ATLAS POTENTIAL FOR BEAUTY PHYSICS MEASUREMENTS*

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The main focus of ATLAS b physics has traditionally been on the standard model. In the last few years also the aspects of new physics in B-decays has been addressed. Another new field of studies started recently is a beauty production. We give an overview of the older as well as more recent results. After an introduction outlining selected trigger and detector performance characteristics, we explain methods and goals of CP violation measurements in decay channels of B_d^0 meson, physics of B_s^0 system and of rare decays. Finally, the ATLAS program for beauty production measurements is presented.

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1. Introduction

During last years b physics received a lot of attention and presently first results of B-factories are being published. CDF and D0 has already started RUN-II. Although the physics potential of these experiments is promising it may well be that the very precise B-decay measurements needed for finding the evidence of new physics will be left for LHC experiments. LHC also provide an opportunity for QCD tests in beauty production at the highest energies of colliding protons.

2. Selected trigger and detector performance characteristics

ATLAS detector has been primarily designed to search for new particles at highest mass scale, however b physics has influenced the detector layout as well as the ATLAS trigger.

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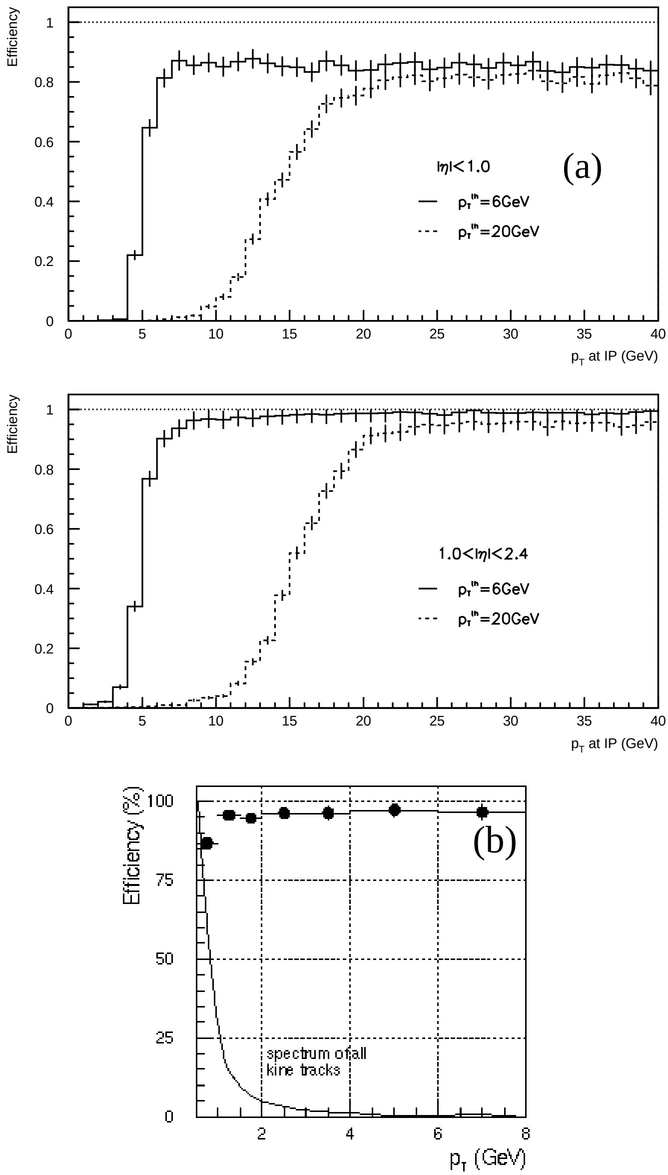

Fig. 1. (a) First level muon trigger efficiency as a function of muon $p_{\rm T}$ in barrel and end-cap parts of trigger chambers. The lower threshold of 6 GeV will be used for b physics. (b) Example of a high performance of second b physics trigger: a track reconstruction efficiency as a function of $p_{\rm T}$ in Inner Detector part, TRT, using fast look-up-table algorithm implemented in a dedicated FPGA processors.

