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A FEASIBILITY STUDY OF MEASURING CP-VIOLATION IN B-DECAYS WITH A pp COLLIDER EXPERIMENT

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The feasibility of measuring CP-violation in B-meson systems at the Large Hadron Collider with a mainstream collider experiment has been studied. The decay channel $B_d^0 \rightarrow \psi K_S^0$ was investigated in detail by simulating the acceptance and resolution of an experiment proposed to be built for LHC. Compared with dedicated b -physics experiments planned for LHC and other accelerators, the sensitivity of a general purpose detector in measuring CP-violation in ψK_S^0 final states was found to be similar.

1. Introduction

The aim of this paper is to study the sensitivity of a general purpose detector, operating at the Large Hadron Collider (LHC), for measuring CP-violation in B-meson decays. Several dedicated b -physics experiments have been proposed for the LHC, including a small angle collider experiment [1], a fixed target experiment [2] and a gas-jet target experiment [3]. The b -physics potential of a big multipurpose LHC experiment, however, has not been investigated so far, and b -identification has been considered interesting only as a tool for tagging top quarks and possibly Higgs bosons. Preliminary studies for b -physics in the central production region in pp-collisions have been made for SSC [4]. Extensive simulations in view of measuring CP-violation with an asymmetric e^+e^- B-factory have been reported in [5].

The decay mode $B_d^0 \rightarrow \psi K_S^0$, which is expected to be the B-meson channel most sensitive to CP-violation, was used as a benchmark. By using a detector simulation following the ATLAS Letter of Intent [6], the achievable statistics was estimated, taking into account the relevant background channels and several sources of dilution of the signal. Dilution effects turn out to be less severe than in dedicated b -experiments due to different trigger requirements. Small signal dilution, together with a high $b\bar{b}$ production rate and a good tracking performance of the proposed collider detector, were found to result in a sensitivity to CP-violation similar to dedicated b -experiments.

2. CP Violation in Neutral B-meson systems

In the three generation Standard Model, CP-violation originates from the single complex phase of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Experimentally, CP-violating

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effects have been observed only in neutral kaon systems. The origin of the observed CP-violation, however, has not been established yet.

B-mesons offer a direct possibility to measure whether CP-violation is due to the CKM-matrix. Given the three generations, the unitarity constraint implies triangle relations among the matrix elements, for example

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0. \quad (1)$$

Since matrix elements $V_{ud} \simeq 1$, $V_{tb} \simeq 1$, the relation becomes

$$V_{ub}^* + V_{cb}^* V_{cd} + V_{td} = 0. \quad (2)$$

This equation can be represented as a triangle in the complex plane, see Fig. 1. The equation can be verified by overconstraining the triangle, i.e. by measuring its three angles. The presence of more than three quark generations, for example, would be demonstrated if the sum of the angles were not 180° , since Eq. 1 would have more than three terms. On the other hand, if measurements showed that all the angles were either zero or 180° , this would mean that all the CKM matrix elements were real and the CP-violation would have to originate from other sources than from the complex phase of the CKM-matrix.

Neutral B-meson decays in which both B^0 and $\bar{B}^0$ decay into the same final state, which is a CP-eigenstate, provide a theoretically well understood signature. The exponential decay rate of the B-meson is modulated by the $B^0 - \bar{B}^0$ mixing in such a way that the oscillation term is multiplied by a factor related to the relevant angle in the unitarity triangle. This factor is of different sign for B^0 and $\bar{B}^0$, thus producing a measurable asymmetry in the production rates.

The three angles, α , β and γ of the unitarity triangle, can be measured for example from neutral B-decays $B_d^0 \rightarrow \pi^+ \pi^-$, $B_d^0 \rightarrow \psi K_S^0$, $B_s^0 \rightarrow \rho K_S^0$, respectively. Current constraints on the angles come from measurements of $|V_{ub}/V_{cb}|$, CP-violation in $K^0 - \bar{K}^0$ mixing, and $B_d^0 - \bar{B}_d^0$ mixing. For top masses between 90 and 200 GeV/ c^2 , the allowed range for the angle β is estimated in Ref. [7] to be

$$0.08 \leq \sin 2\beta \leq 1,$$

while for $\sin 2\alpha$ and $\sin 2\gamma$ all values between -1 and 1 are allowed.

