On the Study of $B\bar{B}$ Correlations at HERA-B

R. Rylko[a]

[a] Department of Physics, Brunel, The University of West London, Uxbridge UB8 3PH, UK

Abstract: We analyze the possibility of studying the heavy flavour hadroproduction properties at the HERA-B experiment. In addition to the high statistics single inclusive B spectra measurements, the measurement of the $B\bar{B}$ meson correlations is considered. The techniques of momentum estimators, widely used in the charm sector, are demonstrated to be useful for the $B\bar{B}$ correlation studies at HERA-B. The kinematic limits for the precision of the momentum estimator within which the pair spectra can be measured are determined. The errors are weakly dependent on the topology of the multibody B meson decay.

1 Introduction

Although the flagship goal of the HERA-B experiment is to study the CP violation in the B system, there should be quite an interesting data sample available for studies of production properties of heavy hadrons. Here we report on a study of possibilities for measurements of various heavy hadron production properties with an emphasis on the measurements of the distribution of pairs. We concentrate on beauty hadrons, as the momentum estimators were already demonstrated to be a useful tool in the charm sector. First, we briefly review the existing experimental results on the fixed target hadroproduction of heavy hadron pairs (mostly for the charm sector) and we briefly discuss the momentum estimator techniques used. Next, we find the lower boundaries for the systematic errors for the distributions of pairs when the momentum estimator is used in the kinematic situation of HERA-B. This is illustrated for a typical B decay channel. The major systematic effect on the momentum estimator coming from the secondary vertex resolution is also evaluated. Finally, the errors of the momentum estimator are studied for a wide range of B decays classified topologically.

2 Single inclusive B production

With a heavy hadron sample of the order of 10^5 B mesons per year [1] the HERA-B will be a very competitive experiment for the study of properties of the single inclusive production. Although the QCD calculations of the single inclusive heavy hadron production have been performed some time ago [2], the next-to-leading order (NLO) QCD calculations [3] must be supplemented by various soft phenomena [4] in order to give predictions that agree with the experimental data. There are two sources of theoretical uncertainties: the choice of the heavy quark masses, the renormalization and factorization scales etc., which are input for the NLO QCD calculations, as well as the parameters of the nonperturbative models which supplement them. Thus, the resulting total cross-section for the bottom production at HERA-B energies is predicted only within a range of 6-17 nb. The single inclusive Feynman-x and the transverse momentum spectra are predicted with similar uncertainties [4].

On phenomenological grounds, the high statistics sample of B mesons may be used to answer questions concerning the x_F and p_T spectra for heavy hadrons. Namely, several experiments (see e.g. [5] and references cited therein) report non-vanishing x_F^0, the center of Feynman-x distribution

$$\frac{d\sigma}{dx_F} \sim (1 - |x_F - x_F^0|)^n \ . \tag{1}$$

This offset, although predicted by the theory, is experimentally demonstrated only within one standard deviation. Another problem is the shape (of the tail) of the p_T spectrum. While the $e^{-b_2 p_T^2}$ form is used for most of the data, some collaborations find the simple exponential form $e^{-b_1 p_T}$ better describes the data, particularly in the high p_T region (see e.g. [5]).

3 Current results $B\bar{B}$ correlations

The perturbative and nonperturbative input parameters produce considerable uncertainties for the predictions of the single inclusive heavy hadron production. The distributions of heavy hadron pairs seems to be even more sensitive to the choice of those parameters. In addition, some nontrivial effects for distributions of pairs, absent in the leading order QCD (where the heavy hadron pair is produced back-to-back), arise entirely as the NLO or the nonperturbative effects. Thus, the distributions of heavy hadron pairs, although more difficult from experimental point of view, are an excellent place to study the effects of higher order QCD and nonperturbative contributions.

The kinematic variables commonly used to study the hadroproduction of heavy hadron pairs may be divided into two groups

- the angular variables, e.g.
  - azimuthal angle difference $\Delta\phi = |\phi_1 - \phi_2|$,
  - *pseudo*rapidity difference $\Delta\eta = |\eta_1 - \eta_2|$;
- the momentum variables, e.g.
  - the Feynman-x of a pair x_F^{pair},
  - the effective mass of the pair M_{eff},
  - the transverse momentum of the pair $p_{sum\ T}^{\ 2} = (\vec{p}_{1T} + \vec{p}_{2T})^2$,
  - the rapidity difference $y_{diff} = |y_1 - y_2|$.

