Studies on $B$ hadron production, spectroscopy and decays at CMS

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Abstract. We review several recent results of the CMS experiment in the field of $B$ hadron productions, spectroscopy and decays. We performed a flavour-untagged measurement of the width difference $\Delta \Gamma_s$ in the $B_s \rightarrow J/\psi \phi$ decays. With an assumption of zero mixing phase, reconstructed $B_s$ signal candidates are used to measure the polarization amplitudes in an angular and proper decay time analysis.

1. Introduction
The study of heavy-quark production in high-energy hadronic interactions plays a critical role in the testing next-to-leading order (NLO) quantum chromodynamics (QCD) calculations. Historically, the measured inclusive $b$-hadron production cross sections were significantly higher than the theory predictions [1], more data is needed to distinguish conclusively between the various theoretical approaches, particularly at large transverse momentum $p_T$ [2]. Among the $b$-hadrons, the flavour mixing property of the $B_s$ meson is particularly interesting, where the measurement of the lifetime difference ($\Delta \Gamma_s$) of the two mass eigenstates can be performed using the proper decay time distribution of $B_s$ meson [3, 4].

2. The CMS detector
The CMS detector [5] is a general purpose detector at the LHC. It’s inner tracker consists of silicon pixel and silicon strip layers. Muons are measured by drift tubes (DT), cathode strip chambers (CSC) and resistive plate chambers (RPC). The dimuon mass resolution is less than 1%, which makes it a powerful tool for $B$-physics study.

3. $B$-Hadron Production
The $B$-hadron production rates as a function of the hadron transverse momentum has been measured using the 7 TeV data on CMS shown in Figure 1, where the large normalization uncertainties for $\Lambda_b$ and $B_s$ are dominated by the poorly measured branching fractions for the decay channels used in the analysis. The $B$-hadron cross section are also measured and compared with theory predictions as shown Figure 2. Moreover, the first direct observation of a new strange heavy $b$ baryon $\Xi_b$ strongly decaying to a $\Xi_b^-$ baryon and a charged pion is reported in [6].
Figure 1. Comparison of b-hadron production rates versus hadron transverse momentum, where the inner error bars correspond to the bin-to-bin uncertainties, while the outer error bars represent the bin-to-bin plus normalization uncertainties added in quadrature.

Figure 2. Summary of B hadron cross section measurements performed by CMS with 7 TeV p-p collisions at LHC. The inner error bars of the data points correspond to the statistical uncertainty, while the outer (thinner) error bars correspond to the quadratic sum of statistical and systematic uncertainties. The outermost brackets correspond to the total error, including a luminosity uncertainty which is also added in quadrature. Theory predictions at NLO are obtained using “MC@NLO”.

4. Measurement of the $B_s$ lifetime difference

The decay of a $B_s$ meson is characterized by the possibility of the mixing between its two flavour eigenstates ($B_s - \bar{B}_s$) [7]. In the decay $B_s \rightarrow J/\psi\phi$ with $J/\psi \rightarrow \mu^+\mu^-$ and $\phi \rightarrow K^+K^-$, the final state is an admixture of the CP-even and CP-odd eigenstates. Since $B_s$ is a pseudo-scalar meson, while $J/\psi$ and $\phi$ are vector mesons, the orbital angular momentum can have the values $L = 0, 1, 2$. To measure the lifetime difference ($\Delta \Gamma_s$) for the decay rates of the two $B_s$ mass eigenstates [3, 4], an analysis is needed to disentangle the two CP eigenstates.

The decay topology is described by three angles $\Theta = (\theta_T, \psi_T, \varphi_T)$ in the transversity basis [8], as shown in Figure 3. The decay of vector mesons is further described by the time evolution of three different amplitudes with different angular dependencies. The amplitudes at time $t = 0$ are defined using the longitudinal component $A_0(0)$ for $L = 0$, which is CP-even, and the transverse components $A_\perp(0)$ for $L = 1$ and $A_\parallel(0)$ for $L = 2$ which are CP-odd and CP-even, respectively. In addition, the two strong phases are denoted by $\delta_\parallel$ and $\delta_\perp$.

