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Measurement of ϕ_s at LHCb

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A time dependent angular analysis of the decay mode $B_s \rightarrow J/\psi\phi$ allows for the measurement of the mixing induced CP-violating phase ϕ_s. Within the Standard Model ϕ_s is theoretically precisely predicted to be very small, however many Standard Model extensions predict sizeable contributions to this phase [2]. The current experimental knowledge of ϕ_s has very larger uncertainties. However already with the data expected to be delivered within the next year, the LHCb experiment at the Large Hadron Collider at CERN, has the potential to improve significantly existing measurements.
In a data set of up to 37.5 pb^{-1} taken in 2010, first physics signals in the LHCb detector are reconstructed and their properties are compared to Monte Carlo predictions. Based on recently published measurements of $b\bar{b}$ cross-sections from the LHCb collaboration [3], the sensitivity on the CP violating phase ϕ_s in the decay $B_s \rightarrow J/\psi\phi$ is evaluated.
Additionally an alternative method to potentially extract complementary information on ϕ_s from the measurement of the asymmetry in semileptonic final states is presented.

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1 Introduction

The phenomenological aspects linked to $B_s \rightarrow J/\psi\phi$ decays are discussed in many articles [4]. The main parameters involved are introduced briefly here.
$|B_s>$ and $|\bar{B}_s>$ are flavour eigenstates with the quark content: $|\bar{b}s>$ and $|b\bar{s}>$ respectively. Any arbitrary combination of flavour eigenstates has a time evolution described by an effective Schrödinger equation:

$$i\tfrac{\partial}{\partial t}\left(\frac{|B_s(t)>}{|B_s(t)>}\right) = \left(M^s - \tfrac{i}{2}\Gamma^s\right)\left(\frac{|B_s(t)>}{|B_s(t)>}\right)$$

where $\mathbf{M}$ and $\mathbf{\Gamma}$ are 2×2 hermitian matrices. The heavy and light mass eigenstates of the Schrödinger equation are given via:

$$\begin{aligned} |B_H> &= p|B_s> - q|\bar{B}_s>, \\ |B_L> &= p|B_s> + q|\bar{B}_s> . \end{aligned}$$

The complex coefficients p and q obey the normalizations condition: $|p|^2 + |q|^2 = 1$. The mass difference Δm_s and the width difference $\Delta\Gamma_s$ between the mass eigenstates are defined by:

$$\Delta m_s = M_H - M_L, \quad \Delta\Gamma_s = \Gamma_L - \Gamma_H.$$

Hence, the average mass and width can be written:

$$M_{B_s} = \tfrac{M_H + M_L}{2}, \quad \Gamma_s = \tfrac{\Gamma_L + \Gamma_H}{2}$$

Δm_s and $\Delta\Gamma$ are related to the Hamiltonian of the Schrödinger equation via $\Delta m_s = 2|M_{12}|$ and $\Delta\Gamma = 2|\Gamma_{12}|\cos\phi_s$ respectively. The phase is defined as $\phi_s = arg(-\frac{M^s_{12}}{\Gamma^s_{12}})$ and predicted to be $(3.40^{+1.32}_{-0.77}) \times 10^{-3}$ rad [2] within the Standard Model.

The decay $B_s \rightarrow J/\psi\phi$ is dominated by a single tree level decay with the complex phase ϕ_D (Fig. 1). The B_s can either directly decay into the final state $J/\psi\phi$ or first mix into its antiparticle $\bar{B}_s$ via the box diagram displayed in Figure 2, and then decay into the same final state. The observable phase $\phi^{J/\psi\phi}$ which we will measure in the presented analysis is the phase difference of the phase of the mixing diagram ϕ_M and th phase of the decay: $\phi_s^{J/\psi\phi} = \phi_M - 2\phi_D$. Neglecting any contributions from penguin decays [1] and any contributions from u and c quarks in the mixing box diagrams, the measured phase is given by the following relation of CKM matrix elements: $\phi_s^{J/\psi\phi} = 2arg(\frac{V^*_{ts}V_{tb}}{V^*_{cs}V_{cb}}) = -2\beta_s$.
The phases $\phi_s = arg(-\frac{M^s_{12}}{\Gamma^s_{12}})$ and $\phi_s^{J/\psi\phi}$ are two different quantities [5]. There is no trivial relation between these two observables. However both are predicted to be small in the Standard Model and most important, any sizeable New Physics contribution will affect both observables similarly:

$$\phi_s = \phi_s^{SM} + \phi_s^{NP}; \qquad -2\beta_s = -2\beta_s^{SM} + \phi_s^{NP};$$

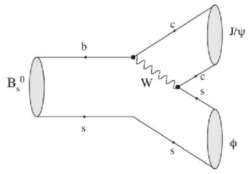

Figure 1: Tree-level decay of $B_s \rightarrow J/\psi\phi$.

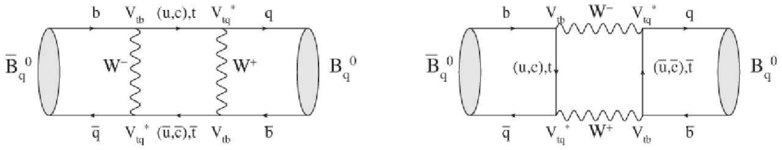

Figure 2: $B_q - \bar{B}_q$ mixing diagrams (q=s,d).

2 The ϕ_s Analysis Roadmap

The decay $B_s \rightarrow J/\psi\phi$ is a pseudo-scalar to vector-vector decay. Angular momentum conservation implies that the final state is an admixture of CP-even and CP-odd components. By performing a time-dependent angular analysis using the transversity angles $\Omega = (\theta, \phi, \psi)$ (Fig. 3) it is possible to statistically disentangle the different CP eigenstates by the differential decay rate for B_s and $\bar{B}_s$ mesons produced as flavour eigenstates at $t = 0$ is given by:

$$\frac{\partial^4 \Gamma(B_s \rightarrow J/\psi\phi)}{\partial t \;\partial \cos\theta \;\partial\phi \;\partial\cos\psi} \propto \sum_{k=1}^{6} h_k(t) f_k(\theta, \psi, \phi)$$

The definitions of the time angular dependent functions are given in [6]. $\phi_s^{J/\psi\phi}$ typically appears in these functions multiplied with terms such as $\sin(\Delta m_s t)$. Since these terms have opposite sign between B_s and $\bar{B}_s$ the analysis benefits significantly from flavour tagging, especially for small values of $\phi_s^{J/\psi\phi}$. We extract a measurement of $\phi_s^{J/\psi\phi}$ by performing an unbinned negative log-likelihood to the proper time t, Ω, B_s mass and initial flavour tag of the selected $B_s \rightarrow J/\psi\phi$ events. Additional physics parameters in the fit are $\Delta\Gamma_s$, Γ_s, the CP amplitudes ($A_\perp$, $A_\parallel$, A_0) and corresponding strong phases ($\delta_\perp, \delta_\parallel, \delta_0$). Parameters describing the background, and detector effects such as the proper time resolution, mistag probability and angular acceptances corrections are included in the PDF which will be fitted to the data as well.

3 Monte Carlo Based Expectations

Dedicated LHCb Monte Carlo simulations predict 117k triggered and reconstructed $B_s \rightarrow J/\psi\phi$ signal candidates in 2 fb^{-1} of data taken at $\sqrt{s} = 14$ TeV, with a running scenario of in average one interaction per bunch crossing. The following performance numbers are derived from a Monte Carlo corresponding to these conditions.
A tagging performance of $\epsilon D^2 = 6.2 \pm 0.2\%$ is expected. About 60% of the tagging power comes from so-called opposite side tagging exploiting information related to the other B hadron in the event. 40% comes from a so-called same side tagger, which exploits fragmentation properties of the B_s signal candidate. The proper time resolution is found to be σ_t= 38 ± 5 fs.

