Submitted to the 30th International Conference on High-Energy Physics ICHEP2000,
Osaka, Japan, July 2000

Measurement of the Beauty Production Cross Section at HERA Using Lifetime Information

H1 Collaboration

Abstract

Beauty production has been observed in ep collisions at a centre-of-mass energy of 300 GeV. A central silicon vertex detector is used to identify b-hadrons by their decay length. The cross section is extracted from the impact parameter distribution of muons in dijet events. The result, based on this observable alone, is $\sigma_{vis}(ep \to b\bar{b}X \to \mu X) = [159 \pm 30\ (stat.)\ \pm 29\ (syst.)\ ]$ pb for the kinematic range $Q^2 < 1$ GeV^2, $0.1 < y < 0.8$, $p_T(\mu) > 2$ GeV and $35° < \theta(\mu) < 130°$. It confirms the earlier H1 measurement based on the transverse momentum of muons relative to jets. Using both observables and combining with the earlier result, the cross section is determined to be $\sigma_{vis} = (170 \pm 25)$ pb. It again exceeds NLO QCD predictions.

Abstract: 979,982
Parallel session: 7
Plenary talk: 3

1 Introduction

At HERA, heavy long-lived quarks are studied to test QCD, to probe proton structure and more general the structure of the interaction in ep collisions [1, 2, 3]. The masses of the charm, and even more so of the beauty quark introduce a scale that renders QCD perturbation theory to be applicable to the calculation of the production process [4, 5]. However, it has been observed in hadron hadron collisions [6], and recently also in two photon interactions [7], that measurements of b production cross sections tend to overshoot theoretical expectations in next-to-leading order. The first measurement of open b production at HERA [3] revealed a photoproduction cross section almost a factor of two above theoretical prediction, albeit with limited experimental accuracy.

The previous H1 result [3] has relied on the signature of semileptonic decays of b hadrons in jets and is based on the high transverse momentum p_T^{rel} with respect to the jet direction, which the lepton acquires due to the higher b mass. The long lifetimes of b hadrons, which can be measured with micro-vertex detectors, provide an independent signature. Beauty production at HERA has a small cross section, which is two and three orders of magnitude below the charm production and total cross sections respectively, and which falls steeply with increasing transverse momentum. Therefore most b hadrons are produced with small boost in the laboratory frame. Here, for he first time, is presented a measurement of the b production cross section, which uses the H1 central silicon tracker (CST) [8].

The analysis is performed with a sample of dijet photoproduction events with an identified muon, collected with the H1 detector [9] in 1997 when the CST was fully commissioned. For each muon candidate, the impact parameter δ is calculated in the plane transverse to the beam axis. Its magnitude is given by the distance of closest approach of the track to the primary event vertex. Its sign is positive if the intercept of the track with the jet axis is downstream of the primary vertex, and negative otherwise. Decays of long-lived particles are signalled by positive impact parameters, whereas the finite track resolution yields a symmetric distribution. The b cross section is extracted by decomposing the impact parameter distribution.

The paper starts with a brief description of the CST and its performance. The event selection and the impact parameter analysis are described subsequently. Finally, the cross section is extracted and discussed with respect to the previous H1 measurement and to theoretical expectations.

2 The H1 Central Silicon Tracker

The H1 detector has been described elsewhere [9]. The CST consists of two cylindrical layers of silicon strip detectors, surrounding the beam pipe at radii of $R = 57.5$ mm and $R = 97$ mm, respectively, from the beam axis. With an effective length of 358 mm the CST covers a large part of the ep interaction region and has a polar angle acceptance of $30^0 < \theta < 150^0$ for the outer layer. Double sided silicon detectors with readout strip pitches of 50 μm and 88 μm provide resolutions of 12 μm in $r\phi$ and 25 μm in z. Average hit efficiencies reach values of 97 (92)% in $r\phi$ (z).

The achieved dca[1] resolution of tracks with CST hits in both layers can be parameterized

[1] The dca is the transverse distance of the track to the center of the H1 detector.

as $\sigma_{dca} \approx 40\ \mu\text{m} \oplus 100\ \mu\text{m}/p_T[\text{GeV}]$. The first term represents the intrinsic resolution and the second the contribution from multiple scattering in the beam pipe. The intrinsic resolution is about 20% worse than expected from the Monte Carlo simulation, which is caused by imperfections in the calibrations of the drift chamber and the CST. In the analysis this is taken into account by an appropriate additional smearing of the Monte Carlo simulation.

