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Studies of $B_S^0 \to J/\psi\phi$ decays with the CMS experiment

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A measurement of the total and differential cross sections of B_s mesons produced in pp collisions at $\sqrt{s} = 7$ TeV is presented, using the $J/\psi\phi$ decay channel. In addition, prospects for the measurement of the CP violating phase are discussed.

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1. Introduction

The CP violation in the Standard Model (SM) can be described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix[1]. The recent independent and complementary measurements performed at B Factories [2] and Tevatron laboratory [3] [4] [5] seem to confirm the validity of the theoretical description of the violation mechanism. Nevertheless many questions remain open: SM still has many free parameters; what is the origin of dark matter and dark energy; how the current matter-antimatter asymmetry is generated; the baryon number violation is not explained in SM; suggesting that SM is probably just low energy approximation of final big theory of everything.

It is highly interesting to extend the search for CP violation to the neutral B_S^0 mesons. Peculiarity of this system is that it combines fast particle-antiparticle oscillation (as in the B^0 system) with an observable separation into distinct lifetime states (best known from the neutral kaon system).

B_S^0 mesons can decay into $B_S^0 \to J/\psi\phi$ through tree (dominating) and penguin processes, described by a single weak phase $\Phi_D = arg(V_{cb}V_{cs}^*)$ [1]. Before decaying into $J/\psi\phi$, B_S^0 mesons can also first oscillate into $\overline{B}_S^0$, with a B_S^0 mixing phase $\Phi_M = 2arg(V_{ts}^*V_{tb})$. The interference between the two possible decays gives rise to the CP violating phase $\Phi_S = \Phi_M - 2\Phi_D = -2\beta_s$ (β_s corresponds to the smaller angle of the "b-s unitary triangle" of the CKM matrix[1]). New Physics can manifest itself through new particles contributing to the $B_S^0\overline{B_S^0}$ box diagram, and have the potential to modify Φ_S from the SM expectation.

The roadmap to be able to measure -2β is composed of several steps. The statistics from 2010 data taking allowed us to perform the first step, which was an untagged analysis of the final state. The main attention was devoted to optimizing the selection procedure. The measurement of the proper time, three angles and CP parameters, will be possible with the expected summer 2011 statistics of 1fb^{-1}; the following step, an Φ_S tagged analysis, will be performed as soon as sufficient statistics (beyond 1 fb-1) will be reached during 2011.

The analysis, presented in this paper, describes the measurement of the total and differential cross sections for the decay $B_s^0 \to J/\psi\phi$, as function of the B_s transverse momentum, $d\sigma/dp_T^{P_B}$, and rapidity, $d\sigma/dy^{P_B}$; it is based on the first 39.9 pb^{-1} data collected during 2010 with the CMS experiment at the CERN LHC collider. A full description of the experiment can be found in [7] and in these proceedings [8].

2. B_S^0 candidate selection

Reconstruction of $B_S^0 \to J/\psi\phi$ candidates begins by identifying $J/\psi \to \mu^+\mu^-$ decays, triggered by requiring two muons without any explicit requirement on the muon momentum. The J/ψ candidates are reconstructed by forming a vertex (estimated with the Kalman Filter formalism) out of every unique pair of muon candidates with opposite electric charge. The muons are required to lie within a kinematic acceptance region defined by: $p_T^\mu > 3.3$ GeV/c for $|\eta^\mu| < 1.3$; $p^\mu > 2.9$ GeV/c for $1.3 < |\eta^\mu| < 2.2$; and $p_T^\mu > 0.8$ GeV/c for $2.2 < |\eta^\mu| < 2.4$. All J/ψ candidates that have an invariant mass within 150 MeV/c^2 of the world average value [9], and a transverse momentum $p_T > 0.5$ GeV/c are retained.

[1]CKM matrix element described in [1]

Candidate ϕ mesons are reconstructed from pairs of oppositely charged tracks with $p_T >$ 0.7 GeV/c that are selected from a sample from which the J/ψ muon candidate tracks are removed. The tracks should have at least five hits, and a normalized track fit χ^2 of less than five. Each track is assumed to be a kaon and the invariant mass of a track pair has to be within 10 MeV/c^2 of the world average ϕ-meson mass [9].

B_S^0 candidates are formed by combining a J/ψ with a ϕ candidate. A kinematic fit is performed with the two muons and the two kaon tracks, where the dimuon invariant mass is constrained to be the nominal J/ψ mass. The selected events must have a resulting χ^2 probability greater than 2% and an invariant mass between 5.2 GeV/c^2 and 5.65 GeV/c^2 . Candidate B_S^0 are accepted if the proper range of decay length is in the range $-0.05 < ct < 0.35$ cm. The proper decay length is calculated as $ct = c(M_B/p_T^B)L_{xy}$, where the transverse decay length L_{xy} is the length of the vector $\vec{s}$ pointing from the primary vertex to the secondary vertex projected onto the B_S^0 transverse momentum: $L_{xy} = (\vec{s}\cdot\vec{p}_T^B)/\vec{p}_T^B$, where M_{B_s} is the reconstructed B_S^0 mass, and p_T^B is the transverse momentum respectively.

