Prospects of ATLAS and CMS for B Physics and CP Violation

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ATLAS and CMS experiments are designed primarily for high-p_T physics. However, they will be able to make precise measurements of B-hadron production, CP violation and rare decays. For a number of channels, ATLAS and CMS will be competitive and complementary to dedicated B-physics experiments such as LHCb and will cover a large region of unexplored phase space.

1 Introduction

The cross section for the production of $b\bar{b}$ pairs at LHC is expected to be much higher than at the e^+e^- B factories and $\sigma(b\bar{b})/\sigma_{tot}$ is significantly higher at LHC than at the Tevatron. A value of $\sigma(b\bar{b})$=500 μb has been assumed.

ATLAS [1] and CMS [2] are multi-purpose detectors optimized for high-p_T physics (for instance Higgs and Supersymmetry searches). However, their design is such that B-physics studies can easily be accommodated in their physics programmes.

Most of the B-physics studies are planned for the first period of low-luminosity running when the LHC will not yet have reached the design luminosity of 10^{34} cm^{-2} s^{-1}. During this period triggering and reconstruction of low-p_T events, as required for B physics, will be easier.

As described below, precision measurements are possible in ATLAS and CMS in several channels thanks to the high statistics. The achievable precision will be better than at the Tevatron and at the e^+e^- B factories and is in some cases competitive with LHCb, the LHC experiment dedicated to B physics.

The B-physics possibilities of ATLAS and CMS cannot be fully described in these proceedings. Some benchmark channels have been looked in great detail, using full detector simulation and sophisticated analysis method. Some of these results are summarized here.

2 Trigger and B selection strategies

For ATLAS, a flexible trigger strategy has been developed. A dimuon trigger will be used to select events for B-physics studies even at high luminosity. At lower luminosity, where there are sufficient resources in the trigger system, additional triggers will be included. These will require a low-p_T jet or electromagnetic cluster in addition to a single muon in the first-level

	$\epsilon(\%)$	D
lepton (OS)	4	0.4
jet charge (OS)	65	0.18
$B-\pi$ (SS, ATLAS)	82	0.16
$B-\pi$(SS, CMS)	21	0.32
jet charge (SS)	65	0.18

Table 1: Indicative efficiencies and dilution factors for flavour-tagging algorithms studied by ATLAS and CMS. The first two rows refer to Opposite Side (OS) tagging algorithms and the remaining ones to Same Side (SS) algorithms.

trigger (level-1). All level-1 objects will guide reconstruction in the second-level trigger (level-2), and results of level-2 will seed reconstruction in the Event Filter. The di-muon trigger provides a very effective selection of several important channels, e.g. $B_d \rightarrow J/\psi(\mu^+\mu^-)K_s^0$, $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi$ and $B_{d,s} \rightarrow \mu^+\mu^- X$. For example, at a luminosity of 10^{33} cm^{-2} s^{-1}, p_T thresholds of 6 GeV and 5 GeV for first and second muons in the event respectively would give a trigger rate of 180 Hz after sharp muon-p_T cuts. The jets-muon trigger will cover hadronic final states, e.g. $B_s^0 \rightarrow D_s\pi$, $B_s^0 \rightarrow D_s a_1$ and $B_d \rightarrow \pi^+\pi^-$. All the processes will contain a muon which can be used to tag the B-hadron flavour. The electron muon trigger is used to select channels such as $B_d \rightarrow J/\psi(e^+e^-)K_s^0$ with opposite-side muon tag, or $B_d \rightarrow J/\psi(\mu^+\mu^-)K_s^0$ with opposite-side electron tag. After one year, the ATLAS trigger system could deliver to permanent storage about 10^8 events with beauty hadron decays.

Several characteristics of the ATLAS and CMS designs are well suited for B-physics studies. Good secondary-vertex resolution is guaranteed by the presence of pixel detector layers (three layers in the barrel region) close to the interaction point. In CMS low-p_T muon identification is done by the muon spectrometer and low-p_T electron identification is possible thanks to a high resolution crystal calorimeter together with the tracking system. Similarly in ATLAS low-p_T muons can be reconstructed, and the finely-segmented liquid-argon calorimeter together with the transition-radiation tracker provide electron identification. The stronger field in CMS than in ATLAS (4 T with respect to 2 T) has the consequence that a better mass resolution is achievable.

Neither ATLAS nor CMS have dedicated detectors for hadron identification. However, in ATLAS a limited π/K separation will be obtained indirectly by using dE/dx energy loss in the straw tracker. The separation obtained is about 1.0 σ (it is p_T dependent) and, used on a statistical basis, has proven to be very useful in some of the analyses.

Many of the flavour-tagging algorithms developed in the past years by the LEP experiments and by CDF appear feasible in ATLAS and CMS. Indicative efficiencies[1],ϵ, and dilution factors[2], D, are summarized in Table 1.

[1] ϵ is the ratio of the number of tagged signal events to the total number of signal events: $N_{tag}^{obs} = \epsilon N^{obs}$.

