PROCEEDINGS OF SCIENCE

$B_s \rightarrow J/\psi\phi$ with ATLAS/CMS

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There is large potential for New Physics to be discovered in $B_s^0 - \overline{B}_s^0$ mixing-induced CP violation. At the LHC it will be possible to extract the CP-violating weak mixing phase ϕ_s from the $B_s \rightarrow J/\psi\phi$ decay by a time dependent, multi-angular analysis of the final state particles. This presentation describes how both ATLAS and CMS will attempt to perform this measurement and their expected sensitivities with early data.

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1. Introduction

New phenomena beyond the Standard Model (SM) may alter the CP violation in B-decays. A prominent example that has received much experimental and theoretical attention is the decay $B_s \to J/\psi\phi$. The oscillation frequency of $B_s^0 - \overline{B}_s^0$ mixing is characterized by the mass difference ΔM_s of the “heavy" (B_H) and “light" (B_L) mass eigenstates, and by a CP-violating mixing phase ϕ_s which describes “mixing-induced" CP violation. In the SM this phase is small and precisely predicted: $\phi_s = -0.0368 \pm 0.0018$ [1]. New Physics Models can predict large ϕ_s whilst satisfying all existing constraints, including a measurement of ΔM_s at the Tevatron: 17.77 ± 0.10 (stat.) ± 0.07 (syst.) ps^{-1} [2].

The third physical quantity involved in $B_s^0 - \overline{B}_s^0$ oscillations is the width difference $\Delta\Gamma = \Gamma_L - \Gamma_H$ of B_L and B_H. New physics cannot significantly affect $\Delta\Gamma$ [3]; extracting $\Delta\Gamma$ from data is nevertheless helpful as it provides constraints on the ratio $\Delta\Gamma/\Delta M_s$, which is free of most theoretical uncertainties and is therefore easier to calculate [1].

Due to the high luminosity at the LHC, the large b-cross section and dedicated triggers, both ATLAS and CMS will be able to collect $B_s \to J/\psi\phi$ events in large numbers, allowing a measurement of ϕ_s.

2. Phenomenological aspects of the decay $B_s \to J/\psi\phi$

The time-dependent angular distribution of the decay chain $B_s \to J/\psi\phi$ can be generically described by equation 2.1 taken from [4]:

$$f(t,\Omega) = \sum_k \mathcal{O}_k(t) g_k(\Omega), \tag{2.1}$$

where t is the proper time, and the angles characterizing the kinematics of the decay products of $J/\psi \to \mu^+\mu^-$and $\phi \to K^+K^-$ are denoted by Ω.

The functions $\mathcal{O}_k(t)$ describe the evolution of the angular distributions with the proper lifetime of the decaying B_s, and can be expressed in terms of real or imaginary parts of bilinear combinations of decay amplitudes.

$$\begin{aligned}
\mathcal{O}_1 &= \frac{|A_0(0)|^2}{2}\left[(1+\cos\phi_s)e^{-\Gamma_{\mathrm{L}}^{(s)}t} + (1-\cos\phi_s)e^{-\Gamma_{\mathrm{H}}^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right] \\
\mathcal{O}_2 &= \frac{|A_\parallel(0)|^2}{2}\left[(1+\cos\phi_s)e^{-\Gamma_{\mathrm{L}}^{(s)}t} + (1-\cos\phi_s)e^{-\Gamma_{\mathrm{H}}^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right] \\
\mathcal{O}_3 &= \frac{|A_\perp(0)|^2}{2}\left[(1-\cos\phi_s)e^{-\Gamma_{\mathrm{L}}^{(s)}t} + (1+\cos\phi_s)e^{-\Gamma_{\mathrm{H}}^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right] \\
\mathcal{O}_4 &= \frac{1}{2}|A_0(0)||A_\parallel(0)|\cos(\delta_2-\delta_1)\times\left[(1+\cos\phi_s)e^{-\Gamma_{\mathrm{L}}^{(s)}t} + (1-\cos\phi_s)e^{-\Gamma_{\mathrm{H}}^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right] \\
\mathcal{O}_5 &= \pm|A_\parallel(0)||A_\perp(0)|\left[e^{-\Gamma_s t}\{\sin\delta_1\cos(\Delta m_s t) - \cos\delta_1\sin(\Delta m_s t)\cos\phi_s\} \mp \frac{1}{2}\left(e^{-\Gamma_{\mathrm{H}}^{(s)}t} - e^{-\Gamma_{\mathrm{L}}^{(s)}t}\right)\cos\delta_1\sin\phi_s\right] \\
\mathcal{O}_6 &= \pm|A_0(0)||A_\perp(0)|\left[e^{-\Gamma_s t}\{\sin\delta_2\cos(\Delta m_s t) - \cos\delta_2\sin(\Delta m_s t)\cos\phi_s\} \mp \frac{1}{2}\left(e^{-\Gamma_{\mathrm{H}}^{(s)}t} - e^{-\Gamma_{\mathrm{L}}^{(s)}t}\right)\cos\delta_2\sin\phi_s\right].
\end{aligned} \tag{2.2}$$

