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First Observation of Open b Production at HERA

H1 Collaboration

Abstract

The first observation of open b production in ep collisions is reported. The measurement was carried out using data taken by the H1 experiment at HERA at a centre of mass energy of $\sqrt{s}$ = 300 GeV. Events containing muons and jets were used to select a data sample enriched in b events. The cross section is found to be a factor $\sim$ 5 higher than calculations based on LO-QCD models.

Abstract: 575
Parallel sessions: 7,5
Plenary sessions: 9,7

1 Introduction

The study of heavy quark production in electron–proton scattering provides an important testing ground for QCD. At the electron–proton collider HERA with an ep centre of mass energy $\sqrt{s} = 300$ GeV, heavy quarks are produced predominantly by the photon gluon fusion process $\gamma g \to q\bar{q}$ ($q = c, b$), where a real or virtual photon emitted by the electron and a gluon from the proton generate a heavy quark pair.

The kinematics of the ep interactions are described by three independent variables, the centre of mass energy $\sqrt{s}$, the photon four momentum squared $q^2 = -Q^2$ and either one of the scaling variables $y = (q \cdot P/l \cdot P)$, the inelasticity of the ep-interaction, or the Bjorken- x $x = Q^2/(2P \cdot l)$, where P and l denote the four-momenta of the proton and the electron, respectively. The $\gamma - p$ centre of mass energy squared is given by $W^2_{\gamma p} = W^2 \approx ys - Q^2$. When y is calculated with the Jacquet-Blondel method [1], it is denoted as y_{JB}.

The dominant contribution to heavy quark production is due to the exchange of an almost real photon (*photoproduction*), where the negative squared four-momentum transfer carried by the photon is $Q^2 \approx 0$. The heavy quarks hadronize and are then either detected as *"open charm (beauty)"*, i.e with charm(beauty) hadrons, or alternatively as *"hidden charm(beauty)"* states such as $J/\psi(\Upsilon)$. The mean photon-proton center-of-mass (cms) energy $W_{\gamma p} \sim 200\,\mathrm{GeV}$ is roughly an order of magnitude larger than at previous fixed-target experiments.

Heavy quark production at HERA is dominated by charm quarks. The total cross section of open b production at HERA, $\sigma(ep \to b\bar{b}X)$, is expected to be about two orders of magnitude smaller than $\sigma(ep \to c\bar{c}X)$. The predictions for open b production at HERA for the NLO QCD calculations [2, 3, 4] are between 4.7 and 10 nb depending on the assumptions for the mass of the b quark and the parton distribution function (pdf) used. The expectation of the AROMA [5] Monte Carlo event generator, which is based on LO-QCD matrix elements with parton showers, is 3.8 nb for a mass of the b quark, $m_b = 4.75\,\mathrm{GeV}/c^2$ and the MRS(G) pdf. The first observation of open b production at HERA is reported here. The semileptonic decays of b quarks into muons were used as a tool to find a sample of events enriched in b decays. Two independent methods were used in the analysis. The first uses events with one muon candidate and two jets whereas the second uses events with two muon candidates.

The measurement is made in a visible range determined by the leptons from the heavy quark decay. The NLO calculations stop at the parton level and do not produce the decay leptons. Therefore, the result is compared to the LO-QCD models where this information is available. An estimate for the NLO-QCD contributions can be extracted from the prediction for the total cross section, $\sigma(ep \to b\bar{b}X)$, which are given above.

2 Data Selection and Analysis

The present analysis is based on data collected with the H1 detector during the 1995–96 running periods, corresponding to an integrated luminosity of $\mathcal{L} = 8.3\,\mathrm{pb}^{-1}$ at a centre of mass energy of 300 GeV. A detailed description of the detector and its trigger capabilities can be found elsewhere [6].

