Status and prospect of CP violation experiments

Tatsuya Nakada
LPHE, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland
E-mail: tatsuya.nakada@cern.ch

Abstract. Symmetry plays a crucial role in constructing a theory which describes the building blocks of the material and interactions between them. From the experimental observation of CP violation, existence of the third quark family had been revealed well before the second family was experimentally established. In this article, we recall the historical development of CP violation, and review the current important experimental results and prospects in near future. Then, it concludes with a general reflection.

1. Introduction and historical development

While it was shown that quantum field theory must be invariant under the combined transformations of space reflection (P), charge conjugation (C), and time reversal (T), so called CPT theorem [1], there is no principle reason for the theory to be invariant under individual transformations. The idea of parity violation in the weak interactions was proposed [2] in 1956 and experimentally confirmed [3] in 1957. This lead to a consideration that the combination of C and P would be conserved in the weak interactions [4], in conjunction with the handiness of the neutrino. Indeed a standard weak interaction theory developed afterward [5] fully explains P violation but it is CP invariant.

Violation of CP was discovered through the observation of a CP violating decay mode $\text{K}_L \rightarrow \pi^+\pi^-$ [6] in 1964. More intuitive demonstrations were made by comparing initial $\text{K}^0$ and $\overline{\text{K}}^0$ decaying into a CP eigenstate such as $\pi^+\pi^-$ as a function of the decay time [7]. Figure 1 shows such a comparison [8], where the interferences between the CP conserving $\text{K}_s \rightarrow \pi^+\pi^-$ and CP violating $\text{K}_L \rightarrow \pi^+\pi^-$ decay amplitudes are clearly visible. Note that the interference terms have opposite signs between the initial $\text{K}^0$ and $\overline{\text{K}}^0$.

If CPT symmetry holds, CP violation clearly implies T violation. Analyses [9] of CP violating and conserving parameters measured in the neutral kaon system show that they are compatible with CP and T violation together with CPT conservation. Those analyses are done based on the Bell-Steinberger relation [10], which assumes unitarity of the system. Again a more intuitive demonstration of T violation was made with the initial $\text{K}^0$ and $\overline{\text{K}}^0$ by noting that the time dependent oscillation rates for $\text{K}^0 \rightarrow \overline{\text{K}}^0$, $R_-(t)$, and $\overline{\text{K}}^0 \rightarrow \text{K}^0$, $R_+$, are CP and T conjugate to each other. Then, non-zero value of a time dependent asymmetry $A_T(t)$ defined as

$$A_T(t) = \frac{R_+ - R_-(t)}{R_+ + R_-(t)}$$

is a sign of T violation. Experimentally, the flavour at $t$ can be obtained by the semileptonic decay assuming the $\Delta Q = \Delta S$ rule, which can be easily explained by the quark model. In this

© 2009 IOP Publishing Ltd
neutral kaon decay time $\tau_S$

Figure 1. Time dependent decay rates for the initial $K^0$ (open circle) and $\bar{K}^0$ (closed circle) decaying into the $\pi^+\pi^-$ final state in a unit of the $K_S$ lifetime.

The measured value of the off-set, $(6.6 \pm 1.3) \times 10^{-3}$, is consistent with $2 \times \delta_\ell$ where $\delta_\ell$ is the charge asymmetry in the $K_L$ semileptonic decays. This agrees with the picture of violating CP and T symmetries while maintaining CPT symmetry.

As we learn in quantum mechanics the time reversal operator is antiunitary, thus when it acts on a $c$-number, the $c$-number must be complex conjugated. Therefore, it is easy to imagine that T violation, hence CP violation, can be generated by having a complex coupling constant in the system being considered.

Soon after the discovery of CP violation, a Superweak Model [12] was proposed where a new interaction much weaker than the weak interaction with a complex coupling constant contributes to the $\Delta S = 2$ $K^0\bar{K}^0$ transition amplitude, in addition to the existing second order weak interactions. In this model, CP violation in the $K^0\bar{K}^0$ transition amplitude is generated by the

Figure 2. A time dependent rate asymmetry [11] between $\bar{K}^0 \to K^0$ and $K^0 \to \bar{K}^0$, $A_T(t)$ defined in Equation 1, measured by the semileptonic decays of the initial $\bar{K}^0$ and $K^0$ as a function of the decay time in a unit of the $K_S$ lifetime.
interference between the absorptive part, which has only the weak interaction contribution, and dispersive part where both the weak and Superweak interactions contribute. In the decay, the Superweak contribution becomes negligible since it has to compete with the first order weak interaction. Therefore, all the CP violation effects are originating from the oscillations.

