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MEASURING THE ANGLE γ AT LHCb*

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The ability to perform precision measurements on the CKM angle γ in many different decay channels using B_s^0, B_d^0 and $B^\pm$ decays is one of LHCb's most exciting features, promising to thoroughly over-constrain the SM of CP violation and quark mixing. Here we will outline proposed methods and expected event yields and precisions on γ for several of these methods.

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1. Introduction

LHCb is a dedicated B-physics experiment at the future LHC collider, making use of the large number of B-hadrons expected at the LHC. The experiment is scheduled to start taking physics-quality data in 2008. Here we will focus on one of LHCb's most exciting features, its ability to perform precision measurements on the CKM angle γ in many different decay channels using B_s^0, B_d^0 and $B^\pm$ decays. This will thoroughly over constrain the Standard Model description of CP violation and quark mixing, and provide a sensitive probe for New Physics.

2. CP violation, the CKM matrix, γ

In the Standard Model, CP violation can be accommodated by a single complex phase δ_{13} in the CKM matrix, which is the matrix that relates the mass-eigenstates of the down-type quarks to the weak isospin partners of the up-type quarks. Up to $\mathcal{O}(\lambda^3)$ in the Wolfenstein parametrisation of the CKM matrix [5], only the two smallest elements have complex phases (these phases are not independent and would vanish if δ_{13} were 0):

$$V_{td} = |V_{td}|\, e^{-i\beta} \qquad \text{and} \qquad V_{ub} = |V_{ub}|\, e^{-i\gamma}\,. \tag{1}$$

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By convention, a third angle α is introduced, defined by $\alpha \equiv \pi - \beta - \gamma$. Measurements in charmless B_d^0 decays, like $B_d^0 \to \rho\rho$, that are sensitive to $2\beta + 2\gamma = 2(\pi - \alpha)$ are classified as α measurements. These are discussed in Olivier Deschamps' contribution to these proceedings. Other measurements involving γ are classified as γ measurements — they are the subject of this contribution.

While the angle β has been measured very precisely by the B factories, γ (and α) are only weakly constrained. The current constraints from direct measurements of the angle γ come from $B^\pm \to DK^\pm$ [1, 2] and $B_d^0 \to D^{(*)}\pi$ [3, 4] decays. The combined result is $\gamma = 71^\circ{}^{+22^\circ}_{-30^\circ}$ [6] (status Winter 06). The SM constraint from indirect measurement (including β and α) is far more accurate with $\gamma = 60^\circ{}^{+5^\circ}_{-4^\circ}$. To progress further in our search for inconsistencies in SM flavour physics, requires precision measurements of γ in many independent decay channels of B_d, $B^\pm$ and B_s mesons. LHCb is in a unique position to perform such a series of measurements.

3. LHCb

Due to the huge $b\bar{b}$ production cross section of $\sim 500\mu$b at 14 TeV proton–proton collisions [7], and the high luminosity, LHC will be the most copious source of B hadrons in the world by several orders of magnitude. It will produce large numbers of all kinds of B hadrons, including B_d, $B^\pm$, B_s, B_c and Λ_b. First collisions at reduced energy are expected in 2007, with full physics runs commencing in mid 2008. LHCb is specifically designed to make best use of the large number of $b\bar{b}$ pairs produced at the LHC. Due to its moderate luminosity requirements of $2 \cdot 10^{32}$ cm^{-2}s^{-1}, LHCb can start its full physics programme right from the beginning of LHC operation in 2008. Within one year of data taking, LHCb expects to collect 2 fb^{-1} of data. Amongst its most important features are a good acceptance up to high pseudo-rapidity to maximise B-hadron yield, excellent proper time resolution, RICH particle identification and a dedicated B trigger, including a decay-time based hadron trigger. More details about the LHCb detector can be found in [8].

4. Measuring γ in time-dependent decay rate asymmetries

4.1. Basic principle

The complex CKM elements result in phase differences between interfering decay paths to the same final state, one with and one without mixing. These phase differences can be extracted from the amplitudes of time dependent decay rate asymmetries:

$$\mathrm{Asy}_f(t) = \frac{\Gamma(B^0 \to f) - \Gamma(\overline{B^0} \to f)}{\Gamma(B^0 \to f) + \Gamma(\overline{B^0} \to f)} = A_f^{\mathrm{dir}} \cos(\Delta m\, t) + A_f^{\mathrm{mix}} \sin(\Delta m\, t)\,, \quad (2)$$

where B^0 and $\overline{B^0}$ refer to the state at the time of creation and Δm is the mass difference between the two CP eigenstates of the B. For decays to CP eigenstates $f = \pm\mathrm{CP}(f) \equiv \bar{f}$, any observation of a non-zero asymmetry is evidence of CP violation. For non-CP eigenstates $f \neq \pm\bar{f}$, the CP violation manifests itself as the difference between two asymmetries, $\mathrm{Asy}_f(t)$ and its CP-conjugate, $\mathrm{Asy}_{\bar{f}}(t)$. In either case, interpreting a measurement of A_f^{dir} and A_f^{mix} in terms of the CKM angles β, γ can be non-trivial (see Section 4.3).

