CMS Conference Report

April 13, 2001

Prospects of B-Physics with CMS^{a)}

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Abstract

Prospects of studies of properties of b flavoured hadrons in the Large Hadron Collider with the CMS experiment have been reviewed. CP violation measurements in the decays of B_d and B_s mesons are described in detail. Possibilities of studies of B_s oscillation and rare B decays are also discussed.

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^{a)} Talk given at Beauty 2000, Magaan, Israel, September 2000

1 Introduction

Studies of decays of b flavoured hadrons offer a very fertile testing ground of the Standard Model description of electroweak interactions. These studies will be interesting at the Large Hadron Collider (LHC) even 6 years after the commissioning of the B-factories. During the first three years of low luminosity run of LHC, typically 5×10^{12} $b\bar{b}$ events will be produced per year in pp interactions at centre of mass energies of 14 TeV. At these high energies all kinds of b -hadrons will be produced. So B physics studies can start from the young days of LHC. With such a huge sample of $b\bar{b}$ events, rare B decays can be probed down to a level of 10^{-10} . B_s decays can also be studied in detail which cannot be efficiently done at B-factories. Excited states of B and b baryons will also be looked into.

Experimental conditions are however harder at the Large Hadron Collider. There will be about 2 to 3 pile-up events even in the low luminosity operation of LHC. At these high centre of mass energies, too many particles will be produced so that triggering and pattern recognition become difficult. Because of proton-proton interaction in the LHC, there will be a small production asymmetry of B mesons (between B and $\bar{B}$). Further, B and $\bar{B}$ need not be back to back due to different production mechanisms (gluon-gluon fusion versus gluon splitting).

The scope of B physics reviewed here is in the context of the Compact Muon Solenoid (CMS) experiment [1]. In the following sections, the experimental condition will be reviewed and the physics reaches in CP violation studies of B_d and B_s systems, in B_s oscillation and in rare B decays are discussed.

2 The CMS Experiment

The Large Hadron Collider situated in the 27 km circumference tunnel at CERN will provide pp collision at 14 TeV centre of mass energy with initial luminosity of $10^{33} \text{ cm}^{-2}\text{s}^{-1}$. This high luminosity is obtained using a large number of bunches in the machine which will result bunch collision rate of 40 MHz. To obtain a reasonable event recording rate (~ 100 Hz), one requires multi-level trigger with the first level bringing down the rate to 50–100 kHz.

The Compact Muon Solenoid (CMS) experiment, to be located at the fifth collision point, will be equipped to utilise the full capability (available luminosity) of the LHC. The CMS detector will have an excellent electron/photon detection using a crystal calorimeter. The resulting energy resolution will be better than 1% for energy above 100 GeV and angular resolution of $40/\sqrt{E}$ mrad. The precise muon spectrometer, consisting of drift tubes, cathode strip and resistive plate chambers located in the return yoke of the 4 Tesla magnetic field, will give rise to p_T resolution of 2% for 100 GeV muons over a large solid angle ($|\eta| < 2.4$). The inner tracker, made of 3 layers of silicon pixel and 10 layers of silicon strip detectors, will provide very accurate and efficient track measurements and excellent secondary vertex detection.

The trigger system, relevant for B physics studies, relies on soft lepton signature at level one. The p_T thresholds for single or two lepton triggers are summarised in table 1. Level one trigger rates are approximately 11 kHz and 10 kHz respectively for $\mu/e + \mu$ and e triggers and $\sim 90\%$ of the trigger rate is due to single leptons, but the two-leptons trigger is the most efficient for $B_d \rightarrow J/\psi K_s$ and $B_s \rightarrow J/\psi \phi$ channels. The higher level trigger will be implemented in several stages with level 2 output limited to 1 kHz. The high level trigger will redefine p_T calculation and set the thresholds differently, will reconstruct di-lepton mass precisely or B_d mass from $\pi^+\pi^-$ decays and will utilise impact parameter measurements. The tuning of high level trigger is currently under progress.

Trigger Type	One μ	Two μ 's	One e	Two e 's	$e + \mu$
p_T Threshold (GeV/c)	7.0	2.0 – 4.0	12.0	5.0	5.0 + 4.0

Table 1: Level 1 p_T threshold for soft lepton trigger in CMS

Selection of final states of interest utilises the key features of the CMS detector. The good energy and momentum resolution of the leptons enable excellent mass resolution of the J/ψ system which is estimated to be 15 MeV in the barrel detector and 30 MeV in the endcap. Secondary vertices are determined with excellent resolution. As an example, in B_s decaying to di-lepton system, the B_s vertex can be determined with a precision of $67\mu\text{m}$ along the flight path so that the flight distance is measured with a precision of 3.2%. Good mass resolution of di-pion system together with good secondary vertex capability gives clear discrimination of K_s (high signal to background) with good reconstruction efficiency ($\approx 60\%$ over a large rapidity region $\eta < 2.4$ in B_d decays to $J/\psi K_s$).