3. The Decay $B_d^0 \rightarrow \psi K_S^0$

To investigate the sensitivity of a collider experiment to CP-violation, the decay channel $B_d^0 \rightarrow \psi K_S^0$ was studied. The signal is experimentally the cleanest one among the neutral B-meson decays involving CP-violation. Furthermore, with this channel, one can measure the β angle, for which the present experimental limits are tightest.

The time-dependent decay rates of B_d^0 and $\bar{B}_d^0$ are

$$\begin{aligned}
N(B_d^0(t) \rightarrow \psi K_S^0) &\propto \exp^{-\Gamma t} (1 - \sin 2\beta \sin \Delta m t) \\
N(\bar{B}_d^0(t) \rightarrow \psi K_S^0) &\propto \exp^{-\Gamma t} (1 + \sin 2\beta \sin \Delta m t)
\end{aligned} \tag{3}$$

where $\Gamma = 1/\tau$ is the average of the widths Γ_1 and Γ_2 of the B-meson mass eigenstates, and Δm is the mass difference of the eigenstates. Experimentally, $x = \Delta m/\Gamma \simeq 0.71 \pm 0.11$ [8].

Measurement of the CP-violation parameter $\sin 2\beta$ can be performed in two ways. If secondary vertex reconstruction in B-decays is feasible, then one can measure directly the proper time of the B-decay from the secondary vertex of the ψ -decay, and look for deviations from a pure exponential decay. CP-violation should reveal itself as a deviation from the exponential, which is of different sign for B_d^0 and $\bar{B}_d^0$. The sensitivity of the measurement is dictated by the resolution which can be obtained in fitting the proper time distributions.

A more straightforward method is to study the asymmetry, when integrating over all decay times. From Eq. 3, one obtains a time-integrated asymmetry

$$\begin{aligned}
A &= \frac{N(B_d^0 \rightarrow \psi K_S^0) - N(\bar{B}_d^0 \rightarrow \psi K_S^0)}{N(B_d^0 \rightarrow \psi K_S^0) + N(\bar{B}_d^0 \rightarrow \psi K_S^0)} \\
&= x/(1 + x^2) \times \sin 2\beta.
\end{aligned} \tag{4}$$

The factor multiplying the $\sin 2\beta$ comes from the time-integration and is about 0.5.

The identity of the B-meson is defined by requiring a semileptonic decay of the other b -quark in the event. Charged kaons could also be used for this purpose, if particle identification were feasible. B_d^0 and $\bar{B}_d^0$ mesons are distinguished by the charge of the lepton. Wrong assignments, ‘tags’, are caused by cascade decays of the b , additional c - and b -quark pairs created in the parton shower, misidentified leptons, and $B^0 - \bar{B}^0$ oscillations. If the total dilution factor is defined as

$$D' = \frac{N(\text{correct tags}) - N(\text{wrong tags})}{N(\text{correct tags}) + N(\text{wrong tags})}, \tag{5}$$

then the observed asymmetry is

$$\begin{aligned}
A^{obs} &= \frac{N_{rec}(\psi K_S^0(+)) - N_{rec}(\psi K_S^0(-))}{N_{rec}(\psi K_S^0(+)) + N_{rec}(\psi K_S^0(-))} \\
&= D' \times x/(1 + x^2) \times \sin 2\beta.
\end{aligned} \tag{6}$$

The expected error on $\sin 2\beta$ is finally

$$\begin{aligned}
\delta(\sin 2\beta) &= \left[\left(\frac{\sqrt{1 - (D' \times x/(1+x^2) \times \sin 2\beta)^2}}{D' \times x/(1+x^2) \times \sqrt{N_{rec}}} \right)^2 \right. \\
&\quad + (\sin 2\beta \times \Delta D'/D')^2 \\
&\quad + \left. \left(\sin 2\beta \times (x^2 - 1)/(x(x^2 + 1)) \times \Delta x \right)^2 \right]^{1/2} \\
&\simeq \frac{1}{D' \times x/(1+x^2) \times \sqrt{N_{rec}}}, \sin 2\beta \ll 1.
\end{aligned} \tag{7}$$

where $N_{rec} = N_{rec}(\psi K_S^0 \ell^+) + N_{rec}(\psi K_S^0 \ell^-)$.