In 1973, it was realised [13] that by introducing the third quark family, CP violation can be naturally incorporated in the renormalisable electroweak Hamiltonian through a unitary three by three matrix, usually referred as Cabibbo-Kobayashi-Maskawa mass mixing matrix (CKM-matrix) providing the coupling of the W bosons with the flavour changing charged current. With the two quark families, the matrix (two by two) describes basically the Cabibbo mixing [14]. Once there are three families, some of the CKM-matrix elements, \( V_{ij} \) where \( i = u, c, t \) and \( j = d, s, b \), are generally complex, while with one or two families they must be all real. In this model, CP violation is generated not only in the \( S = 2 \) \( K_L \to 2\pi \) transition \[15, 16\] but also in the \( S = 1 \) first order weak interaction decay amplitude, although it is suppressed by the GIM mechanism \[17\] and observed dominance of the \( I = 1/2 \) decay amplitude.

Figure 3 summarises some of the past experimental efforts to observe CP violation in the decay amplitude \[18, 19\]. It shows the evolution of the \( 1 - |\eta_{00}/\eta_{+-}| \) measurements, where \( \eta_{00} \) and \( \eta_{+-} \) are the the ratios of the CP violating decay amplitude \( K_L \to 2\pi \) and the CP conserving one \( K_S \to 2\pi \) for \( 2\pi = \pi^0\pi^0 \) and \( = \pi^+\pi^- \), respectively. If CP violation in the decay amplitude is absent, CP violation parameters should not depend on the final states, i.e. \( |\eta_{00}| \neq |\eta_{+-}| \). Finally in 2001, \( |\eta_{00}| \neq |\eta_{+-}| \) was established after 30 years of work, excluding the Superweak model as the dominant source of CP violation.

Once the b quark had been discovered in 1977 \[20\], serious consideration on CP violation in the B-meson system started. While early studies \[16, 21\] discussed CP violation in the \( B^0, \bar{B}^0 \) oscillations, a possibility that the KM mechanism based on the complex CKM-matrix could generate a very large CP violation effect of > 0.1 in the interplay between the decay and oscillation was first pointed out in 1980 \[22\]. Golden CP violation channels, \( B^0 \) and \( \bar{B}^0 \to J/\psi K_S \) were pointed out in 1981 \[23\] and used as a reference for experimentally testing the KM mechanism. Different methods to generate observable CP violation in various B-meson...
Figure 4. Measurements of the amplitude for the time dependent CP asymmetry in the initial $B^0$ and $\bar{B}^0$ decaying into a charmonium and $K_S$ or $K_L$ final state (for the LEP and Tevatron experiments, only $J/\psi K_S$). The band shows the prediction by the Standard Model at around 2002.

decay modes were already pointed out in the same paper, and some of them were later developed in detail in various papers. When the $B^0$-$\bar{B}^0$ oscillation was discovered [24], it was pointed out that the size of CP violation, i.e. the amplitude of the time dependent decay asymmetry in the $B^0$ and $\bar{B}^0 \rightarrow J/\psi K_S$, could be predicted in the KM mechanism by combining the $B^0$-$\bar{B}^0$ oscillation frequency and CP violation in the $K^0$-$\bar{K}^0$ oscillations, without knowing the top quark mass [25].

For many B-meson factory projects discussed between the end of 80’s and the beginning of 90’s, discovery of CP violation in the $B \rightarrow J/\psi K_S$ decays was the primary goal, defining the luminosity requirement of the machines. Experiments at LEP and Tevatron measured this amplitude [26] without any conclusive result. Then the two B-factory experiments at PEP-II and KEKB respectively started to measure this amplitude [27]. In addition to the $J/\psi K_S$ final state, they added final states with other charmoniums and $K_L$, which were expected to produce the same amplitude as $J/\psi K_S$, in order to increase the statistics. In 2001, one experiment saw a signal with a significance of more than five standard deviations and the other very close to [28], and in 2002, the both experiments clearly established the CP violation effect [29] and the results were in a very good agreement with the prediction made by the KM mechanism. This is summarised in Figure 4.

