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B-Physics Possibilities with pp Colliders

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Abstract

In the following we discuss some aspects of B -physics that could be studied with pp interactions. We consider the cases of pp colliders, the LHC and SSC projects, and those where the p -beams interact with a fixed target (pA collisions). We mention some difficulties and advantages in using pp interactions.

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1 - Introduction

During the last years, important efforts have been made to examine the possibilities of studying B -physics with e^+e^- interactions^{1,2}. The construction of B -factories has been foreseen³. By using the $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ reaction, the accelerator has to be asymmetric in order to allow one to search for CP violation in the $B_d^0 \rightarrow f$ and $\bar{B}_d^0 \rightarrow \bar{f}$ decays¹. An asymmetric B -factory has many advantages but does not lead to a large $B\bar{B}$ production rate (see below).

For pp interactions there are two methods for studying the $pp \rightarrow B\bar{B}X$ interactions (X meaning anything). The first one consists in using the pp collider⁴ (LHC or SSC projects), whereas the second method uses the interaction of a p -beam of the collider with a fixed (external or gas-jet) target^{5,6}. The $B\bar{B}$ production rates are much larger than in the e^+e^- case. There are, however, experimental difficulties that will be briefly mentioned in Section 2. We will also discuss some aspects of B -physics that could be studied in pp interactions (Section 3). Finally, we try to present some preliminary conclusions concerning the interest of pp collisions.

2 - Production rates

a) The pp collider

Let us first make some remarks about the pp collider. Table 1 indicates the $b\bar{b}X$ production rates expected for the LHC (c.m. energy of $\sqrt{s} = 16$ TeV) and the SSC ($\sqrt{s} = 40$ TeV). For comparison, we also give the production rate expected in the B -factory. For pp interactions the inelastic (σ_T) and $b\bar{b}X$ [$\sigma(b\bar{b})$] cross-sections are theoretical predictions⁷. The luminosity is taken as $L = 10^{32} \text{cm}^{-2} \text{s}^{-1}$ in order to decrease the multiple interactions per bunch crossing (in principle, the LHC project could reach $L = 10^{34} \text{cm}^{-2} \text{s}^{-1}$). This can be estimated by the $P(2 \text{ or } 3)/P(1)$ ratios. Here $P(m)$ is the probability of having m interactions per bunch crossing. Assuming that $P(m)$ follows a Poisson distribution, one obtains for the LHC project:

$$\frac{P(2)}{P(1)} \simeq 0.10, \quad \frac{P(3)}{P(1)} \simeq 0.006,$$

which appear to be acceptable. Note that these values correspond to an average of $\langle m \rangle \simeq 0.2$ interaction per bunch crossing.

From Table 1, we see that the $b\bar{b}X$ production rate is much larger for the pp interactions than for $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$. However, the difficulties in detecting the B mesons in pp interactions are not negligible⁸. Some of them can be summarized as follow:

Table 1 - The comparison of luminosity (L), charged multiplicity ($\langle n \rangle$), total (σ_T) and $b\bar{b}X$ [$\sigma(b\bar{b})$] cross- sections of the LHC, SSC and B -factory project. For pp interactions the multiplicities are calculated for non-diffractive events (see reference 8). The number of $b\bar{b}X$ interactions per year ($N(b\bar{b})/10^7 s$) as well as the number of interactions per second (N_{int}/s) are also given.

	LHC 16 TeV	SSC 40 TeV	$e^+e^- \rightarrow \Upsilon(4S)$ 0.011 TeV
L $cm^{-2}s^{-1}$	10^{32}	10^{32}	3×10^{33}
$\langle n_c \rangle$	~ 80	~ 115	~ 12
σ_T	$\sim 110 mb$	$\sim 120 mb$	$4 nb$
$\sigma(b\bar{b})$	$\sim 200 \mu b$	$\sim 500 \mu b$	$1.2 nb$
$\sigma(b\bar{b})/\sigma_T$	$1/550$	$1/240$	$\sim 1/4$
$N(b\bar{b})/10^7 s$	2×10^{11}	5×10^{11}	3.6×10^7
N_{int}/s	1.1×10^7	1.2×10^7	1.4×10^1

- The important number of interactions per second ($N_{int}/s \sim 10^7$) leads to a major triggering problem,
- For B emission angles with respect to the beam direction, $\Theta_B > 1^\circ$, the B momentum is small⁸ (60 - 70 GeV/c) yielding small decay lengths, $\sim 0.4 cm$,
- The radiation damage near the beam line complicates the construction of multivertex detectors (is smaller luminosity be needed?),
- The multivertex detector should have large dimensions (at the LHC, the bunch length should be $\sim 10 cm$).

