CP Violation in the B sector at the LHC

G. Wilkinson[a]

[a]Particle and Astrophysics Laboratory, University of Oxford, United Kingdom

The need for a B physics programme at the LHC to make a thorough study of CP violation is presented. The experimental attributes relevant for B physics of ATLAS, CMS and LHCb are discussed. Some example topics in the B_d^0 and B_s^0 sectors are given.

1. Introduction

CP violation arises naturally within electroweak theory, where it enters as an imaginary phase in the quark mixing matrix. Experimentally, however, it is one of the least constrained phenomena in particle physics. It has been observed in the kaon system, but the small size of the effects and the accompanying hadronic uncertainties mean that these measurements are inadequate for confirming the Standard Model explanation. Measurements of new CP violating observables are required to test the broad validity of this description, to provide insight into other open questions of the quark sector, such as why is there an extreme mass hierarchy, and to search for new physics. New physics is not in general expected to be CP conserving, and its presence therefore would generate inconsistencies in the interpretations of CP violating phenomena made within the Standard Model. Indeed, suggestions that such effects may exist come from cosmology. The observed matter-antimatter asymmetry in the universe requires CP violation, but at a higher level than that expected within the present theory. For all these reasons a thorough experimental programme of CP violation studies is of the utmost importance.

The best laboratory for CP violation physics is the B meson system. Here a large number of significant CP violating observables are expected which can be relatively cleanly related to Standard Model expectations. This programme is usually discussed within the unitarity triangle formalism, where the unitarity triangles are geometric expressions in the complex plane of relationships within the quark mixing matrix. The triangles are shown in figure 1 and have angles denoted by α, β, γ and $\delta\gamma$. It is these angles which in the Standard Model can be extracted from asymmetries formed in certain B meson decays. Other B physics observables can be used to constrain the sides. If CP violation is as described by the Standard Model then all measurements will return a consistent set of parameters.

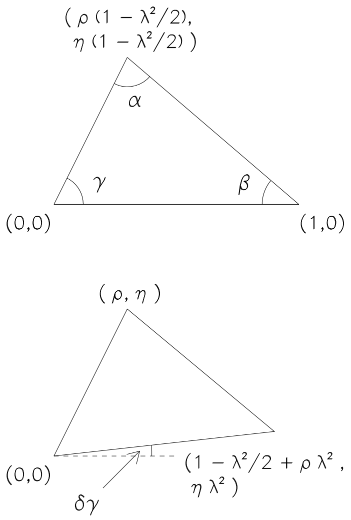

Figure 1. The unitarity triangles, showing the angles α, β, γ and $\delta\gamma$. ρ, λ and η are parameters of the quark mixing matrix in the Wolfenstein parameterisation.

The unitarity triangles will be probed by the recently commissioned BaBar and Belle detectors at $e^+e^- \to \Upsilon(4S)$ B factories, by the HeraB experiment operating in fixed target pN mode at DESY, and by CDF and D0 in $p\overline{p}$ collisions in the Tevatron Run II. Such experiments represent an exciting exploratory phase of B meson CP violation studies, and have the potential to establish a breakdown in the Standard Model. However, the very small branching ratios of most channels of interest (10^{-5} and less) will limit the accuracy of the measurements. Furthermore, the e^+e^- machines will operate at the $\Upsilon(4S)$ and will not be able to study the many interesting effects expected with $\mathrm{B_s^0}$ mesons. In contrast, the huge $b\overline{b}$ production cross-section at the LHC of $\sim 500\mu$b presents an opportunity to make a *complete* study of CP violation with the *full* spectrum of B hadrons. This study is a central goal of the LHC programme and will be conducted both by the general purpose detectors, ATLAS and CMS, and by the dedicated B physics forward spectrometer, LHCb.

