Charm and Bottom Production Measurements at the LHC

Wolfgang Walkowiak
on behalf of the ATLAS and CMS collaborations

University of Siegen, Department of Physics, Experimental Particle Physics,
57068 Siegen, Germany

Early data of the ATLAS and CMS experiments at the LHC will allow us to measure the cross sections for beauty and heavy quarkonia production in $pp$ collisions at a center-of-mass energy of 14 TeV to a reasonable precision. Different experimental approaches employing single or di-muon triggered events and $b$-tagging methods are discussed. The potential for extracting the polarization of vector states from the decays $J/\psi \rightarrow \mu^+\mu^-$ and $\Upsilon \rightarrow \mu^+\mu^-$ is presented.

1 Introduction

The Large Hadron Collider (LHC) at CERN is expected to start operating in 2008. With an expected $b\bar{b}$ cross section $\sigma_{b\bar{b}}$ of approximately 500 $\mu$b, corresponding to one $b\bar{b}$ event in 100 proton-proton collisions, the LHC provides about $2 \times 10^{12} b\bar{b}$ per year (at $\mathcal{L} = 10^{-33}$ cm$^{-2}$s$^{-1}$). However, due to uncertainties in the extrapolation of $\sigma_{b\bar{b}}$ from measurements at lower energies being as large as a factor two, it is necessary to measure $\sigma_{b\bar{b}}$ as well as differential cross sections as functions of $p_T$ and $\eta$ with early LHC data.

The measurement of the production cross sections $\sigma_{J/\psi}$ and $\sigma_{\Upsilon}$ for prompt heavy quarkonia, i.e. bound states of $c\bar{c}$ and $b\bar{b}$ quarks, provide a good testbed for various QCD models. The theoretical description of the measured excess, e.g. in the direct $J/\psi \rightarrow \mu^+\mu^-$ cross section $\frac{d\sigma_{J/\psi}}{dp_T}$ at CDF, required a contribution in addition to the color singlet model (CSM). Although the color octet model (COM), which includes an evolution of the quark-antiquark quantum mechanical state produced to the bound quarkonium state, describes $\frac{d\sigma_{J/\psi}}{dp_T}$ well, some predictions of the COM for the polarization of quarkonia decays such as $\Upsilon \rightarrow \mu^+\mu^-$ are very different from Tevatron data.

The trigger strategies for $B$ physics and quarkonia at ATLAS and CMS rely on single and di-muon trigger elements with low $p_T$ thresholds. At Level 1, implemented in hardware, single muon trigger thresholds from $p_{T,\mu} > 4$ GeV upwards and di-muon $p_T$ thresholds as low as

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*aEmail: wolfgang.walkowiak@cern.ch*
\[ p_{T,\mu} > 3 \text{ GeV} \] will be employed, depending on the instantaneous luminosity. The software-implemented higher level trigger algorithms (HLT) will partially reconstruct exclusive \( B \) decays involving e.g. \( D_s \rightarrow \phi \pi \) and \( J/\psi \) to \( e/\gamma \) or \( \mu^+\mu^- \) final states. CMS plans to implement an inclusive trigger for charm and bottom decays using b-tagging algorithms. At ATLAS the single muon trigger rate is expected to reach approximately 10 kHz (with \( p_{T,\mu} > 6 \text{ GeV} \) at \( \mathcal{L} = 10^{33} \text{ cm}^{-2}\text{s}^{-1} \)) with the di-muon trigger rate being about two orders of magnitude lower. Prompt \( J/\psi \rightarrow \mu^+\mu^- \) production contributes at the level of a few Hertz only.

## 2 b Cross Section Measurements

Two methods for the measurement of the inclusive \( b \) cross section at low \( p_T \) have been studied by ATLAS for the early data taking period. The first method considered employs a di-muon \( J/\psi \) trigger (\( p_{T,\mu} > 4 \text{ GeV} \)), applies offline cuts of 6 and 4 GeV \( p_T \) to the two identified muons and reconstructs the \( J/\psi \rightarrow \mu^+\mu^- \) signature requiring a detached \( J/\psi \) vertex. Requesting a minimum impact parameter of the leading muon of 0.08 mm results in an efficiency of about 60% for the \( b\bar{b} \rightarrow J/\psi X \) signal decays while almost all prompt \( J/\psi \) events are rejected (Fig. 1). The second method is based on semileptonic \( b \rightarrow \mu \) decays. A single muon (\( p_{T,\mu} > 6 \text{ GeV} \)) plus a jet region-of-interest is required (13.5% trigger efficiency). Events containing \( b \)-induced jets are enriched using \( b \)-jet weight tagging and exploiting the fact that the relative momentum of an associated muon w.r.t. the jet axis \( p_{T,\text{rel}} \) is on average larger for jets containing a \( b \) particle than for other jets. The signal reconstruction efficiency amounts to 85%. A fit of the simulated data to shape templates in \( p_{T,\text{rel}} \), which are determined from Monte Carlo, is used to extract the relative fractions of signal (\( b \rightarrow \mu \) and \( b \rightarrow c \rightarrow \mu \)) and background (\( c \rightarrow \mu \) and \( \pi/K \rightarrow \mu \)) events (Fig. 2).

A statistical precision of the \( b\bar{b} \) cross section measurement of \( \mathcal{O}(1\%) \) after typically one month of data taking is expected (at \( \mathcal{L} = 10^{31} \text{ cm}^{-2}\text{s}^{-1} \) or higher), with estimated systematic uncertainties of approximately 9% for 300 pb\(^{-1} \).

