The dependence of dijet production on photon virtuality in ep collisions at HERA

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Bottom photoproduction measured using decays into muons in dijet events in $ep$ collisions at $\sqrt{s} = 318$ GeV


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The production of bottom quarks in events with two jets and a muon has been measured with the ZEUS detector at HERA using an integrated luminosity of 110 pb$^{-1}$. The fraction of jets containing $b$ quarks was extracted from the transverse momentum distribution of the muon relative to the closest jet. Differential cross sections for bottom production as a function of the transverse momentum and pseudorapidity of the muon, of the associated jet and of $x_b^{\mu \nu}$, the fraction of the photon’s momentum participating in the hard process, are compared with MC models and QCD predictions made at next-to-leading order. The latter give a good description of the data.

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I. INTRODUCTION

The production of bottom quarks in ep collisions at HERA is a stringent test for perturbative quantum chromodynamics (QCD) since the large $b$-quark mass ($m_b \sim 5$ GeV) provides a hard scale that should ensure reliable predictions. When $Q^2$, the negative squared four-momentum exchanged at the electron vertex, is small the reaction $ep \rightarrow e'b\bar{b}X$ can be considered as a photoproduction process in which a quasi-real photon, emitted by the incoming electron, interacts with the proton. For $b$-quark transverse momenta comparable to the $b$-quark mass, next-to-leading-order (NLO) QCD calculations in which the $b$ quark is generated dynamically are expected to provide accurate predictions for $b$ photoproduction [1]. The corresponding leading-order (LO) QCD processes are the direct-photon process, in which the quasi-real photon enters directly in the hard interaction, $\gamma g \rightarrow b\bar{b}$, and the resolved-photon process, in which the photon acts as a source of partons that take part in the hard interaction ($gg \rightarrow b\bar{b}$ or $gq \rightarrow b\bar{b}$).

The bottom-production cross section has been measured in $p\bar{p}$ collisions at the ISR [2], $Sp\bar{p}S$ [3] and Tevatron colliders [4], in $\gamma\gamma$ interactions at LEP [5] and in fixed-target $\pi N$ [6] and $pN$ [7] experiments. Apart from the $Sp\bar{p}S$ data and the fixed-target experiments, the results were significantly above the NLO QCD prediction. The H1 measurement in ep interactions at HERA [8] found a cross section significantly larger than the prediction. The previous ZEUS measurement [9] was above, but consistent with, the prediction.

This paper reports a measurement of bottom photoproduction in events with two jets and a muon, $ep \rightarrow e' b\bar{b} X \rightarrow e'jj\mu X'$, for $Q^2 < 1$ GeV$^2$.

II. EXPERIMENTAL SETUP

The data sample used in this analysis corresponds to an integrated luminosity $L = 110.4 \pm 2.2$ pb$^{-1}$, collected by the ZEUS detector in the years 1996–1997 and 1999–2000. During the 1996–1997 data taking, HERA provided collisions between an electron$^1$ beam of $E_e = 27.5$ GeV and a proton beam of $E_p = 820$ GeV, corresponding to a center-of-mass energy $\sqrt{s} = 300$ GeV ($L_{300} = 38.0 \pm 0.6$ pb$^{-1}$). In the years 1999–2000, the proton-beam energy was $E_p = 920$ GeV, corresponding to $\sqrt{s} = 318$ GeV ($L_{318} = 72.4 \pm 1.6$ pb$^{-1}$).

A detailed description of the ZEUS detector can be found elsewhere [10]. A brief outline of the components that are most relevant for this analysis is given below.

Charged particles are tracked in the central tracking detector (CTD) [11], which operates in a magnetic field of 1.43 T provided by a thin superconducting solenoid. The CTD consists of 72 cylindrical drift chamber layers, organized in nine superlayers covering the polar-angle$^2$ region $15^\circ < \theta$.

$^1$Electrons and positrons are not distinguished in this paper and are both referred to as electrons.

$^2$The ZEUS coordinate system is a right-handed Cartesian system.
B/RMUON consists of limited-streamer forward direction, of two iron toroids magnetized to exploit the magnetic field of the iron yoke and, in the covering the angular region from 5° to 32°. The muon system consists of polar angles from 34° to 135° and momentum.

The luminosity was measured using the bremsstrahlung process $e p \rightarrow e p \gamma$. The resulting small-angle energetic photons were measured by the luminosity monitor [14], a lead-scintillator calorimeter placed in the HERA tunnel at $Z = −107$ m.

### III. DATA SELECTION

The data were selected online by requiring either a high-momentum muon reaching the external B/RMUON chambers or two jets reconstructed in the CAL. A dedicated trigger requiring two jets and a muon with looser jet and muon thresholds was also used in the last part of the data taking.

Muons were reconstructed offline using the following procedure: a muon track was found in the inner and outer B/RMUON chambers or crossing at least 4 FMUON planes, then a match in position and momentum to a CTD track was required. The angular acceptance of the F/B/RMUON and of the CTD, and the requirement that the muons reach the external chambers, define three regions of good acceptance:

- **rear**: $-1.6 < \eta^\mu < -0.9, \ p_T^\mu > 2.5$ GeV;
- **barrel**: $-0.9 < \eta^\mu < 1.3, \ p_T^\mu > 2.5$ GeV; (1)
- **forward**: $1.48 < \eta^\mu < 2.3, \ p_T^\mu > 4$ GeV, $p_T^\mu > 1$ GeV;

with the $Z$ axis pointing in the proton beam direction, referred to as the “forward direction,” and the $X$ axis pointing left towards the center of HERA. The coordinate origin is at the nominal interaction point.

where $\eta^\mu$, $p_T^\mu$, and $p_T^\mu$ are the muon pseudorapidity, momentum, and transverse momentum, respectively.

