MEASUREMENT OF THE BOTTOM QUARK PRODUCTION CROSS-SECTION IN PROTON - ANTIPROTON COLLISIONS AT $\sqrt{s}$ = 0.63 TeV.

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ABSTRACT

I 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 measure the bottom quark production cross-section in different transverse momentum ranges from 6 to 30 GeV. The measured cross-section cannot be explained by lowest order QCD calculations only. 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. The shape of the $O(\alpha_s^3)$ spectrum is used to estimate the total cross-section for production of bottom quark pairs: $\sigma(b\bar{b}) = 10.2 \pm 3.3\ \mu b$.

The CERN proton-antiproton collider can be considered as 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 be produced at a detectable rate. A limit on the top quark mass, $m_t > 44$ GeV at 95% confidence level, has been obtained in UA1 by using a lower bound of the $t\bar{t}$ production cross-section based on lowest order QCD calculations [2]. Recently Nason et al. have completed a full QCD calculation to $O(\alpha_s^3)$ of the heavy quark total cross-section in hadronic collisions [3]. The full calculation of the heavy quark differential spectrum $d^2\sigma/dydP_T^2$ is expected soon by the same authors and preliminary results have already been presented [4]. In this talk I will summarize the results obtained in UA1 on the inclusive b-quark cross-section in the central rapidity region, $|y_b| < 1.5$, using four different muon data samples.

Bottom quarks are not directly recognized 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 has 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 and, once a muon P_T cut is applied, $b\bar{b}$ production is strongly favoured over $c\bar{c}$ production.

In order to extract cross-sections for bottom production from muon measurements one needs to know the shape of the differential cross-section, $d\sigma/dP_T$, and the fragmentation and decay properties of the bottom quark. Fragmentation of bottom quarks and semileptonic decays of B-hadrons have been measured in e^+e^- experiments. For the production spectrum of the b-quark we use the ISAJET Monte Carlo program [8]. The fragmentation of heavy quarks in ISAJET has been tuned to reproduce e^+e^- measurements: The fragmentation distribution of the leading heavy hadron is parametrised with the Peterson et al. form [9], characterised by a parameter, ε, which depends on the quark mass. We use the value $\varepsilon_c = 0.30$ to reproduce the measured fragmentation $c \to D^*$; for bottom we use $\varepsilon_b = 0.02$. The uncertainty on ε_b ($0.001 < \varepsilon_b < 0.05$) results in a 20% error on the inferred bottom quark cross-section, given the measured muon yield. To model B-hadron semileptonic decays, ISAJET uses V-A matrix elements and an average branching ratio $Br(B \to \mu) = 12 \pm 1.2$ %. We have checked that ISAJET reproduces the lepton spectrum resulting from B-hadron decays at the $\Upsilon(4S)$ resonance.

The model used for b-quark production in ISAJET is described in [7]. Three contributions are considered independently:

1) Flavour creation: $q\bar{q} \to b\bar{b}$, $gg \to b\bar{b}$
2) Flavour excitation: $qb \to qb$, $gb \to gb$
3) Gluon splitting: $g \to b\bar{b}$.

The differential bottom cross-sections estimated by ISAJET are shown in Fig. 1 for these three sub-processes, together with their sum; the predictions are for the central rapidity region $|y| < 1.5$ which matches the acceptance of our muon trigger. At low P_T, cut-offs are applied in ISAJET which suppress the flavour excitation and the gluon splitting mechanisms. As a consequence, in the low P_T region ($P_T(b) < 10$ GeV), flavour creation dominates and the shape is given by the "scaling" spectrum for massive quarks [10]: $d\sigma/dP_T^2 = f(m_T/\sqrt{s})/m_T^4$, where $m_T = (P_T^2 + m_b^2)^{1/2}$ and f(x) is a decreasing function of x determined by the parton densities. At large P_T, the three sub-processes have approximately the same P_T dependence, as expected from the scaling properties of the hard partonic cross-section, the structure functions and the gluon splitting function; they contribute roughly 1/3 each.

