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Remarks about B Production in pA Collisions with a p-Beam of 8 TeV

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Abstract

We discuss pA collisions that can be used for studying B -physics with a proton beam of ~ 8 TeV/c. In particular we study $R(A) = \sigma^A(b\bar{b})/\sigma_T^A$ as well as the number of interactions per bunch crossing of the beam with the various targets. We also estimate the average charged multiplicity for pA collisions. Finally some comments are made for the case of using external or gas jet targets.

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1 - Introduction

In this note we discuss the kind of target that can be used in order to study B -physics with a proton beam having a momentum of 8 TeV/c. We will discuss the value of the ratio

$$R(A) = \frac{\sigma^A(b\bar{b})}{\sigma_T^A}.$$

The A value is the target nuclear mass number (often called the atomic number corresponding to the number of nucleons in the target) whereas the T index indicates the total inelastic case. Thus, σ_T^A and $\sigma^A(b\bar{b})$ are the inelastic and $b\bar{b}X$ cross sections, respectively (X meaning anything). In principle, the possibility of increasing $R(A)$ may decrease the background among the events used for studying $B - \bar{B}$ physics. This might be very helpful for pN interactions with an 8 TeV beam where the background is estimated to be important (see below). We will also estimate the number of interactions per bunch crossing of the beam with the various targets as well as the average charged multiplicity for pA collisions.

For the time being the experimental data do not allow an estimate of $R(A)$ for $B\bar{B}$ production. Therefore, the study of charm and $\Upsilon(nS)$ production may suggest values for the $B\bar{B}$ case. In the next section we will discuss some features related to the $R(A)$ quantity. Then we will examine the charm and $\Upsilon(nS)$ production (Section 3). Finally we will make some remarks about the nuclear targets that can be used for studying B -physics (Section 4).

2 - The $R(A)$ dependance

Usually the dependance of the inelastic and hadroproduction cross sections on a nuclear target with a given incident beam particle type are parametrized by $\sigma \sim A^\alpha$. Here α is a parameter which can be determined experimentally. In fact one assumes that with the same type of beam one has:

$$\begin{aligned}\sigma^A(h) &= \sigma^0(h) A^{\alpha(h)} \\ \sigma_T^A &= \sigma_T^0 A^{\alpha(T)}\end{aligned}$$

where h is the particle observed in the inclusive reaction. Here σ_T^0 , $\sigma^0(h)$ denote parameters close to the σ_T and $\sigma(h)$ cross sections of the beam on a proton target (the beam- p and beam- n cross section are assumed to be equal). The experimental data show that the above hadronic cross sections are well determined by the A^α parametrization for $A \geq 4$. With an hydrogen target the data tend to be somewhat

below such a fit¹. One also compares the results obtained with two different targets (A_1, A_2) by using

$$E \frac{d^3\sigma^{A_2}(h)}{dp^3} = E \frac{d^3\sigma^{A_1}(h)}{dp^3} \times \left(\frac{A_2}{A_1}\right)^{\alpha(h)}$$

whereas E, p are the energy and momentum of the outgoing h particle. Nevertheless, in order to estimate

$$R(A) = \frac{\sigma^A(h)}{\sigma_T^A} = \frac{\sigma^0(h)}{\sigma_T^0} A^{\alpha(h)-\alpha(T)}$$

we will assume that $\sigma^0(h)/\sigma_T^0 = \sigma(h)/\sigma_T$.

If one assumes that the total cross section is proportional to the surface of the nucleus target, $\alpha(T) \sim 2/3$ (see for instance Ref. 2). However, the A dependence of σ_T for $\pi^\pm, K^\pm, p$ and $\bar{p}$ beams have been investigated³ for incident momentum of 60 - 280 GeV/c. For p beams it was found that

$$\alpha(T) = 0.72 \pm 0.01$$

while another pA experiment⁴ at 400 GeV/c gives

$$\alpha(T) = 0.77 \pm 0.03.$$

For the present discussion we will use $\alpha(T) = 0.72$, a value which is usually taken for beams with large incident momentum⁵.

According to the QCD model, $\alpha(h)$ is expected to be ~ 1 (Ref. 6) for h particles containing heavy quarks (charm or bottom). Coherent effects may decrease the transparency of the nucleus and $\alpha(h)$ could then be reduced. Experimentally, one has found that $\alpha(h)$ depends on x_F and p_T . Here x_F is the Feynman scaling variable (in the beam-nucleon cm system) of the h particle while p_T is its transverse momentum (the Fermi motion of the nucleon inside the target is usually neglected). Thus, one has observed that for hadroproduction^{7,1}:

