HEAVY PARTICLE PRODUCTION AND LIFETIMES

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Conclusions And Overview

The following conclusions were reached by the members of the group.

1. Expected event rates for B-meson or baryon production in hadron beams at Tevatron energies should allow for the measurement of the lifetimes of these short-lived particles (expected in the range of 10^{-14} sec to 10^{-13} sec). One will further be able to obtain cross-section estimates and possibly construct a few final states.

2. The photoproduction of $b\bar{b}$, $c\bar{c}$ pairs can be done with the Tevatron. Another tantalizing possibility is the Primakoff production of η_c and η_b along with a small Υ signal. Pair production of $\tau^+\tau^-$ will allow a study of the lifetime and couplings of the τ. Because of the large charm cross sections a more careful study of the elastic and inelastic ψ production and open charm production can be done. These will provide stringent tests on existing theory for production mechanisms.

3. Charm cross sections in hadron beams will produce a large sample of charmed particles which can be detected with little background in a vertex detector with a good spatial resolution. A careful study of the production mechanisms of charm can be done with reconstruction of final states, leading to good measurement of branching ratios at the 1 per cent level. Physical parameters of charmed particles such as spin, magnetic moments, etc. may possibly be measured. It is likely that Tevatron energies may be necessary to study Λ_c^+ and F^+ decay modes.

4. The kind of physics outlined in the above will require new types of detectors. For the optimum physics the detectors will require two crucial properties: good spatial resolution at the vertex ($\lesssim$ 5 microns), an event acceptance of 10% or greater including efficiency. Such properties have not yet been achieved but are expected to become available in the future. Further

required properties are good particle identification for both charged and neutral particles, good trigger rejection ratio (10^{-4} or better), and capability for handling large multiplicity.

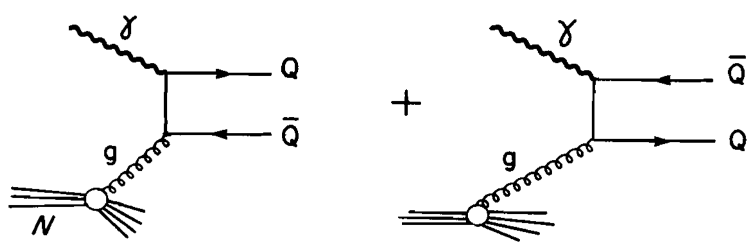
A more modest enterprise which can readily be achieved could be not to insist on total reconstruction of events but to study semi-inclusive processes, overall rates, and lifetimes. The value of this more modest goal should not be minimized.

I.A. CROSS-SECTION ESTIMATES

In this subsection we shall present cross-section estimates for production of charmed and bottom particles in photon, muon, and hadron beams. In each case we have selected various estimates in the literature. We shall also give a few details about the theoretical assumptions used to obtain these cross sections. For clarity we treat the various beams separately.

1. Photon Beams and Muon Beams

We shall use the photon-gluon fusion[1] ($\gamma\lambda$) model which has correctly predicted cross sections for Ψ photo and muon production at present energies. The relevant diagrams are



The cross sections for real photoproduction are shown in Fig. 1. The "naive" gluon-fusion model curves are obtained as follows: The gluon distribution function is the counting rule distribution $G(\eta) = 3(1-\eta)^5/\eta$; the strong coupling constant is $\alpha_s \simeq 1.5/\ln(4m_Q^2)$ with m_Q the heavy quark mass ($m_c = 1.5$ GeV, $m_b = 4.5$ GeV was assumed). For the production of $\Psi(\Upsilon)$, semi-local duality was assumed, i.e., the cross section is obtained by restricting the invariant mass of the $c\bar{c}$ ($b\bar{b}$) pair from the threshold $4m_c^2$ ($4m_b^2$) to the continuum $4m_D^2$ ($4m_B^2$) and dividing by the number of resonances in that mass interval N = 8 (N = 18). The curves labelled Gluck-Reya are from Ref. 2. We also show the predictions of Margolis et al.[3] We refer to the original papers for details of these latter calculations.

