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Prospects for CP violation measurements with ATLAS and CMS

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Abstract

Very high LHC luminosity will result in $\sim 10^{13}$ b-particles produced per year allowing general purpose detectors ATLAS and CMS to contribute to the exploration of phenomena in B physics. A review of simulation studies made by ATLAS and CMS B-physics groups is given. The expected numbers of reconstructed events, sensitivities to CP violating parameters, the x_s measurements, and possibilities to observe very rare B-decays are discussed.

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[a)] on leave of absence from Institute of Experimental Physics, Warsaw University, Warsaw, Poland

Prospects for CP violation measurements with ATLAS and CMS

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Very high LHC luminosity will result in $\sim 10^{13}$ b-particles produced per year allowing general purpose detectors ATLAS and CMS to contribute to the exploration of phenomena in B physics. A review of simulation studies made by ATLAS and CMS B-physics groups is given. The expected numbers of reconstructed events, sensitivities to CP violating parameters, the x_s measurements, and possibilities to observe very rare B-decays are discussed.

1. INTRODUCTION

B-physics is regarded as a possible way to clarify in the near future the mechanism of CP violation. It offers a way for testing the description of electroweak interactions in the Standard Model. Unfortunately, clear signatures of CP violation are expected in relatively rare decays, and a special experimental effort is required to ensure the statistical significance. One way is to use dedicated e^+e^- B-factories. Another way is to use high luminosity hadronic machines. Both ways are followed. The BaBar and BELLE experiments at B-factories (PEP-II and KEKB) would acquire 10^7–10^8 low background $b\bar{b}$ events per year. Higher statistics (but with much higher background) are available for experiments at existing hadronic machines: $\sim 10^8$ $b\bar{b}$/year in HERA-B, up to $\sim 10^{11}$ $b\bar{b}$/year for Tevatron experiments (general purpose CDF/D0 and dedicated for B-physics BTEV).

The LHC proton-proton collider with centre of mass energy of 14 TeV and expected initial luminosity of 10^{33}cm^{-2}s^{-1} (one year corresponds to $\int L\,dt = 10^4$pb^{-1}) offers an unique way to explore CP violation effects. Since the predicted cross-section for a $b\bar{b}$ pair production is large (~ 0.5 mb) one should expect $5 \cdot 10^{12}$ $b\bar{b}$ events per year at designed initial luminosity, offering even to general purpose experiments - ATLAS and CMS - possibility to measure CP violation effects with significant accuracy. At LHC all kinds of b-particles will be produced so CP violation can be studied effectively not only with B_d mesons but also with B_s, which are not produced at $\Upsilon(4S)$ B-factories. With the large number of LHC b-events several rare B-decays with a very small branching ratio will be reachable, offering another interesting test of the Standard Model and a way to look for New Physics.

The results presented in this article are based on simulation studies made by the ATLAS and CMS B-physics groups for *The Workshop on Standard Model Physics (and more) at the LHC* published in [1] with later updates[2].

2. ATLAS AND CMS

2.1. An overview

ATLAS [3] and CMS [4] are general purpose LHC detectors. They are designed for the high luminosity mode of LHC operation to search for new particles and phenomena.

The ATLAS magnet system consists of air-core toroids in barrel and endcaps supplemented with a barrel solenoid providing 2 Tesla magnetic field for the inner tracking detector. The toroids are surrounded by muon chambers for muon identification and measurement ($|\eta| < 2.7$). The electromagnetic calorimeter is a sampling lead-liquid argon calorimeter with a 10% stochastic term. The hadronic calorimeter is a sampling calorimeter with the resolution of $\sigma/E \approx 50\%/\sqrt{E} \oplus 0.03$. Both calorimeters are outside the magnetic field.

