Potential for precise Unitarity Triangle angles measurements in LHC

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The Large Hadron Collider (LHC) will represent a very important opportunity for B physics research. The two multi-purpose experiments, ATLAS and CMS will have the capability to realize competitive programmes, while a dedicated experiment LHCb will have the explicit task to exploit a wide range of physics decays involving B mesons. This paper is a review of the main characteristics of the future measurements of the Unitarity Triangle angles at these experiments, and the expected achievable precisions.

1. Present results

The Standard Model (SM) allows for the CKM unitarity triangle [1] only a very restricted region of the $(\bar{\eta}, \bar{\rho})$ plane. In Figure 1 the present knowledge of the angles of Unitarity Triangle (plus ε_K) is represented, the most stringent constraint coming from the β angle [2]. The general consistency of the various available measurements is very good. Together with the measurements of the sides and Δm_s recent results, it leads to rather precise predictions for all the three angles:

$$\alpha = 94.6^\circ \pm 4.6^\circ \tag{1}$$

$$\beta = 23.9^\circ \pm 1.0^\circ \tag{2}$$

$$\gamma = 61.3^\circ \pm 4.5^\circ \tag{3}$$

$$\phi_s = 2.1^\circ \pm 0.2^\circ \tag{4}$$

New Physics effects are certainly capable of modifying this pattern, but it will need quite a high statistical and systematic precision in order to disentangle them from SM components effects.

2. LHC Experiments

Three experiments are foreseen at LHC which may give important contribution to the CKM Triangle determination. ATLAS [3] and CMS [4] will explore B physics mainly through the use of high p_T muons, and in decay modes involving di–muons. The LHCb [5] experiment is dedicated explicitly to B-physics. It consists of a single-arm spectrometer in the "forward" region. To that extent, it is complementary to ATLAS and CMS experiments which are sensitive to the central rapidity region. LHCb will have a $b\bar{b}$ production cross section of 230μb, more than a factor 2 with respect to ATLAS and CMS.

Trigger and B flavour tagging are very important and challanging aspects for all the three experiments due to the enormous inelastic cross section and the fact that the B mesons are produced incoherently. ATLAS will have a trigger output rate of 10–15 Hz, with a tagging effective efficiency of about 4%. CMS foresees to have 5 Hz of inclusive and about 1 Hz of exclusive trigger output rate and comparable tagging power. They will both run a few years at $L = 2 \cdot 10^{33}/\mathrm{cm}^2/\mathrm{s}$. LHCb will run at ten times less luminosity reducing the probability of pile-up down to 0.5. The tagging effective efficiency will range between 4%–5%, and 7%–9% for B_d and B_s respectively. The LHCb output rate will amount to 200 Hz of exclusive B modes plus 900 Hz of inclusive b (e.g. b$\rightarrow \mu X$).

3. Unitarity angle measurements

The potential for the future determination of each of the unitarity angles is reviewed in the fol-

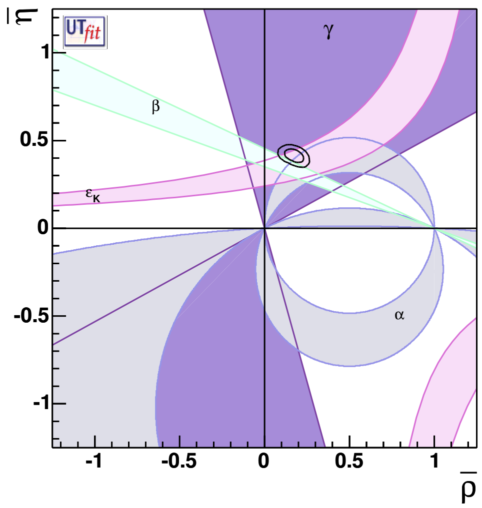

Figure 1. The allowed region in the $(\bar{\eta}, \bar{\rho})$ plane for the vertex of the Unitarity Triangle [1].

lowing.

3.1. Angle β

The β angle is already well measured at the B factories through the decay $B_d \to J/\Psi K_s$. Still it is an important measurement given the amount of statistics available at LHC. The extraction of β proceeds through the fit of the time dependance of the CP asymmetry:

$$A_{CP}(t) = A^{dir}\cos(\Delta m_d t) + A^{mix}\sin(\Delta m_d t) \quad (5)$$

the first term being 0 in the SM. In one year LHCb will collect 2/fb in this channel allowing to reach a precision of $\sigma(\beta) = 0.6°$. ATLAS will achieve similar sensitivity with 30/fb. Thanks to the high statistics, it might be feasible to compare against other channels like $B_d \to \phi K_s, \eta' K_s$, where a preliminary estimate of the yield gives a precision on $\sigma(\sin 2\beta_{eff}) \approx 0.4$.