Preliminary results from the full $O(\alpha_s^3)$ calculation of the integral spectrum $\sigma(\bar{p}p \to b + x, P_T(b) > P_T^{min}) = f(P_T^{min})$ have been presented [4], with and without the rapidity cut $|y| < 1.5$. The following two properties are observed: (1) The $O(\alpha_s^3)$ P_T spectrum

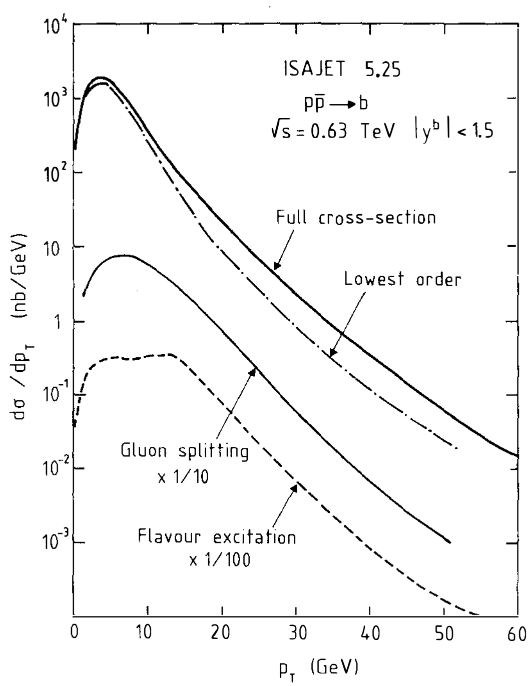

Fig. 1 The inclusive differential bottom cross-section as estimated by the ISAJET Monte Carlo (version 5.25) in the central rapidity region $|y| < 1.5$ for proton-antiproton collisions at $\sqrt{s} = 0.63$ TeV(full line). The contributions of the different sub-processes are also indicated: Lowest order flavour creation (dash-dotted line), Gluon splitting scaled down by 1/10 (2nd full line), Flavour excitation scaled down by 1/100 (dashed line).

and the $O(\alpha_s^2)$ one have very similar shapes (Fig. 3); (2) The rapidity cut $|y| < 1.5$ affects the $O(\alpha_s^3)$ and the $O(\alpha_s^2)$ spectra in the same way. The shape of the ISAJET spectrum used to estimate the acceptance of our muon cuts differs from the lowest order shape in the region 5 GeV < P_T < 15 GeV; it does not agree with the exact $O(\alpha_s^3)$ shape in this region. We have therefore estimated an acceptance correction factor resulting from changing the shape of the P_T spectrum from the full ISAJET calculation to the lowest order one. We find that the correction factor varies from 1.1 for $P_T(b)$ > 6 GeV to 1.2 for $P_T(b)$ > 10 GeV, falling back to 1.0 for $P_T(b)$ > 20 GeV. A full discussion of the theoretical error affecting the shape of the $O(\alpha_s^3)$ P_T spectrum is not available. Based on the above numbers we include in the acceptance calculation a systematic error of ±20% due to the uncertainty on the shape of the P_T spectrum.

We discuss below the results obtained on b-quark production from our four muon data samples. The integrated luminosity for samples (i), (iii) and (iv) is 556 nb^{-1} (1984 and 1985 data only); for sample (ii) (which also includes 1983 data), the integrated luminosity is 664 nb^{-1}.

i) The J/ψ sample [7] 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 $J/\psi \to \mu^+\mu^-$ events is observed from which we derive a cross-section for J/ψ production at large P_T: $B.\sigma(\bar{p}p \to J/\psi \to \mu^+\mu^-) = 7.5 \pm 0.7(\text{stat}) \pm 1.2(\text{syst})$ nb for $P_T^{J/\psi}$ > 5 GeV in the rapidity range $|y| < 2$. Two mechanisms lead to large-P_T J/ψ production in hadronic reactions: (1) High-P_T production of χ states [11] followed by $\chi \to J/\psi + \gamma$ and (2) high-P_T b-quark production followed by $b \to J/\psi + x$. Only the second mechanism gives J/ψ inside jets. An analysis of the topology of the J/ψ events leads to a cross-section $B.\sigma(\bar{p}p \to b \to J/\psi \to \mu^+\mu^-) = 1.8 \pm 0.6 \pm 0.9$ nb for $J/\psi \to \mu^+\mu^-$ production via B-hadrons with $P_T^{J/\psi}$ > 5 GeV in the rapidity range $|y| < 2$; the ISAJET model for bottom production predicts 1.8 nb (±35%) for this process. The total error on the ISAJET prediction includes: the error on $Br(b \to J/\psi + x)$ (25%), the error on $Br(J/\psi \to \mu^+\mu^-)$ (13%), and the error on ε_b (20%). Hence we get a ratio N = DATA/ISAJET = 1.0 (±69%).

