

Flavour Physics at B-factories and other machines

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I review some of the highlights of results from non-hadron collider flavor experiments shown at the EPS conference in the summer of 2009. These include highlights of the latest results from the BABAR and Belle B-factories, CLEO-c, BES-III, NA48, KTeV, KLOE, NA62, MEG, and $\mu \rightarrow e$ conversion experiments.

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1. Introduction

The highlight of flavor physics over the past year has been the accolade awarded to Kobayashi and Maskawa by the Nobel Prize committee for their work on extending the theory of 2 generation quark mixing to include a third generation, and in doing so to naturally allow for the phenomenon of CP violation [1] via a single complex phase. This results in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing mechanism [2, 3]. After 37 years of testing, all observed CP conserving and violating phenomenon in the quark sector have been found to agree with the CKM theory. Much of these proceedings are devoted to experimental tests of predictions made by the CKM matrix.

The experimental results from non-hadron flavor experiments are summarized in these proceedings, including results from the *BABAR* and Belle B-factories, CLEO-c, BES-III, NA48, KTeV, KLOE, NA62, MEG, and $\mu \rightarrow e$ conversion experiments. Many of these measurements can be used to constrain our knowledge of CP violation and quark mixing, and in doing so they confirm that the CKM mechanism is the leading order description of nature. However the current precision of results allows for significant new physics contributions as a second order correction to the CKM picture. The remainder of these proceedings discuss recent results from experiment.

2. The B-factories

2.1 The Unitarity Triangle

The angles of the unitarity triangle (weak phases) are α , β , and γ . Some of the literature, including journal papers from the Belle experiment, use an alternate notation where $(\beta, \alpha, \gamma) = (\phi_1, \phi_2, \phi_3)$. Only two of these angles are independent parameters, predicted by the CKM mechanism, the third is constrained via $\alpha + \beta + \gamma = 180^\circ$.

2.1.1 The angle β

The measurement of β using $B^0 \rightarrow J/\psi K_S^0$ decays was the *raison d'être* of the B Factories. Not only has this measurement been made, but a number of ancillary measurements of B meson decays to final state comprising a Charmonium and neutral K or K^* have been made by these experiments. One of the impressive achievements of both experiments is the measurement of $\sin 2\beta$ from tree level processes with a Charmonium in the final state, and the good agreement between all of these measurements. Table 1 summarises these measurements in terms of S and C, where $S = \sqrt{1 - C^2} \sin 2\beta$ in the SM. Even though the B Factories have surpassed their designed luminosities and recorded some 1.5ab^{-1} of data, the measurement of $\sin 2\beta$ is still statistically limited: $\beta = (21.1 \pm 0.9)^\circ$ [4].

2.1.2 The angle α

The second angle to be measured by the B Factories is α . Measurements use B decays into final states including $\pi\pi$, $\rho\pi$, $\rho\rho$, and $a_1\pi$ that have undergone a $b \rightarrow u\bar{u}d$ transition. The tree level contribution to this process competes with a significant loop (penguin) amplitude that has a different weak phase to the tree. As a result one has to determine or constrain the bias from penguin amplitudes in order to measure α . There are a number of different recipes in the literature describing the steps required to constrain penguin contributions and thus measure α . The most

Table 1: Measurements of $\sin 2\beta$ made from tree level Charmonium decays at the B Factories. The combined results quote statistical and systematic uncertainties added in quadrature. Other results quote statistical errors followed by statistical uncertainties, and where only one error is given it is the statistical error.

Mode	BABAR	Belle	Average
$J/\psi K_S^0$	$0.657 \pm 0.036 \pm 0.012$	0.643 ± 0.038	–
$J/\psi K_L^0$	$0.694 \pm 0.061 \pm 0.031$	0.641 ± 0.057	–
$J/\psi K^{*0}$	$0.601 \pm 0.239 \pm 0.087$	–	–
$\eta_c K_S^0$	$0.925 \pm 0.160 \pm 0.057$	–	–
$\chi_{1c} K_S^0$	$0.614 \pm 0.160 \pm 0.040$	–	–
$\psi(2S) K_S^0$	$0.897 \pm 0.100 \pm 0.036$	$0.718 \pm 0.090 \pm 0.031$	0.798 ± 0.071
combined	0.691 ± 0.031	0.650 ± 0.034	0.672 ± 0.023

popular method is the Gronau-London $SU(2)$ Isospin analysis of $\pi\pi$ and $\rho\rho$ decays [5], although it is also possible to use an $SU(3)$ based approach to measure α from $\rho^+\rho^-$ and $K^{*0}\rho^+$ decays [6] to obtain a measurement of α with similar precision.

The most precise constraint on α comes from $B \rightarrow \rho\rho$ decays, where two improvements have occurred in the past year: i) a proof-of principle time-dependent CP asymmetry measurement has been performed in $B^0 \rightarrow \rho^0\rho^0$ decays, and ii) an updated branching fraction measurement of $B^+ \rightarrow \rho^+\rho^0$ has been performed. A precision time-dependent measurement of $B^0 \rightarrow \rho^0\rho^0$ at a future Super Flavour Factory would help us to remove ambiguities in the measurement of α , coming from the construct used to constrain penguin contributions, and in taking the arcsine of $S/\sqrt{1-C^2}$. The main impact on the constraint on α comes from the updated branching fraction measurement of $B^+ \rightarrow \rho^+\rho^0$. This is important as the $\rho^+\rho^0$ amplitude normalizes the base of the Isospin triangles used to constrain penguin contributions. The latest world average branching fraction of $(24 \pm 2) \times 10^{-6}$ means that the base of the triangle is a similar length to the side given by $\rho^+\rho^-$. The corollary of this is that uncertainties in penguin contributions are all degenerate, and the precision on α using this methods is significantly reduced. The precision on α from $\rho\rho$ decays is now $\pm 6.5^\circ$ with the $SU(2)$ approach [7], and $\pm 7^\circ$ with the $SU(3)$ approach [8].

The world average constraint on α from $\pi\pi$, $\rho\pi$ and $\rho\rho$ decays is $(89_{-4.2}^{+4.4})^\circ$ (CKM Fitter) [9] and $(92 \pm 7)^\circ$ (UTfit) [10]. The constraints from CKM Fitter are shown in Fig. 1 and do not include a measurement using $B \rightarrow a_1^\pm \pi^\mp$ decays with a precision of 13° on α . At the end of data taking for the B Factories it is interesting to note that of the four measurements of α , the one with the worst precision $B \rightarrow \pi\pi$ was originally envisaged as the best way to measure this angle.