3.1 Production rate

A proton-proton collider produces $b\bar{b}$ final states copiously. The total production cross section is estimated to be between 100 and 700 μb [9] for LHC operating at a center of mass energy of 16 TeV. This analytical calculation of the production cross section, based on Ref. [10], is sensitive to a number of parameters, including the b -quark mass, Λ_{QCD} , the gluon structure functions, and the contribution of higher order terms. The lowest order production channels for b -quark pairs are quark and gluon fusion. The higher order QCD reactions are expected to dominate the production cross section, but the ratio of the higher order production rate versus the lowest order rate is not well known and estimates are between 1 and 10. Different Monte Carlo programs give production cross sections in the same range. A recent experimental measurement on the $b\bar{b}$ production cross section at a center of mass energy of 1.8 TeV gave a result which is approximately 1.6 standard deviations above the theoretical calculation [11]. Among the events which are triggered with a high transverse momentum (p_T) lepton trigger, where p_T is defined with respect to the beam direction, $b\bar{b}$ events with the lepton coming from the primary b -decay are expected to dominate beyond a trigger threshold of about 5 GeV/c.

A general purpose collider detector, covering the central range in pseudorapidity, is well suited for b -physics. The $b\bar{b}$ events are collected effectively with a high p_T lepton trigger. Furthermore, the high p_T lepton giving the trigger signal in a $b\bar{b}$ event is most likely the lepton coming from the primary b -decay, because the transverse momentum threshold suppresses the fraction of leptons coming from cascade decays and hadron background. Pile-up effects and ambiguities of primary vertex position can be avoided by using data collected during a low luminosity operation of the machine. For LHC operating at a luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, the average number of collisions is roughly one per crossing of the beams, compared to about 20 at the highest design luminosity of $1.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

The branching ratio $\text{Br}(B_d^0 \rightarrow \psi K_S^0)$ is 3.3×10^{-4} [12], with a relative uncertainty of about 50%. The total branching fraction combining $\text{Br}(\bar{b} \rightarrow B_d^0)$, $\text{Br}(B_d^0 \rightarrow \psi K_S^0)$,

$\text{Br}(\psi \rightarrow \ell^+ \ell^-)$, $\text{Br}(K_S^0 \rightarrow \pi^+ \pi^-)$ is equal to 1.1×10^{-5} , where ℓ is either a muon or an electron.

Table 1 summarizes the $pp \rightarrow b\bar{b} \rightarrow \mu X$ cross sections and production rates for $b\bar{b} \rightarrow \mu^- B_d^0 \rightarrow \mu^- \psi K_S^0 \rightarrow \mu^- (\ell^+ \ell^- \pi^+ \pi^-)$ (including the charge conjugate process) for different thresholds on the transverse momentum of the triggering muon. Electrons from b -decay are not expected to be efficiently triggered on and are therefore not included in the expected rates. The trigger muon was required to be in the pseudorapidity range $|\eta^\mu| \leq 2$. The relative production rates with different trigger thresholds were taken from Ref. [13], scaling the rates down with a factor of two to normalize the total $b\bar{b}$ cross-section to roughly $300 \mu\text{b}^2$. The luminosity was assumed to be $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, corresponding to an integrated luminosity of 10^4 pb^{-1} per year.

