Quarkonia and open beauty production in ATLAS

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Abstract

When the LHC starts up in 2009, ATLAS will have unique opportunities to study beauty production from pp collisions at ≥ 10 TeV making use of first data. In the initial phase of the LHC operation at lower luminosity several Standard Model physics analyses have to be performed to contribute to the commissioning and validation of the ATLAS detector and trigger system. One of the initial measurements is that of the inclusive $b\bar{b}$ production cross-section, quarkonium spectroscopy and polarization. Furthermore, the $B^+ \to J/\psi K^+$ channel will be an important reference channel for the search for di-muons from rare B decays and a control channel for the CP violation measurement used to estimate systematic uncertainties and tagging efficiencies at higher luminosities. Due to the huge $b\bar{b}$ cross-section and the expected high rates of the corresponding triggers, the data collection for beauty measurements can be done easily during the low luminosity phase. We describe the ATLAS expectations and strategies for open and hidden b-quark production where we expect to have first results already in the first few hundred pb^{-1} of data.

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1 Introduction

ATLAS [1] is a general-purpose experiment with main emphasis on searches for new phenomena based on high p_T particles. Since most of the B-physics appears in the lower p_T range, triggering within the LHC environment on those events is a challenge. Nevertheless, ATLAS has good capabilities for a rich B-physics program, based on the dedicated and flexible trigger, the precise and flexible vertexing and tracking, the good muon identification and the high-resolution calorimetry. Furthermore, theoretical descriptions of heavy flavored hadrons need input from the LHC, where precision measurements are already achievable after one year of data taking. The expected inclusive production cross-section for $b\bar{b}$ pairs at LHC is estimated to be $\sigma_{b\bar{b}} \approx 500\ \mu$b leading to more than 10^6 produced pairs per second at design luminosity. The experimental precision reached at ATLAS should at least allow the verification of the Standard Model (SM) prediction. In the case of the rare B-decays, clearly higher luminosity is needed to achieve sensitive upper limits for the indirect beyond the Standard Model (BSM) searches. Therefore, the most relevant part of the ATLAS B-physics program will take place in the initial phase at lower luminosities with an extension into the high luminosity phase. The envisaged measurements are extending the discovery potential for physics beyond the SM by the measurement of CP violation parameters, predicted to be to be small in the SM, and of rare B decays.

The exclusive B^+ channel provides a clean reference signal. Due to the clear event topology and its rather large branching ratio, it can be measured during the initial luminosity phase of the LHC. The $B^+ \to J/\psi K^+$ decay can serve as a reference channel for the measurement of the decay probability of a very rare decay channel $B_s \to \mu^+\mu^-$, which is strongly suppressed in the Standard Model and therefore offers a good sensitivity to new physics. The total and differential cross-sections of the rare B decays will be measured relative to the $B^+ \to J/\psi K^+$ cross-section allowing thus the cancellation of common systematic errors. Furthermore, it can also act as a control channel for the CP violation measurement and can be used to estimate the systematic uncertainties and efficiencies of flavour tagging algorithms. Finally, the relatively large statistics for this decay allows for initial detector performance studies.

The trigger menu for the ATLAS B-physics program has been designed to take maximum advantage of the early run phases at lower luminosities ($\mathcal{L} < 10^{33}$ cm^{-2}s^{-1}). Since only 5 - 10 % of the limited bandwidth of the ATLAS trigger system is devoted to the B-physics triggers, highly efficient and selective triggers are needed. Most B-physics triggers are based on single- and di-muon events in the final state leading to a clean signature for triggers and flavor tagging [2]. In the early data taking period the main B-physics triggers are expected to run without a need of prescales, allowing for low p_T muon and low E_T electron triggers (the latter will be however prescaled at 10^{32} cm^{-2} s^{-1}). In general, the trigger strategy is mainly based on a single muon trigger at the first level, which could be combined with certain calorimeter trigger objects at higher trigger levels to select hadronic final states ($B_s \to D_s\pi$) or e/γ final states ($J/\psi \to e^+e^-$, $K^*\gamma$ or $\phi\gamma$). In order to not exceed the available bandwidth, in the phase of higher luminosities above $2 \cdot 10^{33}$ cm^{-2}s^{-1} the main working trigger will be based on di-muons on the first level, enabling a clean measurement of rare B-decays ($B \to \mu\mu$ or $B \to K^{*0}\mu\mu$), double semi-leptonic decays and the $B \to J/\psi(\mu\mu)$ decay channels.