For the time being there are essentially two approaches in order to use the pp collider for studying B -physics. One method consists in attempting to detect the B that would be emitted with a small Θ_B angle. For instance, the use of detectors allowing one to detect mesons with $2 < \Theta_B < 600 mrad$ is under investigation⁹. Apparently this kind of spectrometer would need small beam sizes and a low luminosity ($L = 10^{31} cm^{-2}s^{-1}$). Another approach consists in studying B mesons emitted with small rapidities. Following the results of the CDF experiment at Fermilab, such an approach could perhaps accept pp interactions with

$L > 10^{32} \text{cm}^{-2} \text{s}^{-1}$. Clearly, detailed investigations have to be made in order to evaluate the real possibilities of pp colliders for studying B -physics.

b) The fixed target

The utilization of beam-target interactions has some advantages. Although the c.m. energy with the LHC (SSC) beam is small, $\sqrt{s} = 0.12$ (0.19) TeV, the average B decay length in the laboratory is of the order⁸ of $\sim 4 \text{ cm}$ ($\sim 8 \text{ cm}$). This should simplify the B reconstruction efficiency. Moreover, the large momentum of the lepton (l) in the $B \rightarrow lX$ decay should also decrease the triggering difficulty. Note that for an external or gas-jet target one still expects to have $\sim 10^7$ interactions per second¹⁰, similar to the number expected for the pp collider.

Because of the low c.m. energy, the $b\bar{b}X$ cross-section is expected to be $\sigma(b\bar{b}) \sim 1 \mu\text{b}$ for the LHC case. Assuming that the total (inelastic) cross-section is about $\sigma_T \sim 50 \text{ mb}$, one has for an hydrogen target:

$$R(A=1) = \frac{\sigma(b\bar{b})}{\sigma_T} \approx \frac{1}{50000} ,$$

which is much smaller than the collider case given in Table 1 (A denotes the target nuclear mass number). The background is expected to be large since in $\sim 5 \times 10^5$ events one will only have ~ 1 $b\bar{b}X$ event. Therefore, one should consider pA collisions where, in principle, the ratio

$$R(A) = \frac{\sigma^A(b\bar{b})}{\sigma_T^A} = \frac{\sigma(b\bar{b})}{\sigma_T} \times A^{\alpha(T)-\alpha(b)}$$

may increase. Here σ_T^A and $\sigma^A(b\bar{b})$ are the total (inelastic) pA and $pA \rightarrow b\bar{b}X$ cross-sections, respectively. They are related to the pp cross-sections by the relations

$$\begin{aligned} \sigma_T^A &= \sigma_T A^{\alpha(T)} \\ \sigma^A(b\bar{b}) &= \sigma(b\bar{b}) A^{\alpha(b)} \end{aligned}$$

For p beams it was found experimentally¹¹ that $\alpha(T) = 0.72 \pm 0.01$. The QCD models predict that $\alpha(b) = 1$, although experimental results on charm and $\Upsilon(nS)$ production indicate that $\alpha(b)$ could be smaller but close to one¹⁰. In any case, one could have an increase of $R(A)$ by a factor of 2 to 3 if $A \geq 80$ and $\alpha(b) \geq 0.9$.

One has also to notice that the average charged multiplicity on a nuclear target, $\langle n(pA) \rangle$, is larger than that obtained in pp collisions, $\langle n \rangle$. The experimental data indicate¹² that

$$r = \frac{\langle n(pA) \rangle}{\langle n \rangle} \simeq \frac{1 + \bar{\nu}}{2}.$$

Here $\bar{\nu}$ is the average number of collisions of the incident particle in the nuclear target. Using $\bar{\nu} = A\sigma_T/\sigma_T^A$, one obtains Fig. 1. For instance, with a tungsten target, one would have $\langle n(pA) \rangle \sim 2.7 \times 17$ (for the pp case, $\langle n \rangle \sim 17$), still much smaller than the multiplicities expected for the LHC and SSC collider (Table 1). One has also to take into account that secondary interactions in an external fixed target may also increase the average charged multiplicity.

