COMMENTS ON THE PRODUCTION OF $b\bar{b}$ PAIRS AT THE SSC

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Summary

Some features of heavy flavor quark pair production particularly $b\bar{b}$ pairs have been investigated using the ISAJET(5.23) Monte Carlo program. The sources and cross sections for $b\bar{b}$ quark pair production as a function of transverse jet momentum are studied. For p_T below 10 GeV/c gluon fusion is the dominant mode. However, $b\bar{b}$ pairs from gluon fragmentation in both the initial and final state jets are found to dominate the cross sections for jet p_T above 10 GeV/c. The origin of this result is discussed, and a comparison of the gluon fusion and fragmentation production modes is made. The impact of some features of B meson decay on the design of microvertex detectors is briefly examined.

Sources of $b\bar{b}$ Pairs

Table I contains the cross sections for $b\bar{b}$ production as a function of p_T for the following production channels: (a) $gg \to b\bar{b}$ (gluon fusion); (b) $g_f \to b\bar{b}$ (gluon fragmentation by a gluon contained in a final state jet); (c) $g_i \to b\bar{b}$ (gluon fragmentation by a gluon in an initial state jet; (d) (b or $\bar{b}$) + X $\to$ (b or $\bar{b}$) + X (direct b or $\bar{b}$ scattering). The values were generated using version 5.23 of the ISAJET Monte Carlo program. p_T is the transverse momentum of either final state parton in a two jet process. In (a) both the b and its partner have transverse momentum p_T. For (b) p_T is the transverse momentum of either final state jet, one of which contains a gluon fragmenting into a $b\bar{b}$ pair. In (c) p_T is again the transverse momentum of either final state jet, but the gluon which fragments into a $b\bar{b}$ pairs is in one of the initial state jets. Finally in (d) p_T is the transverse momentum of either the final state b or $\bar{b}$ parton which undergoes the hard scatter and its partner is part of the initial state radiation. In the cases of (a) and (d) the ISAJET program is able to generate the events directly by specifying the appropriate final state jet parameters. For (b) and (c) it is necessary to generate a large set of twojet events and then search through them looking for the $b\bar{b}$ pairs. For each entry in Table I the cross section has been integrated over the indicated p_T range even though the bin size is not the same in every case. The total cross section for a particular channel is the sum of the entries for that channel. The results are plotted in Fig. 1.

Although gluon fusion is the largest contributor to the total $b\bar{b}$ pair cross section and completely dominates the production for jet p_T < 10 GeV/c; the contribution of $b\bar{b}$ pairs from gluon fragmentation (first from final state jets and at higher p_T from both initial and final state jets) dominate the production for p_T > 10 GeV/c. Since this prediction may be somewhat suprising, it is worthwhile to comment on it origin.

Table I: Cross sections for $b\bar{b}$ pairs vs final state jet p_T. Cross sections have been integrated over the p_T bin. The total cross section for a particular channel is the sum of the relevant column.

p_T range (GeV/c)	$gg \to b\bar{b}$ (μb)	$g_f \to b\bar{b}$ (μb)	$g_i \to b\bar{b}$ (μb)	$\begin{pmatrix} b \\ \bar{b} \end{pmatrix} X \to \begin{pmatrix} b \\ \bar{b} \end{pmatrix}^* X$ (μb)
2.5 - 5	91.6	0	0	0
5 - 10	73.4	0	0	0
10 - 25	25.5	67.5	18.1	44.2
25 - 50	2.45	29.9	15.5	10.3
50 - 100	2.89×10^{-1}	6.01	3.45	1.59
100 - 250	2.59×10^{-2}	7.10×10^{-1}	5.34×10^{-1}	1.69×10^{-1}
250 - 500	7.11×10^{-4}	2.83×10^{-2}	2.42×10^{-2}	5.05×10^{-3}
500 - 1000	3.46×10^{-5}	1.71×10^{-3}	1.77×10^{-3}	2.61×10^{-4}
1000 - 2500	1.17×10^{-6}	6.54×10^{-5}	8.75×10^{-5}	9.02×10^{-6}
2500 - 5000	—	4.25×10^{-7}	6.43×10^{-7}	—

*The heavy quark partner to the final state b or $\bar{b}$ jet is part of the initial jet radiation.

