LHC sensitivity to new physics in B_s parameters

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The detectors of the Large Hadron Collider will fully exploit the large b-quark production rate which is expected from the LHC. Precise measurements of quantities associated with the B_s system, with the aim of identifying deviations from the Standard Model, form an important component of the LHC beauty programmes. The expected performance of the ATLAS and LHCb detectors with respect to these measurements will be reviewed.

1. INTRODUCTION

The B_s^0-$\bar{B}_s^0$ system is subject to mixing due to second-order (ΔB=2) weak interactions. Over time a meson initially in the state $|B_s^0\rangle$ will evolve into a mixed state containing both $|B_s^0\rangle$ and $|\bar{B}_s^0\rangle$ components. The mass eigenstates differ in mass and width and are denoted B_H^0 and B_L^0. The system is characterised by the difference in width ($\Delta\Gamma_s$) and mass (ΔM_s) between the states B_H^0 and B_L^0. The latter quantity is also referred to as the *oscillation frequency.* The B_s^0 system differs from the B_d^0 system in that the oscillation frequency is much higher ($\sim 20ps^{-1}$ as opposed to $\sim 5ps^{-1}$). The ratio of $\Delta\Gamma$ to the mean width Γ is also much greater for the B_s^0 system - $\sim 10\%$ - whereas the equivalent ratio for the B_d^0 system is close to zero.

It is thought that CP-violating processes can arise through neutral B-meson mixing, either in the mixing amplitudes themselves, or in interference between the mixing and the amplitudes describing the decay of the mesons to their final states. In the Standard Model these processes are admitted through a complex phase in the CKM matrix. For the latter type of CP-violating processes the CP-asymmetry is encoded in a third parameter, the *weak mixing phase* ϕ_s, which in the Standard Model is small (~ 0.04 radians) and is given by

$$\phi_s^{SM} = 2\arg V_{ts}^* V_{tb} \tag{1}$$

Any additional sources of mixing-induced CP-violation from beyond the Standard Model are expected to increase this figure. The oscillation frequency ΔM_s is expected to be similarly modified by new physics processes. The expected behaviour of the weak mixing phase and the oscillation frequency under varying levels of new physics contributions have been elucidated in a model-independent manner by Ball *et al* [1].

2. MEASUREMENT OF THE PARAMETERS

A number of studies [3] have identified the processes $B_s^0 \rightarrow J/\psi\phi$ and $B_s^0 \rightarrow D_s\pi$ as ideally suited to the measurement of ϕ_s and ΔM_s respectively. It must be pointed out that each channel is insensitive to the other's parameter and ultimately a combined analysis of the two channels will be required.

2.1. Measurement of ϕ_s with $B_s^0 \rightarrow J/\psi\phi$

$B_s \rightarrow J/\psi\phi$ is a decay of a scalar meson to two vectors, so the final state is an admixture of three helicity configurations. These can be expressed in terms of the decay amplitudes A_0, $A_\perp$ and $A_\parallel$ (the *transversity amplitudes*), which are CP-eigenstates and only two of which are independent. As both the B_s and the $\bar{B}_s$ decay to the same final state in this channel, measurement of the CP-violating weak phase ϕ_s requires that the contributions from the amplitudes be separated out. An angular analysis is deployed to achieve this.

In the rest frame of the decaying B-meson, the process is characterized with three decay angles, θ_1, θ_2 and ϕ, which are defined in [3]. The expression for the time dependent angular distribution can be derived by combining the equations of $S \to VV$ decays and $B_s - \bar{B}_s$ mixing[2]:

$$W^{\pm}(\theta_1, \theta_2, \phi, t) = \frac{1}{(4\pi)^2} \frac{9}{8} \sum_{i=1}^{6} f(t)_i^{\pm} F_i(\theta_1, \theta_2, \phi) \tag{2}$$

The $f(t)_i^{\pm}$ are bilinear combinations of the amplitudes A_0, $A_\perp$, $A_\parallel$, and the F_i are trigonometric functions of the three angles. The precise forms can be found in [3]. The expression (2) is a function of eight parameters: ΔM_s, $\Delta\Gamma_s$, the average width (Γ_s), the relative strong phases $\delta_1 = \delta_0 - \delta_\perp$ and $\delta_2 = \delta_0 - \delta_\parallel$, the weak phase ϕ_s, and the magnitudes of the two independent amplitudes. New physics will force the parameters away from their Standard Model values, but is not expected to alter the overall structure of the expression [3]. In principle, therefore, it should be possible to measure the angular and decay time distributions and fit these to the theoretical probability density function to untangle the contributions from the state and anti-state components, and thereby extract the mixing parameters. It should be noted that a *tagged* sample is required for this exercise; that is to say, the flavour of a given meson at time $t = 0$ needs to be identified.

