Measurement of the $b\bar{b}$ Cross Section at HERA–B

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Abstract. The $b\bar{b}$ production cross section has been measured in collisions of 920 GeV protons off a nuclei target using the HERA–B detector. The identification of $b\bar{b}$ events was done via inclusive bottom quark decays into J/ψ by exploiting the longitudinal separation of the $J/\psi \to l^+l^-$ decay vertices from the primary proton nucleus interaction, where both the $\mu^+\mu^-$ and the e^+e^- decay channels have been reconstructed. The first measurement, using data collected during a short period in 2000, yields a cross section in the combined analysis of $\sigma(b\bar{b}) = 32^{+14}_{-12}(\text{stat})^{+6}_{-7}(\text{sys})$ nb/nucleon. On the most recent data samples taken in 2002/3, a much more accurate measurement with the uncertainties reduced to 10% is expected.

INTRODUCTION

Despite the good theoretical description of open charm and charmonium production in various experimental environments, the open beauty production description is still not satisfactory at least for higher center of mass energies. While the behavior of differential cross sections as a function of kinematical variables is usually reproduced quite well, the absolute values are still in disagreement by a factor of 2 to 7 [1]. This has been observed by several experiments: in $\gamma\gamma$ reactions at LEP (OPAL [2] and L3 [3]), in $p\bar{p}$ interactions at CDF [4], and in ep scattering at HERA (H1 [5, 6] and ZEUS [7]). Although new calculations for CDF of the theoretical cross section [8] reduced the discrepancy, the theoretical predictions contain still large uncertainties and the measured cross sections and QCD NLO expectations are not yet in good agreement [9]. This emphasizes the need of precise measurement of the $b\bar{b}$ production cross sections as an important input to perturbative QCD calculations.

For the measurement of $\sigma(b\bar{b})$ in the kinematical region of $\sqrt{s} \approx 40$ GeV the recent situation is not satisfactory. Only two experimental measurements exist for this region those of the E789 [10] and E771 [11] collaborations (see. Tab. 1). Their results show large uncertainties and poor compatibility. A new accurate measurement is therefore highly desirable and would be a sensitive test for QCD predictions.

TABLE 1. Other $\sigma(b\bar{b})$ Measurements

Exp.	E_p [**GeV**]	$\sigma(J/\psi)$ [**nb/nucleon**]	**channel**
E789	800	$5.7 \pm 1.5 \pm 1.3$	$b \to J/\psi(\mu^+\mu^-)X$
E771	800	$43\,^{+27}_{-17}\,\pm 7$	μ(s.l.) / $b(\bar{b})$ dec.
Theory prediction: $9 \leq \sigma(b\bar{b}) \leq 55$ nb/nucleon			

THE HERA–B EXPERIMENT

The HERA–B [12, 13] experiment (Fig. 1) has been designed to identify B–mesons decays in a dense hadronic environment with a large geometrical coverage. The B mesons are produced by interaction of the proton in the halo of the 920 GeV HERA beam with different target wires, which can be used individually or simultaneously. Since there are various target materials available, the A–dependence of heavy quark production can be measured. The events from different wires can be separated easily by applying accurate spatial separation cuts.

The $b\bar{b}$ production cross section $\sigma^A_{b\bar{b}}$ on a nucleus of atomic number A is obtained from the inclusive reaction

$$pA \to b\bar{b}X \text{ with } b\bar{b} \to J/\psi X' \to (e^+e^-/\mu^+\mu^-)X' \quad (1)$$

The b–hadron decays into a J/ψ are distinguished from the large prompt J/ψ background by exploiting the long b lifetime in a detached vertex analysis. HERA–B is able to reconstruct the J/ψ either in the $\mu^+\mu^-X$ or in the e^+e^-X decay channel. The availability of both channels is important to increase the statistics and to cross check the results.