- α increases with p_T
- α increases when x_F decreases

Fig. 1 presents some results of various experiments⁹⁻¹¹. In the region where x_F and p_T have large values the number of events is rather small as the inclusive differential cross section can be parametrized by^{8,12}

$$\frac{d^2\sigma}{dx_F dp_T^2} \sim (1 - |x_F|)^n f(p_T) \quad (1)$$

Here $f(p_T)$ is taken as

$$e^{-b_2 p_T^2} \quad \text{or} \quad e^{-b_1 p_T}$$

(Ref. 8), n and $b_{1,2}$ being fitted parameters. In principle n is related to the parton structure functions. For instance, $\pi^- A$ interactions with a beam of 340 GeV/c leads for charm production to⁸, $n = 3.40 \pm 0.45$ and $b_1 = 2.00 \pm 0.12$ GeV/c⁻¹ whereas for pp interactions¹³ it was found that $3 \leq n \leq 12$. In any case one sees from equation (1) that the average α value will not vary very much if the experiment will not be able to detect events with large p_T or x_F .

From some experimental results⁹ one observed that for a given type of beam, $\alpha(h)$ tends to increase with the mass of the h particle. This behaviour is not confirmed by reference (1). However, a recent experiment with a 340 GeV/c π^- beam⁸ (WA82 charm production) has measured

$$\begin{aligned} \alpha(K_S^0) &= 0.70 \pm 0.005 \pm 0.05, \quad < x_F > = 0.05 \\ \alpha(D) &= 0.89 \pm 0.05 \pm 0.05, \quad < x_F > = 0.2. \end{aligned}$$

According to our discussion $\alpha(D)$ will tend to be larger if $< x_F >$ will have the lower value used for the $\alpha(K_S^0)$ case. Thus, one sees again that $\alpha(h)$ tend to increase with the mass of the observed outgoing particle.

3 - Charm and beauty production

For the time being the experimental data do not allow to estimate $R(A)$ for $B/\bar{B}$ production with A targets. As mentioned above the study of the D , $\bar{D}$, and J/ψ or ψ' production may indicate a lower limit of $\alpha(b)$ for the outgoing $B/\bar{B}$. Table 1 and 2 give the α values found for the $D/\bar{D}$ and ψ production. A recent experiment²² has also studied the Υ , Υ' and Υ'' production in pA collisions at a p momentum of 800 GeV/c (Table 2). As expected the $\alpha(\Upsilon)$ appear to be rather large, namely ~ 0.95 .

For the charm production there might be differences between samples heaving leading and non leading²³ $D/\bar{D}$. For instance, the π^-p reactions at 340 GeV/c indicates²⁴ that the x_F distribution for the non leading charm mesons has more events for small x_F than the sample containing leading charm mesons. This effect has not been confirmed by recent results⁸. For the present discussion we will not consider the possibility that α might depend from the presence of leading meson in the final state. In any case this problem does not exist for the J/ψ , ψ' or $\Upsilon(nS)$ production.

From Table 1 one sees that $\alpha(D)$ appears to be in the 0.76 - 0.97 range, the errors of the experimental results being rather large. For the J/ψ production (Table 2) the values tend to be larger than most of those given in Table 1. The large $\alpha(J/\psi)$ values determined with the H and Pt targets¹⁹ might also be due to the fact that the cross sections on proton are below the fits obtained with $A \geq 4$. However, the recent results^{21,22} obtained with large statistics indicate that $\alpha(J/\psi) \simeq 0.92$ and $\alpha(\Upsilon) \sim 0.95$. In any case new experiments will certainly help to clarify the values of the α parameter for charm and beauty production.

Let us now comment the $pN \rightarrow B\bar{B}X$ reactions resulting from a proton beam interacting with a fixed target. For the LHC project (p beam of 8 TeV) there are theoretical predictions^{25,26} for the total (σ_T) and $b\bar{b}X$ ($\sigma(b\bar{b})$) cross sections, namely $\sigma_T \sim 50$ mb and $\sigma(b\bar{b}) \sim 1$ μ b yielding

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

In other words such a ratio indicate that 50 000 inelastic interactions have to occur in order to have 1 $B\bar{B}$ event. The tagging, the detection efficiencies as well as the triggering method for a specific experiment will, of course, decrease the non- $B\bar{B}$ events (the background events). This could only be estimated by defining:

- the type of B decays which will be studied
- the detector properties.

One has, however, to emphasize that for the pp collider one may have larger values, namely

$$R(A=1) \sim \frac{1}{550} \sim \frac{1}{200}$$

for the LHC or SSC projects²⁷, respectively. For the pA collisions we estimate

$R(A) = \sigma(b\bar{b})/\sigma_T F(A)$ with

$$F(A) = A^{\alpha(B)-0.72}$$

and using the predicted pN cross sections. With the range of $0.9 \leq \alpha(B) \leq 1$, corresponding to the $\alpha(D)$, $\alpha(J/\psi)$ and $\alpha(\Upsilon)$ values, one obtains estimates of $F(A)$ (See the scheme shown in Fig. 2). Clearly the utilization of A targets could only be useful if $\alpha(B) \geq 0.9$ and $A \geq 80$. In these cases $R(A)$ will increase by a factor of ~ 2.5 with respect to the $A = 1$ case.