[2] The observable asymmetry is $a_{obs}(t) = D a_{CP}(t) = D \sin\phi_M \sin\Delta m_s t$ where D combines all the experimental dilution factors due to mistagging, decay time resolution, fit statistics and background.

	$\Delta\Gamma_s$	Γ_s	$\phi_s(x_s = 20)$	$\phi_s(x_s = 40)$
ATLAS	12%	0.7%	0.03	0.05
CMS	8%	0.5%	0.014	0.03

Table 2: ATLAS and CMS relative statistical uncertainties on $\Delta\Gamma_s$, Γ_s and absolute uncertainty on ϕ_s for two different values of x_s after three years of running at 10^{33} cm^{-2} s^{-1}.

3 Some benchmark channels

3.1 B$_s$ studies and precise measurements

LHC era will be the "El Dorado" of B_s studies. The decay $B_s^0 \to D_s^+\pi^-$ with $D_s^+ \to \phi\pi^+$ can be used to measure the oscillation parameter ΔM_s. ATLAS also considers the decay $B_s^0 \to D_s^+a_1^-$ with $D_s^+ \to \phi\pi^+$ and $a_1^- \to \rho_0\pi^- \to \pi^+\pi^-\pi^-$. Good resolution is achievable on the B_s^0 proper decay time to resolve the rapid oscillations. ATLAS estimates a proper-time resolution of about $\sigma(\tau) = 50$ fs while CMS estimates $\sigma(\tau) = 70$ fs. After one year of data taking at low luminosity, each experiment would have a 95 % CL sensitivity up to ΔM_s of about 30 ps^{-1}. This is well above the allowed range in the Standard Model. Indications from experimental searches [3] and fits to the CKM matrix [4] are that ΔM_s should not be larger than 25 ps^{-1}. In this hypothesis the Tevatron experiments should be able to observe the B_s^0 oscillations before the LHC start. So it may be more interesting to evaluate the precision on ΔM_s measurement. For example, assuming an already-observed mixing of $\Delta M_s = 20$ ps^{-1}, an uncertainty of $\sigma(\Delta M_s) = 0.11$ ps^{-1} has been estimated.

Large and clean samples of $B_s^0 \to J/\psi\phi$ decays will also be available in ATLAS and CMS. It is estimated that ATLAS will reconstruct about 100k of these (untagged) events in one year of data taking, and CMS will reconstruct about twice this number (with S/B of about 6 and 10, respectively). This decay may be used to probe the $B_s^0 - \overline{B_s^0}$ weak mixing phase $\phi_s = -2\delta\gamma = -2\lambda^2\eta$ (where $\delta\gamma$ is an angle related to the other non-squashed unitary triangle of the CKM matrix and λ and η are Wolfenstein parameters). The $J/\psi\phi$ final state in this decay is an admixture of different CP eigenstates and an angular analysis of the decay products $J/\psi(\mathrm{l^+l^-})\phi(\mathrm{K^+K^-})$ is needed. In principle, eight independent parameters could be extracted by this analysis. However, as was done in Ref [5], because of the experimental precision available, one can extract only ϕ_s, two unknown amplitudes $|A_\perp(0)|$ and $|A_\parallel(0)|$, the decay-rate difference $\Delta\Gamma_s = \Gamma_H - \Gamma_L$ and the mean decay rate $\Gamma_s = (\Gamma_H + \Gamma_L)/2$ of the mass eigenstates B_H^0 and B_L^0, and fix the remaining parameters, i.e. two strong phases δ_1 and δ_2 and the mass difference ΔM_s. The precision available after three years of running at low luminosity on some of these parameters is summarized in Table 2. Note that the observation of CP-violation in this channel, significantly beyond the Standard-Model expectations, would be a clear sign of new physics.

Large and clean samples of $B_d^0 \to J/\psi K_s^0$ will be available in ATLAS and CMS. It is expected that about 165k events will be collected by ATLAS in one year and about 450k events/year by CMS. The higher CMS yield is due to the presence of a lower-p_T dimuon trigger. ATLAS may be able to increase its sample size by lowering its thresholds. This channel is universally considered the golden channel to measure the angle β of the unitary triangle of the Cabibbo-

	Signal $B_s \to \mu^+\mu^-$	Signal $B_d \to \mu^+\mu^-$	background
ATLAS	92	14	660
CMS	26	4	< 6

Table 3: Signal and background numbers of reconstructed $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ for one year of running at a luminosity of 10^{34} cm^{-2} s^{-1}.

Kobayashi-Maskawa (CKM) quark-mixing matrix. In fact, to a very good approximation this decay is dominated by only one CKM amplitude in the Standard Model and the time-dependent CP asymmetry. The large number of events available in ATLAS and CMS implies an excellent resolution for the measurement of $\sin 2\beta$. After just one year of data taking, a precision of $\sigma(\sin 2\beta) = 0.017$ for ATLAS and $\sigma(\sin 2\beta) = 0.015$ for CMS can be obtained. The direct component of the time-dependent CP asymmetry in this decay, A_{CP}^{dir}, is expected to be very small in the Standard Model. In a study performed by ATLAS [6], it has been estimated that a 5 σ discovery could be obtained if A_{CP}^{dir} is at least 0.10.