The hadronic system (including the muon) was reconstructed from energy-flow objects (EFOs) [15] which combine the information from calorimetry and tracking, corrected for energy loss in dead material. A reconstructed four-momentum $(p_X^\mu, p_Y^\mu, p_Z^\mu, E^\mu)$ was assigned to each EFO.

Jets were reconstructed from EFOs using the $k_T$ algorithm [16] in the longitudinally invariant mode [17]. The $E$ recombination scheme, which produces massive jets whose four-momenta are the sum of the four-momenta of the clustered objects, was used. Muons were associated with jets by the $k_T$ algorithm: if the EFO corresponding to a reconstructed muon was included in a jet, then the muon was considered to be associated with the jet.

The event inelasticity $y$ was reconstructed from the Jacquet–Blondel estimator $y_{\text{JB}} = (E - p_Z)/(2E_p)$ [18], where $E - p_Z = \Sigma_i E_i - p_i^Z$ and the sum runs over all EFOs.

A sample of events with one muon and two jets was selected by requiring

(i) $\geq 1$ muon in one of the three-muon-chamber regions defined in Eq. (1);
(ii) $\geq 2$ jets with pseudorapidity $|\eta^\text{jet}| < 2.5$, and transverse momentum $p_T^\text{jet} > 7$ GeV for the highest-$p_T^\text{jet}$ jet and $p_T^\text{jet} > 6$ GeV for the second-highest-$p_T^\text{jet}$ jet;
(iii) that the muon was associated with any jet with $p_T^\text{jet} > 6$ GeV and $|\eta^\text{jet}| < 2.5$. To assure a reliable $p_T^\text{jet}$ measurement (see Sec. V), the residual jet transverse momentum, calculated excluding the associated muon, was required to be greater than 2 GeV;
(iv) a reconstructed vertex compatible with the nominal interaction point;
(v) no scattered-electron candidate found in the CAL;
(vi) $0.2 < y_{\text{JB}} < 0.8$.

The last two cuts suppress background from high-$Q^2$ events and from non-$ep$ interactions, and correspond to an effective cut $Q^2 < 1$ GeV$^2$ and $0.2 < y < 0.8$.

After this selection, a sample of 3660 events remained.

### IV. ACCEPTANCE CORRECTIONS AND BACKGROUND SIMULATION

To evaluate the detector acceptance and to provide the signal and background distributions, Monte Carlo (MC) samples of bottom, charm, and light-flavor (LF) events were generated, corresponding respectively to six, five, and three times the luminosity of the data. PYTHIA 6.2 [19,20] was used as the reference MC, and HERWIG 6.1 [21] for systematic checks. The branching ratios for direct semi-leptonic $b \rightarrow \mu X$ decays and for indirect cascade decays into muons via charm, anti-charm, $\tau^\pm$ and $J/\psi$, were set to $B_{\text{dir}} = 0.106 \pm 0.002$ and $B_{\text{indir}} = 0.103 \pm 0.007$ [22], respectively. The distribution of the decay-lepton momentum in the B-meson center-of-mass system from PYTHIA and HERWIG has been compared with measurements from $e^+e^-$ collisions [23] and found to be in good agreement. The generated events were passed through a full simulation of the ZEUS detector based
They were then subjected to the same trigger requirements and processed by the same reconstruction programs as for the data.

Figure 1 shows the kinematic distributions of $p_T$ and $\eta$ for the jet associated with the muon, as well as for highest-$p_T$ jet that was not associated with a muon (other jet). The muon kinematic variables $p_T^\mu$ and $\eta^\mu$ are displayed, as well as $x_g^\text{jets}$, the fraction of the total hadronic $E-p_Z$ carried by the two highest-$p_T$ jets:

$$x_g^\text{jets} = \frac{\sum_{j=1,2} (E_{j}^\text{jet}-p_Z^j)}{E-p_Z}. \quad (2)$$

The data are compared in shape to the PYTHIA MC sample in which the relative fractions of bottom, charm, and LF were mixed according to the cross sections predicted by the simulation. The comparison shows that the main features of the dijet-plus-muon sample are well reproduced by this MC mixture. The PYTHIA MC predicts that the non-$b\bar{b}$ background comprises 57% prompt muons from charmed-hadron decays and 43% muons from light-flavor hadrons, mostly due to in-flight decays of $\pi$ and $K$ mesons, with a small amount (~5% of the LF component) from muons produced in interactions with the detector material. The punch-through contribution is negligible. The HERWIG Monte Carlo (not shown) also gives a good description of the data.

The detector acceptance for the final cross sections was calculated using the $b\bar{b}$ PYTHIA Monte Carlo, in which events were reweighted such that the transverse momentum distribution of the $b$ quark agreed with that of the NLO cal-

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$^3x_g^\text{jets}$ is the massive-jets analogue of the $x_{\text{obs}}$ variable used for massless jets in other ZEUS publications [25].
where the $f_{\text{rel}}$ distribution of bottom, $f_{b\bar{b}}$, was taken from the PYTHIA MC; $f_{c\bar{c}}^x = f_{c\bar{c}}^{x,\text{MC}}$, and that of the background, $f_{\text{bkg}}$, was obtained as explained below.

