**Measurement of the Bottom Quark Production Cross-section in
Proton - Antiproton Collisions at $\sqrt{s} = 0.63$ TeV.***UA1 Collaboration, CERN, Geneva, Switzerland*

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ABSTRACT

We summarize the results obtained in the UA1 experiment on the production of bottom quarks in proton-antiproton collisions at $\sqrt{s} = 0.63$ TeV. Independent muon data samples are used to determine the bottom quark production cross-section in different transverse momentum ranges from 6 to 30 GeV. A recent theoretical calculation to $O(\alpha_s^3)$ of the inclusive bottom quark transverse momentum spectrum in hadronic collisions shows reasonable agreement with the data. We extrapolate the integral P_T distribution to $P_T = 0$ and in rapidity to estimate the total cross-section for the production of bottom quark pairs. Assuming the shape in P_T and rapidity given by the $O(\alpha_s^3)$ calculation, we obtain $\sigma(\bar{p}p \rightarrow b\bar{b}+X) = 10.2 \pm 3.3 \mu\text{b}$.

The CERN proton-antiproton collider is a heavy quark factory; charm and bottom quarks are produced with large cross-sections [1]. If it is not too heavy, the top quark should also be produced at a detectable rate. A limit [2] on the top quark mass, $m_t > 44 \text{ GeV}$, has been obtained in UA1 by comparing a lower bound of the $t\bar{t}$ production cross-section based on lowest order QCD calculations with the 95% C.L. upper limit on the production cross-section from muon-jet measurements. Recently, Nason et al. have completed a full QCD calculation to $O(\alpha_s^3)$ of the heavy quark total production cross-section in hadronic collisions [3]. The full calculation by the same authors of the heavy quark differential spectrum $d^2\sigma/dy dP_T^2$ is expected soon and preliminary results have already been presented [4].

In this letter we summarize the results obtained in UA1 on the inclusive b-quark cross-section in the central rapidity region, $|y| < 1.5$, using four different muon data samples. From each data sample we extract the inclusive cross-section for b-quarks produced with transverse momentum $P_T^b > P_T^{\min}$. The total production cross-section, $\sigma(\bar{p}p \rightarrow b\bar{b}+X)$, is then obtained by extrapolating the integral transverse momentum distribution to $P_T^{\min} = 0$.

Bottom quarks are not directly identified in UA1, but they can be tagged by the presence of one or more muons embedded inside a hadronic jet. The detector and muon triggering system of the experiment have been used to accumulate four different muon data samples which are discussed extensively in our previous publications [1,5,6,7]. We find that the dominant source of events with high- P_T muons inside jets is strong production of $b\bar{b}$ pairs. Charm and bottom quarks are produced at large P_T with similar rates, but the harder bottom fragmentation results in a harder P_T spectrum of muons. Thus when a muon P_T cut is applied, $b\bar{b}$ production is enhanced with respect to $c\bar{c}$ production.

The cross-section which is measured at the muon level, $\sigma_{\text{UA1}}(\text{muon-level})$, is related to the quark-level cross-section by fragmentation functions, branching-ratios and decay kinematics. All of these have been studied extensively in experiments at e^+e^- colliders and are well understood. The method used to calculate cross-sections for b-quark production in our analysis is the following: We use QCD to calculate a differential cross-section, $d\sigma/dP_T^b$, for the purposes of evaluating the acceptance to detect bottom events in our muon sample. We calculate the cross-section for events fulfilling our selection criteria at the muon level, $\sigma_{\text{MC}}(\text{muon-level})$, using a Monte Carlo program to integrate over fragmentation functions, and to include branching-ratios and the decay kinematics. We choose to quote the b-quark cross-section for $P_T^b > P_T^{\min}$, where $P_T^{\min}$ is defined such that 90% of the muon events have $P_T^b > P_T^{\min}$. The b-quark cross-section, $\sigma_{\text{UA1}}(P_T^b > P_T^{\min})$, is then obtained using the following expression:

$$\sigma_{\text{UA1}}(P_T^b > P_T^{\min}) = \sigma_{\text{UA1}}(\text{muon-level}) \cdot \frac{\sigma_{\text{MC}}(P_T^b > P_T^{\min})}{\sigma_{\text{MC}}(\text{muon-level})}.$$

The cross-sections are the sum of the b-quark and $\bar{b}$ -antiquark inclusive cross-sections. We add in quadrature the independent statistical and systematic errors discussed below.