The CMS collaboration chosen a solenoidal magnetic field formed by a large solenoid. The in-

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[2] The author's contribution to CMS B-physics studies can be found in [2].

ner tracker and calorimeters operate in the 4 Tesla magnetic field. The CMS electromagnetic calorimeter is a $\mathrm{PbWO_4}$ homogeneous calorimeter (stochastic term 2–5%) with a preshower. The sampling hadronic calorimeter has a resolution of $\sigma/E \approx 65\%/\sqrt{E} \oplus 0.05$. The CMS muon system ($|\eta| < 2.4$) consists of 4 muon stations positioned inside an iron return yoke (1.8 Tesla).

Although ATLAS and CMS are not optimised for B-physics where the reconstruction of low momenta ($\sim$ 1 GeV) particles is important, some of the features supporting B-physics studies were accommodated into the design. The most important aspects of detectors performance related to B-physics are given in the following subsections.

2.2. Triggering

The LHC bunch collision frequency will be 40 MHz. With the inelastic $p-p$ cross-section of 80 mb one may expect of the order of ten pp collisions in each bunch crossing for high luminosity mode and a few pp collisions at $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Thus triggering is a key issue for all the LHC studies, including low luminosity B-physics.

The first level triggers of ATLAS and CMS are partly programmable hard-wired systems operating on reduced granularity data from muon system and calorimeters. They will reduce the LHC event rate down to 50-100 kHz storing the output in readout memories. The higher level triggers of the LHC detectors consist of a set of CPUs where the full information from muon system, calorimeters (rate reduction down to 1 kHz) and finally inner tracking detectors will be accessible (they will reduce the event recording rate to 100 Hz).

The relatively soft spectrum of particles from decays of B mesons favours low p_T triggering. For this reason, it is extremely important to keep the level one thresholds as low as possible, still keeping the outgoing rate capable by level two. The base ATLAS trigger is a single muon trigger with a p_T threshold of 6 GeV. The CMS threshold for single muons is higher but CMS accepts also single electron trigger and general di-lepton ones. In the case of the most effective di-muon trigger the (η-dependent) p_T threshold is limited by the muon penetration length. Since that type of trigger appears to be very efficient the possibility of di-muon trigger is under study by ATLAS. All trigger types and thresholds used by CMS and ATLAS for B-physics studies (low luminosity) are listed in Table 1.

Table 1
Trigger types used for B-physics studies.

ATLAS	p_T *cut* [GeV/c]
one muon	6
di-lepton	under study
CMS	
one muon	7
di-muon	2–4
single electron	12
di-electron	5
electron $\oplus$ muon	5 $\oplus$ 2-4

2.3. Tracking

To collect the maximal number of events one has to push down the cuts on transverse momenta of final stable particles, resulting in a need for efficient reconstruction of low p_T (hadronic) tracks. The minimal p_T varies (it is channel and detector dependent) from a few hundreds MeV up to a few GeV. The low p_T track measurements needed for reconstruction of invariant masses and secondary vertexes rely on the Inner Trackers.

The CMS inner detector consists of 3 layers of Silicon Pixels (the minimal distance from the beam pipe is 4.3 cm) followed by layers of Silicon Microstrips. The ATLAS detector has also Silicon Pixels (down to 5 cm) and Silicon Strips, but in addition also the TRT (Transition Radiation Tracker) at larger radii. Due to the smaller magnetic field the ATLAS momentum resolution is worse. However the TRT allows e/π distinction and dE/dx based K/π separation (the latter one not very accurate, but used in $B \rightarrow \pi\pi\ KK$ likelihood studies.)

ATLAS and CMS measure accurately the impact parameter in the r-φ plane (see Fig. 1). The high p_T plateau for ATLAS and CMS transverse impact parameter resolution is about $10\ \mu$m. It is much worse for low p_T particles due to multiple scattering.