2. Experimental Challenges

The primary challenge in exploiting the B physics potential of the LHC lies in triggering on the decays of interest and rejecting the superficially similar background, at a crossing rate of 40 MHz. Offline the experiments must be able to flavour tag the meson of interest at production time and be able to reconstruct the rapid proper time oscillations of $\mathrm{B_s^0}$ mesons. These attributes are possessed by all experiments under discussion. The important ability to distinguish pions from kaons is unique to LHCb.

The main features of the ATLAS and CMS experiments are well known from elsewhere; here are given those aspects of relevance for B physics studies. Both experiments will rely on single lepton triggers to accumulate B events, with transverse momentum p_t thresholds of $6-7\,\mathrm{GeV/c}$, supplemented by dilepton triggers with looser p_t requirements. It is expected these thresholds can be maintained for the initial $2-3$ years of 'low luminosity' running ($\mathcal{L} = 10^{33}\,\mathrm{cm^{-2}s^{-1}}$); it is assumed that the highest sensitivity to B physics will be in this period. Offline the flavour of the meson of interest at production time will be tagged by the charge of a lepton from the accompanying B hadron, or a close lying pion originating from a $B^{\star\star}$ decay or associated fragmentation production. Cylindrical tracking detectors lying close to the beampipe will give proper time resolutions of $\sim$ 60fs.

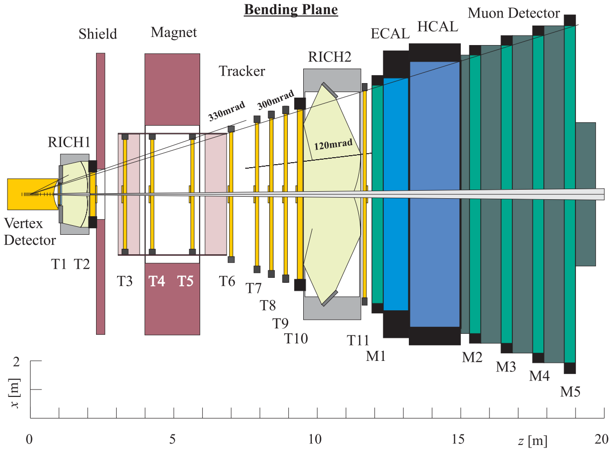

Figure 2. A schematic of the LHCb experiment. The interaction point is at $z = 0$.

As an experiment designed specifically for B physics study, LHCb differs in several notable ways from the central detectors. These are:

- **Forward Geometry**
  The $b\overline{b}$ production mechanism at the LHC means that both B hadrons are preferentially produced in a *correlated* manner, flying in the forward (or backward) direction. By building a spectrometer spanning the polar interval $10-300\,\mathrm{mrad}$, a substantial fraction ($\sim 10-15\%$) of B decays are fully contained within the acceptance. The high probability of the accompanying hadron being close by in angle is exploited in the trigger and flavour tagging. The forward geometry also allows for a planar vertex detector to approach to $\sim 1\,\mathrm{cm}$ of the beam within

Roman pots. This enables decays to be reconstructed with a proper time time resolution of 40 fs, which is a great asset in B_s^0 studies. A schematic of LHCb is shown in figure 2.

- **Dedicated trigger**
  LHCb's trigger strategy is designed to provide high efficiency across all B decays of interest, not only those involving leptons. The earliest level of triggering will indeed consist of single lepton triggers, operating with thresholds of $\sim 1\,\mathrm{GeV/c}$, but these will be complemented by a selection searching for single high p_t clusters ($> 2.5\,\mathrm{GeV/c}$) in the hadron calorimetry. Events fulfilling these criteria will then be processed by a secondary vertex trigger, which will efficiently select B decays, with only a weak dependence on final state topology. Finally DAQ triggers refine these decisions, and perform partial event reconstruction. The efficiency of these triggers is shown in table 1, for several channels of interest.