4 - The A targets for B production

For an LHC type of project, there are difficulties to build an external p beam of ~ 8 TeV/c. In the case that such an eventual beam could have an intensity of $\sim 10^8$ p/s , one obtains the luminosities given in Table 3 for various A targets. For the present example we used targets with a length of 0.2cm (along the beam direction). Table 3 gives also the number of $b\bar{b}X$ events in 1 year (10^7 s) of running ($N(b\bar{b})/y$), the number of inelastic interactions per second (N_{int}/s) as well as the $R(A)$ ratio calculated with $\alpha_T = 0.72$ and $\alpha(B) = 1$. We note that the $N(b\bar{b})/y$ are much smaller than those expected for the LHC ($\sim 2 \cdot 10^{11}/y$) or the SSC ($\sim 5 \cdot 10^{11}/y$) collider projects²⁷. Assuming here that an external beam would have the same structure form as in the collider, one may estimate the multiple interactions per bunch crossing with the fixed target. This might be done by estimating the $P(2)/P(1)$ and $P(3)/P(1)$ ratios. Here $P(m)$ is the probability of having m interactions per bunch crossing and assumed to follow a Poisson distribution. We see from Table 3 that these effects are small ($\leq 2.5 \cdot 10^{-2}$). Note that in order to increase $N(b\bar{b})/y$, one can also consider several target planes^{5,8} (each plane has then the same values of $P(m)/P(1)$ and $R(A)$). In this case one has to take into account the secondary interactions introduced by the outgoing particles.

In principle the gas jet target has the possibility of having large luminosities as the beam intensity in the LHC collider project is expected to be $\sim 5.4 \cdot 10^{18}$ p/s . The luminosity has, however, to be limited if one wants to avoid multiple interactions per bunch crossing. In Table 4 we calculate the luminosities for the various A targets in order to have $P(2)/P(1) = 0.05$ using a gas jet target with a length of 0.8 cm along the beam direction²⁸. This correspond to $N_{int}/s = 5.5 \cdot 10^6$. It would certainly be useful to also investigate the possibility of using several gas jet targets in a given experiment²⁹. For instance, with three Xe gas jet target, one could eventually obtain $\sim 10^{10}$ $b\bar{b}X$ events per year. Clearly a detailed study has to be done in order to estimate the real number of $B\bar{B}$ that could be detected.

The average charged multiplicity on a nuclear target ($\langle n(pA) \rangle$) is expected to be larger than that obtained in pp collisions ($\langle n(pp) \rangle$). The experimental data indicate³⁰ that

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

Here $\bar{\nu}$ is the average number of collisions of the incident particle in the nuclear target which can be estimated by³⁰

$$\bar{\nu} = \frac{A\sigma_T}{\sigma_T^A}$$

The r values calculated by this method are given in Table 3 and 4. We see that the $\langle n(pA) \rangle$ values are not much larger than $\langle n(pp) \rangle$ (about 17 at the considered cm energy²⁷).

To summarize, we discussed the $R(A) = \sigma^A(b\bar{b})/\sigma_T^A$ quantity estimated by using experimental results of D , J/ψ and $\Upsilon(nS)$ produced in hadron- A collisions. Within the QCD approach, it appears that for $A \geq 80$, $R(A)$ will increase by a factor of ~ 3 with respect to $R(A = 1)$ corresponding to pp collisions. Thus the utilization of $A \geq 80$ targets might be useful to increase the signal to background ratio in the $B\bar{B}$ samples. We also estimated the $\langle n(pA) \rangle$ values which appear to be larger by a factor of 2 to 3 with respect to pp interactions. Further detailed analyses are necessary in order to appreciate the real usefulness of A -targets with realistic detectors.

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Table 1 - Some α values obtained from charm production. We took only experiments where the beam momentum is larger 100 GeV/c.

beam GeV/c	target	some details	α	reference
π^- , 320	Al, Fe, U	prompt $\mu^\pm$	$\alpha(\mu^+) = 0.76 \pm 0.08$ $\alpha(\mu^-) = 0.83 \pm 0.06$	14
p , 300	Al, Fe, U	prompt $\mu^\pm$ $x_F > 0.1$	$\alpha(\mu^+) = 0.79 \pm 0.12$ $\alpha(\mu^-) = 0.76 \pm 0.13$	15
p , 400	Be, Cu, W	prompt $(\nu_e + \bar{\nu}_e)$	0.75 ± 0.05	16
$\pi^\pm$, 250	Be, Al, Cu, We		$\alpha(D^+) = 0.97 \pm 0.07$ $\alpha(D^0) = 0.92 \pm 0.08$	17
$\pi^\pm$, 250	Si, W	$\langle x_F \rangle = 0.24$	$\alpha(D) = 0.88 \pm 0.05$	18