![Figure 3. Definition of the three angles, $(\theta_T, \psi_T$ and $\varphi_T)$, used for the description of the decay topology.](image)

The differential decay rate can be represented [8] as:

$$\frac{d^4\Gamma(B_s(t))}{d\Theta dt} = f(\Theta, t; \alpha) = \sum_{i=1}^{6} O_i(\alpha, t) g_i(\Theta),$$

where $O_i$ are kinematics-independent observables, $g_i$ are the angular distributions, and $\alpha$ denotes a set of physics parameters of interest ($\Gamma_s$, $\Delta \Gamma_s$, $|A_0|^2$, $|A_\parallel|^2$, $\delta_\parallel$). The kinematic
observables are described using the following equations:

\begin{align*}
O_1 &= |A_0(t)|^2 = |A_0(0)|^2 e^{-\Gamma_s t} [\cosh(\Delta \Gamma_s t/2) - \cos \phi_s \sinh(\Delta \Gamma_s t/2)] \\
O_2 &= |A_{||}(t)|^2 = |A_{||}(0)|^2 e^{-\Gamma_s t} [\cosh(\Delta \Gamma_s t/2) - \cos \phi_s \sinh(\Delta \Gamma_s t/2)] \\
O_3 &= |A_{\perp}(t)|^2 = |A_{\perp}(0)|^2 e^{-\Gamma_s t}[\cosh(\Delta \Gamma_s t/2) + \cos \phi_s \sinh(\Delta \Gamma_s t/2)] \\
O_4 &= \text{Im}(A_{||}^*(t)A_{||}(0)) = |A_{||}(0)||A_{||}(0)| e^{-\Gamma_s t} [-\cos(\delta_{||} - \delta_{\perp}) \sin \phi_s \sinh(\Delta \Gamma_s t/2)] \\
O_5 &= \text{Re}(A_0^*(t)A_{||}(t)) = |A_0(0)||A_{||}(0)| \cos\delta_{||} e^{-\Gamma_s t} [\cosh(\Delta \Gamma_s t/2) - \cos \phi_s \sinh(\Delta \Gamma_s t/2)] \\
O_6 &= \text{Im}(A_0^*(t)A_{\perp}(t)) = |A_0(0)||A_{\perp}(0)| e^{-\Gamma_s t} [-\cos \delta_{\perp} \sin \phi_s \sinh(\Delta \Gamma_s t/2)] ,
\end{align*}

where \( \phi_s \) is the mixing phase. Constraining \( \phi_s \) to zero allows the terms containing \( O_4(\alpha, t)\cdot g_4(\Theta) \) and \( O_6(\alpha, t)\cdot g_6(\Theta) \) to be omitted. The individual angular distributions are given by the following equations:

\begin{align*}
g_1 &= 2 \cos^2(\psi_T)(1 - \sin^2(\theta_T) \cos^2(\varphi_T)), \\
g_2 &= \sin^2(\psi_T)(1 - \sin^2(\theta_T) \sin^2(\varphi_T)), \\
g_3 &= \sin^2(\psi_T) \sin^2(\theta_T), \\
g_4 &= -\sin^2(\psi_T) \sin^2(2\theta_T) \sin(\varphi_T), \\
g_5 &= \frac{1}{\sqrt{2}} \sin(2\psi_T) \sin^2(\theta_T) \sin(2\varphi_T), \\
g_6 &= \frac{1}{\sqrt{2}} \sin(2\psi_T) \sin^2(2\theta_T) \sin(2\varphi_T) .
\end{align*}

The theoretical expectation for the ratio \( \Delta \Gamma_s/\Gamma_s \) is 0.12 \pm 0.06 [7].

The events are selected by requiring two oppositely charged muons and two oppositely charged tracks. Then the \( B_s \) are built from 4-track vertex fit, where the dimuon invariant mass is constrained to the known \( J/\psi \) mass [9] and the invariant mass of a track pair is required to be within 10 MeV of the world average \( \phi(1020) \)-meson mass [9].

The overall efficiency includes: detector acceptance, the trigger conditions, and the selection cuts. No sizable correlation between the proper time and the angular variables is found. The correlation amongst the angular observables is also negligible. The proper decay length efficiency is almost flat in the range [0.02-0.3] cm.

An unbinned maximum likelihood fit to the data is performed by including the information on the invariant mass \( m \), proper decay time \( t \) and the three decay angles \( \Theta \) of the reconstructed \( B_s \) candidates. From this five-dimensional fit, the physics parameters of interest \( \Delta \Gamma_s, \Gamma_s, |A_{\perp}|^2, |A_0|^2 \) and \( \delta_{\perp} \) are determined, assuming that the mixing phase \( \phi_s \) is zero.