4.2. Flavour tagging

Measuring time-dependent decay rate asymmetries requires the knowledge as what the reconstructed B meson was born — as a $B_d^0\,(B_s^0)$ or a $\overline{B_d^0}\,(\overline{B_s^0})$. The figure of merit for the tagging performance is given by the "effective tagging efficiency" $\varepsilon_{\mathrm{eff}} = \epsilon D^2 = \epsilon(1-\omega)^2$, which is derived from the tagging efficiency ϵ and the mistag fraction ω. It is defined such that the statistical significance of N events with an effective tagging efficiency $\varepsilon_{\mathrm{eff}}$ is equivalent to $\varepsilon_{\mathrm{eff}} \cdot N$ perfectly tagged events. At LHCb, depending on the signal decay channel under consideration $\varepsilon_{\mathrm{eff}} \sim 4\%$–$5\%$ for B_d^0 decays, and for B_s^0 decays (where there is additional information from same-side Kaon tagging) $\varepsilon_{\mathrm{eff}} \sim 7\%$–$9\%$.

4.3. $B_d \to \pi\pi$ and $B_s \to KK$

The decay $B_d \to \pi\pi$ is, due to the $b \to u$ transition in the tree contribution to the decay, sensitive to the CKM angle γ. However, the presence of penguin contributions, while providing interesting physics, severely complicates the interpretation of the observed asymmetries in terms of CKM angles. A possible strategy that allows the tree and penguin contributions to be disentangled, and thus measure γ, is due to Fleischer [24], and uses U-spin symmetry of the strong interaction to relate observables in $B_d \to \pi\pi$ and $B_s \to KK$.

LHCb relies heavily on its K/π separation capabilities to achieve the required sample purity, as otherwise the different hadronic two body decay modes of B hadrons are virtually indistinguishable. LHCb expects ~ 26k $B_d \to \pi\pi$ events and 37k $B_s \to KK$ events in 2 fb^{-1} with a $S/B > 1.4$ and $S/B > 2$ respectively. For $\Delta m_s = 17.8$ ps [25], we expect a statistical uncertainty on γ from this analysis of $\sim 5°$.

4.4. $B_s \to D_s K$

An alternative way to tackle the problem of penguin contributions is to look at decays that do not have any, like $B_s \to D_s K$, or $B_d \to D^{(*)}\pi$ [26]. These decays are expected to be rather insensitive to New Physics contributions, and therefore measure a "Standard Model γ", providing a benchmark that other decays, that are more sensitive to New Physics, can be compared against. Further details are given in [26]. The particle ID capabilities of LHCb are crucial for the reconstruction of this decay, that would otherwise be swamped by background from $B_s \to D_s^- \pi^+$, which has a ~ 10 times higher branching ratio. LHCb expects to reconstruct 5.4k $B_s \to D^- K^+$ events per year with $S/B > 2$. This translates into a sensitivity on γ of $\sim 13°$ for $\Delta m_s = 17.8$ ps^{-1}.

5. Untagged, time-integrated $B^\pm \to DK^\pm$ and $B^0 \to DK^*$

As in the previously discussed time-dependent measurements, in this time-independent untagged method [19–22] the CKM phases manifest themselves in the interference between two or more decay paths to the same final state. As illustrated in Fig. 1, the interfering decay paths are $B^- \to D^0 K^-$ and $B^- \to \overline{D^0} K^-$ where the D^0 and the $\overline{D^0}$ decay to the same final state f, for example K^+K^-. Decay rates in these channels are sensitive to the amplitude ratios

$$\frac{A(B^- \to \overline{D^0}K^-)}{A(B^- \to D^0 K^-)} = r_B e^{i(\delta-\gamma)}, \quad \frac{A(B^+ \to D^0 K^+)}{A(B^+ \to D^0 K^+)} = r_B e^{i(\delta+\gamma)}, \quad (3)$$

which can be parametrised by three parameters, the absolute ratio of the amplitudes r_B, their phase difference induced by the strong interaction δ, and the CKM phase γ.