The ratio of Monte Carlo cross-sections depends on the assumed shape of the quark-level cross-section, but not on its normalization. We use the ISAJET Monte Carlo program [8] to calculate $d\sigma/dP_T^b$, using $O(\alpha_s^2)$ QCD matrix elements [9], convoluted with EHLQ set I structure functions [10]. Only the flavour creation processes ($gg \rightarrow b\bar{b}$ and $q\bar{q} \rightarrow b\bar{b}$) are included in the calculation (except for the high-mass dimuon sample where all processes are included). In ISAJET, the additional processes of flavour excitation ($gb \rightarrow gb$ and $qb \rightarrow qb$) and gluon splitting (e.g. $gg \rightarrow gg$; $g \rightarrow b\bar{b}$) can be calculated in a parton shower approximation. If these were included, the different shape of the differential cross-section, shown in Fig. 1, would lead to a slightly lower cross-section ratio. The maximum size of this effect is a 20% shift in the cross-section ratio; motivated by this we use 20% as the systematic error due to our lack of knowledge of the shape of $d\sigma/dP_T^b$. The shape of the full $O(\alpha_s^3)$ QCD curve of Nason et al. is very similar to the $O(\alpha_s^2)$ curve which we have used, as discussed later.

Heavy quark fragmentation is parameterized in ISAJET using the Peterson et al. form [11], characterized by a parameter, ϵ , which depends on the mass of the quark. We use $\epsilon_c = 0.30$ to reproduce the measured fragmentation $c \rightarrow D^*$; for bottom we use $\epsilon_b = 0.02$ obtained by tuning ISAJET to reproduce e^+e^- data [12]. The uncertainty on ϵ_b ($0.001 < \epsilon_b < 0.05$) results in a 20% error on the Monte Carlo cross-section ratio. B-hadron semi-leptonic decays are modelled in ISAJET using V-A matrix elements and an average semi-muonic branching-ratio of 12.0% [13]. We have checked that ISAJET reproduces the lepton spectrum resulting from B-hadron decays at the $Y(4S)$. We estimate a 10% error on the Monte Carlo cross-section ratio due to the uncertainty on both the shape and the normalization of the lepton spectrum from B-hadron semi-leptonic decays.

The muon level cross-sections and their experimental errors are given below for the four muon data samples; more details can be found in the relevant references [1,5,6,7]. The quoted uncertainties include the statistical error and the systematic errors on the integrated luminosity (15%), on the subtraction of backgrounds and on the acceptance.

i) The J/ψ sample [6] consists of 434 unlike-sign dimuon events where one muon has to satisfy the cut $P_T(\mu) > 3$ GeV and the muon pair has to satisfy $P_T(\mu\mu) > 4$ GeV. A clear signal of 293 ± 22 $J/\psi \rightarrow \mu^+\mu^-$ events is observed from which we derive a branching-ratio times cross-section for J/ψ production at large P_T : $B(J/\psi \rightarrow \mu^+\mu^-) \cdot \sigma(\bar{p}p \rightarrow J/\psi + X) = 7.5 \pm 0.7(\text{stat}) \pm 1.2(\text{syst})$ nb for $P_T^{J/\psi} > 5$ GeV in the rapidity range $|\eta| < 2$. Two mechanisms lead to large- P_T J/ψ production in hadronic reactions: (1) High- P_T production of charmonium, mainly χ states [14] followed by $\chi \rightarrow J/\psi + \gamma$ and (2) high- P_T b-quark production followed by $b \rightarrow J/\psi + X$. Only the second mechanism gives J/ψ inside jets. An analysis of the topology of the J/ψ events leads to a branching-ratio times cross-section $B(J/\psi \rightarrow \mu^+\mu^-) \cdot \sigma(\bar{p}p \rightarrow b \rightarrow J/\psi + X) = 1.8 \pm 0.6 \pm 0.9$ nb for $J/\psi \rightarrow \mu^+\mu^-$ production via B-hadrons with $P_T^{J/\psi} > 5$ GeV in the rapidity range $|\eta| < 2$.