Origin of Heavy Flavor Pairs in Gluon Fragmentation

Perturbative QCD predicts a relatively large probability for the fragmentation of massive gluons into heavy flavor quark pairs.[1] These effects can be expected to be important at the large SSC energies. If ρ is the average number of heavy quark pairs resulting from the fragmentation of a gluon jet of virtual mass Q, then ρ is given by

$$\rho = \frac{1}{3\pi}\int_{4M^2}^{Q^2} \frac{dK^2}{K^2}\alpha_s(K)(1+2M^2/K^2)\left(\frac{1}{4}-\frac{M^2}{K^2}\right)^{\frac{1}{2}} n_g(Q^2,K^2) \qquad (1)$$

where

$$n_g(Q^2,K^2) = \frac{[\ln(Q^2/\Lambda^2)/\ln(K^2/\Lambda^2)]^a \exp\{[(2C_A/\pi b)\ln(Q^2/\Lambda^2)]^{\frac{1}{2}}\}}{\exp\{[(2C_A/\pi b)\ln(K^2/\Lambda^2)]^{\frac{1}{2}}\}}$$

is a factor to account for the multiplicity of gluons having mass K, and

$$a = -\frac{1}{4}[1+(2N_f/3\pi b)(1-C_F/C_A)], \quad b = (11C_A-2N_f)/12\pi,$$

$$C_F = 4/3 \quad \text{and} \quad C_A = 3.$$

Using Λ = 0.2 GeV and 1.6, 4.8, and 40 GeV for the masses of the c, b, and t quark; the evaluation of Eq. (1) is shown in Fig. 2. Preliminary results from UA1 on D^* production[2, 3] indicate that open charm is present in approximately 10% of the high p_T jets in rough agreement with the prediction shown in Fig. 2.

These fragmentation effects are further enhanced relative to the higher order fusion process by the the fact that $\sigma(gg\to gg)/\sigma(gg\to q\bar{q}) = 27N^3/(N^2-2) = 104$. This is a color factor which happens to be large.[3] In this way gluon fragmentation $O(\alpha_s^3)$ dominates over gluon fusion $O(\alpha_s^2)$. The situation is analogous to pair production by high energy photons interacting with matter $O(\alpha^3)$ which dominates over Compton scattering $O(\alpha^2)$.

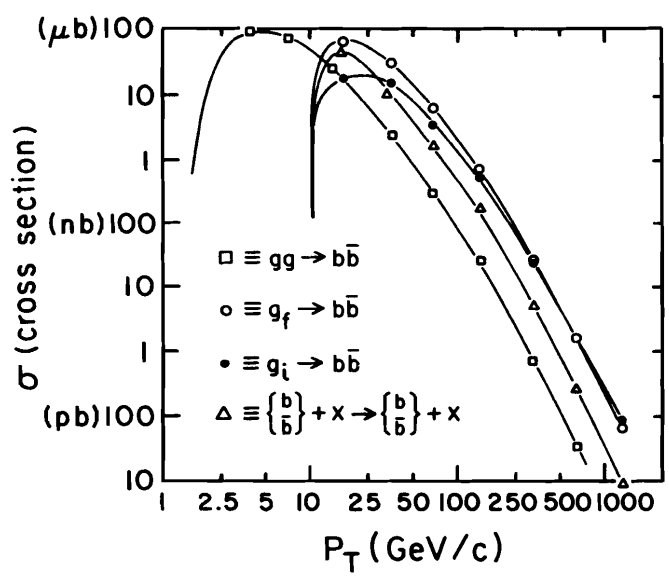

Figure 1. Production cross sections for $b\bar{b}$ pairs as listed in Table I.

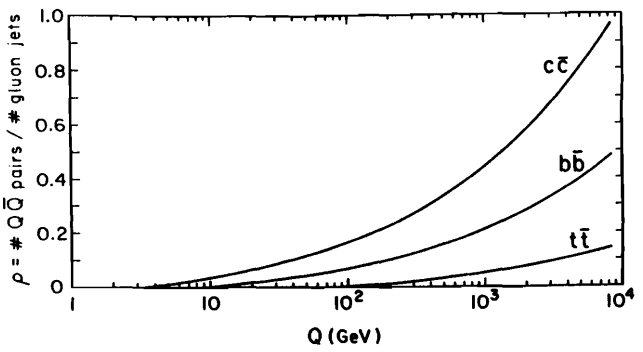

Figure 2. Results of the evaluation of Eq. (1) for the probability of gluon fragmentation into heavy quark pairs ($c\bar{c}$, $b\bar{b}$ and $t\bar{t}$). Q is the virtual mass of the initial gluon.