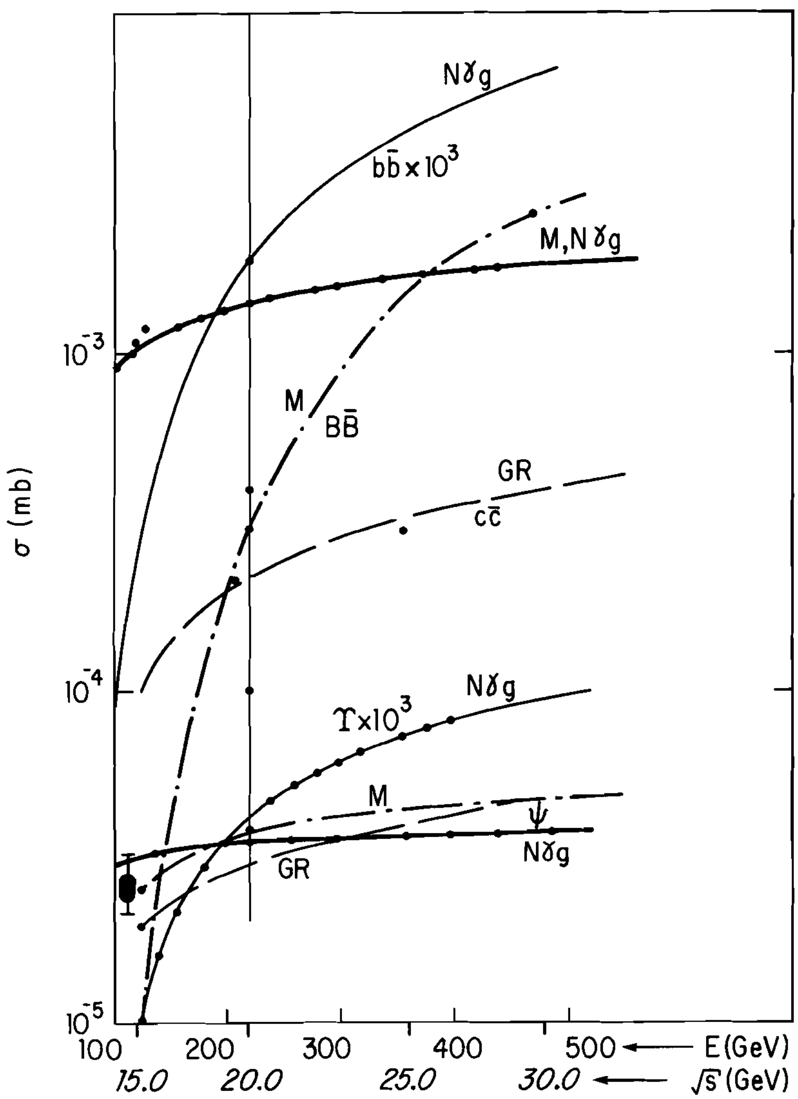


Fig. 1(a). Photon cross sections: M = Margolis et al., Nγg = Naive γg fusion, GR = Gluck-Reya.

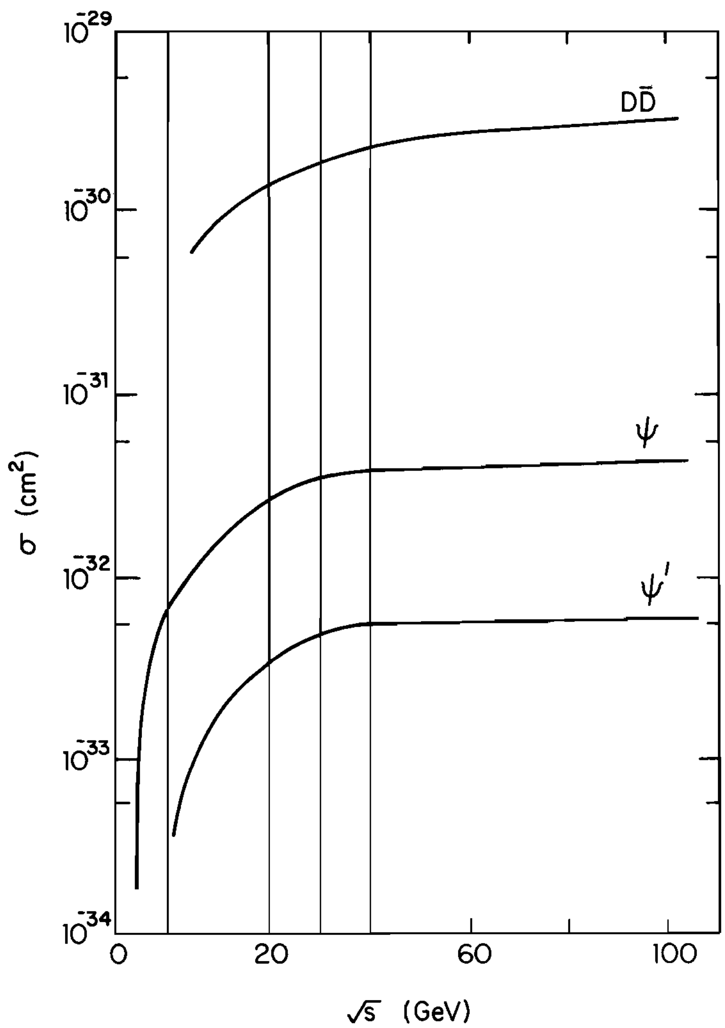


Fig. 1b, from Ref. 3. The curves labeled ψ and ψ' represent predictions for ψ (3.1) and ψ' (3.685) production cross sections in photon- proton interaction as a function of $(s)^{1/2}$. These results are obtained using (see text and Ref. 1) $\xi =$ 0.42 GeV, m_c = 0.15 GeV, N = 0.2. The curve labeled $D\bar{D}$ corresponds to the DD production cross section in photon-proton interaction evaluated in QCD with m_c = 1.2 GeV.