The functions $g_k(\Omega)$ depend on how the coordinate system describing the decays is defined. CMS use the same angular definitions as both CDF and DØ use. This has the advantage that if you integrate over two of the angles then several of the physics parameters drop out producing a much simpler fit. This integration does significantly reduce the sensitivity of the fit to ϕ_s but in fits with low numbers of signal events it can be useful. The coordinate system ATLAS use is symmetric which leads to simpler background distributions.

For ATLAS the overall rest frame is taken to be the rest frame of the B_s. In this rest frame the two daughter particles, the J/ψ and ϕ are produced back to back. Two additional coordinate systems are defined in the rest frames of the daughter particles, the J/ψ and ϕ. The $\hat{z}$ axis of each daughter rest frame is defined as the direction of the momentum of each daughter particle in the rest frame of the B_s.

The $\hat{x}$ axis for each daughter rest frame is defined in the same direction. The polar angles Θ_1 and Θ_2 for the J/ψ and ϕ respectively are defined as the angle in the rest frame of that particle. This defines the azimuthal angle χ and sets the phase convention of the helicity amplitudes. Figure 2 illustrates how these three angles are defined.

$$
\begin{aligned}
g_1 &= \sin^2\Theta_1 \cos^2\Theta_2, \\
g_2 &= (1+\cos^2\Theta_1)\sin^2\Theta_2 \\
&\quad -\sin^2\Theta_1 \sin^2\Theta_2 \cos 2\chi, \\
g_3 &= (1+\cos^2\Theta_1)\sin^2\Theta_2 \\
&\quad +\sin^2\Theta_1 \sin^2\Theta_2 \cos 2\chi, \\
g_4 &= 2\sin^2\Theta_1 \sin^2\Theta_2 \sin 2\chi, \\
g_5 &= \sqrt{2}\sin 2\Theta_1 \sin 2\Theta_2 \cos\chi, \\
g_6 &= \sqrt{2}\sin 2\Theta_1 \sin 2\Theta_2 \sin\chi.
\end{aligned}
$$

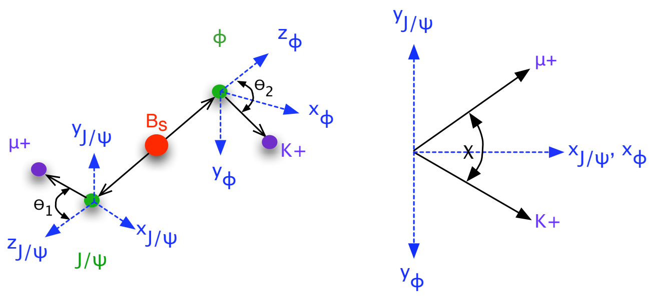

Figure 1: Schematic representation of the $B_s \to J/\psi\phi$ decay showing the definitions of the angles; Θ_1, Θ_2 and χ in the coordinate system used by ATLAS. The list of g_k terms corresponding to this coordinate system is also shown.

