Prospects for CP violation at LHCb

Géraldine Conti for the LHCb Collaboration

EPFL, 1015 Lausanne, Switzerland

DOI: will be assigned

The determination of the CP-violating phase $\Phi_s^{J/\psi\phi}$ in a flavour-tagged, time-dependent, angular analysis of the decay $B_s^0 \to J/\psi\phi$ is one of the key goals of the LHCb experiment. Its small value predicted in the Standard Model could be significantly enhanced by New Physics contributions. The CKM unitarity triangle angle γ will also be measured precisely, both in modes where tree-level processes dominate and where loop diagrams are significant. Comparison of the two sets of results will be a sensitive probe for New Physics. Here, we will review the prospects for the determinations of $\Phi_s^{J/\psi\phi}$ and γ using 2 fb^{-1} of data at $\sqrt{s}$ =7 TeV [1].

1 Introduction

1.1 The LHCb experiment

The LHCb experiment at the LHC is dedicated to B physics [2]. Its goal is to make precision measurements of CP violation in B decays, which could lead to indirect discoveries of New Physics. The LHCb detector is a single-arm forward spectrometer, which is expected to see at the nominal luminosity an integrated $b\bar{b}$ cross-section of 500 μb, corresponding to $\sim 10^{12}$ $b\bar{b}$ pairs per year. Until now (June 1st, 2010), the LHCb experiment has collected $\sim$ 14 nb^{-1} of data at 7 TeV.

1.2 CKM angles β_s and γ

In the Standard Model, the source of CP violation arises from a complex phase in the CKM matrix. The CKM matrix can be represented by six unitarity triangles, from which four parameters are needed to describe the CKM matrix, the β, γ, β_K and β_s angles [3]. Two of these angles are of interest in this paper. First, the β_s angle will be linked to the study of the CP-violating phase in $B_s^0 \to J/\psi\phi$ decays. From global fits to experimental data, it is predicted to be $2\beta_s = (0.0360^{+0.0020}_{-0.0016})$ rad [3]. Second, the γ angle will be precisely measured at LHCb. Current experimental constraints give $\gamma = 73^{+22}_{-25}{}^\circ$ [3].

2 CP-violating phase in $B_s^0 \to J/\psi\phi$

2.1 Phenomenology

B_s^0 mesons can decay into $J/\psi\phi$ through tree and penguin processes driven by $\bar{b} \to \bar{c}c\bar{s}$ quark level transitions. The tree diagram dominates with a single weak phase $\Phi_D = \arg(V_{cs}V_{cb}^*)$.

Before decaying into $J/\psi\phi$, B_s^0 mesons can also oscillate into $\bar{B}_s^0$ through box diagrams, with a mixing phase Φ_M. The interference between the two paths to $J/\psi\phi$ gives rise to the CP-violating phase $\Phi_s^{J/\psi\phi} = \Phi_M - 2 \cdot \Phi_D$. In the Standard Model, $\Phi_s^{J/\psi\phi}$ is equal to $-2\beta_s$, hence it is predicted to be very small. However, new particles could contribute to the B_s^0 -$\bar{B}_s^0$ box diagram and have the potential to modify $\Phi_s^{J/\psi\phi}$ significantly from its expectation.

$B_s^0 \to J/\psi\phi$ is a pseudo-scalar to vector-vector decay. Due to total angular momentum conservation, the final state is an admixture of CP-even (ℓ=0,2) and CP-odd (ℓ=1) states, ℓ being the orbital angular momentum between J/ψ and ϕ. An angular analysis of the decay products is required to disentangle statistically between the final states with the two different CP eigenvalues. The decay product angles $\Omega = \{\theta, \varphi, \psi\}$ in the transversity basis are defined in [1].

2.2 Analysis strategy

$\Phi_s^{J/\psi\phi}$ is obtained by fitting the theoretical expressions of the differential decay rates $d\Gamma/d\Omega$ to data as a function of proper time and the transversity angles (the detailed theoretical expressions can be found in [1]).

The flavour specific $B^0 \to J/\psi K^{*0}$ and $B_u \to J/\psi K^+$ channels will be used as control channels to estimate the mistag rates and check the proper time resolution. The $B^0 \to J/\psi K^{*0}$ channel will also be used to validate the angular acceptances corrections and the fit procedure, by comparing the fitted values of the amplitudes and the strong phase differences with those already obtained by other experiments [4, 5].

In its 14 nb^{-1} data sample, LHCb has started collecting $B_s^0 \to J/\psi\phi$, $B^0 \to J/\psi K^{*0}$ and $B_u \to J/\psi K^+$ candidates. An untagged sample will be studied first. Once the tagging is calibrated and a good proper time resolution achieved, a simplified one-angle time-dependent tagged analysis integrated over $\cos(\psi)$ and φ will be performed, before the three-angle analysis.