2.1 Detector Description

Here, a short description of the detector components which play a major role in this analysis is given. Charged particles are measured by two cylindrical jet drift chambers [7], mounted concentrically around the beam line inside a homogeneous magnetic field of 1.15 Tesla, yielding particle charge and momentum from the track curvature in the polar angular range[1] of 20° to 160°. Two double layers of cylindrical multiwire proportional chambers (MWPC) [8] with pad readout for triggering purposes are positioned inside and in between the two drift chambers, respectively. The tracking detector is surrounded by a fine grained liquid argon calorimeter [9], consisting of an electromagnetic section with lead absorbers and a hadronic section with steel absorbers. It covers polar angles between 4° and 154°. The detection of muons is made in the instrumented iron return yoke which surrounds the superconducting coil. The scattered electron from the deep inelastic scattering (DIS) is detected by a spaghetti type lead-scintilator-fibre calorimeter [10] which covers the backward region of the detector up to an angle of $\theta_e < 177.8°$.

2.2 Single Muon Analysis

Events are selected with the requirement of at least two jets with $E_T > 6\,\mathrm{GeV}$ in the pseudorapidity range $|\eta| < 2.5$. The jets were identified using a cone algorithm with radius $r = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 1$. In addition it was required that no electron candidate was found with $\theta_e < 177.8°$, which limits the data sample to photoproduction events with $Q^2 < 1$ GeV^2. To identify b events the semileptonic b decays into muons are used where at least one muon is identified in the central region of the detector ($35° < \theta^\mu < 130°$) where a transverse momentum $p_T^\mu > 2\,\mathrm{GeV}/c$ is required. The muon has to be found within one of the jets. Beauty and charm events are separated on a statistical basis using the transverse momentum of the muon $p_{T,rel}^\mu$ relative to the thrust axis of the jet defined as the direction in which T is maximum, with

$$T = \max \frac{\sum |p_i^L|}{\sum |p_i|} \quad i = \text{all the particles in the jet except the muon},$$

where p_i is the momentum and p_i^L its longitudinal component with respect to the thrust axis. Because the b quark is heavier than the c quark it is expected that the $p_{T,rel}^\mu$ distribution tends to higher values for the former. The shapes of the $p_{T,rel}^\mu$ distributions for beauty and charm are taken from the AROMA Monte Carlo event generator.

To check that the Monte Carlo simulation describes the energy distribution within the jet, a data sample enriched in charm quarks was studied, where events with at least one D^* candidate in the decay products were selected. The D^* candidate was identified through its decay $D^{*\pm} \rightarrow \overset{(-)}{D^0}\,\pi^\pm \rightarrow K^\mp\pi^\pm\pi^\pm$. This data sample passed through the jet finding algorithm and the energy flow within the jet was compared to the energy flow as given from the AROMA Monte Carlo event generator for charm events with a D^*. The result is shown in figure 1. From this study it is concluded that the Monte Carlo models the energy flow within the jet very well.

The main problem is to identify the background contribution in the event sample.The background consists of events with two jets and with one of the hadrons identified as a fake muon in the detector. To solve this problem it is essential to know the probability that a hadron h fakes a muon.

[1] H1 is using a right-handed coordinate system with the z axis pointing in the direction of the proton beam (forward), the x axis pointing towards the centre of the storage ring. The direction of the incoming positron beam is termed backward. The polar angle θ is measured with respect to the proton direction.

The probability functions $\mathcal{P}_h^\mu(p,\theta)$, where $h = \pi, K, p$, are parametrized as a function of the momentum and the polar angle of the hadron.