2.1.3 The angle γ

The third unitarity triangle angle to measure is γ . This is relatively simple to measure from a theoretical viewpoint, however it is experimentally challenging by virtue of the low decay rates of interesting channels. γ is measured from charged B meson decays to $D^{(*)}K^*$ final states.

There are several theoretical schemes used to constrain this angle on the market. The most popular ones are the ADS [11], GLW [12] and GGSZ [13] methods. In the longer term a precision

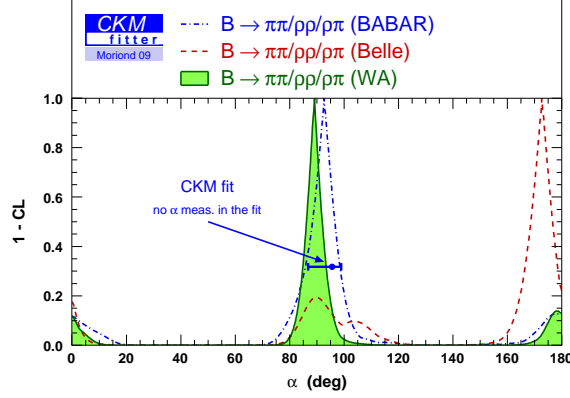


Figure 1: The distribution of one minus the confidence level for α obtained from $\pi\pi$, $\rho\pi$, and $\rho\rho$ decays (From CKM Fitter [9]).

measurement will be obtained from each of these methods, however given the current data samples, it is the latter method that dominates the precision of our knowledge on γ . This method utilizes the interference pattern in the $D \rightarrow K_S \pi^+ \pi^-$ Dalitz plot of $B \rightarrow \bar{D}^{(*)} K^*$ decays, where the difference between the B^+ and B^- decays contains information about this weak phase. Using 605fb^{-1} of data Belle have been able to determine $\gamma = (78.4^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^\circ$ [14]. This last uncertainty is dominated by the lack of knowledge of the $D \rightarrow K_S \pi^+ \pi^-$ Dalitz plot. This error can be reduced as discussed later in Section 4. *BABAR* have performed similar measurements [15], where the precision of the final result differs as *BABAR* use less data, and they extract a smaller value for the ratio of Cabibbo suppressed to allowed decays: r_B .

The world average constraint on γ from the ADS, GLW and GGSZ methods is $(70^{+27}_{-30})^\circ$ (CKM Fitter) [9] and $(78 \pm 12)^\circ$ (UTfit) [10] (See Fig. 2).

2.1.4 Summarizing the angles and testing the standard model

The direct measurements of α and β alone are sufficient to constrain the unitarity triangle to a precision of 5° . This constitutes a precision test of the CKM picture of CP violation in B meson decays. If one includes γ it is possible to check that the angles of the unitarity triangle sum to 180° as expected. The precision of these tests is $(180^{+27}_{-30})^\circ$ and $(191 \pm 14)^\circ$ for results from the CKM fitter [9] and UTfit [10] groups, respectively.

Having constrained the unitarity triangle, it is possible to start to test the SM description in various ways. One of these tests has been to compare the measured value of $\sin 2\beta$ in Charmonium decays with the measurements of $\sin 2\beta_{eff}$ made in loop (penguin) dominated processes. The caveat to making such a comparison is that the penguin dominated modes may have additional topologies that could lead to a difference between $\sin 2\beta_{eff}$ and $\sin 2\beta$. If these SM corrections Δ_{SM} are well known then any residual difference $\Delta S = \sin 2\beta_{eff} - \sin 2\beta - \Delta_{SM}$ would be from new physics. It is recently been pointed out that there are additional tests one should make, by using indirect constraints on CKM related processes in order to compute the expected value of $\sin 2\beta$ from the SM. This inferred value of $\sin 2\beta$ should be compared with both the directly measured

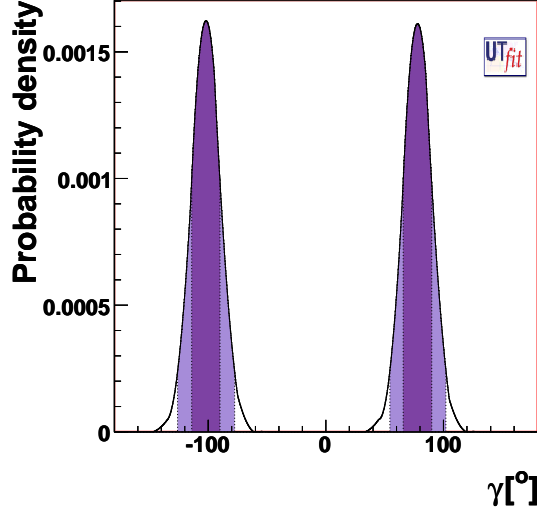


Figure 2: The distribution of the probability for γ obtained from the ADS, GLW and GGSZ methods (From UTFit [10]).

Charmonium and penguin dominated measurements. Figure 3 summarizes the different constraints on $\sin 2\beta$, where the difference between the measured and inferred values of $\sin 2\beta$ have a significance of 2.1 to 2.7σ .

2.2 Direct CP violation

The B-factories have performed many searches for direct CP violation over the past decade. These searches have resulted in the observation ($> 5\sigma$ significance) of this phenomenon in two decay modes: $B^0 \rightarrow K^\pm \pi^\mp$ and $B^0 \rightarrow \pi^+ \pi^-$, and a handful of channels indicating evidence ($> 3\sigma$) of this effect including B decays to ηK^* , ηK^\pm , $\rho^0 K^\pm$, $\rho^\pm \pi^\mp$, and $D^{0*} K^\pm$ final states. Theoretically the level of direct CP violation depends on strong phase differences between interfering amplitudes. These phase differences are hard to calculate so it is difficult to try and interpret these measurements.

One conundrum that has been perplexing the community for several years is the so called $K\pi$ puzzle. In the SM the difference between the direct CP asymmetry in $B^0 \rightarrow K^\pm \pi^\mp$ and $B^\pm \rightarrow K^\pm \pi^0$ is expected to be small and positive. The world average of this quantity turns out to be -0.148 ± 0.028 , which is clearly different from expectations. It has been noted that the difference observed here could be a sign of new physics, however the question of whether a more detailed understanding of the hadronic dynamics of these decays would resolve the discrepancy remained a possibility. At this conference S. Mishima presented work that was able to account for the large negative difference in asymmetries [16].

