dynamically speaking, this is no different from the SM.

It was shown [17] that the 4th generation could account for $\Delta A_{K\pi}$, and $\Delta S$ then moves in the right direction [28]. This was done in the PQCD approach up to next-to-leading order (NLO), which is the state of the art. We note that PQCD is the only QCD-based factorization approach that predicted [29] both the strength and sign of $A_{CP}(B^0 \to K^+\pi^-)$. At NLO, the $\Delta A_{K\pi}$ saw improvement by enhancement of $C$ [14], although this also demonstrated that a calculation approach could not generate $|C/T| > 1$. It is nontrivial, then, that incorporating the nondecoupled 4th generation $t'$ quark to account for $\Delta A_{K\pi}$, can also move $\Delta S$ in the right direction.

The really exciting implication, however, is the impact on $\sin 2\Phi_{B_s}$: the $t'$ effect in the box diagram also enjoys nondecoupling. As the difference of $\Delta A_{K\pi}$ in Eq. (4) is large, both the strength and phase of $V_{ts}^* V_{tb}$ is sizable [17], and the phase is not far from maximal. As we have mentioned, a near maximal phase from $t'$ allows precisely the minimal impact on $\Delta m_{B_s}$, as it adds only in quadrature to the real contribution from top. But it makes the maximal impact on $\sin 2\Phi_{B_s}$. Furthermore, the $t'$ effect can partially cancel against too large a $t$ contribution in the real part, if the indication for large $f_{B_s}$ from experiment is carried over to a larger $f_{B_s}$ value than current lattice results.

We show in Fig. 7 the variation of $\Delta m_{B_s}$ and $\sin 2\Phi_{B_s}$, with respect to the new CPV phase $\phi_{sb} \equiv \arg V_{ts}^* V_{tb}$ in the 4th generation model, for the nominal $m_{t'} = 300$ GeV and $r_{sb} = |V_{ts}^* V_{tb}| = 0.02, 0.025,$ and 0.03, where stronger $r_{sb}$ gives larger variation. Using the central value of $f_{B_s}/\sqrt{B_{B_s}} = 295 \pm 32$ MeV, we get a nominal 3 generation value of $\Delta m_{B_s}|_{\text{SM}} \sim 24$ ps$^{-1}$, which is the dashed line. The CDF measurement of Eq. (7) is the rather narrow solid band, attesting to the precision already reached by experiment, and that it is below the dashed line. Combining the information from $\Delta A_{K\pi}$, $\Delta m_{B_s}$, and $B(b \to s\ell^+\ell^-)$, the predicted value is [30]

$$\sin 2\Phi_{B_s} = -0.5 \text{ to } -0.7,$$

(4th generation) (14)

where even the sign is predicted. Basically, the range can be demonstrated by using the (stringent) $\Delta m_{B_s}$ vs (less stringent) $B(B \to X_s\ell^+\ell^-)$ constraints alone, with $\Delta A_{K\pi}$ selecting the minus sign in Eq. (14), as can be read off from Fig. 7. Note that for different $m_{t'}$, it maps into a different $\phi_{sb}$ range, with little change in predicted range for $\sin 2\Phi_{B_s}$.

We stress that Eq. (14) can be probed even before LHCb gets first data, and should help motivate the Tevatron experiments. It’s not over until it’s over, and 2009-2010 could be rather interesting indeed.
2.3.4 Recent Progress at Tevatron

We already have a glimpse of what lies ahead in 2008!

Using 1.35 fb\(^{-1}\) data, CDF has performed the first tagged and angular-resolved time-dependent CPV study of \(B_s \to J/\psi \phi\). The result [31], in terms of \(\beta_s\), is shown in Fig. 8. A similar analysis has been conducted by D0, assuming Eq. (7) for \(\Delta m_{b_s}\) as input. The result [32] \((\phi_s = \Phi_{b_s})\), using 2.8 fb\(^{-1}\), is also shown in Fig. 8. Up to a two-fold ambiguity in the CDF result, to the eye, one sees that both experiments find \(\Phi_{b_s}\) to be negative, and is more consistent with the 4th generation prediction of Eq. (14), than with the SM prediction of Eq. (10).

The UTfit group has made the bold attempt to combine the results of \(\Delta m_{b_s}\) as well as Figs. 5 and 8, to claim [33] \textit{first evidence} (3.7\(\sigma\)) for New Physics in \(b \leftrightarrow s\) transitions, \(\Phi_{b_s} = -19.9^\circ \pm 5.6^\circ\), or

\[
\sin 2\Phi_{b_s} = -0.64^{+0.16}_{-0.14}. \quad \text{(UTfit of Tevatron data)} (15)
\]

which is tantalizingly consistent with Eq. (14), the prediction of the 4th generation model that combined \(\Delta m_{b_s}\) and \(\Delta A_{K_s}\) results! The significance is much better than estimated in Table 1, maybe in part because it contains information beyond \(B_s \to J/\psi \phi\) TCPV analysis. But one should wait for an official Tevatron average.

Whether measurements with LHC data become available or not, much progress is expected in the coming year or two, so we will leave things as it is. We note that models like squark-gluino loops, or \(Z'\) models with specially chosen couplings, could also give large \(\sin 2\Phi_{b_s}\), but they would be unable to link with \(\Delta A_{K_s}\).

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

Suppose there is New Physics in the \(B^+ \to K^+\pi^0\) electro-weak penguin. Rather than turning into a \(\pi^0\), the \(Z^*\) from the effective \(bsZ^*\) vertex could turn into a \(J/\psi\) as well. 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 colour-suppressed \(b \to cc\bar{s}\) amplitude, which is proportional to the CKM element product \(V_{ub}^*V_{cb}\) that is real to very good approximation. At the loop level, the penguin amplitudes are proportional to \(V_{ub}^*V_{cb}\) in the SM. Because \(V_{ub}^*V_{cb}\) is very suppressed, \(V_{ub}^*V_{cb} \cong -V_{ub}^*V_{cb}\) is not only practically real (Eq. (9)), it has the same phase as the tree amplitude. 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 [34] of \(B^0 \to J/\psi K_S\) that combines QCDF-improved factorization and the PQCD approach confirms the 3 generation SM expectation that \(\mathcal{A}_{CP}(B^+ \to J/\psi K^+)\) 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 \(b \leftrightarrow s\) transitions, while stimulating theoretical efforts to compute the strong phase difference between \(C\) and \(P_{EW}\).

We shall argue that, in the 4th generation scenario, DCPV in \(B^+ \to J/\psi K^+\) decay could be at the \(\%\) level.

Experiment so far is consistent with zero, but has a somewhat checkered history. Belle has not updated from their 2003 study based on 32M \(BB\) pairs, although they now have more than 20\(\times\) 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 rules out, for example, the suggestion [35] of enhanced \(H^+\) effect at 10\(\%\) level.

One impediment to higher statistics \(B\) factory studies is the systematic error, and it seems difficult to break the 1\(\%\) barrier. Recent progress has been made, however, by D0. Based on 2.8 fb\(^{-1}\) data, D0 measures [36]

\[
\mathcal{A}_{B^+ \to J/\psi K^+} = 0.75 \pm 0.61 \pm 0.27 \%. \quad \text{(D0)} \quad (16)
\]

We should note that there is a correction twice as large as the value in Eq. (16) for the \(K^\pm\) asymmetry due to detector effects, because of its matter composition. Despite this, of special note is the rather small (roughly a
quarter \%!) systematic error. This is because one enjoys a larger control sample in hadronic production, as compared with B factories, e.g. in $D^*$ tagged $D^0 \to K^- \pi^+$ decays. Thus, even scaling up to 8 fb$^{-1}$, one is still statistically limited, and 2$\sigma$ sensitivity for \% level asymmetries could be attainable. CDF should have similar sensitivity, and the situation can drastically improve with LHCb data once it becomes available.