In the data taking period of 2002/03 starting in October 2002 HERA–B was routinely running and able to collect $164 \cdot 10^6$ events triggered by a dilepton J/ψ–trigger. The data were taken using a trigger configuration, selecting the events by the requirement of two pretrigger (PT) seeds originating either from the muon pre-

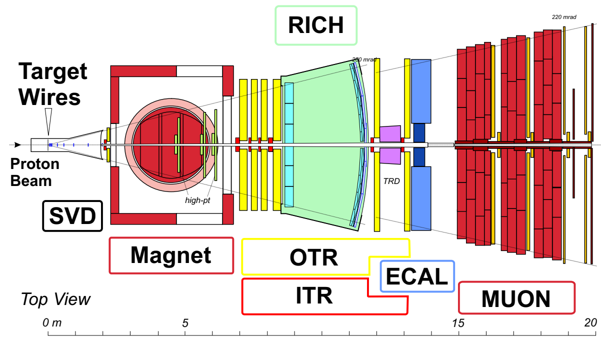

FIGURE 1. HERA–B is a fixed target spectrometer at the HERA proton beam at $E_p = 920$ GeV

trigger or the pretrigger of the electromagnetic calorimeter (ECAL). The PT information was then used as seeds for the first level trigger (FLT), where a single track candidate was searched. The PT and FLT information was finally passed to the second level trigger (SLT) where the FLT track had to be confirmed and combined with a second track. On the SLT in addition a vertex constraint was applied. Using this trigger configuration, HERA-B was able to collect up to 1400 fully reconstructed J/ψ's per hour. With the achieved event yield and an interaction rate of 5 MHz we collected about 300.000 J/ψ's approximately equally distributed to both decay channels $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$. Furthermore, for other charmonium states a quite large statistics could be achieved: $N(\chi_c) \approx 20000$, $N(\psi') \approx 5000$. In the B–sector the number of candidates was increased by more than an order of magnitude with respect to the year 2000: $N(b \to J/\psi X) \approx 180$, $N(\Upsilon(1S)) \approx 60$.

MEASUREMENT

In order to minimize the systematic errors and to remove the dependence on the absolute luminosity determination, the $\sigma(b\bar{b})$ cross section is measured relative to the known prompt J/ψ cross section $\sigma^A_{J/\psi}$ [14, 15]. Within the HERA–B acceptance, the first fixed–target experiment covering the negative x_f region ($x_F \in [-0.35, 0.15]$, $x_F = \frac{p_L^{cms}}{(p_L^{cms})_{max}}$), the cross section can be written as as:

$$\Delta\sigma_{b\bar{b}} = \Delta\sigma_r \cdot \frac{n_B}{n_P} \cdot \frac{1}{\varepsilon_R \cdot \varepsilon_B^{\Delta z} \cdot BR(b\bar{b} \to J/\psi X)} \qquad (2)$$

where n_B/n_P are the observed b and prompt J/ψ events, ε_R the relative efficiency ($\varepsilon_R = \varepsilon_B^{J/\psi}/\varepsilon_P^{tot}$, $\varepsilon_B^{tot} = \varepsilon_B^{J/\psi} \cdot \varepsilon_B^{\Delta z}$) of B– to prompt J/ψ–efficiency ratio (trigger + reconstruction + selection), $BR(b\bar{b} \to J/\psi) = (2.32 \pm 0.20)\,\%$ is the branching ratio measured at LEP [16], $\Delta\sigma_r$ is the reference (prompt J/ψ) cross section re-weighted to the HERA–B acceptance and finally $\Delta\sigma_{b\bar{b}}$ the measured cross section in HERA–B acceptance.

TABLE 2. Reference J/ψ–prompt cross sections of other experiments.