2.3 The polarization puzzle

The study of B meson decays to final states with two vector ($J^P = 1^-$) particles V has presented us with a decade long puzzle. The fraction of longitudinally polarized events f_L in such decays is

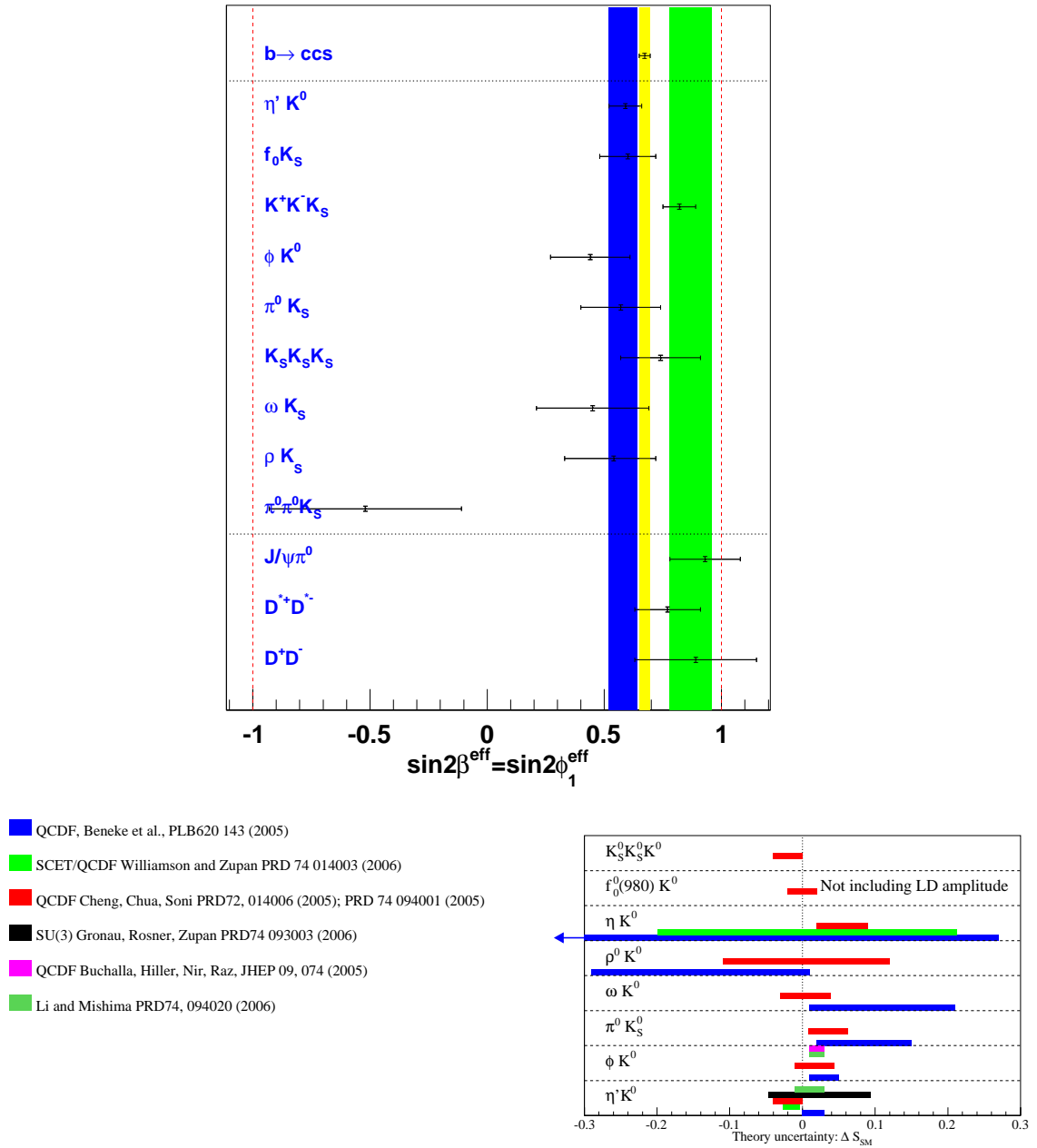


Figure 3: (top) The measured values of $\sin 2\beta$ in (yellow) Charmonium decays, (blue) penguin decays, and (green) inferred from indirect measurements. The constraint from penguin decays is an average of the two theoretically clean modes: $B^0 \rightarrow \eta' K^0$ and $B^0 \rightarrow \phi K^0$. (bottom) Theoretical uncertainties Δ_{SM} calculated for $b \rightarrow s$ penguin decays, with references given in the legend on the left.

expected to be $1 - m_V^2/m_b^2 \sim 1$. This naive expectation works well for some decays such as the $B \rightarrow \rho\rho$ channels discussed above. However there are clear deviations from this expectation, most

notably in $B \rightarrow \phi K^*$ decays where $f_L \sim 0.5$. Experimentally it is possible that deviations from the expectation of $f_L = 1$ could come from new physics, although additional experimental data would be useful in resolving this conundrum. The experimental situation is summarized in Figure 4, where it is clear that precision measurements of a number of these rare Charmless B decays would help to elucidate the non-trivial pattern of f_L .

In order to try and address the limited data, experimentalists have been searching for rare B decays to final states that also include axial-vector ($J^P = 1^+$) mesons A. Searches for the AV final states $a_1^\pm \rho^\mp$ [17], $a_1^\pm K^{*\mp}$, and combinations of a b_1 particle with a ρ or K^* [18] have so far yielded negative results. However *BABAR* recently reported observation of the decay $B^0 \rightarrow a_1^\pm a_1^\mp$ with a branching fraction central value of $(11.8 \pm 2.6 \pm 1.6) \times 10^{-6}$. The corresponding measurement of $f_L = 0.31 \pm 0.24$ [19] which is another non-trivial result on the polarization puzzle. In the longer term one could envisage obtaining information on the unitarity triangle angle α from this channel.