Apart from the necessity of counting the resulting heavy flavor pairs, approximations to these gluon fragmentation predictions have been included in the ISAJET Monte Carlo program. There is some ambiguity in choosing the mass of a gluon which initiates a jet. The choice Q = p_T is made which implies a so called K factor of 1. In the absence of any evidence to the contrary the gluon fragmentation predictions of the ISAJET program have been presented at face value for the purposes of this study. The experimental verification of these perturbative QCD predictions for gluon fragmentation into heavy flavors would be an interesting test of the theory.

Comparison of Gluon Fusion and Fragmentation

Signal Strength vs Background

Although the total cross section for $b\bar{b}$ pairs from gluon fusion is larger than for the other production channels, it peaks at low p_T, approximately 5 GeV/c, where the single jet cross section is also very large. In comparison $b\bar{b}$ pairs arising from final state jet gluon fragmentation are also a substantial contributor to the total $b\bar{b}$ pair cross section. Since the gluon fragmentation channel peaks at a larger p_T, it represents a larger fraction of the total single jet cross section. For example the cross section for $b\bar{b}$ pairs from final state jet gluon fragmentation in the p_T interval between 10 and 50 GeV/c is 97 μb while in the p_T interval between 2.5 and 25 GeV/c, the gluon fusion channel $gg \to b\bar{b}$ has a cross section of approximately 191 μb. Although these cross sections differ by only a factor of two, there is roughly a factor of 12 difference in the single jet background. For gluon fusion ($gg \to b\bar{b}$) the ratio of pair cross section to the single jet cross section is 8.3 x 10^{-4} averaged over the interval 2.5 GeV/c < p_T < 25 GeV/c; whereas, for final state jet gluon fragmentation ($g_f \to b\bar{b}$) the ratio of the pair cross section to the single jet cross section is 1.0 x 10^{-2} averaged over the interval 10 GeV/c < p_T < 50 GeV/c. Thus, the higher p_T interval 10 GeV/c < p_T < 50 GeV/c has the advantage that the $b\bar{b}$ pairs are enhanced relative to the single jet background by a factor of 12 at the expense of a loss of a factor of two in the $b\bar{b}$ pair production cross section compared with the lower p_T interval 2.5 GeV/c < p_T < 25 GeV/c.

Central and Forward Directions Compared

In Table II we compare the cross sections for $b\bar{b}$ pair production from both gluon fusion and gluon fragmentation in the forward (y > 3.0) and central (-1.5 < y < 1.5) regions. For p_T below 10 GeV/c gluon fusion is the only contributor, but above 10 GeV/c gluon fragmentation is the largest component of the cross section. For example in the forward region in the interval 2.5 < p_T < 25 GeV/c if we require both partons to have y > 3.0, gluon fusion gives a pair cross section of ~ 27 μb (90% is at p_T < 10 GeV/c), while in the interval 10 < p_T < 50 GeV/c gluon fragmentation gives a pair cross section of ~ 23 μb. One feature of the forward direction is that ~ 11 μb of the gluon fragmentation cross section arises from fragmentation of gluons in the initial parton jets. The central region is similar in that for p_T below 10 GeV/c the pair cross section is dominated by gluon fusion while above 10 GeV/c gluon fragmentation is more important. If we require both partons to satisfy -1.5 < y < 1.5, then for 2.5 < p_T < 25 GeV/c gluon fusion gives ~ 27 μb while in the interval 10 < p_T < 50 GeV/c gluon fragmentation gives ~ 31 μb. In the central region only 1.8 μb comes from gluon fragmentation of the initial parton jets.

Table II(a): Cross sections for gluon fusion ($gg \to b\bar{b}$) in the forward and central region. "Either" or "both" means that one or both of the partons satisfy the rapidity cut.

p_T range (GeV/c)	Forward region y > 3.0 Either (μb)	Forward region y > 3.0 Both (μb)	Central region -1.5 < y < 1.5 Either (μb)	Central region -1.5 < y < 1.5 Both (μb)
2.5 - 5	22.4	14.5	19.6	11.5
5 - 10	14.4	9.7	19.3	10.6
10 - 25	4.4	2.7	8.8	5.0

Table II(b): Cross sections for gluon fragmentation in the forward and central region. "Either" or "both" means that one or both partons satisfy the rapidity cut. (f) means $g_f \to b\bar{b}$ and (i) is $g_i \to b\bar{b}$.

p_T range (GeV/c)	Forward region y > 3.0 Either (μb)	Forward region y > 3.0 Both (μb)	Central region -1.5 < y < 1.5 Either (μb)	Central region -1.5 < y < 1.5 Both (μb)
10 - 25 (f)	10.7	9.2	26.3	20.8
10 - 25 (i)	6.7	6.4	0.5	0
25 - 50 (f)	4.2	3.3	11.0	8.4
25 - 50 (i)	4.7	4.3	2.5	1.8

Two comments are possible: (1) Cross sections for the production of $b\bar{b}$ pairs are quite comparable in the central and forward directions at low p_T; (2) gluon fragmentation as a source of $b\bar{b}$ pairs which are localized in rapidity is comparable to that from gluon fusion (actually its larger in the central region), and has the additional advantage of peaking at larger p_T where the single jet cross section is smaller.