Table 1. The cross-sections and production rates per year, with $|\eta^\mu| \leq 2$.

$$N_{\text{prod}} = N(\mu^- \ell^+ \ell^- \pi^+ \pi^-) + N(\mu^+ \ell^+ \ell^- \pi^+ \pi^-).$$

	$p_T^\mu \geq 6 \text{ GeV}/c$	$p_T^\mu \geq 12 \text{ GeV}/c$	$p_T^\mu \geq 20 \text{ GeV}/c$
$\sigma_{b\bar{b}\mu}$	$1.5 \cdot 10^6 \text{ pb}$	$3.5 \cdot 10^5 \text{ pb}$	$5.5 \cdot 10^4 \text{ pb}$
$N_{b\bar{b}\mu} \text{ per year}$	$1.5 \cdot 10^{10}$	$3.5 \cdot 10^9$	$5.5 \cdot 10^8$
$N_{\text{prod}} \text{ per year}$	165,000	38,500	6,000

3.2 Simulation of the signal

To estimate reconstruction efficiencies, $b\bar{b}$ -events with $\bar{b} \rightarrow B_d^0 \rightarrow \psi K_S^0 \rightarrow (\ell^+ \ell^- \pi^+ \pi^-)$, $b \rightarrow \mu^- X$, were generated with the PYTHIA Monte Carlo program. The nominal beam energy was 8 TeV. Subsequently, the events were passed through a detector simulation, parametrized in terms of angular acceptance, track finding efficiency, lepton identification efficiency and momentum resolution (see Appendix A for details). Events were accepted if the trigger muon had a p_T^μ larger than a certain threshold, and a pseudorapidity in the range ± 2 .

According to the simulation, with a trigger muon p_T threshold of 20 GeV/c, a mass resolution of $48 \text{ MeV}/c^2$ can be obtained for the B_d^0 meson in the pseudorapidity range of ± 2 . The simulated mass resolution for a K_S^0 is $3 \text{ MeV}/c^2$, and mass resolution for ψ is $37 \text{ MeV}/c^2$. The reconstructed mass distributions are shown in Fig. 2. Lowering the trigger threshold improves the mass resolution slightly, because the p_T resolution is better at lower momenta.

²The cross sections in [13] were calculated with the ISAJET Monte Carlo program [14]. The normalization was performed by comparing the cross-sections obtained from the PYTHIA Monte Carlo program [15] and ISAJET at muon p_T threshold of 6 GeV/c, assuming that the muon p_T spectra given by the two simulation programs extrapolate similarly to zero.

The reconstruction efficiencies were calculated by demanding that the events satisfied the following cuts: a) K_S^0 decay length in the transverse plane with respect to the beam axis greater than 1 and less than 30 cm, b) all four final state particles within the tracking volume, and correctly identified, c) transverse momentum of the K_S^0 greater than 1 GeV/c and transverse momentum of the ψ greater than 10 GeV/c, d) angle between the K_S^0 and ψ less than 45° , e) reconstructed K_S^0 and ψ mass within four standard deviations of the nominal values (± 12 and ± 148 MeV/c², respectively).

The reconstruction and trigger efficiencies for three different trigger thresholds are shown in Table 2, together with the numbers of reconstructed events per year in the decay channel $\mu^- B_d^0 \rightarrow \mu^- \psi K_S^0 \rightarrow \mu^- (\ell^+ \ell^- \pi^+ \pi^-)$ (including the charge conjugate process).

Table 2. Reconstruction and trigger efficiencies, and numbers of reconstructed events per year, with $|\eta^\mu| \leq 2$. $N_{rec} = N_{rec}(\mu^- \ell^+ \ell^- \pi^+ \pi^-) + N_{rec}(\mu^+ \ell^+ \ell^- \pi^+ \pi^-)$.

	$p_T^\mu \geq 6$ GeV/c	$p_T^\mu \geq 12$ GeV/c	$p_T^\mu \geq 20$ GeV/c
ϵ_{rec}	0.04	0.08	0.10
ϵ_{trig}	0.95	0.95	0.95
N_{rec}	6,270	2,930	570

The reconstruction efficiencies could be further optimized at trigger thresholds of 6 and 12 GeV/c for example by lowering the p_T cut for the ψ along with the trigger threshold, which could be allowed for if no muon identification were required. Enlargening the tracking device coverage would also help in improving the efficiency. Varying the coverage of the tracking volume in pseudorapidity between ± 1.5 and ± 2.5 , the reconstruction efficiencies were found to change by $\pm 20\%$.