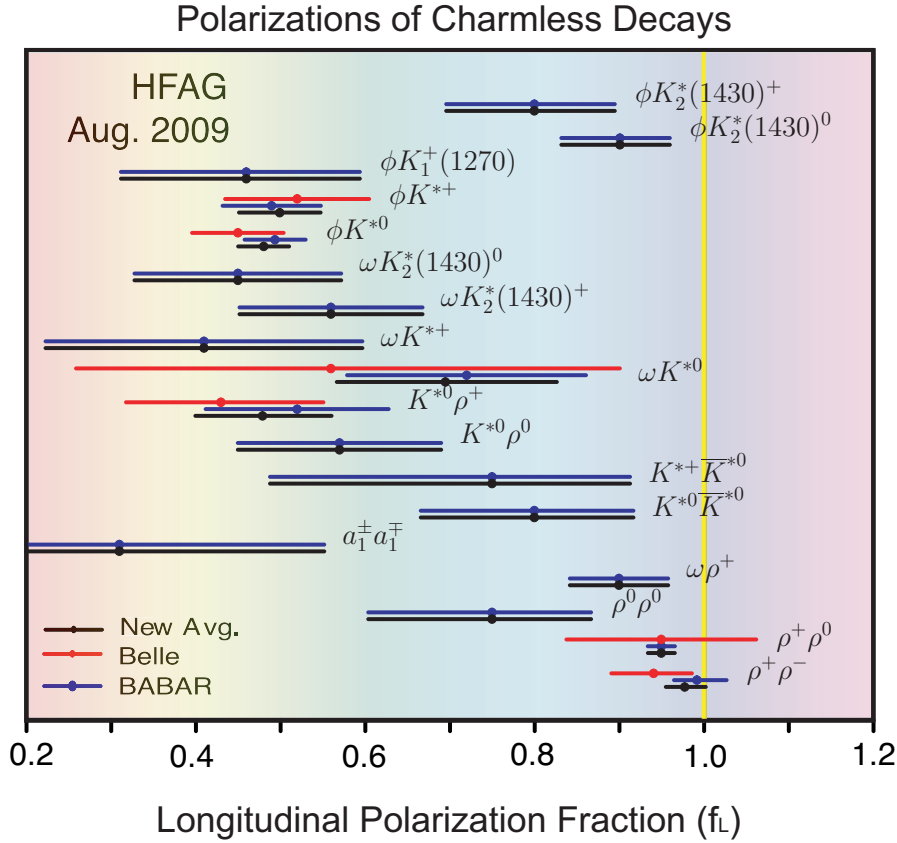


Figure 4: The measured values of f_L from B meson decays to final states with two spin one particles (Figure from Ref. [4]).

2.4 Rare B decays

The B Factory experiments are able to constrain new physics through the study of rare or SM suppressed processes. I highlight only two of the many different channels that can be studied: $B^\pm \rightarrow \tau^\pm \nu$, and $B \rightarrow s \ell^+ \ell^-$.

2.5 $B^\pm \rightarrow \tau^\pm \nu$

Identifying this final state is experimentally challenging as there are two neutrinos from the signal decay. The method used by the B Factories is to fully reconstruct one of the B mesons in the event, and then fully reconstruct the signal B , modulo the neutrinos. If a signal event has been correctly identified at this stage, then there will be no other activity in the detector. Following this reconstruction scheme, it is possible to use the remaining energy in the calorimeter as a discriminating variable which goes into a multi-dimensional maximum-likelihood fit in order to extract signal. Both $BABAR$ and Belle follow this scheme, and in doing so they obtain a branching fraction world average of $(1.73 \pm 0.35) \times 10^{-4}$ for this decay. The SM prediction is $(1.6 \pm 0.4) \times 10^{-4}$, where the dominant uncertainties on this prediction come from the uncertainty in V_{ub} and f_B .

Having made a measurement of this branching fraction, it is possible to constrain NP parameter space for a number of different models, including 2HDM [20], MSSM [21], and unparticles [22]. If we take the example of 2HDM, the observed branching fraction could be enhanced or suppressed by a factor of $(1 - m_B^2 \tan^2 \beta / m_H^2)^2$. The corresponding constraint on m_H^+ as a function of $\tan \beta$ exceeds 1TeV for $\tan \beta > 40$, and is about 100 GeV for $\tan \beta = 5$. The constraint on m_H^+ vs. $\tan \beta$ obtained for MSSM is similar. The constraint expected to be obtained from the LHC is typically $\leq 160 \text{ GeV}$ (95% C.L.) using 30 fb^{-1} of data [23]. The $gg/gb \rightarrow t[b]H^+$ channel, with $H^+ \rightarrow \tau^+ \nu$ can provide more stringent exclusions for large values of $\tan \beta$, than this. However it is worth noting that the indirect constraints from rare B decays already provides stronger constraints than expected from any direct search using a 10 fb^{-1} data sample at the LHC, and the LHC would need to record at least 30 fb^{-1} of data before it can make a significant impact in this area.

2.6 $B \rightarrow s \ell^+ \ell^-$

In analogy to the B meson decays to final states with two vector particles that are discussed above, there are many interesting observables that can be measured in the decay of B mesons to inclusive and exclusive $s \ell^+ \ell^-$ final states, where s is a strangeness one meson. These observables include f_L , forward-backward asymmetry A_{FB} , isospin asymmetry A_I , and the ratio of rates to $e^+ e^-$ and $\mu^+ \mu^-$ final states $R_{s \ell \ell}$. Recent results from the B Factories show that data are consistent with expectations from the SM, however it is clear that there is limited statistics available [24, 25]. If one compares the data to the A_{FB} expectation (see Fig. 5) of a new physics scenario with a sign-flipped Wilson coefficient of the effective Hamiltonian C_7^{eff} , then it is clear that the data prefer this expectation to that of the SM. Any significant quantitative test of this agreement will require more statistics than currently available, so this tantalising hint will either be refuted or confirmed by future experiments.

2.7 Lepton flavour violation in τ decays

The B Factory experiments are also τ factories. There is a wide range of SM tests and NP searches that can be performed at these experiments. One of the most promising sets of LFV measurements that can be performed are the $\tau \rightarrow 3 \ell$ decays. These are expected to occur in the SM with $\mathcal{B} \sim 10^{-54}$ [26] based on the known level of neutrino mixing.

The B Factories have searched for all possible three-lepton final states using blind analyses optimised on signal and background Monte Carlo simulated data, as well as data sidebands. The

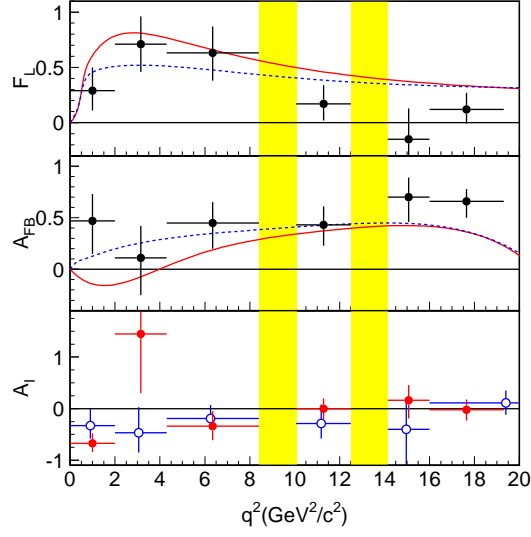


Figure 5: The forward-backward asymmetry distributions from Belle [25]. The solid line corresponds to the SM expectation, and the dashed line corresponds to a NP scenario with a sign-flipped C_7^{eff} .

upper limits obtained from these analyses are summarised in Table 2. The sensitivity of the current experiments reaches down to $1 - 2 \times 10^{-8}$. This is sufficient to constrain a number of LFV NP scenarios, and also surpasses the sensitivity expectations of the LHC [27].