A majority of data comes from the fixed target hadroproduction of charmed pairs. The only result for bottom is based on 9 pairs (not fully reconstructed). The results are collected in Table 1. In all these studies momentum estimators have been used.

experiment	No. of pairs	$< p^2_{sum\,T} >$ [GeV^2]	$< M_{eff} >$ [GeV]	$< y_{diff} >$ [1]	$< \Delta\phi >$ [^{o}]
E653 p-em. 800 GeV [6]	35	-	$5.56^{+0.21}_{-0.37}$	$1.21^{+0.10}_{-0.13}$	107.1 ± 9.6
WA75 π^-−em. 350 GeV [7]	177	$2.0^{+0.50}_{-0.33}$	$4.59^{+0.14}_{-0.09}$	0.80 ± 0.05	109.2 ± 4.0
WA92 π^-−Cu 350 GeV [8]	475	1.90 ± 0.17	5.02 ± 0.16	-	102.4 ± 3.6
NA32 π^-−Cu 230 GeV [9, 10]	557	1.98 ± 0.11	4.45 ± 0.03	0.54 ± 0.02	109.2 ± 2.4
E653 π^--em. 600 GeV [11]	9 $B\bar{B}$	5.0 ± 2.5	-	-	147.3 ± 19

Table 1: *Experimental results for the heavy hadron momentum correlations. The first four are the results for the charm pairs, the last one is for the beauty pairs.*

4 Momentum estimators

To study the distributions of angular variables of the heavy hadrons one needs to know the flight directions of both hadrons. This is achieved from the precisely determined primary and secondary vertices. It is enough that one (or even none) of the hadrons is fully reconstructed.

In order to study the momentum correlations, one needs to know the momenta of both heavy hadrons[1]. There are various techniques used for the estimation of the momentum of decaying heavy hadrons. They are based on the precise measurement of the position of the primary and secondary vertex and the measurement of the charged decay products' momenta. The kinematic techniques described below are often supplemented by Monte Carlo information. There are two popular approaches:

- estimator EQ, the problem may be solved exactly with three inputs: the heavy hadron flight vector, the visible decay products' momenta and the effective mass of the invisible decay products.
- estimator ET, relies on the assumption that the invisible decay products' momentum, in the rest frame of the heavy hadron, is perpendicular to its flight vector. Then the corresponding boost from the rest frame may be found to match the laboratory visible momentum.

The estimator EQ gives the exact answer, which is ambiguous. Then either the most probable solution (as suggested by MC or the ET estimator) or just the average of the two solutions may be used. For this estimator one needs to know the effective mass of the invisible decay products. This is simple when the invisible decay product is e.g. one π^0, neutrino or a narrow state decaying into neutrals. But in a case of e.g. nonresonant $\pi^0\pi^0$ in the final state, the necessary estimates of the invisible effective mass and the experimental uncertainties of the

[1] There is an alternative approach to study the correlations of heavy hadron pairs in a case of experiment like HERA-B [12]. In this report we concentrate on the momentum estimator approach.

measured quantities needed for the exact solution, limit the applicability of this estimator to a small class of events.

The ET estimator is simple to apply and works well for multibody final states [2]. It has been used for studies of the single inclusive distributions by the E653 collaboration [13], and the charm hadron momentum correlations in the E653 [6], WA75 [7], WA92 [8] and NA32 [9] data.

5 HERA-B and $B\bar{B}$ correlations

According to expectations [1], the HERA-B experiment should collect a sample of about 10^5 $B\bar{B}$ events per year. The advantage of the design of the experiment is that one of the B hadrons in each event will be fully reconstructed. The other B hadron will decay into any decay mode. The momentum estimator ET has typically a sizable error, however, the estimated momentum of the other B will be added to the well measured, fully reconstructed B. Thus, the relative error of the momentum of the $B\bar{B}$ pair will be roughly halved. The results of the simulation [14], with HERA-B parameters and x_F and p_T acceptances [1], for the $B\bar{B}$ pairs with one of the B mesons fully reconstructed and the other decaying into $B^- \to D^{*+}(2010)\pi^-\pi^-\pi^0 \to (K^-\pi^+\pi^0)\pi^+\pi^-\pi^-\pi^0$ chain (D^0 decay products are in the brackets and both π^0s are unmeasured) are shown in Fig.1. The resolution of the momentum estimator for the laboratory momentum of the single B meson is 18 %, while for the laboratory momentum of the pair p_{lab}^{pair} is 9.1%. This results in the errors for the pair variables[3] Δx_F^{pair}=0.027, $\Delta p_{sum\ T}^2$=1.3 GeV^2, ΔM_{eff}= 0.34 GeV and Δy_{diff}=0.16.