3.3 Background

Background to the signal can be produced by other B-meson decays. B-meson decays with a true ψ and K_S^0 in the final state are $B_d^0 \rightarrow \psi K^{*0} \rightarrow \psi K_S^0 \pi^0$ and $B^+ \rightarrow \psi K^{*+} \rightarrow \psi K_S^0 \pi^+$.

The branching ratio of the decay $B_d^0 \rightarrow \psi K^{*0}$ is 1.3×10^{-3} , and the total branching ratio $\text{Br}(b \rightarrow (\ell^+ \ell^-)(\pi^+ \pi^-) \pi^0)$ is equal to 7.2×10^{-6} , about two thirds of the branching ratio of the signal. The branching ratio of the charged B-meson decay, $B^+ \rightarrow \psi K^{*+}$, is 1.4×10^{-3} , and the total branching ratio $\text{Br}(b \rightarrow (\ell^+ \ell^-)(\pi^+ \pi^-) \pi^+)$ is equal to 2.0×10^{-5} , about 1.8 times the branching ratio of the signal.

These background channels were generated and simulated in the same way as the signal, and the the same selection criteria were applied. The reconstruction efficiencies were found to be similar to the signal because of the genuine ψ and K_S^0 in the final state. These channels, however, involve five particles in the final state, and thus mass resolution is

crucial for separating the signal. The reconstructed (ψK_S^0)-mass distributions for the signal and background, after all the cuts, are shown in Fig. 3, assuming a trigger threshold of 20 GeV/c. The distributions are normalized to the number of accepted events per year at this trigger threshold. Lowering the trigger threshold improves the mass resolution, resulting in even better separation of the signal from the background.

If the additional pion could be reconstructed and correctly assigned to the B-meson decay vertex, the signal to background ratio could be further improved. This requires a hermetic detector and a good precision of secondary vertex reconstruction. For the charged B-meson decay mode this should be relatively easy, whereas it is doubtful whether a calorimetric measurement of the direction of the π^0 can provide good enough resolution.

The decay modes $B_d^0 \rightarrow \psi K^+ \pi^-$ (non-resonant) and $B_d^0 \rightarrow \psi K^{*0} \rightarrow \psi K^+ \pi^-$ (resonant) can also be a source of background, when misidentifying a K^+ as a π^+ produces a fake K_S^0 . The total branching ratio for the non-resonant decay $\text{Br}(b \rightarrow (\ell^+ \ell^-)(K^+ \pi^-))$ is equal to 4.9×10^{-5} , about 4.5 times the branching ratio of the signal. The branching ratio of the resonant decay mode is equal to 4.3×10^{-5} , about 3.9 times the branching ratio of the signal.

These channels are, however, effectively rejected by the cut on the minimum flight path of the K_S^0 , and the cut on the reconstructed K_S^0 mass. From the simulation it was found that after the selection cuts, the number of remaining background events from the non-resonant decay mode was about 0.5% compared to the number of signal events, and 1.2% from the resonant decay mode.

In Table 3, the signal to background ratios for the background channels considered above are given for the triggered events, for the events after all the cuts, and for the events in which the reconstructed B_d^0 mass is within four standard deviations of the nominal value ($\pm 192 \text{ MeV}/c^2$). Reconstruction and trigger efficiencies are included in the table as well. The background fraction is insensitive to variations in the trigger threshold, since the background considered here originates from other B-meson decay modes.

Events with b quarks as decay products, together with a trigger lepton, can result from $t\bar{t}$ events and gauge boson pair production. Secondary b 's do not change the signal to background ratio, since they decay similarly to primary b 's. They could, however, affect the dilution factor due to different correlations of the lepton charge and the B-meson.

