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CMS performance for CP Violation measurements

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Abstract

Recent set of structure functions, branching ratios and the current understanding of detector performance lead to a new evaluation of the CP reach of CMS. Compared to previous analysis, expected numbers of fully reconstructed and μ tagged B events are smaller, but are partly recovered thanks to progress on low p_T electron identification based upon the high-resolution and fine granular electromagnetic calorimeter. This allow to use electrons for tagging purpose as well as for $J/\psi \rightarrow e^+ e^-$ reconstruction.

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Figure 1 : A 3D view of the CMS detector.

2 The CMS detector

In CMS a uniform magnetic field of 4 T is produced by a superconducting solenoid of 13 m length and 6 m diameter. The inner tracker, electromagnetic (ECAL) and hadron (HCAL) calorimeters are located inside the coil. The magnetic flux is returned via a 1.8 m thick iron yoke which is instrumented with muon stations. A three dimensional view of the CMS detector is shown in Fig.1.

The inner tracker consists of three parts: silicon pixels (two layers located at mean radii of 7.7 and 11.7 cm for barrel, and three for endcap) are closest to the beam pipe, silicon microstrips are located behind the pixels and microstrip gas chambers represent the external layers. On average 12 hits per track are provided and half of the measurements have stereo information. The material budget of the tracker varies from 20% to 40% of the radiation length (X_0) depending on polar angle.

For tracks not associated to the primary vertex the momentum resolution in the entire rapidity range $|\eta| \leq 2.4$ and up to $p_T \sim 10$ GeV is better than 1%. The expected mass resolutions for $K_S^0(\rightarrow \pi^+ \pi^-)$, $J/\psi(\rightarrow \mu^+ \mu^-)$ and $B_d^0(\rightarrow \pi^+ \pi^-)$ are 8.6, 16 and 27 MeV, respectively. In the transverse plane the impact parameter resolution ranges from 100 μm to 30 μm for values of p_T from 2 GeV to 10 GeV. The proper time resolution, $\sigma_{t/\tau}$ (t in units of B_d^0 lifetime τ), obtained from detailed simulations is between 7% and 10% depending on the particular channel. Details of the tracker performance can be found in ref. [5].

Figure 2: Layout of the barrel and endcap PbWO_4 electromagnetic calorimeter.

The CMS ECAL is shown in Fig.2; it is made of $\sim 110\,000$ PbWO_4 crystals. The granularity is $\Delta\eta \times \Delta\phi = 0.0145 \times 0.0145$ in the barrel region ($|\eta| < 1.56$) and varies from 0.022×0.022 to 0.043×0.043 in the endcap region ($|\eta| < 2.6$), depending on η . In front of the endcap ECAL a preshower (SF) is placed; it consists of two planes of silicon strip detectors interleaved with lead planes of $2\,X_0$ and $1\,X_0$, respectively. This detector is primarily designed to measure impact points of photons, but also helps for electron/hadron separation. At high luminosity, a preshower (SB) will be added to the barrel covering the region $|\eta| < 1.1$.

The expected ECAL energy resolution in the barrel is shown in Fig.3, where a stands for the stochastic term, b for the constant term and c for the energy equivalent of noise which dominates at these low energies. Beam test data show, that $a = 5\%$, $b = 0.5\%$ and $c = 0.2$ can be easily achieved with the current design of the CMS ECAL. In our analysis we conservatively assume the values quoted above. The presence of the preshower in front of the endcap ECAL leads to a degradation of the energy resolution by a factor of 1.5 to 2 depending on incident energy.

The hadron calorimeter consists of copper/scintillator sandwiches. The lateral granularity is $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ and matches the one of the ECAL. The energy resolution is expected to be: $\sigma/E = 0.65/\sqrt{E} \oplus 0.06$.

Muons in CMS are measured in the inner tracker and identified and measured in four identical muon stations that cover the rapidity range of $|\eta| < 2.4$. In front of the outermost station the absorber thickness is about 20 nuclear interaction length so that only muons can reach it. Each muon station consists of several planes of drift chambers (barrel) or cathode strip chambers (endcap) designed to give a muon momentum vector with $\sim 100\,\mu\text{m}$ precision in position and better than 1 mrad in direction. Muon stations also include resistive plate chambers which are dedicated to the first-level trigger.