The flavour of the decaying B-meson at production time needs to be tagged in order to study CP violation. CMS collaboration has looked into several of these tagging methods: (a) from the other b -quark through the charge of the lepton from its semileptonic decay (this has low efficiency due to small semi-leptonic branching ratio but very

high purity); (b) from jet-charge measurement of the other b -quark; (c) from jet-charge measurement of the same side jet; (d) exploiting B^{**} resonance decays via $\pi^\pm B^*(\bar{B}^*)$ to final state $\pi^\pm \gamma B(\bar{B})$. The last method [2] uses π 's of $p_T > 1$ GeV/c and a mass window of $5.6 - 5.9$ GeV of the B^{**} .

The observed asymmetry between B and $\bar{B}$ decays is a product of the true asymmetry and a dilution factor. The dilution is due to (a) underlying background, $D_{\text{BKG}} = \sqrt{\frac{N_s}{N_s + N_{\text{BKG}}}}$; (b) the tagging method used, $D_{\text{Tag}} = 1 - 2w$, where w is the rate of wrong tags; (c) integration over time for time-integrated measurement, $D_{\text{Int}} = \frac{x_q}{1 + x_q^2}$, where $x_q = \frac{\Delta m_q}{\Gamma_q}$. As an example tag efficiency (ε_{Tag}) and dilution factor for $B_d \rightarrow J/\psi K_s$ is summarised in table 2. The same event can be tagged by more than one method. There is a strong correlation ($\sim 40\%$) between B^{**} and same side charge methods. Tags are considered in decreasing order of D_{Tag} and if a tag is given by a method, the event is not considered for a "lower tag". For example, the overall quality factor ($\varepsilon_{\text{Tag}} \times D_{\text{Tag}}^2$) for $B_d \rightarrow J/\psi K_s$ is $\approx 5\%$.

Tagging Method	ε_{Tag}	D_{Tag}	Quality Factor: $\varepsilon_{\text{Tag}} D_{\text{Tag}}^2$
μ tagging	3.4 %	0.44	0.66 %
e tagging	2.7 %	0.44	0.52 %
B^{**}	21 %	0.32	2.15 %
Same side charge	50 %	0.23	2.65 %
"Opposite" jet charge	65 %	0.18	2.1 %

Table 2: Tag efficiency, dilution factor for the different tagging methods for the study of $B_d \rightarrow J/\psi K_s$

3 The Channel $B_d \rightarrow J/\psi K_s$

CP violation in the B_d system can be studied from the asymmetry in the decay of B_d ($\bar{B}_d$) in the final state $J/\psi K_s$:

$$A_{J/\psi K_s}(t) = \frac{N(B_d \rightarrow J/\psi K_s) - N(\bar{B}_d \rightarrow J/\psi K_s)}{N(B_d \rightarrow J/\psi K_s) + N(\bar{B}_d \rightarrow J/\psi K_s)} = \sin 2\beta \star \sin \left(x_d \frac{t}{\tau} \right)$$

Selection of the final state utilises good reconstruction capability of K_s and good mass resolution of di-leptons. Using these one can suppress various backgrounds, the most dominant of the backgrounds being due to $b\bar{b} \rightarrow J/\psi X$. B_d 's are selected with $S/B \approx 8$ (2) from di-muon (di-electron) channels where the mass resolution of the B_d system is 16 MeV (22 MeV). Trigger, reconstruction efficiency and expected number of events from one year's data are summarised [3] in table 3.

	Channel	Efficiency	Events
bb events produced/year			72.6×10^6
Trigger:	1μ and 2μ	4.9%	3.42×10^6
	$1e$ and $2e$	0.64%	0.465×10^6
	$e\mu$	0.67%	0.486×10^6
	Total		4.36×10^6
Reconstruction:	$B_d \rightarrow J/\psi K_s \rightarrow \mu^+ \mu^- \pi^+ \pi^-$	11%	401×10^3
	$B_d \rightarrow J/\psi K_s \rightarrow e^+ e^- \pi^+ \pi^-$	5.5%	49×10^3
	Total $B_d \rightarrow J/\psi K_s$		450×10^3

Table 3: Trigger and reconstruction efficiency and expected number of events for the final state with $B_d \rightarrow J/\psi K_s$