The 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, 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. The ISAJET inclusive b-quark cross-section for P_T > 6 GeV and $|y| < 1.5$ is 4.1μb. In this range we estimate an acceptance correction factor of 1.1 (±20%) to correct for the wrong shape of the ISAJET bottom production spectrum. We therefore extract (table 1, row 1) the cross-section:

$$\sigma(\bar{p}p \to b \text{ or } \bar{b} + x, P_T > 6 \text{ GeV}, |y| < 1.5) = 4.5 \ \mu b \ (\pm 72\%).$$

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, we are left with 296±34 heavy flavour events. An analysis of the distribution of the muon momentum perpendicular to the jet axis, P_T^{rel}, shows that these events are a mixture of (92±6)% $b\bar{b}$ + (8±6)% $c\bar{c}$ in agreement with the ISAJET prediction of 90% $b\bar{b}$ + 10% $c\bar{c}$. We therefore estimate in the data 272±36 events from $b\bar{b}$. The ISAJET prediction for the same experimental cuts is 392 $b\bar{b}$ events (±50%). The total error on the ISAJET prediction is dominated by the systematic uncertainties affecting

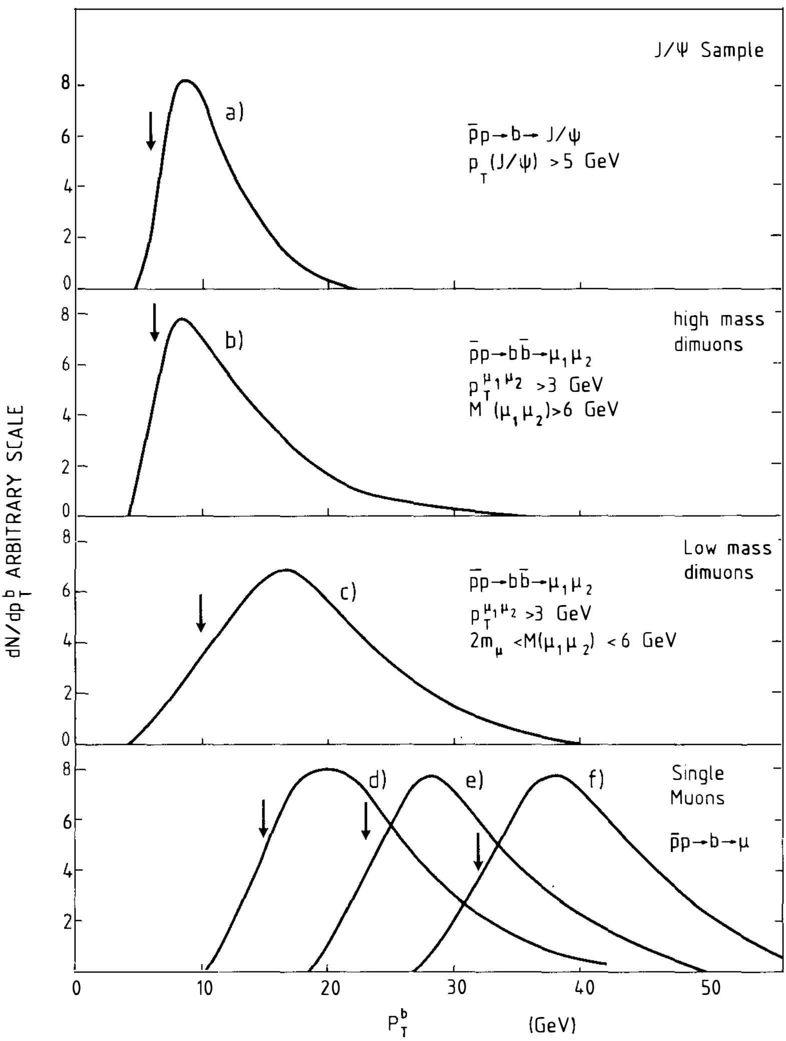

Fig. 2 Parent b-quark P_T distribution for the four muon data samples.