The Tevatron study was in fact inspired by a 4th generation study [37], following the lines that have already been presented in the previous sections. The 4th generation parameters are taken from the $\Delta A_{P^+}$ study [17]. By 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 colour-suppressed amplitude $C$ for $B^+ \to J/\psi K^+$ would likely possess a strong phase of order 30$^\circ$. The $P_{EW}$ amplitude is assumed to factorize and hence does not pick up a strong phase. Heuristically this is because the Z$^*$ produces a small, colour singlet $c\bar{c}$ that penetrates and leaves the hadronic "muck" without much interaction, subsequently projecting into a $J/\psi$ meson. With a strong phase in $C$ and a weak phase in $P_{EW}$, one then finds $A_{B^+ \to J/\psi K^+} \simeq \pm 1\%$.

We plot $A_{B^+ \to J/\psi K^+}$ vs phase difference $\delta$ in Fig. 9, with $\phi_{cb}$ fixed to the range corresponding to Eq. (14), and notation as in Fig. 7. Negative sign is ruled out by Eq. (16). But of course, DCPV is directly proportional to the strong phase difference, which is not well predicted.

We remark that models like Z$^*$ with FCNC couplings could also generate various effects we have discussed. For example, with $\delta \sim 30^\circ$, $A_{B^+ \to J/\psi K^+}$ could be considerably larger than a percent. With the DØ result of Eq. (16), however, only \% level asymmetries are allowed, ruling out a large (and in any case quite arbitrary) region of parameter space for Z$^*$ effects.

### 3 $H^+$ Probes

When $b \to s\gamma$ was first announced by CLEO [38] in 1994 with 3 fb$^{-1}$ data on the $\Upsilon(4S)$, it provided one of the most powerful constraints on many kinds of New Physics that enter the loop. Here we illustrate the stringent bound it provides on the charged Higgs boson $H^+$ that automatically exists in minimal SUSY. A second probe of $H^+$, becoming relevant only recently at the B factories is, surprisingly, a tree level effect in $B^+ \to \tau^+\nu$.

#### 3.1 $b \to s\gamma$

The inclusive $b \to s\gamma$ decay, identified with $B \to X_s\gamma$ experimentally, where $X_s$ are reconstructed [38] as $K + n\pi$ (partial reconstruction), is one of the most important probes of NP. There had been good agreement for the past few years between NLO theory and the experimental average of [5]

$$B_{B \to X_s\gamma} = (3.55 \pm 0.26) \times 10^{-4} \quad \text{(HFG 06)}$$

which has gone beyond partial reconstruction, but on background reduction after selecting an energetic photon.

Recently, however, the NNLO theory prediction has shifted lower [39, 40] to $\sim 3 \times 10^{-4}$, with errors comparable to experiment. Although the NNLO work continues, the ball appears to be in the experiments’ court.

To improve on the experimental error, besides an ever larger dataset, the photon energy cut, e.g. $E_\gamma > 1.8$ GeV (see Fig. 10) in the Belle study using [41] 152M $BB$ pairs, should be lowered further. Dutifully, Belle has just come out [42] with a new analysis using 657M $BB$ pairs, while managing to lower $E_\gamma$ cut to 1.7 GeV. Agreement with theory is slightly improved.

To confront the theoretical advancement, however, a fresher approach may eventually be needed. A promising new development, as the B factories increase in data, is the full reconstruction of the tag side $B$ meson. The signal side is then just an energetic photon, without specifying the $X_s$ system. The systematics would be quite different from previous approaches. A first attempt has been performed by BaBar [43] recently. But since full reconstruction takes a $10^{-3}$ hit in efficiency, it seems that the NNLO theory development would demand a Super B factory upgrade to continue the supreme dialogue between theory vs experiment in this mode.

This close dialogue allowed $b \to s\gamma$ to provide one of the most stringent bounds on NP models. The process is sensitive to all types of possible NP in the loop, such as...
stop-charginos, where a large literature exists. However, $b \to s\gamma$ is best known for its stringent constraint on the MSSM (minimal SUSY SM) type of $H^+$ boson. Furthermore, the SUSY related studies all need mechanisms to cancel against the large charged Higgs effect. We therefore focus on the $H^+$ effect in the loop.

MSSM demands at least two Higgs doublets (2HDM), where one Higgs couples to right-handed down type quarks, the other to up type. The physical $W^+$ is a cousin of the $\phi_W^+$ Goldstone boson of the SM that gets eaten by the $W^+$. It is the $\phi_W^+$ that couples to masses, and is at the root of the nondecoupling phenomenon of the heavy top quark in the loop. In $bs\gamma$ coupling, however, the top is effectively decoupled (less than logarithmic dependence on $m_t$), by a subtlety of gauge invariance. This underlies the reason why QCD corrections make such large impact [44] in this loop-induced decay. It also makes the process sensitive to NP such as $H^+$.

Replacing the $W^+$ by $H^+$ in the loop, in the MSSM type of 2HDM, the $H^+$ effect always enhances $b \to s\gamma$ rate, regardless of $\tan\beta$, which was pointed out 20 years ago [45, 46], where $\tan\beta$ is the ratio of v.e.v.s between the two doublets. Basically, the $H^+$ couples to $m_t\cot\beta$ at one end of the loop, and to $-m_b\tan\beta$ on the other end, so this contribution is independent of $\tan\beta$, and the sign is fixed to be always constructive with the SM amplitude.3

We take the plot from Ref. [39], where the NNLO result of $B(B \to X_s\gamma)$ vs $m_{H^+}$ is compared with data [5]. A nominal $\tan\beta = 2$ is taken. By comparing the lower range of NNLO result with the higher range of Eq. (17), one has the bound

$$m_{H^+} > 295 \text{ GeV (NNLO + HFAG06)},$$

at 90% C.L. If one takes the central value of both results seriously, one could say [39] that an $H^+$ boson with mass around 695 GeV is needed to bring the NNLO rate up to Eq. (17). Again, this is because the $H^+$ effect in the MSSM type of 2HDM is always constructive [46] with $\phi_W$ effect in SM.

3 In the other type of 2HDM, where both $u$ and $d$ quarks get mass from the same Higgs doublet, the $H^+$ effect is destructive [46].

Fig. 11. $B(B \to X_s\gamma)$ vs $m_{H^+}$ in MSSM type two Higgs doublet model, with $\tan\beta = 2$ (taken from [39]). For large $m_{H^+}$, one approaches SM (dashed lines), while for low $m_{H^+}$ there is great enhancement. Dotted lines is experimental range.

The ongoing saga should be watched. It would be interesting with LHC turn on, especially if a charged Higgs boson is discovered. Much more information could be extracted in the future with a Super B Factory.

3.2.1 $B \to \tau\nu$ Measurement

As a cousin of the $\phi_W^+$, the $H^+$ boson has an amazing tree level effect that has only recently come to fore by the prowess of the B factories.

Like $\pi^+, K^+ \to \ell^+\nu_\ell$ decay, one has the formula for $B^+ \to \tau^+\nu_\tau$ decay,

$$B_{B \to \tau \nu} = \frac{G_F^2 m_B m_{H^+}^2}{8\pi} \left[ 1 - \frac{m_{\tau}^2}{m_{H^+}^2} \right] \tau_B f_B^2 |V_{ub}|^2,$$  \hspace{1cm} (19)

where $r_H = 1$ for SM, but [47]

$$r_H = \left[ 1 - \frac{m_{B^+}^2 \tan^2\beta}{m_{H^+}^2} \right]^2,$$  \hspace{1cm} (20)

for 2HDM. Within SM, the pure gauge $W^+$ effect is helicity suppressed, hence the effect vanishes with the $m_{\tau}$ mass. For $H^+$, there is no helicity suppression, but one has the “Higgs affinity” factor, i.e. mass dependent couplings. With $m_{\nu}$ negligible, the $H^+$ couples as $m_{\tau} m_{b} \tan^2\beta$. This leads to the $r_H$ factor of Eq. (20), where the sign between the SM and $H^+$ contribution is always destructive [47].