The first level trigger will be working at the event rate of 40MHz. The fast muon trigger chambers will be able to select muons with momenta transverse to a beam direction as low as 6 GeV [1] with the high efficiency, Fig. 1(a). At initial LHC luminosity of $10^{33}\text{cm}^{-2}\text{s}^{-1}$ accepting all the events with at least one such muon will reduce the event rate to 10 kHz containing 25 % of events with beauty quark [2]. Such a rate is sufficiently low to allow the second level processing, which is based on full detector granularity data. While in the muon system and in the calorimetry only data from the selected regions need to be analysed, the whole volume of the Inner Detector should be searched for trajectories of secondary particles coming from B-decays. It was demonstrated that a look-up-table algorithm implemented in FPGA processors [3] can accomplish this task in average within 5 ms, satisfying time requirements of second level processing. The performance (Fig. 1(b)) is comparable to that in off-line tracking [4]. After one year ATLAS trigger system will deliver to permanent storage $\sim 10^8$ events with opened beauty hadrons and quarkonia.

A strong feature of ATLAS detector is a lepton identification over a wide range of transverse momenta, that allows a clean signal selection. Electrons with $p_{\mathrm{T}} > 0.5\,\mathrm{GeV}$ are identified in the Transition Radiation Tracker (TRT),

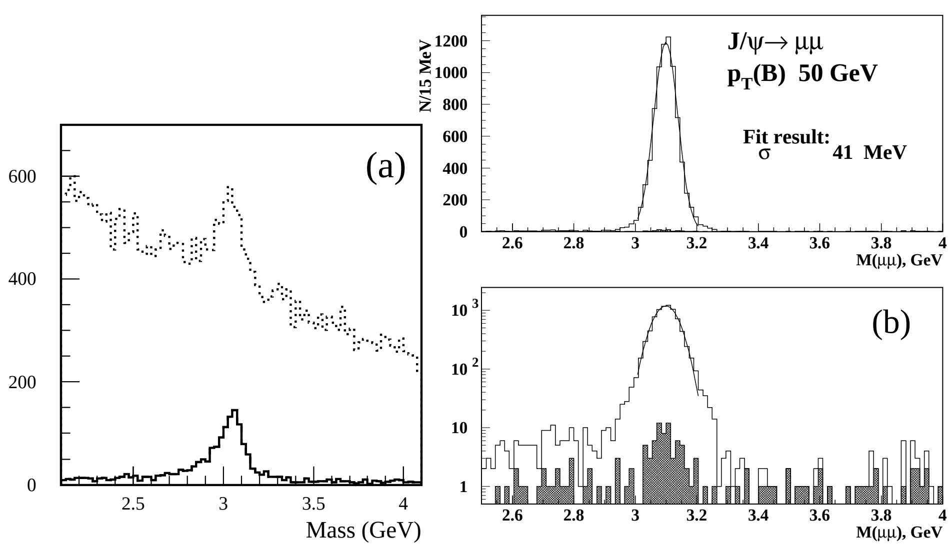

Fig. 2. (a) Rejection of combinatorial background using electron identification in Transition Radiation Tracker. Invariant mass of all track combinations in events containing $J/\psi \to e^+e^-$ before (dashed) and after (solid) identification cuts. (b) The J/ψ mass reconstruction in $B_d \to J/\psi(\mu^+\mu^-)K^0$ events (linear and logarithmic scales). In part of events a muon detected in muon system was associated with the wrong track in Inner Detector (black area).

the outer part of ATLAS Inner Detector (ID) tracking system. An example in Fig. 2(a), taken from [4], shows $J/\psi \to e^+e^-$ background rejection. For $p_{\rm T} > 2\,{\rm GeV}$ an additional identification arises from the electromagnetic calorimeter.

ATLAS excellent muon performance is achieved combining precision muon chambers with the ID. The reconstruction may be more complicated inside higher $p_{\rm T}$ b-jets due to more difficult matching between muon chambers and ID, however, a study made for $B_d \to J/\psi\,(\mu^+\mu^-)K^0$ events showed, Fig. 2(b), that the mass reconstruction is not degraded even in cases where the $p_{\rm T}$ of b quark is larger than $50\,{\rm GeV}$ [5].