Due to the huge event rate at the LHC, the main issue is to trigger on $b\bar{b}$ events. CMS considers three low- p_T lepton triggers at the first-level [6]:

- an inclusive single muon trigger which can be kept at an acceptable rate ($< 10\,\text{kHz}$) for $p_T^\mu > 6.5\,\text{GeV}$ in $|\eta^\mu| < 2.4$;
- a dimuon trigger which allows to lower the p_T threshold depending on rapidity. The optimal solution is: $p_T^\mu > 4.5, 3.6$ and $2.6\,\text{GeV}$ for $|\eta^\mu| < 1.5, 2.0$ and 2.4 , respectively;
- a single electron trigger.

In the latter case a dedicated (fine grain) trigger algorithm has been studied in the barrel ECAL which allows to keep

Figure 3: Expected energy resolution in barrel ECAL ($\oplus$ denotes a quadratic sum).

Figure 4: QCD jet trigger rate for different algorithms as function of transverse ECAL energy.

the high trigger rates from QCD background at an acceptable level. The corresponding lowest possible threshold for the transverse energy E_T is ~ 10 GeV as illustrated in Fig.4.

3 Low p_T electron finding

The goal of the low p_T electron finding algorithm is to show that by off-line analysis one can efficiently recognize low $p_T \sim 2$ GeV electrons with a good purity, even if CMS is not optimized for it.

The following procedure is adopted. First, tracks are reconstructed using the Kalman filtering method; at least 6 measured points and $\chi^2/NDF < 6$ are required. All the ECAL crystals hit by tracks are determined. Then, around these crystals, the measured energy, $E(5 \times 7)$, is summed in a $\Delta\eta \times \Delta\phi = 5 \times 7$ array of crystals to form a cluster. Only one charged particle is allowed to point to the cluster. At this step, about 20% of electrons are lost due to bremsstrahlung in the material in front of the ECAL.

Figure 5: Energy deposited in the ECAL by electrons (top) and hadrons (bottom).

Due to the fine granularity of the CMS ECAL and a small Molière radius of PbWO_4 crystals, an electron deposits most of its energy in a few crystals, as illustrated in Fig.5. To exploit this local isolation of the electromagnetic shower, we require, in barrel region, that three 'hottest' crystals contain more than 70% of the cluster energy. In endcap region, the presence of the preshower detector degrades the local isolation of the shower and therefore the above quoted cut value is relaxed down to 55%. The energy deposited in silicon planes of the preshower detector must exceed 3 MeV and is used to correct for the energy lost in the lead. We require then that there be no energy deposit in the HCAL towers behind the cluster of the electron candidate. Finally, the cluster energy $E(5 \times 7)$ should match the momentum p of the particle reconstructed in the tracker: $0.85 < E/p < 1.15$ (1.35) for the barrel (endcap), see Fig.6. This is the most powerful tool: rejecting $\sim 95\%$ of the hadrons, more than 90% of the electrons are kept. The remaining background comes from hadrons which deposit all their energy in ECAL or are accompanied by photons.

For tracks with $p_T > 2.5$ GeV, this algorithm provides a hadron rejection factor of more than 400 with an electron finding efficiency of $\sim 60\%$ [7]. Fig.7 shows the fraction of wrong tags, $W = N_{\text{wrong tags}} / (N_{\text{wrong tags}} + N_{\text{good tags}})$, as function of electron transverse momentum, p_T^e . The hadron contamination is reduced to a few percent level and the dominant sources of mistags are $b \rightarrow c \rightarrow e$ cascade decays.

Figure 6: E/p ratio for electrons (full line) and hadrons (dashed line).

Figure 7: Fraction of wrong tags as function of p_T^e . The curve corresponds to an exponential fit.