$B^+ \to \tau^+\nu$ followed by $\tau^+\nu$ decay results in at least two neutrinos, which makes background very hard to suppress in the $BB$ production environment. Thus, for a long time, the limit on $B^+ \to \tau^+\nu$ was rather poor and not so interesting. This had allowed for the possibility that the effect

Fig. 12. Data showing evidence for $B \to \tau\nu$ (hadronic tag) search by Belle [49] and BaBar [50].
of the $H^+$ could even dominate over SM,\(^4\) given that the SM expectation was only at $10^{-4}$ level. The change came with the enormous number of B mesons accumulated by the B factories, allowing the aforementioned full reconstruction method to become useful.

Fully reconstructing the tag side B meson in, e.g. $B^- \to D^0 \pi^-$ decay, one has an efficiency of only 0.1%-0.3%. At this cost, however, one effectively has a “B beam”. As shown in Fig. 12, using full reconstruction in hadronic modes and with a data consisting of 449M $BB$ pairs, in 2006 Belle found 17.2\(^{+5}_{-4.3}\) events, where the $T$ decay was searched for in decays to $e\nu\nu$, $\mu\nu\nu$, $\pi\nu$ and $\rho\nu$ modes. This constituted the first evidence (at $3.5\sigma$) for $B^+ \to T^+\nu$, with\(^4\)

$$B_{B^+\to T^+\nu} = (1.79^{+0.56+0.46}_{-0.49-0.51}) \times 10^{-4} \quad (\text{Belle 449M}). \quad (21)$$
With 320M $BB\bar{B}$s and $D\ell\nu$ reconstruction on tag side, however, BaBar saw no clear signal, giving $(0.88^{+0.68}_{-0.67} \pm 0.11) \times 10^{-4}$. Updating more recently to 383M, the $D\ell\nu$ tag result of $(0.9 \pm 0.6 \pm 0.1) \times 10^{-4}$ is not different from the 320M result. However, with hadronic tag, BaBar now also reports some evidence, at $(1.8^{+0.9}_{-0.8} \pm 0.4 \pm 0.2) \times 10^{-4}$ (Fig. 12), which is quite consistent with the Belle result of Eq. (21). The combined result for BaBar is \(^{50}\)

$$B_{B^+\to T^+\nu} = (1.2 \pm 0.4 \pm 0.36) \times 10^{-4} \quad \text{(BaBar 383M)}, \quad (22)$$
where we have followed HFAG to combine the background and efficiency related errors. Eq. (22) has 2.6\$\sigma$ significance, and is diluted by the semileptonic tag measurement, but it is basically consistent with the Belle result.

Taking central values from lattice for $f_B$, and $|V_{ub}|$ from semileptonic decays, the nominal SM expectation is $(1.6 \pm 0.4) \times 10^{-4}$, Thus, Belle and BaBar have reached SM sensitivity, and Eqs. (21) and (22) now place a constraint on the tan $\beta$-$m_{H^+}$ plane through $\tau_H \approx 1$. If one has a Super B factory, together with development of lattice QCD, this can become a superb probe of the $H^+$, complementary to direct $H^+$ searches at the LHC. A particularly nice feature is its theoretical cleanliness, all hadronic effects being summarized in $f_B$.

3.2.2 $B \to D^{(*)}\ell\nu$ Measurement

An analogous mode with larger branching ratio, $B \to D^{(*)}\ell\nu$, has recently emerged. In 2007 Belle announced the observation of \(^{51}\)

$$B_{D^{(*)}\to \ell\nu} = (2.02^{+0.40}_{-0.37}) \pm 0.37\% \quad \text{(Belle 535M)}, \quad (23)$$

based on $60^{+12}_{-11}$ reconstructed signal events, which is a 5.2\$\sigma$ effect. Subsequently, based on 232M $BB\bar{B}$ pairs, BaBar announced the observation (over 6\$\sigma$) of $D^{(*)}\ell\nu$, and evidence for $D^{+}\tau\nu$ [52]

$$B_{D^{(*)}\to \tau\nu} = (1.81 \pm 0.33 \pm 0.11 \pm 0.06) \% \quad (\text{BaBar 232M}), \quad (24)$$

where the last error is from normalization.

The SM branching ratios, at 1.4% for $B \to D^{(*)}\ell\nu$, are poorly estimated. Furthermore, though the $H^+$ could hardly affect the $B \to D^{(*)}\tau\nu$ rate, it could leave its mark on the $D^*$ polarization. The $B \to D\tau\nu$ rate, like $B \to \tau\nu$ itself, is more directly sensitive to $H^+$ [53]. More theoretical work, as well as polarization information, would be needed for BSM (in particular, $H^+$ effect) interpretation. But it is rather curious that, almost 25 years after the first B meson was reconstructed, we have a newly measured mode with $\sim 2\%$ branching fraction!

3.2.3 Comment on New Physics in $D^+_s \to \mu^+\nu$, $\tau^+\nu$

The process $D^+_s \to \ell^+\nu$, where $\ell = \mu$, $\tau$, proceeds via $c\bar{s}$ annihilation, and the decay branching ratio formula is very similar to Eq. (19), with $\tau_H$ set to 1 in SM. Since this is a tree level process proceeding without CKM suppression, New Physics effect through the charged Higgs is expected to be small [47]. The rate measures $f_{D_s}|V_{cs}|$ in a rather clean way.

The experimental measurement has become rather precise [21, 22] recently

$$f_{D_s}|_{\text{expt}} = 277 \pm 9 \text{ MeV}, \quad (25)$$

assuming $|V_{cs}| = 1$. Given confirmation between two experiments,\(^5\) there is little likelihood that the experimental number would change much.

The experimental result has been compared \([55]\) recently with a very precise result from the lattice \([56]\),

$$f_{D_s}|_{\text{latt}} = 241 \pm 3 \text{ MeV}, \quad \text{("rooting") \quad (26)}$$

Note the % level errors! This precision arises in the staggered fermion approach in lattice QCD, with a big assumption to simplify the computation of the fermion determinant, called “rooting”. Ref. \([55]\) claims that the precision of Eq. (26) can stand scrutiny, then goes on to claim that this discrepancy suggests New Physics.

It is not our purpose to go into detail or comment on the intricacies of lattice QCD computations, although we have used the discrepancy of the above two equations to argue, in an intuitive way, that $B_s$ mixing in SM is likely to be larger than the experimental measurement of Eq. (7). But we do find the claim of Ref. \([55]\) incredulous. The percent level numerical accuracy of a lattice calculation should be scrutinized thoroughly by the lattice QCD community before such a claim can be made. Afterall, unlike

\(^4\) In fact, the $H^+$ effect had originally been used to enhance \([48]\) $b \to c\tau\nu$ rate to 10% level, in an attempt to account for a discrepancy in the measured semileptonic branching ratio. This possibility was subsequently ruled out by experimental measurement \([3]\) of $b \to c\tau\nu$ to be at SM expectation level.

\(^5\) We note that the BaBar measurement \([54]\) is not an absolute branching ratio measurement. But the result is similar in any case.
the experimental situation, the lattice result of Eq. (26) is so far a stand-alone result. Furthermore, the New Physics “models” proposed by Ref. [55] are rather ad hoc and constructed, and not the ones that this brief Review would like to contemplate.

To paraphrase Einstein, God may not be subtle at all, but malicious, if the tree dominant and Cabibbo allowed $D_s^+ \to \ell^+\nu$ was chosen as the first place to reveal to us signs of New Physics.

4 Electroweak Penguin: $bsZ$ Vertex, $Z'$, DM

In Sec. 2.2, we discussed the effects of the $b \to s\bar{q}q$ electroweak penguin interfering with the strong penguin and tree amplitudes. The quintessential electroweak penguin would be $b \to s\bar{t}\ell^-\ell^-$ decay, or $b \to s\nu\bar{\nu}$ that has no photonic contribution. We now discuss how the study of these processes, present already in SM, could help us probe New Physics as well.