3. CP violation measurements in B_d^0 decays

ATLAS made detailed investigations to establish the optimal methods of CP violation measurements in processes $B_d \to J/\psi K^0_{\rm S}$ and $B_d \to \pi^+\pi^-$. Analyses were done in terms of time depended CP asymmetry $\mathcal{A}_{CP}$

$$\mathcal{A}_{CP} \equiv \frac{\Gamma(t) - \overline{\Gamma}(t)}{\Gamma(t) + \overline{\Gamma}(t)} \sim \mathcal{A}_{CP}^{\rm mix} \sin(\Delta\, mt) + \mathcal{A}_{CP}^{\rm dir} \cos(\Delta\, mt)\,, \qquad (1)$$

separated into mixing-induced and direct CP violation parts, which are simply related to weak phases of these two decays.

3.1. *Precise* $\sin(2\beta)$ *measurement from* $B_d \to J/\psi K^0_{\rm S}$

In case of $B_d \to J/\psi K^0_{\rm S}$ the term $\mathcal{A}_{CP}^{\rm dir}$ is expected to be small [6] and was neglected in analyses. The weak phase β was extracted from a fit to the time dependent asymmetry of the form:

$$\mathcal{A}_{CP} = D\, \mathcal{A}_{CP}^{\rm mix} \sin(\Delta\, mt) = D \sin(2\beta) \sin(\Delta\, mt)\,, \qquad (2)$$

where D is an overall dilution factor due to both tagging and background. The only free parameter of the fit is $\sin(2\beta)$. High sensitivity of ATLAS in this channel will be achieved by dedicated triggers selecting $J/\psi \to \mu^+\mu^-$ and $J/\psi \to e^+e^-$ and by a combination of tagging methods [7] using muon or electron from the associated B-decay and those using the charge of the same-side jet. The expected event yields and the precisions obtained with different tagging methods are summarized in Table I, extracted from [7]. Combining all tags the precision on $\sin(2\beta)$ of 0.01 is expected after 3 years at luminosity $10^{33}{\rm cm}^{-2}{\rm s}^{-1}$. It was estimated that a corresponding systematic error of 0.005 can be obtained.

TABLE I

Summary of the expected event yields and the results obtained with different tagging methods.

	Stat. after 1 year $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$\delta\sin(2\beta)_{\mathrm{sta}}$	
First trigger level	800 k	lepton tag $J/\psi\to\mu^+\mu^-$	0.039
Second trigger level	550 k	lepton tag $J/\psi\to e^+e^-$	0.031
off-line	170 k	jet/ch. tag	0.026
Signal/Background	31	total	0.017
		Total 3 years	0.01
		ATLAS, CMS, LHCb	0.005

3.2. Measurement of CP violation in $B_d\to\pi^+\pi^-$

Process $B_d\to\pi^+\pi^-$ allows to probe another CKM angle α. Unfortunately, large penguin contributions suggested by theoretical calculations [8] and also indicated by latest CLEO results [9], makes the interpretation of $B_d\to\pi^+\pi^-$ measurements in terms of α difficult. The CP asymmetry observables $\mathcal{A}_{CP}^{\mathrm{mix}}$ and $\mathcal{A}_{CP}^{\mathrm{dir}}$

$$\mathcal{A}_{CP}^{\mathrm{mix}}=2\left|\frac{P}{T}\right|\sin\delta\sin\alpha\,,\quad \mathcal{A}_{CP}^{\mathrm{dir}}=-\sin(2\alpha)-2\left|\frac{P}{T}\right|\cos\delta\cos(2\alpha)\sin\alpha\,, \quad (3)$$

contain other unknown parameters: ratio of penguin and tree amplitudes $|P/T|$ and a strong phase δ.

Low branching ratio and lack of sub-mass constraints make reconstruction of $B_d\to\pi^+\pi^-$ a demanding task. Additional problems are posed by isolating the signal from other two-body topologies, such as $B_d\to K^\pm\pi^\pm$, $B_d\to K^+K^-$, $B_s\to K^\pm\pi^\pm$, $\Lambda_b^0\to p\pi^-$ and $\Lambda_b^0\to pK^-$ decays.

ATLAS used the method of maximum likelihood fit to extract CP asymmetry parameters (3) of $B_d\to\pi^+\pi^-$ simultaneously with asymmetry parameters of other two-body classes. Information on dE/dx from TRT, allowing to achieve a certain level of $\pi^\pm-K^\pm$ separation was used at probabilistic level in the fit.