In an ATLAS study for the channel \( B^+ \rightarrow J/\psi K^+ \), a di-muon \( J/\psi \) trigger is used (82% efficiency). The offline algorithms reconstruct \( J/\psi \) candidates (\( p_{T,\mu_1} > 6 \text{ GeV}, p_{T,\mu_2} > 3 \text{ GeV} \)) requiring a displaced vertex (\( \lambda > 100 \mu m \)) with an efficiency of 55.8% to reduce combinatorial background from prompt \( J/\psi \). Adding an additional track with \( p_T > 1.5 \text{ GeV} \) and a large impact parameter, the \( B^+ \) candidates are selected by cuts on the vertex displacement (\( \lambda > 100 \mu m \)) and
on a mass window of $\pm 120$ GeV around the nominal $B^+$ mass. An overall signal reconstruction efficiency of $(29.8 \pm 0.84)\%$ and a $B^+$ mass resolution of $(42.2 \pm 1.3)$ MeV are obtained. An early data sample of e.g. $13.2 \text{ pb}^{-1}$, corresponding to about $2100$ signal events, will allow us to measure the cross section and mass resolution to about $3\%$ and the $B^+$ lifetime to about $2\%$ statistical precision.

The CMS study for an inclusive $b$-jet cross section measurement\cite{5} requires a trigger on a single muon of $p_{T,\mu} > 14$ GeV within $|\eta| < 2.1$ at Level 1 (18% efficiency) and a muon of $p_{T,\mu} > 19$ GeV and a jet with $E_{T,jet} > 50$ GeV within $|\eta| < 2.4$ at the HLT (60% efficiency). The offline selection combines a $b$-tagged jet with similar properties, reconstructed with 65% (55%) efficiency in the barrel (endcap), with a muon associated with this jet. The total efficiency of about 5% results in 16 million $b\bar{b}$ events per $10 \text{ fb}^{-1}$. Again, the relative momentum of the muon w.r.t. the $b$-jet axis $p_{rel}^T$ is used in order to extract the $b$-jet fraction from a shape template fit, see Fig. 3. The light-quark background shape will be derived directly from data by applying an anti-$b$-tag selection, while the shapes of the $b$ and $c$ contributions will be taken from Monte Carlo. The $b$-jet purity varies from 70% to 55% as the jet $p_T$ increases. We expect to observe $B$ hadrons with a $p_T$ up to 1.5 TeV. Fig. 4 displays the estimated statistical, systematic and total uncertainty as a function of the $b$-tagged jet $p_T$. The systematic uncertainties are dominated by uncertainties in the jet energy scale (12%) and in the fragmentation modelling (9%).

### 3 Heavy Quarkonia

For the measurement of the prompt $J/\psi$ and $\Upsilon$ cross sections, the ATLAS collaboration plans to use two methods. The first method relies on a di-muon trigger ($p_{T,\mu} > 4$ GeV), applies offline cuts of 6 and 4 GeV $p_T$ to the two muon tracks and requires them to originate from the primary vertex (pseudo-proper time < 0.2 ps). Within a mass window of $m_{J/\psi}^{PDG} \pm 300$ MeV ($m_{\Upsilon}^{PDG} \pm 1$ GeV) about 150 000 $J/\psi$ (25 000 $\Upsilon$) are reconstructed with a signal over background ratio of $S/B = 60$ (10) per 10 pb$^{-1}$, see Fig. 5. The second method employs a single muon trigger ($p_{T,\mu} > 10$ GeV), requires a track within a cone of $\Delta R < 3$ around the muon direction and forces both to originate from the primary vertex. About 160 000 $J/\psi$ (20 000 $\Upsilon$) with a lower $S/B = 1.2$ (0.05) are selected per 10 pb$^{-1}$. A combined measurement precision on the 1% (5%) level is estimated for $d\sigma/dp_T$ for 10 pb$^{-1}$ of $J/\psi$ ($\Upsilon$) events.

The CMS collaboration plans similar measurements, relying on the reconstruction of $J/\psi$ mesons. As an example for CMS’s capabilities\cite{6}, the extraction of $J/\psi$ mesons from 200 000
Monte Carlo $B_s \rightarrow J/\psi (\mu^+ \mu^-) \phi$ events results in an overall Level 1 trigger plus reconstruction efficiency of 10.1%. A $J/\psi$ mass resolution of 34 MeV is achieved.

In order to extract the $J/\psi$ and $\Upsilon$ polarizations $\alpha = (\sigma_T - 2\sigma_L)/(\sigma_T + 2\sigma_L)$ the simulated data are fitted to the acceptance-corrected $\cos \theta^*$ distributions, where $\theta^*$ specifies the polarization angle of the $\mu^+$ w.r.t. the $J/\psi$ momentum in the rest frame of the $J/\psi$. Because of the different kinematic acceptance regions in $\cos \theta^*$ of the di-muon and single-muon trigger cuts, the sensitivity may improve when both samples are combined. As shown in Fig. 6, the different polarization states of the $J/\psi$ can be distinguished well. With 10 pb$^{-1}$ of data, ATLAS estimates the statistical precision for the measurement of $\alpha$ in $p_T$ bins up to 20 GeV to be of order 0.02 – 0.06 for $J/\psi$, depending on the level of polarization itself, and of order 0.20 in the case of the $\Upsilon$.

4 Conclusions

The ATLAS and CMS collaborations are preparing to measure the cross sections for beauty and heavy quarkonia production at low $p_T$ via methods involving muonic decays or the $p_T^{rel}$ method, and for higher $p_T$ using $b$-tagging methods. These and measurements of the polarization of $J/\psi$ and $\Upsilon$ mesons will be performed with early data (10 to 100 pb$^{-1}$).

5 Acknowledgements

We are indebted to our colleagues in ATLAS and CMS, and the funding agencies supporting the experiments. We thank the Moriond QCD team for organizing this excellent conference, and are grateful to the German Ministry for Education and Research (BMBF) for financial support.

6 References

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