Another parameter related to B-physics studies is the proper time resolution, which is crucial especially for time-dependent analyses in the B_s-meson sys-

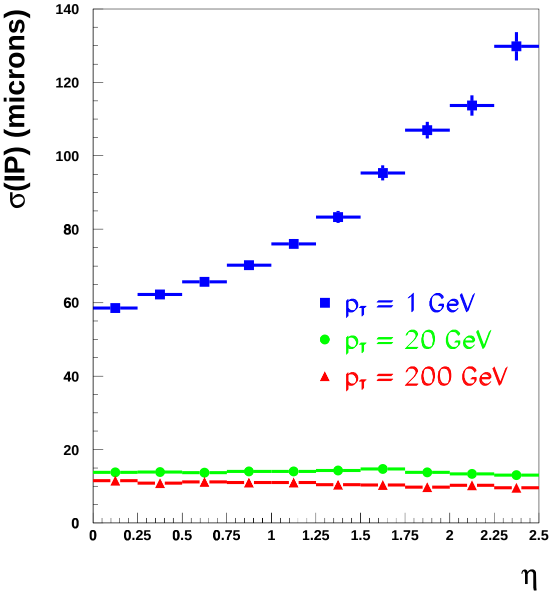

Figure 1. Resolution of the Impact Parameter (ATLAS) as a function of pseudorapidity. The transverse momenta values relevant for B-physics studies are $\sim$ 1 GeV.

tem. Both experiments will be able to reconstruct the proper decay time with a resolution of about 60–70 fs.

2.4. Tagging

To measure CP violation asymmetries, one has to count the number of produced B and $\bar{B}$ mesons decaying to the same CP eigenstate. The flavour of the initial B-meson has to be provided from elsewhere. This is the purpose of tagging. The quality of tagging can be expressed in terms of tagging efficiency ϵ (the fraction of events selected by a given technique) and asymmetry dilution. The dilution factor D_{tag} is defined as $D_{tag} = 1 - 2w$ where w is the fraction of wrong assignments of the flavour at production time of the B which decays in the channel of interest.

Since b quarks are produced in pairs one may tag the flavour of signal B by measuring the flavour of the associated b-particle. This class of tagging is called Opposite Side tagging. Another category is Same Side tagging where the flavour of signal B is determined by looking at signal B and particles in its neighbourhood.

Several tagging techniques were studied by ATLAS and CMS (see Table 2).

The *lepton tagging* method can be applied to events where an additional lepton is produced. This lepton is assumed to come from semileptonic decays of associated b-particle ($b \to l^-$, $\bar{b} \to l^+$). The most important fractions of mistaggings come from cascade decays ($b \to c \to l^+$; $\bar{b} \to \bar{c} \to l^-$) and mixing (if the associated b forms neutral B). The p_T threshold for a tagging lepton used by ATLAS is 5 GeV (the same for muons and electrons) while CMS uses a 2–5 GeV (η-dependent) cut for muons and 2.5 GeV cut for electrons. The lepton tagging is the purest one but has rather low efficiency due to the small $b \to l$ branching ratio ($\approx 10\%$).

The jet tagging techniques deduce the flavour of the signal B from the total charge of tracks belonging to the fragmentation of either the associated b (*opposite side jet tagging*) or signal b (*same side jet tagging*). The jet charge is a weighted average over the charges of tracks in a jet (in the same side tagging, the decay products of signal B are excluded from the sum). Jet tagging techniques are efficient but polluted.

In the B–π *correlation tagging* method (ATLAS) the flavour of signal B is determined from the charge of the hadron accompanying the signal B (exploring the correlation between them). A similar technique is used by CMS (B^{**} *tagging*) but with stronger requirements for the charged hadron (assumed to be a pion), which is expected to come from the B^{**}. The pion is combined with the B_d to give an invariant mass in the window 5.6–5.9 GeV. The mass window is wide because low p_T photons produced in B^{**} decays are not reconstructed.