It is interesting to note that CP violation in the decay amplitude was established in the neutral kaon system at around the same time when CP violation in the neutral B-meson system was first observed. With those results, it became clear that the Standard Model, through the KM mechanism, was largely responsible for the observed CP violation in phenomena particle physics.
2. Current status and near future

2.1. Kaon system

In the neutral kaon system, CP violation in the decay amplitude is now well established for the decays into two-pion final states, $\pi^+\pi^-$ and $\pi^0\pi^0$. The most recent measurements [19, 30] gives

$$1 - \left| \frac{\eta_{00}}{\eta_{+-}} \right| = (4.10 \pm 0.69) \times 10^{-3} \left( \equiv 3\epsilon' \epsilon \right).$$

As discussed by A. Buras in these proceedings, the result given by Equation 2 is in a good agreement with the Standard Model predictions. There is no further plan to improve this measurement. Already now, the current theoretical errors due to the uncertainties in evaluating the soft hadronic interaction effects are larger than the experimental ones. Future progress in the lattice QCD calculation could allow a better control on those errors, but it is not clear whether the relative error can be reduced to a 10% level.

Current experimental efforts are focusing on the preparation for the rare $K^+ \rightarrow \pi^+\nu\bar{\nu}$ decay measurement at CERN, and CP violating $K_L \rightarrow \pi^0\nu\bar{\nu}$ decay measurement at JPARC in Japan. For both cases, hadronic uncertainties are very small and the theoretical errors could be made below 10%. But the expected branching fractions are very small, $\sim 10^{-10}$ and $\sim 10^{-11}$ respectively. For the charged kaon decays, three candidates have been seen by an experiment at BNL [31] giving a branching fraction compatible with the Standard Model prediction. A major improvement could be expected from the CERN experiment. On the other hand, the current upper limit for the $K_L$ decay [32] is still three orders of magnitude higher than the Standard Model expectation.

2.2. B meson system

In the b-quark sector, CP violation is unambiguously established for the following three cases:

- CP violation in the $B^0 \rightarrow K^+\pi^-$ and $\bar{B}^0 \rightarrow K^-\pi^+$ decays [33, 34]. The decay time integrated CP asymmetry of the two most recent measurements give

$$A_{CP}^{neutral} = \frac{\text{Br}(\bar{B}^0 \rightarrow K^-\pi^+) - \text{Br}(B^0 \rightarrow K^+\pi^-)}{\text{Br}(\bar{B}^0 \rightarrow K^-\pi^+) + \text{Br}(B^0 \rightarrow K^+\pi^-)} = -0.10 \pm 0.01.$$  

i.e. CP violation in the decay amplitudes is clearly established. This was done only six years after the the first observation of CP violation in the B-meson system. As in the case of $\epsilon'$, its interpretation is less clear.

- Time dependent CP asymmetries in the decays of initial $B^0$ and $\bar{B}^0$ into CP eigenstates, which are composed of a charmonium ($J/\psi, \psi(2S), \eta_c$ etc.) and $K_S$ or $K_L$: By denoting $R_\ell(t)$ and $\overline{R}_\ell(t)$ to be the time dependent rates of the initial $B^0$ and $\bar{B}^0$ decaying into a CP eigenstate "$f$", respectively, the time dependent decay asymmetries are given by:

$$\frac{\overline{R}_\ell(t) - R_\ell(t)}{\overline{R}_\ell(t) + R_\ell(t)} = C_\ell \cos(\Delta m \cdot t) + (-1)^{CP_\ell}S_\ell \sin(\Delta m \cdot t)$$

where $CP_\ell$ is the CP eigenvalue of "$f$". For the $(\tau\bar{\tau})$-$K_S$ or -$K_L$ state, an average of the latest measurements [35] shows that $C_\ell$ is consistent with 0 and $S_\ell = 0.679 \pm 0.025$. This is by far the most accurately measured CP violating parameters in the B-meson system. The values of $C_\ell$ and $S_\ell$ agree with the Standard Model expectations very well.