Table 2: 90% C.L. Upper limits on the branching fraction of $\tau \rightarrow 3\ell$ decays.

Mode	ϵ [%] <i>BABAR</i> (Belle)	UL [$\times 10^{-8}$] <i>BABAR</i> (Belle)
$e^+e^-e^+$	8.6 (6.0)	2.9 (2.7)
$e^+e^-\mu^+$	8.8 (9.3)	2.2 (1.8)
$e^+e^+\mu^-$	12.6 (11.5)	1.8 (1.5)
$e^+\mu^-\mu^+$	6.4 (6.1)	3.2 (2.7)
$e^-\mu^+\mu^+$	10.2 (10.1)	2.6 (1.7)
$\mu^+\mu^-\mu^+$	6.6 (7.6)	3.3 (2.1)

There are a number of other searches for LFV in τ decay and many measurements of SM processes that have been performed at the B Factories. Unfortunately time constraints did not permit these to be discussed.

2.8 $|V_{ub}|$

In the past 12 months there has been little change in this area. The multiple inclusive measurements of V_{ub} are all in agreement with each other. Similarly the multiple exclusive measurements all agree. There is a tension between the inclusive and exclusive results, that remains at the level of

$1 - 2\sigma$ as shown in Figure 6. The measured value of $\sin 2\beta$ is more compatible with the exclusive $|V_{ub}|$ measurement.

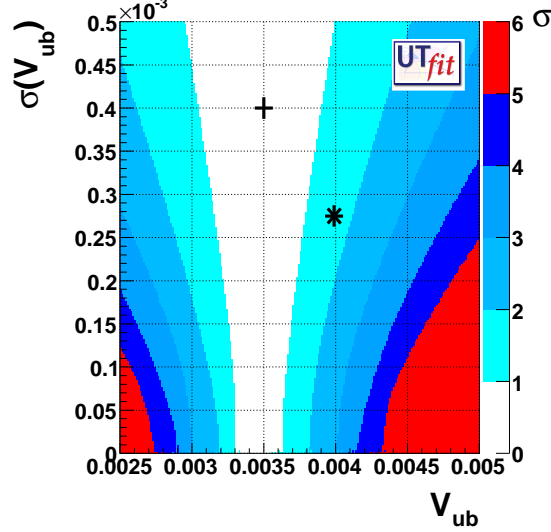


Figure 6: The compatibility plot for the inclusive (*) and exclusive (+) $|V_{ub}|$ measurements (From UT-fit [10]).

2.9 $|V_{cb}|$

As with the $|V_{ub}|$ measurements, there is some disagreement between the inclusive and exclusive $|V_{cb}|$ determinations using $b \rightarrow c\ell\nu$ decays with D^* mesons in the final state. These results are discussed in more detail in Refs. [28].

2.10 Charm mixing

The charm production cross section at the $\Upsilon(4S)$ is larger than the B production cross section. As a result the B factories have recorded hundreds of millions of charm decays. There is a very broad charm physics programme in studying this data, however both the focus and highlight of the past two years has been the study of neutral charm meson mixing.

We can define mixing parameters x and y which are related to the mass and width differences (Δm and $\Delta\Gamma$) of the two mass eigenstates $|D_1\rangle$ and $|D_2\rangle$. Where the mass eigenstates are related to the strong eigenstates via $p|D^0\rangle \pm q|\bar{D}^0\rangle$. The mixing parameter $x = \Delta m/\Gamma$, and $y = \Delta\Gamma/2\Gamma$, where Γ is the sum of the widths of D_1 and D_2 . There have been a number of different measurements of x and y performed by the B Factories, CLEO-c and CDF. The combined average of these measurements has a significance of a non-zero value of x and y which is 10.2σ . This constraint is shown in Figure 7. It is still interesting to note that while charm mixing has been firmly established, no single measurement has yet produced a signal greater than 5σ .

Now that charm mixing has been established, the next logical question is whether or not there is CP violation in charm decays, or mixing. As one expects a small level of CP violation in charm

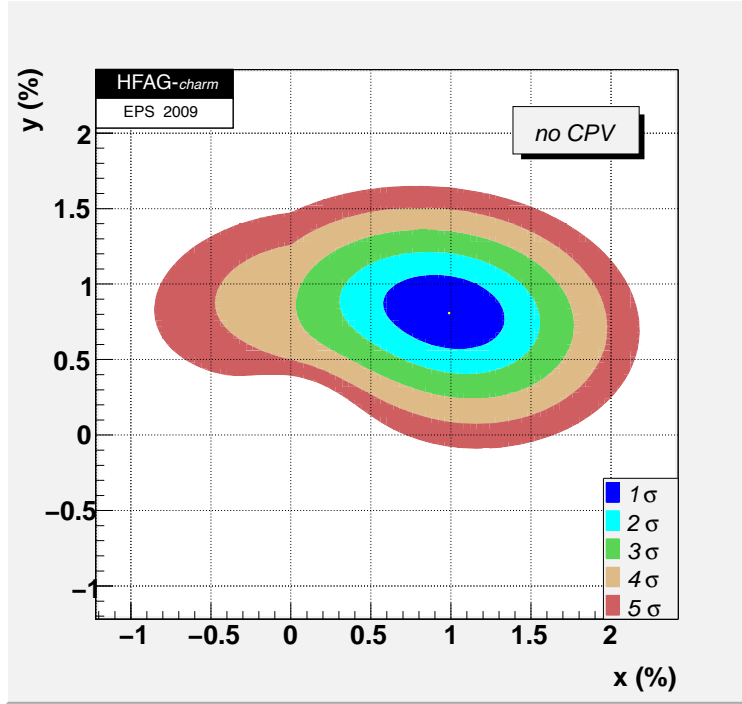


Figure 7: The constraint on x and y from all available measurements given by HFAG [4]. The significance of $(x, y) \neq (0, 0)$ is 10.2σ .

decays from SM related effects, and large effects (at the few % level) would be a clear indication of new physics. The search for CP violation in mixing yields a result compatible with CP conservation and $|q/p| = 1$.

Another possible test for charm mixing is the comparison of the lifetime measured for Cabibbo allowed $D \rightarrow K\pi$ and Cabibbo suppressed $D \rightarrow h^+h^-$ decays. If these lifetimes differ significantly, then mixing will have occurred. This is tested via the measurement of the quantity $y_{CP} = \tau_{D \rightarrow K\pi} / \tau_{D \rightarrow h^+h^-} - 1$, where a non-zero result indicates mixing. The world average result for $y_{CP} = (1.07 \pm 0.21)\%$, which again confirms the effect of mixing in charm decays.