- **Dedicated luminosity**
  B events occurring in single interactions are most valuable in the offline analysis from the aspects of track multiplicity and an unambigous primary vertex; furthermore bunch-crossings with multiple background interactions risk saturating the trigger. For these reasons the beams will be defocussed at the LHCb interaction point to achieve a mean running luminosity of $2 \times 10^{33}\,\mathrm{cm^{-2}s^{-1}}$, which will both optimise the fraction of crossing with single interactions, and protect the close lying detector components against radiation damage. This operation is compatible with $10^{34}\,\mathrm{cm^{-2}s^{-1}}$ running at the other interaction points.

- **Hadron identification**
  Many final states of interest have same topology background involving kaons instead of pions, and vice versa. Examples include the channel $B_d^0 \to \pi^+\pi^-$which has background from πK and KK modes, and the $B_s^0 \to D_s K$, which has contamination from $B_s^0 \to D_s\pi$. In order to solve this problem LHCb is equipped with two Ring Imaging Cherenkov counters (RICHes), one upstream of the dipole magnet, optimised for low momentum particle identification, and one downstream, for lower angle, faster tracks. The choice of radiators (upstream: aerogel and C_4F_{10}, downstream: CF_4) provides π/K separation over a momentum interval of $1 < p < 150\,\mathrm{GeV/c}$. Identified kaons can also be used in the flavour tagging to supplement lepton tagged events.

3. Example B_d^0 modes

The B physics topics accessible at the LHC are very diverse. Here some example modes are presented [1], beginning with selected topics in the B_d^0 sector. These include modes which will initially be studied at the B factories – here it is explained what new insight the LHC will bring – and channels where there will be insufficient statistics for meaningful measurements at the earlier experiments.

3.1. $B_d^0 \to J/\psi K_0^s$

The determination of $\sin 2\beta$ from the CP asymmetry in $B_d^0 \to J/\psi K_0^s$decays is the primary goal of the first generation of B physics experiments. The combined precision of these measurements is likely to be impressive, with $\sigma_{\sin 2\beta} < 0.05$ in 2005. Nonetheless, the huge statistics of the LHC can bring valuable new insights to this important channel, with the leptonic final state ensuring that all three experiments make equally important contributions. The expected statistical precision of the combined LHC experiments is 0.011 in one year of operation, with no serious systematic uncertainty anticipated. Therefore a true 'LEP style' precision measurement of this fundamental parameter can be expected.

With such statistical power higher order effects can be explored. The general form of the CP asymmetry, A_{CP}, with proper time t is

$$A_{\mathrm{CP}}(t) = A_{\mathrm{dir}} \cos \Delta m t + A_{\mathrm{mix}} \sin \Delta m t \qquad (1)$$

where the A_{dir} term represents direct CP vi-

Table 1
LHCb trigger efficiencies for certain B decays. The p_t trigger efficiency is defined with respect to events useful in the offline analysis, and the other efficiencies with respect to the preceeding trigger level.

Channel	High p_t trigger	Vertex trigger	DAQ triggers
$\mathrm{B_d^0} \to \pi^+\pi^-$	0.76	0.48	0.83
$\mathrm{B_d^0} \to \mathrm{J}/\psi(\mu^+\mu^-)\mathrm{K_0^s}$	0.88	0.50	0.81
$\mathrm{B_d^0} \to \mathrm{J}/\psi(\mathrm{e^+e^-})\mathrm{K_0^s}$	0.72	0.42	0.81
$\mathrm{B_s^0} \to \mathrm{D_sK}$	0.54	0.59	0.92

olation and A_{mix} mixing induced CP violation (here Δm is the mass splitting between the eigenstates). In $\mathrm{B_d^0} \to \mathrm{J}/\psi\mathrm{K_0^s}$decays A_{dir} is usually ignored and A_{mix} taken to be $\sin 2\beta$. However in the Standard Model, though A_{dir} is expected to be small, it is not necessarily zero. Figure 3 shows a fit to a Monte Carlo sample of LHCb events equivalent to one year's data taking, generated with a small direct CP violating contribution. It can be seen that the LHC experiments have sensitivity to such effects.