Table 1

Inclusive bottom cross sections

Muon Sample	P_T^{min} [GeV]	σ(ISAJET) $P_T > P_T^{min}$ $\|y(b)\| < 1.5$ [μb]	$N = \frac{DATA}{ISAJET}$	Acceptance correction factor	σ(b) $P_T > P_T^{min}$ $\|y(b)\| < 1.5$ [μb]
J/Ψ Sample	6	4.1	1.0 (±69%)	1.1	4.5 (±72%)
High Mass Dimuons	6.5	3.5	0.69(±51%)	1.0	2.4 (±55%)
Low Mass Dimuons	10	1.2	0.58 (±44%)	1.2	0.83 (±48%)
Single Muons $10 < P_T^{\mu} < 15$ GeV	15	0.32	1.27(±40%)	1.05	0.42 (±45%)
Single Muons $15 < P_T^{\mu} < 20$ GeV	23	0.049	1.56 (±41%)	1.0	0.076(±46%)
Single Muons $20 < P_T^{\mu} < 25$ GeV	32	0.0083	2.83 (±44%)	1.0	0.023(±48%)

bottom fragmentation: We have added in quadrature the following systematic errors: the statistical error on the Monte Carlo sample (4%), the error on the integrated luminosity (15%), the error on the geometrical acceptance (15%), the error on ε_b (2x20%), and the error on the semi-leptonic branching ratio (2x10%). Hence for the dominant $b\bar{b}$ component, the ratio N = DATA/ISAJET = 0.69 (±51%).

Because of the dimuon mass cut, the two muons must originate from different b-quarks produced mainly in opposite azimuthal hemispheres. This cut tends to suppress higher order QCD contributions. According to ISAJET 75% of the high-mass dimuons come from lowest order contributions. Of the parent b-quarks producing high-mass dimuons, 90% have $P_T > 6.5$ GeV (fig. 2b). To extract an inclusive b-quark cross-section, we tentatively assume that $b\bar{b}$ correlations are properly simulated in ISAJET and we apply no correction factor. We do, however, include an additional 20% error on the acceptance to account for the uncertainty in the shape of the bottom production cross-section. The above assumption cannot be confronted to the exact $O(\alpha_s^3)$ calculation, which presently exists only for inclusive bottom production. The ISAJET cross-section for $P_T > 6.5$ GeV, $|y| < 1.5$ is 3.5 μb. Hence we extract from the data (table 1, row 2):

$$\sigma(\bar{p}p \rightarrow b \text{ or } \bar{b} + x, P_T > 6.5 \text{ GeV}, |y| < 1.5) = 2.4\ \mu b\ (\pm 55\%).$$

In [1] we published an exclusive cross-section for the lowest order process of flavour creation: $\sigma(\bar{p}p \rightarrow b\bar{b} + x$, with $P_T > 5$ GeV and $|y| < 2.0$ for both b's) = 1.1 ± 0.1 ± 0.4 μb. Within the ISAJET model the two cross-sections are consistent by definition. Note that the first cross-section is inclusive (b or $\bar{b}$) within the restrictions mentioned above and includes the 25% contribution from the higher order processes of flavour excitation and gluon splitting. The charm contribution to this data sample is too small to extract any meaningful measurement of charm production.

iii) The low-mass dimuon sample [6] is the complementary sample of the above one. It consists of 304 dimuon events with $P_T(\mu_1) > 3$ GeV, $P_T(\mu_2) > 3$ GeV and $2m_\mu < M(\mu\mu) < 6$ 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 mass spectrum gives a contribution of 48 events (±23%) from heavy flavour processes. The ISAJET prediction for the heavy flavour contribution is 83 events (±38%). The total error on the ISAJET prediction includes: the statistical error on the Monte Carlo sample (6%), the error on the integrated luminosity (15%), the error on the geometrical acceptance (15%), the error on ε_b (20%), the error on the yield of primary and secondary muons from B decays (23%), and the error on the efficiency of the isolation cut (5%). Hence we get a ratio N = DATA/ISAJET = 0.58 (±44%). Of the b-quarks contributing to this sample 90% have $P_T > 10$ GeV (fig. 2c). The ISAJET b-quark cross-section for $P_T > 10$ GeV and $|y| < 1.5$ is 1.2 μb. In this range we estimate an acceptance correction factor of 1.2 (±20%) to correct for the wrong shape of the ISAJET bottom production spectrum. We therefore extract the cross-section estimate (table 1, row 3):