The distribution $f_{b\bar{b}}$ was obtained from the sum of a LF, $f_{\text{LF}}$, and a charm, $f_{c\bar{c}}^x$, distribution weighted according to the charm fraction $r$ obtained from the charm and LF cross sections given by PYTHIA:

$$f_{\text{bkg}} = r f_{c\bar{c}}^x + (1 - r) f_{\text{LF}}.$$  \hspace{1cm} (5)

The distribution $f_{\text{LF}}$ can be obtained from the $p_{T}^{\text{rel}}$ distribution of a sample of CTD tracks not identified as muons but fulfilling the same momentum and angular requirements applied to muons (called “unidentified tracks” in the following). The $p_{T}^{\text{rel}}$ distribution for unidentified tracks, $f_x$, is expected to be similar to $f_{\text{LF}}$, under the assumption that the probability for an unidentified track (typically a $\pi$ or a $K$ meson) to be identified as a muon, $P_{\text{ident}}$, does not depend strongly on $p_{T}^{\text{rel}}$. This assumption is validated by the MC, since the MC distributions for the LF background, $f_{\mu}^{x,\text{EMC}}$, and for the unidentified tracks, $f_{x}^{x,\text{MC}}$, are indeed very similar, as shown in Fig. 2.

Figure 2(b) shows the $f_x$ distribution obtained from a dijet sample selected without muon requirements. The shape obtained from PYTHIA, $f_x^{x,\text{MC}}$, underestimates the tail (for example, by 24% at 2.625 GeV). The $p_{T}^{\text{rel}}$ shape of the LF background was therefore obtained as

$$f_{\mu}^x = f_x^{x,\text{EMC}}.$$  \hspace{1cm} (6)

where the ratio $f_{\mu}^{x,\text{EMC}}/f_x^{x,\text{MC}}$ is a MC-based correction that accounts for possible differences between $f_{\mu}^x$ and $f_x$, due to a residual $p_{T}^{\text{rel}}$ dependence of $P_{\text{ident}}$ and to the charm and bottom contamination ($\sim$28% and $\sim$2% respectively) in the dijet sample.

The data cannot be used to extract the distribution $f_{c\bar{c}}^x$. Two cases were therefore considered: the distribution given by the PYTHIA MC, $f_{c\bar{c}}^{x,\text{MC}}$, and the distribution obtained from the unidentified track sample, as in the case of the LF background: $f_{c\bar{c}}^x f_{\text{LF}}^{x,\text{MC}}$. The average of these two cases was then taken as the nominal $f_{c\bar{c}}^x$.

Figure 3 shows the result of the $p_{T}^{\text{rel}}$ fit for muons in the rear, barrel, and forward regions. The sum of the two components reproduces the data reasonably well. The fraction of $b$ in the total sample of dijet events with a muon is $a_{b\bar{b}}$ events. The $p_{T}^{\text{rel}}$ distribution for bottom peaks at $\sim$2 GeV and is well separated from those from charm and LF which are peaked close to zero. Since the shapes of $f_{\mu}^{x,\text{EMC}}$ and $f_{c\bar{c}}^{x,\text{MC}}$ are very similar, the fraction of bottom ($a_{b\bar{b}}$) and background ($a_{\text{bkg}}$) events in the sample was obtained from a two-component fit to the shape of the measured $p_{T}^{\text{rel}}$ distribution $f_{\mu}$ with a bottom and a background component:

$$f_{\mu} = a_{b\bar{b}} f_{b\bar{b}} + a_{\text{bkg}} f_{\text{bkg}},$$  \hspace{1cm} (4)

V. SIGNAL EXTRACTION AND CROSS SECTION MEASUREMENT

Because of the large $b$-quark mass, muons from semileptonic B-hadron decays tend to be produced with large transverse momentum with respect to the direction of the jet containing the B-hadron. The bottom signal was extracted by exploiting the distribution of the transverse momentum of the muon with respect to the momentum of the rest of the associated jet, $p_{T}^{\text{rel}}$, defined as

$$p_{T}^{\text{rel}} = \frac{|p^{x} \times (p^{x} - p^{\mu})|}{|p^{x} - p^{\mu}|},$$  \hspace{1cm} (3)

where $p^{\mu}$ is the muon and $p^{x}$ the jet momentum vector. Figure 2(a) shows the distributions, normalized to unity, of the reconstructed muon $p_{T}^{\text{rel}}$ as obtained from the PYTHIA MC, for bottom ($f_{b\bar{b}}^{x,\text{MC}}$), charm ($f_{c\bar{c}}^{x,\text{MC}}$), and LF ($f_{\mu}^{x,\text{EMC}}$) calculations. The effect of this reweighting on the distributions in Fig. 1 was small.
=0.224±0.017 (stat.). In the determination of the cross sections, the fraction of beauty events in the data was extracted by a fit performed in each cross-section bin.