2.2. Measurement of ΔM_s with $B_s^0 \to D_s\pi$

In $B_s^0 \to D_s\pi$, the probability p_- that an initially pure B_s^0 state will decay as a $\bar{B}_s^0$ (that is, to the final state $D_s^+\pi^-$) is given by

$$p_{\pm}(t) = e^{-\Gamma_s t}\left(\cosh\frac{\Delta\Gamma_s}{2}t \pm \cos\Delta M_s t\right)\frac{\Gamma_s^2 - \Delta\Gamma_s}{2\Gamma_s} \tag{3}$$

where p_+ is the probability for the conjugate process, an initially pure $\bar{B}_s^0$ decaying to $D_s^-\pi^+$. In principle, therefore, given techniques for identifying the charge of the final states and the initial flavour of the B-meson, it is possible to access ΔM_s by counting decays:

$$r(t) = \frac{p_+(t) - p_-(t)}{p_+(t) + p_-(t)} = \frac{\cos\Delta M_s t}{\cosh\frac{\Delta\Gamma_s}{2}t} \tag{4}$$

3. DETECTOR PERFORMANCE

The ATLAS and LHCb experiments are currently under construction at CERN and are due to begin studying collisions in late 2007. ATLAS is a general purpose detector whereas LHCb is a dedicated B-physics experiment making use of Ring Imaging Cherenkov Detectors (RICH) for hadron identification, and a locally defocussed beam to reduce the luminosity in the interaction region. The sensitivity of the detectors to the mixing parameters will be strongly dependent on the resolution of the B-meson proper decay time and the effectiveness of the analysis algorithms in rejecting background and correctly tagging the initial state of the B-mesons. These performance parameters must be obtained before any estimates on the sensitivity of the detectors to the mixing and CP-violating quantities can be estimated. To this end, large quantities of Monte Carlo data have been generated, passed through detector simulation and reconstructed using the LHC Computing Grid.

3.1. $B_s^0 \to J/\psi\,(\mu\mu)\,\phi\,(KK)$

For this analysis, the process begins with identifying all final state muons and kaons from the reconstructed tracks, for events passing the triggers. In the case of ATLAS, the muon spectrometer and the inner tracking systems are utilised, whereas LHCb can also use information from the RICH subdetectors. Following appropriate kinematic cuts on the tracks they are formed into oppositely charged pairs and fitted to common vertices, with the aim of identifying the $J/\psi \to \mu\mu$ and $\phi \to KK$ decays. Pairs of tracks passing this stage are then formed into groups of track quadruplets and fitted to a common vertex, to identify the B-meson decays. The decay angles and the proper decay time can then be calculated for each B_s decay candidate. Finally, the initial state of the decaying meson must be identified. In the case of exercises involving Monte Carlo, the expected detector performance can be assessed as the results from the analysis of the reconstructed tracks can be compared directly with the original data from the event generator.

Table 1 shows the expected detector perfor-

Table 1
Expected $B_s^0 \to J/\psi\,(\mu\mu)\,\phi\,(KK)$ performance in LHCb and ATLAS

	ATLAS	LHCb
Statistics	270000 ($30fb^{-1}$)	125000 ($2fb^{-1}$)
Proper time resolution, fs	81	35
Mass resolution, MeV	18	8
Background	15%	$S/B > 3$

Table 2
ATLAS and LHCb - expected precisions on mixing parameters with $B_s^0 \to J/\psi\,(\mu\mu)\,\phi\,(KK)$

	ATLAS, $30fb^{-1}$	LHCb, $2fb^{-1}$	LHCb, $10fb^{-1}$
$\sigma_{\Delta\Gamma_s}/\Delta\Gamma_s$	13%	1.1%	-
$\sigma_{\Gamma_s}/\Gamma_s$	1%	-	-
σ_{ϕ_s}	0.046	0.031	0.013

mances for ATLAS and LHCb based on recent simulations. The statistics are estimated from the reconstruction efficiencies as determined in the simulation, and the cross sections for the channel based on the Pythia and EvtGen event generator packages. The resolutions in B-meson proper decay time are calculated by taking the difference, for each event, between the decay time set by the event generator, and the time calculated from the decay length of the reconstructed B-meson vertex. The resolutions in mass are determined from the distributions of the reconstructed invariant mass for the signal tracks (where the signal tracks are identified using the Monte Carlo truth). The principal backgrounds to this channel include the decay $B_d^0 \to J/\psi\,(\mu\mu)\,K^{0*}\,(K^+\pi^-)$ and processes of the type $b\bar{b} \to J/\psi\,(\mu\mu)\,X$, where X is any other particle or particle chain. Directly produced J/ψ mesons can also contribute to the background if they decay to two muons.