4.1 $A_{FB}(B \to K^*\ell^+\ell^-)$

The $B \to K^*\ell^+\ell^-$ process ($b \to s\bar{t}\ell^-\ell^-$ at inclusive level) arises from photonic penguin, $Z$ penguin and box diagrams. The top quark exhibits nondecoupling in the latter diagrams, analogous to the electroweak penguin effect in $B^+ \to K^+\pi^0$, and the box diagrams for $B_s^0-B_s^0$ mixing. It turns out that, due to this nondecoupling effect of the top quark, the $Z$ penguin dominates the $b \to s\bar{t}\ell^-\ell^-$ decay amplitude [57]. Interference between the vector ($\gamma$ and $Z$) and axial vector ($Z$ only) contributions to $\ell^+\ell^-$ production gives rise to an interesting forward-backward asymmetry [58]. This is akin to the familiar $A_{FB}$ in $e^+e^- \to f\bar{f}$, except the enhancement of $bsZ$ penguin with respect to $bs\gamma$, brings the $Z$ much closer to the $\gamma$ in $B$ decay, and one probes potential New Physics in the loops.

Both the inclusive $B \to X_s\ell^+\ell^-$ and exclusive $B \to K^{(*)}\ell^+\ell^-$ decays have now been measured [3]. Interest has turned to $A_{FB}$ for $B \to K^*\ell^+\ell^-$. The study for inclusive $A_{FB}$ is more challenging, and largely impossible in hadronic environment. A commonly used formula for the differential $A_{FB}$ is

$$dA_{FB}(q^2) \propto C_{10}(q^2) \left[ \text{Re}(C_9^{\text{eff}}) F_1 + \frac{1}{q^2} C_7^{\text{eff}} F_2 \right],$$

where $C_i$ are Wilson coefficients, and formulas for $\xi(q^2)$ and the form factor related functions $F_1$ and $F_2$ can be found in Ref. [59]. From the $1/q^2$, it is clear that $C_7$ is effectively the photon contribution, while $C_9^{\text{eff}}$ and $C_{10}$ are from $Z$ penguin and box diagram. Within SM, these Wilson coefficients are practically real, as is apparent from the formula. $C_7^{\text{eff}}$ receives some long distance $c\bar{c}$ effect.

As shown in Fig. 13, the study of forward-backward asymmetry in $B \to K^*\ell^+\ell^-$ by Belle with 386M $B\bar{B}$ pairs [60] is consistent with SM, and rules out the possibility of flipping the sign of $C_9$ or $C_{10}$ separately from SM value, but having both $C_9$ or $C_{10}$ flipped in sign (equivalent to flipping sign of $C_7$) is not ruled out. BaBar took the more conservative approach of giving $A_{FB}$ in just two $q^2$ bins, below and above $m_{J/\psi}^2$. With 229M, the higher $q^2$ bin is consistent [61] with SM and disfavors BSM scenarios. Interestingly, in the lower $q^2$ bin, while sign-flipped BSM’s are less favored, the measurement is $\sim 2\sigma$ away from SM.

BaBar has just updated to 384M [62]. For the high $q^2$ bin, the results are qualitatively the same as before. For the low $q^2$ bin ($4m_b^2$ to 6.25 GeV$^2$/c$^4$), as can be seen from the second plot in Fig. 13, BaBar has improved its measurement to $A_{FB}^{\text{low } q^2} = 0.24^{+0.18}_{-0.03}\pm 0.05$. This compares with the SM expectation that $A_{FB}^{\text{SM }} = -0.03\pm 0.01$. Though not excluded, viewed together with the Belle result, it seems that the low $q^2$ behavior is not quite SM-like.

While the above is interesting, it is clear that the $B$ factory statistics is still rather limited, and cannot be much improved without a Super $B$ factory. But LHCb can do very well in this regard within a couple of years.

In the context of LHCb prospects, it was recently noticed [63] that, in Eq. (27), there is no reason a priori why the Wilson coefficients should be kept real when probing BSM physics! Note that $\text{Re}(C_9)$ in Eq. (27) differs from $C_9$ within SM by just a small correction arising from long distance $c\bar{c}$ effects. But if one keeps an open mind (rather than, for example, taking the oftentimes tacitly assumed Minimal Flavour Conservation mindset), Eq. (27) should be restored to its proper form

$$\text{Re} \left( C_9^{\text{eff}} C_{10}^{\ast} \right) F_1 + \frac{1}{q^2} \text{Re} \left( C_7^{\text{eff}} C_{10}^{\ast} \right) F_2,$$

where $F_1$ are form factor combinations. We are not concerned with $CP$ conserving long distance effects, but the
Fig. 14. Possible $A_{FB}$ in $B \to K^*\ell^+\ell^-$ allowed by complex Wilson coefficients, Eq. (28). The three data points are taken from 2 fb$^{-1}$ LHCb Monte Carlo for illustration, which has the power to distinguish between SM (solid curve) vs e.g. fourth generation model (dashed curve).

possibility that the $C_{7,8}$ may pick up BSM CP violating phases. If present, they could enrich the interference pattern through Eq. (28), compared with Eq. (27), which has practically assumed real short distance Wilson coefficients. After all, the equivalent $C_9$ and $C_{10}$ for $B^+ \to K^+\pi^0$ decay seem to carry large weak phases, if $F_{\text{EW}}$ is the culprit for the $\Delta A_{K\tau}$ problem discussed in Sec. 2.2. Let Nature speak through data!

Taking the sign convention of LHCb, which is opposite to Belle and BaBar, we illustrate [63] in Fig. 14 the situation where New Physics enters through effective $bsZ$ and $bs\gamma$ couplings. In this case, $C_9$ and $C_{10}$ cannot differ by much at short distance, which is the reason for the “degenerate tail” for larger $s \equiv q^2/m_B^2$. But by allowing the Wilson coefficients to be only constrained by the measured radiative and electroweak penguin rates, $A_{FB}$ could in fact vary in the shaded region, practically for $q^2 < m_H^2/m_B$, and not just in the position of the zero. The fourth generation with parameters as determined from $\Delta m_{B_C}$, $B(B \to X_c\ell^+\ell^-)$ and $\Delta A_{K\tau}$ belongs to this class of BSM models, and is plotted as the dashed line for illustration. To get a feeling for the future, we take the MC study [64] for 2 fb$^{-1}$ data by LHCb (achievable in a couple years of running) and plot three sample data points to illustrate expected data quality. These data points are based on the SM (solid line), and it is clear that LHCb can distinguish between SM and the 4th generation.

Back to the present. From Fig. 14 we could also compare with Belle and BaBar data [60,62] shown in Fig. 13, and see that the current data is already probing the difference between SM and the 4th generation model, or the statement that Wilson coefficients $C_i$ could be complex. As stated, SM expectation is $A_{FB} \sim -0.03$ (note the $B$ factory sign convention) for the region $q^2 \in (4m^2_{\mu}, 6.25$ GeV$^2/c^4)$. This can be understood from the solid line in Fig. 14, where the corresponding region is $s < 0.22$. Since there is a crossing over zero, and since the region below the zero is slightly larger than above, we see that the SM expectation is slightly negative. But Belle and BaBar data both indicate that $A_{FB} > 0$ is preferred, often phrased as $C_7 = -C_7^{\text{SM}}$ seems preferred from $A_{FB}$ data. This should be viewed as just a way of expression, since it has been pointed out [65] that $C_7 = -C_7^{\text{SM}}$, i.e. flipping the sign of the photonic penguin, would lead to too large a $B \to X_c\ell^+\ell^-$ rate as compared with experiment. It actually illustrates our point to use Eq. (28) rather than Eq. (27) in fitting data. In fact, we could even claim that Belle and BaBar data favor somewhat the 4th generation curve in Fig. 14. Compared with the solid line, the zero for the dashed line has moved to much lower $q^2$, together with a drop in peak value. Therefore $A_{FB} > 0$ for the 4th generation model motivated by $\Delta A_{K\tau}$. Note that this model predicts large and negative $\sin 2\beta_{B_s}$.