Fig. 3, taken from [7], shows a sensitivity to α as a function of α for a given $\delta=0^\circ,30^\circ,60^\circ$ and $|P/T|=0.2$. Depending on exact values of α, δ and theoretical uncertainty of $|P/T|$ the decay $B_d\to\pi^+\pi^-$ can provide a constraint on α with a precision approaching 2° after 3 years.

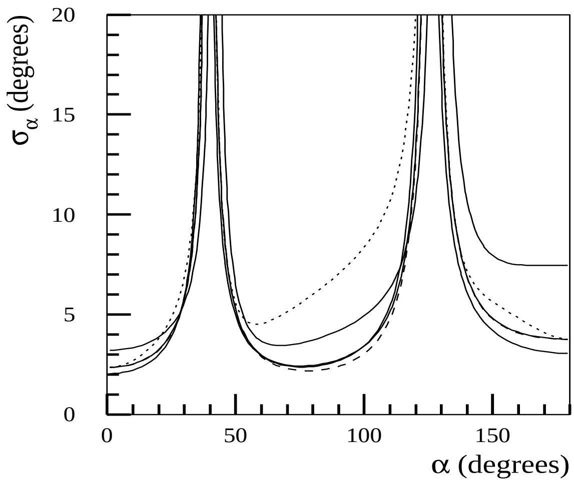

Fig. 3. Precision of measuring α from $B_d \to \pi^+\pi^-$ as a function of α after three years of low luminosity data taking. The three solid lines were obtained (from bottom to top) with $\delta = 0°, 30°, 60°$ and with $|P/T| = 0.2 \pm 0.02$. The dashed line obtained with $\delta = 30°$ and no uncertainty on $|P/T|$, dotted line with the uncertainty 50%.

4. Physics of B_s^0 mesons

4.1. Oscillation measurements

The B_s^0 and $\overline{B}_s^0$ mesons mix on account of weak interactions. The B_s^0–$\overline{B}_s^0$ system is characterized by two physics eigenstates with different masses and decay rates. Both the mass difference ΔM_s and the rate difference $\Delta\Gamma_s$ can be described in Standard Model (SM) by second order weak processes with $\Delta B = 2$. Their experimental determination will be valuable input for flavour dynamics in both SM and its possible extensions.

It has been proved that both variables are accessible by measurement in ATLAS. For ΔM_s best candidates are B_s^0 decays to flavour specific states $B_s^0 \to D_s\pi$, $B_s^0 \to D_s a_1$. $\Delta\Gamma_s$ can be precisely measured in $B_s^0 \to J/\psi\phi$.

4.2. ΔM_s measurement with $B_s^0 \to D_s\pi$, $B_s^0 \to D_s a_1$

In $B_s^0 \to D_s\pi$, $B_s^0 \to D_s a_1$, the probability p_- that an initially (time $t = 0$) pure B_s^0 will be observed as a $\overline{B}_s^0$ and the probability p_+ that it will remain a B_s^0 are described in terms of Γ, $\Delta\Gamma_s$ and ΔM_s by the following formulae

$$p_\mp(t) = \mathrm{e}^{-\Gamma t}(\cosh \frac{\Delta\Gamma_s}{2}\, t \mp \cos \Delta M_s\, t)\frac{\Gamma^2 - {\Delta\Gamma_s}^2}{2\Gamma}\,. \tag{4}$$

The parameter ΔM_s then can be derived from the ratio:

$$r(t) = \frac{p_+(t) - p_-(t)}{p_+(t) + p_-(t)} = \frac{\cos \Delta M_s \, t}{\cosh \frac{\Delta\Gamma_s}{2} \, t}\,, \qquad (5)$$

which is diluted in case of $\Delta\Gamma_s \neq 0$ by the time dependent hyperbolic function. It was shown however that for $\Delta\Gamma_s/\Gamma \leq 0.2$ no significant change in sensitivity range of ΔM_s is expected. The ATLAS precision for $B_s^0 \to D_s\pi$, $B_s^0 \to D_s a_1$ processes and the background were determined by detector simulations and corresponding parameters were used as input to a fit in repeated Monte Carlo experiments. Summary of analyses and results is given in Table II, extracted from [7]. It is clear that already after 1 year at luminosity $10^{33}\text{cm}^{-2}\text{s}^{-1}$ ATLAS can fully explore SM allowed range of ΔM_s.

TABLE II

Summary of B_s^0 oscillation frequency measurement in channels $B_s^0 \to D_s\pi$, $B_s^0 \to D_s a_1$.