3. SIMULATION

B-events were produced with the Monte-Carlo generator PYTHIA 5.7/JETSET 7.4 [5] under control of steering packages developed especially for the ATLAS and CMS b-physics groups. The CTEQ2L structure functions with Peterson fragmentation ($\epsilon_b = 0.007$) were used. Both gluon splitting and gluon fusion – the main $b\bar{b}$ production processes – were simu-

Table 2
Tagging methods studied by ATLAS and CMS and their quality ($B_d \to J/\psi K_S$ sample)

	ATLAS		CMS	
Method	*efficiency*	*dilution*	*efficiency*	*dilution*
μ tagging	0.025	0.52	0.034	0.44
e tagging	0.016	0.46	0.027	0.44
jet charge (OS)	–		0.70	0.18
B-π / B**	0.82	0.16	0.22	0.32
jet charge (SS)	0.62	0.23	0.50	0.23

lated explicitly by ATLAS and CMS.

The products of the simulation at the particle level were reconstructed with fast parametrisations of the detector response and passed to detailed, GEANT [6] based reconstruction packages (in some studies only a fast simulation based on detector parametrisations has been used). The detailed event reconstruction includes full pattern recognition in the tracking detectors, secondary vertex reconstruction and particle identification (ATLAS).

The events were normalised to the $b\bar{b}$ cross section of 0.5 mb.

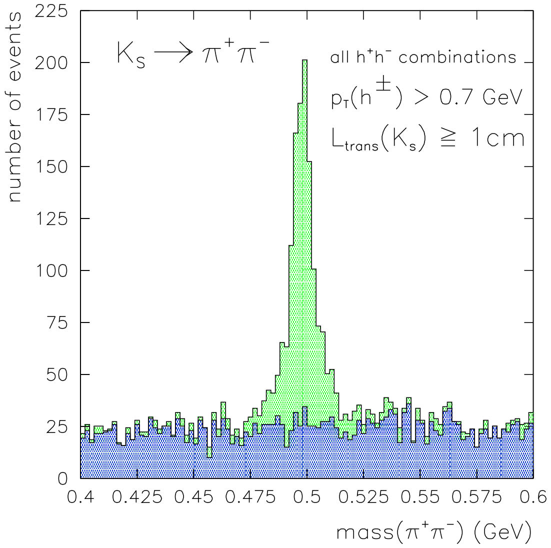

Figure 2. Reconstructed K_S mass peak (CMS).

4. $B_d \to J/\psi K_S$ CHANNEL

With the $B_d \to J/\psi K_S$ decay one can probe $\sin 2\beta$ of the Unitary Triangle. This can be done by measuring the time-dependent or time-integrated asymmetry between the number of B_d^0 and $\bar{B}_d^0$ decaying to $J/\psi K_S$:

$$a(t) = -\sin(2\beta)\sin(x_d \cdot t/\tau) \quad (1)$$

$$A = -\frac{x_d}{1+x_d^2}\sin 2\beta \quad (2)$$

Since the mixing parameter x_d is rather small both methods lead to similar accuracies for the $\sin 2\beta$ measurement.

Both experiments are looking for final state signatures of two hadrons of opposite charge assuming they are pions ($K_S \to \pi^+\pi^-$) and leptons ($J/\psi \to \mu^+\mu^-$,e^+e^-). The most difficult step in the event analysis is the K_S reconstruction (Fig. 2). To study the efficiency of the algorithms large number of K_S from $B_d \to J/\psi K_S$ decays were fully simulated using GEANT based detector simulations. For the track reconstruction at least 6 hits were required by ATLAS (5 by CMS). To form the K_S all the combinations of opposite charged hadrons with $p_T > 0.5$ GeV in ATLAS or $p_T > 0.7$ GeV in CMS were combined and fit to a common vertex, and the invariant mass was computed. Only events with the vertex in a predefined volume (1 cm$< r <$37 cm in ATLAS and $r >$1 cm in CMS) and in the K_S mass window ($\pm 3\sigma$ in ATLAS and $\pm 2.5\sigma$ in CMS) were kept. The reconstruction efficiency depends on η and on the location of the K_S decay vertex. The obtained overall efficiency is about 40% in case of ATLAS and 35% in CMS.