2 Beauty Production Cross-Section Determination

The $b\bar{b}$ production cross-section will be measured using inclusive and exclusive methods in parallel to control the systematics. For the inclusive methods ATLAS looks at the semi-leptonic $b \to \mu + X$ and the $B \to J/\psi(\to \mu^+\mu^-) + X$ decay modes. In the next section we will briefly describe the measurement of the exclusive $B^\pm \to J/\psi K^\pm$ cross-section. The measurement of the J/ψ mass and its detection efficiency is a central task for the analysis of the first ATLAS data, providing the tools to validate the detector by extracting muon energy scale determination in the low p_T region and detector misalignments (Sect. 5). Finally, the mass measurement and reconstruction efficiency for B^+, the total and differential cross-sections and its lifetime measurements will be of interest for other B-physics analyses.

The main backgrounds that are competing with the signal are single-muon from $c\bar{c}$ decays and direct J/ψ's from $pp \to J/\psi + X$. In the first case, the p_T distribution of the muons is softer as compared to the muon spectrum from $b\bar{b}$ decays while in the latter no displaced secondary vertex is expected. In consequence the following parameters are used for b-tagging:

- the signed transverse impact parameters d_0 of charged particles originating from B-meson decays at a secondary vertex due to the long lifetime of B-mesons.
- the relative transverse momentum $p_T^{\rm rel}$ of the muon of the b-decay with respect to the axis of the associated jet.

The measurement of the $p_T^{\rm rel}$ distribution of the selected muons offers a good possibility to determine the b-contents fraction in the offline analysis. In the rest frame of the decaying B-meson, the muon gets a high transverse momentum, which is significantly larger than in the case of charm or light quark decays. The relative transverse muon momentum, $p_T^{\rm rel}$ can therefore be used to determine the b-content of a selected data sample by fitting Monte Carlo templates to data. For the B-mesons at ATLAS, generally decay lengths of the order of several mm are expected which are at the same order of magnitude as the expectation for D-mesons. The signed transverse impact parameter d_0 is a boost independent quantity. For large transverse momenta ($p_T^\mu > 10$ GeV) d_0 is proportional to the lifetime of the decaying particle and positive values of d_0 are preferable. The significance of signed impact parameter for muons with an associated b-jet and the distributions of the relative transverse momentum are shown in Fig. 1 and Fig. 2 respectively. In both cases, the selection power is clearly visible.

The $b\bar{b}$ production cross-section measurement based on the single-muon and jet requirements at the trigger level is then obtained according to the usual relation

$$\sigma(b\bar{b} \to \mu(p_T^\mu > 6 \text{ GeV})X) = \frac{N_b^{\rm sel}}{\int \mathcal{L}\,\mathrm{d}t} \cdot \frac{f_b}{\epsilon_b^{\rm trig} \cdot \epsilon_b^{\rm rec}} \qquad (1)$$

where the b-trigger efficiency was found to be $\epsilon_b^{\rm trig} = 0.135$ and the combined muon reconstruction efficiency is $\epsilon_b^{\rm rec} = 0.85$. The determination of the b content, f_b, of the selected sample is extracted by fitting the simulated $p_T^{\rm rel}$ distribution to the data. This can be done by a binned maximum likelihood fit taking into account the finite size of both, the data sample and the simulated Monte Carlo templates. In

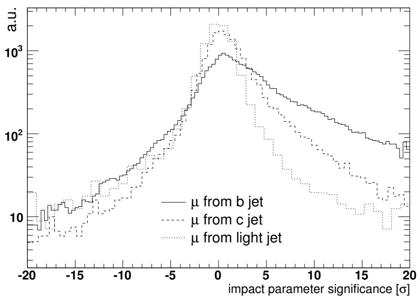

Fig. 1: The distribution of the significance of the signed impact parameter d_0/σ

