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ON THE CHARGE ASYMMETRY OF THE LIKE-SIGN LEPTON PAIRS INDUCED BY $B-\overline{B}$-PRODUCTION ASYMMETRY

A. Belkov, T. Ilitcheva, S. Shulga[1]

Joint Institute for Nuclear Research, Dubna

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 $B-\overline{B}$-production asymmetry. In this way, the $B-\overline{B}$-production asymmetry could be studied experimentally without full reconstruction of B mesons.

С помощью моделирования pp- и pn-взаимодействий методом Монте-Карло показано, что зарядовая асимметрия пар лептонов с одинаковым знаком является следствием асимметрии рождения $B-\overline{B}$-мезонов. Таким образом асимметрию (B–анти-B)-рождения можно изучать без реконструкции B-мезонов.

It is known that the asymmetry between decays of B and $\overline{B}$ mesons provides a signal for CP violation, but can also be caused by the production asymmetry between B and $\overline{B}$ 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 nontrivial 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 flavors that are available in the remnants of the initial hadron for B-meson formation (see Fig. 1).

Quark hadronization includes nonperturbative QCD processes and is treated and simulated by PYTHIA package [3] in the framework of the string fragmentation model. The Monte Carlo studies by using PYTHIA (see Ref. [2]) show that the overall $B-\overline{B}$-production asymmetry is expected to be below one percent for pp collisions at LHC and becomes 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 $B-\overline{B}$-production asymmetry should therefore be most feasible at HERA-B with a 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 nonperturbative dynamics of quark hadronization. According to Monte Carlo studies of

[1]Permanent address: Francisk Skarina Gomel State University, Belarus.

Ref. [2], the $B{-}\overline{B}$-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 $B{-}\overline{B}$ asymmetry for CP-violation studies and as a test of hadronization models as well as a means to constrain their parameters, no measurements of this effect in hadronic B-meson production have yet been performed. The direct measurement of the $B{-}\overline{B}$ 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 $\overline{B} \to l^-X$ 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 $\overline{D}^{(*)} \to l^-X$.

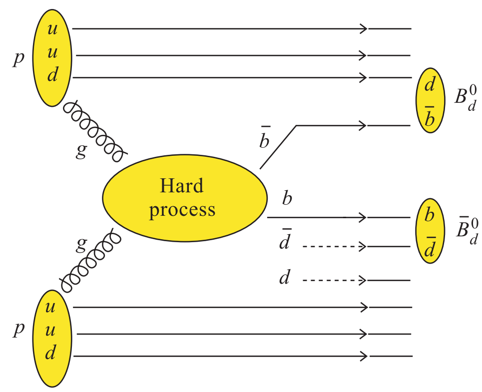

Fig. 1. The mechanism of the production asymmetry in pp collisions due to asymmetry in flavors of quarks and antiquarks with which the produced b and $\bar{b}$ quarks can combine to form B mesons

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 charmed 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 $B{-}\overline{B}$-production asymmetry induces the charge asymmetry in like-sign lepton pairs which, therefore, reflects the nonperturbative 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 $B^0{-}\overline{B}^0$ oscillations which obscure the lepton-pair asymmetry induced by asymmetry of $B{-}\overline{B}$ production (see also discussions in Ref. [2]).

In this paper we consider only pp interactions at a fixed target with a 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 $Q\overline{Q}$ (Q denotes c or b quark) predominantly via the hard scattering processes of parton fusion $q\bar{q} \to Q\overline{Q}$ or $gg \to Q\overline{Q}$, 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.

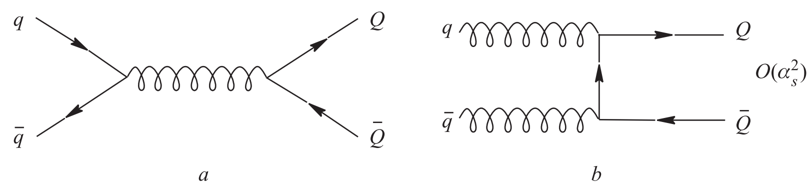

Fig. 2. Feynman diagrams for direct production of heavy quarks (Q is c or b quark) via parton fusion mechanisms