4 CP Violation measurement

To estimate the angles of the unitarity triangle, we compute the time-integrated asymmetry by measuring the number $N^\pm$ of events with negatively and positively charged leptons coming from the associated B -hadron:

$$A = \frac{N^- - N^+}{N^- + N^+} = A_0 + D_{int} \times D \times \sin 2\phi_i \quad (1)$$

where A_0 reflects the $B^0/\bar{B}^0$ production asymmetry in pp collisions and a possible charge asymmetry of the apparatus; $D_{int} = [\sin(x_d \frac{t_0}{\tau}) + x_d \cos(x_d \frac{t_0}{\tau})]/(1 + x_d^2)$ is the time integration factor between $[t_0; \infty]$; $D = D_t \times D_m \times D_{S/B}$ is the overall dilution factor; $D_t = 1 - 2 \times W$ is the dilution due to wrong tags; $D_m = 0.75$ the dilution due to mixing and $D_{S/B} = N_S/(N_S + N_B)$ the dilution due to admixture of N_B background events to N_S signal events. An angle $\phi_i = \alpha, \beta, \gamma$ of the unitarity triangle can be measured with the statistical error:

$$\delta(\sin 2\phi_i) = \frac{\sqrt{N_S + N_B}}{D_{int} \times D_t \times D_m \times N_S} \quad (2)$$

In our calculations we assume a total $b\bar{b}$ production cross-section of $500 \mu\text{b}$ at $\sqrt{s} = 14 \text{ TeV}$. The integrated luminosity is $L_{int} = 10^4 \text{ pb}^{-1}$. Gluon-fusion and gluon-splitting events are generated with PYTHIA 5.7 [8] using CTEQ2L structure functions [4]. We neglect the penguin diagram contribution, though this might not be the case for $B_d^0 \rightarrow \pi^+ \pi^-$ decay.

4.1 The $B_d^0 \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) K_S^0$ channel

The $B_d^0 \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) K_S^0(\rightarrow \pi^+ \pi^-)$ decay channel is the most suited to measure the angle β of the unitarity triangle. An extra lepton, muon or electron, is required in the event to tag the flavor of the associated B -hadron.

Events are selected by the two muon first-level trigger. Pions from K_S^0 are required to have $p_T^\pi > 0.7 \text{ GeV}$ in $|\eta^\pi| < 2.4$; the K_S^0 decay vertex has to be within 2 to 40 cm from the primary vertex in the transverse plane. The B_d^0 signal is formed after J/ψ and K_S^0 candidates have been selected in $\pm 2\sigma$ mass window.

Figure 8: $\mu^+ \mu^- \pi^+ \pi^-$ invariant mass spectrum with J/ψ and K_S^0 mass constraints. The dashed histogram corresponds to background events.

In the $2\mu + e$ sample, the tagging electron is identified by the low p_T electron finding algorithm (section 3) imposing $p_T > 5 \text{ GeV}$ and $|\eta| < 2.6$. For the 3μ final state the third muon is required to reach at least the first muon station. At least one combination of two muons has to be consistent with the J/ψ mass. The tagging (third) muon is required to have $p_T > 5 \text{ GeV}$ within $|\eta| < 2.4$. Fig.8 shows the reconstructed B_d^0 mass spectrum when J/ψ and K_S^0 masses

are constrained to their nominal values. In a $\pm 2\sigma_B$ mass window the number of signal events is 3000 with a signal to background ratio of ~ 9 . The background is dominated by inclusive $B \rightarrow J/\psi$'s combined with two hadrons fulfilling the K_S^0 selection criteria.

4.2 The $B_d^0 \rightarrow J/\psi(\rightarrow e^+e^-)K_S^0$ channel

To study the $B_d^0 \rightarrow J/\psi(\rightarrow e^+e^-)K_S^0(\rightarrow \pi^+\pi^-)$ decay channel we use the trigger provided by the decay into a muon of the associated B -hadron in the event. Pions from K_S^0 are selected in the same way as in section 4.1. Electrons from J/ψ have to pass the electron finding algorithm (section 3) and satisfy $\Delta R^{ee} = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 1$.

The e^+e^- invariant mass spectrum is shown in Fig.9a and Fig.9b, for J/ψ reconstructed by the ECAL (using the azimuthal and polar angles measured by the tracker) and the tracker, respectively. There is a long tail forwards lower J/ψ masses in Fig.9b. This is due to radiated photons in the tracker material which can partly be recovered in the ECAL using a dedicated algorithm [9]. The result is shown in Fig.9a, where the e^+e^- invariant mass is reconstructed from the energy deposited in ECAL. Finally, even if the mass resolution is inferior to that of Fig.9b, we find the same signal to background ratio for $\sim 10\%$ more signal events. The background predominantly comes from two real electrons from $b \rightarrow e$ or $b \rightarrow c \rightarrow e$ decays, or from combinations of a hadron and a real electron.