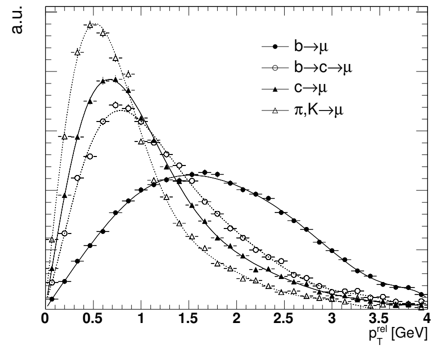

Fig. 2: The p_T^{rel} distribution for different processes considered in the b-jet selection.

the signal template, the direct $b \to \mu$ and cascade $b \to c \to \mu$ contributions are contained, whereas all others are summarized in the background template. The distribution can be seen in Fig. 3. With this fit, a b-content of $f_b = 0.23$ was obtained, and a corresponding background fraction of $f_{bg} = 0.77$. The values obtained in this study are in good agreement with the values obtained by the Tevatron experiments [3]. Combining both methods, the $b\bar{b}$ production cross-section is expected to be measured with a statistical precision better than $\mathcal{O}(1~\%)$ with $\approx 100~\mathrm{pb}^{-1}$ of integrated luminosity. The systematic uncertainty is dominated by the luminosity measurement. It is estimated to be $10~\%$ in the initial phase, and reduced to about $6.5~\%$ after the first $0.3~\mathrm{fb}^{-1}$. The scale uncertainty of the NLO calculations is about $5~\%$, while the PDF uncertainty is estimated to be $3~\%$. Finally, the uncertainty originating from the muon identification is about $3~\%$, leading to a systematic uncertainty of $12~\%$ and $9.2~\%$ correspondingly in the initial and later phase .

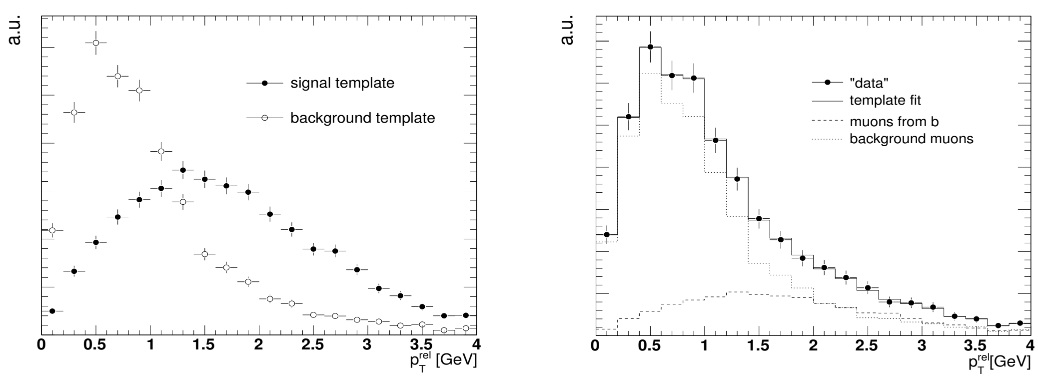

Fig. 3: The generated p_T^{rel} templates (left) and fraction of the b-content of the selected b-jet sample (right) showing comparison of the fitted to the true values from Monte Carlo.

3 B^+ Reference Channel

Negligible direct CP violation is expected in the $B^\pm \to J/\psi K^\pm$ decay because for $b \to c + \bar{c}s$ transitions the SM predicts that the leading and higher order diagrams are characterized by the same weak phase. The only source of asymmetry is the different interaction probability for K^+ and K^- with the detector material. The B^+ candidates are reconstructed based on the $J/\psi(\to \mu^+\mu^-)$ selection, and combined with K^+ candidates formed from inner detector tracks.