The accuracy in the measurement of the CP angle, $\delta(\sin 2\beta)$, depends on event statistics (N_{untag}), tagging efficiency (ε_{Tag}) and the different dilution parameters:

$$\delta(\sin 2\beta) \propto \frac{1}{\sqrt{N_{\text{untag}} \varepsilon_{\text{Tag}} D_{\text{Tag}} D_{\text{BKG}} D_{\text{Int}}}}$$

Utilising all 4 tagging methods, one gets an accuracy of 0.015 in measuring $\sin 2\beta$ from one year's low luminosity run with CMS. Measuring proper time with the good vertexing, asymmetry can be determined as a function of time. The time dependent asymmetry gives similar precision as time integrated measurement of $\sin 2\beta$. After 3 years data taking, an accuracy of 0.01 can be obtained by CMS for $\sin 2\beta$. Then one needs to worry about systematic uncertainties: (a) in production process (comparison with other channels), (b) from the detector: trigger, reconstruction, tagging methods and backgrounds, (c) from theory.

4 The Channel $B_s \rightarrow J/\psi\phi$

This final state can be studied from the single and two lepton triggers. Selection of the final state requires two charged tracks of p_T above 1 GeV/c together with the two leptons coming from a secondary vertex which is separated from the primary vertex by 3 standard deviation. The main background to this process is due to B decaying to J/ψ and two hadrons like $B_d \rightarrow J/\psi K^*$. The unconstrained mass resolution for B_s is 27 MeV and this helps a very good signal to background rejection as can be seen from the mass distribution of the four body system ($\ell^+\ell^-K^+K^-$) in figure 1. Trigger, reconstruction efficiency and expected number of events from one year's data are summarised in table 4.

Figure 1: Signal and background events in the $\ell^+\ell^-K^+K^-$ mass distribution plot

	Channel	Efficiency	Events
bb events produced/year			36.3×10^6
Trigger:	1μ and 2μ	4.5%	1.63×10^6
	$1e$ and $2e$	0.62%	0.22×10^6
	$e\mu$	0.65%	0.24×10^6
	Total		2.09×10^6
Reconstruction:	$B_s \rightarrow J/\psi\phi \rightarrow \mu^+\mu^-K^+K^-$	38%	616×10^3
	$B_s \rightarrow J/\psi\phi \rightarrow e^+e^-K^+K^-$	17%	65×10^3
	Total $B_s \rightarrow J/\psi\phi$		6810×10^3

Table 4: Trigger and reconstruction efficiency and expected number of events for the final state with $B_s \rightarrow J/\psi\phi$

The Standard Model predicts a tiny CP asymmetry in B_s decays to $J/\psi\phi$ system. It is $\sim \lambda^2\eta$ in Wolfenstein parametrisation and of the order of a few percent. On the other hand B_s oscillates very rapidly ($x_s > 10$) so that no time integration method is possible in measuring CP asymmetry of B_s system. Using complete pattern recognition and reconstruction of secondary vertices, proper time resolution for B_s system in CMS has been estimated to be 68 fsec which is good enough in disentangling time-dependent CP asymmetry measurement of $B_s \rightarrow J/\psi\phi$.

Tagging method in B_s studies will be similar to those in B_d (with the exception of B^{**} method). From asymmetry measurements of tagged events, the weak phase angle can be determined with a precision depending on x_s as given in table 5. For $x_s > 10$, the dilution factor is mainly due to proper time resolution. Using variation of the resolution on p_T and η of the B_s system, one improves substantially the sensitivity of asymmetry measurement. The asymmetry is measured with accuracy better than 5σ for x_s values up to 55.

x_s	10	20	30	40	50
$\sigma(\phi_s)$	0.036	0.046	0.068	0.12	0.24

Table 5: Sensitivity of ϕ_s measurement in CMS as a function of x_s

Both J/ψ and ϕ are spin one particles. The decay angular distributions of these particles can be written in terms of the basic amplitudes, A_0 , $A_{\parallel}$, $A_{\perp}$ and B_s decay parameters like $\Delta\Gamma_s$, Γ_s , ϕ_s . CMS has flat acceptance for these angular distributions. A study of the decay angular distributions has been carried out [4] using the method of angular moments as described in [5]. The statistical accuracy for the determination of various parameters are summarised in table 6. Combining the ϕ_s measurements from the tagged sample, one gets a 3σ discrimination line for ϕ_s down to a value of ~ 0.05 for $x_s \approx 20$ (as shown in figure 2), which is in the range of the Standard Model prediction. Thus CMS will have sufficient accuracy in testing the Standard Model in B_s decays.