The predicted transverse momentum spectrum of the parent bottom quarks producing J/ψ 's with $P_T > 5$ GeV is shown in Fig. 2a. The arrow indicates the value $P_T^{\min} = 6$ GeV, chosen such that 90% of the parent b-quarks have $P_T > P_T^{\min}$. The distribution is relatively narrow: Because of its large mass, the J/ψ takes most of the transverse momentum of the parent b-quark.

Taking $B(b \rightarrow J/\psi) = 1.2 \pm 0.3$ % and $B(J/\psi \rightarrow \mu^+ \mu^-) = 6.9 \pm 0.9$ % [15], and using the method described above, we extract the cross-section:

$$\sigma(\bar{p}p \rightarrow b \text{ or } \bar{b} + X, P_T > 6 \text{ GeV}, |\eta| < 1.5) = 4.5 \pm 3.2 \text{ } \mu\text{b}.$$

ii) *The high-mass dimuon data* [1] consist of 512 dimuon events with $P_T(\mu_1) > 3$ GeV, $P_T(\mu_2) > 3$ GeV and $M(\mu\mu) > 6$ GeV. After subtraction of the background (mainly from decays in flight of pions and kaons), Drell-Yan and $\Upsilon \rightarrow \mu^+ \mu^-$ dimuon production, 296 ± 34 heavy flavour events remain. An analysis of the distribution of the muon momentum perpendicular to the axis of the nearest reconstructed jet, P_T^{rel} , shows that these events are a mixture of $(92 \pm 6)\%$ $b\bar{b}$ + $(8 \pm 6)\%$ $c\bar{c}$. We therefore estimate in the data 272 ± 36 events from $b\bar{b}$. From this we obtain a cross-section for the production of muon pairs in $b\bar{b}$ events with $P_T(\mu) > 3$ GeV and pseudo-rapidity $|\eta| < 1.5$ for both muons, and $M(\mu\mu) > 6$ GeV: $\sigma(\bar{p}p \rightarrow b\bar{b} \rightarrow \mu\mu) = 1.7 \pm 0.2 \pm 0.4$ nb. The first error is statistical and the second includes systematic uncertainties on the integrated luminosity and acceptance.

Because of the dimuon mass cut, the two muons must originate from different b-quarks produced mainly with azimuthal opening angles greater than 90° ; this sample cannot, therefore, be used to make an inclusive measurement of b-quark production. The cuts tend to suppress higher order QCD processes such as gluon-splitting and flavour excitation. According to ISAJET, 75% of the high-mass dimuons come from lowest order contributions. To extract an inclusive b-quark cross-section, we tentatively assume that $b\bar{b}$ correlations are properly simulated in ISAJET when flavour excitation and gluon splitting processes are included in the Monte Carlo. The above assumption cannot be confronted with the exact $O(\alpha_s^3)$ calculation, which presently exists only for inclusive bottom production.

Of the parent b-quarks producing high-mass dimuons, 90% are predicted to have $P_T > 6.5$ GeV (Fig. 2b). Using the method described above, we obtain:

$$\sigma(\bar{p}p \rightarrow b \text{ or } \bar{b} + X, P_T > 6.5 \text{ GeV}, |\eta| < 1.5) = 2.4 \pm 1.3 \text{ } \mu\text{b}.$$

The errors from fragmentation and semi-leptonic branching-ratios are included twice in the total error because the two muons come from two different quarks.

In [1] we published an exclusive cross-section for the lowest order process of flavour creation: $\sigma(\bar{p}p \rightarrow b\bar{b} + X, \text{ with } P_T > 5 \text{ GeV and } |\eta| < 2.0 \text{ for both } b\text{'s}) = 1.1 \pm 0.1 \pm 0.4 \text{ } \mu\text{b}$. Note that the first cross-section is inclusive (b or $\bar{b}$) within the restrictions mentioned above and includes the contribution from the higher order processes of flavour excitation and gluon splitting, whereas the second one is the cross-section for producing $b\bar{b}$ pairs by flavour creation.