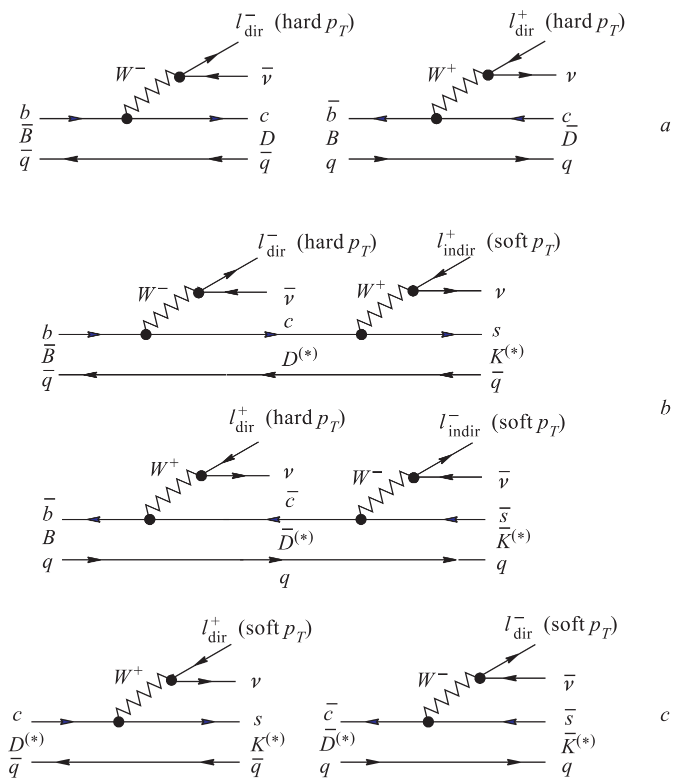

Fig. 3. Classification of leptons induced by semileptonic decays of heavy quarks: *a*) direct leptons from b or $\bar{b}$ due to transitions $b \to l^- X$ or $\bar{b} \to l'^+ X'$; *b*) indirect (cascade) leptons from b or $\bar{b}$ due to transitions $b \to l^- X c(\to l'^+ X')$ or $\bar{b} \to l^+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

Therefore, we use PYTHIA 6.158 with the option MSEL $= 5$ to generate the $b\bar{b}$ events and MSEL $= 4$ for production of $c\bar{c}$ pairs (MSEL is a steering parameter in the 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 $Q\overline{Q}$ 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 MSTP(51) = 4 (by default) and MSTJ(11) = 3, respectively. By default, the mechanism of neutral B-meson oscillations is switched on, which corresponds to setting MSTJ(26) = 2 with oscillation parameters PARJ(76) = $x_d = 0.7$ and PARJ(77) = $x_s = 20$.

Let us distinguish between 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.

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**

Event selection	Values	No p_T cut	$p_T \geqslant 1$ GeV
Events with one	$\sigma_{b\bar{b}}^{(l\geqslant 1)}/\sigma_{b\bar{b}}^{\rm tot}$	0.63	0.26
or more	$\sigma_{c\bar{c}}^{(l\geqslant 1)}/\sigma_{c\bar{c}}^{\rm tot}$	0.34	0.012
charged leptons	$\sigma_{c\bar{c}}^{(l\geqslant 1)}/\sigma_{b\bar{b}}^{(l\geqslant 1)}$	540	45
	$\sigma_{b\bar{b}}^{\mu^\pm e^\mp}/\sigma_{b\bar{b}}^{\rm tot}$	0.089	$8.9 \cdot 10^{-3}$
$\mu^\pm e^\mp$ pairs	$\sigma_{c\bar{c}}^{\mu^\pm e^\mp}/\sigma_{c\bar{c}}^{\rm tot}$	0.019	$2.8 \cdot 10^{-5}$
	$\sigma_{c\bar{c}}^{\mu^\pm e^\mp}/\sigma_{b\bar{b}}^{\mu^\pm e^\mp}$	210	3.2
	$\sigma_{b\bar{b}}^{(l^\pm l^\pm)}/\sigma_{b\bar{b}}^{\rm tot}$	0.096	$6 \cdot 10^{-3}$
Like-sign	$\sigma_{c\bar{c}}^{(l^\pm l^\pm)}/\sigma_{c\bar{c}}^{\rm tot}$	0.0014	$6 \cdot 10^{-8}$
lepton pairs $l^\pm l^\pm$	$\sigma_{c\bar{c}}^{(l^\pm l^\pm)}/\sigma_{b\bar{b}}^{(l^\pm l^\pm)}$	15	0.01