The initial pure state of the B-meson must be tagged to extract the mixing parameters. ATLAS studies currently utilise a combined jet-charge and lepton tagging mechanism, which first aims to identify semi-leptonic decays of the so-called “opposite side” b-quark and thereby tag the flavour of the meson through the charge of the lepton. In the event that no such semi-leptonic decay can be found the algorithm exploits correlations between the initial state of the signal B-meson and a quantity referred to as the jet charge Q_{jet}, given by

$$Q_{\text{jet}} = \frac{\sum_i q_i p_i^\kappa}{\sum_i |p_i|^\kappa} \tag{5}$$

where the index i runs over all tracks within a cone whose central axis is defined by the momentum vector of the B-meson. p_i is a measure of the momentum of the ith track, and q_i is its electric charge. The tracks within the cone are referred to as the *jet*; it is expected that, on average, the sign of the jet charge associated with a $\bar{b}$-quark will be positive, and vice versa for the conjugate case, so this allows an informed guess as to the flavour of the signal meson. The latest ATLAS studies suggest an efficiency of 52% and a wrong-tag fraction of 37%, leading to a quality factor of 0.033. LHCb deploys similar techniques in a neural network - latest studies suggest a quality factor of 0.09.

4. SENSITIVITY STUDIES

4.1. ϕ_s with $B_s^0 \to J/\psi\,(\mu\mu)\,\phi\,(KK)$

The final stage of the analysis involves the fitting of the collected decay angles and times to the theoretical probability density function in equation 2. It is expected that the detector will distort the distributions to an extent, so adequately calculating the acceptance correction functions is an important part of these analyses. The sensitivity studies conducted thus far have utilised "toy" Monte Carlo events, generated with an accept-reject algorithm according to the theoretical distribution, and then smeared according to the detector performance.

ATLAS currently produces events according to a probability density function consisting of three angles and the decay time, which are then smeared according to the proper time resolution (under the assumption that this is well-described by a Gaussian). It is also assumed in these studies that there is no angular dependence in the background, and that there is no asymmetry in the production of B_s^0 and $\bar{B}_s^0$. The wrong-tag fractions as determined in the performance studies are fixed parameters in the fit. The ATLAS assessment is based on ~ 100 "toy" experiments each corresponding to $30 fb^{-1}$ of data.

The LHCb studies have produced ~ 250 "toy" experiments each corresponding to $2 fb^{-1}$ of data. Unlike the ATLAS scheme, the distributions have used the one angle probability density function described in [2]. The likelihood function is also *simultaneously* maximized with the $B_s \rightarrow D_s \pi$ control sample to allow a coincident fitting of ΔM_s, whereas this parameter is fixed in the ATLAS study. The wrong-tag fractions are also treated as fit parameters in this study.

The expected precisions on the quantities of interest has yielded precisions as displayed in table 2. If there are no new physics contributions to ϕ_s and the Standard Model value (~ 0.04) holds true, then ATLAS will not be able to make a statistically significant measurement of this, whereas LHCb will be able to access it within $10 fb^{-1}$. ATLAS will, however, be able to exclude certain models predicting substantially larger values of ϕ_s (e.g. [1]). ATLAS has also conducted a study of the correlations between the various parameters; some of these are large. In particular, the moduli ($|A_\perp|$ and $|A_\parallel|$) and phases (δ_1 and δ_2) of the transversity amplitudes appear to be correlated above 95%.

4.2. ΔM_s with $B_s^0 \rightarrow D_s \pi$

CDF recently made a measurement [4] of $\Delta M_s = 17.31^{+0.33}_{-0.18} \pm 0.07 ps^{-1}$, which has informed the studies of both experiments.

Simulations suggest that ATLAS will be able to measure ΔM_s with around $10 fb^{-1}$ of data if the CDF measurement is correct. This corresponds to about a year of data taking at the initial "low" LHC luminosity ($2 \times 10^{33} cm^{-2} s^{-1}$). LHCb expects to be able to measure ($\geq 5\sigma$) ΔM_s for values up to $\Delta M_s = 68 ps^{-1}$. However, the CDF measurement is much lower than this, and if true, would mean that LHCb could make an almost immediate measurement of the quantity, that is, with an integrated luminosity of less than $0.25 fb^{-1}$.

5. CONCLUSIONS

A combination of detector simulation and toy Monte Carlo studies have estimated that the weak mixing phase ϕ_s could be measured (3σ confidence limit) by LHCb, after five years of running, even if this parameter has the small value expected by the Standard Model. ATLAS could exclude some Standard Model extensions (which predict a much larger value of ϕ_s after three years of low luminosity running, but cannot access the Standard Model value.

ATLAS may be able to reach the 5σ confidence limit for ΔM_s after one year ($10 fb^{-1}$) given the CDF results for this parameter, and LHCb could make the same measurement in much less than a year.

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