3.2. $\mathrm{B_d^0} \to \pi^+\pi^-$

The CP asymmetry in $\mathrm{B_d^0} \to \pi^+\pi^-$decays can be related to the angle α. Events in this mode will be reconstructed by the B factory experiments, but the small branching ratio of 5×10^{-6} [2] means that only $\sim$ 100 offline reconstructed and flavour tagged events per year will be recorded. In one year of operation, however, the LHC experiments expect to accumulate $\sim$ 8 k reconstructed and tagged events. Over half of these will come from LHCb, which has higher efficiency on account of its triggering strategy.

In measuring the $\mathrm{B_d^0} \to \pi^+\pi^-$CP asymmetry the experiments will encounter the problem of the sample being dominated by same topology background from the $\mathrm{B_d^0} \to \mathrm{K}^+\pi^-$, $\mathrm{B_s^0} \to \mathrm{K}^+\pi^-$, $\mathrm{B_s^0} \to \mathrm{K^+K^-}$, $\Lambda_\mathrm{b} \to \mathrm{p}\pi$ and $\Lambda_\mathrm{b} \to \mathrm{pK}$ channels. Some of this background is expected to carry its own asymmetry. In principle signal and background asymmetries can be fitted simultaneously, using the vertex mass under different particle hypotheses, the tagged production flavour, proper time, and external constraints on the branching ratios. The RICH system of LHCb, however, enables this background to be suppressed to a neglible level and makes for improved systematic

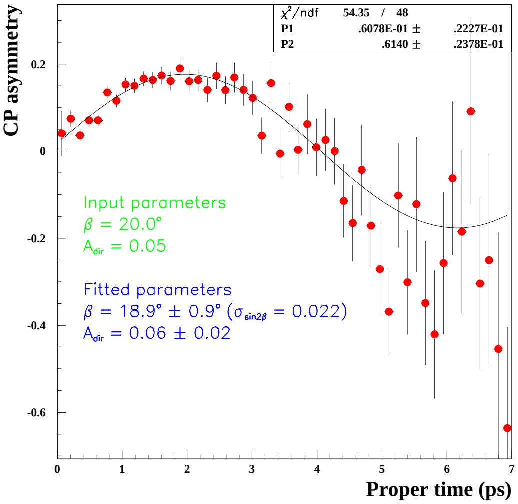

Figure 3. A fit to the CP asymmetry for a simulation sample of one year's LHCb yield in the channel $\mathrm{B_d^0} \to \mathrm{J}/\psi\mathrm{K_0^s}$. Both direct and mixing induced terms are included in the generation and the fit.

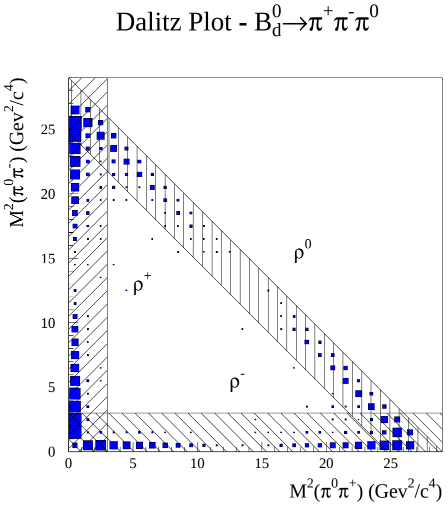

Figure 4. A Dalitz plot of the $\mathrm{B_d^0} \to \pi^+\pi^-\pi^0$ final state, showing the $\rho^+\pi^-$, $\rho^-\pi^+$ and $\rho^0\pi^0$ contributions. Helicity effects enhance the population in the interference regions.

stability. Both coefficients of the CP asymmetry will be fitted with a precision of ≈ 0.08.