It is clear that the LHCb has good discovery potential using $A_{FB}$ to probe complexity of short distance Wilson coefficients, without measuring CPV. In fact, once again the Tevatron could make earlier impact. With 1 fb$^{-1}$ data, CDF has demonstrated [66] branching ratio measurement in $B^0 \to K^{0}\mu^+\mu^-$, comparable to that of Belle and BaBar. Given that CDF and D0 expects to accumulate of order 6 to 8 fb$^{-1}$ data per experiment, if such studies could continue towards $A_{FB}$ measurement, there is good potential for Tevatron to improve on Belle and BaBar results, which would also be updated. A more definite statement on whether SM is disfavored could come forth before LHCb data arrives.

We note that if there are New Physics that affects the $bs\ell\ell$ as a 4-quark operator, for example in $Z'$ models with FCNC couplings, the allowed range for $A_{FB}$ is practically unlimited. If such large effects are uncovered, one would expect sizable direct CPV in $b \to s\gamma$ [63], which is another goal for Super B factory studies.

4.2 $B \to K^*\nu\nu$

The $B \to K^*\nu\nu$ (and $b \to s\nu\nu$) decay mode is attractive from the theory point of view, since it can arise only from short distance physics, such as $Z$ penguin and box diagram contributions [57]. The photonic penguin does not contribute. In turn, these processes allow us to probe, in principle, what happens in the loop. Interestingly, since the neutrinos go undetected, the process also allows us to probe light dark matter (DM), which is complementary to the DAMA/CDMS type of direct search. This is because the latter type of experiments rely on detecting special electronic signals arising from a nucleus displaced by a DM particle. But this means that the approach loses sensitivity for light DM particles. But for such particles, DM pairs could arise from exotic Higgs couplings to the $b \to s$ loop.

BaBar has pioneered $B \to K^*\nu\nu$ search. More recently, as a companion study to $B \to \tau\nu$ search, Belle has searched in many modes with a large dataset of 535M $BB$ pairs [67], using the aforementioned method of full reconstruction of the other $B$. No signal is found, and the most stringent limit is $1.4 \times 10^{-5}$ in $B^+ \to K^+\nu\nu$. This is still a factor of 3 above the SM expectation of $\sim 4 \times 10^{-6}$ for this mode. However, it strengthens the bound on light DM production in $b \to s$ transitions [68]. A complemen-
tary approach for search of light DM, as well as light exotic Higgs bosons, is discussed in a different section.

It seems that, to measure the theoretically clean $B \rightarrow K^* \nu \nu$ modes, one again requires a Super B factory. Furthermore, here one really needs to improve on background suppression, which seems challenging. After all, $B \rightarrow \tau \nu$ has just very recently been discovered through the technique of fully reconstructing the other $B$, where the issues for improving the measurements are common, i.e. the challenge of modes with missing mass. Even with full reconstruction of the other $B$, one probably needs to improve on detector hermeticity. We note that there is no resort to LHCb for this mode. Thus, it should be an emphasis for the Super B factory effort.

5 RH Currents and Scalar Interactions

It should be clear that loop-induced $b \rightarrow s$ transitions offer many good probes of TeV scale New Physics. As last examples of their usefulness, we discuss probing for right-handed (RH) interactions via time-dependent CP violation in $B^0 \rightarrow K_S^0 \pi^0 \gamma$ decay, and searching for enhancement of $B_s \rightarrow \mu^+ \mu^-$ as probe of BSM neutral Higgs boson effects. The former is best done at a (Super) B factory, while the latter is the domain of hadron colliders, where great strides have already been made.

5.1 TCPV in $B \rightarrow X_0 \gamma$

With large QCD enhancement [44], the the $b \rightarrow s \gamma$ rate is dominated by the SM. The left-handedness of the weak interaction dictates that the $\gamma$ emitted in $B^0 \rightarrow K^{*0} \gamma$ decay has left-handed helicity (defined somewhat loosely), with the emission of right-handed (RH) photons suppressed by $\sim m_s/m_b$. This reflects the need for a mass insertion for helicity flip, and the fact that a power of $m_b$ is required by gauge invariance (or current conservation) for the $b \rightarrow s \gamma$ vertex. For $B^0 \rightarrow K^{*0} \gamma$ decay that involves $b \rightarrow s \gamma$, the opposite is true, and the emitted photon is dominantly of RH kind.

The fact that photon helicities do not match for $B^0 \rightarrow K^{*0} \gamma$ vs $B^0 \rightarrow K^{*0} \gamma$ has consequences for a very interesting probe [69]. Mixing-dependent CPV, i.e. TCPV, involves the interference of $\bar{B}^0$ and $\bar{B}^0 \rightarrow B^0$ decays to a common final state that is not flavour-specific (i.e. no definite flavour). For radiative $B^0 \rightarrow K^{*0} \gamma$ decay (vs $\bar{B}^0 \rightarrow B^0 \rightarrow K^{*0} \gamma$ decay), the common final state is $K_S^0 \pi^0$. Since the $B^0 \rightarrow K^{*0} \gamma$ process produces $\gamma_R$, while the $B^0 \rightarrow K^{*0} \gamma$ process gives $\gamma_L$, they cannot interfere as they are orthogonal to each other! The interference is suppressed by the helicity flip factor of $m_s/m_b \sim$ few $\%$ within SM. However, if there are RH interactions that also induce $b \rightarrow s \gamma$ transition, then $B^0 \rightarrow K^{*0} \gamma$ would acquire a $\gamma_R$ component to interfere with the $\bar{B}^0 \rightarrow B^0 \rightarrow K^{*0} \gamma$ amplitude. Thus, TCPV in $B^0 \rightarrow K^{*0} \gamma$ decay mode probes RH interactions!

Alas, Nature plays a trick on us. As mentioned, $K^{*0} \gamma$ has to be in a CP eigenstate, such as $K^{*0} \rightarrow K_S^0 \pi^0$, so the final state is $K_S^0 \pi^0 \gamma$. The $\pi^0$ and $\gamma$ certainly do not lead to vertices. For the $K_S$, though “short-lived”, it typically decays at the edge of the silicon detector, and one has poor vertex information. Thus, it seems impossible for TCPV to be studied in the $K_S^0 \pi^0 \gamma$ final state, and the intriguing suggestion of Ref. [69], beautiful as it is, appeared to be just an impossible dream. Fortunately, with a larger vertex detector than Belle with a extra silicon plane, BaBar pushed forward a technique, called “$K_S$ vertexing”. It was demonstrated [70] that, though degraded, the $K_S \rightarrow \pi^+ \pi^- \gamma$ decay does give some vertex information. The key point is the availability of the beam direction information because of the boost, providing a “beam profile” for the somewhat rudimentary $K_S$ momentum vector to point back to. The method was validated with gold plated modes like $B^0 \rightarrow J/\psi K_S$ (by removing the $J/\psi \rightarrow \ell^+ \ell^-$ tracks), and have been extended to TCPV studies such as in $B^0 \rightarrow K_S K_S K_S$.

The current status of TCPV in $B^0 \rightarrow K^{*0} \gamma$ decay, combining the 535M $BB$ pair result from Belle [71], and the 232M result from BaBar [72], gives the average of $S_{K_S \pi^0 \gamma} = 0.28 \pm 0.26$, which is consistent with zero. A recent BaBar update with 431M gives [73] $S_{K_S \pi^0 \gamma} = -0.08 \pm 0.31 \pm 0.05$. Measurements have also been made in $B^0 \rightarrow K_S \pi^0 \gamma$ mode without requiring the $K_S \pi^0$ to reconstruct to a $K^{*0}$, as well as in the $B^0 \rightarrow \eta K_S \gamma$ mode.