The K_S is combined with the J/ψ reconstructed from its leptonic decay products to form the B_d (Fig. 3). Mass constraints on K_S and J/ψ are used to obtain resolutions 16–24 MeV on the B_d mass (Tab. 3). The proper time resolution is about 61 fs in

Table 3
$B_d \to J/\psi K_S$ reconstruction: number of (non tagged) events for $\int L\,dt = 10^4$pb^{-1}, signal/background ratio and mass resolution. The event numbers for J/ψ decaying to $\mu^+\mu^-$ and e^+e^- differs due to trigger aspects.

	ATLAS		CMS	
	$\mu^+\mu^-$	e^+e^-	$\mu^+\mu^-$	e^+e^-
Reconstructed $B_d \to J/\psi K_S$ev.	160k	4.8k	384k	49 k
Signal/Background	31	16	8	4
B$_d$ mass resolution [MeV/c^2]	18	24	16	22

CMS and 73 fs in ATLAS. The main source of background comes from (real) J/ψ from $B \to J/\psi X$ decays combined with accidental (real) K_S.

The expected sensitivity to $\sin 2\beta$ is 0.017 in case of ATLAS and 0.015 for CMS for $\int L\,dt = 10^4$pb^{-1}, corresponding to one year of LHC data taking. The sensitivity will improve to approximately 0.01 for three years.

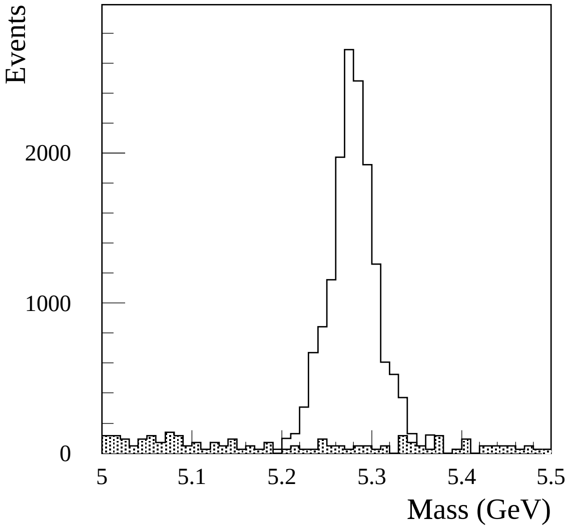

Figure 3. $B_d \to J/\psi K_S$: the B_d invariant mass spectrum of $e^+e^-\pi^+\pi^-$with J/ψ and K_S mass constraints (ATLAS).

5. $B_s \to J/\psi\phi$ CHANNEL

The $B_s \to J/\psi\phi$ decay channel is of central interest for the LHC experiments. It is sensitive to new physics scenarios and will not be studied with large accuracy before LHC.

At a first glance $B_s \to J/\psi\phi$ looks very similar to $B_d \to J/\psi K_S$ but the Standard Model predicts a very tiny asymmetry of $2\lambda^2\eta$ (where λ and η are parameters of Cabibbo-Kobayashi-Maskawa matrix in Wolfenstein parameterisation) which is expected to be about 0.03.

The extraction of the CP violating parameter is complex. Unlike B_d, the $B_s$meson mass eigenstates may differ significantly in decay widths ($\mathcal{O}$(15%)). The B_s oscillates rapidly ($x_s \sim$ 20–40). Moreover, the $J/\psi\phi$ final state is an admixture of different CP eigenstates. To fully exploit the physics information one has to perform a time-dependent angular analysis of the decay products (Fig. 4). One can apply the method of moments analysis [7] (CMS) or a general maximal likelihood fit to the expected distribution (ATLAS).