The quoted errors of the pair variables are the lower limits, determined by the production and the decay kinematics, when the momentum estimator ET is used. One of the most important sources of additional systematics is the secondary vertex resolution[4]. To use the momentum estimator, only the flight vector direction, and not e.g. the decay length, must be known. The longitudinal resolution has a little influence on the flight vector direction. This is further reduced if the decay length cut is applied. Indeed, the simulation with the secondary vertex resolution $\sigma_z = 500\mu m$ and $\sigma_x = \sigma_y = 25\mu m$ [1] results in small changes of the momentum estimator errors for the pair Feynman-x, Δx_F^{pair}=0.028, and for the rapidity difference, Δy_{diff}=0.17, once the cut[5] of 3 mm on the decay length is applied. The effect is stronger for the transverse momentum $\Delta p_{sum\ T}^2$=1.8 GeV^2 and the effective mass ΔM_{eff}= 0.38 GeV.

[2]In practical applications, in order to reduce the error of the estimator, the measured distributions are cut at the very tail (with a typical loss of a few percent of events). A strong improvement for the momentum estimator comes from the application of the cut on the transverse momentum of the visible decay products with respect to the flight vector. This cut, however, has much stronger influence on the statistics. For the following studies of the errors of the momentum estimator we do not optimize the selection cuts, thus keeping more than 90% of events.

[3]The B mesons in the $B\bar{B}$ pair are uncorrelated, thus giving the averages $< p_{sum\ T}^2 >$=10.3 GeV^2 and $< M_{eff} >$=11.8 GeV.

[4]The primary vertex resolution at HERA-B is of the order of 10μm [1] and is neglected here.

[5]The mean flight path of the B meson at HERA-B energies is of the order of 9 mm.

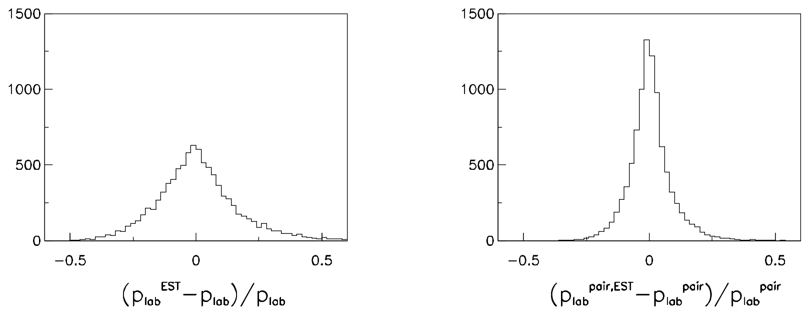

Figure 1: *The relative difference of the estimated and the true laboratory momentum for the single B meson (left) and for the $B\bar{B}$ pair (right). One of the B mesons in the pair decays into* $B^- \to D^{*+}(2010)\pi^-\pi^-\pi^0 \to (K^-\pi^+\pi^0)\pi^+\pi^-\pi^-\pi^0$ *with both π^0s being unmeasured. The other B meson is fully reconstructed.*

6 Topological approach

As shown in the previous section, the ET momentum estimator is adequate within a typical error of $\sim$10% for the laboratory momentum of the $B\bar{B}$ pair. The studied decay channel has the branching ratio of (1.5$\pm$0.7)% [15] only. On the other hand, the inclusive branching ratios for B mesons are $B \to D^+X = (26 \pm 4)\%$ and $B \to D^0X = (54 \pm 6)\%$ [15]. As the B mesons decay in a large number of channels with small branching ratios, in any practical approach, one needs to identify the decay vertex of the other B hadron and all tracks which belong to this vertex. Exact knowledge of the decay channel and the decay chain is not necessary for the momentum estimator ET to be applied. The dependence on the decay chain for the decays with the same number of tracks emerging from the secondary vertex is week (see Table 2). In addition, the vertex missing mass may be used to estimate the number of missing neutrals. The events may be classified topologically and their systematics studied for the whole class of events.