This is a very interesting direction to explore, but again one needs a Super B factory to seriously probe for RH interactions. At the LHCb, which lacks the “beam profile” technique for $K_S$ vertexing, the $B_s \rightarrow \phi \gamma$ mode may be used, although the $\phi$ is not so good in providing a vertex, since the $K^+ K^-$ pair is rather colinear because of $2m_K \sim m_{\phi}$. Probably the LHCb upgrade would be needed to be competitive with a Super B factory. Other ideas to probe RH currents in $b \rightarrow s \gamma$ are $\gamma \rightarrow e^+ e^-$ conversion, $A$ polarization in $L_b \rightarrow L \gamma$ decay, and angular $F_L$ and $A_T$ measurables in $B \rightarrow K^{\pm} \ell^+ \ell^-$.  

5.2 $B_s \rightarrow \mu^+ \mu^-$

$B_s \rightarrow \mu^+ \mu^-$ decay has been a favorite mode to probe exotic Higgs sector effects in MSSM, because of possible large $\tan \beta$ enhancement.

The process proceeds in SM just like $b \rightarrow s \ell^+ \ell^-$, except $\bar{s}$ is the spectator quark that annihilates the $b$ quark. Since $B_s$ is a pseudoscalar, the photonic penguin does not contribute, and one is sensitive to scalar operators. The SM expectation is only $(3.4 \pm 0.5) \times 10^{-9}$ [75], because of $f_{B_s}$ and helicity suppression. In MSSM, a $t$-$W$+$H^+$ loop can emit neutral Higgs bosons that turn into muons, providing rise to an amplitude $\propto \tan^6 \beta$ [74], which could greatly enhance the rate even with modest pseudoscalar mass $m_A$. Together with the ease for trigger and the enormous number of $B$ mesons produced, this is the subject vigorously pursued at hadron facilities, where there is enormous range for search.
With Run-II data now taking good shape, the Tevatron experiments have improved the limits on this mode considerably. The recent 2 fb$^{-1}$ limits from CDF and DØ are $< 5.8 \times 10^{-8}$ [76] and $9.3 \times 10^{-8}$ [77] respectively at 95% C.L., combining to give $B(B_s \rightarrow \mu^+\mu^-) < 4.5 \times 10^{-8}$. This is still an order of magnitude away from SM.

The expected reach for the Tevatron is about $2 \times 10^{-8}$. Further improvement would have to come from LHCb. LHCb claims [78] that, with just 0.05 fb$^{-1}$, it would overtake the Tevatron, attain 3$\sigma$ evidence for SM signal with 2 fb$^{-1}$, and 5$\sigma$ observation with 10 fb$^{-1}$. To follow our suggested modest 0.5 fb$^{-1}$ expectation for the first year of LHCb data taking, we expect LHCb to exclude branching ratio values down to SM expectation.

Clearly, much progress will come with the turning on of LHC, where direct search for Higgs particles and charginos would also be vigorously pursued.

## 6 Bottomonium Decay and New Physics

We make a detour from our $b \rightarrow s$ loop probes of New Physics, and give some account of a special area for New Physics search, in the decays of bottomonium, namely $\Upsilon(nS)$, $n = 1 - 3$. As we have mentioned in Sec. 4.2, the CDMS/DAMA type of approaches for Dark Matter search are not sensitive to light DM. The bottomonium offers to cover such a window. At the same time, the related exotic Higgs sector can also be probed.

Motivated by a theoretical suggestion that $B(\Upsilon(1S) \rightarrow \chi \chi)$ could be of order 0.6% [79], where $\chi$ is a dark matter particle lighter than $m_b$, Belle made an innovative special data run of 2.9 fb$^{-1}$ on the $\Upsilon(3S)$ to pursue DM search. Using $\pi^+\pi^-$ as kinematic tag for $\Upsilon(1S)$ to *nothing* in $\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(1S)$ decay events, no signal was found, and a limit below the theoretical prediction was set [80]. This was followed by a search by CLEO [81] using 1.2 fb$^{-1}$ on the $\Upsilon(2S)$ for $\pi^+\pi^- \Upsilon(1S)$ decay where the $\Upsilon(1S)$ decays invisibly. A limit slightly poorer than that of Belle is set.

When the PEP-II accelerator had to be terminated earlier than scheduled because of US funding, Babar decided to take 30 fb$^{-1}$ on $\Upsilon(3S)$ (10 times Belle data) in early 2008, followed by 15 fb$^{-1}$ on $\Upsilon(2S)$ (12 times CLEO data). Further New Physics motivation for taking data on bottomonia came from the potential to search for the exotic pseudoscalar Higgs boson $a_1$ via $\Upsilon(1S) \rightarrow \gamma a_1$ followed by $a_1 \rightarrow \pi^+\pi^-$. The light $a_1$ could even be the 214.3 MeV $\mu^+\mu^-$ events observed [82] by the HyperCP experiment in $\Sigma^+ \rightarrow p\mu^+\mu^-$, which provides further motivation.

The DM search with 30 fb$^{-1}$ data on $\Upsilon(3S)$ awaits data analysis. Let us elucidate the physics of light $a_1$ as follows. In NMSSM (N stands for “Next to”), a light pseudoscalar $a_1$ could be lighter than $2m_b$, allowing the SM-like neutral scalar $H$ to be still lighter than 100 GeV, i.e. evade LEP bound, by decaying via $H \rightarrow a_1a_1 \rightarrow 4\tau$. Such a scenario [83] is difficult to unravel at a hadronic collider. However, the light $a_1$ can precisely be searched for in $\Upsilon \rightarrow \gamma a_1$ decay, where a lower bound on this rate is given [83]. If $a_1$ is lighter than $2m_\tau$, then $a_1 \rightarrow \mu^+\mu^-$ would dominate. It has been suggested that the $3 \mu^+\mu^-$ events at 214.3 MeV as seen by HyperCP at Fermilab, could be [84] such a light pseudoscalar. Thus, besides DM search, BaBar was motivated to run on $\Upsilon(3S)$ and $\Upsilon(2S)$ for direct radiative decay to $a_1$, or via $\Upsilon(3S)$, $\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon$, followed by $\Upsilon \rightarrow \gamma a_1$.

Using 21.5M $\Upsilon(1S)$ collected by the CLEO III detector, however, it was claimed [85] very recently that most of the parameter space for $2m_{\chi} < m_{a_1} < 7.5$ GeV, and all the parameter space for light $a_1$ ($m_{a_1} < 2m_\tau$), are ruled out.

It seems that, besides intrinsic interests in spectroscopy, the bottomonium system also provides a window on New Physics. A future Super B factory could probe this arena with ease, if flexible in its energy reach.

## 7 D/K: Box and EWP Redux

We touch upon $D$ and $K$ mesons only very briefly.

### 7.1 $D^0$ Mixing

$D^0$-$\bar{D}^0$ mixing is the last neutral meson mixing to be measured. Observation was claimed in 2007, which was quite some feat of experimental effort.

Box diagrams, much like the $K^0$, $B^0_d$ and $B^0_s$ meson systems, govern short distance contributions to $D^0$ mixing. Unfortunately, the $d$ and $s$ quark masses are small compared to $m_b$, hence only $b$ quark contributes in the box at short distance. But $m_b$ is also tiny compared to $m_t$. Furthermore, $V_{ub}V^*_{cb}$ is extremely small compared to the leading $V_{us}V_{cs}^* \simeq -V_{us}V_{cs}^* \simeq -0.22$ in the CKM triangle relation

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0.$$  \hspace{1cm} (29)

Thus, in the SM, $D^0$ mixing receives very tiny short distance effects, making it susceptible to long distance contributions.

The quark level $s\bar{s}$ and $d\bar{d}$ intermediate states in the box diagram are suppressed only by $V_{us}$ or $V_{cd}$, and correspond to mesonic final states from $D^0$ decay. Common final states for $D^0$ and $\bar{D}^0$ can cause interfere and generate a *width difference*, much like in $K^0$-$\bar{K}^0$ and $B^0_d$-$B^0_s$ systems. It has been argued [86] that SU(3) breaking effects in $PP$ and $4P$ (where $P$ stands for $K$ or $\pi$) final states can generate a percent level $y_D \equiv \Delta m_D/2\Gamma_D$, the parameter usually used in place of the width difference $\Delta \Gamma_D$. It was further shown that a $y_D$ at the percent level can generate [86], via a dispersion relation, width mixing $x_D = \Delta m_D/\Gamma_D$ that is comparable in size to $y_D$. Unfortunately, the hadronic uncertainties are uncontrollable. But with the observation of $D^0$-$\bar{D}^0$ mixing in 2007, so far $x_D \sim y_D \sim 1\%$ seems to be the case, i.e. consistent with long distance effects.

