On the Charge Asymmetry of the Like-Sign Lepton Pairs Induced by $B - \bar{B}$ Production Asymmetry

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Abstract

In Monte Carlo simulation of $pp$ and $pn$ interactions, it is shown that the charge asymmetry of like-sign lepton pairs can be observed as a manifestation of $B - \bar{B}$ production asymmetry. In this way, the $B - \bar{B}$ production asymmetry could be studied experimentally without full reconstruction of $B$-mesons.

It is known that the asymmetry between decays of $B$ and $\bar{B}$ mesons provides a signal for CP violation, but can also be caused by the production asymmetry between $B$ and $\bar{B}$ mesons in $pp$ or $pn$ collisions. The physics origin of asymmetry of heavy-meson production in hadronic interactions is related to a simple effect of the valence quarks in the colliding hadrons and non trivial dynamics of the hadronization process \[1, 2\].

At the parton level, the $b$ and $\bar{b}$ quarks are generated symmetrically since their production is described within perturbative QCD by diagrams of hard scattering of partons which always arise through the $g \to b\bar{b}$ or $gg \to b\bar{b}$ couplings. As the result of the strong interaction in the confinement region of QCD, the colored quarks produced perturbatively in the hard scattering processes are transformed into colorless hadrons. In the case of $b$ quarks, this transformation (quark hadronization) may introduce an asymmetry between a $B$ meson and its antiparticle if there is an asymmetry in the quark and antiquark flavours that are available in the remnants of the initial hadron for $B$-meson formation (see Fig. \[1\]).

Quark hadronization includes non-perturbative QCD processes and is treated and simulated by PYTHIA package \[3\] in the frame of the string fragmentation model. The Monte Carlo studies by using PYTHIA (see Ref. \[2\]) show that the overall $B - \bar{B}$ production asymmetry is expected to be below one percent for $pp$ collisions at LHC and becomes

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Figure 1: The mechanism of the production asymmetry in \( pp \) collisions due to asymmetry in flavours of quarks and antiquarks with which the produced \( b \) and \( b \) quarks can combine to form \( B \) mesons

larger at smaller energies, giving a few percent or even above ten percent for \( pp \) and \( pn \) interactions at HERA-B. Thus, an experimental study of the \( B - \bar{B} \) production asymmetry should therefore be most feasible at HERA-B with proton beam of 920 GeV. The measurement of the asymmetry in the restricted phase space regions, i.e. as a function of transverse momentum, rapidity, pseudorapidity, or Feynman variable \( x_F \) of \( B \) mesons, provides much more information on the non-perturbative dynamics of quark hadronization. According to Monte Carlo studies of Ref. [2], the \( B - \bar{B} \) production asymmetry is positive and of order 10% in the central region of phase space, but becomes negative and very large in the extreme forward/backward regions close to the remnants.

In spite of the great importance of a better understanding of \( B - \bar{B} \) asymmetry for CP-violation studies and as a test of hadronization models as well as a mean to constrain their parameters, no measurements of this effect in hadronic \( B \)-meson production has yet been performed. The direct measurement of the \( B - \bar{B} \) asymmetry requires a triggering and reconstruction of \( B \)-decays. One of the possible ways to perform the asymmetry measurement is to use lepton pairs from doubly semileptonic decays \( B \to l^+X \) and \( \bar{B} \to l^-X \) to trigger the \( B \)-meson signal. The main difficulties in this case are related with the high rate of background from leptons coming from decays of charmed particles, resonances, kaons and pions. A separation of \( e\mu \) pairs avoids resonance decays, Drell Yan production and other processes which feed di-electron and di-muon channels. But even after applying the additional kinematical cuts the problem of background reduction is not completely solved because of the dominance of the \( e\mu \) signal from the doubly semileptonic decays of charmed particles, mainly from decays \( D^*(\to l^+X) \) and \( \bar{D}^*(\to l^-X) \).

