Truncated QCD Shower Calculation of Heavy-Quark Production in $p\bar{p}$ Collisions with B^0-$\bar{B}^0$ Mixing

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Characteristics of W production are well described by a parton-shower approximation, based solely on the $q\bar{q} \to Wg$ subprocess with a low-p_T cutoff chosen to reproduce the total cross section through order α_s. We apply this approach to $Q\bar{Q}$ production from the $2 \to 3$-parton subprocesses in $p\bar{p}$ collisions. The results agree with CERN dimuon events for a B^0-$\bar{B}^0$ mixing parameter $\epsilon \gtrsim 0.1$, which is at the e^+e^- experimental limit and larger than standard-model expectations.

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The UA1 experiment at the CERN $p\bar{p}$ collider has accumulated over 200 low-mass dimuon events,[1] presumed to come from the production of Υ states, Drell-Yan pairs, and pairs of heavy quarks with semileptonic decays. Like-sign dimuons are of particular interest, since they are expected only from $b\bar{b}$ production (to the extent that t-quark production can be neglected) and offer an opportunity to study B^0-$\bar{B}^0$ mixing.[2,3] Heavy-quark (Q) production proceeds in lowest order by $q\bar{q} \to Q\bar{Q}$ and $gg \to Q\bar{Q}$ subprocesses, which give the total cross section (modulo K factors), and in the next order by $q\bar{q} \to Q\bar{Q}g$, $gq \to Q\bar{Q}q$, $gg \to Q\bar{Q}g$ subprocesses, which give the p_T dependence of the $Q\bar{Q}$ system at large p_T but require a low-p_T cutoff to regulate soft and collinear divergences. Previous calculations[2,4,5] of dimuons from heavy quarks have added these two contributions, but have some arbitrariness arising from the cutoff. In this Letter we present new calculations of $b\bar{b}$ and $c\bar{c}$ production using a truncated shower prescription based on the $2 \to 3$ tree diagrams alone, with a low-p_T cutoff adjusted to give the correct total cross section for each mass of the $Q\bar{Q}$ system.

Our approach is motivated by the success of a similar approximation[6] in describing W^+, Z, and Drell-Yan pair production. There the W^+ total cross section (for example) is given by the factor[7] $K = 1 + (16\pi^2/9) \times \alpha_s(M_W^2)/2\pi$ times the $2 \to 1$ Born cross section from $u\bar{d} \to W^+$, folded with quark densities. The p_T dependence at large p_T is given by the $O(\alpha_s)$ cross section from $u\bar{d} \to W^+g$ scaled up by approximately the same K factor [7] at all p_T (contributions from crossed subprocesses $qg \to Wq$ are negligible). With a smooth p_T cutoff factor $f(p_T) = 1 - \exp(-p_T^2/4)$, or equally well a sharp p_T cutoff at 1.3 GeV, the $O(\alpha_s)$ subprocess alone reproduces the total W cross section:

$$\sigma_{\text{tot}}(W) = K\sigma(2 \to 1) = \int fK\sigma(2 \to 2). \tag{1}$$

It also correctly predicts the p_T dependence (except for unmeasured details in the cutoff region), $W +$ one-jet distributions, and the dominant ($n = 0$ and 1)-jet multiplicities in the correct ratio. In these observables the truncated shower approximation is indistinguishable from full QCD shower calculations[8] of W, Z, and Drell-Yan production. Full QCD shower formulations of $Q\bar{Q}$ production are in various stages of development,[9] but we expect an analogous truncated shower to give an adequate approximation for the salient features.

Our calculation of the $2 \to 3$ subprocesses proceeds as in Ref. 2, except for the $p_T(Q\bar{Q})$ cutoff prescription. Ignoring K-factor corrections at the present stage, we choose a p_T cutoff factor $f(p_T(Q\bar{Q}), m(Q\bar{Q}))$ such that the sum of the $2 \to 3$ cross sections folded with parton densities reproduces the $2 \to 2$ folded cross sections at each $m(Q\bar{Q})$,

$$\sum \int f\sigma(2 \to 3) = \sum \sigma(2 \to 2). \tag{2}$$

Choosing a Gaussian dependence for the cutoff, we determine

$$\begin{aligned} f(p_T, m) &= 1 - \exp(-0.5p_T^2) \quad \text{for } c\bar{c}, \\ &= 1 - \exp\left[-\left(0.35 + \frac{4.2}{m}\right)^2 p_T^2\right] \quad \text{for } b\bar{b}. \end{aligned} \tag{3}$$

The primary heavy-quark fragmentation is described by the Peterson *et al.* form[10] with parameter $\epsilon_P = 0.5/m_Q^2$; other aspects of the fragmentation and $V - A$ decays follow Ref. 2.