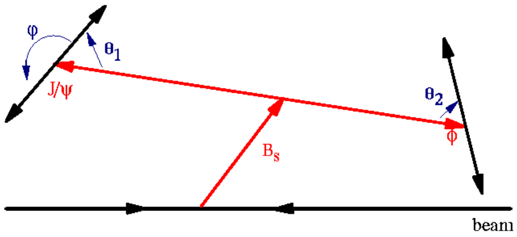

Figure 4. Physical angles χ, θ' and θ'' used in the angular analysis of the $B_s \to J/\psi\phi$ decay .

The final state signature consists of two leptons ($J/\psi \to \mu^+\mu^-$,e^+e^-) and two hadrons of opposite charges that are assumed to be K^+K^- ($\phi \to K^+K^-$). The expected number of events for

$\int L\,dt = 3 \cdot 10^4 \mathrm{pb}^{-1}$ (3 years of initial LHC luminosity) is 300000 in case of ATLAS and 700000 in CMS (although the CMS trigger used in the study was not optimised [8]).

The four final state particles come from the same decay vertex giving an additional constraint to background reduction (Fig 5) and proper time resolution (about 63 fs for both detectors). The expected signal to background ratio is 7 (ATLAS) or 10 (CMS) with main contribution coming from real J/ψ(from $B \to J/\psi X$) combined with real ϕ. The tagging aspects are identical to $B_d \to J/\psi K_S$ but B^{**} method cannot be used.

The large statistics allows CMS to measure the CP violating term $2\lambda^2\eta$ with accuracies of 0.014 (for $x_s = 20$) down to 0.03 ($x_s = 40$). The corresponding ATLAS reach is 0.03 and 0.05 respectively.

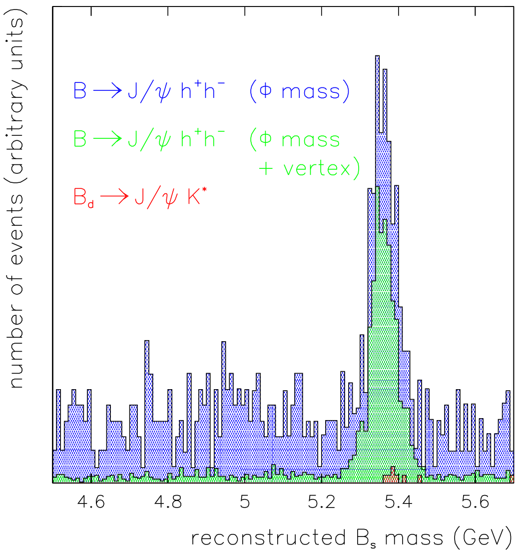

Figure 5. The example of B_s mass peak from $B_s \to J/\psi\phi$ reconstruction with the background reduction due to vertex constraints (CMS).

6. $B_d \to \pi^+\pi^-$ AND $B_s \to K^+K^-$ CHANNELS (ATLAS)

The time dependent asymmetries in $B_d \to \pi^+\pi^-$ decay provide a way to measure $\sin 2\alpha$ of the Unitary Triangle. The asymmetry is given by [9]:

$$a(t) = A_{dir} \cos\left(x_d \cdot t/\tau\right) + A_{mix} \sin\left(x_d \cdot t/\tau\right) \quad (3)$$

where (neglecting $\mathcal{O}(|P/T|^2)$ terms):

$$\begin{aligned} A_{dir} &= 2|\frac{P}{T}|\sin\delta\sin\alpha \\ A_{mix} &= -\sin 2\alpha - 2|\frac{P}{T}|\cos\delta\cos 2\alpha\sin\alpha \end{aligned}$$

There are three unknowns: α of the Unitarity Triangle, the ratio of penguin to tree amplitudes $|P/T|$, and the strong phase δ. Only two of these parameter can be fitted while one (presumably $|P/T|$) has to be provided by theory.