In this paper we propose to trigger the \( B \)-meson signal by selection of the like-sign
lepton pairs $l^\pm l^\pm$. This makes it possible to largely suppress the background originating from decays of charm particles and, after applying an additional cut on lepton transverse momentum, the $l^\pm l^\pm$ signal from doubly semileptonic decays of $B$ mesons becomes clearly seen. Moreover, the $B - \bar{B}$ production asymmetry induces the charge asymmetry in like-sign lepton pairs which, therefore, reflects the non-perturbative dynamics of hadronization processes but can be measured directly without reconstruction of $B$-meson decays. The detailed Monte Carlo studies of lepton pair production in $pp$ interactions at the proton energy of HERA-B have been performed for this paper by using the version PYTHIA 6.158. We analyze the contribution of various physical sources to like-sign lepton pair production and their asymmetries. A special study has been devoted to the role of $B^0 - \bar{B}^0$ oscillations which obscure the lepton-pair asymmetry induced by asymmetry of $B - \bar{B}$ production (see also discussions in Ref. [2]).

In this paper we consider only $pp$ interactions at fixed target with proton beam energy of 920 GeV. Generation of $b\bar{b}$ and $c\bar{c}$ events in PYTHIA is based on the description of heavy flavor production within the usual parton model. At HERA-B energy, this approach assumes that light partons in the incoming protons collide and produce pairs of heavy quarks $Q\bar{Q}$ ($Q$ denotes $c$ or $b$ quark) predominantly via the hard scattering processes of parton fusion $q\bar{q} \rightarrow Q\bar{Q}$ or $gg \rightarrow Q\bar{Q}$ corresponding to the lowest-order (leading) graphs shown in Fig. [2]. The next-to-leading order graphs of flavor excitation and gluon splitting mechanisms gain in importance only as the c.m. energy is considerably increased.

![Feynman diagrams](image)

Figure 2: Feynman diagrams for direct production of heavy quarks ($Q$ is $c$ or $b$ quarks) via parton fusion mechanisms

Therefore, we use PYTHIA 6.158 with the option $\text{MSEL} = 5$ to generate the $b\bar{b}$ events and $\text{MSEL} = 4$ for production of $c\bar{c}$ pairs ($\text{MSEL}$ is a steering parameter in the $\text{PYSUBS}$ common block). In this regime the simulation of heavy flavor production is performed only via the parton fusion mechanism with massive matrix elements for quark generation. Each event contains at least one $Q\bar{Q}$ pair. The Glück-Reya-Vogt (GRV94L) leading order proton parton distribution set and SLAC (Peterson) fragmentation function have been used, which are available when setting $\text{MSTP}(51) = 4$ (by default) and $\text{MSTJ}(11) = 3$, respectively. By default, the mechanism of neutral $B$-meson oscillations is switched on, which corresponds to setting $\text{MSTJ}(26) = 2$ with oscillation parameters $\text{PARJ}(76) = x_d = 0.7$ and $\text{PARJ}(77) = x_s = 20$. 

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Let us distinguish three types of leptons originating from semileptonic weak transitions of heavy quarks – direct and indirect leptons from $b\bar{b}$ events, and direct leptons from $c\bar{c}$ events – according to the classification illustrated in Fig. 3. In Fig. 3 only specific decays of heavy mesons are shown but a full sample of events generated by PYTHIA contains also leptons originating from decays of heavy quark in baryons as well as decays of other particles.

![Diagram](image)

**Figure 3:** Classification of leptons induced by semileptonic decays of heavy quarks: a) direct leptons from $b$ or $\bar{b}$ due to transitions $b \rightarrow l^- X$ or $\bar{b} \rightarrow l'^+ X'$; b) indirect (cascade) leptons from $b$ or $\bar{b}$ due to transitions $b \rightarrow l^- Xc(\rightarrow l'^+ X')$ or $\bar{b} \rightarrow l'^+ X\bar{c}(l'^- X')$; c) direct leptons from $c$ or $\bar{c}$ due to transitions $c \rightarrow l^+ X$ or $\bar{c} \rightarrow l'^- X'$. 