The impact parameter method requires the precise knowledge of the ep-interaction point. The transverse profile of the interaction region at HERA has a Gaussian width of about $150\ \mu$m in the horizontal and of about $30\ \mu$m in the vertical direction. The average x and y coordinates are determined for each run by collecting information from many events.

3 Event Selection

The events were triggered by a coincidence of signals from the muon system, the central drift chamber and the multi-wire proportional chambers. The data set corresponds to an integrated luminosity of 14.7 pb^{-1}.

Photoproduction events are selected by requiring that there be no electromagnetic cluster with an energy above 8 GeV in the backward calorimeter. The accepted range of negative four-momentum transfer squared is thus restricted to $Q^2 < 1$ GeV^2. An inelasticity cut 0.1 $< y <$ 0.8, where y is calculated using the Jacquet-Blondel method [10], further reduces remaining background from deep inelastic scattering. Jets are reconstructed using the inclusive k_t algorithm [11] with parameter $R = 1$ in the energy weighted recombination scheme. Calorimeter clusters and charged particle tracks are combined, avoiding double counting. The selection requires at least 2 jets with transverse energy $E_T > 5$ GeV, of which at least one contains a muon candidate. Muons are identified in the barrel part of the instrumented iron, corresponding to polar angles $35^o < \theta(\mu) < 130^o$, and are required to have transverse momentum $p_T > 2$ GeV. At least two hits in the CST must be associated with the muon candidate track, measured in the central drift chambers. The combined track fit probability must exceed 10%. The final sample consists of 1403 events with 1415 muon candidates.

Monte Carlo event samples for the processes $ep \to b\bar{b}X$ and $ep \to c\bar{c}X$ have been generated using the AROMA program [12] which is based on leading order QCD and parton showers. The selection efficiency (10%) has been obtained from these Monte Carlo simulations. The trigger efficiency (79%) was determined from data, using an independent, calorimeter-based trigger.

The background from fake muons, i.e. hadrons misidentified as muons, is determined using tracks from a tagged photoproduction event sample, which fulfill the same selection criteria as the signal sample, except that no muon identification is required.

4 Impact Parameter Analysis

For each event the knowledge of the ep collision point is significantly improved by applying a primary vertex fit to selected tracks with CST information. The muon track candidate under

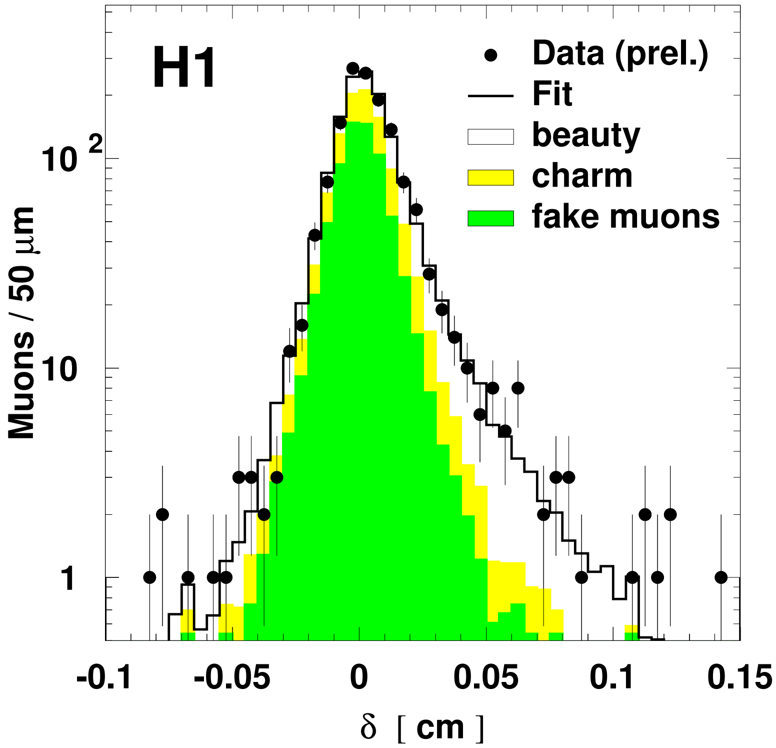

Figure 1: Impact parameter distribution and decomposition from the likelihood fit.

consideration is excluded from this fit. An average muon impact parameter resolution of 80 μm has been achieved with comparable contributions from the muon track reconstruction and the primary vertex determination.