Exp.	**Target**	E_p [**GeV**]	$\sigma(J/\psi)$ [**nb/nucleon**]	α
E789	Au	800	$442 \pm 2 \pm 88$	0.9 ± 0.02
E771	Si	800	$375 \pm 4 \pm 30$	0.92 ± 0.008

The reference prompt J/ψ production cross section per nucleon $\sigma(pN \to J/\psi X)$ was previously measured by two fixed target experiments (E789 and E771, see Tab. 2, [14, 15]). After correcting for the most recent measurement of the nuclear dependence A^α using $\alpha = 0.955 \pm 0.005$ (E866, [17]) and scaling to HERA–B energies [18] a reference cross section of $\sigma(pN \to J/\psi) = (357 \pm 8 \pm 27)$ nb/nucleon is obtained. Within the acceptance of HERA-B only a fraction of $f_P = (77 \pm 1)\,\%$ [14] of the prompt J/ψ and $f_B = (90.6 \pm 0.5)\,\%$ of the $b\bar{b}$ events can be measured. Therefore, the reference prompt J/ψ cross section to be used writes as:

$$\Delta\sigma_r = f_P \cdot \sigma(pN \to J/\psi) \cdot A^\alpha \qquad (3)$$

Since no nuclear suppression has been observed in D–Meson production [19] and a similar behavior is expected in the b channel, a nuclear dependence of $\alpha = 1.0$ is assumed for the $b\bar{b}$ production cross section [20] in this analysis, i.e. $\sigma^A_{b\bar{b}} = \sigma(pN \to b\bar{b}) \cdot A$.

MONTE CARLO MODELS

A Monte Carlo (MC) simulation is used to determine the efficiencies of Eq. 2 and to describe the background contribution of the prompt J/ψ events to the $b \to J/\psi X$ decay channel. The simulation of heavy flavour quark (Q) production in $pA \to Q\bar{Q}X$ interactions and the heavy quark hadronization in the nuclear environment is done using the PYTHIA 5.7 event generator [21]. For the remaining part of the process (X) as light quark production inside the nucleus, secondary interactions and pA inelastic interactions, the FRITIOF 7.02 [22] package is used.

The $b\bar{b}$ events generated by PYTHIA are weighted using a model with various contributions. First, the generated b–quark kinematics (x_F, p_T) are given by a model by M. Mangano [23, 24] based on the most recent next-to-next-to-leading-logarithmic (NNLL) MRST parton density functions [25] with a b–quark mass of $m_b = 4.75$ GeV$/c^2$ and a QCD renormalization scale of $\mu_R = \sqrt{m_b^2 + p_T^2}$. Furthermore, the intrinsic transverse momenta k_T of the colliding partons are smeared with

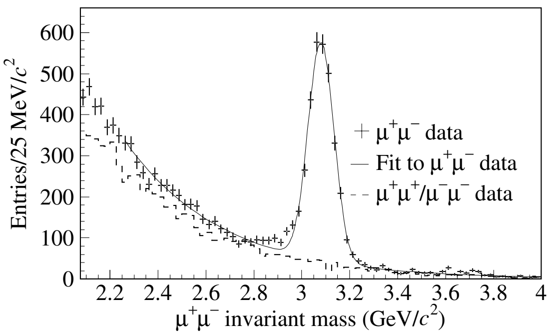

FIGURE 2. The prompt $J/\psi \to \mu^+\mu^-$ signal of the data taken in 2000. The signal has been optimized to obtain a higher significance $\Sigma = \sqrt{S/(S+B)}$. The fit (solid line) assumes a Gaussian in the signal region and describes the background with an exponential.