All the cross sections reported in Sec. VIII, with the exception of that for \( b \) quarks, are inclusive muon (or \( b \)-jet) cross sections, obtained by counting muons (or \( b \)-jets) rather than events. Muons coming from both direct and indirect \( b \) decays are considered to be part of the signal. The cross sections are given for dijet events passing the following requirements: \( Q^2<1 \text{ GeV}^2 \), \( 0.2<y<0.8 \) and at least two hadron-level jets with \( p_T^{\text{jet}1}>7 \text{ GeV} \), \( p_T^{\text{jet}2}>6 \text{ GeV} \) and \( \eta^{\text{jet}1}, \eta^{\text{jet}2}<2.5 \). These jets were defined using the \( k_T \) algorithm on stable hadrons, where the weakly decaying B hadrons were considered stable. For dijet events with a muon passing the cuts of Eq. (1), the acceptance varies from 10\% at low \( p_T^{\mu} \) to 20\% at large \( p_T^{\mu} \).

The cross sections were measured from data collected at two different center-of-mass energies, \( \sqrt{s}=300 \text{ GeV} \) and \( \sqrt{s}=318 \text{ GeV} \). They were corrected to \( \sqrt{s}=318 \text{ GeV} \) using the NLO QCD prediction. The effect of this correction on the final cross section is \(-2\%\).

VI. THEORETICAL PREDICTIONS AND UNCERTAINTIES

The measured cross sections are compared to NLO QCD predictions based on the FMNR \cite{Zhao:2004} program. The parton distribution functions used for the nominal prediction were GRVG-HO \cite{GRVG-HO} for the photon and CTEQ5M \cite{CTEQ5M} for the proton. The \( b \)-quark mass was set to \( m_b=4.75 \text{ GeV} \), and the renormalization and factorization scales to the transverse mass, \( m_r=m_f=m_T=\frac{1}{2}\sqrt{(p_T^{\mu})^2+(p_T^{\text{jet}1})^2+m_b^2} \), where \( p_T^{\mu} \) is the transverse momentum of the \( (\bar{b}) \) quark in the laboratory frame. Jets were reconstructed by running the \( k_T \) algorithm on the four momenta of the \( b \) and \( \bar{b} \) quarks and of the third light parton \( \mu \) if present generated by the program.

The fragmentation of the \( b \) quark into a B hadron was simulated by rescaling the quark three-momentum in the frame in which \( p_T^Z=0 \), obtained with a boost along \( Z \) according to the Peterson \cite{Peterson} fragmentation function with \( \epsilon=0.0035 \). The muon momentum was generated isotropically in the B-hadron rest frame from the decay spectrum given by PYTHIA, which is in good agreement with measurements made at B factories \cite{Bfactories}.

To evaluate the uncertainty on the NLO calculations, the \( b \)-quark mass and the renormalisation and factorization scales were varied simultaneously, to maximize the change, from \( m_b=4.5 \text{ GeV} \) and \( \mu_r=\mu_f=m_T/2 \) to \( m_b=5.0 \text{ GeV} \) and \( \mu_r=\mu_f=2m_T \), producing a variation in the cross section from \(+34\%\) to \(-22\%\). The effect on the cross section of a variation of the Peterson parameter \( \epsilon \) from 0.002 to 0.0055 \cite{Peterson2} and of a change of the fragmentation function from the Peterson to the Kartvelishvili parametrization (with \( \alpha=13 \), as obtained from comparisons between NLO QCD and MC distributions) \cite{Kartvelishvili} was less than \( \pm3\% \). The effects of us-
ing different sets of parton densities and of a variation of the 
strong coupling constant \( \alpha_{\text{QCD}}^{(5)} = 0.226 \pm 0.025 \text{ MeV} \) were 
all within \( \pm 4\% \).

The NLO cross sections, calculated for jets made of 
partons, were corrected for jet hadronization effects to allow a 
direct comparison with the measured hadron-level cross 
sections. The corrections were derived from the MC simulation 
as the ratio of the hadron-level to the parton-level MC cross 
section, where the parton level is defined as being the result of 
the parton showering stage of the simulation. The average 
between the corrections obtained from PYTHIA and HERWIG 
was taken as the central value and their difference as the 
uncertainty. The effect of the hadronization correction was 
largest in the rear region, where the cross section was re-
duced by \( (20 \pm 6)\% \) and smallest at large \( p_T \) where it was 
reduced by \( (3.0 \pm 0.3)\% \).

The measured cross sections are also compared to the 
absolute predictions of two MC models, PYTHIA 6.2 and 
CASCADE 1.1. The predictions of PYTHIA 6.2 were obtained 
[20] by mixing direct- \( (\gamma g \rightarrow b\bar{b}) \) and resolved-photon \( (gg 
\rightarrow b\bar{b}, q\bar{q} \rightarrow b\bar{b}) \) flavor-creation processes calculated using 
massive matrix elements and the flavor-excitation (FE) pro-
cesses \( (bg \rightarrow bg, bq \rightarrow bq) \), in which a heavy quark is 
extracted from the photon or proton parton density. The FE 
processes contribute about 27% of the total \( b\bar{b} \) cross section. The small \( (\sim 5\%) \) contribution from gluon splitting in parton 
showers \( (g \rightarrow b\bar{b}) \) was not included. The parton density 
CTEQ4L [33] was used for the proton and GRV-G-LO [27] 
for the photon; the \( b\)-quark mass was set to 4.75 GeV and the 
\( b\)-quark string fragmentation was performed according to the 
Peterson function with \( \epsilon = 0.0041 \) [34].