2 - Some B-physics aspects

In the following we wish to discuss some of the measurement possibilities of CP violation in the B_d^0 decay. We will also make some comments about the B_s^0 decay. Finally we will mention some interest in measuring $B_c^\pm$ decay.

a) The B_d^0 and $\bar{B}_d^0$ decay

Let us consider the case where the B_d^0 decays into a self-conjugated state, f ($f = \bar{f}$). Thus, CP violation would mean that differences should be observed between the decay rates of $B_d^0 \rightarrow f$ and $\bar{B}_d^0 \rightarrow f$. Because of the B^0 mixing, the search for CP violation would need the tagging of the associated beauty particle. For the present discussion we consider that the tagging is given by the charge of the lepton ($l^\pm$) in the semileptonic decay ($B \rightarrow l^+ X$, $\bar{B} \rightarrow l^- X$). The CP violation could be searched for by comparing the number of $l^- X f$ (N_-) and $l^+ f X$ (N_+) events. This means that CP violation will be observed if

$$A = \frac{N_+ - N_-}{N_+ + N_-} \neq 0.$$

In pp interactions the B and $\bar{B}$ are not produced in equal amounts¹³. Then, without CP violation one can have $A \neq 0$. The rough estimates of reference 13 give $A \sim 10^{-2}$ for $B/\bar{B}$ emitted with small transverse momentum, $p_T < 5$ GeV/c, and $A \sim 10^{-3}$ for $p_T \gg 5$ GeV/c. In any case the $B/\bar{B}$ amounts have to be measured by using decay channels without CP violation effects.

The unequal B and $\bar{B}$ amounts can also lead to some advantages¹⁴. Without any tagging procedure the time-dependent rate of $B_d^0 \rightarrow f$ and $\bar{B}_d^0 \rightarrow f$ can be

written¹⁵ as

$$\begin{aligned}\frac{dN(B_d^0 \rightarrow f)}{d\tau_d} &\propto N(B_d^0) e^{-\tau_d} [1 - n \sin(x_d \tau_d)] \\ \frac{dN(\bar{B}_d^0 \rightarrow f)}{d\tau_d} &\propto N(\bar{B}_d^0) e^{-\tau_d} [1 + n \sin(x_d \tau_d)] .\end{aligned}$$

Here τ_d is the meson decay time in lifetime units and expressed in the meson rest frame whereas x_d is a mixing parameter¹⁵ of the B_d^0 or $\bar{B}_d^0$ meson. The CP violation effect is described by the parameter¹⁶, $n \equiv \text{Im } \lambda$ ($0 \leq n \leq 1$). Thus, without any tagging procedure, the time-dependence of the decay state f is given by

$$\begin{aligned}\frac{dN(B_d^0 \rightarrow f)}{d\tau_d} + \frac{dN(\bar{B}_d^0 \rightarrow f)}{d\tau_d} &\propto e^{-\tau_d} [1 - \bar{A} n \sin(x_d \tau_d)] \\ \bar{A} &= \frac{N(B_d^0) - N(\bar{B}_d^0)}{N(B_d^0) + N(\bar{B}_d^0)} .\end{aligned}$$

Using reference 13, one obtains the rough estimates of $\bar{A} \simeq 1.3 \times 10^{-2}$ and 10^{-3} for the small ($p_T \leq 5$ GeV/c) and large ($p_T \gg 5$ GeV/c) transverse momentum, respectively. Further studies should certainly be made in order to see if $\bar{A}$ can be increased by taking B mesons in a specific kinematical region. Note also that because of the non-tagging procedure one could, eventually, consider larger luminosities for the pp collider ($L > 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$).

One could also investigate the time-dependent rate whereas the second B is tagged by its semileptonic decay. For instance, let us consider the $l^+ f$ case in the final state. It can be produced by one of the following combinations:

- 1) $B^+ \bar{B}_d^0$
- 2) two neutral mesons $B_s^0 \bar{B}_d^0$
- 3) two neutral mesons $B_d^0 \bar{B}_d^0$
- 4) $\bar{N}_b \bar{B}_d^0$

where the particles are those given at the production time ($t = 0$). Note that $\bar{N}_b \equiv \bar{b}\bar{q}\bar{q}$ is a beauty baryon.