Table 1: Fractions of events with charged leptons without and with applying a cut on lepton transverse momentum $p_T$ for various types of event selection: a) events with one or more charged leptons; b) $\mu^\pm e^\mp$ pairs; c) like-sign lepton pairs $l^\pm l^\pm$

| Event selection | Values | No $p_T$ cut | $p_T \geq 1$ GeV |
|-----------------|--------|--------------|------------------|
| a)              | $\sigma^{(\geq 1)}_{b\bar{b}}/\sigma^{tot}_{b\bar{b}}$ | 0.63 | 0.26 |
|                 | $\sigma^{(\geq 1)}_{c\bar{c}}/\sigma^{tot}_{c\bar{c}}$ | 0.34 | 0.012 |
|                 | $\sigma^{(\geq 1)}_{c\bar{c}}/\sigma^{(\geq 1)}_{b\bar{b}}$ | 540 | 45 |
| b)              | $\sigma^{\mu^\pm e^\mp}_{b\bar{b}}/\sigma^{tot}_{b\bar{b}}$ | 0.089 | $8.9 \times 10^{-3}$ |
|                 | $\sigma^{\mu^\pm e^\mp}_{c\bar{c}}/\sigma^{tot}_{c\bar{c}}$ | 0.019 | $2.8 \times 10^{-5}$ |
|                 | $\sigma^{\mu^\pm e^\mp}_{c\bar{c}}/\sigma^{\mu^\pm e^\mp}_{b\bar{b}}$ | 210 | 3.2 |
| c)              | $\sigma^{(l^\pm l^\pm)}_{b\bar{b}}/\sigma^{tot}_{b\bar{b}}$ | 0.096 | $6 \times 10^{-3}$ |
|                 | $\sigma^{(l^\pm l^\pm)}_{c\bar{c}}/\sigma^{tot}_{c\bar{c}}$ | 0.0014 | $6 \times 10^{-8}$ |
|                 | $\sigma^{(l^\pm l^\pm)}_{c\bar{c}}/\sigma^{(l^\pm l^\pm)}_{b\bar{b}}$ | 15 | 0.01 |

The rates of various types of $b\bar{b}$ and $c\bar{c}$ events with charged leptons in final state, estimated using PYTHIA, are shown in Table 1. The ratios of cross sections of $c\bar{c}$ and $b\bar{b}$ leptonic events were calculated assuming a ratio of total cross sections $\sigma^{tot}_{c\bar{c}}/\sigma^{tot}_{b\bar{b}} \approx 1000$. The leptons in the final state of $b\bar{b}$ and $c\bar{c}$ events can arise from both decays of heavy mesons or baryons and other sources including decays of kaons and pions. Table 1 shows that the $c\bar{c}$ background dominates not only in the case of $e\mu$-pair selection but even for events with like-sign lepton pairs $l^\pm l^\pm$ if no cut on lepton transverse momentum $p_T$ has been applied. A significant relative decrease of $c\bar{c}$ background in the case of $l^\pm l^\pm$ selection as compared with $e\mu$ pairs is caused by a fact that the contribution of doubly semileptonic decays of $b\bar{b}$ to $l^\pm l^\pm$ sample arises as a combination of direct and indirect leptons,

$$b \rightarrow l^- X \; \& \; \bar{b} \rightarrow l^+ Xc(\rightarrow l'^- X') \; \text{or} \; b \rightarrow l^- Xc(\rightarrow l'^+ X) \; \& \; \bar{b} \rightarrow l'^- X',$$

and combination of direct leptons due to $B^0 - \bar{B}^0$ oscillations,

$$b \rightarrow l^- X \; \& \; \bar{b} \rightarrow b \rightarrow l^- X \; \text{or} \; b \rightarrow \bar{b} \rightarrow l^- X' \; \& \; \bar{b} \rightarrow l'^- X',$$

while the contribution of $c\bar{c}$ events to the $l^\pm l^\pm$ sample arises mainly as a combinatorial background involving decays of kaons and pions.