The B^+ invariant mass distribution $M(K^+\mu^+\mu^-)$ of the candidates, fulfilling the selection cuts, is presented in Fig. 4 for signal and background with a maximum-likelihood fit, where the likelihood function is a Gaussian for the signal region and a linear function for the background ($b\bar{b} \to J/\psi + X$). The mass range of the fit is taken from 5.15 GeV to 5.8 GeV in order to reduce contributions from partially reconstructed B meson decays. The background at the right of the mass peak originates from misidentified π^+ from $B^+ \to J/\psi\pi^+$ decays. The fit result for the B^+ mass is: $M(B^+) = (5279.3 \pm 1.1)$ MeV with a width of $\sigma(B^+) = (42.2 \pm 1.3)$ MeV. The relative errors, scaled properly for an integrated luminosity of about 10 pb^{-1}, are about 0.02% and 3.5% respectively. The slight shoulder to the left of the mass distribution is due to the background shape in this mass region and has been included in the systematic uncertainties of the fit model.

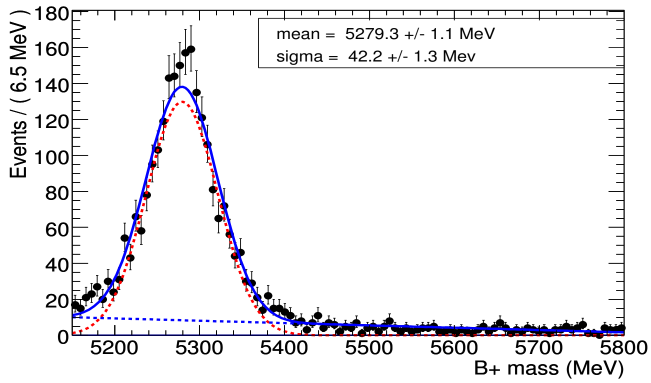

Fig. 4: B^+ mass fit with the both signal (red) and background (blue) contributions shown separately.

With the first 10 pb^{-1} of LHC data a total and differential production cross-section measurement of the $B^+ \to J/\psi K^+$ can be achieved. The differential cross-section $\mathrm{d}\sigma/\mathrm{d}p_T$ can be obtained from the usual form:

$$\frac{\mathrm{d}\sigma(B^+)}{\mathrm{d}p_T} = \frac{N_{\text{sig}}}{\Delta p_T \cdot \mathcal{L} \cdot \mathcal{A} \cdot \mathrm{BR}} \tag{2}$$

where N_{sig} is the number of reconstructed B^+ obtained from the mass fit and the size of the p_T bin is denoted with Δp_T. Furthermore, $\mathcal{L}$ is the total luminosity to which the dataset corresponds and is obtained from PYTHIA output and BR is the product of the branching ratios using the world average [4] branching ratios of $\mathrm{BR}(B^+ \to J/\psi K^+) = (10.0 \pm 1.0) \times 10^{-4}$ and $\mathrm{BR}(J/\psi \to \mu^+\mu^-) = (5.88 \pm 0.10) \times 10^{-2}$. The overall efficiency $\mathcal{A}$ is calculated for each p_T range separately as the ratio of the number of signal events determined from the previous fit procedure and the number of the Monte Carlo signal events within the same p_T range. To measure the B^+ total cross-section a similar procedure with that used for the calculation of the differential cross-section is followed.

The measurement of the lifetime τ of the selected B^+ candidates is a sensitive tool to confirm the beauty content in a sample, in particular the number of the reconstructed $B^+ \to J/\psi K^+$ decays obtained in the $b\bar{b} \to J/\psi X$ dataset. The proper decay-time is defined as $t = \lambda/c$. The proper decay-time distribution in the signal region $B^+ \to J/\psi K^+$ can be parametrized as a convolution of an exponential function with a Gaussian resolution function, while the background distribution parametrization consists of two different exponential functions, where each is convoluted with a Gaussian resolution function. In the $b\bar{b} \to J/\psi X$ no zero lifetime events are expected since there is no prompt J/ψ produced. In the realistic case, where zero lifetime events will be present, an extra Gaussian centered at zero is needed in order to properly describe those events.