2.11 Spectroscopy

One of the surprises of the B Factories was the many new states that have been uncovered since 2003. These started with Belle's discovery of the $X(3872)$ [29], and a second boost to this activity was initiated by the discovery of the $Y(4260)$ in the study of $J/\psi\pi\pi$ using ISR data at $BABAR$ [30]. A total of 11 new Charmonium states have been found as a result of these searches. These fit into the pattern of expected SM states above the open charm threshold. However there are a number of details that remain unanswered about the nature of these states. These questions range from simple confirmation of a state by a second experiment, as is the case for the recently discovered $Z(4430)$, to the nature of the particle itself, weather they are mesons, or some exotic hybrid state. Given that the B Factories are at the end of their data taking life, it is likely that many of these questions will remain unanswered until new experiments (such as the Super Flavour Factories discussed below)

are built.

2.12 Light Higgs Searches

It is possible to search for light scalar Higgs particles, such as the A^0 predicted by NMSSM to have a mass $< 10\text{GeV}/c^2$ using data collected at the $\Upsilon(3S)$ by *BABAR*. This mass range is inaccessible to LEP, the Tevatron, and the LHC. If NMSSM is a more precise description of nature than the SM, we need to have low energy e^+e^- collider programme to detect the A^0 and study its properties. *BABAR* have recently reported the results of searches for $\Upsilon(3S) \rightarrow \gamma A^0$, with the A^0 decaying into either a $\tau^+\tau^-$ [31], $\mu^+\mu^-$ [32], or a $\nu\bar{\nu}$ [33] final state. For $m_{A^0} < 10\text{GeV}/c^2$ the $\tau^+\tau^-$ channel is expected to dominate. No signal was found for any of the final states studied, and the limits placed on $\Upsilon(3S) \rightarrow \gamma A^0$ are significant improvements over previous studies. The limits for the $\tau^+\tau^-$ channel are of the order of a few $\times 10^{-5}$.

2.13 Light Dark Matter Searches

It is possible that light dark matter could be detected in decays of light mesons into invisible final states. Here the amplitude of a meson decay into a pair of dark matter particles could swamp the SM amplitude, leading to a significant enhancement in the measured branching fraction [34]. The *B* Factories have searched for $\Upsilon(1S) \rightarrow \textit{invisible}$ final states in order to test this model. The *BABAR* result uses $\Upsilon(3S) \rightarrow \Upsilon(1S)\pi\pi$, and tags the $1S$ sample using two soft pions. The limit placed on $\Upsilon(1S) \rightarrow \textit{invisible}$ by *BABAR* is $< 3.0 \times 10^{-4}$ (90% C.L.) [35], which places non trivial constraints on NP predictions, and is a factor of ten better than the previous search [36].

3. Super Flavour Factories

The *B* Factories have surpassed all expectations and accumulated 1.5ab^{-1} of data. The type of physics that has been done at these experiments encompasses much more than was originally envisaged when they were being constructed. The next phase in flavour physics studies using e^+e^- colliders operating with a center of mass energy in the vicinity of the $\Upsilon(4S)$ anticipates a data sample of 50 to 75ab^{-1} at a so-called Super Flavour Factory. There are two proposals being pursued: Belle-II at KEK in Japan [37], and SuperB near Frascati in Italy [38, 39]. The former aims to integrate 50ab^{-1} by the end of 2020, and the latter experiment aims to integrate 75ab^{-1} of data on a similar time-scale. The physics goals of these experiments are to elucidate the nature of high-energy interactions through the study of rare or forbidden decays. This is possible through the precision study of rare decays, utilizing the uncertainty principle so that virtual massive particles interfere with or dominate the SM amplitudes. Such measurements have an energy reach way beyond that of the brute force approach taken by hadron colliders such as the Tevatron and the LHC. Until recently the KEK Super Flavour Factory intended to construct an accelerator based on a high current scheme. However recently this has been abandoned in favor of the low emittance scheme developed for the SuperB programme in Italy. In addition to the higher luminosity goals of SuperB, that experiment will be built with polarized electron beams and the ability to collect data at the charm threshold center of mass energy corresponding to the $\psi(3770)$. These additional features give the SuperB experiment a broader physics programme than Belle-II.

4. CLEO-c

4.1 Constraining the model uncertainty on γ

As discussed in Section 2.1.4, there is a non-trivial model uncertainty on the measurement of γ that comes from a lack of detailed understanding of the $D \rightarrow K_S \pi \pi$ Dalitz structure. If this model uncertainty were to have remained, then the GGSZ method for measuring γ would be limited to an ultimate precision of the order of ten degrees. However it is possible to utilize quantum correlations at charm threshold to improve the knowledge of the Dalitz model, and hence the precision on γ [40]. CLEO-c have accumulated 818pb^{-1} of data running at a center of mass energy corresponding to charm threshold: $\psi(3770)$. Using this data, CLEO-c have performed a detailed analysis of $D \rightarrow K_S h^+ h^-$ decays, where $h = \pi, K$ [41]. These results are estimated to reduce the model uncertainty on γ from the GGSZ method from 9° to 1.7° . As the results are not systematically limited, measurements of this Dalitz plot in the future by BES-III and at SuperB could further reduce the model uncertainty on the GGSZ γ measurement.

4.2 Other charm results

In addition to the aforementioned measurements, CLEO-c has accumulated 586pb^{-1} of data above charm threshold at a center of mass energy of 4170 MeV. In addition to producing D^0 and D^+ mesons, one also produces D_s particles. A vast array of measurements of the branching fractions and properties of D^0 , D^+ , and D_s decays have been produced using these data [42]. Many of the D_s results have been published using 300pb^{-1} of data in Ref. [43]. In addition to the aforementioned results, CLEO-c have managed to measure semi-leptonic D decays [44], however time did not permit these results to be discussed.

5. Charmonium Factories: BES-III and KEDR

The BES-III Charmonium factory has been running routinely, having achieved luminosities of $3 \times 10^{32} \text{cm}^{-1} \text{s}^{-2}$. Thus far the experiment has collected $10^8 e^+ e^- \rightarrow \psi(2S)$ transitions and is in the process of analyzing this data sample. The detector is now well understood and has started to produce preliminary results. One such result is the confirmation of the decay $\psi(2S) \rightarrow \pi^0 h_c$, with the subsequent decay $h_c \rightarrow \gamma \eta_c$ [45]. BES-III is currently running on the J/ψ resonance, and aims to integrate 3 to 5×10^8 decays at this center of mass energy. Later plans for this experiment include running at charm threshold in order to accumulate $\mathcal{O}(20 \text{fb}^{-1})$.