Table 2 - Same as in Table 1 but for J/ψ , ψ' and $\Upsilon(nS)$ production.

beam GeV/c	target	some details	α	reference
π^- , 150	H, Pt	J/ψ	0.95 ± 0.02	19
π^- , 200		$\mu^+\mu^-$	0.97 ± 0.02	
π^- , 280		$x_F > 0$	0.95 ± 0.02	
π^+ , 200			0.96 ± 0.02	
p , 200			0.94 ± 0.03	
π^- , 530	C, Al, Cu Pb	J/ψ $0.1 < x_F < 0.8$	0.85 ± 0.008	20
p , 800	d, C, Ca, Fe, W	J/ψ or ψ' $0.15 < x_F < 0.65$	0.92 ± 0.008	21
p , 800	d, C, Ca, Fe, W	Υ $0 < x_F < 0.6$ $p_T < 4$ GeV/c	0.962 ± 0.014	22
p , 800	d, C, Ca, Fe, W	Υ' or Υ'' $0 < x_F < 0.6$ $p_T < 4$ GeV/c	0.948 ± 0.020	22

Table 3 - The production rate, $N(b\bar{b})/y$ and N_{int}/s , for various external targets having a length of 0.2 cm, assuming the existence of an external beam of 10^8 p/s. Here $\langle l_i \rangle$ and $\langle l_r \rangle$ are the average interaction and radiation length, respectively, of various targets. The luminosity is denoted by L whereas $R(A) = \sigma^A(b\bar{b})/\sigma_T^A$ are calculated with $\alpha_T = 0.72$ and $\alpha(B)=1$. The $P(m)$ quantity represents the probability of having m interactions per bunch crossing.

	Be A=9	Si A=28	Cu A=63	W A=184
$\langle l_i \rangle$, cm	40.6	45.5	15.0	9.6
$\langle l_r \rangle$, cm	35.2	9.4	1.4	0.35
L , $cm^{-2}s^{-1}$	$3 \cdot 10^{30}$	$2 \cdot 10^{30}$	$1.7 \cdot 10^{30}$	$1.6 \cdot 10^{30}$
N_{int}/s	$6 \cdot 10^5$	$5.5 \cdot 10^5$	$1.7 \cdot 10^6$	$2.7 \cdot 10^6$
$N(b\bar{b})/y$	$2.2 \cdot 10^8$	$2.8 \cdot 10^8$	$1.7 \cdot 10^9$	$2.4 \cdot 10^9$
$P(2)/P(1)$	$0.6 \cdot 10^{-2}$	$0.5 \cdot 10^{-2}$	$1.6 \cdot 10^{-2}$	$2.5 \cdot 10^{-2}$
$P(3)/P(1)$	$0.2 \cdot 10^{-4}$	$0.17 \cdot 10^{-4}$	$1.7 \cdot 10^{-4}$	$4.2 \cdot 10^{-4}$
$\langle n(pA) \rangle / \langle n(pp) \rangle$	1.43	1.77	2.10	2.65
$R(A)$	1/27K	1/20K	1/16K	1/12K

Table 4 - The estimates of the $N(b\bar{b})/y$ production rate for various gas jet targets having a length of 0.8 cm (along the beam direction) and $P(2)/P(1)=0.05$. This leads to $N_{int}/s = 5.5 \cdot 10^6$ (and to $P(3)/P(1)=1.7 \cdot 10^{-3}$) for all cases. For each target the number of atoms per cm^3 (N_{at}/cm^3), the luminosity L as well as $R(A)$ have been calculated. Note that the Xe (A=131) and Cs (A=133) gas are nearly identical.

	H A=1	Ar A=40	Xe A=131
N_{at}/cm^3	$2.5 \cdot 10^{13}$	$1.8 \cdot 10^{12}$	$7.5 \cdot 10^{11}$
L , $cm^{-2}s^{-1}$	$5.4 \cdot 10^{32}$	$7.7 \cdot 10^{30}$	$3.3 \cdot 10^{30}$
$N(b\bar{b})/y$	$1.1 \cdot 10^9$	$3.1 \cdot 10^9$	$4.3 \cdot 10^9$
$\langle n(pA) \rangle / \langle n(pp) \rangle$	1	1.90	2.46
$R(A)$	1/50K	1/18K	1/13K

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Fig. 1 - The $\alpha(x_F, p_T)$ dependance on x_F and p_T for strange particle production in pA collisions^{10,11}.

Fig. 2 - Scheme of the $F(A)$ dependence.