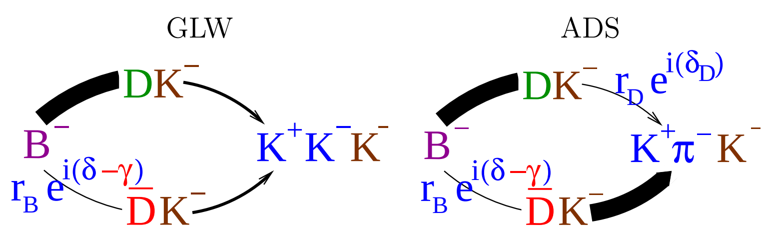

Fig. 1. CKM phases manifest themselves in interfering decay paths to the same final states. The differences of GLW vs ADS are explained in the text.

One distinguishes the "GLW" method after Gronau, London and Wyler [19] and the "ADS" method after Atwood, Dunietz and Soni [20]. In the GLW approach, $f(D)$ is a CP-eigenstate, so that parameters related to the $D^0 - \overline{D^0}$ amplitude ratio cancel. However, because one of the two $B^\pm$ amplitudes is colour suppressed relative to the other, the two interfering amplitudes are of very different magnitude and interference effects are small. In the ADS approach D^0 decays to non-CP eigenstates, where $A(D \to f) \neq A(\bar{D} \to f)$, are used to partially compensate for that imbalance. This achieves larger interference effects and, for the same number of events, a higher sensitivity to γ, but also introduces a new set of parameters describing the ratio of the D^0 decay amplitudes involved, $r_D e^{i\delta_D}$. This is illustrated in Fig. 1. Time-integrated CP asymmetries in ADS modes can be very large, for example [23]:

$$\frac{\Gamma(B^- \to D(K^-\pi^+)K^-) - \Gamma(B^+ \to D(K^-\pi^+)K^+)}{\Gamma(B^- \to D(K^-\pi^+)K^-) + \Gamma(B^+ \to D(K^-\pi^+)K^+)} \approx 0.4\,.$$

5.1. γ from counting event rates

In a simultaneous analysis of 60k $K\pi$, 60k $K\pi\pi\pi$[1] and 8k KK and $\pi\pi$ events (corresponding to approximately 2 fb^{-1} of LHCb data) a precision on γ between 4° and 14° is achieved, depending on input parameters [23]. The simultaneous analysis of several decay modes allows all parameters, including the phase differences δ_D of the ADS modes to be extracted from the fit. The only external inputs are the easily obtainable r_D parameters for the ADS modes.

5.2. Amplitude analyses of multi body decays of the D

With multibody D^0 decays, the decay can proceed via a large number of sub-resonances, so instead of two interfering decay paths, one has to deal with a multitude of them. In the case of three body decays, the decay kinematics can be parametrised by two parameters (Dalitz plot). Effectively every point in the two-dimensional Dalitz plot corresponds to another decay path with different r_D and δ_D. The Dalitz structure of D^0 decays is modified if the D^0 mesons come from $B^\pm$ decays due to the interference effects discussed above. If the raw Dalitz plot (for D^0s that do not come from $B^\pm$) is well understood, these modifications can be used to extract all B-related quantities, r_B, δ, and γ [21, 22].

5.2.1. $B^\pm \to D(K_s\pi\pi)K^\pm$

Fig. 2 shows the result of a generator study at LHCb for the case where the D^0 decays to $K_s\pi^+\pi^-$. The study concluded that, within the limited statistics available, the LHCb acceptance is flat over the Dalitz plot area.

[1] In this analysis, the resonant structure of multibody decays was ignored.

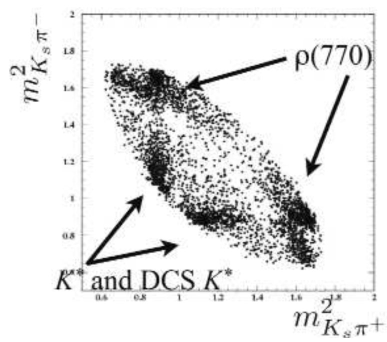

Fig. 2. Dalitz Plot for $D \to K_s\pi^+\pi^-$ from generator-level study at LHCb. The most important resonances are pointed out, but more than 15 subresonances contribute to the decay.