The results on the lifetime measurements are shown in Fig. 5. The background can be best described with the two lifetime components (τ_1 and τ_2). For the events in the mass region of the signal within $M(B^+) \in [5.15, 5.8]$ GeV the proper decay-time found from the decay length is compared to the generated B^+ lifetime. The differences are well centered at zero with a Gaussian distribution and sigma 0.088 ps. It should be noted that the resolution as well as its σ in η bins of 0.25 is found to be independent of η.

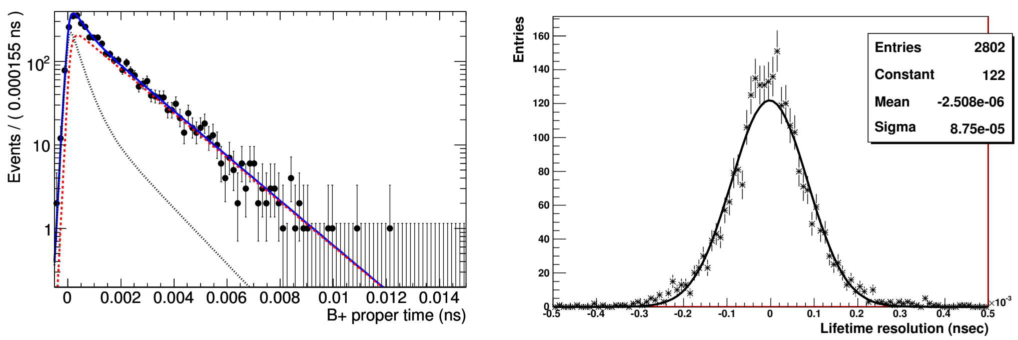

Fig. 5: The B^+ lifetime fit (left) with the signal (dashed red) and the background (dashed black) contributions shown separately. The B^+ lifetime resolution (right).

4 Open Flavor: Rare B-Decays

Flavor changing neutral currents, a direct transition from $b \to d/s$, are forbidden at the tree level in the SM and occur at the lowest order through one loop diagrams. They are a sensitive test of the SM and its possible extension(s), providing information on the long distance QCD effects and enabling a determination of the CKM matrix elements $|V_{td}|$ and $|V_{ts}|$. Furthermore, some of the rare decay channels contribute to the background for other channels, which are very sensitive to BSM effects.

An upper limit of the branching ratio $BR(B_s^0 \to \mu^+\mu^-) = (1-2) \cdot 10^{-8}$ at 90 % confidence level or of $(2-3) \cdot 10^{-8}$ at 3σ evidence based on $N_B = 1.1$ events that can already be extracted from an integrated luminosity of 2 fb^{-1}. This is clearly better than the current CDF limit of $4.7 \cdot 10^{-8}$ at 90 % confidence level. Already at 1 fb^{-1} ATLAS is able to collect $\mathcal{O}(10^6)$ di-muon events in the mass window of 4 GeV $< M(\mu^+\mu^-) <$ 7 GeV. This is after the selection based on cuts on p_T, the invariant mass $M_{\mu^+\mu^-}$, the transverse decay length L_{xy} of the di-muon system, and on isolation requirements. Based on this data, an upper limit on the number of signal events, N_B, corresponding to a given confidence level will be determined. The main background sources originate from combinatorial decays as $b\bar{b} \to \mu^+\mu^- X$, from misidentifications ($B_s^0 \to \pi^+\pi^-$, $B_s^0 \to K^+K^-$, $B_s^0 \to \pi^+K^-\nu_\mu$) or from other rare decays ($B_s^0 \to \mu^+\mu^-\mu^+\nu_\mu$, $B_s^0 \to \mu^+\mu^-\gamma$). N_B will be used to extract the upper limit on the $B_s^0 \to \mu^+\mu^-$ branching ratio $BR(B_s^0 \to \mu^+\mu^-)$, using the reference channel $B^+ \to J/\psi K^+$ as described in Sec. 3, since trigger and offline reconstruction efficiencies largely cancel for di-muons in these channels. In this procedure, a ratio of geometric and kinematical acceptances of the signal and the reference channel will be determined from the Monte Carlo simulations. With an integrated luminosity of 30 fb^{-1}, corresponding to three years of initial data taking, the SM predictions could be tested with a 3 σ sensitivity. The continuation of this measurement at nominal LHC luminosities has been proved to lead to a clear statement with a 5 σ sensitivity after already one additional year of data taking at design luminosity of 10^{34}cm^{-2}s^{-1}.