The B_d^0 signal is obtained from combining a K_S^0 with a J/ψ candidate in the mass window $[2.8(2.6) 3.4(3.15) \text{ GeV}]$ when reconstruction is done with the ECAL (tracker). The result are shown in Fig.10a and Fig.10b. Even if the signal to background ratio is half times smaller in former case, the number of signal events in a $\pm 2\sigma_B$ mass window is estimated to be $\sim 20\%$ bigger corresponding to 1000 events for $L_{int} = 10^4 \text{ pb}^{-1}$ integrated luminosity. Half of the background comes from combinations of fake J/ψ and real K_S^0 while the remainder comes from inclusive $B \rightarrow J/\psi$ decays combined with any two tracks passing the K_S^0 selection criteria.

Figure 9: e^+e^- invariant mass spectrum when J/ψ is reconstructed by: a) the ECAL and b) the tracker. The dotted histogram corresponds to signal and the dashed line fits background events.

When combining the results obtained in all $B_d^0 \rightarrow J/\psi K_S^0$ channels for a time-integrated analysis, the sensitivity to the angle β is estimated to be $\delta(\sin 2\beta) = 0.057^{+0.018}_{-0.012}$. This value is obtained with an optimal proper time cut, $t/\tau > 0.5$, for B_d^0 decays using the J/ψ decay vertex. The systematic error includes uncertainties due to the $b\bar{b}$ production cross-section, b -quark fragmentation, the overall dilution factor, as well as the selection procedure. Results for measurements of $\sin 2\beta$ are summarized in table 1 [10].

Figure 10: $e^+e^-\pi^+\pi^-$ invariant mass spectrum with J/ψ and K_S^0 mass constraints, when $J/\psi \rightarrow e^+e^-$ is reconstructed by: a) the ECAL and b) the tracker. The dashed histogram corresponds to background events.

Table 1: Summary on $\sin 2\beta$ measurement

$J/\psi \rightarrow$	μ^{tag}		e^{tag}	$\mu^{tag} \oplus e^{tag}$
	$\mu^+\mu^-$	e^+e^-	$\mu^+\mu^-$	
N_S	3000	1000	1300	5300
N_B	330	430	140	900
D	0.45	0.37	0.44	
T-int.	0.074	0.14	0.12	$0.057^{+0.018}_{-0.012}$
T-dep.	0.069	0.14	0.11	$0.053^{+0.017}_{-0.012}$

4.3 The $B^{**} \rightarrow B_d^0 (\rightarrow J/\psi K_S^0) \pi$ channel

In ref. [11] it was proposed to tag the B 's via a nearby charged pion in phase-space. Four orbitally excited B^{**} states are expected, and recently a resonance structure below 5.8 GeV has been observed at LEP [12]. We assume $B(\bar{b} \rightarrow B^{**+}) \times B(B^{**+} \rightarrow B_d^0 \pi^+) = 0.12 \times 2/3 = 0.08$, and we assign a mass (width) of 5.6 GeV (60 MeV) and 5.7 GeV (20 MeV) to the lightest and heaviest B^{**} states, respectively.

The selection procedure of $B_d^0 \rightarrow J/\psi (\rightarrow \mu^+\mu^-) K_S^0 (\rightarrow \pi^+\pi^-)$ signal events is described in section 4.1. The invariant mass of the B_d^0 and a nearby charged hadron with $p_T > 1.5$ GeV and $|\eta| < 2.4$ is required to be in the mass range $5.5 \text{ GeV} < M_{B\pi} < 5.8 \text{ GeV}$. An event is kept if only one combination satisfies these requirements. For $L_{int} = 10^4 \text{ pb}^{-1}$ integrated luminosity, ~ 3600 fully reconstructed B^{**} events are expected [10]. We obtain $D_t = 0.47$ and $D = 0.42$ giving a statistical error $\delta(\sin 2\beta) = 0.071$. Large uncertainties are associated with this estimate as B^{**} states are not yet well established. Therefore we do not combine this result with the one obtained using lepton tags.