- Time dependent CP asymmetry in the initial $B^0$ and $\bar{B}^0 \rightarrow \pi^+\pi^-$ decays, which is given by Equation 3. The last measurements [36, 33] for $C_{\pi^+\pi^-}$ and $S_{\pi^+\pi^-}$ are shown in Figure 5. Note that $C_{\pi^+\pi^-}$ and $S_{\pi^+\pi^-}$ are constrained to be $C_{\pi^+\pi^-}^2 + S_{\pi^+\pi^-}^2 = 1$ by construction.
Both measurements clearly establish CP violation in this decay modes. The two $S_{\pi^+\pi^-}$ measurements are in good agreement. While the two measurements on $C_{\pi^+\pi^-}$ are not in strong disagreement, their interpretations are very different; i.e. no CP violation in the decay amplitude versus observation of CP violation in the decay amplitude. Since the PEP-II has stopped and KEK-B will not run at $\Upsilon(4S)$ for the remaining year, this discrepancy will likely remain till a dedicated flavour physics experiment at LHC, LHCb [37], will start. Since it has an excellent hadron identification capability based on two Ring Imaging Cherenkov detectors, it will be well suited for the measurement. With the expected event rate, one year of nominal data should be sufficient for LHCb to settle this issue.

$$\begin{array}{c|c|c|c|c|c|c}
\text{B}^0 & \text{B}^0 & \text{B}^0 & \text{B}^0 & \text{B}^0 & \text{B}^0 & \text{B}^0 \\
\hline
1 & 0.5 & 0 & 0.5 & 1 & -0.5 & -1 \\
\hline
0 & 1 & 0.5 & 0 & 0.5 & 1 & 0 \\
\hline
-0.5 & 0 & 1 & 0.5 & 0 & 0.5 & 1 \\
\hline
-1 & -0.5 & 0 & 1 & 0.5 & 0 & 0.5 \\
\end{array}$$

Figure 5. CP violation parameters measured from the time dependent CP asymmetry in the initial $B^0$ and $\bar{B}^0 \to \pi^+\pi^-$ decays.

There are also a couple of intriguing results:

- As discussed already, CP violation in the decay amplitude is well established in the $K^\pm\pi^\mp$ decays. Naively, one expect the same CP violation effect for $B^\pm \to K^\pm\pi^0$ decays. However, it was found [38, 34] that

$$A_{CP}^{charged} = \frac{Br(B^- \to K^-\pi^0) - Br(B^+ \to K^+\pi^0)}{Br(B^- \to K^-\pi^0) + Br(B^+ \to K^+\pi^0)} = 0.06 \pm 0.02 \neq A_{CP}^{neutral}$$

with more than 5 $\sigma$ significance. Unfortunately, this is most likely to be due to the hadronic effects rather than physics beyond the Standard Model. CP violation in the decay amplitudes is always difficult to interpret due to the uncertainties in evaluating effects of hadronic interactions. On the other hand, it has a unique feature that the asymmetry is not only sensitive to the phases but also the moduli of the amplitudes contributing to the decay. With improved understandings on hadronic interactions in future, one might be able to see a deviation from the Standard Model predictions even with a new physics model which does not introduces new phases in the amplitude. LHCb can add measurements there in the $B_s$ sector.

- Tevatron experiments are producing very interesting flavour physics results. After the measurement of the $B^0_s - \bar{B}^0_s$ oscillation frequency [39], which is in full agreement with the Standard Model prediction, they are probing now CP violation in the $B^0_s$ and $\bar{B}^0_s \to J/\psi\phi$ decays. This is an analogous channel to the $J/\psi K_S$ decay in the $B^0$ meson system. $S_{J/\psi\phi}$ obtained from the time dependent decay rates [40] are shown in Figure 6 together with $\Delta\Gamma$,
which is the decay widths difference between the two $B_s$ mass eigenstates. The Standard Model prediction for $S_{J/\psi\phi}$ is very small, $\sim 0.04$. The current measurements are compatible with the Standard Model prediction, but the preferred values are much larger. LHCb should be able to test whether this large preferred values are correct or not very quickly. This is one of the few places where a large contribution from physics beyond the Standard Model is not yet excluded. Expected LHCb final error on $S_{J/\psi\phi}$ is 0.01.