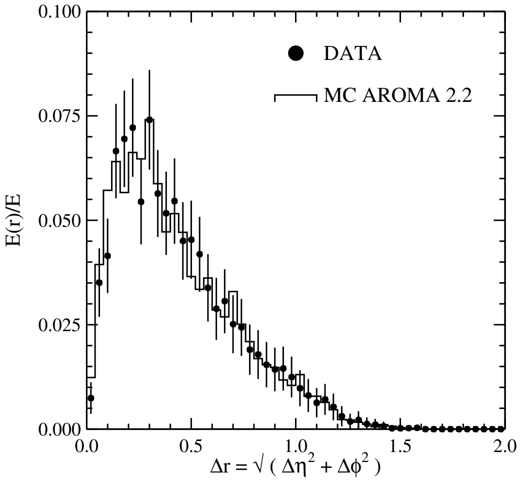

Figure 1: Fractional energy flow within jets as a function of the distance to the jet axis. The data points (filled dots) correspond to a data sample enriched in charm decays and the full histogram to a Monte Carlo simulation where only charm quarks were generated.

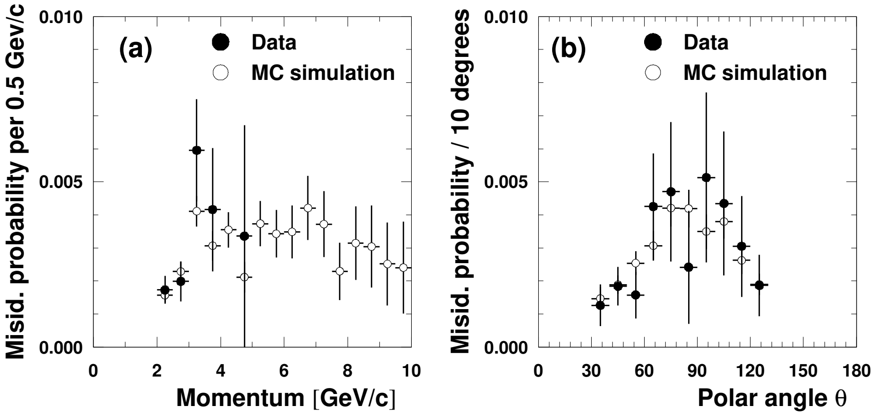

Figure 2: Momentum (a) and polar angle (b) distribution of pion misidentification probabilities $P_\pi^\mu(p)$ and $P_\pi^\mu(\theta)$ describing the probability that a pion is identified as muon in the instrumented iron return yoke. The filled points show the misidentification probability for pions obtained from data; the open points give the corresponding quantities for a Monte Carlo simulation.

These probability functions can be determined directly from the data by studying K_S^0, ϕ and Λ decays as a clean source of pions, kaons and protons. However, the available data do not allow the determination of these functions to sufficient precision. Therefore, after it was checked that the detector simulation describes the data very well (figure 2), large Monte Carlo samples with single pion, kaon and proton events were generated, passed through the full detector simulation and were used to determine the probability functions $\mathcal{P}_h^\mu(p,\theta)$.

To verify that the method of finding the fake muons works, the sample of pions from the K_S^0 decays in the data is used. In this sample, the number of pions misidentified as muons is known.

Then for each of the pions of the sample the probability that it fakes a muon is calculated and is used as weight to plot the θ, p distributions. As can be seen in figure 3, the agreement of the distributions expected after applying the $\mathcal{P}_\pi^\mu(p,\theta)$ on the data with the fake muons actually found is very good, both in shape and magnitude. Similar tests have been performed for the case of the kaons using events of elastic ϕ production. The misidentification probability, $\mathcal{P}_h^\mu(p,\theta)$, varies with the polar angle but it does not exceed $6 \cdot 10^{-3}$ in the case of pions and $2 \cdot 10^{-2}$ in the case of kaons. For protons the misidentification probability was found to be lower than $2 \cdot 10^{-3}$.