4.4 The $B_d^0 \rightarrow \pi^+ \pi^-$ channel

The decay $B_d^0 \rightarrow \pi^+ \pi^-$ is one of the most promising channel to measure the angle α of the unitarity triangle. Recently, CLEO measured the sum of the two branching ratios $B(B_d^0 \rightarrow \pi\pi, K\pi) = 1.8 \times 10^{-5}$ [13]. We assume the following branching ratios for the B-hadron two body decays: 0.9×10^{-5} for $B_d^0 \rightarrow \pi\pi$, $B_d^0 \rightarrow K\pi$, $B_s^0 \rightarrow KK$, $B_s^0 \rightarrow K\pi$; 3×10^{-5} for $\Lambda_b \rightarrow p\pi$.

Figure 11: $B_d^0 \rightarrow \pi^+ \pi^-$ signal with 2-body and combinatorial backgrounds included. The dashed histogram corresponds to the case of particle identification.

The trigger is provided by the semileptonic decay of the associated B -hadron, where the tagging muon (electron) is required to have $p_T > 6.5$ (10) GeV in $|\eta| < 2.4$ (1.5). The $B_d^0 \rightarrow \pi^+ \pi^-$ candidate is then selected in the following way [10]:

- two opposite-charge hadrons, with $p_T > 3.5$ GeV (> 5 GeV in electron tag sample) within tracker acceptance and with $\Delta R^{\pi\pi} < 1.6$ (< 1 in electron tag sample) to which we assign the pion mass,
- a transverse impact parameter significance $\sigma_{IP} = |IP|/\sigma > 2$ for each pion and a B_d^0 decay proper time $t/\tau > 0.5$,
- a good matching between the B_d^0 flight path (primary-secondary vertex) and the reconstructed B_d^0 momentum in transverse plane,
- a good isolation for the two pions.

The $\pi^+ \pi^-$ invariant mass distribution for the muon tag channel including all backgrounds is shown in Fig.11. In a mass window $-1.5\sigma_B < M_{\pi\pi} < 2\sigma_B$ around the peak the number of signal events is about 3000 with a signal to background ratio of ~ 1 . More than 90% of the background comes from two-body decays of B -hadrons.

The results are summarized in table 2. The sensitivity to the angle α , when combining electron and muon samples in a time-integrated analysis, is estimated to be $\delta(\sin 2\alpha) = 0.067^{+0.020}_{-0.015}$. Systematic errors include the uncertainties mentioned previously.

4.5 Time-dependent asymmetry

A better sensitivity to the angles of the unitarity triangle can be achieved by measuring the time-dependent asymmetry, A :

$$A \propto D \times \eta_{CP} \times \sin 2\phi_i \times \sin x_d t / \tau, \quad (3)$$

Table 2: Summary on $\sin 2\alpha$ measurement

	μ^{tag}	e^{tag}	$\mu^{tag} \oplus e^{tag}$
N_S	3070	330	3400
N_B	3000	300	3300
D	0.27	0.31	
Time-integrated	0.071	0.19	$0.067^{+0.020}_{-0.015}$
Time-dependent	0.062	0.17	$0.060^{+0.018}_{-0.014}$

where η_{CP} is the CP-parity of the final state. As an example, we consider the muon tag samples of $B_d^0 \rightarrow \pi^+ \pi^-$ and $B_d^0 \rightarrow J/\psi K_S^0$ channels selected by the procedure adopted for the time-integrated analysis. It is assumed, that the time distribution of background events is exponential and identical to the one of B_d^0 . Fig.12a shows the expected asymmetry for $\sin 2\alpha = 0.4$. The statistical error from the fit is $\delta(\sin 2\alpha) = 0.062$. The analogous asymmetry in the $B_d^0 \rightarrow J/\psi K_S^0$ channel is shown in Fig.12b and $\delta(\sin 2\beta) = 0.069$.

Figure 12: Time-dependent asymmetry in: a) $B_d^0 \rightarrow \pi^+ \pi^-$ and b) $B_d^0 \rightarrow J/\psi K_S^0$ decays.

5 Conclusions

The CMS performance for CP violation measurements is reevaluated using a recent set of structure functions, branching ratios and the current understanding of detector performance. In one year of LHC runs at low luminosity a sensitivity to $\sin 2\alpha$ of ~ 0.06 and $\sin 2\beta$ of ~ 0.05 can be achieved. These results are obtained with single lepton and dimuon first-level triggers and include the possibility to identify low p_T electrons.

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