Comments on Gluon Fragmentation

Gluon fragmentation produces $b\bar{b}$ pairs which are relatively localized in both rapidity and azimuthal angle ϕ. This is in contrast to $b\bar{b}$ pairs from gluon fusion which are localized in rapidity (somewhat less so than in the fragmentation case — see Table II), but have azimuthal angles separated by 180°. Thus, it might be expected that for jet p_T > 10 GeV/c it would be possible to isolate samples of gluon jets based on the presence of $b\bar{b}$ pairs kinematically characteristic of gluon fragmentation. Furthermore, measuring the relative strength of the $b\bar{b}$ pair cross section from gluon fragmentation as a function of jet p_T is an interesting test of perturbative QCD. Given the dominance of this mechanism for jet p_T > 10 GeV/c, this would appear feasible.

Gluon fragmentation also appears to offer the possibility of doing high statistics heavy flavor experiments in both the forward and central regions. Since the $b\bar{b}$ pair is localized in both rapidity and azimuthal angle, a limited aperture experiment in the central region is possible because one does not have to look on both sides of the interaction for the bottom meson and its partner.

Simulation

Since the production of $b\bar{b}$ pairs at p_T > 10 GeV/c is dominated by gluon fragmentation, simulation of such events would appear to be the most suitable for the study of the tracking capabilities of microvertex detectors either in the central region or at small angles. In Figs. 3a and 3b are plotted a sequence of charged particle distributions for an event containing a $b\bar{b}$ pair resulting from gluon fragmentation. The gluon jet

containing the $b\bar{b}$ has p_T = 25 GeV/c near y = 0. The sequence is repeated in Figs. 4a and 4b for an event with p_T = 250 GeV/c. In both cases (a) shows the charged particle distribution in the interval −4.0 < y < 4.0, and (b) is an enlargement showing just the region of y−ϕ space containing the charged particles from the decays of the B meson and its partner.

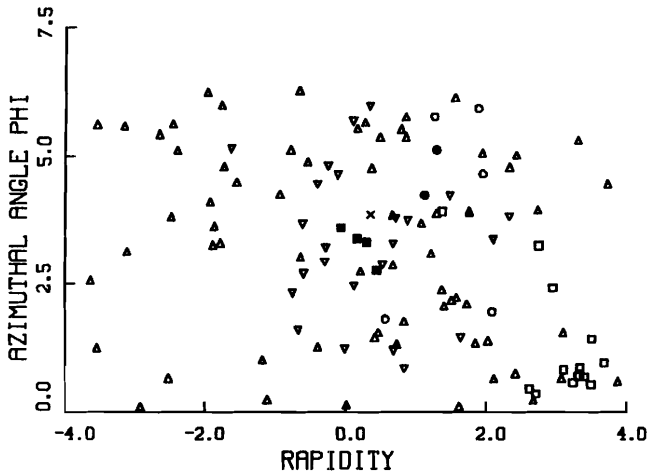

Figure 3a. Distribution of charged particles for a two jet event at p_T = 25 GeV/c containing a $B\bar{B}$ messon pair from gluon fragmentation. The cross (x) indicates the direction of the initial gluon. The meson pair decay products are solid circles and squares. Open circles are other particles in the gluon jet, open squares are from the other final state jet, ∇'s are initial jet particles and Δ's are beam jet particles.

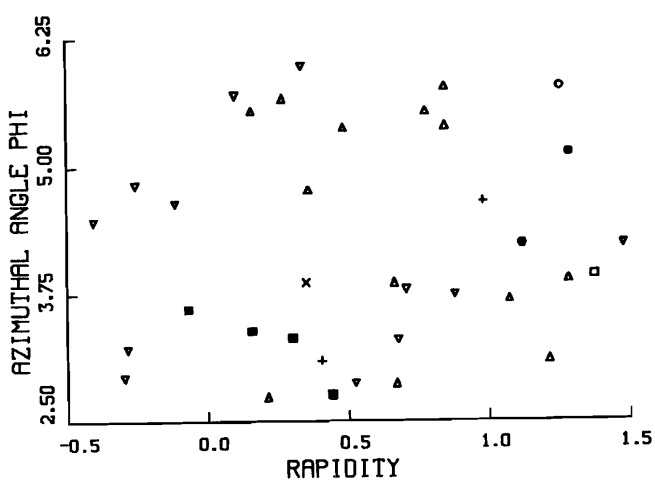

Figure 3b. Enlargement of the y−ϕ region containing the charged decay particles from the $B\bar{B}$ meson pair. The (+) symbols indicate the direction of the initial B and $\bar{B}$ meson. The other symbols are the same as Fig. 3a.