Figure 1 shows the observed impact parameter distribution in the data together with histograms indicating the contributions from b production and from the backgrounds. The decomposition is obtained from a likelihood fit to the δ spectrum, following the method of [13]. The fit uses the shapes of the δ distributions of beauty and charm events from the AROMA Monte Carlo simulation and of fake muon events from real data. The relative weights of all three components are adjusted such that the likelihood is maximized. The fit yields a sample composition of $f_b = (26 \pm 5)\%$ (beauty), $f_c = (24 \pm 12)\%$ (charm) and $f_{fake} = (50 \pm 10)\%$ (fake muons). The correlation coefficients are $\rho_{b,c} = -0.7$, $\rho_{b,fake} = 0.4$ and $\rho_{c,fake} = -0.9$. The statistical errors of the fit include a non negligible contribution from the limited statistics of the samples representing the different components.

As a cross-check the fractions can be compared with predictions from the Monte Carlo or measurements in the real data. The charm result translates into a total $c\bar{c}$ cross section of 840 nb. Within errors this is in agreement with the H1 measurement of D^* photoproduction [1]. The fraction of fake muons from the fit is in good agreement with an estimate of (56$\pm$6)% from momentum and polar angle dependent misidentification probabilities [3].

The results from the impact parameter analysis can be compared with an independent measurement using the transverse momentum p_T^{rel} of the muon candidate relative to the jet axis. Figure 2 shows the observed p_T^{rel} distribution of the data. The estimated signal and backgrounds,

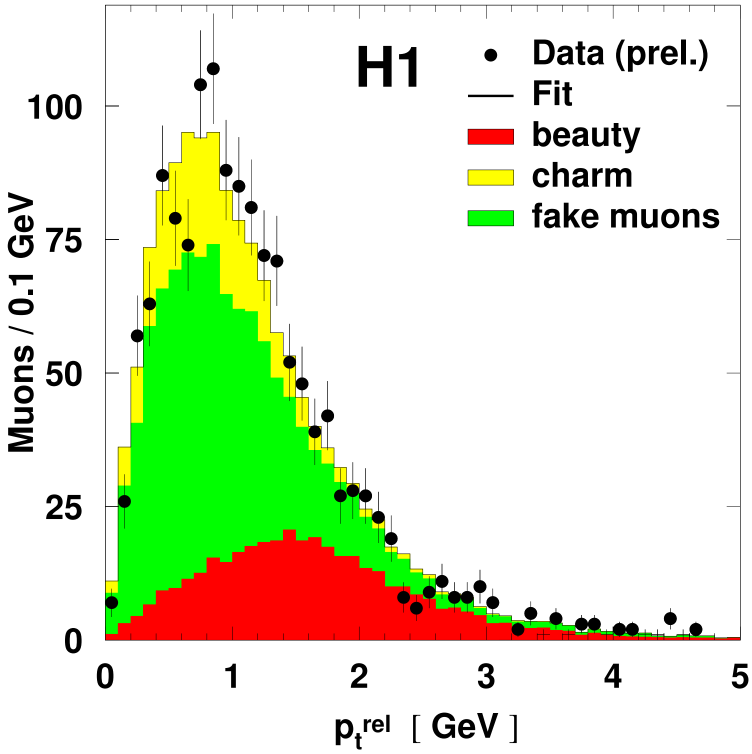

Figure 2: p_T^{rel} distribution and decomposition from the likelihood fit with fixed normalization for the fake muon contribution.

also shown in Figure 2, are taken from a likelihood fit, using the same method as for the δ fit. As the p_T^{rel} distributions of charm and fake muon events cannot be well distinguished, the fake muon contribution is fixed at $f_{fake} = 56\%$. The fit yields a b fraction of $f_b = 27 \pm 3\%$. The obtained p_T^{rel} fit results for the sample composition are in good agreement with the values from the δ fit. The p_T^{rel} method exhibits smaller statistical errors, due to a better shape discrimination of the beauty events in p_T^{rel}, but the fake muon component must here be fixed in order to obtain meaningful fit results.

To further elucidate the consistency of the two observables δ and p_T^{rel} one can enrich the b component in the events by restricting the range of one variable and then studying the distribution of the other quantity. Figure 3 shows the observed δ spectrum obtained after a cut $p_T^{rel} > 2$ GeV. The different contributions, shown in Figure 3a, are the absolute predictions from the above δ fit for the limited p_T^{rel} region. The observed impact parameter spectrum and the fit prediction, with a dominating beauty component, agree within the errors. Figure 3b shows the p_T^{rel} spectrum after a cut on $\delta > 500$ μm. The spectrum also agrees within the statistical errors with the fit prediction.