Due to simple kinematical arguments the lepton transverse momentum $p_T$ is larger for leptonic decays of heavier particles. Therefore, one can expect that the $p_T$ cut can
significantly reduce the combinatorial $c\bar{c}$ background to the signal of doubly semileptonic decays of $b\bar{b}$, especially, in the case of selection of like-sign lepton pairs. Table 1 shows such a reduction of the $c\bar{c}$ background and its complete elimination in the case of $l^\pm l^\pm$-pairs selection after applying the requirement $p_T \geq 1$ GeV. Thus, the selection of like-sign lepton pairs with the additional $p_T$ cut can be efficiently used to trigger the signal of doubly semileptonic decays induced by decays of $b\bar{b}$. Therefore, to study the asymmetry of lepton pairs induced by $B - \bar{B}$ production asymmetry, we restrict ourself to consideration only of the $l^\pm l^\pm$ pairs.

Let us define the overall charge asymmetry of like-sign lepton pairs as

$$ A = \frac{N(l^+l^+) - N(l^-l^-)}{N(l^+l^+) + N(l^-l^-)}. \quad (3) $$

For Monte Carlo studies, a sample of more then $2 \times 10^6 b\bar{b}$ events with $l^\pm l^\pm$ pairs in final state with $p_T \geq 1$ GeV has been generated by PYTHIA. The prehistory of each particle from an event can be derived from the information stored in PYJETS common block, and the origin of each lepton can be traced back to the parton level, i.e. to the decay of heavy quark inducing the lepton. In this way, in accordance with the classification of leptons given in Fig. 3, each event can be characterized by a code number “IJK”, where “I” is the number of direct leptons from $b\bar{b}$, “J” is the number of indirect leptons from $b\bar{b}$, and “K” is the number of leptons from other quarks.

There are two types of events dominating in the generated sample with $b\bar{b}$-induced $l^\pm l^\pm$ pairs corresponding with the following code numbers:

- “110” – with one direct and one indirect lepton originated from doubly semileptonic decays of $b\bar{b}$;
- “200” – contribution of $B^0 - \bar{B}^0$ oscillations.

The full Monte Carlo sample also contains a fraction of events (about 20% in total) with the code numbers “210”, “120”, “020”, “101” and “011”. The event statistics and results on the estimates of overall asymmetry for the full sample of $b\bar{b}$-induced like-sign lepton pairs and the dominating fraction of “110” and “200” events are shown in Table 2 for various $p_T$ cuts. The fraction of the “110” events is decreased while the fraction of the $B^0 - \bar{B}^0$ oscillation contribution “200” is increased when increasing the $p_T$ cut.

The main source of $b\bar{b}$ events contain decays of $B$-mesons while the contribution of $b$-baryon decays does not exceed 1%. Therefore the contribution of the $b$-baryon production asymmetry to the total charge asymmetry of lepton pairs is small, and the latter one reflects mainly the $B - \bar{B}$-production asymmetry. If we define the overall $B - \bar{B}$-production asymmetry as

$$ A(B_q) = \frac{N(B^{(bq)}) - N(\bar{B}^{(bq)})}{N(B^{(bq)}) + N(\bar{B}^{(bq)})}, \quad (4) $$
Table 2: Total Monte Carlo statistics, fraction of “110” and “200” events, and overall charge asymmetries (3) for $b\bar{b}$-induced like-sign lepton pairs for various $p_T$ cuts