The event likelihood function \( \mathcal{L} \) can be represented as

\begin{align*}
\mathcal{L} &= L_{\text{signal}} + L_{\text{background}} , \\
L_{\text{signal}} &= (f(\Theta, t; \alpha) \times G(t, \kappa, \sigma(t))) \cdot M(m) \cdot \epsilon(t) \epsilon(\Theta) , \\
L_{\text{background}} &= b(\Theta, t, m) ,
\end{align*}

where \( L_{\text{signal}} \) is the PDF that describes the \( B_s \to J/\psi \phi \) signal model, \( L_{\text{background}} \) describes the background contributions, and \( f(\Theta, t; \alpha) \) is the differential decay rate function. Here \( G \) is a Gaussian resolution function which makes use of the per event proper decay time uncertainty \( \sigma(t) \) scaled by a factor \( \kappa \), \( \epsilon(t) \) is the proper decay time efficiency function, \( \epsilon(\Theta) \) is the angular efficiency function, and \( b(\Theta, t, m) \) describes the background model. The signal mass PDF \( M(m) \) is given by the sum of two Gaussian functions.
To extract the physics parameters of interest, a five-dimensional fit procedure is taken with several steps. First a one-dimensional fit of $B_s$ mass to get the mean and the smaller of the two Gaussian function widths. Then fit the sideband region for the angular background shapes. Finally fit the full mass range. The mass distribution of the reconstructed $B_s$ candidates is shown in Figure 5, together with the overlaid five-dimensional fit projection. The measured signal yield is $14456 \pm 140$, with a fitted mass mean of $5366.8 \pm 0.1$ MeV. The full fit was finally performed in the full mass range, and the one-dimensional projections on the distributions of the proper decay length distributions and the angular variables are shown in Figure 6 and Figure 7 respectively.

The total estimated systematic uncertainties are presented in Table 1, where the main contribution sources are background angular model, and proper time resolution.

| Table 1. Systematic uncertainties associated to the quantities measured in the analysis. |
| --- |
| Uncertainty source | $\Delta \Gamma_s$ [ps$^{-1}$] | $c\tau$ [cm] | $|A_0|^2$ | $|A_1|^2$ | $\delta_\parallel$ [rad] |
| **Signal PDF modeling** | | | | | |
| Signal mass model | 0.00072 | 0.00012 | 0.0022 | 0.0006 | 0.039 |
| Proper time resolution | 0.00170 | 0.00006 | 0.0007 | 0.0000 | 0.007 |
| $\phi_s$ approximation | 0.00000 | 0.00001 | 0.0000 | 0.0000 | 0.002 |
| S-wave assumption | 0.00109 | 0.00001 | 0.0130 | 0.0066 | 0.056 |
| **Background PDF modeling** | | | | | |
| Background mass model | 0.00019 | 0.00000 | 0.0000 | 0.0001 | 0.003 |
| Background lifetime model | 0.00040 | 0.00000 | 0.0001 | 0.0002 | 0.003 |
| Peaking $B^0$ background | 0.00025 | 0.00006 | 0.0002 | 0.0022 | 0.050 |
| Background angular model | 0.00175 | 0.00003 | 0.0001 | 0.0064 | 0.161 |
| **Limited simulation statistics** | | | | | |
| Angular efficiency parameters | 0.00019 | 0.00002 | 0.0057 | 0.0055 | 0.037 |
| Temporal efficiency parameters | 0.00000 | 0.00005 | 0.0000 | 0.0000 | 0.000 |
| Temporal efficiency parametrization | 0.00181 | 0.00014 | 0.0005 | 0.0007 | 0.001 |
| Angular efficiency parametrization | 0.00063 | 0.00003 | 0.0021 | 0.0086 | 0.007 |
| Likelihood function bias | 0.00000 | 0.00004 | 0.0004 | 0.0000 | 0.014 |
| **Total uncertainty** | 0.00341 | 0.00022 | 0.0146 | 0.0140 | 0.187 |