The contribution from boson pair production is negligible. The production cross-sections are [16, 17]

$$\begin{aligned}\sigma(t\bar{t}) &\simeq 10 - 0.5 \text{ nb}, \quad m_t = 90 - 200 \text{ GeV}/c^2, \\ \sigma(W^+W^-) &\simeq 100 \text{ pb}, \\ \sigma(W^\pm Z^0) &\simeq 30 \text{ pb}, \\ \sigma(Z^0 Z^0) &\simeq 10 \text{ pb}.\end{aligned}$$

By requiring a triggering muon with a p_T of at least 20 GeV/c, the relative rate of top pair events versus $b\bar{b}$ events is about 0.01, for a top mass equal to 130 GeV/c² (the top-pair

Table 3. Signal to background ratios and reconstruction efficiencies for background from other B-meson decays. B-mass region refers to the mass range $M_B = (5279 \pm 192)$ MeV/ c^2 . Superscripts S and B signify signal and background, respectively.

	$\psi K^{*0} \rightarrow \psi K_S^0 \pi^0$	$\psi K^{*+} \rightarrow \psi K_S^0 \pi^+$	$\psi K^+ \pi^-$	$\psi K^{*0} \rightarrow \psi K^+ \pi^-$
N_{prod}^S/N_{prod}^B	1.5	0.55	0.22	0.25
ϵ_{rec}^B	0.10	0.10	0.0001	0.0003
ϵ_{trig}^B	0.95	0.95	0.95	0.95
N_{rec}^S/N_{rec}^B	1.5	0.55	190	81
N_{rec}^S/N_{rec}^B in B-mass region	21	11	190	81

cross-section with this trigger threshold was taken from Ref. [13]). These events contribute to the class of wrong tags, since the muon charge follows the charge of the top, and not the b . The contribution is 1% absolute increase of the number of events with a wrong tag. The fraction of wrong tag events from top decays, however, goes down if the trigger threshold is decreased, since the $b\bar{b}$ production rate increases more than the $t\bar{t}$ rate. At a trigger threshold of 12 GeV/ c the wrong tag contribution from top decays is 0.2%.

Background from accidental correlations of ψ and K_S^0 were shown to be small in dedicated b-experiments [2], and we assume the same in the present study.

3.4 Dilution effects

The reconstructed B-meson is defined to be B_d^0 or $\bar{B}_d^0$ according to the charge of the trigger muon, which is assumed to come from the semileptonic decay of the other b -quark in the event. Classification is diluted by muons with a wrong charge, produced by i) cascade decays of the b , ii) extra c - and b -quark pairs produced in the parton phase, iii) top decays, iv) hadron background (π , K-decays, punchthrough), and v) $B^0 - \bar{B}^0$ oscillations. The dilution is dominated by cascade decays, and oscillations.

If the fraction of wrong sign muons from sources other than $B^0 - \bar{B}^0$ oscillations is W , the effect of oscillations is to increase this to

$$\begin{aligned}
 W' &= f^+ \times W \\
 &+ f^0 \times (P(B_d^0 \rightarrow B_d^0) \times W + P(B_d^0 \rightarrow \bar{B}_d^0) \times (1 - W)) \\
 &+ f^s \times 0.5
 \end{aligned} \tag{8}$$

where f^+ is the fraction of trigger muons coming from decays of charged B-mesons or b -flavoured baryons, which do not oscillate, f^0 is the fraction of muons from B_d^0 mesons

and f^s is the fraction of muons from B_s^0 mesons. The relative fractions were assumed to be $f^+ = 0.5$, $f^0 = 0.4$ and $f^s = 0.1$. The oscillation probability for B_d^0 is

$$P(B_d^0 \rightarrow \bar{B}_d^0) = \frac{x^2}{2(1+x^2)} \simeq 0.17.$$

The B_s^0 is assumed to have full mixing,

$$P(B_s^0 \rightarrow \bar{B}_s^0) = 0.5.$$

Finally, the dilution factor D' (see Eq. 5) is $D' = 1 - 2 \times W'$.