$\Delta\Gamma_s$	Γ_s	$A_{\parallel}$	$A_{\perp}$	δ_1	δ_2
8.0 %	0.5 %	0.6 %	2.0 %	0.09 rad	0.08 rad

Table 6: Statistical accuracy of determination of various parameters for the decay of B_s to $J/\psi\phi$ from analysis of angular distribution

Figure 2: Sensitivity of measuring weak phase angle ϕ_s from the LHC experiments

5 B_s Oscillations

$B_s \leftrightarrow \bar{B}_s$ oscillation can be studied using the final decay channel $B_s(\bar{B}_s) \rightarrow D_s^{\mp} \pi^{\pm}$ with $D_s^{\mp} \rightarrow \phi \pi^{\mp}$. The final state can be triggered with a soft muon with $p_T > 10$ GeV and the sign of the muon can be used to tag the B_s , produced in association with the one decaying to the muon. The event sample is selected using tight criteria of identifying secondary vertex ($d_{\perp} > 2\sigma_{\perp}$) and opening angle (between the $D_s^{\mp} \pi^{\pm}$ -system and the vector joining the primary and the secondary vertex to be less than 100 mrad).

Typically 4500 signal events are expected from one years data taking with signal to background ~ 1 . The proper time spectrum of the difference in B_s and $\bar{B}_s$ system can be Fourier analysed [6] and with a dilution factor ≈ 0.56 , sensitivity for a 3σ measurement can be reached for x_s values up to 42.

6 Rare B Decays

The di-muon decay mode of B_s is expected to be rare in the Standard Model (branching ratio $\approx (3.5 \pm 1.0) \times 10^{-9}$). Using di-muon trigger with $p_T^{\mu} > 4.3$ GeV/c for $|\eta| < 2.4$ and kinematical consideration of $p_T^{\mu\mu} > 12$ GeV/c and $0.4 < \Delta R_{\mu\mu} < 1.2$, one expects 66 signal events in one year [7]. $\Delta R_{\mu\mu}$ refers to the separation between the two muons in the η - ϕ plane. On the other hand, backgrounds from gluon splitting will give rise to 2.9×10^7 events.

Suppression of such a huge background can be achieved by utilising (a) isolation of the di-muon system, (b) good di-muon mass resolution, and (c) precise determination of the secondary vertex.

The isolation criterion has been imposed by demanding (i) No charged particle of $p_T > 0.9$ GeV/c within a cone $R < (0.5 \times \Delta R_{\mu\mu} + 0.4)$, and (ii) $E_T < 4$ GeV measured with the calorimeter in the same cone. The isolation criterion gives a background rejection factor of 1.32×10^{-2} .

The CMS tracker provides a mass resolution of 31 MeV in the entire acceptance (23 MeV for $|\eta| < 0.8$). So choosing a mass window of 80 MeV around the B_s mass, a rejection factor of 1.10×10^{-2} on the background can be achieved.

The tracker provides excellent secondary vertex reconstruction capability with a resolution of $67 \mu\text{m}$ along the B-direction. Using a cut on the distance between the muons, impact parameter and separation between the secondary and primary vertices, background rejection factor of 2.3×10^{-4} is obtained.

These cuts yield $\approx 10\%$ efficiency for signal events. So from one year data taking at low luminosity, one will get 7 signal events with < 1 background event at 90% confidence level. The di-muon trigger may also be operational during the high luminosity phase of LHC where this analysis gives 26 (< 6.4) signal (background) events in one year.

Rare semileptonic B decays with FCNC have also been studied with the CMS detector configuration. The channels considered are (a) $B_d \rightarrow K^* (\rightarrow K\pi) \mu^+ \mu^-$; (b) $B_s \rightarrow \phi (\rightarrow KK) \mu^+ \mu^-$; (c) $B_d \rightarrow \rho (\rightarrow \pi\pi) \mu^+ \mu^-$. Careful studies indicate that signals can be seen in all these 3 channels. One can achieve reasonable good statistics (4200, 1180 and 350 events respectively in the three channels) with signal to background ratio $\sim 9, 14$ and 1 for K^* , ϕ and ρ channels respectively.

7 Summary

The B-Physics programme with CMS at LHC will be exciting and it will start from the very beginning of data taking. The accuracy of $\sin 2\beta$ measurements from B-factories will be improved from studies of B_d decays to $J/\psi K_s$ final state. There is a rich programme with B_s decays which can probe physics beyond the Standard Model. Several rare decays of B have been examined. These will allow to check several SUSY-extensions of the Standard Model. Rare decay studies can be pursued even during the high luminosity phase of LHC.

Acknowledgements

We acknowledge with appreciation Y. Rozen and P. Schlein for their support and hospitality in the Beauty 2000 conference. We would like to thank Y. Lemoigne, D. Denegri, A. Caner and A. Nikitenko for many instructive discussions.

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