The charm contribution to this data sample is too small to extract any meaningful measurement of charm production.

iii) *The low-mass dimuon sample* [5] is the complementary sample of the above one. It consists of 304 dimuon events with $P_T(\mu_1) > 3 \text{ GeV}$, $P_T(\mu_2) > 3 \text{ GeV}$ and $2m_\mu < M(\mu\mu) < 6 \text{ GeV}$. We use the sub-sample of 174 non-isolated, unlike-sign events to measure bottom production. The largest heavy flavour contribution comes from cascade decays $b \rightarrow c\mu\nu$; $c \rightarrow s\mu\nu$, which result in unlike-sign dimuons with masses peaked around 2 GeV. The shape of the dimuon mass spectrum from bottom cascade decays does not depend on the production mechanism. A fit to the observed dimuon mass spectrum by a sum of distributions for different sources gives a contribution of 48 ± 11 events from heavy flavour processes. The ISAJET prediction for the fraction of heavy flavour events in this sample coming from $b\bar{b}$ is 96%. Using this, we obtain a cross-section for the production of $\mu^+\mu^-$ pairs with $P_T(\mu) > 3 \text{ GeV}$ and pseudo-rapidity $|\eta| < 1.5$ for both muons, and $2m_\mu < M(\mu\mu) < 6 \text{ GeV}$: $\sigma(\bar{p}p \rightarrow b\bar{b} \rightarrow \mu^+\mu^-) = 0.42 \pm 0.10 \pm 0.09 \text{ nb}$.

Of the b -quarks contributing to this sample, 90% are predicted to have $P_T > 10 \text{ GeV}$ (Fig. 2c). Using the method described above, we extract the cross-section:

$$\sigma(\bar{p}p \rightarrow b \text{ or } \bar{b} + X, P_T > 10 \text{ GeV}, |\eta| < 1.5) = 0.83 \pm 0.40 \text{ } \mu\text{b},$$

including in the error a 23% uncertainty on the yield of primary and secondary muons from B decays.

iv) *The inclusive muon sample* [7] consists of about 20,000 events containing at least one reconstructed muon with $P_T(\mu) > 6 \text{ GeV}$. We find that in the region $10 \text{ GeV} < P_T(\mu) < 15 \text{ GeV}$, $|\eta_\mu| < 1.5$ the dominant contribution is bottom and charm production. Using the distribution of the muon momentum perpendicular to the axis of the nearest reconstructed jet, P_T^{rel} , the ratio $N_\mu(b)/(N_\mu(b) + N_\mu(c))$ was estimated to be $(76 \pm 12)\%$. Subtracting from the measured inclusive muon cross-section in this P_T region all contributions not arising from heavy flavour production, and multiplying by the measured fraction of bottom events, we get a muon cross-section due to bottom decays of $3.1 \pm 0.4 \pm 0.7 \text{ nb}$. The total error includes the following: the statistical error on the sample; the errors due to the subtraction of background and of muons from decays of W , Z , J/ψ and Υ particles and the Drell-Yan mechanism ($\pm 20\%$); the error on the estimate of the fraction of bottom events in the data; the errors on integrated luminosity and acceptance.

The predicted parent b-quark transverse momentum spectrum is shown in Fig. 2d. Using the method described above, we obtain:

$$\sigma(\bar{p}p \rightarrow b \text{ or } \bar{b} + X, P_T > 15 \text{ GeV}, |y| < 1.5) = 0.42 \pm 0.19 \mu\text{b}.$$

We can also extract from this data sample the ratio of cross-sections for charm and bottom production at large P_T . In ISAJET, at the quark level, the ratio $\sigma(c)/\sigma(b) = 2.32$ for $P_T > 15$ GeV and $|y| < 1.5$. This results in a ratio $N_\mu(c)/N_\mu(b) = 0.35 \pm 0.08$ for the inclusive muon sample to be compared to the measured value 0.32 ± 0.21 . We therefore extract the ratio $\sigma(c)/\sigma(b) = 2.1 \pm 1.8$ in the range $P_T > 15$ GeV and $|y| < 1.5$. We remark that the value $\sigma(c)/\sigma(b) \approx 1$ is predicted at high- P_T only at lowest order in α_s .