2.3 Sensitivity studies

An expected performance for the $\Phi_s^{J/\psi\phi}$ measurement at the LHCb experiment is shown in Figure 1 for different integrated luminosities, for a LHC centre of mass energy of 7 TeV.

The lines above and below the sensitivity curve indicate uncertainties coming from the $b\bar{b}$ cross-section and the visible branching ratio of $B_s^0 \to J/\psi\phi$. It has to be noted that the value used for the $\sigma(b\bar{b})$ is rather conservative, at least with respect to the value given by Pythia of 0.457 μb. The Standard Model prediction of $2\beta_s$, 0.0368, bounded by its uncertainties, is also drawn. The black line shows the combined CDF/D⊘ uncertainty scaled to 16 fb^{-1}.

With an integrated luminosity of 2 fb^{-1}, the statistical uncertainty on $\Phi_s^{J/\psi\phi}$, $\sigma(\Phi_s^{J/\psi\phi})$, is expected to be ~ 0.07.

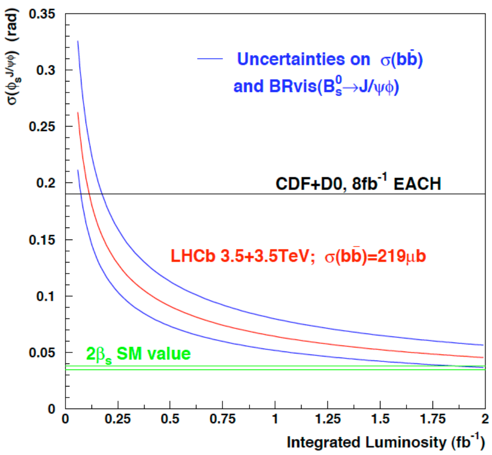

Figure 1: Statistical uncertainty on $\Phi_s^{J/\psi\phi}$ versus the integrated luminosity at a LHC centre of mass energy $\sqrt{s} = 7$ TeV.

3 γ from tree processes

The measurement at tree level of γ can be performed using several different B decays, using either direct CP violation or time-dependent effects. Three methods that will be used at LHCb (ADS/GLW, GGSZ and time-dependent studies) are explained in the following. A global fit to all the measurements at tree level will allow to obtain the best sensitivity to γ. It is foreseen to be $\sim 7^\circ$ with 1 fb^{-1} of data at 7 TeV. Already with 100 pb^{-1}, LHCb will be able to improve some B-factory measurements.

3.1 $\mathrm{B}^{\pm(0)} \to \mathrm{D(hh)K}^{\pm(*0)}$ decays with ADS/GLW method

γ is extracted through the interference between the amplitudes of $\mathrm{B}^{\pm(0)} \to \mathrm{D(hh)K}^{\pm(*0)}$ decays, with D representing a D^0 or a $\bar{\mathrm{D}}^0$. The final states hh used in the GLW method are CP eigenstates ($\mathrm{f_D} = \mathrm{K}^+\mathrm{K}^-$ or $\pi^+\pi^-$). In the ADS method, the D decays to doubly Cabbibo favoured and suppressed states $\mathrm{f_D} = \mathrm{K}^\pm\pi^\mp$.

Combining the ADS and GLW modes results in a total of six rates (four ADS, two GLW), with five parameters. These are the CP-violating weak phase γ, the ratio $r_{\mathrm{B}^{\pm(0)}}$ between the magnitude of the two tree amplitudes, the CP-conserving strong phase difference $\delta_{\mathrm{B}^{\pm(0)}}$ between $\mathrm{B}^{+(0)}$ and $\mathrm{B}^-(\bar{\mathrm{B}}^0)$, the ratio $r_{\mathrm{K}\pi}$ between the favoured and suppressed D decay tree diagrams and the D decay strong phase difference $\delta_{\mathrm{K}\pi}$. The last parameter can be constrained using external measurements made at CLEO-c [6].

In the neutral B meson case, both trees are colour-suppressed. The sensitivity is enhanced as r_{B^0}, governing the size of the asymmetry, is bigger than $r_{\mathrm{B}^\pm}$ of the charged B meson case. However, signal rates are lower for the neutral B meson case than for the charged one.

The sensitivity to γ can be improved by adding a Dalitz plot analysis of the neutral $\mathrm{B}^0 \to \mathrm{D}\pi^-\mathrm{K}^+$ decay mode [7] or taking into account the ADS $\mathrm{B}^\pm \to \mathrm{D}(\mathrm{K}\pi\pi\pi)\mathrm{K}^\pm$ decay mode.

3.2 $\mathrm{B}^\pm \to \mathrm{D}(\mathrm{K^0_S}\pi^+\pi^-)\mathrm{K}^\pm$ decays with GGSZ (Dalitz) method

The GGSZ (Dalitz) method is applied to the three-body $\mathrm{D} \to \mathrm{K^0_S}\pi^+\pi^-$ decays. γ is extracted here through the difference in densities observed in the Dalitz planes of $\mathrm{D} \to \mathrm{K^0_S}\pi^+\pi^-$ coming from $\mathrm{B}^\pm \to \mathrm{DK}^\pm$ decays. The extraction of γ is performed either by using an model-dependent unbinned fit or a model-independent binned fit, where the bins are determined by δ_D coming from external measurements [1].