CASCADE [35] is a Monte Carlo implementation of the 
CCFM evolution equations [36]. Heavy-quark production is 
obtained from the \( O(\alpha_s) \) matrix elements for the process 
\( \gamma g \rightarrow b\bar{b}_1 \), in which the initial gluon can be off-shell. The 
gluon density, unintegrated in transverse momentum \( (k_T) \), is 
obtained from an analysis of the proton structure functions 
based on the CCFM equations [37]; in the event generation the 
gluon density used corresponds to the set named “J2003 
sen 2.” The mass of the \( b \) quark was set to 4.75 GeV and \( \alpha_s \) 
was evaluated at the scale \( m_T \). As for PYTHIA, the \( b\)-quark 
string fragmentation was performed according to the 
Peterson function with \( \epsilon = 0.0041 \).

\section*{VII. SYSTEMATIC UNCERTAINTIES}

The main experimental uncertainties are described below:

\begin{itemize}
  \item[(i)] The muon acceptance, including the efficiency of the 
  muon chambers, of the reconstruction and of the 
  MUON-CTD matching, is known to about 10% from 
  a study based on an independent dimuon sample [38].
  \item[(ii)] The uncertainty on the \( p_T^{\text{rel}} \) shape of the LF and charm 
  background was evaluated by 
  \begin{itemize}
    \item[(a)] varying the charm fraction in the background, \( r \), 
    by \( \pm 20\% \). This range was obtained by fixing the 
    absolute charm-MC normalization to a measurement 
    of the charm dijet cross section [39] and 
    using the PYTHIA or HERWIG MC to extrapolate to the 
    kinematic range of the present measurement;
    \item[(b)] varying the jet-track association in the 
    unidentified-track sample;
    \item[(c)] extracting \( f_\mu \) from a sample of unidentified CTD 
    tracks, reweighted with a MC-based parametrization 
    of \( P_{x \rightarrow \mu} \) depending on polar angle and mo-
    mentum;
    \item[(d)] varying the \( p_T^{\text{rel}} \) shape of the charm component of 
    the background between the prediction from 
    PYTHIA and the value obtained from the uniden-
    tified track sample;
    \item[(e)] using HERWIG instead of PYTHIA to simulate the 
    background.
  \end{itemize}
\end{itemize}

The total uncertainty from these sources is about 10%. As a 
cross-check, a different definition of \( p_T^{\text{rel}} \) was used to extract 
the beauty fraction, namely the transverse momentum of the 
muon with respect to the whole jet, including the muon it-
self, as used in a previous ZEUS publication [9]. The results 
were found to be in good agreement:

\begin{itemize}
  \item[(iii)] The 2% uncertainty on the direct-decay branching ra-
    tio \( B_{\text{dir}} \) introduces a 2% uncertainty on the \( b\)-jet and 
    on the \( b\)-quark cross sections while it has no effect on 
    the visible muon cross sections. The 7% uncertainty 
    on the branching ratio for indirect decays \( B_{\text{indir}} \) pro-
    duces an uncertainty of 1% on the measured cross 
    sections.
  \item[(iv)] The uncertainties on the dijet selection, on the energy 
    scale, on the jet and \( y_B \) resolution and trigger efficiency add up to a 7% 
    uncertainty on the cross sections.
  \item[(v)] The Peterson fragmentation parameter \( \epsilon \) in the MC 
    was varied from 0.002 to 0.006 as allowed by LEP 
    and SLD measurements [34,40,41]. The Lund–
    Bowler fragmentation function was used as an alter-
    native, both with the default PYTHIA parameters and 
    with parameters taken from OPAL measurements [34] 
    (\( \pm 2\% \)).
  \item[(vi)] Instead of using PYTHIA reweighted to the NLO \( p_T^{\text{jet}} \) 
    distribution it was reweighted as a function of \( \eta^{\text{jet}} \) and 
    \( p_T^{\text{jet}} \) to agree with the measured differential distributions 
    (\( \sim -2\% \)) or without reweighting (\( +2\% \)).
  \item[(vii)] The fraction of flavor-excitation events in PYTHIA was 
    varied up and down by a factor of 2 (\( \pm 4\% \)), as al-
    lowed by comparisons to the \( x_T^{\text{jet}} \) distribution of the data.
  \item[(viii)] HERWIG was used instead of PYTHIA (\( \sim -2\% \)).
\end{itemize}

The total systematic uncertainty was obtained by adding the 
above contributions in quadrature. A 2% overall normaliza-
\section*{VIII. RESULTS}

All the cross sections reported below, except for the 
\( b\)-quark cross section, are given for dijet events with \( p_T^{\text{jet}} \).
FIG. 4. Cross sections for muons coming from $b$ decays in dijet events with $p_T^{jets}>7$, 6 GeV, $y^{jets}$, $y^{jets}<2.5$, $Q^2<1$ GeV$^2$, and $0.2<y<0.8$. (a) The cross section for the forward, barrel, and rear regions [defined in Eq. (1)]. (b) The differential cross section as a function of $x_{y^{jets}}$. The data (points) are compared to the predictions of NLO QCD (dotted line: parton-level jets; dashed line: jets corrected to the hadron level). The full error bars are the quadratic sum of the statistical (inner part) and systematic uncertainties. The band around the NLO prediction represents the variation on the theoretical predictions obtained by varying the $b$-quark mass, $\mu$, and $\mu_y$, as explained in the text. The data are also compared to the predictions of the PYTHIA (solid line histogram) and CASCADE (dot-dashed line histogram) Monte Carlo models.