The time-dependent rates for these cases are given by^{14,17}

$$\frac{d\sigma_1(l^+ f_d)}{d\tau_d} = \frac{|T_d|^2}{\Gamma + \Gamma_d} e^{-\tau_d} [1 - n \sin(x_d \tau_d)] \quad (1)$$

$$\frac{d\sigma_2(l^+ f_d)}{d\tau_d} = \frac{|T_d|^2}{\Gamma_s \Gamma_d} e^{-\tau_d} \left[1 - \frac{n}{1+x_s^2} (x_s \cos(x_d \tau_d) + \sin(x_d \tau_d)) \right] \quad (2)$$

$$\frac{d\sigma_3(l^+ f_d)}{d\tau_d} = \frac{|T_d|^2}{\Gamma_d^2} e^{-\tau_d} \left[1 - \frac{n}{1+x_d^2} (x_d \cos(x_d \tau_d)) \right] \quad (3)$$

$$\frac{d\sigma_4(l^+ f_d)}{d\tau_d} = \frac{|T_d'|^2}{\Gamma_N \Gamma_d} e^{-\tau_d} [1 - n \sin(x_d \tau_d)] \quad (4)$$

Here Γ_+ , $\Gamma_{d,s}$, and Γ_N are the decay widths of the B^+ , $B_{d,s}^0$, and $\bar{N}^b$, respectively. The mixing of the $B_{d,s}^0$ meson is given by $x_{d,s}$. The T_d and T_d' are amplitudes which will be taken as being the same in all cases. This is because we assume that the beauty hadron decay is essentially due to the decay of the b (or $\bar{b}$) quark¹⁴. This means that we also assume that $\Gamma_+ = \Gamma_d = \Gamma_s = \Gamma_N$.

The observed $d\sigma(l^+ f)/d\tau_d$ distribution will then be obtained by adding (incoherently) the above equations (1 to 4) each of them being weighted by its production value. We note that $d\sigma(l^+ f)/d\tau_d$ is not very sensitive to the variation of production values within a few percent. This means that the unequal amount of $B/\bar{B}$ production has no real influence on the $d\sigma(lf)/d\tau_d$ distribution. In the absence of CP violation in the decay amplitude¹⁵ one has $|\bar{T}_d| = |T_d|$ and $|\bar{T}_d'| = |T_d'|$. Then the above formulae can also be used for the $l^- f_d$ case changing $n \rightarrow -n$.

As an example, we consider the distribution obtained for the $l^+ f$ case with $n = 0.25$, $x_d = 0.72$, $x_s = 8$, and using the following production ratios:

$$bu : bd : bs : bqq = 0.38 : 0.38 : 0.14 : 0.10 .$$

This gives Fig. 2, the $|T_d|^2 e^{-\tau}/\Gamma_s \Gamma_d$ being factorized out. We note that the distribution is not very sensitive to the B_s^0 production rate in the range of 0.10 to 0.30 and to $8 < x_s < 30$. For comparison we also present in Fig. 2 the distribution obtained by only tagging B^+ (equation 1). One sees that the distribution obtained in the general case is smaller than that given only by formula 1. In the present example, the events with two (or more) $b\bar{b}$ pairs were not taken into account. Such events may tend to decrease the oscillation shown in Fig. 2.

b) The B_s^0 and $\bar{B}_s^0$ decay

Let us remember that in $B_{d,s}^0, \bar{B}_{d,s}^0 \rightarrow f$ decay, one usually assumes the following hypotheses^{15,16}:

- No CP violation in the $B_{d,s}^0 - \bar{B}_{d,s}^0$ mixing,

- No CP violation in the decay amplitudes ($|\langle f|B_{d,s}^0\rangle| = |\langle f|\bar{B}_{d,s}^0\rangle|$),
- The phases in the amplitudes are given by the CKM matrix element V_{ij} .

Then a CP violation effect in the B_s^0 decay will be due to the imaginary part ($Im \lambda$) of

$$\lambda = \eta \frac{\langle f|\bar{B}_s^0\rangle}{\langle f|B_s^0\rangle},$$

$$\eta \propto \frac{V_{tb}^*}{V_{tb}} \frac{V_{ts}}{V_{ts}^*},$$

where η is due to the $B_s^0 - \bar{B}_s^0$ mixing (see Fig. 3a). By using the Wolfenstein parametrization, the V_{ij} are real apart from V_{ub} and V_{td} . One then has a real value of η for the $B_s^0 - \bar{B}_s^0$ mixing. Moreover, for $f = \bar{f}$, the V_{ij} elements entering into the $b \rightarrow c$ (or $\bar{b} \rightarrow \bar{c}$) are also real (see Fig. 3b). Therefore, in the standard model, no CP violation is expected for $B_s^0, \bar{B}_s^0 \rightarrow f$ when $\bar{f} = \bar{f}$ and $b \rightarrow c$ (or $\bar{b} \rightarrow \bar{c}$).