The 2007 observation of $D^0$ mixing rests in i) Belle analysis of 540 fb$^{-1}$ data in $D^0 \rightarrow K^+K^-, \pi^+\pi^-$ (CP eigenstates) to extract $y_{CP}$ [87]; ii) a Dalitz analysis by
Belle [88] of \(D^0 \rightarrow K_S\pi^+\pi^-\) with 540 fb\(^{-1}\) to extract \(x_D\) and \(y_D\); iii) both Belle and BaBar analyzed \(D^0 \rightarrow K^\pm\pi^\pm\) (Cabibbo allowed vs suppressed), with 400 fb\(^{-1}\) and 384 fb\(^{-1}\) data respectively, to extract \(x_D^q\) and \(y_D^q\), where \(x_D^q\) and \(y_D^q\) is a rotation from \(x_D\) and \(y_D\) by a strong phase \(\delta_D\) between the Cabibbo allowed and suppressed \(D^0 \rightarrow K^\pm\pi^\mp\) decays. The analyses are too complicated to report here. Suffice it to say that \((x_D, y_D) = (0, 0)\) was excluded at the 5\(\sigma\) level (see Fig. 15), and \(D^0\) mixing became established. The best fit, assuming \(CP\) invariance, gives,

\[
x_D = 0.87^{+0.30}_{-0.34}\%, \quad y_D = 0.66^{+0.21}_{-0.20}\% ,
\]

with \(\delta_D = 0.33^{+0.26}_{-0.29}\) rad. While \(y_D\) is more solid, a finite level \(x_D\) is indicated. Further progress has been made after summer 2007. But rather than going into any detail, we just quote the FPCP2008 results from HFAG [5]. As significance has been further improved, we quote the fit that allows \(CP\) violation (although data is consistent with no \(CP\) violation),

\[
\begin{align*}
x_D &= 0.89^{+0.26}_{-0.27}\%, \quad y_D = 0.75^{+0.17}_{-0.18}\%, \quad \text{(FPCP2008)}
\end{align*}
\]

with \(\delta_D = (21.9^{+11.3}_{-12.4})\)\(^\circ\).

It is of interest to note that, if the 4P final state dominates the long distance contribution, which is consistent with \(y_D \sim 1\%\), then \(x_D^{LD}\) and \(y_D\) (necessarily long distance) should be of the opposite sign [89], while data show the same sign. Although it has been checked [86] that changing hadronic parameters does not change this conclusion, unfortunately the hadronic effects are not well under control to make a definite statement. In any case, one should remember the \(\Delta m_K\) enterprise of 20-30 years ago. That is, although the observed strength could arise from long distance effects, comparable BSM, at twice the observed \(x_D\), is always allowed.

Besides continued progress, there are two things to watch in regards \(D^0\) mixing. While other measurements have seen steady progress for several years, it is for the first time that the Dalitz analysis of Belle [88] sees an indication for \(x_D\). Second, to unravel some of the hadronic physics in the decay final state, one needs to gain access to strong phases. By a tagged Dalitz analysis in \(\psi(3770) \rightarrow D^0\bar{D}^0\), one can [90] extract the strong phase \(\delta_D\), which would in turn feedback on \(x\) and \(y\) extraction. Unfortunately, CLEO-c ended up not taking enough data on the \(\psi(3770)\) resonance before shutdown. But in the future, BES-III and other possible charm factories could aid the \(D^0\) mixing program considerably through this type of studies. Basically, the Dalitz type of analysis, with the help of quantum coherence, holds the power for the future.

What we are interested in is the New Physics impact, rather than hadronic physics. For the moment, though one has made great experimental stride, there is no indication of New Physics in \(D^0\) mixing. A comprehensive study for New Physics implications can be found in Ref. [93]. Ultimately it seems, one would need to measure \(CPV\), expected to be tiny within SM (with or without long distance dominance), to find unequivocal evidence for BSM. This is an area where a Super B factory can compete well with LHCb because of its diversity. However, LHCb can also play a role, as evidenced by the CDF study [91] of \(D^0 \rightarrow K^\pm\pi^\mp\) mode with 1.5 fb\(^{-1}\), which has results that are complementary to Belle and BaBar in this mode.

7.2 Rare K Decays

This field saw its last hurrah in \(\varepsilon'/\varepsilon\) almost a decade ago. Despite the top effect through the electroweak penguin allowed it to vanish, unfortunately, the interpretation of \(\varepsilon'/\varepsilon\) is almost completely clouded by long-distance effects.

With the cancellations of CKM at Fermilab and KOPIO at BNL, the kaon program in the US has withered,\(^6\) despite a long standing hint of 3 events for \(K^+ \rightarrow \pi^+\nu\nu\) at BNL by E787/949. At CERN, there is the P236 proposal (has become NA62) to use the SPS, aiming at reaching \(O(80)\) events with 2 years of running, assuming the SM branching ratio of \(\sim 10^{-10}\). Once approved, data taking could start in 2012. If successful, the hope is to upgrade the CERN proton complex towards “EUREKA” (European Rare-decays Experiments with Kaons).

In Japan, one has the E391A experiment at KEK PS, which just came out with a new limit [92] on \(K_L \rightarrow \pi^0\nu\bar{\nu}\), of less than \(6.6 \times 10^{-9}\) at 90\% C.L., improving its previous limit by a factor of 3. Another dataset equivalent in size is being analyzed. Though one is far from probing the SM expectation of \(10^{-11}\), there is New Physics potential. But E391A should be viewed as the pilot study for the more ambitious E14 proposal to the J-PARC facility, which aims at eventually reaching below \(10^{-12}\) sensitivity to probe BSM. The first step for E14, besides a new beam-line, is to use the upgraded E391A detector (e.g. with CsI crystals from the KTeV experiment at Fermilab). The earliest start is 2011, hopefully seeing 1 event with SM branching ratio.

If there is New Physics enhancement, then discovery could come earlier, but if SM persists, then a 10\% measurement

\(^6\) Can the US revamp its kaon program with Project-X at Fermilab? Let’s wait and see.
requiring $\mathcal{O}(100)$ events, and it would probably take a decade from the present time.

The $K^+ \to \pi^+\nu\nu$ and $K_L \to \pi^0\nu\nu$ decays are clean modes theoretically, and especially the latter holds big room for discovering BSM physics. The challenge is to get the experiment done, but these are some years away.

8 $\tau$: LFV and $(B - L)V$

Before concluding, we touch upon exciting developments in rare tau decays: radiative decays which have $b \to s$ echoes, and the enigmatic (if found) baryon number violating decays. There should be no doubt that we would have uncovered Beyond the Standard Model physics if any of these are observed.

8.1 $\tau \to \ell\gamma$, $\ell\ell\ell'$

The $\tau \to \ell\gamma$ processes are extremely suppressed in SM by the very light neutrino mass. This opens up the opportunity to probe BSM, just like the venerable $\mu \to e\gamma$ (where there is the fabulous MEG experiment at PSI). Observation of lepton flavor violating (LFV) decays would definitely mean New Physics! Besides, there is also the backdrop of large neutrino mixings. Again, the favorite is SUSY, ranging from sneutrino-chargino loops, exotic Higgs, $R$-parity violation, $\nu_R$ in SO(10), or large extra dimensions (LED). Predictions for $\tau \to \mu\gamma$, $\ell\ell\ell'$, $\ell M^0$ (where $M^0$ is a neutral meson) could reach the $10^{-7}$ level.