The rates of various types of $b\bar{b}$ and $c\bar{c}$ events with charged leptons in the 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 $\sigma_{c\bar{c}}^{\rm tot}/\sigma_{b\bar{b}}^{\rm tot} \approx 1000$. 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 $l^\pm l^\pm$-pair selection as compared with $e\mu$ pairs is caused by the 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,

$$b \to l^- X \ \ \& \ \ \bar{b} \to l^+ X \bar{c}(\to l'^- X') \quad \text{or} \quad b \to l^- X c(\to l^+ X) \ \ \& \ \ \bar{b} \to l'^- X', \tag{1}$$

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

$$b \to l^- X \ \ \& \ \ \bar{b} \to b \to l^- X \quad \text{or} \quad b \to \bar{b} \to l'^- X' \ \ \& \ \ \bar{b} \to l'^- X', \tag{2}$$

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 $l^{\pm}l^{\pm}$-pair selection after applying the requirement $p_T \geqslant 1$ 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 the $B{-}\overline{B}$-production asymmetry, we restrict ourselves to consideration of only the $l^{\pm}l^{\pm}$ pairs.

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

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

For Monte Carlo studies, a sample of more than $2 \cdot 10^6$ $b\bar{b}$ events with $l^{\pm}l^{\pm}$ pairs in the final state with $p_T \geqslant 1$ 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 (1) of $b\bar{b}$;

• «200» — contribution of $B^0{-}\overline{B}^0$ oscillations (2).

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 (3) 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 $B^0{-}\overline{B}^0$ oscillation contribution «200» is increased when increasing the p_T cut.

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, %		
		«110»	«200»	Total	«110»	«200»
1	3 251 390	43	41	2.00 ± 0.06	-0.99 ± 0.09	5.79 ± 0.11
2	128 987	27	70	3.55 ± 0.27	-1.92 ± 0.63	5.84 ± 0.44
3	5128	19	78	2.22 ± 1.4	2.8 ± 3.6	0.5 ± 1.7

The main source of $b\bar{b}$ events contains 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 $B-\overline{B}$-production asymmetry. If we define the overall $B-\overline{B}$-production asymmetry as

$$A(B_q) = \frac{N(B^{(\bar{b}q)}) - N(\overline{B}^{(b\bar{q})})}{N(B^{(\bar{b}q)}) + N(\overline{B}^{(b\bar{q})})}, \tag{4}$$

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

$$A(B_d^0) \approx -0.3\%, \qquad A(B^\pm) \approx 4.2\%, \qquad A(B_s^0) \approx -10.2\%.$$

The lepton charge asymmetries in the restricted phase space regions, i.e., as functions of lepton transverse momentum p_T, Feynman variable x_F and rapidity y of $l^\pm l^\pm$ pairs, are shown in Figs. 4–6. 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 dependences of the contribution of «110» events on this kinematical parameter. The shapes of the corresponding histograms for «110» events in Figs. 4–6 reproduce qualitatively the p_T, x_F and y dependences of $B-\overline{B}$-production asymmetries.