Interpreting the $\mathrm{B_d^0} \to \pi^+\pi^-$asymmetry is however less straightforward than in the $\mathrm{B_d^0} \to \mathrm{J}/\psi\mathrm{K_0^s}$case. A significant contribution from gluonic Penguins is expected, which means that the A_{dir} term of expression 1 cannot be neglected and that A_{mix} is not equal to $\sin 2\alpha$. External knowledge of the relative strength of the Penguin contribution allows α to be fitted, together with any strong phase difference between the Penguin and tree diagrams. Various proposals exist to determine this contribution (see [3] for a review), but such is the statistical power of the LHC experiments that it is unrealistic to expect the control of the Penguin induced theoretical error to match the experimental precision after a year or so of data taking. In section 4.3 an alternative method of interpretting the CP asymmetry in this channel is explored.

The mode $\mathrm{B_d^0} \to \pi^+\pi^-\pi^0$ in principle provides sufficient observables for Penguin and tree contributions to be extracted separately, and thus for α to be determined cleanly. This analysis is made in proper time bins of Dalitz plots such as the one shown in figure 4, where bands from the $\rho^+\pi^-$, $\rho^-\pi^+$ and $\rho^0\pi^0$ intermediate states can be seen. Even in the challenging hadronic environment of the LHC it seems feasible to reconstruct these decays. LHCb expect about 1000 such reconstructed and tagged events a year, after background cuts, with a B_d^0 mass resolution of 45 MeV. This is again substantially more that will be seen at the B factories. The precision expected on α for various scenarios is under study.

3.3. $\mathrm{B_d^0} \to \overline{\mathrm{D}}^{*-}\pi^+$

Measurement of the time dependent rates for the four decays of the class $\mathrm{B_d^0}, \overline{\mathrm{B_d^0}} \to \overline{\mathrm{D}}^{*-}\pi^+, \mathrm{D}^{*+}\pi^-$ allows the CKM phase $2\beta + \gamma$ to be determined. Assuming that 2β may be fixed from the $\mathrm{B_d^0} \to \mathrm{J}/\psi\mathrm{K_0^s}$analysis, this channel then gives a measurement of the angle γ. The γ sensitivity comes from the interference of tree diagrams and there are no Penguin contributions. Therefore this channel can be regarded as providing a theoretically clean measurement of γ; one which is expected to be insensitive to new physics contributions and therefore important as a benchmark against which to compare other determinations. However the fact that one of the contributing diagrams is doubly Cabibbo suppressed means that the amplitude of any CP asymmetry will be $\mathcal{O}(1\%)$. Therefore very high statistics are required for a meaningful measurement, making this a natural target of the LHC programme.

LHCb have explored the potential of this channel. A method which uses the direction of the slow pion from the $\mathrm{D}^\star$ to reconstruct the B mass and momentum, without any information from the D^0 decay, enables 300k events to be reconstructed and tagged each year with a signal to background of > 10. A similar yield is expected from the channel $\mathrm{B_d^0} \to \overline{\mathrm{D}}^{*-}\mathrm{a}_1^+$. With such samples γ can be fitted with interesting precision, as is clear from figure 5, which gives the error on $2\beta + \gamma$ as a function of $2\beta + \gamma$ for one year and five years operation.

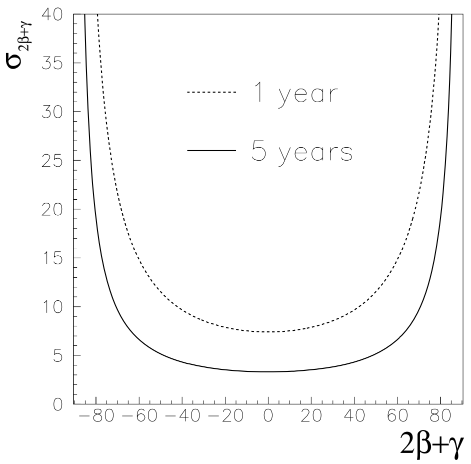

Figure 5. The fitted error on $2\beta+\gamma$ as a function of $2\beta+\gamma$ for one year and five years of LHCb data taking in the $\mathrm{B}^0_\mathrm{d} \to \overline{\mathrm{D}}^{*-}\pi^+$, a_1 channels. Here the strong phase difference has been set to zero.