Figure 6. CP violation parameter, $\arcsin(S_{J/\psi\phi})$ and the decay widths difference $\Delta\Gamma$ measured from the time dependent decay rates for the initial $B_s^0$ and $\bar{B}_s^0 \to J/\psi\phi$ decays by the two Tevatron experiments.

2.3. D meson system

There is now a strong evidence for $D^0-\bar{D}^0$ oscillations [41, 42] measured at the B factories and Tevatron. The observed effects are compatible with the Standard Model expectation, although the long range hadronic interactions in the $D^0-\bar{D}^0$ transition amplitude makes theoretical predictions very difficult. The next experimental step is to search for CP violation in the decay modes such as $\pi^+\pi^-$ and $K^+K^-$. The Standard Model expectation is very small $\sim 10^{-3}$ and with the current experiments [42, 43], it is difficult to reach that level. LHCb will have enough statistics to achieve such a level of sensitivities, provided that systematic effects could be kept under control. If New Physics preferentially couples to the up-type quarks, there could be a large enhancement in CP violation.

3. Foresight

Symmetry plays a fundamental role in constructing a theory of the building blocks of the material and interaction between them. However, violation of symmetry gives us even dipper understandings. CP violation phenomena seen in the neutral kaons and B meson systems are fully compatible with the Standard Model predictions. Neither precision electroweak measurements nor many measurements on the flavour changing neutral currents show any deviation from the Standard Model picture. This is somewhat contradictory to a common expectation that physics beyond the Standard Model is just around the corner and many new particles will be found at LHC. In fact we are already in the situation that either the energy threshold of New Physics is above the LHC reach, or the flavour structure of New Physics is very close to that of the Standard Model, or even a combination of the two.

In flavour physics, one of the ways to look for physics beyond the Standard Model is to test the consistency of the CKM matrix: For example, the phase of $V_{ub}$ (in a phase convention where $V_{cb}$ is real), $\gamma$, extracted from CP violation in the $B \to DK$ decays and $|V_{ub}/V_{cb}|$ from the semileptonic and hadronic B-meson decays, always provide the two of the four Wolfenstein’s
parameters [44] of the CKM-matrix, ρ and η, even if New Physics were present. One can then compare them with the Standard Model prediction
\[ S_{J/ψK_S} = \frac{2\eta(1-\rho)}{\eta^2 + (1-\rho)^2}, \]
where \( S_{J/ψK_S} \) is obtained from the time dependent CP asymmetry in \( B^0 \) and \( B^0 \rightarrow J/ψK_S \). With presence of New Physics in \( B^0, B^0 \) oscillations, the phase of the \( B^0, B^0 \) transition amplitude deviates from that of the Standard model and \( S_{J/ψK_S} \) becomes
\[ S_{J/ψK_S} = 2\frac{\eta(1-\rho)}{\eta^2 + (1-\rho)^2} \times \cos \Phi_{NP} \times \frac{\eta^2 - (1-\rho)^2}{\eta^2 + (1-\rho)^2} \times \sin \Phi_{NP}, \]
where \( \Phi_{NP} \) is the New Physics phase in the oscillations.

It is worth noting that γ and the phase of the \( B^0, B^0 \) transition amplitude (from \( S_{J/ψK_S} \)) can be extracted with little theoretical uncertainties. One hopes that the relative error on \( |V_{ub}|/V_{cb}| \), which is currently more than 10% and totally dominated by the theoretical uncertainties in the hadronic interactions, will improve to well below 10%, as little as 5%. The current error on γ is \( ∼12^o \) and with LHCb, one hopes to go down to \( 2 ∼ 3^o \). \( S_{J/ψK_S} \) is by far the best measured CP violation parameter, although at LHC one might be able to reduce the error even below \( 10^{-2} \).

However, if new physics has indeed a flavour structure similar to that of the Standard Model, \( S_{J/ψK_S} \) would not deviate from the Standard Model value, even if new physics contributes to the \( B^0, B^0 \) oscillation. A similar situation applies to CP violation in the \( B_s \rightarrow J/ψϕ \) decays. In such a case, so called a minimal flavour violation scenario, one may need to reconsider the search strategy. With such a scenario, phase measurements from CP violation, such as \( B^0 \) and \( B^0 \rightarrow ϕK_S \) and \( B^0_s \) and \( B^0_s \rightarrow ϕϕ \), where one tries to measure the phase of the \( b \rightarrow s \) penguin diagram, become less sensitive to New Physics.