The first set of measurements are bottom cross sections for muons passing the cuts defined in Eq. (1). The results for the forward, barrel, and rear muon-chamber regions are shown in Fig. 4(a) and Table I and compared with the NLO prediction and MC models. Both the NLO and the MC models are in reasonable agreement with the data.

Figure 4(b) and Table II show the differential cross-section $d\sigma/dx_{y^{jets}}$ for muons in the range defined by Eq. (1) in dijet events. The $x_{y^{jets}}$ variable corresponds at leading order to the fraction of the exchanged-photon momentum in the hard scattering process. It provides a tool to measure the relative importance of photon-gluon fusion, $\gamma g\rightarrow b\bar{b}$, which gives a peak at $x_{y^{jets}}\sim 1$, and of other contributions, such as gluon fusion (with a gluon coming from the photon) or higher-order diagrams, which are distributed over the whole $x_{y^{jets}}$ range. The sample is dominated by the high-$x_{y^{jets}}$ peak, but a low-$x_{y^{jets}}$ component is also apparent. The NLO QCD prediction describes the distribution well. PYTHIA is also able to give a good description of the data due to the large contribution from flavor excitation at low $x_{y^{jets}}$. CASCADE, which generates low-$x_{y^{jets}}$ events via initial-state radiation without using a parton density in the photon, tends to underestimate the cross section at low $x_{y^{jets}}$.

The differential cross sections in the muonic variables were measured for $p_T^{jets}>2.5$ GeV and $-1.6<y<2.3$. Figure 5 and Table III show the differential cross sections $d\sigma/dy^{\mu}$ and $d\sigma/dp_T^{\mu}$ for muons in dijet events. The NLO QCD predictions and the MC models describe the $y^{\mu}$ distribution well. The $p_T^{\mu}$ distribution is well reproduced by NLO QCD.

TABLE I. For each muon-chamber region defined in Eq. (1) the columns show the number of selected muons; the beauty fraction $a_{bb}$ obtained from the $p_T^{rel}$ fit; the measured bottom cross section with the statistical and systematic uncertainties; the NLO QCD prediction corrected to the hadron level with the theoretical uncertainty and the hadronization correction. For further details see the caption to Fig. 4.

<table>
<thead>
<tr>
<th>\mu-chambers</th>
<th>Muons</th>
<th>$a_{bb}$</th>
<th>$\sigma^{\pm \text{stat.} \pm \text{syst.}}$ (pb)</th>
<th>$\sigma^{\text{NLO}} \times C_{\text{had}}$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>rear</td>
<td>484</td>
<td>0.15</td>
<td>$6.5\pm 1.5^{+3.6}_{-1.6}$</td>
<td>$4.3\pm 1.6$</td>
</tr>
<tr>
<td>barrel</td>
<td>2316</td>
<td>0.25</td>
<td>$38.2\pm 4.2^{+10.7}_{-5.8}$</td>
<td>$33.9\pm 7.0$</td>
</tr>
<tr>
<td>forward</td>
<td>868</td>
<td>0.21</td>
<td>$16.6\pm 3.3^{+2.8}_{-4.6}$</td>
<td>$6.5\pm 1.6$</td>
</tr>
</tbody>
</table>

TABLE II. Differential hadron cross section as a function of $x_{y^{jets}}$. The multiplicative hadronization correction applied to the NLO prediction is shown in the last column. For further details see the caption to Fig. 4.

<table>
<thead>
<tr>
<th>$x_{y^{jets}}$ range</th>
<th>$d\sigma/dx_{y^{jets}}^{\pm \text{stat.} \pm \text{syst.}}$ (pb)</th>
<th>$C_{\text{had}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00, 0.25</td>
<td>$12.9\pm 6.7^{+4.2}_{-2.6}$</td>
<td>0.68</td>
</tr>
<tr>
<td>0.25, 0.50</td>
<td>$20.8\pm 7.2^{+8.2}_{-7.2}$</td>
<td>0.83</td>
</tr>
<tr>
<td>0.50, 0.75</td>
<td>$30.0\pm 5.2^{+4.1}_{-4.1}$</td>
<td>0.86</td>
</tr>
<tr>
<td>0.75, 1.00</td>
<td>$165\pm 14^{+22}_{-34}$</td>
<td>0.90</td>
</tr>
</tbody>
</table>
QCD while the $p_T$ slope tends to be too soft in CAScade and PYTHIA.

The jet associated with the muon (or $\mu$-jet) reproduces the kinematics of the $b$ (or $\bar{b}$) quark to a good approximation. The $\mu$-jet is defined as the jet containing the B hadron that decays into the muon. Figures 6(a) and 6(b) and Table IV show the differential cross section for the jet associated with a muon passing the cuts of Eq. (1) as a function of the jet pseudorapidity, $d\sigma/d\eta^{\mu\text{-jet}}$, and transverse momentum, $d\sigma/dp_T^{\mu\text{-jet}}$, for $\eta^{\mu\text{-jet}}<2.5$ and $p_T^{\mu\text{-jet}}>6$ GeV. The $\mu$-jet distributions are well reproduced by the NLO and by the MC models.