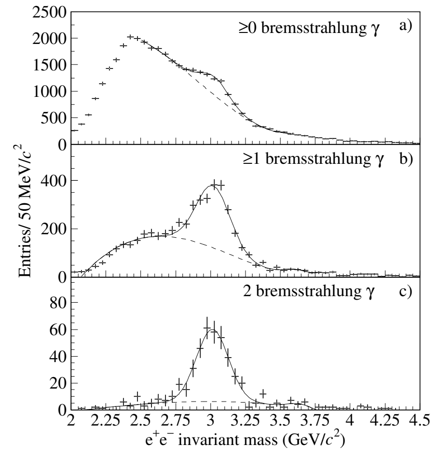

FIGURE 3. The prompt $J/\psi \to e^+e^-$ signal of the data taking period of 2000, with an E/p cut at 1 σ and 0 (a), 1 (b) or 2 (c) BR requirements in addition. The signal is described by a Gaussian and the background shape by a polynomial.

a Gaussian distribution leading to $\langle k_T^2 \rangle = 0.5$ GeV$^2/c^2$ [26]. Finally, the b fragmentation to hadrons is described by a Peterson function using a parameter of $\varepsilon_{peterson} = 0.006$ [27].

To obtain a realistic description of the kinematical distribution of the prompt J/ψ's, the generated events are re-weighted to match the known prompt J/ψ differential cross sections measured in proton–gold collisions [14]. These results were obtained in the positive x_F ($x_f > -0.05$) region while HERA–B has mainly access to the negative x_f region. MC studies based on the Color Octet Model [28] of charmonium production show a symmetric X_F distribution of the prompt J/ψ decays. Therefore the experimental parameterization of [14] was used to extrapolate to the full x_F space.

PROMPT J/ψ SELECTION

Since the number of prompt J/ψ decays n_P is used as a normalization factor of the $b\bar{b}$ cross section measurement, n_P will be determined before applying the detached vertex cuts. The selection of the $J/\psi \to l^+l^-$ differs between the μ– and e–channel due to the different shapes of the background. To select the $\mu^+\mu^-$ decays, a dimuon vertex is required in addition to muon identification cuts in the Muon and RICH systems. The final selection used for the analysis based on the data taken in 2000 is presented in Fig. 2. The selection of the e–events is more difficult. Aside from the dilepton vertex two additional identifications cuts were applied:

- Electrons are fully absorbed in the ECAL, therefore the ratio of the cluster energy E associated with the track and the track momenta p should be around 1. The E/p spectrum has to be compatible with a Gaussian distribution of mean 1.00 and width $\sigma \approx 9\,\%$.
- Bremsstrahlung (BR) photons that are emitted by electrons traveling through the layers of material before the magnet keeping the original direction of the lepton. To purify the electron signal, a photon cluster in the ECAL could be required in conjunction with the electron.

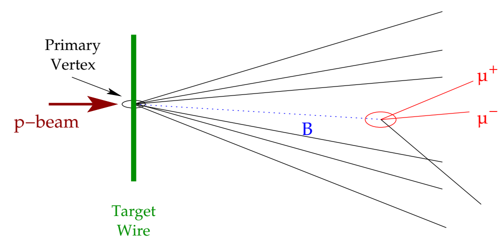

FIGURE 4. Average decay length of B–mesons at HERA–B: $DL \approx 8$ mm $\gg \sigma_{\Delta z}$

In Fig. 3 the invariant mass distributions for the data taken in 2000 are presented. In addition to the requirement that E/p is within $\pm 3\sigma$ it shows, how the significance of the signal improves by requiring 1 or 2 BR clusters.

DETACHED ANALYSIS

To identify b–hadrons from the decay chain in Eq. 1 their decay length Δz, defined as the distance along the beam axis between the J/ψ decay vertex and the closest target wire, is used (Fig. 4). Additionally, cuts on the