One of the more efficient approaches for this scenario is to measure the branching fractions of decay modes which are very suppressed in the Standard Model, such as the \( B_s \rightarrow µ^+µ^- \) decays, as well as CP violation in the decay amplitudes. Another possibility is to probe the Lorentz structure of the flavour changing neutral current, since new scalar particles contributing there would modify the Lorentz structure from that of the Standard Model particles. In practice, this can be done by measuring the polarisation of the photon in the \( b \rightarrow s\gamma \) radiative penguin process. The photon can be virtual and it generates decays such as \( B^0 \rightarrow K^{*0}µ^+µ^- \). Both the angular distribution of the \( µ^+µ^- \) pairs and the polarisation of \( K^{*0} \) carry the information on the photon polarisation. For a real photon, CP violation can be used. In the chiral limit, the photons from \( B_s \rightarrow ϕγ \) and \( \overline{B}_s \rightarrow ϕγ \) have opposite polarisation and the two decay amplitudes cannot interfere. Therefore, no CP violation is expected in the time dependent CP asymmetry in the initial \( B_s \) and \( \overline{B}_s \rightarrow ϕγ \) decays. Observing time dependent CP asymmetry would be an unambiguous sign of physics beyond the Standard Model.

Those are the crucial measurements for the LHCb experiment: LHCb will collect two orders of magnitude more \( B^0 \rightarrow K^{*0}µ^+µ^- \) decays than the current experiments. Due to the large number of the \( B_s \) mesons, the upper limit on the \( B_s \rightarrow µ^+µ^- \) could be reduced to a level of the Standard Model prediction with one nominal year of data.

Given the conservation of lepton flavour is violating in the neutrino sector, this could also happen in the charged lepton sector, e.g. in tau decays such as \( τ \rightarrow 3µ \) and \( τ \rightarrow µγ \), which might be a window for physics beyond the Standard Model. A Super-B factory would be needed, in particular for the latter decay mode.

Once one sees some clear sign of New Physics at LHC, either an evidence of new particles by ATLAS and CMS or new flavour phenomena by LHCb, or both, one will know better what
to expect from new physics in a more concrete way. It might be indeed a new round of flavour experiments such as a Super B factory or Super LHCb would become real vital. We are about to enter a very exciting period.

Acknowledgments
The organisers of the conference are highly appreciated for their successful effort to organise this very interesting and stimulating conference as well as the warm hospitality, which made the participation truly memorable.

References
[1] Schwinger J 1951 Phys. Rev. 82 914
[2] Pauli W 1955 Niels Bohr and the Development of Physics: Essays Dedicated to Niels Bohr on the Occasion of His Seventieth Birthday ed. Pauli W, Rosenfeld L and Weisskopf V (New York, McGraw-Hill) p 30
[3] Bell J S 1955 Proc. R. Soc. Lond. A 231 479
[4] Wu C S, Ambler E, Hayward E R W, Hoppes D D and Hudson R P 1957 Phys. Rev. 105 1413
[5] Garwin R L, Lederman L M and Weinrich M 1957 Nucl. Phys. 3 127
[6] Sudarshan E C G and Marshall R E 1958 Phys. Rev. 19 1860
[7] Feynman R P and Gell-Mann M 1958 Phys. Rev. 109 193
[8] Theis W R et al. 1958 Z. Physik 150 590
[9] Lüders G 1954 Mat.-fys. Medd. 28(5) 1
[10] Pauli W 1955 Niels Bohr and the Development of Physics: Essays Dedicated to Niels Bohr on the Occasion of His Seventieth Birthday ed. Pauli W, Rosenfeld L and Weisskopf V (New York, McGraw-Hill) p 30
[11] Bell J S 1955 Proc. R. Soc. Lond. A 231 479
[12] Wu C S, Ambler E, Hayward E R W, Hoppes D D and Hudson R P 1957 Phys. Rev. 105 1413
[13] Garwin R L, Lederman L M and Weinrich M 1957 Phys. Rev. 105 1415
[14] Landau L D 1957 Nucl. Phys. 3 127
[15] Sudarshan E C G and Marshall R E 1958 Phys. Rev. 19 1860
[16] Feynman R P and Gell-Mann M 1958 Phys. Rev. 109 193
[17] Theis W R et al. 1958 Z. Physik 150 590
[18] Lüders G 1954 Mat.-fys. Medd. 28(5) 1
[19] Bell J S 1955 Proc. R. Soc. Lond. A 231 479
[20] Wu C S, Ambler E, Hayward E R W, Hoppes D D and Hudson R P 1957 Phys. Rev. 105 1413
[21] Garwin R L, Lederman L M and Weinrich M 1957 Phys. Rev. 105 1415
[22] Landau L D 1957 Nucl. Phys. 3 127
[23] Sudarshan E C G and Marshall R E 1958 Phys. Rev. 19 1860
[24] Feynman R P and Gell-Mann M 1958 Phys. Rev. 109 193
[25] Theis W R et al. 1958 Z. Physik 150 590
[26] Garwin R L, Lederman L M and Weinrich M 1957 Phys. Rev. 105 1415