When the oscillations were switched off in the simulation, the fraction of wrong sign muons was found to be 11% due to cascade decays and from multiple production of $b\bar{b}$ -pairs at a muon trigger p_T threshold of 20 GeV/ c (with a dominant contribution from cascade $b \rightarrow c \rightarrow \mu$ decays)³.

At a 20 GeV/ c threshold, hadron decays have no effect on the dilution factor. The total rate of hadron decays producing a muon trigger is 10^{-2} compared to b -decays at this threshold [18]. Since the ratio between the $b\bar{b}$ cross section and the total hadronic cross section is of the order of 10^{-2} , the probability to have a fake muon from a hadron decay in a $b\bar{b}$ -event is at the level of 10^{-4} . The fraction of fake muon triggers from hadron punchthrough is even lower than from hadron decays.

The total fraction W of wrong sign muons was thus found to be 0.12 from sources other than oscillations at a trigger p_T threshold of 20 GeV/ c , taking into account the increase of the total rate by 1% due to top-decays, which contribute to the wrong tag class. Using Eq. 8 to include the effect of oscillations, the total fraction of wrong sign muons is then $W' = 0.21$, which corresponds to dilution factor D' equal to 0.58.

With a trigger threshold of 12 GeV/ c , the fraction of wrong sign muons from cascade decays and from extra b -quark pairs was found to be 11%. The fraction of muon triggers coming from hadron decays in $b\bar{b}$ -events at 12 GeV/ c threshold is 10^{-3} . The contribution of top-decays is below 1%. Hence, the total fraction of wrong sign muons is $W' = 0.20$, giving a dilution factor D' equal to 0.60.

Lowering the trigger threshold further to 6 GeV/ c , which can be considered to present the lower limit for a muon trigger due to the amount of material in a big multipurpose detector, the fraction of wrong sign muons was found to be 15% from cascade decays and extra quark pairs. The fake muon background from hadron decays is 1%, contributing equally to the right and wrong sign muon classes. This gives a dilution factor equal to 0.54.

³The fraction of wrong sign muons was estimated with the PYTHIA Monte Carlo program, with lowest order processes included to generate the $b\bar{b}$ -events. Higher order processes might enhance the fraction of wrong sign muons coming from multiple heavy quark production.

3.5 Sensitivity on $\sin 2\beta$

The error on $\sin 2\beta$ is given by Eq. 7. With one year of running, with a tracking coverage of ± 2 in pseudorapidity, and a muon trigger with p_T greater than 6 GeV/c and $|\eta^\mu|$ less than 2, one can measure the value of $\sin 2\beta$ with an accuracy of ± 0.05 . With a trigger threshold of 12 GeV/c, the error on the $\sin 2\beta$ would be equal to ± 0.07 , and ± 0.15 at a trigger threshold of 20 GeV/c.

The estimated performance and sensitivity for measuring $\sin 2\beta$ are summarized in Table 4 for different trigger thresholds assuming a trigger acceptance of ± 2 in pseudorapidity. It was assumed that $\sin 2\beta \ll 1$ when calculating the errors. The final result includes the extra dilution factor coming from the time integration (see Eq. 7). The rates are scaled for one year of data taking, corresponding to an integrated luminosity of 10^7 pb^{-1} .

Table 4. Estimated sensitivity of measuring $\sin 2\beta$, for one year of data taking (10^7 s), with $|\eta^\mu| < 2$.

	$p_T^\mu > 6 \text{ GeV}/c$	$p_T^\mu > 12 \text{ GeV}/c$	$p_T^\mu > 20 \text{ GeV}/c$
N_{rec}	6,270	2,930	570
D'	0.54	0.60	0.58
$\delta(\sin 2\beta)$	± 0.05	± 0.07	± 0.15

The results in Table 4 were obtained by assuming the same signal selection criteria for the different trigger thresholds. By releasing the rather conservative p_T cut of the ψ , reconstruction efficiencies could be improved substantially. The lower limit for the p_T threshold is clearly very dependent on the details on the detector design, and further work is needed to optimize the reconstruction efficiencies.