The observed distributions in the regions of high b purity add further confidence that the data are well understood. The two observables δ and p_T^{rel} complement each other in the discrimination of the beauty component in the data against the different background sources. The separation power can be combined in a likelihood fit of the two-dimensional distribution of these variables. The fit yields $f_b = (27 \pm 3)\,\%$, $f_c = (27 \pm 7)\,\%$ and $f_{fake} = (46 \pm 7)\,\%$ with correlation coefficients of $\rho_{b,c} = -0.04$, $\rho_{b,fake} = -0.2$ and $\rho_{c,fake} = -0.9$. The result for the

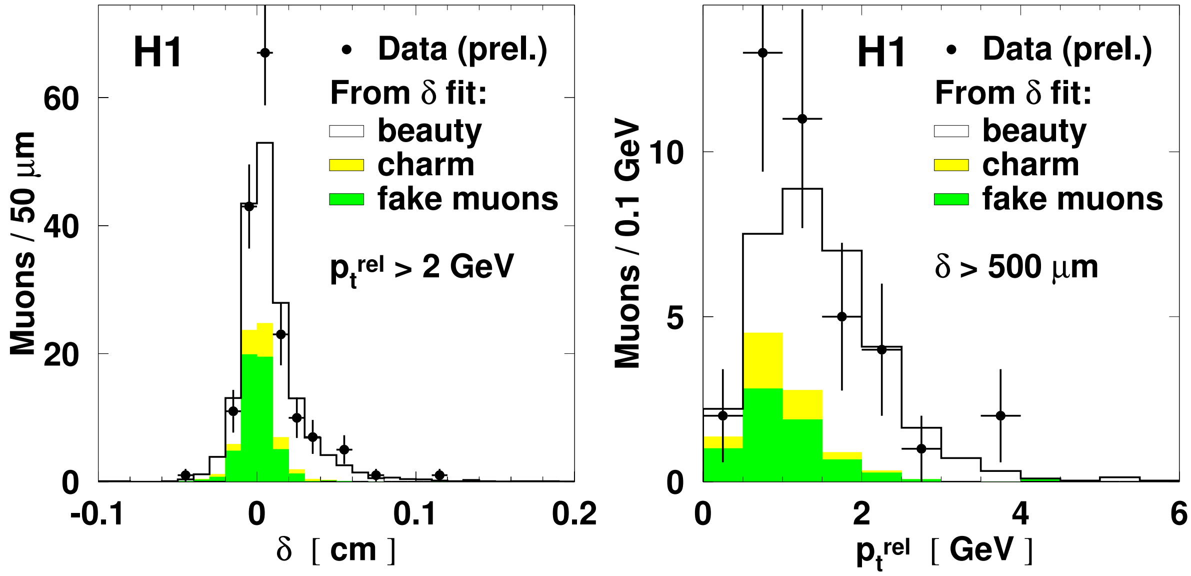

Figure 3: Impact parameter distribution for muon candidates with $p_T^{rel} > 2$ GeV (a) and p_T^{rel} distribution for muon candidates with $\delta > 500\ \mu$m (b), with estimated contributions.

fake muon background, and for the charm fraction, are again consistent with the estimates and measurements quoted above.

5 Beauty Cross Section

The cross section for the production of central muons from b decays for the kinematic range $Q^2 < 1$ GeV^2, $0.1 < y < 0.8$, $p_T(\mu) > 2$ GeV and $35° < \theta(\mu) < 130°$, as determined by the fit to the impact parameter distribution alone yields

$$\sigma_{vis}(ep \to b\bar{b}X \to \mu X) = [159\ \pm\ 30\ (stat.)\ \pm 29\ (syst.)\ ]\ \mathrm{pb}\ .$$

The cross section was previously measured by H1 with the p_T^{rel} method, using data taken in 1996 and a different event selection, to be [3]

$$\sigma_{vis}(ep \to b\bar{b}X \to \mu X) = [176\ \pm\ 16\ (stat.)\ ^{+27}_{-17}\ (syst.)\ ]\ \mathrm{pb}$$

in the same range. The published result is thus confirmed, using an independent signature and data set.

The fit of the two-dimensional (δ, p_T^{rel}) distribution of the new data yields

$$\sigma_{vis}(ep \to b\bar{b}X \to \mu X) = [160\ \pm\ 16\ (stat.)\ \pm 29\ (syst.)\ ]\ \mathrm{pb}\ .$$

The systematic error from variations of the impact parameter analysis and from the modeling of the tracking resolution is 10%. Uncertainties due to the Monte Carlo modeling of the final state affect mostly the selection efficiency and only weakly the impact parameter distribution.