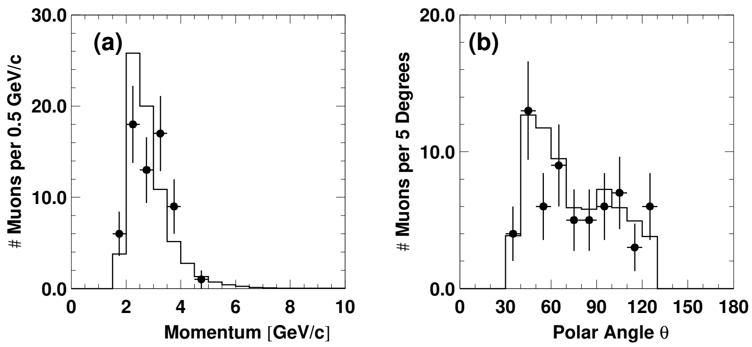

Figure 3: Momentum (a) and polar angle (b) distributions for fake muons due to a pion sample. The pions are identified via the decay $K_S^0 \to \pi^+\pi^-$. The filled points show the muon yield as measured in data. The solid histogram gives the estimate of the muon yield as obtained by assigning $P_\pi^\mu(p,\theta)$ as weight to every pion and summing the weights over the entire pion sample. The measured yield is 64 fake muons; the estimate amounts to 69.8.

The knowledge of the $\mathcal{P}_h^\mu(p,\theta)$ functions allows the calculation of the background directly from the data both in shape and absolute magnitude. For this purpose, events with two jets with $E_T > 6$ GeV were selected. The expected background in the $p_{T,rel}^\mu$ distribution was calculated from all the hadrons, passing the p_T^μ and polar angle requirements. The assignment of a hadron to a pion, kaon or proton was done according to the fractions of these particles as given by JETSET[11]. This hypothesis is supported by the measurements of the SLD[12] and DELPHI[13] collaborations in e^+e^- annihilation.

After the contribution of the fake muons in the $p_{T,rel}^\mu$ spectrum is estimated both in shape and absolute magnitude, the contributions of beauty and charm in addition to the fixed background are fitted to the measured $p_{T,rel}^\mu$ distribution. The result is shown in figure 4.

The relative composition of the data sample is determined from the fit to the $p_{T,rel}^\mu$ distribution and amounts to $f_b = 51.4 \pm 4.4\%$ (beauty), $f_c = 23.5 \pm 4.3\%$ (charm), and $f_{fake} = 23.5\%$ (background, fixed). Distributions of other variables, like the muon transverse momentum and polar angle as well as the jet transverse energy and polar angle distributions, are very well described with this data composition (figure 5). The polar angle distributions of the muon and the jet containing the muon figures 5b,d, indicate that the data are produced mainly in the forward region of the detector.

The open beauty cross section is determined from the number of muons N_b^μ attributed by the fit to b decays which are in the visible range $Q^2 < 1\,\mathrm{GeV}^2$, $0.1 < y_{JB} < 0.8$, $p_T^\mu > 2.0\,\mathrm{GeV}/c$, $35^\circ < \theta^\mu < 130^\circ$:

$$\sigma_{vis}(ep \to b\bar{b}X) \;= [0.93 \pm 0.08(stat.)\,^{+0.21}_{-0.12}(syst.)]\,\mathrm{nb}, \qquad \text{(H1 preliminary)}$$