LHCb expects about 1.3k $B^\pm \to D(K_s\pi\pi)K^\pm$ events per year with a S/B between 0.5 and 3.2. For $\gamma = 60°$, $\delta = 130°$ and $r_B = 8\%$ the expected uncertainty of γ after 1 year is $\sigma(\gamma) \sim 16°$. Note that, for small r_B, the uncertainty on γ is found to be approximately inversely proportional to r_B.

5.2.2. γ from $B^\pm \to D(KK\pi\pi)K^\pm$

The same amplitude analysis that can be done for 3-body D^0 decays can be done for 4-body D^0 decays. The analysis is slightly more tricky for 4 bodies: the amplitude structure is more complicated due to several intermediate states in decay chains, the decay kinematics now depend on five parameters, rather than two, and phase-space is not flat in those five parameters (while it is in the two Dalitz-plot parameters). But the concept is the same. With the same input values as above, including $r_B = 8\%$, we expect $\sigma(\gamma) \sim 20°$ for 1.5k events [27]. Studies for $B^\pm \to D(K\pi\pi\pi)K^\pm$, where we expect a better resolution due to the ADS effect, are ongoing.

5.2.3. γ from $B_d^0 \to D^0 K^{*0}$

The same method as for charged B decays can be applied to neutral B decays, where the $K^* \to K^+\pi^-$ tags the B_d^0 flavour at decay [28]. Because both B_d^0 decay modes are colour suppressed, we expect fewer events, but interference effects are expected to be enhanced relative to $B^\pm$ modes. LHCb expects to reconstruct within 1 year of data taking:

- 3.4k $B_d^0 \to D^0(K^+\pi^-)K^{*0}$ (+c.c.) events with $S/B > 2$
- 0.5k $B_d^0 \to D^0(K^-\pi^+)K^{*0}$ (+c.c.) events with $S/B > 0.3$
- 0.6k $B_d^0 \to D^0(K^-\pi^+)K^{*0}$ (+c.c.) events with $S/B > 0.3$

resulting in an uncertainty on γ of $\sigma(\gamma) \sim 8°$.

6. Summary

The LHCb detector [9] is on track for data taking in 2007, and ready to start its full physics programme with the first 14 TeV collisions at the LHC expected in 2008. The detector is designed to make best use of the vast number of B hadrons of all flavours, that are expected at the LHC. In this report we focused on one of the most exciting prospects at LHCb, the possibility to perform precision measurements of the angle γ in many different decay channels in B_d, $B^{\pm}$, and B_s decays. Some of the measurements will be more and some less susceptible to New Physics contributions. A selection of such channels are listed in Table 1.

TABLE 1

Some γ sensitive channels accessible at LHCb. It is indicated if the channels decay via tree-diagrams only, of if penguin diagrams contribute.

Channel		Tree	Peng
$\left.\begin{array}{l} B_d^0 \to \pi^+\pi^- \\ B_s^0 \to K^+K^- \end{array}\right\}$	U-spin		$\surd$
$\left.\begin{array}{l} B_d^0 \to \rho^+\pi^- \\ B_d^d \to \rho\rho \end{array}\right\}$	measures $\alpha \equiv \pi - \beta - \gamma$		$\surd$ $\surd$
$B_d^0 \to D^{*\pm}\pi^{\mp}$		$\surd$	
$B_s^0 \to D_s^{\pm}K^{\mp}$		$\surd$	
$B^{\pm} \to D^0(K\pi, KK, \pi K)K^{\pm}$		$\surd$	
$B_d^0 \to D^0(K\pi, KK, \pi K)K^{*0}$		$\surd$	
$B^{\pm} \to D^0(K_s\pi\pi)K^{\pm}$		$\surd$	
$B^0 \to D^0(K_s\pi\pi)K^*$	(study in progress)	$\surd$	
$B^{\pm} \to D^0(KK\pi\pi)K^{\pm}$	(study in progress)	$\surd$	
$B^{\pm} \to D^0(K\pi\pi\pi)K^{\pm}$	(study in progress)	$\surd$	

The typical resolution in γ is $5°$–$15°$ for each channel, within a single year of data taking. Channels with significant penguin contributions are expected to be more sensitive to New Physics contribution than tree-only decays. The $B^{\pm} \to DK$ category of analyses is tree-only, but sensitive to new physics in the charm sector. This will thoroughly over constrain the Standard Model description of CP violation, providing important Standard Model measurements with a high sensitivity to New Physics. Such precision measurements in the flavour sector will also severely restrict the parameter space of possible new physics models suggested by direct production of new particles that might be seen at the LHC.

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