The $B_d \to \pi^+\pi^-$ channel[3] is experimentally very difficult due to its small branching ratio (BR($B_d \to \pi^+\pi^-$)$\approx$ $0.5 \cdot 10^{-5}$), triggering aspects (also at higher level) and lack of intermediate particle constraints. The final state consists of two charged hadrons and a tagging (and triggering) muon. The background is not only combinatorial. There are also Λ_b and B_s reflections (Fig. 6). A precision reconstruction of the B_d mass (the ATLAS mass resolution in this channel is 70 MeV), a high quality B_d decay vertex reconstruction and strong isolation criteria are of primary importance for this channel. The results of an event by event likelihood fit (taking into account the available information on K/π separation) shows that the A_{dir} and A_{mix} terms may be reconstructed with accuracies of 0.09 and 0.12 respectively [10]. The sensitivity to α depends on chosen input parameters and their errors (see Fig. 7).

A combined $B_s \to K^+K^-$ and $B_d \to \pi^+\pi^-$ analysis can be used to measure the angle γ of the Unitarity Triangle because the direct and mixing asymmetries in both channels are related, once isospin symmetry is applied [11], to four unknown variables (one of them is γ). Experimentally this channel is very similar to $B_d \to \pi^+\pi^-$. The ATLAS reach [10] is $\delta A_{mix} = \delta A_{dir} = 0.11$. The sensitivity to γ

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[3] The results of simulation presented in this section come from ATLAS study only

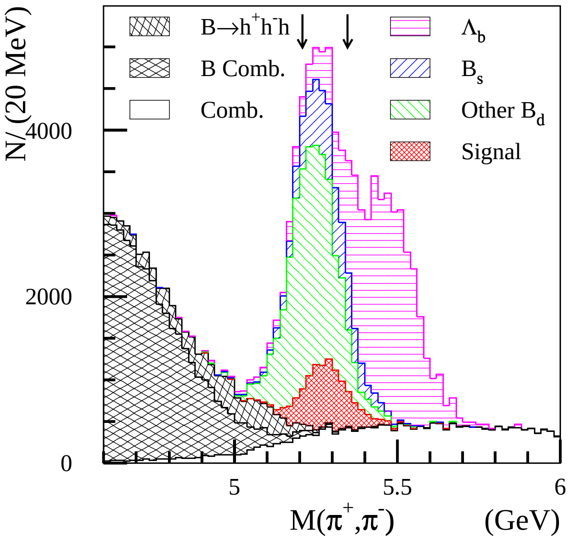

Figure 6. $B_d \to \pi^+\pi^-$reconstruction (ATLAS)

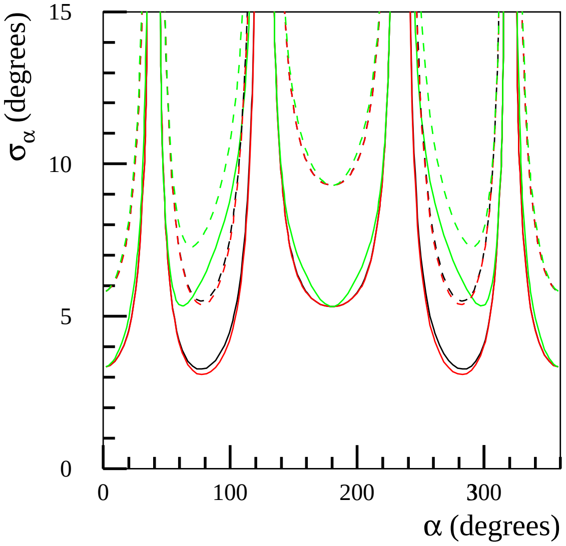

Figure 7. The α resolution in $B_d \to \pi^+\pi^-$channel for strong phase $\delta = 30^o$ and $|P/T| = 0.2$. The solid and dashed curves correspond to one and three years, respectively. In both cases the resolution is estimated for (from bottom to top) $\delta(|P/T|) = 0, 0.02, 0.1$.

strongly depends on input parameters with a minimum of about 8^o (for $\int L\,dt = 3 \cdot 10^4 \mathrm{pb}^{-1}$).