For CMS the angles are formed in the so called transversity basis. In this basis, the angles are defined as follows: θ_{tr} and ϕ_{tr} are the polar and azimuthal angles of the positive lepton in the J/ψ rest frame respectively. In that frame the $\hat{z}$ axis is perpendicular to the ϕ decay plane and the ϕ meson moves along the x direction. The θ_ϕ angle is the angle formed by the positive kaon and $\hat{x}$ axis in the ϕ rest frame. Figure 2 illustrates how these three angles are defined.

3. $B_s \to J/\psi\phi$ at ATLAS

The ATLAS trigger is based on three levels. Different strategies have been developed for B-physics depending on the luminosity. In the first few years of LHC running in the low luminosity period, the level 1 trigger will be a single or di-muon trigger with a p_T threshold of between 4 and 6 GeV. The higher level triggers will look for a di-muon trigger. As the luminosity increases a cut on the invariant mass of the di-muon pair will be added. At high luminosity, $> 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, a secondary vertex cut at the trigger level may have to be introduced to remove the background from direct J/ψ production.

$$
\begin{aligned}
g_1 &= 2\cos^2\psi(1-\sin^2\theta\cos^2\varphi),\\
g_2 &= \sin^2\psi(1-\sin^2\theta\sin^2\varphi),\\
g_3 &= \sin^2\psi\sin^2\theta,\\
g_4 &= \sin^2\psi\sin 2\theta\sin\varphi,\\
g_5 &= 1/\sqrt{2}\sin 2\psi\sin^2\theta\sin 2\varphi,\\
g_6 &= 1/\sqrt{2}\sin 2\psi\sin 2\theta\cos\varphi.
\end{aligned}
$$

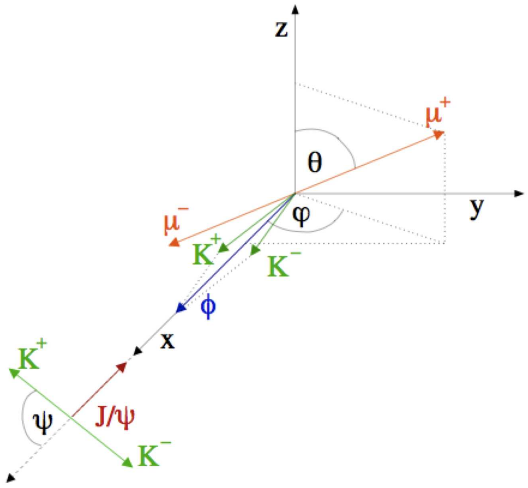

Figure 2: Schematic representation of the $B_s \to J/\psi\phi$ decay showing the definitions of the angles; θ_{tr}, ϕ_{tr} and θ_ϕ in the coordinate system used by CMS. The list of g_k terms corresponding to this coordinate system is also shown.

The offline reconstruction is performed in two stages. Firstly J/ψ candidates are formed by vertexing pairs of oppositely charged muons. The probability of the vertex fit must be greater than 1% and the invariant mass that falls within 3σ ($\sigma = 58$MeV) of the nominal value.

The second stage is the reconstruction of the B_s candidate which is formed by vertexing a J/ψ candidate with an additional pair of oppositely charged tracks. The J/ψ candidate invariant mass if fixed at the nominal value and the vertex is constrained to point towards the primary vertex. The ϕ candidate is required to have a $p_T >$ 2.6 GeV and a mass between 1005 MeV and 1035 MeV. The probability of the vertex fit must be greater than 1%. With these reconstruction cuts ATLAS expects to have 80 000 [1] fully reconstructed signal events with an integrated luminosity of 10fb^{-1} [5].

ATLAS will use a tagging combining the opposite-lepton tag and the jet charge tag methods. For the channel B_s the quality of the tag is dominated by jet charge tagging which can be used in many more events.