The models are often well motivated from observed near maximal $\nu_\mu$-$\nu_\tau$ mixing, or interesting ideas such as leptogenesis through leptogenesis. The great progress in neutrino physics of the past decade has stimulated a lot of interest in these LFV decays.

On the experimental side, the stars are once again the B factories: With $\sigma_{\tau\tau} \sim 0.9$ nb comparable to $\sigma_{bb} \sim 1.1$ nb, B factories are also $\tau$ (and charm) factories! As data increased steadily, the B factories have pushed the limits from $10^{-6}$ of the CLEO era, down to the $10^{-8}$ level. For example, with the 535 fb$^{-1}$ analysis by Belle [94] the limits on $\tau \to \ell\ell\ell'$ modes such as $\mu^+ e^- e^-$ and $e^+ \mu^- \mu^-$ have reached $2 \times 10^{-8}$, with BaBar not far behind [95]. Thus, some models or in their parameter space are now ruled out.

With BaBar closed, and with Belle at best giving result at 1 ab$^{-1}$, one at best touches the $10^{-8}$ boundary. To probe deeper into the parameter space of various LFV rare $\tau$ decays, a Super B factory would be called for. In the near future, LHCb can compete in the all charged track modes, but modes with neutrals would be difficult.

8.2 $\tau \to \Delta\pi$, $p\pi^0$

A somewhat wild idea is to search for baryon number violation (BNV) in $\tau$ decay, i.e. involving the 3rd generation. This was pointed out in Ref. [96], but the same reference argued that, by linking to the extremely stringent limit on proton decay, BNV ($B - L$ violating to be more precise) involving higher generations are in general much too small to be observed. This did not stop Belle from conducting a search [97], followed by BaBar [98]. So far, no signal is found, as expected.

9 Discussion and Conclusion

The last subsection brings us to wilder speculations that we have shunned so far. In the SUSY conference, however, ideas range widely, if not wildly. To this author, from an experimental point of view, the question is identifying the smoking gun, or else it is better to stick to the simplest explanation of an effect that requires New Physics. That has been our guiding principle.

Perhaps the wildest idea in 2007, and probably the one bringing out the most insight, is “unparticle physics” [99]. We do not discuss what this is all about, but it has clearly stimulated much (theoretical) interest. On the flavour and CPV front, for example, there is the suggestion that unparticles could generate DCPV in unexpected places [100]. Sure enough, this suggestion may well have been stimulated by the $3.2\sigma$ indication [101] of DCPV in $B^0 \to D^- D^+ \nu$ by Belle (though the BaBar result is consistent with zero [102]) that is otherwise very difficult to explain.

We note also that further studies of other $B^0 \to D^{(*)} D^{(*)}$ modes have not revealed anything to support the evidence for DCPV in $B^0 \to D^- D^+$. So, the Belle result needs to be revisited with more data. But searching for DCPV in the $B^+ \to \tau^+ \nu$ mode is also suggested [100], which is interesting. If I may speculate, maybe unparticles could generate BNV in the modes of the previous subsection. In any case, new ideas such as these stimulate search efforts in otherwise unmotivated places, hence are very valuable.

To summarize, I have covered a rather wide range of probes of TeV scale physics via heavy flavour processes. At the moment, we have two hints for New Physics: in the $\Delta S$ difference between TCPV in $B \to J/\psi K^0$ vs penguin dominant $b \to s\bar{q}q$ modes; and in the experimentally established difference in DCPV between $B^+ \to K^+ \pi^0$ and $B^0 \to K^+ \pi^-$ modes. These are large CPV effects, but they are not unequivocal, either in experiment, or in interpretation. Because of this, this thing to watch in 2008-2009, in my opinion, is whether the Tevatron could see a hint for large mixing-dependent CPV in $B_s \to J/\psi \phi$, i.e. $\sin 2\Phi_B$. If seen, it would be unequivocal as evidence for BSM. Curiously, a hint has appeared by Winter 2008. Though still too early to conclude, it should be clear that Tevatron can have 3-4 times the data than analyzed, and the hint could turn into evidence, before LHCb physics arrives. In any case, if the hint for sizable $\sin 2\Phi_B$ is true, it can be quickly confirmed by LHCb. If the hint for $\sin 2\Phi_B$ Tevatron fades away, LHCb can probe down to SM expectation rather quickly, with still a lot of range for New Physics discovery. But it would be a great disappointment if we again confirm the Standard Model. Other processes that have good potential for New Physics search emphasized in this brief review are: direct CPV in $B^+ \to$
While we are at the brink of major progress in probing into symmetry breaking physics, from the experimental side, Flavour physics has its own, complementary life. I would stress that all known effects of CPV rest in Yukawa couplings, which appear to be dynamical couplings that have not yet found a Symmetry principle foundation. For that matter, I offer the answer to why I have so often emphasized the possibility of a fourth sequential generation in this contribution on Flavour-TeV link: the 4 generation “Standard Model” can enhance the traditionally held Jarlskog invariant of 3 generations, the venerable $10^{-20}$, by 15 orders of magnitude [104], thereby providing enough CPV for baryogenesis. It is about large Yukawa coupling enhancement, which we already see in the top quark. Considering the Baryon Asymmetry of the Universe, maybe there really is a 4th generation. And that may change our attitude on SUSY.

Appendix: A CP Violation Primer

CPV is defined as a difference in probability between a particle process from the antiparticle process, e.g. between $B \to f$ and $\bar{B} \to \bar{f}$. It requires the presence of two interfering amplitudes. But besides the usual $i$ from quantum mechanics, it needs complex dynamics as well. That is, the interference involves the presence of two kinds of phases. Let us elucidate how CPV occurs.

Consider the particle process amplitude $A = A_1 + A_2$, which is a sum of two terms, where amplitude $A_j$ has both a CP invariant phase $\delta_j$ (imaginary $i$ from QM) and a CPV phase $\phi_j$ (imaginary $i$ from CPV dynamics). Absorbing an overall phase by defining $A_1 = a_1$ to be real, one has

$$A = A_1 + A_2 = a_1 + a_2 e^{i\phi} e^{i\delta},$$

$$\bar{A} = \bar{A}_1 + \bar{A}_2 = a_1 + a_2 e^{-i\phi} e^{-i\delta},$$

(32)

where $a_2 \equiv |A_2|$. The $\delta$ and $\phi$ are called the “strong” and weak phases, respectively. The QM or strong phase $\delta$ does not distinguish between particle or antiparticle, hence sign is unchanged. However, the dynamical or weak phase $\phi$ changes sign for the antiparticle process $\bar{A}$. This enrichment of quantum interference leads to an asymmetry between particle and antiparticle probabilities,

$$A_{CP} = \frac{\Gamma_{B^0 \to f} - \Gamma_{\bar{B}^0 \to \bar{f}}}{\Gamma_{B^0 \to f} + \Gamma_{\bar{B}^0 \to \bar{f}}} = \frac{2a_1a_2 \sin \delta \sin \phi}{a_1^2 + a_2^2 + 2a_1a_2 \cos \delta \cos \phi},$$

(33)

defined with respect to quarks. As $A_{CP}$ vanishes with either $\delta$ or $\phi \to 0$, CPV requires the presence of both CP conserving and CPV phases.

Eq. (32) is illustrated in Fig. 16, which shows geometrically how Eq. (33) materializes. If $\delta = 0$, then $A_1 + A_2$ and $A_1 + \bar{A}_2$ are at angle $\phi$ above or below the real axis, hence of equal length. If $\phi = 0$, then $A_1 + A_2$ and $\bar{A}_1 + \bar{A}_2$ are the same vector. Only when $\delta \neq 0$ and $\phi \neq 0$ does $|A_1 + A_2| \neq |A_1 + \bar{A}_2|$ occur, which gives the asymmetry of Eq. (33).
In the KM model with 3 generations, the CPV phase is put in the 13 and 31 elements ($V_{ub}$ and $V_{td}$) in the standard phase convention [3]. Thus, it is said that one needs the presence of all 3 generations to make CPV to occur.

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