4. Example B^0_s modes

The exploration of the B^0_s sector is a special responsibility of the LHC. It is probable that CDF and D0 will observe B^0_s oscillations during the Tevatron Run II, but unlikely that CP violating phenomena probed to an interesting level. This is possible at the LHC, because of the large event yields and the excellent proper time resolution of the experiments.

4.1. $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$

$\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$ is as important to the B^0_s system as $\mathrm{B}^0_\mathrm{d} \to \mathrm{J}/\psi\mathrm{K}^\mathrm{s}_0$ is to the B^0_d system. The CP asymmetry in this decay measures the $\mathrm{B}^0_\mathrm{s}\overline{\mathrm{B}^0_\mathrm{s}}$ weak mixing phase, 2 $\delta\gamma$, where $\delta\gamma$ is the angle in the second unitarity triangle of figure 1.

Experimentally, however, $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$ is a more demanding channel to study. As well as the need to resolve the rapid oscillations, the decay into two vectors means that an angular analysis is required to separate out the CP even and odd amplitudes. Furthermore $\delta\gamma$ is expected to be small, demanding great sensitivity. Conversely, the smallness of the expected Standard Model CP violation means that any enhancement will be an indication of new physics contributions.

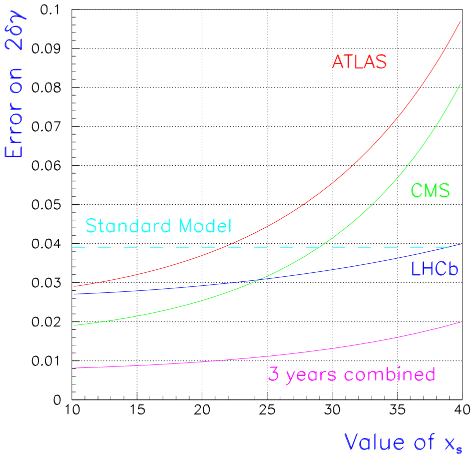

Figure 6. Error on $2\delta\gamma$ from $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$ for the LHC experiments as a function of x_s. The size of the Standard Model expectation is also indicated.

The $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$ potential of all three experiments has been evaluated. As with $\mathrm{B}^0_\mathrm{d} \to \mathrm{J}/\psi\mathrm{K}^\mathrm{s}_0$ the leptonic final state means that both ATLAS and CMS expect large yields ($\sim$ 100k events per year prior to flavour tagging). An indication of the likely error on $2\delta\gamma$ for each experiment in one year and the combined error after 3 years is shown in figure 6, as a function of the B^0_s mixing parameter x_s. It can be seen that sensitivity to Standard Model expectations is rapidly reached and thereafter a precise measurement becomes possible.

4.2. $\mathrm{B}^0_\mathrm{s} \to \mathrm{D_s K}$

The method of determining γ described in section 3.3 has a direct counterpart in the B^0_s system, that from the channel $\mathrm{B}^0_\mathrm{s} \to \mathrm{D_s K}$. Here the CKM phase fitted is $\gamma - 2\delta\gamma$. Assuming that $\delta\gamma$ can be fixed from the $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$ analysis, γ can be extracted. Note that particle identification is required to suppress the order of magnitude higher $B_s^0 \to D_s\pi$ background. LHCb expects a γ precision of $\sim 10°$ for one year's operation, with the exact value of the uncertainty depending on the value of x_s and the strong phase difference between the interferring diagrams.

4.3. $B_s^0 \to K^+K^-$ and $B_d^0 \to \pi^+\pi^-$ revisited

It was seen in section 3.2 that the LHC experiments will have excellent sensitivity to the CP violating observables in $B_d^0 \to \pi^+\pi^-$ decays, but that theoretical problems occur when these observables are interpretted in terms of the angle α. Other methods of analysis are possible, however, such as that which exploits the assumption of U spin flavour symmetry between $B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ [4].