The $\mu$-jet cross sections have been corrected to obtain the

**TABLE III.** Differential muon cross section as a function of $\eta^{\mu}$ and $p_T^{\mu}$. For further details see the caption to Fig. 5.

<table>
<thead>
<tr>
<th>$\eta^{\mu}$ range</th>
<th>$d\sigma/d\eta^{\mu} \pm$ stat. ± syst. (pb)</th>
<th>$C_{had}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-1.6, -0.75$</td>
<td>$4.6 \pm 1.3^{+0.8}_{-0.9}$</td>
<td>0.83</td>
</tr>
<tr>
<td>$-0.75, 0.25$</td>
<td>$18.8 \pm 2.2^{+2.7}_{-2.7}$</td>
<td>0.88</td>
</tr>
<tr>
<td>$0.25, 1.30$</td>
<td>$16.7 \pm 2.4^{+2.9}_{-2.9}$</td>
<td>0.92</td>
</tr>
<tr>
<td>$1.30, 2.30$</td>
<td>$10.0 \pm 2.3^{+1.4}_{-1.6}$</td>
<td>0.91</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$p_T^{\mu}$ range (GeV)</th>
<th>$d\sigma/dp_T^{\mu} \pm$ stat. ± syst. (pb/GeV)</th>
<th>$C_{had}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.5, 4.0$</td>
<td>$16.1 \pm 1.0^{+1.3}_{-1.2}$</td>
<td>0.87</td>
</tr>
<tr>
<td>$4.0, 6.0$</td>
<td>$7.1 \pm 1.0^{+1.3}_{-1.2}$</td>
<td>0.92</td>
</tr>
<tr>
<td>$6.0, 10.0$</td>
<td>$1.69 \pm 0.32^{+0.22}_{-0.24}$</td>
<td>0.97</td>
</tr>
</tbody>
</table>

To compare the present result with a previous ZEUS measurement given at the $b$-quark level, the NLO QCD prediction was used to extrapolate the cross section for dijet events with a muon to the inclusive $b$-quark cross section. The $b$-quark differential cross section as a function of the quark transverse momentum, $d\sigma(\mu \rightarrow bX)/dp_T^{b\text{-jet}}$, for $b$-quark pseudo-rapidity in the laboratory frame $|\eta^{\mu}|<2$ (corresponding to a rapidity in the $ep$ center of mass of $-3.75<Y_{\text{cms}}^{b}<0.25$), for $Q^2<1$ GeV$^2$ and $0.2<\gamma<0.8$, was obtained from the dijet cross section for events with a $\mu$-jet within $|\eta^{\mu\text{-jet}}|<2$ using the NLO prediction corrected for hadronization. The $\bar{b}$ quark was not considered in the definition of the $b$-quark cross section. As a cross-check, the measurement was corrected to the $b$-quark level using the PYTHIA MC, giving a result in agreement within 6%. The result, shown in Fig. 7 and Table VI, is compared to the previous ZEUS measurement [9] of the $b$-quark cross section for $p_T^{b}>p_T^{\text{min}}$ =5 GeV and $|\eta^{b}|<2$, translated into a differential cross section using the NLO prediction and plotted at the average $b$-quark transverse momentum, $\langle p_T^{b}\rangle$, of the accepted events taken from the Monte Carlo:
The two independent measurements are consistent and in agreement with the NLO QCD predictions.

IX. CONCLUSIONS

Bottom production identified by semi-leptonic decay into muons has been measured in dijet events with $Q^2 > 1$ GeV$^2$. Differential cross sections for the reaction $ep \rightarrow e' b\bar{b}X \rightarrow e' jj \mu X'$ have been measured as a function of the pseudorapidity and transverse momentum of the muon and of $x_{B^{+}}$. Differential cross sections for the production of $b$-jets were also measured.

The results were compared to MC models and to a NLO QCD prediction combined with fragmentation and $B$-hadron decay models. This prediction is in good agreement with the data in all the differential distributions. The PYTHIA MC model is also able to give a reasonable description of the differential cross sections. The CASCADE MC model also gives a reasonable description of the data, except for the low-$x_{B^{+}}$ region.

The large excess of the first measurement of bottom photoproduction over NLO QCD, reported by the H1 collabora-
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**TABLE IV. Differential cross section for jets associated with a muon as a function of \( \eta^{\mu\text{-jet}} \) and \( p_T^{\mu\text{-jet}} \). For further details see the caption to Fig. 6.**