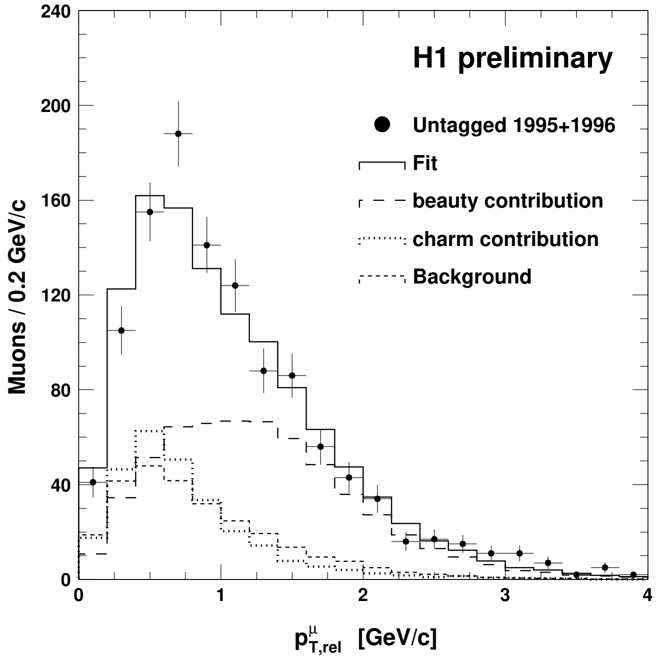

Figure 4: The measured $p^{\mu}_{T,rel}$ distributions and the result of the fit (solid line) are shown. The contributions of beauty (long dashed line) charm (dotted line) and the background (dashed line) are also shown.

where the first uncertainty is statistical and the second systematic. The estimated visible beauty cross section of AROMA amounts to $0.19\,\mathrm{nb}$, which is roughly a factor of five below the measured value. This measurement has been cross-checked using the HERWIG 5.9 [14] Monte Carlo event generator. The difference from AROMA is of the order of 5% and is included in the systematic error. Other sources of systematic uncertainties are the branching fractions $\mathcal{B}(b \to X\mu\nu)$, the background estimation, the energy scale and the trigger efficiency.

The visible charm cross section has been measured with the same method and shows good agreement with the expectation. Using AROMA for the extrapolation to the full kinematic range, the total charm cross section agrees to well within the errors with the total charm cross section measured using the reconstruction of D^* mesons [15].

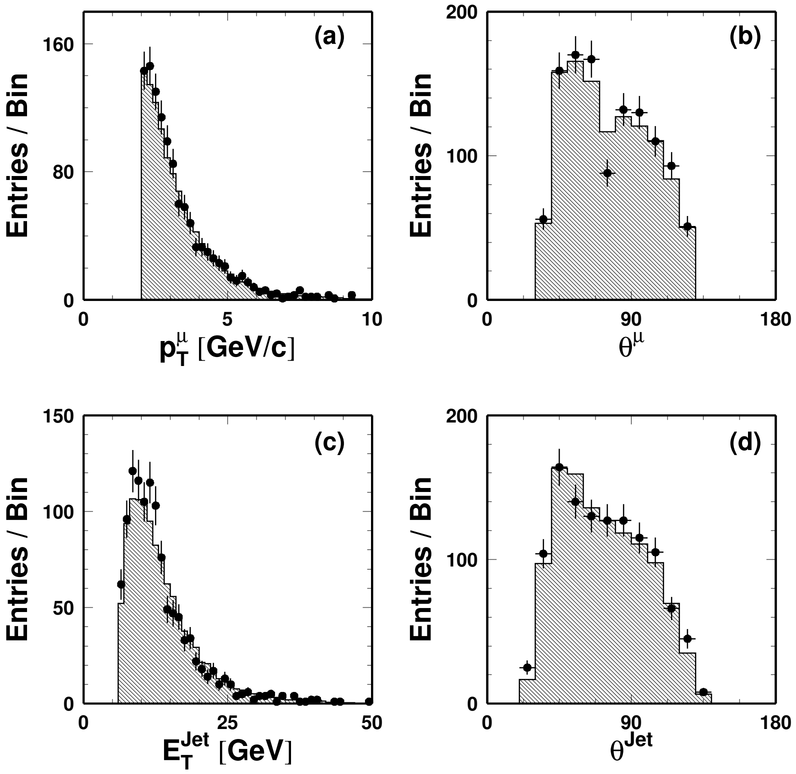

Figure 5: Comparison of measured kinematic distributions (full dots) to the sum of the different components (hatched histogram). (a) The transverse momentum of the muons, (b) the polar angle distribution of the muons, (c) the transverse energy of the jet containing the muon and (d) the polar angle distribution of the jets containing the muon.