B_s^0 channels	$D_s^-\pi^+$
	$D_s^- a_1^+$
D_s^- channels	$\phi\pi^-$
ϕ channel	K^+K^-
a_1^+ channel	$\rho^0\pi^+$
K^{*0} channel	
signal 1 year	3457
proper time resolution	50 fs (60.5%)
Gaussian function(s)	93 fs (39.5%)
ΔM_s 95% CL 1 year	$30\,\text{ps}^{-1}$
x_s reach 95% CL 1 year	46

The precision of $\Delta\Gamma_s$ measurement from $B_s^0 \to D_s\pi$ and $B_s^0 \to D_s a_1$ using the method suggested by Dunietz [10] was estimated. It was shown [11] that these processes do not provide valuable source of $\Delta\Gamma_s$ measurement in ATLAS.

4.3. $\Delta\Gamma_s$ and B_s^0 mixing phase ϕ_s from $B_s^0 \to J/\psi\phi$

The $B_s^0 \to J/\psi\phi$ decay leads to three final state helicity configurations and their linear combinations are CP eigenstates with different CP parities [10]. This means that it is not possible to extract a CP-violating weak mixing phase $\phi_s = \arg\left(V_{cs}^* V_{cb}/V_{cs}V_{cb}^*\right)$ if the helicity amplitudes are not separated. Experiment can measure three independent angles and the B_s^0 proper time of the decay $B_s^0 \to J/\psi\phi \to \mu^+\mu^-K^+K^-$. In some cases also the initial B_s^0 flavour can be tagged. A determination of the background contribution and its physics characteristics brings other important information. The ATLAS precision for these measurements was determined by detector response simulations and was used as input to angular analyses based on a maximum likelihood fit in repeated Monte Carlo experiments. The difference of the mass eigenstate decay rates, $\Delta\Gamma_s$, their average value Γ_s and the weak phase ϕ_s were simultaneously determined along with two helicity amplitude values and their strong phases. The mixing parameter $x_s \equiv \Delta M_s / \Gamma_s$ was assumed to be measured in $B_s^0 \to D_s\pi$ and $B_s^0 \to D_s a_1$ and was fixed. While all eight parameters are independent in the theoretical models, the experimental resolution causes some to become correlated. The highest correlation appeared between the two strong phases and prevented their simultaneous determination. Thus, in final analysis the two parameters were fixed.

After 3 years at luminosity $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ the $\Delta\Gamma_s$ can be determined with the relative error of 12%. The precision of the ϕ_s determination depends on the value of x_s and on the proper-time resolution. The ATLAS discovery

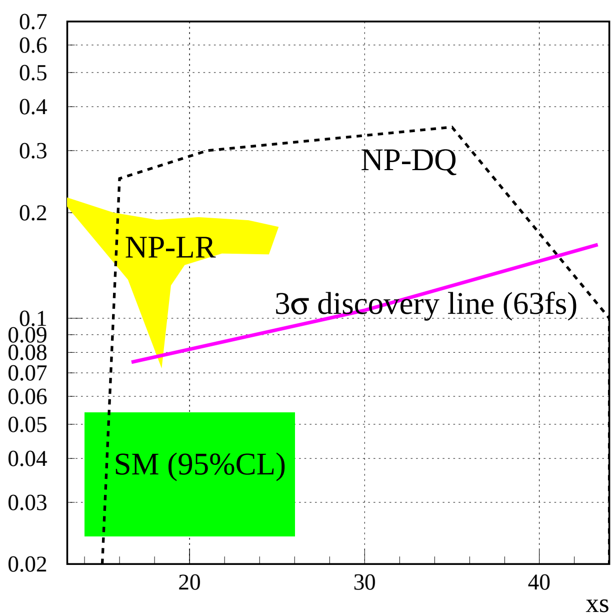

Fig. 4. The x_s–ϕ_s region allowed by SM, left-right symmetric models (NP-LR), iso-singlet down quark mixing Model (NP-DQ) and the region of experimental sensitivity of ATLAS.

line in the (x_s–ϕ_s) plane is displayed in Fig. 4, taken from [12], together with regions allowed by SM and by the two examples of new physics models [13]. The ATLAS precision is high enough to be sensitive to new physics.