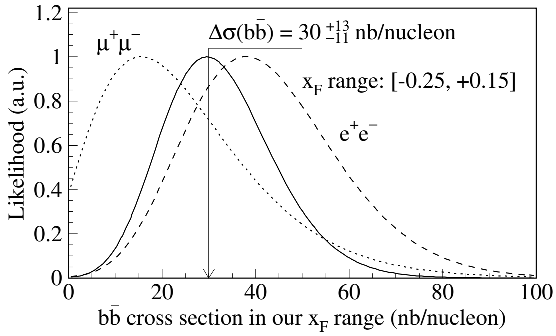

FIGURE 5. The combined fit for the 2000 measurement

minimum impact parameter of both leptons are applied. For the selection in the μ–channel in 2000 the cuts were set for the decay length to $|\Delta z| > 0.4$ cm and $|\Delta z| > 7.5 \cdot \sigma_Z$, where σ_Z is the uncertainty of the secondary vertex position. For the impact parameter to the primary vertex the cut was set at $I_P > 160\ \mu$m. In case of the e–channel the cuts were chosen to $\Delta z > 0.5$ cm, the minimal distance in the z–plane, z_w, of the wire to any other track to $z_W > 250\ \mu$m or for the impact parameter to the wire to $I_W > 200\ \mu$m.

The 2000 $\sigma(b\bar{b})$ Measurement

To extract the number of detached J/ψ's N_B, an unbinned likelihood fit was performed on the invariant mass spectra of the selected detached data. The target materials used in 2000 were mainly carbon (77 %, $A = 12$) and titanium (23 %, $A = 48$). Overall, in the e–channel a number of $n_B = 8.6^{+3.9}_{-3.2}$ detached J/ψ's were found, compared to the number of $n_P = 5710 \pm 380$ of prompt J/ψ's. Due to the good knowledge of the particle identification efficiencies, no BR tag requirement was necessary and n_P was determined applying a $\pm 3\ \sigma$ cut in E/p. For the μ–channel $n_B = 1.9^{+2.2}_{-1.5}$ and $n_P = 2880 \pm 60$ was extracted.

To get the maximum information on the $b\bar{b}$ production cross section a combined fit to the e^+e^- and $\mu^+\mu^-$ data samples was performed (Fig. 5) delivering the final result in the HERA–B x_F range of $\Delta\sigma(b\bar{b}) = 30^{+13}_{-11}$ nb/nucleon. Extrapolating to the full x_F range a value of [29]

$$\sigma(b\bar{b}) = 32^{+14}_{-12}\text{stat}^{+6}_{-7}\text{sys nb/nucleon} \tag{4}$$

was found. The main sources of systematic uncertainties originate (for μ/e) from the reference cross section (11 %), the b production and decay model (8 %), the trigger simulation (5 %) and the description of the background shape (11/20 %) and fluctuations (11/23 %).

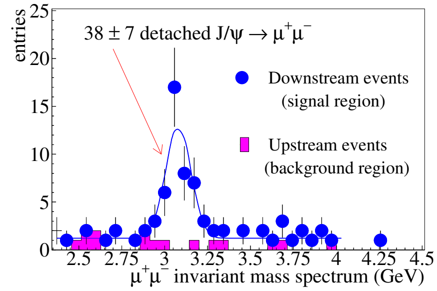

FIGURE 6. Detached Signal of 40 % of the data of 2002/3 in the $\mu^+\mu^-$–channel

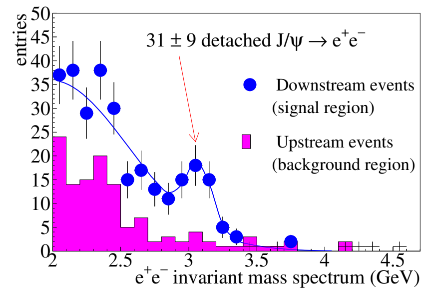

FIGURE 7. Detached Signal of 40 % of the data of 2002/3 in the e^+e^-–channel

New Measurement (2002/3)

The search for detached J/ψ vertices was performed on the new data of 2002/3 on 40 % of the full statistics. Using this amount of data a number of $n_B^\mu = 38 \pm 7$ (Fig. 6) detached J/ψ's were found in the μ–channel and $n_B^e = 31 \pm 9$ (Fig. 7) within the e–channel. Extrapolating these numbers to the full statistics, we expect a total number of detached events in 2002/3 of $n_B^\mu \approx 95 \pm 11$ and $n_B^e \approx 80 \pm 13$. This corresponds to an improvement of the statistical error from ≈ 40 % (2000) to ≈ 10 % (2002/3) and a reduction of the systematic uncertainties from 24 % (33 %) down to 16 % (18 %) for $\mu(e)$.