In any case B_s^0 decay in the kind of process discussed here has to be measured in order to see if other sources might be responsible for CP violation. For instance, 4 generations could lead to CP violation effects. Even if the additional V_{ij} elements are small, the fact that one can then have 3 phases in the CKM matrix may introduce CP violation effects.

c) The B_c meson

Because of the large $pp \rightarrow b\bar{b}X$ cross-section expected at the c.m. energies of the pp collider projects, one could observe $B_c^\pm$ mesons ($B_c^+ \equiv \bar{b}c$). Based on the Monte Carlo calculations there are estimates of^{18,19}

$$\frac{\sigma(pp \rightarrow B_c^\pm X)}{\sigma(pp \rightarrow b\bar{b}X)} \leq 10^{-3}, \leq 10^{-4};$$

As $B_c^\pm$ is formed by two different heavy quarks, the quarkonium type of potential models (as for the charmonium and $\Upsilon(nS)$ cases) could be investigated¹⁸. One could also observe if the decay occurs within the spectator model, namely, by the decay of the b or c quark (Fig. 4). The third diagram shown in Fig 4 will here be more important than in the $B^-(b\bar{u})$ case since $|V_{cb}| > |V_{ub}|$. The contributions of the various diagrams shown in Fig. 4a have been estimated in reference 18.

One also notices that there are specific decay products allowing one to know if the final state could be due to the b or c quark decay. In Fig. 4b, we indicate two examples, namely $B_c^- \rightarrow J/\psi X^-$ ($b \rightarrow c$) and $B_c^- \rightarrow \bar{B}_s^0 X^-$ ($c \rightarrow s$) decays. One

could, for instance, compare the validity of the spectator model in the $B_c^\pm$ decay with that appearing in the $B^\pm$ and $D^\pm$ ones. The lifetime obtained from $B_c^\pm$, $B^\pm$, and $D^\pm$ could, possibly, be compared.

4 - Preliminary conclusions

We have briefly considered the interest of studying B -physics with pp and pA collisions. Because of the large $B\bar{B}$ production rates expected for the LHC and SSC projects, $B_c^\pm$ will also be produced. The decay of these $B_c^\pm$ mesons could be studied.

Aspects of the CP violation measurements of the $B_{d,s}^0$ decays have also been discussed. A comparison of some of the B_s^0 and $\bar{B}_s^0$ decays could allow a better understanding of possible CP violation effects. We also noticed the interest in measuring the relative B and $\bar{B}$ production rates in pp collisions with decay channels without (or with very small) CP violation effects.

From the actual discussions, it appears that study of B -physics in pp and pA interactions might lead to some advantages. Clearly, the construction of the detectors, the triggering processes as well as the radiation damage near the beam pipe have to be further investigated. In the collider case one can also attempt to appreciate the interest and possibility of analysing B -mesons emitted with small or large emission angle (with respect to the beam direction). For pA interactions, one can still examine the interest of using an external or a gas-jet target. In any case, the continuation of the present investigations will be of great importance for our future experiments.

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Fig. 1 - The estimates of the $\langle n(pA) \rangle / \langle n \rangle$ ratio as a function of A , the target nuclear mass number. Here $\langle n(pA) \rangle$ and $\langle n \rangle$ are the average charged multiplicities of pA and pp collisions, respectively.

Fig. 2 - The time-dependent decay distribution for the $l^+ f$ case obtained from equation 1 (full line) and for the general case (dashed line). The $|T_d|^2 e^{-\tau} / \Gamma_i \Gamma_d$ has been factorized out. No CP violation would correspond to a straight line at the ordinate value of 1.

Fig. 3 - a) A mixing diagram for the $\bar{B}_s^0 \rightarrow B_s^0$ case. The η value is given by the dominant t -quark exchange in the diagram. b) Diagrams for the B_s^0 and $\bar{B}_s^0$ decays leading to a system with the same quarks.

Fig. 4 - a) Diagrams contributing to the B_c^- decay. b) Examples of B_c^- decays indicating the $b \rightarrow c$ or the $\bar{c} \rightarrow \bar{s}$ transitions.