5. Rare decays prospects

Flavour changing neutral current decays $b \to s$, $b \to d$ occur only at loop level in SM come with small exclusive branching ratios BR$< \mathcal{O}(10^{-5})$. They are sensitive to new physics. Within the SM, these decays are sensitive to CKM matrix elements $\mid V_{td} \mid, \mid V_{ts} \mid$.

In the era before LHC some rare decays are accessible on e^+e^- factories and Tevatron. In particular for $B^0 \to K^*\gamma$ at time of LHC quite accurate measurements should be available. Process $B^0 \to K^*\mu\mu$ can be seen, however the mass and angular distributions can only be studied at LHC. Purely muonic rare decays can be observed before LHC only if they are drastically enhanced comparing to SM predictions $\mathrm{BR}(B_s^0 \to \mu^+\mu^-) = (3.5 \pm 1.0) \times 10^{-9}$ and $\mathrm{BR}(B_d^0 \to \mu^+\mu^-) = (1.5 \pm 1.0) \times 10^{-10}$ [14].

5.1. Purely muonic decays

Using simulation of the detector response ATLAS has demonstrated that purely muonic decays can be selected by trigger and reconstructed at both low and high luminosities expected to be $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ respectively. It was assumed that the performance of the Inner Detector will not be degraded at higher luminosity case. Expected signal and background statistics for $B_s^0 \to \mu^+\mu^-$ and $B_d^0 \to \mu^+\mu^-$ are summarized in Table III, extracted from [7] and [15].

TABLE III

Expected signal and background numbers of reconstructed $B_s^0 \to \mu^+\mu^-$ and $B_d^0 \to \mu^+\mu^-$ events.

	Signal $B_s^0 \to \mu^+\mu^-$	Signal $B_d^0 \to \mu^+\mu^-$	BG
1 year $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	92	14	660
3 years at $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	27	–	93

Already after one year of high luminosity ATLAS will be able to observe $B_s^0 \to \mu^+\mu^-$ and measure its branching ratio and perform a high sensitivity search for $B_d^0 \to \mu^+\mu^-$.

5.2. Semimuonic decays

Assumming the SM to be valid the measurement of branching fractions of $B_d^0 \to \rho^0\mu^+\mu^-$ and $B_d^0 \to K^{*0}\mu^+\mu^-$ gives, in principle, the possibility to extract the ratio of CKM elements $\mid V_{td} \mid, \mid V_{ts} \mid$. Using detector simulations ATLAS has estimated that the branching fractions ratio can be measured with the statistical accuracy of 14%, however as pointed in [16] the extraction of $\mid V_{td} \mid / \mid V_{ts} \mid$ is limited by theoretical uncertainties of form factors describing $B_d^0 \to K^{*0}\mu^+\mu^-$ and $B_d^0 \to \rho^0\mu^+\mu^-$ decays.

ATLAS studied prospects of measurements of forward-backward asymmetry in $B_d^0 \to K^{*0}\mu^+\mu^-$

$$A_{\rm FB}(\hat{s}) = 1\frac{d}{\Gamma}d\hat{s}\int\limits_0^1 \frac{d^2\Gamma}{d\hat{s}d\cos(\theta)}d\cos(\theta) - \int\limits_{-1}^0 \frac{d^2\Gamma}{d\hat{s}d\cos(\theta)}d\cos(\theta)\,, \qquad (6)$$

where θ is the angle between the μ^+ and the B meson direction in the rest frame of the muon pair. The precision of $A_{\rm FB}$ was estimated in three regions of di-muon invariant mass. The data are presented in Fig. 5, taken from [7],