To get measurements of b-quark production at the highest possible P_T values, we use the measured inclusive muon cross-section for $|y| < 1.5$ in two more P_T intervals: $15 \text{ GeV} < P_T(\mu) < 20 \text{ GeV}$ and $20 \text{ GeV} < P_T(\mu) < 25 \text{ GeV}$. After background subtraction, the heavy flavour contribution in these two P_T regions is 76% and 43% respectively. We have assumed the same bottom fraction as in the previous P_T interval ($76 \pm 12\%$). Above 25 GeV the background from W decays dominates and its subtraction at the inclusive muon level leads to very large errors. With these two new samples, we probe bottom quark production at $P_T > 23$ GeV and $P_T > 32$ GeV (Fig. 2e, 2f). We obtain:

$$\sigma(\bar{p}p \rightarrow b \text{ or } \bar{b} + X, P_T > 23 \text{ GeV}, |y| < 1.5) = 0.076 \pm 0.035 \mu\text{b}.$$

$$\sigma(\bar{p}p \rightarrow b \text{ or } \bar{b} + X, P_T > 32 \text{ GeV}, |y| < 1.5) = 0.023 \pm 0.011 \mu\text{b}.$$

In Fig. 3 we plot the six measurements of the integral cross-section $\sigma(P_T > P_T^{\min})$ for the inclusive reaction $\bar{p}p \rightarrow b \text{ or } \bar{b} + X$ at $\sqrt{s} = 0.63$ TeV in the central rapidity region $|y| < 1.5$. Three absolutely normalized predictions are shown for comparison with the data: The $O(\alpha_s^2)$ and $O(\alpha_s^3)$ QCD calculations of Nason et al. [4] obtained with a scale $\mu = m_b = 5$ GeV and DFLM structure functions [16], and the full ISAJET calculation including the processes of flavour excitation and gluon splitting as well as flavour creation. For P_T values large compared to the mass of the bottom quark, the $O(\alpha_s^3)$ QCD calculation is unreliable [17]. For this reason the curve of Nason et al. is available only up to 15 GeV; in this region it agrees well with the data. At higher P_T , an extrapolation of the $O(\alpha_s^3)$ curve seems to underestimate the data. The parton shower model of ISAJET is compatible with the data over the entire P_T range measured.

We note that the shapes of the $O(\alpha_s^2)$ and $O(\alpha_s^3)$ curves of Nason et al. are very similar, while the full ISAJET curve shows a somewhat harder P_T distribution. Because of the large experimental errors we are unable to discriminate between the different shapes. In order to calculate the acceptance for detecting bottom events in our muon samples, we used the ISAJET Monte Carlo, including only the $O(\alpha_s^2)$ flavour creation processes as discussed above. This choice gives results which are very similar to those one would get using the full $O(\alpha_s^3)$ curve of Nason et al.,

which we consider to be the best available theoretical model, while using an existing Monte Carlo program.

We estimate the b-quark cross-section, integrated down to $P_T = 0$, by fitting the normalization of the $O(\alpha_s^3)$ spectrum to the data shown in Fig. 3. For this we exclude the point from the high-mass dimuon sample which is not a truly inclusive measurement, and we do not use the points above 15 GeV where the $O(\alpha_s^3)$ QCD calculation is unreliable. We obtain the inclusive cross-section,

$$\sigma(\bar{p}p \rightarrow b \text{ or } \bar{b} + X, |y| < 1.5) = 14.7 \pm 4.7 \mu\text{b}.$$

Extrapolating to all rapidity, using the rapidity distribution calculated by Nason et al., we obtain the total cross-section for $b\bar{b}$ pair production,

$$\sigma(\bar{p}p \rightarrow b\bar{b}+X) = 10.2 \pm 3.3 \mu\text{b},$$

where the quoted errors are just the propagation of the three experimental errors, assuming no further error from the uncertainty on the shape of the theoretical distributions used for the extrapolation.