Jet charge tagging is performed by taking tracks from the fragmentation process in a cone (ΔR) around the B_s decay. These tracks are used to define a quantity Q_{jet}, the value of which is then used to determine what tag to assign the events. Q_{jet} is defined as:

$$
Q_{jet} = \frac{\sum_i q_i p_i^\kappa}{\sum_i |p_i|^\kappa}, \tag{3.1}
$$

where q_i is the charge of the track, p_i is the momentum of the track and κ is a tuning parameter. Using Monte Carlo studies it was possible to vary ΔR, κ and Q_{jet} so as to maximize the tag quality. Using jet charge tagging it is predicted that 62.5 ± 0.5% of events will be able to be tagged while the wrong tag fraction will be 37.4 ± 0.5% [5].

[1] In the slides a value for the proper decay time resolution was given, this was not an official ATLAS result.

In order to extract the physics parameters a simultaneous unbinned maximum likelihood fit will be performed on the data. In order to maximize ATLAS's sensitivity to ϕ_sa full angular analysis will be used along with tagging information. The measured lifetime uncertainty will also be taken into account on an event by event basis. The maximum likelihood fit also needs to take into account background events and distortions caused by the detector acceptance, trigger efficiency and the different selection criteria. ATLAS parameterizes the background as two terms in the likelihood fit, one for background from prompt J/ψ decays and one for non-prompt J/ψ decays. The mass distribution of both backgrounds are modeled by polynomials while the lifetime distribution for the direct background is modeled as a gaussian while the in-direct background is modeled by two smeared exponential decays.

In the first LHC run it is expected that up to 200pb^{-1} of data will be collected and this will allow ATLAS to measure the mass and the average lifetime to better understand the detector [5].

4. $B_s \to J/\psi\phi$ at CMS

At CMS the $B_s \to J/\psi\phi$ decay chain will be selected at Level-1 by the di-muon trigger stream, which will use an identical threshold of 3 GeV/c on the transverse momentum of each muon. At the High Level Trigger, a fast track reconstruction in the inner detector will be performed to reconstruct the complete decay chain. At high luminosity, $> 10^{33}$cm^{-2}s^{-1}, a secondary vertex cut at the trigger level may have to be introduced.

The CMS offline reconstruction is similar to that performed by ATLAS. Two tracks identified as muons and of opposite charge along with two additional oppositely charged tracks are constrained in a kinematic fit to come from the same vertex. The invariant mass of the two muons is constrained to be equal to the mass of the J/ψ. The invariant mass of the two kaons is required to be within $\pm$8MeV of the nominal ϕ mass. With this fit, a resolution on the invariant mass of the B_s meson of 14MeV is obtained along with a resolution of the proper decay time of 78fs. With this selection, a yield of 75 000 signal events is expected for an integrated luminosity of 6.8fb^{-1} [6].

With a sample of untagged events CMS will be able to perform an unbinned maximum likelihood fit to extract the two lifetimes, Γ_L and Γ_H the strong phases δ_1 and δ_2, the magnitudes of the amplitudes $A_0(0)$, $A_\perp(0)$ and $A_\parallel$, and the weak phase ϕ_s. The maximum likelihood fit uses an efficiency term to take into account the distortions to the data caused by the detector acceptance, trigger efficiency and the event selection criteria. This efficiency is calculated as a function of proper time and angles and is determined from the distribution obtained from full Monte Carlo simulation. CMS divides the background into two different types of events. Events from the $B_d \to J/\psi K^{0*}$ decay that will have a differential decay rate of the same function form as the signal and those background events from other sources that are assumed to have no angular dependence.

Following the above procedure, with 6.8fb^{-1} CMS expects to be able to measure the relative difference of the widths of the weak eigenstates, $\Delta\Gamma_s/\overline{\Gamma}_s$, with a statistical uncertainty of 0.015 and to have a statistical uncertainty of 0.076 to ϕ_s [6].

5. Summary

Both the ATLAS and CMS experiments will be able to measure with good precision $\Delta\Gamma_s/\overline{\Gamma}_s$, and to get evidence for large new physics effects in ϕ_s. During the first year of data taking, where up to 200pb^{-1} of data will be collected, ATLAS will be able to measure the mass and single lifetime for detector understanding.

References

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