<table>
<thead>
<tr>
<th>( \eta^{\mu\text{-jet}} ) range (( \text{pb} ))</th>
<th>( d\sigma/d\eta^{\mu\text{-jet}} \pm \text{stat.} \pm \text{syst.} )</th>
<th>( C_{\text{had}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( -1.6, -0.6 )</td>
<td>( 8.6 \pm 1.7_{-1.8}^{+1.4} )</td>
<td>0.73</td>
</tr>
<tr>
<td>( -0.6, 0.4 )</td>
<td>( 18.9 \pm 2.2_{-2.7}^{+2.8} )</td>
<td>0.84</td>
</tr>
<tr>
<td>( 0.4, 1.4 )</td>
<td>( 14.3 \pm 2.3_{-3.8}^{+2.5} )</td>
<td>0.97</td>
</tr>
<tr>
<td>( 1.4, 2.5 )</td>
<td>( 14.4 \pm 2.7_{-4.2}^{+2.3} )</td>
<td>1.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( p_T^{\mu\text{-jet}} ) range (( \text{GeV} ))</th>
<th>( d\sigma/dp_T^{\mu\text{-jet}} \pm \text{stat.} \pm \text{syst.} )</th>
<th>( C_{\text{had}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 6, 11 )</td>
<td>( 6.41 \pm 0.67_{-1.24}^{+1.00} )</td>
<td>0.88</td>
</tr>
<tr>
<td>( 11, 16 )</td>
<td>( 2.98 \pm 0.37_{-0.82}^{+0.52} )</td>
<td>0.88</td>
</tr>
<tr>
<td>( 16, 30 )</td>
<td>( 0.51 \pm 0.11_{-0.08}^{+0.08} )</td>
<td>0.90</td>
</tr>
</tbody>
</table>

**TABLE V. Differential cross section for \( b\)-jets as a function of \( \eta^{b\text{-jet}} \) and \( p_T^{b\text{-jet}} \). For further details see the caption to Fig. 6.**

<table>
<thead>
<tr>
<th>( \eta^{b\text{-jet}} ) range (( \text{pb} ))</th>
<th>( d\sigma/d\eta^{b\text{-jet}} \pm \text{stat.} \pm \text{syst.} )</th>
<th>( C_{\text{had}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( -1.6, -0.6 )</td>
<td>( 152 \pm 29_{-24}^{+24} )</td>
<td>0.68</td>
</tr>
<tr>
<td>( -0.6, 0.4 )</td>
<td>( 356 \pm 41_{-53}^{+31} )</td>
<td>0.78</td>
</tr>
<tr>
<td>( 0.4, 1.4 )</td>
<td>( 275 \pm 45_{-73}^{+53} )</td>
<td>0.96</td>
</tr>
<tr>
<td>( 1.4, 2.5 )</td>
<td>( 229 \pm 44_{-69}^{+41} )</td>
<td>1.06</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( p_T^{b\text{-jet}} ) range (( \text{GeV} ))</th>
<th>( d\sigma/dp_T^{b\text{-jet}} \pm \text{stat.} \pm \text{syst.} )</th>
<th>( C_{\text{had}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 6, 11 )</td>
<td>( 137 \pm 14_{-25}^{+21} )</td>
<td>0.85</td>
</tr>
<tr>
<td>( 11, 16 )</td>
<td>( 43.8 \pm 5.5_{-12.9}^{+7.7} )</td>
<td>0.86</td>
</tr>
<tr>
<td>( 16, 30 )</td>
<td>( 5.7 \pm 1.2_{-0.9}^{+1.0} )</td>
<td>0.89</td>
</tr>
</tbody>
</table>

**FIG. 7. Differential cross section for \( b\)-quark production as a function of the \( b\)-quark transverse momentum \( p_T^b \) for \( b\)-quark pseudorapidity \( |\eta^b| \) \( \leq 2 \) and for \( Q^2 < 1 \text{ GeV}^2 \), \( 0.2 < y < 0.8 \). The filled points show the ZEUS results from this analysis and the open point is the previous ZEUS measurement in the electron channel [9]. The full error bars are the quadratic sum of the statistical (inner part) and systematic uncertainties. The dashed line shows the NLO QCD prediction with the theoretical uncertainty shown as the shaded band.**
TABLE VI. Differential $b$-quark cross-section $d\sigma/dp_T^b$. The first columns show the differential $\mu$-jet cross-section $d\sigma/dp_T^{\mu\text{-jet}}$ restricted to $|p_T^{\mu\text{-jet}}| < 2$, the corresponding hadronization correction and the average $b$-quark transverse momentum, $\langle p_T^b \rangle$, as obtained from the PYTHIA MC. The $b$-quark differential cross section $d\sigma/dp_T^b$ for $|p_T^b| < 2$, evaluated at $\langle p_T^b \rangle$, is shown in the last column. For further details see the caption to Fig. 7.

<table>
<thead>
<tr>
<th>$p_T^{\mu\text{-jet}}$ range (GeV)</th>
<th>$d\sigma/dp_T^{\mu\text{-jet}} \pm$ stat. $\pm$ syst. (pb/GeV)</th>
<th>$C_{had}$</th>
<th>$\langle p_T^b \rangle$ (GeV)</th>
<th>$d\sigma/dp_T^b \pm$ stat. $\pm$ syst. (pb/GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6, 11</td>
<td>$6.22 \pm 0.63^{+0.91}_{-1.04}$</td>
<td>0.87</td>
<td>8.5</td>
<td>$70 \pm 7.2^{+1.1}_{-1.1}$</td>
</tr>
<tr>
<td>11, 16</td>
<td>$2.74 \pm 0.36^{+0.47}_{-0.74}$</td>
<td>0.88</td>
<td>13.6</td>
<td>$14.4 \pm 1.9^{+1.1}_{-0.4}$</td>
</tr>
<tr>
<td>16, 30</td>
<td>$0.43 \pm 0.10^{+0.06}_{-0.07}$</td>
<td>0.88</td>
<td>21.25</td>
<td>$1.37 \pm 0.32^{+0.09}_{-0.37}$</td>
</tr>
</tbody>
</table>

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