We also derive a cross-section from the data using a simple parameterization of the P_T distribution. We perform a two parameter fit to the data using the naive, physically motivated function, $d\sigma/dP_T^2 = A \cdot (P_T^2 + m_b^2)^{-n}$, where A and n are free parameters, P_T is expressed in GeV and m_b is fixed at 5 GeV. We use all the data points except for the point from the high-mass dimuon sample which is not a truly inclusive measurement. The result of the fit is given in Fig. 4, where the data are shown on a logarithmic scale, plotted against $\ln\{[(P_{T\text{min}})^2 + m_b^2]/\text{GeV}^2\}$ so that the above parameterization is a straight line. As shown in Fig. 4 the errors used in the fit are taken to be symmetric in $\ln\sigma$. Also shown is the absolutely normalized $O(\alpha_s^3)$ prediction of Nason et al. Remarkably, the best fit to the data matches the QCD prediction to 25% or better in the entire range $P_T < 15$ GeV. By extrapolating the fitted curve we obtain an inclusive cross-section integrated down to $P_T = 0$:

$$\sigma(\bar{p}p \rightarrow b \text{ or } \bar{b} + X, |y| < 1.5) = 19.5^{+17.5}_{-9.3} \mu\text{b},$$

where the error includes the uncertainty on both the normalization and the slope. The fitted parameters are as follows:

$$\begin{aligned} n &= 2.79 \pm 0.24 \\ A &= 1.1 \times 10^4 \mu\text{b} / \text{GeV}^2 \\ m_b &= 5 \text{ GeV (fixed)}. \end{aligned}$$

An analysis [18] based on the $O(\alpha_s^3)$ calculation finds that for bottom production at $\sqrt{s} = 0.63$ TeV, the $O(\alpha_s^3)$ terms are big and are affected by large theoretical errors. The predicted cross-section is $\sigma(\bar{p}p \rightarrow b\bar{b}+X) = 12^{+7}_{-4} \mu\text{b}$ for $m_b = 5$ GeV and $19^{+10}_{-8} \mu\text{b}$ for $m_b = 4.5$ GeV. Within the uncertainties affecting both the measurements and the theory, reasonable agreement is observed between the data and QCD.

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FIGURE CAPTIONS

- Fig. 1** The inclusive differential bottom cross-section as estimated by the ISAJET Monte Carlo (version 5.25) in the central rapidity region $|y| < 1.5$ for proton-antiproton collisions at $\sqrt{s} = 0.63$ TeV (full line). The contributions of the different sub-processes are also indicated: Lowest order flavour creation (dash-dotted line), Gluon splitting scaled down by 1/10 (2nd full line), Flavour excitation scaled down by 1/100 (dashed line).
- Fig. 2** Parent b-quark P_T distributions calculated with ISAJET for the six muon data samples: a) $J/\psi \rightarrow \mu^+\mu^-$, b) high-mass dimuons, c) low-mass dimuons, d) inclusive muon sample $10 \text{ GeV} < P_T^\mu < 15 \text{ GeV}$, e) $15 \text{ GeV} < P_T^\mu < 20 \text{ GeV}$, f) $20 \text{ GeV} < P_T^\mu < 25 \text{ GeV}$. The arrows indicate $P_T^{\min}$ such that 90% of the muon events have $P_T^b > P_T^{\min}$.
- Fig. 3** The inclusive bottom cross-section in proton-antiproton collisions at $\sqrt{s} = 0.63$ TeV for $P_T(b) > P_T^{\min}$ and $|y(b)| < 1.5$ as a function of $P_T^{\min}$. The six experimental points come from the independent measurements discussed in this paper: $J/\psi \rightarrow \mu^+\mu^-$ (solid circle), high-mass dimuons (open circle), low-mass dimuons (triangle), inclusive muon samples (squares). The curves are the absolutely normalized QCD predictions discussed in the text.
- Fig. 4** Fit to the measured b-quark cross-section in $|y| < 1.5$ using the simple parameterization $d\sigma/dP_T^2 = A \cdot (P_T^2 + m_b^2)^{-n}$ (solid line); absolutely normalized QCD prediction (dashed line). The extrapolation to $P_T^{\min} = 0$ is shown (cross).

Fig. 1

Fig. 2

Fig. 3

Fig. 4