$$\sigma(\bar{p}p \rightarrow b \text{ or } \bar{b} + x, P_T > 10 \text{ GeV}, |y| < 1.5) = 0.83\ \mu b\ (\pm 48\%).$$

iv) The inclusive muon sample [7] consists of about 20,000 events containing at least one reconstructed muon with $P_T(\mu) > 6$ GeV. We find that in the region 10 GeV $< P_T(\mu) <$ 15 GeV, $|y_\mu| < 1.5$ the dominant contribution is bottom and charm production. Using the distribution of the muon momentum perpendicular to the jet axis, P_T^{rel}, the ratio $N_\mu(b)/(N_\mu(b)+N_\mu(c))$ was estimated to be (76 ± 12)%. Subtracting from the measured inclusive muon cross-section in this P_T region all contributions not arising from bottom production we get a muon cross-section due to bottom decays, σ(DATA) = 3.1 nb (±25%). The total error includes: the statistical error on the sample and 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 (20%), and the error on estimation of fraction of bottom events in the data (16%). The corresponding ISAJET cross-section due to bottom decays is σ(ISAJET) = 2.5 nb (±31%). The total error on the ISAJET cross-section includes: the error on the integrated luminosity (15%), the error on the geometrical acceptance (15%), the error on ε_b (20%) and the error on the semi-leptonic branching ratio (10%). Hence the ratio N = DATA/ISAJET = 1.27 (±40%). The parent b-quark transverse momentum spectrum is shown in fig. 2d. For $P_T > 15$ GeV we estimate an acceptance correction factor of 1.05 (±20%) to correct for the wrong shape of the ISAJET bottom production spectrum. The ISAJET b-quark cross-section for $P_T > 15$ GeV, $|y| < 1.5$ is 0.32 μb. We extract the cross-section (table 1, row 4):

$$\sigma(\bar{p}p \to b \text{ or } \bar{b} + x,\ P_T > 15\ \text{GeV},\ |y| < 1.5) = 0.42\ \mu b\ (\pm 45\%).$$

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 σ(c)/ σ(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 σ(c)/σ(b) = 2.1 ± 1.8 in the range $P_T > 15$ GeV and $|y| < 1.5$. We remark that the value σ(c)/σ(b) ≈ 1 is predicted at high-P_T only at lowest order.

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 GeV < $P_T(\mu)$ < 20 GeV and 20 GeV < $P_T(\mu)$ < 25 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±12%). Above 25 GeV the background from W decays becomes predominant and its subtraction at the inclusive muon level is uncertain. With these two new samples, we probe bottom quark production at $P_T > 23$ GeV and $P_T > 32$ GeV (Fig. 2e, 2f). At these P_T values, the $O(\alpha_s^3)$ production spectrum is not reliably calculated. We assume that the P_T slope given by the full ISAJET calculation, which is the same as the lowest order slope (Fig. 1), is correct and therefore apply no correction factor. We do, however, include an additional 20% error on the acceptance to account for the uncertainty in the shape of the bottom production cross-section. The numbers used to get a measurement of the bottom production cross-section in these two P_T ranges are given in table 1 (rows 5 and 6); we obtain:

$$\sigma(\bar{p}p \to b \text{ or } \bar{b} + x,\ P_T > 23\ \text{GeV},\ |y| < 1.5) = 0.076\ \mu b\ (\pm 46\%).$$

$$\sigma(\bar{p}p \to b \text{ or } \bar{b} + x,\ P_T > 32\ \text{GeV},\ |y| < 1.5) = 0.023\ \mu b\ (\pm 48\%).$$