We optimize further selection criteria based on the figure-of-merit, $S/\sqrt{S+B}$ where S is the expected signal yield and B is the estimated background.

The main sources of background are originating from : *1)* background from other B meson decays, an important background that results from mis-reconstructed B meson decays (e.g. $B^0 \to J/\psi K^*$ and $B^+ \to J/\psi K^+$ including higher mass kaons); *2)* prompt J/ψ production associated with random tracks; *3)* the generator level. The general combinatorial background was found to be negligible after all the selection cuts have been applied.

A total of 6 200 events pass all of the selection criteria.

3. Fitting procedure

The signal yields in bins of p_T^B and y^B are extracted by using an extended maximum-likelihood fit to the invariant mass M_B and proper decay length ct of the reconstructed candidates. The likelihood for event j is obtained by summing the product of yield n_i and probability density P_i for each of the signal and background hypotheses i. We assume the existence of three components: signal $B_S^0 \to J/\psi\phi$, prompt J/ψ, and non-prompt J/ψ. The extended likelihood function is then the product of likelihoods for each event j:

$$\mathscr{L} = \exp\left(-\sum_i^3 n_i\right)\prod_j\left[\sum_i^3 n_i P_i(M_B;\vec{\alpha}_i)P_i(ct;\vec{\beta}_i)\right]$$

The probabilities P_i are the probability density functions (PDFs) with shape parameters $\vec{\alpha}_i$ for M_B and $\vec{\beta}_i$ for ct, evaluated separately for each of the i fit components. The yields n_i are then determined by minimizing the quantity $-\ln\mathscr{L}$.

After performing the fit, the number of signal events, in the entire data sample in the kinematic range $8 < p_T^B < 50\ GeV/c$ and $|y^B| < 2.4$ is 549 ± 32, where the uncertainty is statistical only. In Figure 1 the fit projections for M_B and ct from the inclusive sample with $8 < p_T^B < 50\ GeV/c$ and $|y^B| < 2.4$ are shown. In the M_B distribution, we apply an additional selection, $ct > 100\ \mu m$, on the proper decay length to visually enhance the signal contributions.

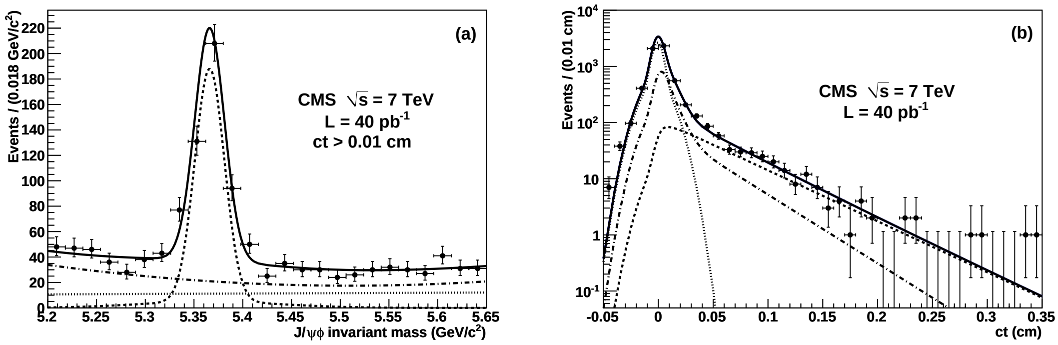

Figure 1: Projections of the fit results in M_B (a) and ct (b) for $8 < p_T^B < 50$ GeV/c and $|y^B| < 2.4$. The curves in each plot are: the sum of all contributions (solid line); signal (dashed); prompt J/ψ (dotted); and non-prompt J/ψ (dot-dashed). The signal peak in the M_B plot is enhanced with the requirement of $ct > 100\,\mu$m.

4. Systematics

Several sources of systematic uncertainties and their effects on the cross section measurement have been considered. The uncorrelated ones are: muon identification, muon tracking and HLT efficiencies uncertainties, which have been measured from the data with the Tag and Probe technique (3 – 5 %); hadron tracking efficiency uncertainties (7.8 %) [10]; reconstruction efficiency uncertainties due to finite MC sample size plus the evaluation of a variation in the selection criteria (2 – 3 %); variations in the alignment, which were estimated by using a different signal MC sample reconstructed by assuming a different alignment and estimating the systematic uncertainty between the two samples as the full difference in reconstruction efficiency between them (2-4%).