A first complete analysis of the $b\bar{b}$ production cross section was done on the sample shown in Fig. 8 corresponding to 16% of the full $\mu^+\mu^-$ data sample of 2002/3. The selection cuts for the detached J/ψ's were set to $|\Delta z| > 0.4$ cm, $|\Delta z| > 12 \cdot \sigma_z$ and $I_P > 160\ \mu$m. Out of a total amount of $n_P = 22658 \pm 172$ prompt events a number of $n_B = 11^{+4.4}_{-3.7}$ events within in the detached signal was extracted. Since this sample was taken using a carbon wire, a value of $\Delta\sigma_r^C = (245 \pm 6 \pm 19)$nb/nucleon was calculated for the corresponding reference prompt J/ψ cross section.

The efficiency evaluations and the detached cut optimizations are under evaluation. The cuts are optimized by maximizing the significance function $\Sigma =$

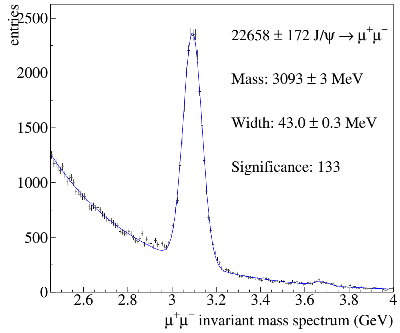

FIGURE 8. The prompt $J/\psi \to \mu^+\mu^-$ signal of 16% of the data taken in 2002/3. The signal has been optimized to obtain a higher significance $\Sigma = \sqrt{S/(S+B)}$.

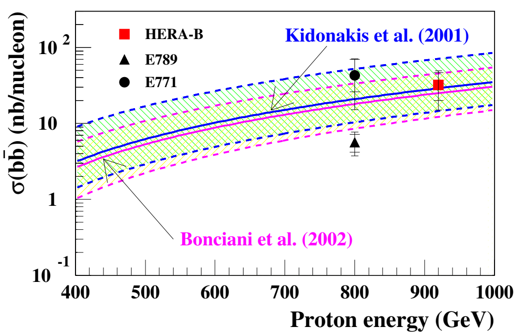

FIGURE 9. Comparison of the HERA–*B* (2000) $\sigma(b\bar{b}$ measurement value with other experiments and the theoretical predictions.

$S/\sqrt{S+BG}$, where S stands for signal events and BG for the corresponding background. Using B events from MC for the signal events, the background is described using various models including real data samples and MC events. Once the cuts are optimized on this subsample, they will be used in a blind analysis for the whole data sample to avoid any biased cut selection. Preliminary evaluation provide a measurement of the production cross section $\sigma(b\bar{b})$ on the 2002/3 data in full agreement with the previous result (Eq. 4).

CONCLUSIONS

The measurement using the data of 2000 shows good agreement with QCD calculations beyond NLO [30, 31] and the existing experimental results (Fig. 9) [10, 11, 29]. The measurement with new data (2002/3), dealing with ~ 30 times more statistics, can be used to reduce the theoretical uncertainties, originating mainly from uncertainties on the mass of the b–quark ($m_b \in [4.5, 5.0]$ GeV). To analyze the full data sample, the cut optimization will be done on the presented 16% of the data. Afterwards, the fixed cuts will be used for a blind analysis on the full sample. For the whole available data sample, ~ 95 detached J/ψ's in the μ–channel and ~ 80 in the e–channel are expected, enabling us to improve the statistical and systematic errors of the first measurement in 2000. From the updated results, an input on b-quark mass and on QCD calculations is expected. A preliminary evaluation of the $b\bar{b}$ production cross sections with reduced statistics is fully compatible with the measurement of 2000.