The KEDR experiment has performed precision measurements of the J/ψ leptonic width obtaining $\Gamma_{ee}^2/\Gamma = 0.3355 \pm 0.0064 \pm 0.0048 \text{keV}$, which shows a marked improvement in precision relative to the DASP experiment performed in 1979 [46]. The cross-section of $e^+ e^- \rightarrow \mu^+ \mu^-$ decays has also been accurately measured in the vicinity of the J/ψ . In addition to these, KEDR have produced precision measurements of the charged and neutral D meson mass, resulting in the most precise measurement of $m_{D^+} = 1869.32 \pm 0.48 \pm 0.22 \text{MeV}$ [46].

6. Kaon physics

6.1 ϵ'/ϵ

A decade ago the NA48 and KTeV collaborations produced their first results on the measurement of ϵ'/ϵ which is obtained via the double ratio of K_L^0 and K_S^0 decays into pairs of neutral and charged pions through

$$R = 1 - 6\Re(\epsilon'/\epsilon) = \frac{N(K_L^0 \rightarrow \pi^0\pi^0)/N(K_S^0 \rightarrow \pi^0\pi^0)}{N(K_L^0 \rightarrow \pi^+\pi^-)/N(K_S^0 \rightarrow \pi^+\pi^-)}. \quad (6.1)$$

The results from these two experiments clearly indicated that $\epsilon'/\epsilon \neq 0$, and in doing so established the phenomenon of direct CP violation in the SM. During the last few years KTeV have been working on finalizing systematic uncertainties related to calorimeter cluster reconstruction and to acceptance effects in their analysis, and have now produced their final result. The measurements of ϵ'/ϵ from these experiments are [47]:

$$(\epsilon'/\epsilon)_{\text{NA48}} = (14.2 \pm 1.4(\text{stat.}) \pm 1.7(\text{syst.})) \times 10^{-4}, \quad (6.2)$$

$$(\epsilon'/\epsilon)_{\text{KTeV}} = (19.2 \pm 1.1(\text{stat.}) \pm 1.8(\text{syst.})) \times 10^{-4}, \quad (6.3)$$

and the corresponding world average is $(16.8 \pm 1.4) \times 10^{-4}$.

6.2 $|V_{us}|$

The quantity $|V_{us}|$ is a fundamental parameter of the SM. The unitarity of the CKM matrix means that we expect $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$, where for simplicity one can neglect the tiny contribution from V_{ub} . There has been some tension highlighted between the SM expectation of unitarity and recent measurements V_{us} and V_{ud} . KLOE have updated their measurement of V_{us} , through the study of $K \rightarrow \pi\ell\nu$ decays. This has resulted in a set of measurements of $f_+(0)|V_{us}|$, where $f_+(0)$ is a form factor calculable on the lattice. The KLOE result for $f_+(0)|V_{us}| = 0.2157 \pm 0.0006$ [48]. Using $f_+(0) = 0.9644 \pm 0.0049$ from UKQCD/RBC [49], and $V_{ud} = 0.97418 \pm 0.00025$ from $0^+ \rightarrow 0^+$ β decays [50], the world average value of $V_{us} = 0.2237 \pm 0.0013$, which includes the aforementioned KLOE result. Using this result, it is clear that the measurements of V_{us} and V_{ud} are compatible with unitarity.

6.3 R_K

One powerful test for new physics through lepton universality violation is the measurement of R_K , which is the ratio of branching ratios for charged kaons decaying into a K_{e2} and $K_{\mu 2}$ final state (i.e. $e\nu$, and $\mu\nu$):

$$R_K = \frac{\Gamma(K^\pm \rightarrow e^\pm\nu)}{\Gamma(K^\pm \rightarrow \mu^\pm\nu)}. \quad (6.4)$$

Enhancements from new physics can be parameterized in a number of ways, for example Ref. [51] uses $\Delta R = R_K^{\text{measured}}/R_K^{\text{SM}} = 1 + \Delta R_{NP}$ to search for signs of new physics giving deviation from the expected SM value R_K^{SM} . In order to compute the SM expectation of R_K one requires a detailed knowledge of the effect of final state radiation for the electron mode [52]. Given that this

is theoretically understood, the crux of this NP search lies in the measurement of the ratio. In itself, the R_K measurement is experimentally very challenging and limited by the experimental determination of the rate of K_{e2} decays. The KLOE experiment at DAΦNE has accumulated a data sample of 13,800 K_{e2} decays. Using this KLOE have achieved a 1% precision measurement of $R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$ which is still limited by statistics [53]. Recently the NA62 collaboration has released a preliminary result based on 40% of its total data sample. Using that data with a sample of 51,089 K_{e2} decays NA62 has reached a 0.6% measurement of $R_K = (2.500 \pm 0.012 \pm 0.011) \times 10^{-5}$ [54]. Here the reported systematic uncertainty is limited by effects that will reduce with statistics. The ultimate precision of R_K from NA62 is expected to be 0.3%. The NA62 result dominates the world average of R_K .

6.4 $K \rightarrow \pi \nu \bar{\nu}$

In a recently approved proposal NA62 [55], will be modified in order to be able to perform a measurement of the branching fraction of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ with a precision of 10%. This branching fraction provides a theoretically clean constraint on the apex of the unitarity triangle. In order to achieve this a number of new detector sub-systems are in the process of being redesigned. This includes a silicon pixel tracker whose purpose is to tag the presence of a K^+ candidate in the detector; a new set of veto anti-counters to surround the decay volume; straw trackers for reconstructing the trajectories of charged particles; and a RICH based particle identification system.

The proposed KOTO [56] experiment at JPARC aims to perform a 15% measurement of the branching fraction of the neutral mode $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$. This is a theoretically clean measurement of the height of the unitarity triangle.

Together with the measurement of ϵ_K , it would be possible to put a competitive constraint on the apex of the unitarity triangle from kaon decays. Such a constraint could be used as a test of the compatibility of results from B and K decays in the quark mixing sector and CP violation. Figure 8 illustrates a prediction of the type of constraint on the unitarity triangle that would be possible from a combination of these three measurements.