The model dependence of the efficiency extracted from an underlying models was reduced by re-calculating the efficiencies with Monte Carlo samples generated with PYTHIA and MC@NLO [11]. This was done in each bin of p_T^B and $|y^B|$. Since the variation in the spectrum is larger for the rapidity bins, which integrate over p_T^B, the corresponding variation in the efficiency calculation is also larger [11] (1 – 3 %); uncertainty due to the choice of the fit PDFs are calculated varying their parameters by one standard deviation, and assigning a systematic to the choice of resolution function parametrization made. The uncertainty on the predicted cross section is calculated by varying the renormalization and factorization scales by factors of two, m_b by ± 0.25 GeV/c^2, and by using the CTEQ6.6 parton distribution set. For reference, the prediction of PYTHIA is also included: it uses using a b-quark mass of 4.8 GeV/c^2, the CTEQ6L1 parton distribution Ref. [13], and the Z2 tune from Ref. [14] to simulate the underlying event.

In addition, there are common uncertainties of 4% from the luminosity measurement [12] and of 30% from the branching fractions [9].

5. Results and conclusions

The CMS collaboration has showed capability for studying this decay channel already with the 2010 data. The integrated luminosity of 39.9 pb^{-1} allowed for the first measurement of the

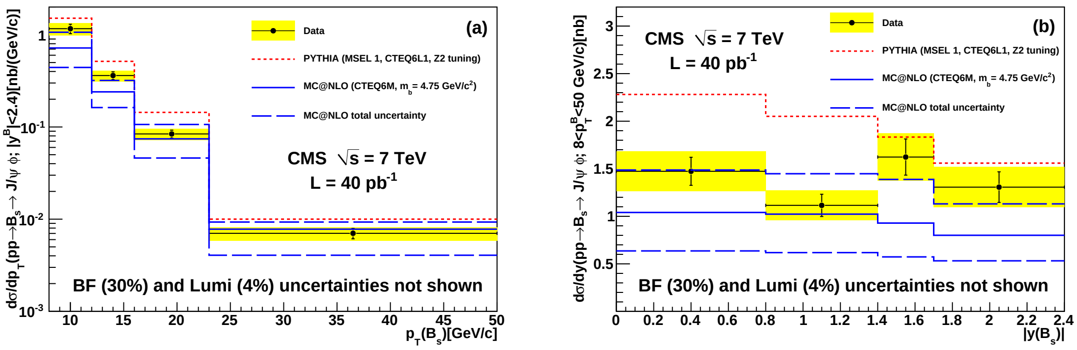

Figure 2: Measured differential cross sections $d\sigma/dp_T^{P_B}$ (a) and $d\sigma/dy^{P_B}$ (b) compared with the theory predictions. The (yellow) band represents the sum in quadrature of statistical and systematic uncertainties. Overall uncertainties of 4% for the luminosity and 30% for the branching fractions are not shown. The red line is the PYTHIA prediction; the blue line is the MC@NLO prediction.

differential cross sections $d\sigma/dp_T^{P_B}$ and $d\sigma/dy^{P_B}$ for $B_S^0 \to J/\psi\phi$ produced in pp collisions at $\sqrt{s} = 7$ TeV, covering the range in $p_T^{P_B}$ from 8 GeV/c to 50 GeV/c, and the rapidity range $|y^B| < 2.4$. The differential cross sections were derived from the measured signal yields, n_{Sig}, as:âĂİ

$$\frac{d\sigma(pp \to B_S^0 \to J/\psi\phi)}{dx} = \frac{n_{sig}}{2 \cdot \varepsilon_{acceptance} \cdot \varepsilon_{2\mu} \cdot \varepsilon_{B_s} \cdot BF(J/\psi \to \mu^+\mu^-) \cdot BF(\phi \to K^+K^-) \cdot \Delta x \cdot \mathscr{L}}$$

and then corrected for detector efficiencies, ε; the branching fractions for the sub-decays, BF; bin size for x, Δx, with $x = p_T^B, |y^B|$; and luminosity, $\mathscr{L}$.

The differential cross sections as functions of p_T^B and $|y^B|$ are shown in Figure 2. They are compared with the predictions of MC@NLO using a b-quark mass of 4.75 GeV/c^2, the renormalization and factorization scale $\mu = \sqrt{m_b^2 + p_T^2}$, and the CTEQ6M parton distribution function [13].

The total integrated cross section for the whole visible range was measured, in the published paper [15], to be $(6.9 \pm 0.6 \pm 0.6)$ nb, where the first uncertainty is statistical, the second is systematic.

The result lies between the theory predictions of MC@NLO, $(4.6^{+1.9}_{-1.7} \pm 1.4)$ nb, and PYTHIA, (9.4 ± 2.8) nb, where the last value is the error due to the branching fraction for $B_S^0 \to J/\psi\phi$ [9]. The measurements of CP parameters and Φ_S are expected for 2011, when a higher statistics will be collected and available.

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