An approximate separation of different dimuon sources is made by muon isolation. Following the procedure of the UA1 Collaboration, the hadronic p_T is summed within cones $\Delta R = [(\Delta\phi)^2 + (\Delta\eta)^2]^{1/2} < 0.7$ around each muon and an isolation parameter $s = \{(\sum_1 p_T)^2 + (\sum_2 p_T)^2\}^{1/2}$ is defined, where subscripts

1 and 2 refer to cones about muons 1 and 2. Dimuon events with $s < 3$ GeV are "isolated," and those with $s > 3$ GeV are "nonisolated." In our calculations we sum the p_T of partons within these cones and add a soft-hadron contribution from the underlying event, assumed to have Gaussian distribution with $\sigma = 1.5$ GeV (which fits the hadronic p_T around the muons in the UA1 data[1] on $W \rightarrow \mu\nu$ and $Z \rightarrow \mu\mu$, as well as minimum-bias events). We impose the most recent UA1 acceptance cuts, $p_T(\mu) > 3$ GeV, $|\eta(\mu)| < 2$, and $m(\mu\mu) > 6$ GeV.

Table I gives the predicted cross sections from the various sources at $\sqrt{s} = 630$ GeV, with the assumption of no B^0-$\bar{B}^0$ mixing. The Drell-Yan (DY) cross section is evaluated with the truncated shower prescription (including the K factor given above with α_s evaluated at $Q^2 = m^2$) with a cutoff factor found to be

$$f(p_T, m) = 1 - \exp[-(0.72 + 0.57/m)^2 p_T^2].$$

The Υ contribution is deduced empirically from the data; after including an estimated acceptance factor 0.35 we find it to be $B_{\mu\mu}\sigma(\Upsilon + \Upsilon' + \Upsilon'') = 100$ pb with an assumed ratio $B\sigma(\Upsilon) : B\sigma(\Upsilon') : B\sigma(\Upsilon'') = 1:0.3:0.15$ and a mass resolution $\delta m/m = 5\%$. Because of underlying-event contributions, about 14% of the DY and Υ events are expected to be nonisolated. Essentially no isolated $c\bar{c}$ events are predicted. To compare with the UA1 data we multiply by integrated luminosities of 0.108 pb^{-1} at $\sqrt{s} = 540$ GeV (with appropriately scaled-down cross sections) plus 0.270 pb^{-1} at $\sqrt{s} = 630$, and also multiply by reported geometry and track acceptance factors, 0.45×0.58. Table I compares the results with preliminary UA1 event rates.[1] For + − (unlike-sign) events, both isolated and nonisolated, the predicted rates agree remarkably well with experiment, especially considering the uncertainties in the overall theoretical normalization coming from K factors, Λ_{QCD}, argument of α_s, number of active flavors, and fragmentation. For ± ± (like-sign) events, however, the predicted event rates are substantially below the data in both isolation categories; this discrepancy cannot be attributed to normalization in view of the + − agreement and therefore suggests the possibility of B^0-$\bar{B}^0$ mixing effects.

TABLE I. Dimuon cross sections (no B^0-$\bar{B}^0$ mixing) and rates for nonisolated (NI) and isolated (I) events.

Category		$\sigma(\sqrt{s} = 630)$ (pb)	Predicted events	UA1 events
+ − NI	$b\bar{b}$	980	92	
	$c\bar{c}$	380	36 } 134	106
	DY + Υ	60	6	
± ± NI	$b\bar{b}$	340	32	55
+ − I	$b\bar{b}$	85	8	
	DY	300	29 } 45	44
	Υ	85	8	
± ± I	$b\bar{b}$	3	0.3	7