5 Quarkonia

Understanding the production of prompt quarkonia at the LHC is an important step to understand the underlying QCD mechanisms, and one that has given rise to controversy, both with respect to the cross-section magnitude [5] and the polarization [6]. The initial discrepancy in cross-section led to the Color Octet Model [7] but more high p_T results are needed to distinguish between this and competing models.

In addition to these open questions, the narrow J/ψ and Υ resonances are ideal for studies of detector performance. The expected abundant production (see Fig. 6) makes this feasible already in the very early data. Both decay channels $J/\psi\ (\Upsilon) \rightarrow \mu^+\mu^-$ and $J/\psi\ (\Upsilon) \rightarrow e^+e^-$ will be used as tools to test

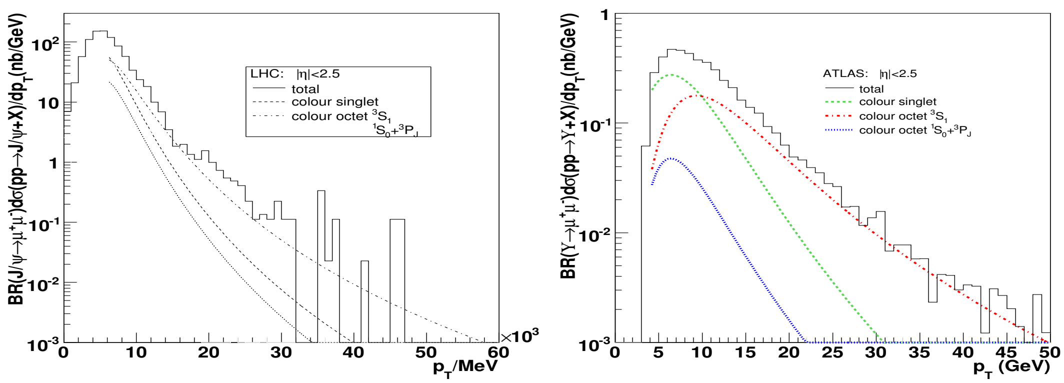

Fig. 6: Differential J/ψ and Υ cross-sections as predicted from the Color Octet Model. Contributions from (singlet) χ production is included.

our detector performance. In the following we consider only the J/ψ and $\Upsilon(1S)$ resonances. Quarkonia selection in ATLAS is mainly based on a di-muon trigger which requires two identified muons, both with $p_T \geq 4$ GeV and within a pseudorapidity of $|\eta| < 2.4$. The di-muon sample considered here has offline p_T cuts of 6 and 4 GeV applied to the two identified muons. To suppress backgrounds (decays-in-flight, heavy flavor decays) we require tracks to come from the same vertex and with a pseudo-proper time cut of $\tau = 0.2$ ps, defined as $\tau = \frac{M \cdot L_{xy}}{p_T(J/\psi)\cdot c}$. In Fig. 7 (left) the resulting di-muon spectrum with background contributions is shown. We expect 15000 J/ψ's and 2500 $\Upsilon(1S)$ per pb^{-1}. The mass resolution for $J/\psi \rightarrow \mu^+\mu^-$ is expected to be 53 MeV, and for $\Upsilon \rightarrow \mu^+\mu^-$ we found 161 MeV on average.