The $B_s$ decay width difference, $B_s$ mean lifetime, transversity amplitudes ($|A_\perp|^2$ and $|A_0|^2$) and the strong phase ($\delta_\parallel$) are measured to be

$$\Delta \Gamma_s = 0.048 \pm 0.024 \text{ (stat.)} \pm 0.003 \text{ (syst.)} \text{ ps}^{-1},$$
$$\tau_{B_s} = 0.04580 \pm 0.00059 \text{ (stat.)} \pm 0.00022 \text{ (syst.)} \text{ cm},$$
$$|A_0|^2 = 0.528 \pm 0.010 \text{ (stat.)} \pm 0.015 \text{ (syst.)},$$
$$|A_\perp|^2 = 0.251 \pm 0.013 \text{ (stat.)} \pm 0.014 \text{ (syst.)},$$
$$\delta_\parallel = 2.79 \pm 0.14 \text{ (stat.)} \pm 0.19 \text{ (syst.) \ rad .}$$

the comparison of the decay width difference with other experiments is illustrated in Figure 4.

5. Summary
CMS is a powerful detector for studying $B$ physics because of its excellent tracking and lepton identification. Several recent results of the CMS experiment in the field of $B$ hadron productions, spectroscopy and decays are reviewed. A study of the $B_s \rightarrow J/\psi \phi$ decay with $J/\psi \rightarrow \mu^+ \mu^-$ and $\phi \rightarrow K^+ K^-$, yield $\Delta \Gamma_s = 0.048 \pm 0.024 \text{ (stat.)} \pm 0.003 \text{ (syst.)} \text{ ps}^{-1}$. We look forward to the new results from CMS.
References

Limited simulation statistics

| Background PDF modeling | Signal PDF modeling |
|-------------------------|--------------------|
| Likelihood function bias | 0.00000 0.00004 0.0004 0.0000 0.014 |
| Angular efficiency parametrization | 0.00063 0.00003 0.0021 0.0086 0.007 |
| Temporal efficiency parametrization | 0.00181 0.00014 0.0005 0.0007 0.001 |

For the CDF Collaboration, “New Measurement of the

I. I. D. I. Dighe and R. Fleischer, “Extracting CKM phases and

I. Dunietz, R. Fleischer, and U. Nierste, “In pursuit of new physics with

Figure 4. Comparison with other experiments. The blue region (CMS) was not in the original version by HFAG [10].

Figure 5. Mass projection of the five-dimensional maximum likelihood fit to the data. The points are the data distribution, the solid blue line shows the full fit, the green dash-dotted line is the signal model component, the red long-dashed line is the background component. The pull between the mass distribution and the fit is shown in the histogram below.
Figure 6. Proper decay length projection of the five-dimensional maximum likelihood fit to the data. The points are the data distribution, the solid blue line shows the full fit, the green dash-dotted line is the signal model component, with the CP-even (odd) component shown in blue short dashed line (magenta dash-dot-dotted line), and the red long dashed line is the background component. The pull between the proper decay length distribution and the fit is shown in the histogram below.

Figure 7. The angular projection of the five-dimensional maximum likelihood fit to the data. The plots show the projections on the angular variables $\cos(\psi_T)$, $\cos(\theta_T)$ and the angle $\phi$. The various fit components are represented as in Figure 6.
References
1. Nason P, Dawson S and Ellis R K 1988 *Nucl. Phys.* B303 607
2. Kniehl B A, Kramer G, Schienbein I and Spiesberger H 2008 *Phys. Rev.* D77 014011 (*Preprint* 0705.4392)
3. Giurgiu G (For the CDF) 2010 *PoS* ICHEP2010 236 (*Preprint* 1012.0962)
4. Uwer U (LHCb) 2011 *PoS* BEAUTY2011 051
5. Chatrchyan S et al. (CMS Collaboration) 2008 *JINST* 3 S08004
6. Chatrchyan S et al. (CMS Collaboration) 2012 *Phys.Rev.Lett.* 108 252002 (*Preprint* 1204.5955)
7. Dunietz I, Fleischer R and Nierste U 2001 *Phys.Rev.* D63 114015 (*Preprint* hep-ph/0012219)
8. IDighe I and RFleischer 1999 *Eur.Phys.J.C* 6
9. Nakamura K et al. (Particle Data Group) 2010 *J.Phys.G* G37 075021
10. Amhis et al. (Heavy Flavor Averaging Group) 2012 (*Preprint* 1207.1158)