The mixing parameter ϵ_s is the fractional probability for $B^0(b\bar{s}) \rightarrow \bar{B}^0(\bar{b}s)$ decay transitions, and similarly ϵ_d describes $B^0(b\bar{d})$ mixing. In the standard model the value of the mixing parameter depends on the product $Bf_B^2 m_t^2 U_{t(s,d)}^2$, where B is the deviation from the vacuum saturation approximation, f_B is the B-decay constant, m_t is the t-quark mass, and U is the weak-current matrix element (see, e.g., Ref. 2 and the work of Pakvasa[11]). A recent determination[12] of f_B finds $f_B < f_\pi$, in which case $Bf_B^2 \lesssim 0.02$ is expected. For $m_t = 40$ GeV this corresponds to mixing parameters $\epsilon_s \lesssim 0.25$ and $\epsilon_d << \epsilon_s$. If we ignore b-baryon production and assume meson production with semileptonic decay to contribute in the ratio $b\bar{u}:b\bar{d}:b\bar{s} = 1:1:0.5$, the overall probability for a single B to give a wrong-sign muon through mixing is $\epsilon = 0.4\epsilon_d + 0.2\epsilon_s \lesssim 0.05$. From dimuons produced in high-energy e^+e^- collisions, Schoad *et al.*[13] have set an upper bound of $\epsilon \leqslant 0.12$ (90% C.L.) for B^0-$\bar{B}^0$ mixing. The predicted dimuon rates with mixing can be easily obtained from those without mixing, from formulas given in Ref. 2.

Table II shows the effects of mixing on the event rates for dimuons coming from $b\bar{b}$ and $c\bar{c}$. Mixing of

TABLE II. B^0-$\bar{B}^0$ mixing effects for nonisolated (NI) and isolated (I) dimuons.

Category	$\epsilon = 0$	$\epsilon = 0.1$	$\epsilon = 0.2$	Preliminary UA1 data
+ − NI events	134	123	115	106 ± 11
± ± NI events	32	42	51	55 ± 8
(± ±)/(+ −) ratio	0.24	0.34	0.44	0.46 ± 0.10 > 0.30 (90% C.L.)
+ − I events	45	44	43	44 ± 7
± ± I events	0.3	1.7	2.7	7 ± 3

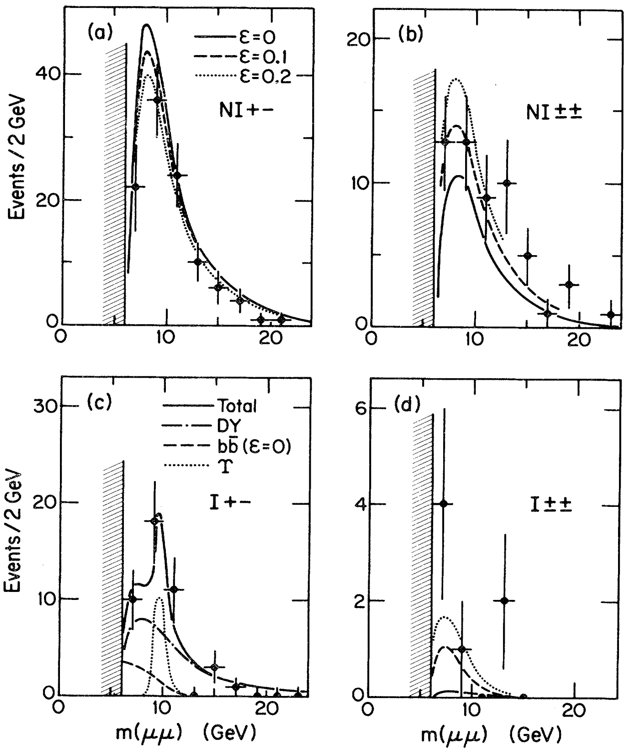

FIG. 1. Event rates vs dimuon mass for (a) + − NI (nonisolated) events, (b) ± ± NI events, (c) + − I (isolated) events, and (d) ± ± I events. Theoretical predictions are compared with preliminary UA1 dimuon data from Ref. 1. In (a), (b), and (d) the effects of B^0-$\bar{B}^0$ mixing are shown for $\epsilon=0$ (solid curves), $\epsilon=0.1$ (dashed curves), and $\epsilon=0.2$ (dotted curves). In (c) the mixing effects are small and we show the contributions from DY (dash-dotted curve, $b\bar{b}$ with $\epsilon=0$ (dashed curve), and $\Upsilon+\Upsilon'+\Upsilon''$ (dotted curve); the solid curve gives the total.

order $\epsilon=0.1$ brings the predictions into closer accord with the preliminary UA1 data. The experimental value of the (± ±)/(+ −) ratio includes a background subtraction and an estimate of systematic errors.

Figure 1 compares the predicted dimuon mass distributions with preliminary UA1 data, again for $\epsilon=0$, 0.1, and 0.2. The principal effect of mixing is to change the normalization of the like-sign dimuon distributions. The presence of two isolated ± ± events in the 12–14 GeV mass bin is not easily explained by mixing, however.