3.2. Angle ϕ_s

The ϕ_s angle can be obtained from $B_s \to J/\Psi\phi, \eta_c\phi, J/\Psi\eta', D_s D_s$ decay modes. The highest yield being the decay to the final state $J/\Psi\phi$ (131k/year at LHCb). This mode for the determination of ϕ_s is the B_s counterpart of the $B_d \to J/\Psi K_s$ for β. In the SM it is expected to be a very small number (≈ 0.04), and therefore can be sensitive to New Physics effects in the B_s–$\bar{B}_s$ system. The analysis is complicated by the fact that the final state is a mixture of 2 CP even and 1 CP odd eigenstates, so that an angular analysis is necessary to disentangle them. The result is then obtained by a simultaneous fit to ϕ_s angle, $\Delta\Gamma_s$ and CP-odd fraction. Assuming $\Delta m_s = 17.5/ps$, $\phi_s = -0.04$ and $\Delta\Gamma_s/\Gamma_s = 0.15$ one obtaines a precision of $\sigma(\phi_s) = 0.022$ rad (with 2/fb at LHCb). ATLAS and CMS will achieve a precision of ≈ 0.08 rad with 10/fb integrated luminosity.

3.3. Angle γ

There are various methods which have been considered to extract the γ angle using different channels.

3.3.1. γ from $B_s \to D_s K$

This channels involves 4 decay rates used for the measurement of 2 time dependent asymmetries which depend on the angle $\gamma + \phi_s$, so that γ can be derived assuming ϕ_s known from elsewhere. In this case, contributions from New Physics are very unlikely because of the large asymmetries induced by the interference of same-order tree level amplitudes proportional to λ^3. In this channel we will collect 5.4k events/year (at LHCb) with an expected precision of $\sigma(\gamma) = 14°$. Discrete ambiguities on the measurement of γ can be resolved if $\Delta\Gamma_s$ is large enough or using $B_d \to D\pi$ [6].

3.3.2. γ from $B^0 \to D^0 K^*$

In the Ref [8] a method has been proposed to evaluate γ from these decays. It makes use of the interference between two color suppressed diagrams which interfere through the D mixing. Decay amplitudes depend on the weak phase γ plus a strong phase Δ. At LHCb experiment, the extraction of γ can be obtained from the measurement of 3 decay rates (plus charge conjugates):
$B^0 \to D^0(K^+\pi^-)K^*(K^+\pi^-)$ (3.4k/year),
$B^0 \to D^0(K^-\pi^+)K^*(K^+\pi^-)$ (0.5k/year)
$B^0 \to D^0_{CP}(K^-K^+)K^*(K^+\pi^-)$ (0.6k/year).
The achievable precision is $\sigma(\gamma) \approx 8°$ (assuming

$55^\circ < \gamma < 105^\circ$, and $|\Delta| < 20^\circ$). In this channel tagging of the B meson is not necessary because of the charge of the kaon in the final state, thus improving the performance.

3.3.3. γ from $B^\pm \to DK^\pm$

Also $B^\pm \to DK^\pm$ decays involve $b \to c$ and $b \to u$ transitions and are therefore sensitive to γ if a common final state is reached for the D and $\bar{D}$ mesons [9]. In this case there are 2 interfering B diagrams (one color suppressed), and 2 interfering D diagrams (one doubly suppressed) leading to large interference effects because of similar final amplitudes. From the measurement of these 4 rates one has 2 observables, but still 4 unknown parameters $(\gamma, \delta_B, r_B, \delta_D^{K\pi})$. To constrain the problem further one can add more decay modes like $D \to K\pi\pi\pi$ (4 rates and one new strong phase $\delta_D^{K3\pi}$) and $D \to KK$ (CP eigenstate, 2 rates) and extract all the unknown parameters in a global fit. The LHCb achievable precision on γ from this method is $\sigma(\gamma) \approx 4^\circ - 13^\circ$, depending on the actual value of strong phases $\delta_D^{K\pi}$ and $\delta_D^{K3\pi}$ (this study assumes $|\delta_D^{K\pi}| < 25^\circ$ and $|\delta_D^{K3\pi}| < 180^\circ$). The extraction of γ via Dalitz plot study using $D \to K_s\pi\pi$ decays is under investigation in LHCb.

3.3.4. γ from $B_d \to \pi\pi, B_s \to KK$

A further metod for γ extraction is from the study of these decay channels where penguin contributions are possible and for this reason can be sensitive to New Physics. For both channels one measures A_{CP}^{dir} and A_{CP}^{mix} which are parameters depending on γ, ϕ_s, ϕ_d and penguin over tree complex ratio $de^{i\theta}$. The U-spin symmetry allows to simplify the real part $d = d_{\pi\pi} = d_{KK}$ and the phase $\theta = \theta_{\pi\pi} = \theta_{KK}$, which remains as a theoretical assumption. The precision on γ in this case is $\sigma(\gamma) \approx 5^\circ$ in one year LHCb data taking.