| $p_T$ cut (GeV) | Number of events | Fraction (%) | Overall asymmetry (%) |
|-----------------|-------------------|--------------|-----------------------|
| 1               | 3 251 390         | “110” 43     | “200” 41              |
|                 |                   | 2.00 ± 0.06  | −0.99 ± 0.09          |
|                 |                   | 5.79 ± 0.11  |                       |
| 2               | 128 987           | “110” 27     | “200” 70              |
|                 |                   | 3.55 ± 0.27  | −1.92 ± 0.63          |
|                 |                   | 5.84 ± 0.44  |                       |
| 3               | 5 128             | “110” 19     | “200” 78              |
|                 |                   | 2.22 ± 1.4   | 2.8 ± 3.6             |
|                 |                   | 0.5 ± 1.7    |                       |

The simulation of $B$-meson production in $pp$-interactions at the HERA-B energy gives the following estimates:

$$A(B^0_d) \approx -0.3\%, \quad A(B^\pm) \approx 4.2\%, \quad A(B^0_s) \approx -10.2\%.$$ 

The lepton charge asymmetries in the restricted phase space regions, i.e. as a function of lepton transverse momentum $p_T$, Feynman variable $x_F$ and rapidity $y$ of $l^\pm l^\pm$ pairs, are shown in Figs. 4, 5, and 6. Within errors due to limited Monte Carlo statistics, there is no noticeable $p_T$ dependence in the lepton charge asymmetry of the $l^\pm l^\pm$ events with the code number “200”, caused by $B^0 - \overline{B}^0$ oscillations. The considerable $p_T$ dependence in the lepton charge asymmetry of total sample of events reflects the strong dependencies of the contribution of “110” events on this kinematical parameter. The shapes of the corresponding histograms for “110” events in Figs. 4, 5, and 6 reproduce qualitatively the $p_T$, $x_F$ and $y$ dependences of $B - \overline{B}$ production asymmetries.

Figure 4: Dependence of charge asymmetry of (a) B-mesons and (b) $b\bar{b}$-induced $l^\pm l^\pm$ pairs on the lepton transverse momentum $p_T$
To ensure that the observed effect of the charge asymmetry of the like-sign lepton pairs is really a manifestation of the $B - \bar{B}$ production asymmetry, we have repeated for the case of heavy-quark production in $p\bar{p}$ collisions a similar analysis of like-sign lepton pairs with the same selection criteria. Because of beam remnant symmetry in $p\bar{p}$ interactions, there is no $B - \bar{B}$ production asymmetry, and no charge asymmetry of lepton pairs was observed.
Summarizing, we have found that at the proton energy $E = 920$ GeV, HERA-B provides a unique opportunity to study the $B - \bar{B}$ production asymmetry, caused at the fragmentation level by effects of asymmetric beam remnants for $b$ and $\bar{b}$ quarks, by direct measurements of charge asymmetry in the production of like-sign lepton pairs without reconstruction of $B$-meson decays. Our estimates shows that during a one year data taking run the statistics on $l^\pm l^\pm$ events at HERA-B would be large enough to provide a statistical error on charge asymmetry measurements at a level of a few percent even in the bins at the edges of the histograms in Fig. 5 and 6 corresponding to the borders of phase space in terms of variable $x_F$ and $y$ where the asymmetry reach maximal values.

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References

[1] E. Norrbin, T. Sjostrand, *Production Mechanisms of Charm Hadrons in the String Model*, Phys. Lett., **B442** (1998) 404.
E. Norrbin, T. Sjostrand, *Production and Hadronization of Heavy Quarks*, Eur. Phys. J., **C17** (2000) 137.

[2] J. Damet and G. Ingelman, *$B - \bar{B}$ Production Asymmetry at LHC and HERA-B*, TSL/ISV-2001-0242, February 2001.

[3] T. Sjostrand, P. Eden, C. Friberg, L. Lonnblad, G. Miu, S. Mrenna and E. Norrbin, Comp. Phys. Comm. **135** (2001) 238.