3.3 Time-dependent $\mathrm{B^0_s} \to \mathrm{D_sK}$ and $\mathrm{B}^0 \to \mathrm{D}^\pm\pi^\mp$ decays

In the time-dependent analysis of the flavour tagged $\mathrm{B^0_s} \to \mathrm{D_sK}$, the $\mathrm{B^0_s}$ mesons can decay directly or oscillate first. The interference between the two paths to the same final state is sensitive to $\gamma - \Phi_\mathrm{M}$. Φ_M is the $\mathrm{B^0_s}$ meson mixing phase, which will be determined from the study of $\mathrm{B^0_s} \to \mathrm{J}/\psi\phi$ decays.

The time-dependent CP asymmetries in $\mathrm{B}^0 \to \mathrm{D}^\pm\pi^\mp$ allow $\gamma + 2\beta$ to be measured. As β is already well measured [3], γ can be determined from these asymmetries. On the way to γ, the first ($\mathrm{B}^0 \to \mathrm{D}^+\pi^- + \mathrm{B}^+ \to \mathrm{D}^0\pi^+$) candidates have been recorded in real data.

4 γ from loop processes

γ is extracted through the combined measurement of the $B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ CP asymmetries. The invariance of the strong interaction under the d and s quarks exchange (U-spin symmetry) is assumed. Depending on the U-spin scenario chosen, the sensitivity to γ for 2 fb^{-1} of data at 14 TeV is $\sim 7-10°$ (numbers not available for 1 fb^{-1} at 7 TeV).

The time-dependent asymmetry for neutral B mesons decaying into a CP eigenstate f is :

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0_{d/s}(t) \to f) - \Gamma(B^0_{d/s}(t) \to f)}{\Gamma(\bar{B}^0_{d/s}(t) \to f) + \Gamma(B^0_{d/s}(t) \to f)} = \frac{-C_{CP}\cos\Delta mt + S_{CP}\sin\Delta mt}{\cosh\frac{\Delta\Gamma}{2}t - A_{CP}^{\Delta\Gamma}\sinh\frac{\Delta\Gamma}{2}t} \quad (1)$$

where $\Gamma(\bar{B}^0_{d/s}(t) \to f)$ and $\Gamma(B^0_{d/s}(t) \to f)$ are the decay rates of the initial $\bar{B}$ and B states respectively. Δm and $\Delta\Gamma$ are the mass and width differences between the two mass eigenstates.

The C_{CP} and S_{CP} terms can be written in terms of the γ angle, for both $B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays. In each case, these terms also depend on two hadronic parameters d and θ, which parameterize the magnitude and phase of the penguin-to-tree amplitude ratio respectively. A total of four equations with five unknowns (d,d',θ,θ',γ) is obtained. To solve the system, the U-spin symmetry is used ($d = d'$ and $\theta = \theta'$). Weaker assumptions can also be made, as for example keeping only the $d = d'$ constraint. An even weaker assumption on the U-spin symmetry is $\xi = d'/d = [0.8, 1.2]$ without any constraint on the phases θ and θ' [8].

5 Conclusions

From the $\sim$14 nb^{-1} sample collected up to now by the LHCb detector at $\sqrt{s}$ =7 TeV, first candidates relevant to the measurements of the CP-violating weak phases $\Phi_s^{J/\psi\phi}$ and γ have been selected. With 1 fb^{-1} of data taken at $\sqrt{s}$ =7 TeV, sensitivites of $\sigma(\Phi_s^{J/\psi\phi}) \sim 0.07$ and $\sigma(\gamma) \sim 7°$ (tree level) are expected from Monte Carlo studies. Both measurements will improve our knowledge about CP-violation and potentially lead to an indirect discovery of New Physics.

6 Acknowledgments

The author would like to thank Marta Calvi, Tim Gershon and Olivier Leroy for their invaluable suggestions in the preparation of the presentation and the present document.

7 Bibliography

References

[1] The LHCb Collaboration, LHCb-PUB-2009-029 (2009).
[2] The LHCb Collaboration, J. Inst. A 3 S08005 (2008).
[3] Amsler C. et al. (Particle Data Group), Phys. Rev. Lett. B 667 (2008) 1.
[4] The Babar Collaboration, PRD-RC 76, 031102 (2007).
[5] The CDF Collaboration, Public note 8950 (2007).
[6] J. L. Rosner et al. (CLEO Collaboration), Phys. Rev. Lett 100, 221801 (2008).
[7] T. Gershon, Phys. Rev. D79:051301 (2009) [arXiv:0810.2706].
[8] J. Nardulli, arXiv:hep-ex/0807.1670v1.