3.4. Angle α

The analysis of $B_d \to \rho\pi$ events allows for the extraction of α. However the simple approach, where the ρ meson is considered as stable particle, is affected by both higher order discrete ambiguities and penguin pollution, like for $B_d \to \pi\pi$. To solve these problems a method was proposed [7] which analyses the decay $B_d \to \pi^+\pi^-\pi^0$ in the ρ resonance region, taking into account interference effects between vector mesons of different charges. The knowledge of the strong decay $\rho \to \pi\pi$, parametrized as a Breit-Wigner amplitude, allows the extraction of α and penguin-to-tree ratio simultaneously from a multi-dimensional fit. To evaluate the precision of the method on α a number of pseudoexperiments were performed including all known experimental smearings, finite resolution, acceptance, and wrong tag fraction. A background/signal ratio equal to 1 was also considered. Under these assumptions the precision of the determination (LHCb, for 1 year data taking) is of the order of 10° with 85% of the pseudoexperiments converging to the correct solution. The probability of mirror solution decreases with the increasing statistics, down to about 0.2% for 10/fb. The inclusion in the analysis of $B_d \to \rho^0\rho^0$ decays can give further contraint to the measurement of α. The result of the fit goes from $98.1^{+14^\circ}_{-8^\circ}$ to $97.0^{+5.9^\circ}_{-3.8^\circ}$ when such events are considered. Figure 2 shows the likelihood of the result of the combination of $B_d \to \rho\pi, \rho\rho$ (with $\rho^0\rho^0$ coming from LHCb) channels after one year data taking.

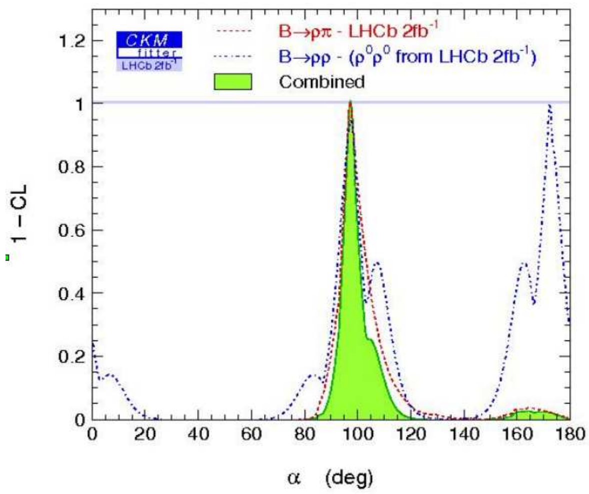

Figure 2. Likelihood function for the combination of $B_d \to \rho\pi, \rho\rho$ channels for the extraction of the angle α.

Table 1
Summary table of the achievable performaces of the LHCb experiment alone on the Unitarity Triangle angles in one year nominal data taking corresponding to 2/fb integrated luminosity.

Angle	Channel	Yield	B/S	Exp. Precision	Theoretical Precision
β	$B_d \to J/\Psi K_s$	216k	0.8	$\sigma(\beta) \approx 0.6°$	$\sigma(\beta) \approx 0.2°$
	$B_d \to \Phi K_s$	0.8k	<2.4	$\sigma(\beta) \approx 12°$	$\sigma(\beta) \approx 2°$
	$B_s \to J/\Psi\phi$	125k	0.3		
ϕ_s	$B_s \to J/\Psi\eta$	12k	2–3	$\sigma(\phi_s) \approx 1.2°$	$\sigma(\phi_s) \approx 0.2°$
	$B_s \to \eta_c\phi$	3k	0.7		
	$B_s \to D_s K$	5.4k	<1	$\sigma(\gamma) \approx 13°$	$\sigma(\phi_s) << 1°$
	$B_d \to \pi\pi$	26k	<0.7		(if U–spin
	$B_s \to KK$	37k	<0.3	$\sigma(\gamma) \approx 5°$	symmetry holds)
	$B_d \to D^0(K^-\pi^+)K^*$	0.5k	<0.3		
γ	$B_d \to D^0(K^+\pi^-)K^*$	2.4k	<2	$\sigma(\gamma) \approx 8°$	–
	$B_d \to D_{CP}(K^+K^-)K^*$	0.6k	<0.3		
	$B^- \to D^0(K^+\pi^-)K^-$	60k	<0.5		
	$B^- \to D^0(K^-\pi^+)K^-$	2k	<0.5	$\sigma(\gamma) \approx 8°–13°$	$\sigma(\gamma) << 1°$
α	$B_d \to \rho\pi, \rho\rho$	14k	<0.8	$\sigma(\alpha) \approx 10°$	$\sigma(\alpha) \approx 1°$

4. Summary

Table 1 shows the status of the expected precisions for the Unitarity Triangle angles at LHC. For each angle, the relevant decay channels are considered together with the annual LHCb yield after trigger and channel selection, and the expected background over signal ratio. In the last column the theoretical precision of the calculation is indicated as well. In all the measurements the uncertainty on the CKM angles will be dominated by the experimental accuracy and not by the theoretical one. After some year of successful running LHC will be able to determine the Unitarity Triangle very precisely, possibly highlighting New Physics effects.

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