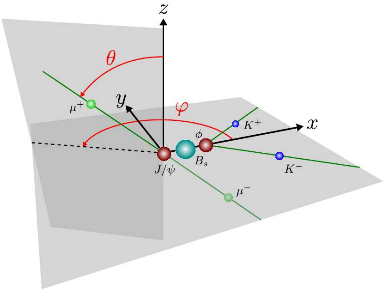

Figure 3: Definition of transversity base.

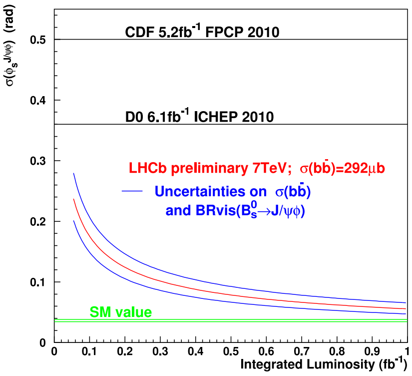

Figure 4: Expected sensitivity on $\phi_s^{J/\psi\phi}$.

The tagging performance will be calibrated on data in various reference channels, such as $B_d \to J/\psi K^*$, $B^+ \to J/\psi K^+$ and $B_s \to D_s\pi$. We expect a precision from the calibration of the mistag probability ω of 3% which results in up to 7% relative bias on $\phi_s^{J/\psi\phi}$ for large New Physics like values. Any bias on the proper time calibration can be corrected in the fitter directly by according floating fit parameters, thus no bias on $\phi_s^{J/\psi\phi}$ is expected from this source. The angular acceptances will be taken from Monte Carlo data, however will be cross-checked in the analysis of the polarization amplitudes of $B_d \to J/\psi K^*$ which are already known from previous experiments [7]. Due to the limited precision of early measurements we can validate the angular acceptances only to a accuracy of ± 5%. This uncertainty results in a systematic uncertainty on $\phi_s^{J/\psi\phi}$ of up to 7%.
More detailed information on the Monte Carlo studies for $\phi_s^{J/\phi\phi}$ can be found in [6]. The LHC started to take data at a center-of-mass energy of $\sqrt{s} = 7$ TeV end of March this year. Two independent analysis using $B \to D\mu\nu X$ and displaced J/ψ candidates resulted in the first measurement of the $b\bar{b}$ cross section at 7 TeV [3]. Combining this measurement with the expectations from Monte Carlo in terms of tagging performance, proper time resolution, background levels and signal reconstruction efficiency results in a sensitivity on $\phi_s^{J/\psi\phi}$ which is displayed in Figure 4. For this study the CP amplitudes and relative strong phase have been taken from recent measurements in the analysis of $B_d \to J/\Psi K^*$ [7]. The world average values on Γ and $\Delta\Gamma$ have been used [8] and ϕ_s was set to Standard Model theory predictions [2].

4 First Look at Signal Candidates in Data

At the time of the CKM workshop several $B \to J/\psi X$ signals based on a sample of up to 3 pb^{-1} have been established. Rates of 400 $B^+ \to J/\psi K^+$, 200 $B^0 \to J/\psi K^*$ and 45 $B_s \to J/\psi\phi$ per pb^{-1} of data have been found, however with rather large uncertainties. A proper time resolution of about 78 fs was reported in data. No tagging peformance was established at that time.