Searches for exclusive b–decay search $B^\pm \to J/\psi K^\pm$, $B^0 \to J/\psi K^\pm \pi^\mp$ and $B^0 \to J/\psi K_s$ are in progress, as well as searches for double semileptonic decays $b\bar{b} \to \mu\mu X$, $b \to \mu\nu X$. These analyses will provide alternative $\sigma_{b\bar{b}}$ measurements and allow to cross check the inclusive cross section measurement.

REFERENCES

1. G.P. Salam, *hep-ph/0207147* (2002).
2. OPAL Collaboration, *OPAL Physics Note PN 455* (2001).
3. A. Acciarri *et al.*, *Phys.Let.*, **B503**, 10 (2001).
4. D. Acosta *et al.*, *Phys.Rev.*, **D65**, 052005 (2002).
5. C. Adloff *et al.*, *Phys.Lett.*, **B467**, 156 (1999).
6. C. Adloff *et al.*, *Phys.Lett.*, **B518**, 331 (2001).
7. J. Breitweg *et al.*, *Eur.Phys.J.*, **C18**, 10 (2001).
8. P. Nason, "Charm, Beauty and CP, proceedings of the first International Workshop on Frontier Science," in *hep-ph/0301003*, 2003.
9. S. Frixione, "proceedings of Int. Eur. Conf. on High Energy Physics," in *hep-ph/0111368*, 2001.
10. D. M. Jansen *et al.*, *Phys.Rev.Lett.*, **74**, 3118 (1995).
11. T. Alexopoulos *et al.*, *Phys.Rev.Lett.*, **82**, 41 (1999).
12. E. Hartouni *et al.*, *DESY-PRC-95-01* (1995).
13. HERA–*B* Collaboration, *DESY-PRC-00-04* (2000).
14. H. M. Schub *et al.*, *Phys.Rev.*, **D52**, 1307 (1995).
15. T. Alexopoulos *et al.*, *Phys.Rev.*, **D55**, 3927 (1997).
16. D. E. Groom *et al.*, *Eur.Phys.J.*, **C15**, 1 (2000).
17. J. M. Leitch *et al.*, *Phys.Rev.Lett.*, **84**, 3256 (2000).
18. T. Alexopoulos *et al.*, *Phys.Lett.*, **B374**, 271 (1996).
19. J. M. Leitch *et al.*, *Phys.Rev.Lett.*, **72**, 2542 (1994).
20. R. Vogt, "Preprint LBNL-45350, proceedings of the Hard Probe Collaboration," in *hep-ph/0111271*, 2003.
21. T. Sjöstrand, *Comp.Phys.Comm.*, **82**, 74 (1994).
22. H. Pi, *Comp.Phys.Comm.*, **71**, 173 (1992).
23. M. Mangano, P. Nason, and G. Ridolfi, *Nucl.Phys.*, **B373**, 295 (1992).
24. P. Nason, S. Dawson and R.K. Ellis, *Nucl.Phys.*, **B327**, 49 (1988).
25. A.D. Martin *et al.*, *Phys.Lett.*, **B531**, 216 (2002).
26. J. Chay, S.D. Ellis, and W.J. Stirling, *Phys.Rev.*, **D45**, 46 (1992).
27. C. Peterson *et al.*, *Phys.Rev.*, **D27**, 105 (1983).
28. P. Cho and A. Leibovich, *Phys.Rev.*, **D53**, 150 (1996).
29. HERA–*B* Collaboration, *Eur.Phys.J.*, **C26**, 345 (2003).
30. N. Kidonakis *et al.*, *Phys.Rev.*, **D64**, 114001 (2001).
31. R. Bonciani *et al.*, *Nucl.Phys.*, **B529**, 24 (1998).