7. B_s OSCILLATION STUDIES AND RARE DECAYS

The B_s mixing parameter $x_s = \frac{\Delta m_s}{\Gamma}$ can be measured by analysing the time-dependent transition probabilities P$(B_s(t{=}0) \to \bar{B}_s(t))$ and P$(B_s(t{=}0) \to B_s(t))$ i.e. the probabilities that the initially produced B_s changes (or not) its flavour at the decay time. The best way is to look at the decay channels where the flavour of decay products tags the flavour of B_s at the decay time. The tagging of the production flavour (t=0) has to be done with a muon which has to provide also the trigger. The ATLAS and CMS groups analysed (for recent CMS studies see [12]) the $B_s \to D_s^{\pm}\pi^{\mp}$ and $B_s \to D_s^{\pm}a_1^{\mp}$ channels with $D_s^{\pm}$ decaying to $\phi\pi^{\pm}$. The expected ATLAS (CMS) measurement limit is $x_s = 46$ (43) for $\int L\,dt = 10^4 \mathrm{pb}^{-1}$.

Rare B-decays are not related directly to CP violation studies, but allow for interesting tests of the Standard Model. The semi-muonic decays $B_d \to \rho^0\mu^+\mu^-$, $B_d \to K^{*0}\mu^+\mu^-$ and $B_s \to \phi^0\mu^+\mu^-$ are examples of FCNC with rather small branching ratios (values of $1 \cdot 10^{-7}$, $1.5 \cdot 10^{-6}$, $1 \cdot 10^{-6}$ were used in the simulation for the above channels, respectively). ATLAS and CMS expect $a\ few \cdot 10^2$ up to $a\ few \cdot 10^3$ events (channel dependent) during 3 years of operation in low luminosity mode with signal to background ratios of 0.2–14.

Reachable statistics and data quality allow to test theoretical predictions for $BR(B_d \to K^{*0}\mu^+\mu^-)/BR(B_d \to \rho^0\mu^+\mu^-)$.

Standard Model predictions (optimistic) for purely leptonic decays $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ are $4 \cdot 10^{-9}$ and $1.5 \cdot 10^{-10}$, respectively. Self triggering signatures and an easily identified final state enables searching for the above decays at LHC in the *high luminosity* mode. The extremely tiny branching ratios require careful background reduction. Strong primary and B-decay vertex cuts supplemented with isolation requirements from tracker and calorimeters can be applied. The event yields for branching ratios given above are shown in Table 4.

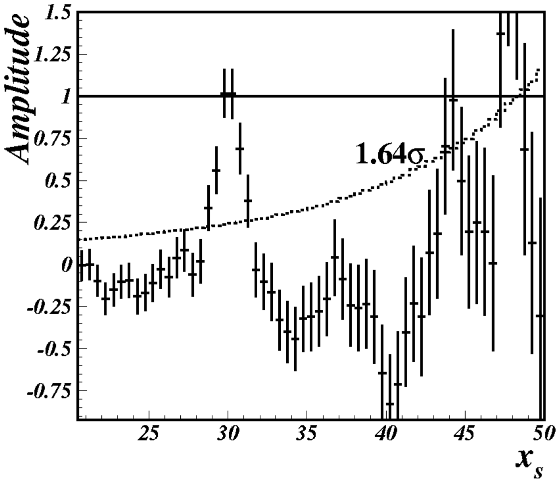

Figure 8. The result of an amplitude fit for an input value of $x_s = 30$. CMS study

Table 4
Expected performance for purely muonic decays $B_{d,s}\rightarrow\mu^+\mu^-$ for one year of LHC operation in high luminosity mode.

1 year @ 10^{34}	ATLAS	CMS
$B_s\rightarrow\mu^+\mu^-$	92	26
$B_d\rightarrow\mu^+\mu^-$	14	4.1
background	660	<6.4

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