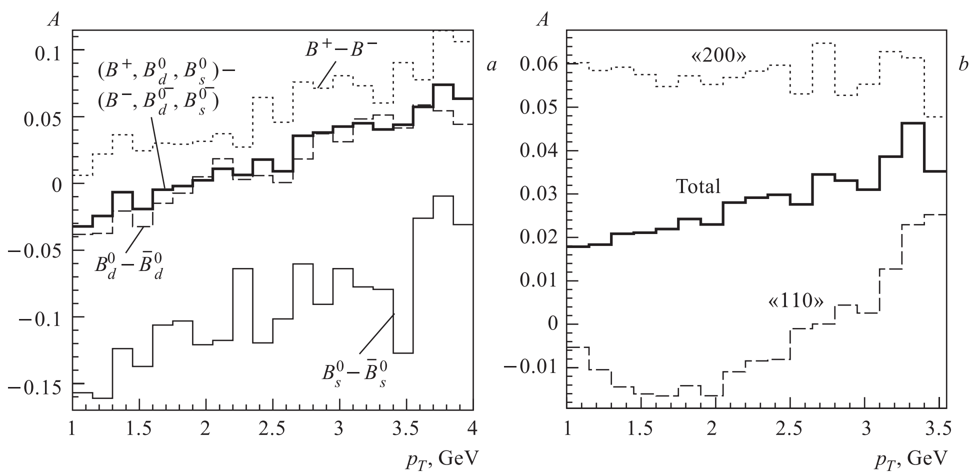

Fig. 4. Dependence of the charge asymmetry of B mesons (a) and $b\bar{b}$-induced $l^\pm l^\pm$ pairs (b) on the lepton transverse momentum p_T

To ensure that the observed effect of the charge asymmetry of the like-sign lepton pairs is really a manifestation of the $B-\overline{B}$-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 $B-\overline{B}$-production asymmetry, and no charge asymmetry of lepton pairs was observed.

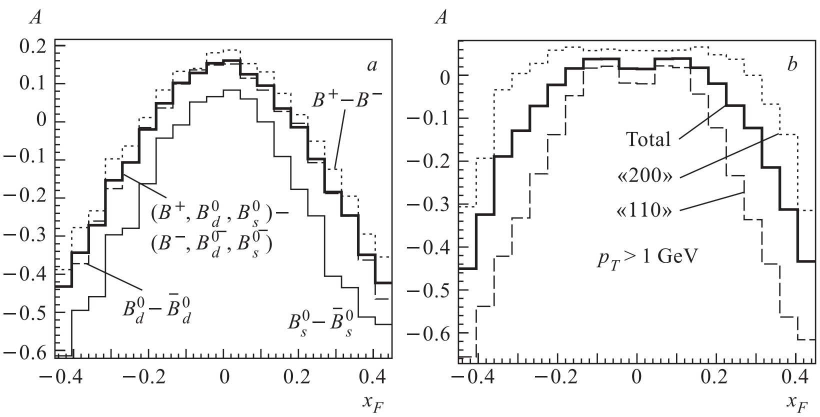

Fig. 5. Dependence of the charge asymmetry of B mesons (*a*) and $b\bar{b}$-induced $l^{\pm}l^{\pm}$ events (*b*) on the Feynman variable x_F

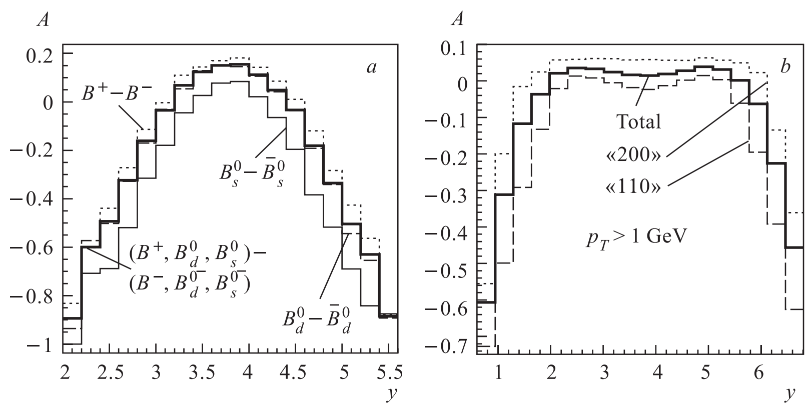

Fig. 6. Dependence of the charge asymmetry of B mesons (*a*) and $b\bar{b}$-induced $l^{\pm}l^{\pm}$ events (*b*) on the rapidity y

Summarizing, we have found that at the proton energy $E = 920$ GeV, HERA-B provides a unique opportunity to study the B–$\overline{B}$-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 show 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 Figs. 5 and 6 corresponding to the borders of phase space in terms of variables x_F and y where the asymmetry reaches maximum values.

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