For comparison, the sensitivities for other experiments, scaled for one year of data taking and using the same branching fraction for $B_d^0 \rightarrow \psi K_s^0 \rightarrow \ell^+ \ell^- \pi^+ \pi^-$ as what was assumed in this work, are: ± 0.02 for Collider B-experiment, ± 0.04 for LHB and Gas Jet Target experiment, and ± 0.13 for SLAC B-factory. The comparisons should be taken as indicative. Given the large uncertainties in the $b\bar{b}$ cross section in pp-collisions with a center of mass energy of 16 TeV, the numbers of reconstructed events in experiments taking data in the collider mode might vary with a factor of ± 3 , corresponding to variations in the estimated errors on $\sin 2\beta$ with a factor ranging from 0.6 to 1.7. Experiments operating in LHC at a fixed target mode (Gas Jet Target, LHB) collect events produced at center of mass energy of about 123 GeV, where the $b\bar{b}$ cross-section is estimated to be between 0.5 and 1 μb . Similarly, the estimation of the dilution factor in pp-experiments is dependent on the Monte Carlo program used due to uncertainties in the lepton p_T spectra originating from the different sources. Keeping these uncertainties in mind, the sensitivities of the different experiments at the future colliders are similar.

4. Conclusions

The decay mode $B_d^0 \rightarrow \psi K_S^0$ was used as a benchmark to study in a realistic way the sensitivity of a general purpose collider mode detector to measure CP-violation at LHC. The obtained results show the potential of such a detector in b -physics. The small fraction of wrong B -quantum number assignments, the large b -quark production cross-section and the good tracking performance of a collider detector, were found to result in a performance comparable to other experiments proposed for b -physics .

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Appendix A. Detector parametrization

The detector modelled in the simulation follows the ATLAS proposal, a general purpose pp collider detector with central solenoidal field for charged particle tracking, high resolution electromagnetic calorimetry for electron identification, and a toroid system for muon identification. The electron momentum measurement is taken from the tracking. The default acceptance of the tracking system is ± 2 in pseudorapidity, but studies were also performed with different acceptance ranges. p_t is the transverse momentum versus the beam direction, and $E_{\min}$ ($p_{\min}$) is the detection threshold.

Table A1. Detector parameters implemented into the simulation.

Tracking detectors	
acceptance (η)	± 2
minimum p_t (GeV/c)	0.4
$\Delta p_t/p_t$ at $\eta = 0$, $p_t = 1$ GeV/c	0.01
$\Delta p_t/p_t$ at $\eta = 2$, $p_t = 1$ GeV/c	0.03
$\Delta p_t/p_t$ at $\eta = 0$, $p_t = 100$ GeV/c	0.03
$\Delta p_t/p_t$ at $\eta = 2$, $p_t = 100$ GeV/c	0.02
track efficiency	0.95
Muon identification	
acceptance (η)	± 2
$p_{\min}$ (GeV/c)	5
efficiency	0.8
Electron identification	
acceptance (η)	± 2
$E_{\min}$ (GeV/c)	3
efficiency	0.8
Muon trigger	
efficiency with $ \eta^\mu < 2$, $p_t^\mu > 6$ GeV/c	0.95

Figure captions

Fig. 1. The unitarity triangle, showing the relations between the CKM-matrix elements and the definitions of the angles α , β and γ .

Fig. 2. Reconstructed mass for a) ψ , b) K_S^0 and c) B_d^0 , after the cuts on the signal. The trigger threshold was assumed to be 20 GeV/c.

Fig. 3. Reconstructed (ψK_S^0)-mass for a) signal (white region) and background from the decay mode $B^+ \rightarrow \psi K^{*+} \rightarrow \psi K_S^0 \pi^+$ (hatched region), and b) signal and background from the decay mode $B_d^0 \rightarrow \psi K^{*+0} \rightarrow \psi K_S^0 \pi^0$ (hatched region). The trigger threshold was assumed to be 20 GeV/c.

Figure 1

Figure 2

Figure 3