We are also studying the possibility of doing performance measurements using di-electron resonances. In that case the E_T cut for both leptons is 5 GeV at trigger level and offline, and $|\eta| < 2$. Tight electron identification cuts are applied to reject background, including E/p, vertexing layer hit on the tracks, and the ratio of high to low threshold hits in the transition radiation tracker. We expect 2500 J/ψ's and 500 $\Upsilon \rightarrow e^+e^-$ per pb^{-1} with an instantaneous luminosity of 10^{31} cm^{-2} s^{-1}. The mass resolution for $J/\psi \rightarrow e^+e^-$ is expected to be about 200 MeV, see Fig. 7 right. The width is mainly constrained by bremsstrahlung due to the large amount of material in the inner detector.

In addition to cross-section measurements ATLAS will use the quarkonia di-muon decays to provide answers to the polarization puzzle and help constrain the models. Defining the polarization parameter α as $\alpha = (\sigma_T - 2\sigma_L)/(\sigma_T + 2\sigma_L)$, we can measure this by θ^*, the angle between J/ψ in rest frame and μ^+, as they are related by:

$$\frac{dN}{d\cos\theta^*} = C \cdot \frac{3}{2\alpha + 6} \cdot (1 + \alpha\cos^2\theta^*) \tag{3}$$

With the di-muon triggers we get a rather narrow $\cos\theta^*$ distribution, with both muons having similar p_T. To access higher values of $\cos\theta^*$ we utilize a single muon trigger where we can pair the trigger muon with a low p_T track to get large Δp_T and $\cos\theta^*$ (see Fig. 8 left). For the result quoted here we used a trigger threshold of 10 GeV for the single muon trigger and the p_T requirement on the second track was 0.5 GeV. The looser cuts allow for more background but still with decent signal to background discrimination

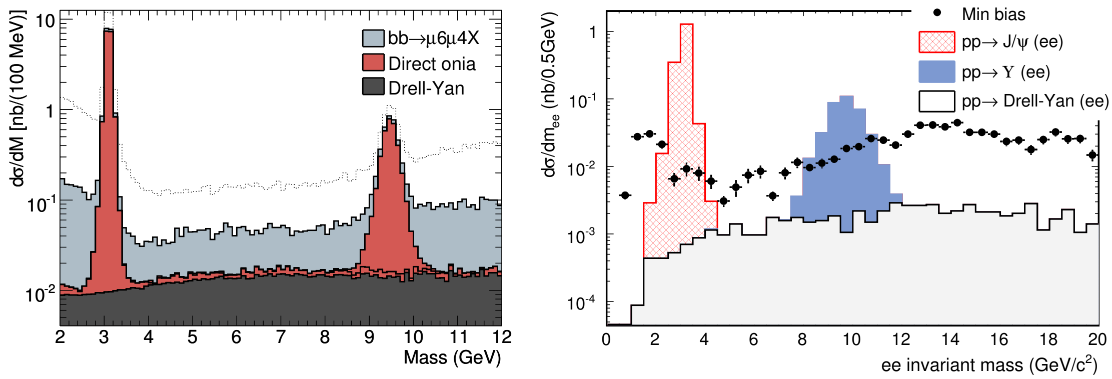

Fig. 7: Di-electron mass distributions for muons (left) and electrons (right). In the left plot the spectrum in case of no vertex cuts (top dashed line) is also shown.