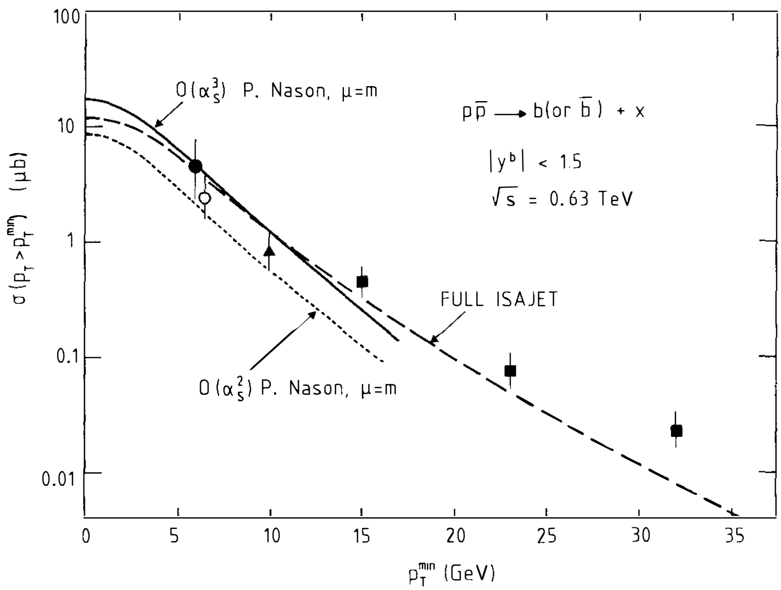

Fig. 3 The inclusive bottom cross-section in proton-antiproton collisions at $\sqrt{s}$ = 0.63 TeV for $P_T(b) > P_T^{min}$ and $|y(b)| < 1.5$ as a function of P_T^{min}. The six experimental points come from the independent measurements discussed in this paper. The curves are discussed in the text.

In Fig. 3 we plot the six measurements of the integral cross-section $\sigma(P_T > P_T^{min})$ for the inclusive reaction $\bar{p}p \rightarrow b$ 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 [13], and the full ISAJET calculation. For P_T values large compared to the mass of the bottom quark, the $O(\alpha_s^3)$ QCD calculation is unreliable [14]. For this reason the curve of Nason et al. is shown 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, including the region P_T > 15 GeV.

We estimate the b-quark cross-section, integrated down to P_T = 0 GeV, 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,

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

and extrapolating over all rapidity values we obtain the total cross-section for $b\bar{b}$ pair production,

$$\sigma(b\bar{b}) = 10.2 \pm 3.3\ \mu b,$$

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, $d\sigma/dP_T^2 = A.\ (P_T^2 + m_b^2)^{-n}$, where A and n are free parameters 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 $\ln\{[(P_T^{min})^2 + m_b^2]/GeV^2\}$ so that the above parameterization is a straight line. Also shown is the absolutely normalized $O(\alpha_s^3)$ prediction of

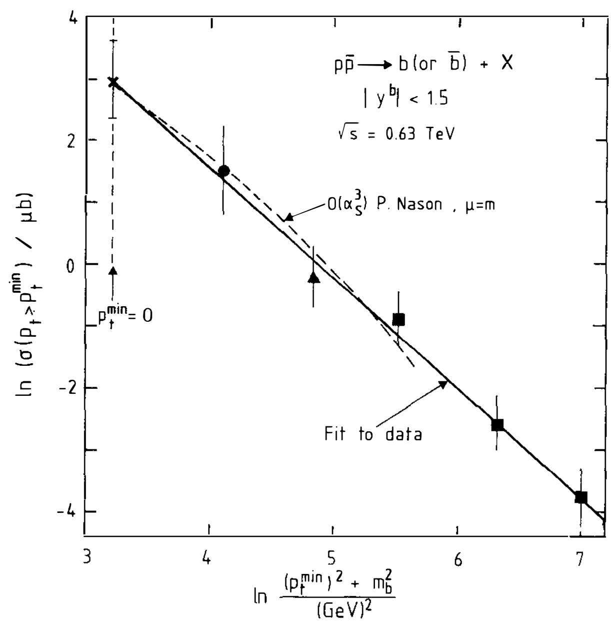

Fig. 4 Fit to the measured b-quark cross-section in $|y| < 1.5$ using the simple parameterization $d\sigma/dP_T^2 = A.\ (P_T^2 + m_b^2)^{-n}$ (solid line); absolutely normalized QCD prediction (dashed line).

Nason et al. Remarkably, the best fit to the data matches the QCD prediction to better than 25% in the entire range $P_T < 15$ GeV. By extrapolating the fitted curve we obtain an inclusive cross-section integrated down to $P_T = 0$ GeV:

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

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

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

A phenomenological analysis [15] based on the $O(\alpha_s^3)$ calculation finds that for bottom production at $\sqrt{s} = 0.63$ TeV, the $O(\alpha_s^3)$ corrections are big and are affected by large theoretical errors. The predicted cross-section is $\sigma(b\bar{b}) = 12^{+7}_{-4}\ \mu b$ for $m_b = 5$ GeV and $19^{+10}_{-8}\ \mu b$ 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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