Figs. 3 and 4 indicate that the charged particles from B meson decays are clustered—more so for higher jet p_T. In searching for particles with large impact parameters this clustering is an obvious advantage. The strategy would be to look for a group of particles coming from a small region of y−ϕ space with large impact parameters. The enlargements shown in Figs. 3b and 4b show this rather explicitly. Averaging over a reasonable sample of events one gets the following results. At a p_T of 25 GeV/c, 80% of the charged particles from B meson decay fall within a rapidity window Δy of 1.0. This can be compared with a rapidity window Δy of 2.4 which includes 80% of the charged particles in the gluon jet containing the B meson pair. At a p_T of 250 GeV/c the numbers for the same two rapidity windows are 0.26 and 1.63 for B meson decay and gluon jet respectively.

Figs. 3b and 4b also give an indication of the spatial resolution required in order to do tracking on charged particles. The angular range covered by 100 strips of a silicon strip detectors with 25 μm pitch located 5 cm from the interaction point corresponds to $\Delta\phi = \Delta y = 0.05$. This is at y = 0. As one goes forward it is necessary to back up to achieve the same resolution.

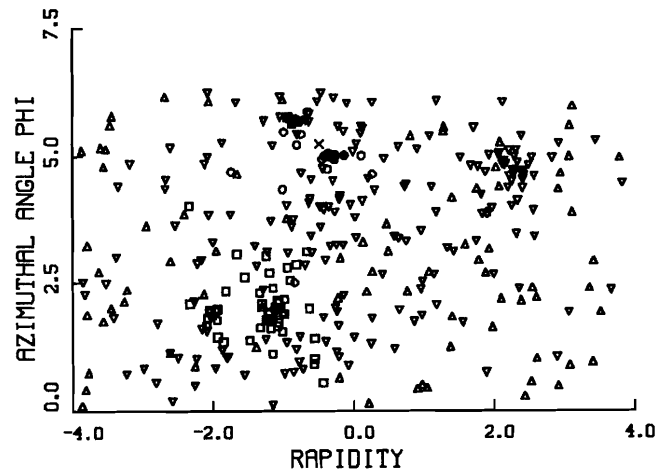

Figure 4a. Similar to Fig 3a, but now the jet p_T = 250 GeV/c. See Figs. 3a and 3b for an interpretation of the symbols.

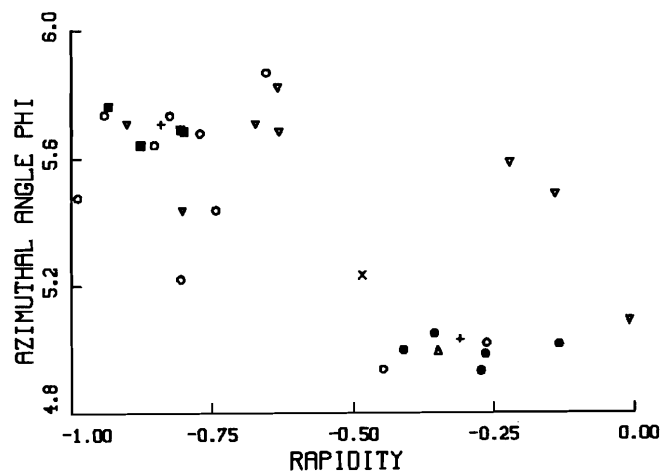

Figure 4b. Enlargement of the y−ϕ region containing the charged decay particles from the $B\bar{B}$ meson pair. See Figs. 3a and 3b.

References

[1] A. H. Mueller and J. Nason, Phys. Lett. 157B, 226 (1985).

[2] R. Frey, "$D^{*\pm}$ Production in Jets at the CERN collider," Oregon Meeting — Annual Meeting of the Division of Particles and Fields of the American Physical Society, Eugene, Oregon, 12 - 15 August, 1985.

[3] F. Halzen, Proceedings of the Oregon Meeting — Annual Meeting of the Division of Particles and Fields of the American Physical Society, Eugene, Oregon, 12 - 15 August, 1985, p. 540.