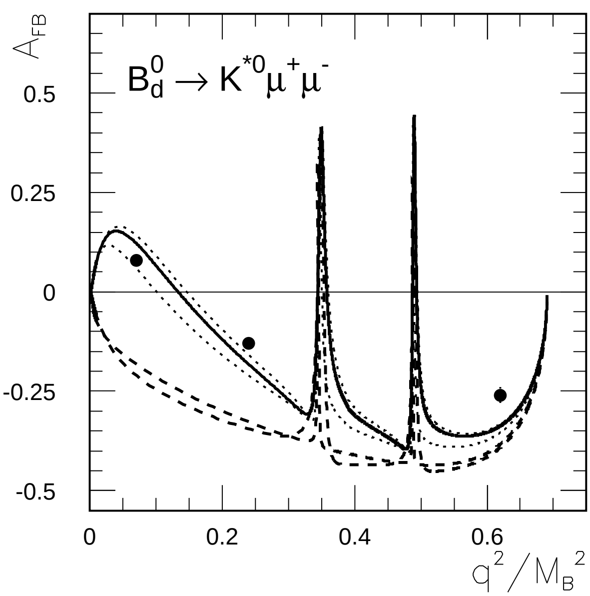

Fig. 5. Sensitivity of asymmetry measurement in $B_d^0 \to K^{*0}\mu^+\mu^-$. Points are the simulation results in three di-muon invariant mass regions. The solid line is SM and dotted and dashed lines are MSSM predictions with different Wilson coefficients $C_{7\gamma}$ (for details see [7]).

together with asymmetry values in SM and an example of super-symmetric model. The accuracy of ATLAS will be sufficient to distinguish between SM and its extension using the measurements in the first region.

6. Beauty production and QCD tests

LHC will probe kinematic regions of strong interactions that have not yet been explored. Compared with previous hadron experiments this will be a higher collision energy, 14 TeV, and a wider Bjorken $x_{\rm F}$ region (ATLAS will be sensitive down to $x_{\rm F} \sim 10^{-4}$ [17]). The high b-production cross section will allow coverage of large transverse momenta, which were difficult to measure in previous experiments due to limited statistics. Larger number of events will also enable measurement of correlations between b-quarks and gluons, and multiple heavy flavour production allowing to test higher order QCD calculations. QCD is nowadays recognized as a well proven theory and new data are expected to determine the boundaries, within which the perturbation theory provides an adequate description.

To initiate a programme of ATLAS b-production studies we first made a comparison of Tevatron data with several models [18]. This allowed us to understand details of the measurements and of data interpretation. Limited statistics lead CDF and D0 experiments to use only semi-inclusive B-decay modes and required cuts leading to information loss. In particular they could not fully establish the contribution of events in which b and $\overline{b}$ quarks are produced close to each other. This region is important for measurements of higher order QCD contributions.

The ATLAS performance simulations were done for two exclusive channels, $B_d \to J/\psi(\mu\mu)\,K^0$ and $B_s \to J/\psi(\mu\mu)\,\phi$, for which $4,8 \times 10^5$ and $3,2 \times 10^5$ events respectively are expected after three years of low luminosity data taking.

To demonstrate a potential for a measurement of the azimuthal angle difference $\Delta\phi(b\bar{b})$ between b and $\overline{b}$ quarks two processes were selected:

$$\begin{aligned} \overline{b} &\to B_d \to J/\psi(\mu\mu)\,K^0, \quad && b \to \mu X\,, \\ \overline{b} &\to B_s \to J/\psi(\mu\mu)\,\phi, \quad && b \to \mu X\,. \end{aligned} \tag{7}$$

The reconstruction efficiency in these events remained acceptably high in cases where the azimuthal angle differences $\Delta\phi(J/\psi - \mu)$ between J/ψ and μ were small, Fig. 6, taken from [5].

Special attention was devoted to the background events in which the muon is produced from the decays $K^\pm, \pi^\pm \to \mu^\pm X$ instead of $b \to \mu X$. The study showed that this background is not problematic in B_d decays, however it is important in the case of the B_s^0 meson. This particle is composed of b and s quarks and so is always accompanied by the associated strange