Following studies with the RAPGAP Monte Carlo generator [14], which includes contributions from resolved photoproduction, a systematic error of 10% is assigned due to uncertainties in the modeling of the hadronic final state. Performing the jet reconstruction with the CDF cone algorithm [15] yields 30% more events, but no significant change in the cross section. Further contributions to the systematic error arise from the statistical error of the trigger efficiency, from the detector simulation, and from the luminosity measurement. Added in quadrature, the total systematic error amounts to 18%.

The measurement is consistent with the previous H1 result [3] within the statistical uncertainty. Both can be combined, taking correlated systematic uncertainties into account. The result is

$$\sigma_{vis}(ep \to b\bar{b}X \to \mu X) = (170 \pm 25)\ \mathrm{pb}\ .$$

The NLO QCD prediction, using a calculation by Frixione et al. [5] and a Peterson type fragmentation ansatz [16] is (104 $\pm$ 17) pb [3] where the error reflects the uncertainties due to variations of the renormalization or factorization scale, and to the fragmentation. That NLO QCD undershoots the measurement is hereby confirmed. Such a discrepancy is now established in both ep and $\bar{p}p$ interactions [6].

6 Conclusion

Open beauty production at HERA has been measured, using for the first time lifetime information. The cross section has been extracted from an analysis of the muon impact parameter spectrum. The result confirms the first H1 measurement, based on kinematic observables. Both measurements are found to be above NLO QCD expectations.

Acknowledgments

We are grateful to the HERA machine group whose outstanding efforts have made and continue to make this experiment possible. We thank the engineers and technicians for their work in constructing and now maintaining the H1 detector, our funding agencies for financial support, the DESY technical staff for continual assistance, and the DESY directorate for the hospitality which they extend to the non-DESY members of the collaboration.

References

[1] H1 Coll., S. Aid *et al.*, Nucl. Phys. B472 (1996) 32,
H1 Coll., C. Adloff *et al.*, Z. Phys. C 72 (1996) 593, Nucl. Phys. B545 (1999) 21.

[2] ZEUS Coll., J. Breitweg *et al.*, Eur. Phys. J. C6 (1999) 67, Eur. Phys. J. C12 (2000) 1.

[3] H1 Coll., C. Adloff *et al.*, Phys. Lett. B467 (1999) 156.

[4] R.K. Ellis and P. Nason, Nucl. Phys. B312 (1989) 551;
J. Smith and W.L. Van Neerven, Nucl. Phys. B374 (1992) 36;
S. Frixione, M.L. Mangano, P. Nason, and G. Ridolfi, Nucl. Phys. B412 (1994) 225;
B.W. Harris and J. Smith, Nucl. Phys. B452 (1995) 109; Phys. Lett. B353 (1995) 535; Phys. Rev. D57 (1998) 2806.

[5] S. Frixione, M.L. Mangano, P. Nason, and G. Ridolfi, Phys. Lett. B348 (1995) 633.

[6] CDF Coll., F. Abe *et al.*, Phys. Rev. Let. 71 (1993) 2396, Phys. Rev. D 53 (1996) 1051;
D0 Coll., S. Abachi *et al.*, Phys. Rev. Let 74 (1995) 3548, Phys. Let. B 370 (1996) 239.

[7] L3 Coll, *Measuremnent of Charm and Beauty Production in $\gamma\gamma$ Collisons at LEP*, contributed paper to the International Europhysics Conference High Energy Physics, Tampere, Finland, 1999.

[8] D. Pitzl *et al*, *The H1 Silicon Vertex Detector*, preprint ETHZ-IPP-PR-2000-01, hep-ex/0002044, 2000.

[9] I. Abt *et al.* (H1 Collaboration) Nucl. Instr. Meth. A386 (1997) 310 and 348.

[10] F. Jacquet, A. Blondel, in: Proc. *Study of an ep Facility for Europe* (Ed. U. Amaldi), DESY 79/48, p 391 (1979).

[11] S. Catani, Yu. Dokshitzer, M.H.Seymour and B.R. Webber, Nucl. Phys. B 406 (1993) 187.

[12] G. Ingelman, J. Rathsman and G.A. Schuler, Comput. Phys. Commun. 101 (1997) 135.

[13] R. Barlow and C. Beeston, Comp. Phys. Comm. 77 (1993) 219.

[14] H.Jung, Comput. Phys. Comm. 86 (1995) 147.

[15] J.E. Huth *et al.*, *Towards a standardization of jet definitions*, presented at Summer Study on High Energy Physics, Research Directions for the Decade, Snowmass, CO, June 25 - July 13, 1990.

[16] C. Peterson, D. Schlatter, I. Schmitt, and P.M. Zerwas, Phys. Rev. D 27 (1983) 105.