The CP violating coefficients of equation 1 in the $B_s^0 \to K^+K^-$ asymmetry [1] may be measured just as those for $B_d^0 \to \pi^+\pi^-$. Experimentally this measurement is well suited to LHCb because of the trigger, particle identification and time resolution. The four coefficients have a dependence on the angles β, γ and $\delta\gamma$. Assuming that β and $\delta\gamma$ may be fixed from other measurements, then γ may be determined. The achievable precision is very promising, as is illustrated by figure 7 which shows the fitted value of γ from many Monte Carlo experiments simulating five years of LHCb running for a particular parameter set.

It should be stressed that this analysis has no Penguin associated uncertainties. Rather the contribution of Penguins are exploited in the relationships and this means that the returned value of γ may be particularly sensitive to effects beyond the Standard Model. These effects would be exposed by a comparison of γ determined with such an approach with measurements made from the 'benchmark' channels $B_d^0 \to \overline{D}^{*-}\pi^+$ and $B_s^0 \to D_sK$.

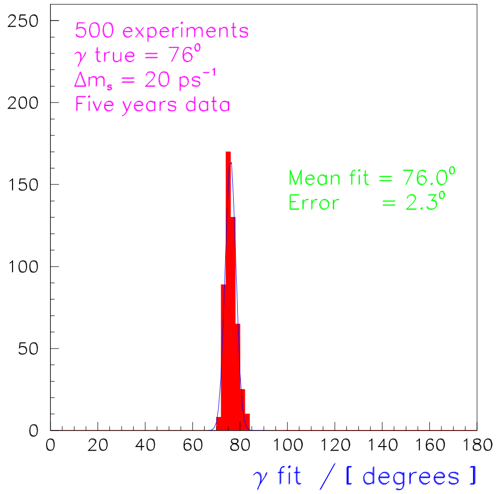

Figure 7. Result of γ fits to LHCb simulation samples of $B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ events.

5. Conclusions

The example channels summarised in this brief review illustrate the richness of CP violation measurements available at the LHC. The enormous statistics will allow precise studies of those topics which will be first explored by the previous generation of experiments, and will permit many complementary measurements of all angles of the unitarity triangles. These measurements will subject the flavour sector of the Standard Model to rigorous examination. Not touched on here are other subjects of interest in the B system, in particular very rare decays. In these also the LHC has unprecedented reach ATLAS, CMS and LHCb will all make important contributions to this work. The dedicated B physics trigger and particle identification of LHCb ensures that the enormous B physics potential of the LHC will be fully exploited.

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[1] Note however that in the B_s^0 case the width splitting between the eigenstates cannot be neglected, and the expression takes on a slightly more complex form.

REFERENCES

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3. J. Charles, 'Taming the Penguin in the $\mathrm{B}_{\mathrm{d}}^{0} \rightarrow \pi^{+}\pi^{-}$CP-Asymmetry: Observables and Minimal Theoretical Input', LPTHE-Orsay 98-35, hep-ph/9806468.
4. R. Fleischer, 'New Strategies to Extract β and γ from $\mathrm{B}_{\mathrm{d}}^{0} \rightarrow \pi^{+}\pi^{-}$and $\mathrm{B}_{\mathrm{s}}^{0} \rightarrow \mathrm{K}^{+}\mathrm{K}^{-}$', CERN-TH/99-79, hep-ph/9903456.

Questions

M. Neubert, SLAC:

How much better are the B physics capabilities of LHCb as compared with CMS and ATLAS ?

G. Wilkinson:

The ability to trigger with high efficiency on non-leptonic final states and to cleanly separate hadron particle types gives LHCb a clear advantage. LHCb will continue its B physics programme into the 'high luminosity' era of the machine, an option which is less straightforward for the general purpose detectors.

U. Nierste, Fermilab:

What are the chances of measuring inclusive CP asymmetries at the LHC ?

G. Wilkinson:

I am unaware of any studies into the feasibility of such measurements. The LHC triggers are necessarily rather selective, and so true inclusive measurements will be difficult to perform.