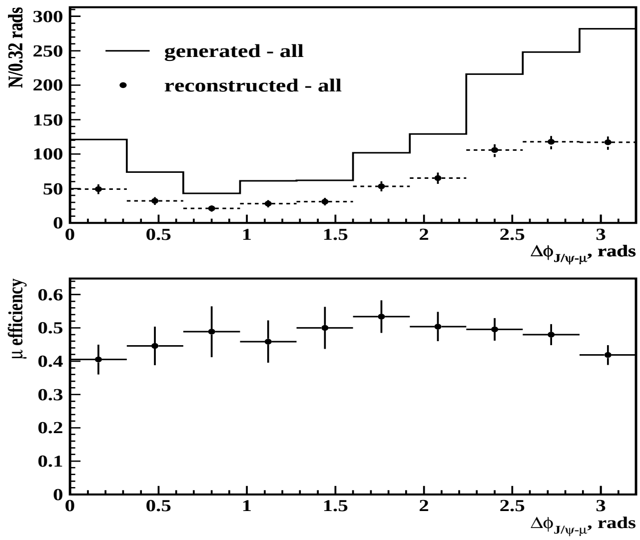

Fig. 6. ATLAS simulation of $b\,\overline{b}$ correlation measurements using events $B_d(J/\psi(\mu^+\mu^-)K^0)\mu X$. The azimuthal angle difference $\Delta\phi(J/\psi-\mu)$ for generated (full line) and reconstructed (points) events (upper figure), and the corresponding reconstruction efficiency (lower figure).

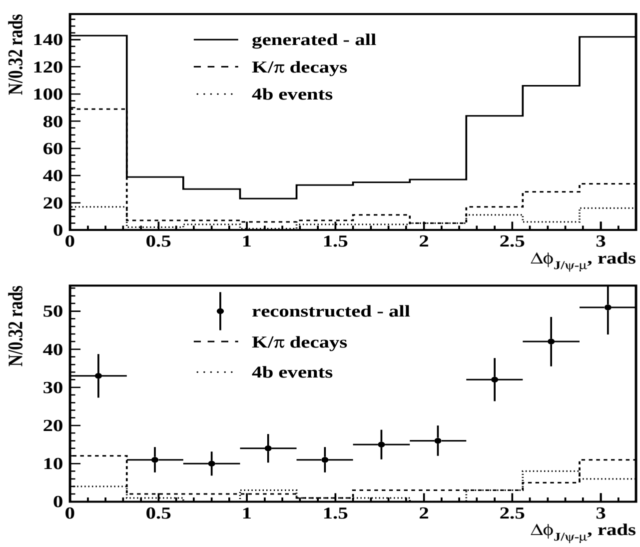

Fig. 7. ATLAS simulation of $b\,\overline{b}$ correlation measurements using events $B_s(J/\psi(\mu^+\mu^-)\phi)\mu X$. The distributions of azimuthal angle difference $\Delta\phi(J/\psi-\mu)$ for generated (upper figure) and reconstructed (lower figure) events.

quark, which mostly hadronizes to a K meson. The characteristic feature of this background is that the muon from the $K^{\pm}$ decay is correlated with the B_s^0 meson. After applying cuts to reject $K^{\pm}, \pi^{\pm} \rightarrow \mu^{\pm} X$ the contribution of this background is still important especially for high $p_{\rm T}$ events, $p_{\rm T}(B_s^0) > 50\,{\rm GeV}$, Fig. 7, taken from [17]. The results of this study show the importance of simultaneous measurements of $b\bar{b}$ correlations and of the production of $b\bar{b}\,s\bar{s}$ combinations.

The beauty production studies will be extended to the semi-inclusive events containing $b\bar{b} \rightarrow J/\psi(\mu^+\mu^-)X$ and to b-jets to access higher-$p_{\rm T}$ region.

7. Conclusions

The ATLAS studies clearly showed that the detector is well equipped for a multi-thematic b physics program. In CP violation the main emphasis will be on underlying mechanisms and the evidence of new physics. ATLAS is especially precise on β. Apart from e^+e^- B-factory "benchmark modes", the LHC gold-platted mode $B_s^0 \rightarrow J/\psi\phi$ was studied. B_s^0 physics studies made it clear that there is a sensitivity to a mass difference ΔM_s far beyond SM expectations. The rate difference $\Delta\Gamma_s$ can be in ATLAS best measured by $B_s^0 \rightarrow J/\psi\phi$. Important for rare decays is a possibility to continue the measurements at full LHC luminosity at which $B_s^0 \rightarrow \mu^+\mu^-$ with a SM ratio 10^{-9} can be observed already after one year. Precision measurements can be done for $B_d^0 \rightarrow K^{*0}\mu^+\mu^-$. Large statistics of exclusive or semi-inclusive B-decay channels, especially those with $J/\psi \rightarrow \mu^+\mu^-$, allow QCD tests on central b-production at LHC, in particular the correlations between b and $\overline{b}$. The ATLAS potential for b physics has not been fully explored yet and other studies in particular on B_c, $B_s \rightarrow J/\psi\eta$ and $B^+ \rightarrow K^+K^+\pi^-$ are ongoing.

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