DISCRETE’08: Symposium on Prospects in the Physics of Discrete Symmetries IOP Publishing
Journal of Physics: Conference Series 171 (2009) 012003 doi:10.1088/1742-6596/171/1/012003
R. Barate R (ALEPH Collaboration) 2000 Phys. Lett. B 492 259
[27] Abashian A et al. (Belle Collaboration) 2001 Phys. Rev. Lett. 86 2509
Aubert B et al. (BABAR Collaboration) 2001 Phys. Rev. Lett. 86 2515
[28] Aubert B et al. (BABAR Collaboration) 2001 Phys. Rev. Lett. 87 091801
Abe K et al. (Belle Collaboration) 2001 Phys. Rev. Lett. 87 091802
[29] Aubert B et al. (BABAR Collaboration) 2002 Phys. Rev. D 66 071102(R)
[30] Batley J R et al. (NA48 Collaboration) 2002 Phys. Lett. B 544 97
Artamonov A V et al. (E949 Collaboration) 2008 Phys. Rev. Lett. 101 191802
[31] Ahn J K et al. (E391a Collaboration) 2008 Phys. Rev. Lett. 100 201802
Aubert B et al. (BABAR Collaboration) 2007 Phys. Rev. Lett. 99 021603
Lin S-W et al. (Belle Collaboration) 2008 Nature 452 332
[32] Chen K-F et al. (Belle Collaboration) 2007 Phys. Rev. Lett. 98 031802
Aubert B et al. (BABAR Collaboration) 2007 Phys. Rev. Lett. 99 171803
Sahoo H et al. (Belle Collaboration) 2008 Phys. Rev. D 77 091103(R)
[33] Ishino H et al. (Belle Collaboration) 2007 Phys. Rev. Lett. 98 211801
Augusto Alves Jr A et al. (LHCb Collaboration) 2008 JINST 3 S08005
Aubert B et al. (BABAR Collaboration) 2007 Phys. Rev. D 76 091102(R)
[34] Abulencia A et al. (CDF Collaboration) 2006 Phys. Rev. Lett. 97 242003
Aaltonen T et al. (CDF Collaboration) 2008 Phys. Rev. Lett. 100 161802
Abazov V. M. et al. (D0 Collaboration) 2008 Phys. Rev. Lett. 101 241801
[35] Aubert B et al. (BABAR Collaboration) 2007 Phys. Rev. Lett. 98 211802
StaricM et al. (Belle Collaboration) 2007 Phys. Rev. Lett. 98 211803
Zhang L M et al. (Belle Collaboration) 2007 Phys. Rev. Lett. 99 131803
Aaltonen T et al. (CDF Collaboration) 2008 Phys. Rev. Lett. 100 121802
[36] Aubert B et al. (BABAR Collaboration) 2008 Phys. Rev. D 78 011105(R)
Adachi I et al. (Belle Collaboration) 2008 Phys. Lett. B 670 190
[37] Wolfenstein L 1983 Phys. Rev. Lett. 21 1945