The input parameter to which the (± ±)/(+ −) ratio is likely most sensitive is the Peterson *et al.* fragmentation parameter. If we double this to $\epsilon_P=1.0/m_Q^2$ instead, the $b\bar{b}$ rates change little (because with large m_b the fragmentation is still concentrated near $z=1$) but the $c\bar{c}$ rates fall by 25%, reducing the + − dimuons. With zero B^0-$\bar{B}^0$ mixing, the predicted ratio for nonisolated dimuons rises from 0.25 to 0.27 and the discrepancy with the data remains.

To conclude, our QCD calculations of dimuons from $b\bar{b}$ and $c\bar{c}$ sources are in broad accord with UA1 results, provided that there is B^0-$\bar{B}^0$ mixing of order $\epsilon \gtrsim 0.1$, which is close to the Mark II Collaboration upper limit and above standard-model expectations. This success of the truncated shower approximation, especially in explaining the shapes of the distributions, suggests that it should also be applicable to other heavy-quark phenomena including $t\bar{t}$ production.

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[1] C. Rubbia (UA1 Collaboration), in Proceedings of the 1985 International Symposium on Lepton and Photon Interactions at High Energies, Kyoto, Japan, August 1985 (to be published); J. Rohlf, in Proceedings of the 1985 Annual Meeting of the Division of Particles and Fields of the American Physical Society, Eugene, Oregon, August 1985 (to be published); K. Eggert, in Proceedings of the New Particles '85 Conference, Madison, Wisconsin, May 1985 (to be published); G Arnison *et al,.,* Phys. Lett. **155B**, 442 (1985).

[2] V. Barger and R. J. N. Phillips, Phys. Lett. **143B**, 259 (1984), and Phys. Rev. D **32**, 1128 (1985).

[3] A. Ali and C. Jarlskog, Phys. Lett. **144B**, 266 (1984).

[4] A. Ali, in *Proceedings of the International Symposium on Physics of Proton-Antiproton Collision,* edited by Y. Shimizu and K. Takikawa (KEK, Tsukuba, Japan, 1985), p. 456; R. Van Eijk, in Proceedings of the New Particles '85 Conference, Madison, Wisconsin, May 1985 (to be published).

[5] F. Halzen and P. Hoyer, Phys. Lett. **154B**, 324 (1985).

[6] V. Barger and R. J. N. Phillips (unpublished), reported by V. Barger, in Proceedings of the 1985 Annual Meeting of the Division of Particles and Fields of the American Physical Society, Eugene, Oregon, August 1985 (to be published), and in Proceedings of the Tenth Hawaii Conference on High Energy Physics, University of Hawaii, Honolulu, Hawaii, August 1985 (to be published); F. E. Paige (private communication) has independently used a similar approximation to *W* production.

[7] G. Altarelli, R. K. Ellis, and G. Martinelli, Nucl. Phys. **B157**, 461 (1979); J. Kubar-André and F. Paige, Phys. Rev. D **19**, 221 (1979); J. Abad and B. Humpert, Phys. Lett. **78B**, 627 (1978).

[8] V. Barger, T. Gottschalk, J. Ohnemus, and R. J. N. Phillips, University of Wisconsin Report No. MAD/PH/247, 1985 (unpublished).

[9] F. E. Paige and T. Gottschalk, in Proceedings of the 1985 Annual Meeting of the Division of Particles and Fields of the American Physical Society, Eugene, Oregon, August 1985 (to be published); T. Sjöstrand, private communication; R. Odorico, Nucl. Phys. **B228**, 331 (1983), and Phys. Rev. D **31**, 49 (1985).

[10] C. Peterson, D. Schletter, I. Schmitt, and P. M. Zerwas, Phys. Rev. D **27**, 105 (1983).

[11] S. Pakvasa, Phys. Rev. D **28**, 2915 (1983).

[12] M. Suzuki, Lawrence Berkeley Laboratory Report No. 19983, 1985 (unpublished). See also M. Claudson, Harvard University Report No. HUTP-81/A016 (unpublished); E. Golowich, Phys. Lett. **91B**, 271 (1980).

[13] T. Schaad *et al.* (Mark II Collaboration), Phys. Lett. **160B**, 188 (1985); see also W. Bartel *et al.*, Phys. Lett. **146B**, 437 (1984).