7. MEG: $\mu^\pm \rightarrow e^\pm \gamma$

The lepton flavor violating process $\mu^\pm \rightarrow e^\pm \gamma$ has a branching fraction of $\sim 10-50$ [57]. New physics could significantly enhance the branching fraction of the signal to the current experimental limits of $\mathcal{O}(10^{-11})$ [58]. The experimental challenge is to identify a back to back e^\pm and γ from the decaying μ^\pm . This signal process has to be isolated from irreducible physics backgrounds where $\mu^\pm \rightarrow e^\pm \nu_\mu \bar{\nu}_e \gamma$ where the neutrinos are low energy, so that the electron and photon are almost back-to-back in the final state. The second main background comes from $\mu^\pm \rightarrow e^\pm \nu_\mu \bar{\nu}_e$ decays with an in time accidental photon. As the final state neutrinos go undetected in the experiment, these two backgrounds are irreducible in the limit of low energy ν_μ and $\bar{\nu}_e$. It is clearly desirable to have excellent tracking and calorimetry for this experiment, and a high level of time resolution in order to reduce backgrounds arising from accidental activity.

MEG has recorded data for approximately 3.4 million seconds during 2008, and will resume taking data later this year. The ultimate design goal is a single event sensitivity of 1×10^{-13} on

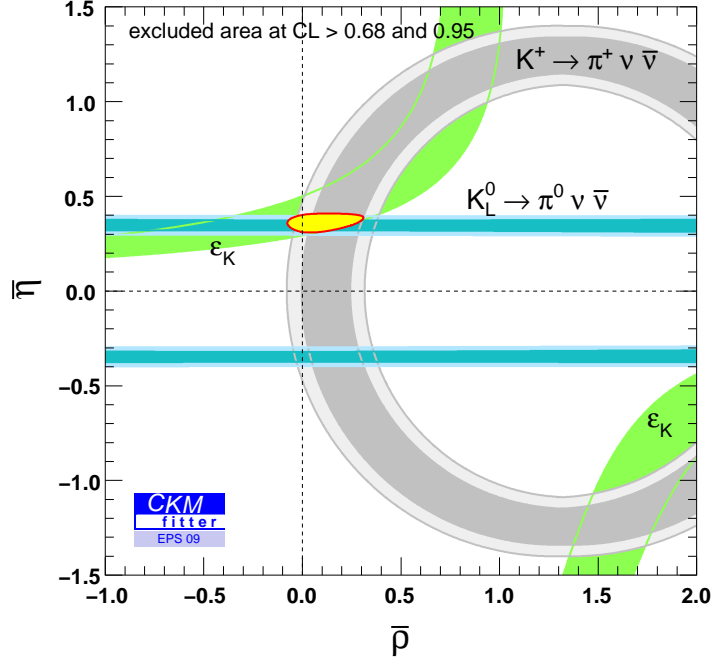


Figure 8: A prediction of the possible constraint on the unitarity triangle made using the existing measurement of ϵ_K and planned measurements of the branching ratios of neutral and charged $K \rightarrow \pi \nu \bar{\nu}$ decays. This prediction has been made by the CKM Fitter group [9].

$\mathcal{B}(\mu^\pm \rightarrow e^\pm \gamma)$. During the first year of data taking MEG encountered an issue with its drift chamber readout, that has since been corrected. The data are currently being analyzed using a blind analysis technique, and the first results from MEG are expected soon. Several weeks after this conference the MEG collaboration released preliminary result based on their 2008 data sample. This was $\mathcal{B}(\mu^\pm \rightarrow e^\pm \gamma) < 3 \times 10^{-11}$ [59]. In comparison, the expected upper limit from the 2009 run will be more than an order of magnitude lower [60].

8. $\mu \rightarrow e$ conversion experiments

In addition to searching for LFV in the μ sector, it is possible to try and observe the behavior of muonic-atoms, where a μ^- may spontaneously decay into an e^- without the emission of an associated neutrino. The new physics scenarios that might lead to an observable signal can differ from the mechanisms giving enhancements to LFV in τ or μ decay. These conversion experiments are very delicate and challenging enterprises, and the best limit on $\mu \rightarrow e$ conversion obtained thus far is from the Sindrum-II experiment. Studying gold the Sindrum-II collaboration placed an upper limit on $\mu \rightarrow e$ conversion at $< 7 \times 10^{-13}$ (90% C.L.) [61]. There are two experimental programmes currently being planned: Mu2e [62] at Fermilab in the US, and COMET [63] at JPARC in Japan. The initial stages of both of these programmes would aim to start collecting data in 2013 and improve upon the Sindrum-II limits by a factor of 1000.

9. Summary

Flavor physics experiments have produced a mind-boggling array of measurements, and only a few of the highlights of this experimental programme have been summarized in these proceedings. The theoretical motivation for much of the programme has been to test the CKM paradigm, and this has been shown to work exceptionally well in B and K decay. Despite this good agreement, there is still plenty of room for new physics effects to be manifest (and subsequently tested). The tests of the CKM paradigm in charm decays is on the cusp of a new era as existing experiments having established charm mixing, are now starting to probe for CP violation in this sector.

There are a number of rare decay tests that are able to constrain new physics scenarios. In some of these cases, for example 2HDM constraints on m_{H^+} vs. $\tan\beta$ using $B^- \rightarrow \tau^- \nu$ decays, and LFV in τ decay, the constraints obtained from the B Factories are more stringent than anything the LHC will be able to produce. It may be possible for the LHC experiments to develop new techniques to marginally improve upon the existing constraints, however a Super Flavor Factory will be required to make a significant improvement over existing limits. With regard to the related decay $\mu^\pm \rightarrow e^\pm \gamma$, the MEG experiment is working on finalizing a preliminary measurement from data recorded in 2008, and is expected to ultimately reach a single event sensitivity of $(30 - 50) \times 10^{-13}$. Significantly improved limits are expected from MEG using data taken in future runs (starting in the autumn of 2009).

The CLEO-c charm factory has produced a large number of branching fraction measurements, and using some of these they have been able to measure form factors f_D and f_{D_s} . A detailed analysis of the Dalitz Plot structure of $D^0 \rightarrow K^0 \pi^+ \pi^-$ decays has been made, and this measurement will lead to significant improvements in the model uncertainty on the γ measurement using the GGSZ method.

The BES-III Charmonium factory has recorded 100 million $\psi(2S)$ decays and is in the process of accumulating between 300 and 500 million J/ψ decays for precision measurements.

In addition to discovering many new particles, the B -factories have been able to accumulate data at the $\Upsilon(N S)$ resonance, where $N = 1, \dots, 5$. Using these data they have been able to test lepton universality, search for light Higgs particles and place limits on light dark matter scenarios. KLOE and NA62 have also been able to test lepton universality through precision measurements of R_K .

There are a number of planned flavor physics experiments to cover B , D , K , τ and μ decays. Together these measurements will provide a broad base of measurements to be performed that will help to elucidate the detailed structure of any new physics found at the LHC.

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