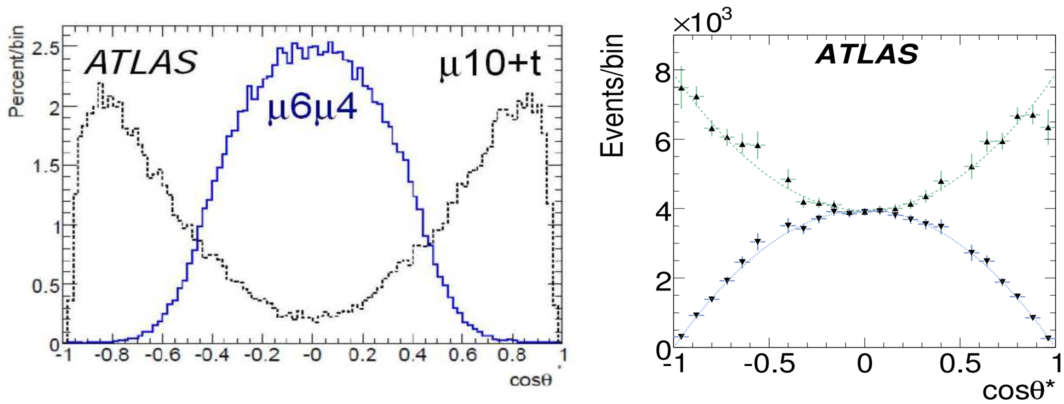

Fig. 8: Left: $\cos\theta^*$ distributions for double and single muon triggered events. Right: Fit to combined events in $p_T \in [12, 13]$ GeV. Top shows longitudinally polarized ($\alpha = -1$) and bottom transverse polarized ($\alpha = 1$) events.

($S/B = 1.2$ for J/ψ). This dataset was added (with corrections for overlaps) to complement the di-muon triggered dataset. The combined $\cos\theta^*$ distributions were then fitted for α and C in slices of p_T. With unpolarized samples the results are given in Table 1 for 10 pb^{-1}. Similar tests have been carried out with $\alpha = \pm 1$. An example is shown in Fig. 8 right.

We expect to be able to measure the J/ψ polarization with the p_T of the J/ψ in the range of 10 GeV (trigger dependent) up to 50 GeV. Already with the first 10 pb^{-1} we can achieve better precision than the current Tevatron measurements - but with J/ψ at high p_T, which is what is needed to truly distinguish between models. For $\Upsilon(1S)$ we can get the same precision with 100 pb^{-1}. In this latter case we have acceptance all the way down to $p_T \approx 0$ for the Υ, which will be a very useful region to compare with the Tevatron results.

6 Conclusions

The ATLAS experiment has a rich B-physics program [8] based on clearly defined trigger strategies for all luminosity phases of the LHC. These measurements will contribute to CP violation studies with B_s-mesons and its sensitivity to BSM as well in studies of rare B decays and quarkonia production. The precision measurement of B-physics processes are an alternative method to explore the presence of new physics at LHC in addition to the direct SUSY searches.

Table 1: 10 pb^{-1}: Measured values of α in p_T bins in simulated datasets with α = 0

p_T (GeV)	9 - 12	12 - 13	13 - 15	15 - 17	17 - 21	> 21
$\alpha(J/\psi)$	0.156 $\pm$0.166	-0.006 $\pm$0.032	0.004 $\pm$0.029	-0.003 $\pm$0.037	-0.039 $\pm$0.038	0.019 $\pm$0.057
$\alpha(\Upsilon)$	-0.42 $\pm$0.17	-0.38 $\pm$0.22	-0.200 $\pm$0.20	0.08 $\pm$0.33	-0.15 $\pm$0.18	0.47 $\pm$0.22

Two inclusive methods for beauty cross-section measurements to be used mainly at the early data taking period of ATLAS were presented. The first method is using the J/ψ signature with detached vertices, while the second one is based on semileptonic $b \to \mu$ decays. The two methods are complementary and the plan is to apply them simultaneously since both signatures will be available with early data. The two methods rely on different trigger algorithms and different physics processes and signatures, therefore the cross-section results obtained from each one can be used for cross checking calibrations of the trigger algorithms used in the measurements. Combining these two methods, the $b\bar{b}$ production cross-sections measurement is expected to reach a statistical precision of $\mathcal{O}(1\ \%)$ after one month of data taking, if the initial LHC luminosity will be $\mathcal{L} = 10^{31}\ \mathrm{cm^2 s^{-1}}$, whereas a systematic uncertainty of $\mathcal{O}(12\ \%)$ is expected. Furthermore, the reference channel $B^+ \to J/\psi K^+$ has been studied and it could be shown, that a lifetime measurement is a good tool to confirm the b content of the selected sample.

In the first data taking period ATLAS will also measure the J/ψ and Υ cross-sections, taking advantage of the favorable trigger situation in the early data. A method to determine the level of polarization is also presented. We expect to measure the J/ψ polarization to within 0.02 - 0.06 in the first 10 pb^{-1}, dependent on the polarization itself.

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