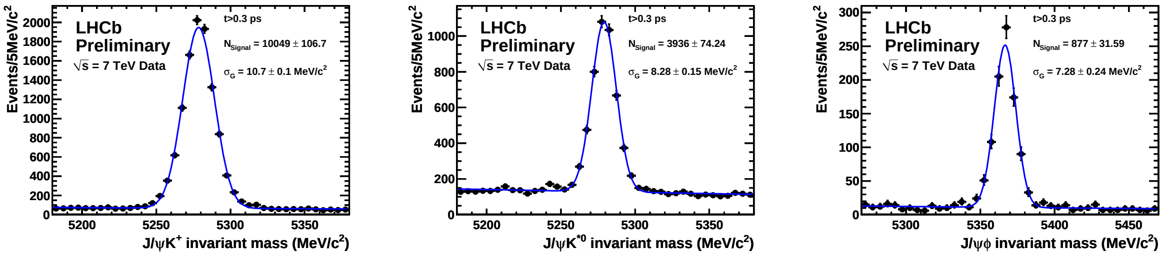

Figure 5: Reconstructed $B^+ \to J/\psi K^+$, $B_d \to J/\psi K^*$ and $B_s \to J/\psi\phi$ candidates in a data set of 34 pb^{-1}. The cut on t $>$ 0.3 ps is for illustrating purposes, but will not be applied in the analysis. Quoted event numbers in the plots include this cut.

In the meantime a sample of an integrated luminosity of 37.5 pb^{-1} is available which will be the basis of the physics results presented at the winter conferences 2011. In 34 pb^{-1} of this sample we find a rate of 360, 150, 30, B^+, B_d and B_s candidates per pb^{-1} respectively (Fig. 5). The reason for the non linear scaling with the luminosity is related to the changed trigger and running conditions. While the initial data set consists of events with in average one interaction per event, a good fraction of the full data set has been taken with in average up to three interactions per event.
It turned out that the extraction of the proper time resolution presented at the CKM workshop was ignoring background contributions from fake J/ψ candidates, which resulted in an overestimate of the proper time resolution.
The dilution on the measured mixing amplitude due to the proper time resolution has been found to be equivalent to a Gaussian of about 50 fs. This is about 20-30% worse than the prediction from Monte Carlo.
First result of the opposite side tagging in $B_d \to D^*\mu\nu X$ decays in data found 60% of the expected performance. Further improvements in this area are ahead. No results on the same side tagger performance are available yet.

5 Extraction of ϕ_s in Semileptonic Asymmetries

An alternative way to access ϕ_s is to measure the final state asymmetry a^s_{fs} in flavour specific B_s decays. This asymmetry is realted to ϕ_s in the following way:

$$a^s_{fs} = \tfrac{\Delta\Gamma^s}{\Delta m_s} \tan\phi_s$$

However the measure asymmetry (both in the B_d or B_s system) is given by:

$$\begin{aligned} A^q_{fs}(t) &= \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})} \\ &= \frac{a^q_{fs}}{2} - \frac{\delta^q_c}{2} - (\frac{a^q_{fs}}{2} + \frac{\delta^q_p}{2})\frac{\cos(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2)} + \frac{\delta^q_b}{2}(\frac{B}{S})^q \end{aligned}$$

Several additional contributions such as the detector asymmetry δ_c ($\sim 10^{-2}$), production asymmetry δ_p ($\sim 10^{-2}$) and background asymmetry δ_b ($\sim 10^{-3}$) make the extraction of the very small value of a^q_{fs} impossible.
However by studying simultaneously B_s and B_d decays with the same final state particles such as $B_s \rightarrow D^-_s(K^+K^-\pi^-)\mu^+\nu$ and $B_d \rightarrow D^-(K^+K^-\pi^-)\mu^+\nu$ the detector asymmetry cancel in the difference $A^d_{fs} - A^s_{fs}$. Performing a time dependent analysis it is possible to extract $a^d_{fs} - a^s_{fs}$. Given the huge statistics expected at the LHC for next year, this analysis will have tiny statistical uncertainties, however to control systematic effects to the required precision will be very challenging.

6 Summary

The LHCb experiment successfully started data taking. First physics signals towards the measurement of $\phi_s^{J/\psi\phi}$ have been established. The huge statistics and very good performance of the experiment results in excellent perspectives for a precision measurement of CP violation in the B_s system with the data taken in 2011.

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