2.3 A Dimuon Analysis

An alternative method to search for b production is based on like-sign dimuon events. As it can be seen in figure 6 the only physics channel, in the lower orders, that can produce like-sign

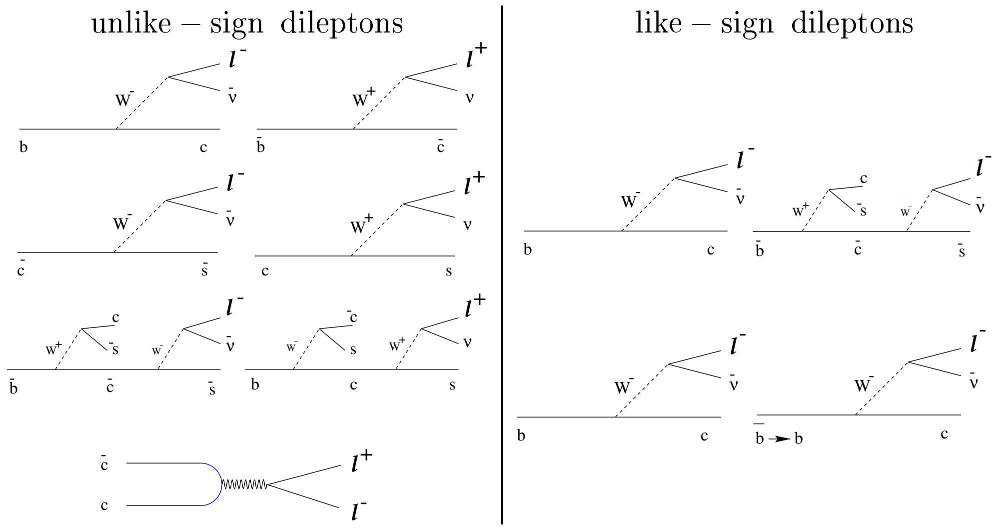

Figure 6: Sources of dilepton events

dimuons at HERA is b production. The number of like-sign dimuon events, $N_{\pm\pm}$, can be written as:

$$N_{\pm\pm} = N_{bb} + N_{bf} + N_{cf} + N_{ff}$$

where N_{bb} is the "real" number of dimuons both coming from b decays, N_{bf} (N_{cf}) the number of events where one $b(c)$ decays via a semi-muonic channel and one like-sign hadron misidentified as a muon, and N_{ff} is the number of events where both muon candidates are due to hadron misidentification. Note that $N_{bf} + N_{cf} + N_{ff}$ is nothing but the data sample with the single muon candidates combined with a hadron faking a muon. Therefore, one can use the single muon event sample in combination with the $\mathcal{P}_h^\mu(p,\theta)$ to estimate the background. Requiring two muons, each one having $P_T^\mu > 2.0\,\mathrm{GeV}/c$ and $35^\circ < \theta^\mu < 130^\circ$, gives 9 events in which like sign dimuons are found the expected background is 3.0 ± 0.15 events. This number of events is translated into a cross section in the visible range $(0.1 < y_{JB} < 0.9$, $P^\mu_{T\ 1(2)} > 2.0\,\mathrm{GeV}/c$, $35^\circ < \theta^\mu < 130^\circ)$ and found to be

$$\sigma_{vis}(ep \to b\bar{b}X) = 55 \pm 30(stat.) \pm 7(syst.)\ \mathrm{pb}, \qquad \text{(H1 preliminary)}$$

The expectation of AROMA is 17 pb. The main source of the systematical uncertainty is due to the errors on the measurements of the branching fractions $\mathcal{B}(b \to c\mu\nu)$ and $\mathcal{B}(b \to c \to s\mu\nu)$.

3 Conclusion

The open b production cross section has been observed for the first time at HERA with the H1 detector using semi-muonic decays of the b quarks. The cross section found to be a factor of ~ 5 higher than an expectation based on LO-QCD. Using events with two like-sign muons, the cross section is larger than the LO-QCD expectation, though the statistical uncertainty of the this latter measurement is large.

Acknowledgments

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