3.2 Rare decays

Flavour-changing neutral-current decays $b \to s, b \to d$ occur only at loop-level in the Standard-Model (SM) and come with small exclusive branching ratios Br $< O(10^{-5})$. However, they are sensitive to new physics. Within the SM, these decays are sensitive to CKM matrix elements $|V_{td}|$, $|V_{ts}|$. In the era before LHC, some rare decays are accessible at e^+e^- factories and the Tevatron. Although the Process $B \to K^*\mu\mu$ can be seen, the mass and angular distributions can only be studied at LHC. Purely muonic rare decays will be observed before LHC only if they are drastically enhanced comparing to SM predictions Br$(B_d \to \mu^+\mu^-) = (3.5 \pm 1.0)\ 10^{-9}$ and Br$(B_s \to \mu^+\mu^-) = (1.5 \pm 1.0)\ 10^{-10}$ [7].

Using a simulation of the ATLAS detector response, it has been demonstrated that purely muonic decays can be selected by the trigger and reconstructed at both low and high luminosities of 10^{33} cm^{-2} s^{-1} and 10^{34} cm^{-2} s^{-1} respectively. It was assumed that the performance of the inner detector will not be degraded in the higher-luminosity case. The expected signal and background statistics for $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ are summarized in Table 3 [5]. Already after one year at high luminosity ATLAS and CMS will be able to observe $B_s \to \mu^+\mu^-$ and measure its branching ratio, and perform a high-sensitivity search for $B_d \to \mu^+\mu^-$.

Assuming the SM to be valid, the measurement of branching fractions of decays $B_d^0 \to \rho^0\mu^+\mu^-$ and $B_d^0 \to K^{*0}\mu^+\mu^-$ gives, in principle, the possibility to extract the ratio of CKM elements $|V_{td}|$, $|V_{ts}|$. Using detector simulation, ATLAS has estimated that the branching fraction ratio can be measured with a statistical accuracy of 14%. ATLAS estimates a precision on the measurement of the forward backward asymmetry of about 5% in each of three bins of dimuon mass squared, in $B_d^0 \to K^{*0}\mu^+\mu^-$ for 3 years at low luminosity. The accuracy of ATLAS will be sufficient to distinguish between SM and its extension, i.e. a significant part of MSSM parameter space.

3.3 B hadron production and QCD tests

LHC will probe kinematic regions of strong interactions that have not yet been explored. Compared with previous hadron experiments it will have a higher collision energy, 14 TeV, and a wider Bjorken-x region (ATLAS will be sensitive down to x$\sim 10^{-4}$ [8]). The high beauty cross section and luminosity at LHC will allow one to extend b-production measurement up to transverse momenta of several hundred GeV and to investigate correlations between b and $\bar{b}$ quarks, as well as studying multiple heavy flavour production. ATLAS performance studies were done for two channels selected to measure the azimuthal-angle difference $\Delta\phi(b\bar{b})$ between b and $\bar{b}$ quarks: $\bar{b} \rightarrow B_d \rightarrow J/\psi(\mu\mu)K^0; b \rightarrow \mu X$ and $\bar{b} \rightarrow B_s \rightarrow J/\psi(\mu\mu)\phi; b \rightarrow \mu X$. The number of events expected after three years at 10^{33} cm^{-2} s^{-1} are 4.8 10^4 and 3.2 10^4 respectively [9]. Beauty-production studies will be extended to semi-inclusive events containing $b\bar{b} \rightarrow J/\psi(\mu^+\mu^-)X$ and to b-jets to access the very high-p_T region.

4 Conclusions

The LHC experiments can significantly contribute to the knowledge of B physics and CP violation due to the unprecedented statistics available. In many channels ATLAS and CMS can give a substantial contribution to the overall LHC performance. A brief and incomplete summary of these studies, including some new results, has been given here. More details of the B-physics potential of the LHC experiments can be found in Ref [5].

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References

[1] ATLAS Detector and Physics performance, TDR I and II, CERN-LHCC-99-015, (1999).

[2] CMS : the magnet project, TDR, CERN-LHCC-97-010, (1997).

[3] The LEP B Oscillation Working Group,`http://lepbosc.web.cern.ch/LEPBOSC`.

[4] M. Ciuchini *et al.*, JHEP **0107** (2001) 013.

[5] ATLAS Collaboration, The Large Hadron Collider collection, CERN 2000-004 (2000).

[6] P. A. Booth *et al.*, ATLAS Physics Note, ATL-PHYS-2001-013.

[7] A. Ali, J.Phys.G18:1605-1626,1992.

[8] S. Frixione et al., J.Phys.G27:1111-1157,2001.

[9] S. Robins, ATLAS Physics Note, ATL-PHYS-2000-026.