7 Conclusions

We show that the HERA-B experiment will provide an excellent opportunity to study the heavy quark hadroproduction and the perturbative and nonperturbative contributions to this process. It should resolve long standing problems of the single inclusive heavy hadron production like the shape of the Feynman-x and p_T distributions. The heavy hadron pair distributions are also worth studying at HERA-B. Firstly, there should be a large $B\bar{B}$ sample for the study of angular correlations (comparing with current results). In addition, the study of the $B\bar{B}$ momentum correlations, although difficult, is possible with the use of momentum estimators. Approximately a few percent of $B\bar{B}$ events, with the first B meson fully reconstructed and the

decay mode	Δp_{lab}^{pair} [%]	Δx_F^{pair}	$\Delta p_{sum\ T}^{2}$ [GeV^2]	ΔM_{eff} [GeV]	Δy_{diff}
$(K\pi)\pi\pi^0\pi^0$	8.1	0.023	1.2	0.30	0.14
$(K\pi\pi^0)\pi\pi\pi^0$	11.1	0.034	1.4	0.43	0.20
$(K\pi\pi^0\pi^0)\pi\pi$	10.9	0.033	1.4	0.43	0.19
$(K\pi\pi)\pi\pi^0\pi^0$	7.5	0.021	1.2	0.28	0.13
$(K\pi\pi\pi^0)\pi\pi\pi^0$	9.1	0.027	1.3	0.34	0.16
$(K\pi\pi\pi^0\pi^0)\pi\pi$	9.2	0.027	1.3	0.35	0.16

Table 2: *Errors of the momentum estimator ET for various classes of the B decaying into the $D^{(*)} + (n\pi)$ channels. In brackets are the decay products of the $D^{(*)}$. The π^0s are not being measured. The other B meson in the event is fully reconstructed.*

second B meson partially reconstructed, could be used, compared with $\ll 10^{-3}$, when both B mesons are required to be fully reconstructed. The kinematic limits on the resolutions of the momentum estimator are of the order of 8-12% for the laboratory momentum of the $B\bar{B}$ pair, resulting in the resolutions

- 0.02-0.04 for the x_F^{pair} distribution,
- 1.2-1.4 GeV^2 for the $p_{sum\ T}^{2}$ distribution (with the average $< p_{sum\ T}^{2} >$=10.3 GeV^2),
- 0.3-0.5 GeV for the M_{eff} distribution (with the average $< M_{eff} >$=11.8 GeV),
- 0.15-0.20 for the y_{diff} distribution.

The source of the main systematic error, namely the effects of the secondary vertex resolution, are under control once the cut on the secondary vertex separation of 2-3 mm is applied.

Acknowledgements

I want to thank the workshop organizers for financial support. My thanks also to Dr. R. Eichler and Dr. A. Hasan for reading the manuscript and their helpful remarks.

References

[1] HERA-B collaboration, E.Hartouni et al., Technical Design Report, DESY-PRC 95/01.

[2] P.Nason, S.Dawson and R.K.Ellis, Nucl. Phys. **B303**(1988)607, **B327**(1988)49; W.Beenakker et al., Phys. Rev. **D40**(1989)54, Nucl. Phys. **B351**(1991)507.

[3] M.Mangano, P.Nason and G.Ridolfi, Nucl. Phys. **B373**(1992)295, Nucl. Phys. **B405**(1993)507.

[4] S.Frixione, M.Mangano, P.Nason, G.Ridolfi, Nucl.Phys. **B431**(1994)453.

[5] J.A.Appel, Annu. Rev. Nucl. Part. Sci. **42**(1992)367.

[6] E653 collaboration, K.Kodama et al., Phys. Lett. **B263**(1991)579.

[7] WA75 collaboration, S.Aoki et al., Phys. Lett. **B209**(1988)113, Prog. Theor. Phys. **87**(1992)1315.

[8] BEATRICE (WA92) collaboration, M.Adamovich et al., Phys. Lett. **B348**(1995)256.

[9] K.Rybicki, R.Rylko, Phys. Lett. **B353**(1995)547.

[10] ACCMOR collaboration, S.Barlag et al., Phys. Lett. **B302**(1993)112.

[11] E653 collaboration, K.Kodama et al., Phys. Lett. **B303**(1993)359.

[12] R.Rylko, *work in progress.*

[13] E653 collaboration, K.Kodama et al., Phys. Lett. **B263**(1991)573.

[14] R.Rylko, DECEST, a package for vertex based momentum estimation and Monte Carlo study of its errors, manual, 1995 (*unpublished*).

[15] Particle Data Group, L.Montanet et al., Review of Particle Properties, Phys. Rev. **D50** No 11, part II (1994).