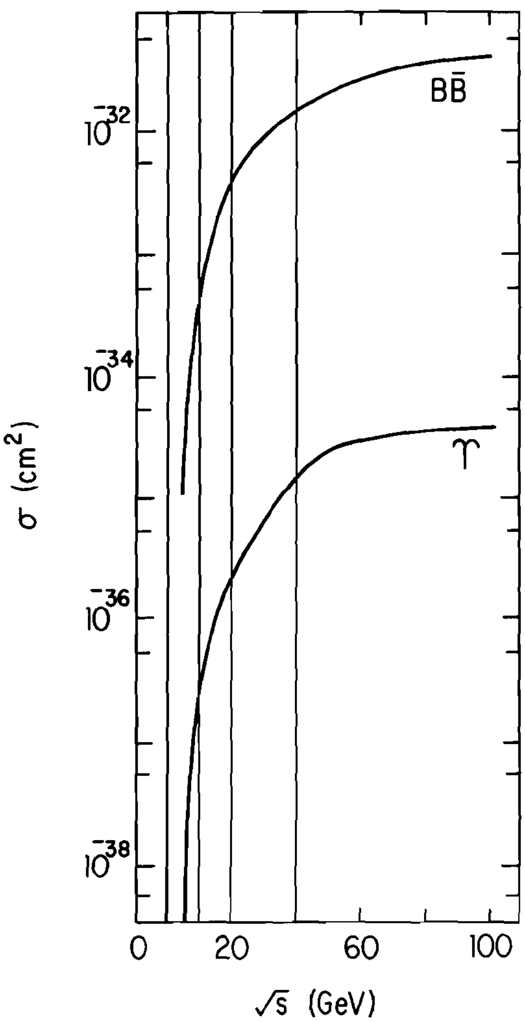


Fig. 1(c), from Ref. 3. The curve labeled Υ represents predictions for Υ^1 (9.46) production cross section in photon-proton interaction as a function of $(s)^{1/2}$. This result is obtained using $\xi = 0.8$ GeV, $m_b = 4$ GeV, $T = 0.15$ GeV, $N = 0.02$, and $\sigma_{qb} \simeq m_c^2/m_b^2 \sigma_{qc}$ (see text and Ref. 1). The curve labeled $B\bar{B}$ represents the $B\bar{B}$ production cross section in photon-proton interaction evaluated in QCD with $m_b = 4$ GeV.

For a nominal photon energy of 300 GeV we have the following cross sections:

$\sigma^{\gamma}(c\bar{c})$ = 1-2 μb Naive γg
~ 2 μb Margolis et al.

$\sigma^{\gamma}(\psi)$ = ~ 40 nb Naive γg
~ 30 nb Margolis et al.

$\sigma^{\gamma}(b\bar{b})$ = ~ 3 nb Naive γg
~ 1-2 nb Margolis et al.

$\sigma^{\gamma}(\Upsilon)$ = ~ 5×10^{-2} nb Naive γg
~ 5×10^{-3} nb Margolis et al.

Figure 2 shows similar cross section in muonproduction as a function of the muon energy. These results are on naive γg fusion and are from Ref. 1.

2. Hadron Beams

All cross section estimates are based on the extension of fusion models to hadro-production.[4] In this model $q\bar{q}$ pairs and gluon pairs from the interacting hadrons collide and form a pair of heavy quarks. At the energies considered, the annihilation of gluons dominates the cross sections. Therefore the results are the same for proton and neutron beams. Similar results should be obtained for π and K beams. The results of the various calculations are shown in Fig. 3. We summarize the cross section for $(s)^{1/2}$ = 43 GeV.

$\sigma^{pp}(c\bar{c})$	=	10-20 μb	Naive gg = $q\bar{q}$[5]
		4-5 μb	Gluck-Reya[4]
		20 μb	Margolis et al.[4]
$\sigma^{pp}(b\bar{b})$	=	10-20 nb	Ref. 5
		40-50 nb	Margolis et al.
$\sigma^{pp}(\psi)$	≈	0.5 μb	Margolis et al.
$\sigma^{pp}(\Upsilon)$	≈	5×10^{-2} nb	Margolis et al.

A comment should be made immediately about the estimates. While the threshold effects have disappeared at the energy considered for charm production, the bb and Υ cross sections are still rising sharply. Hence the $c\bar{c}$ and ψ cross sections can be safely predicted (to within a factor of 2 or so) while large

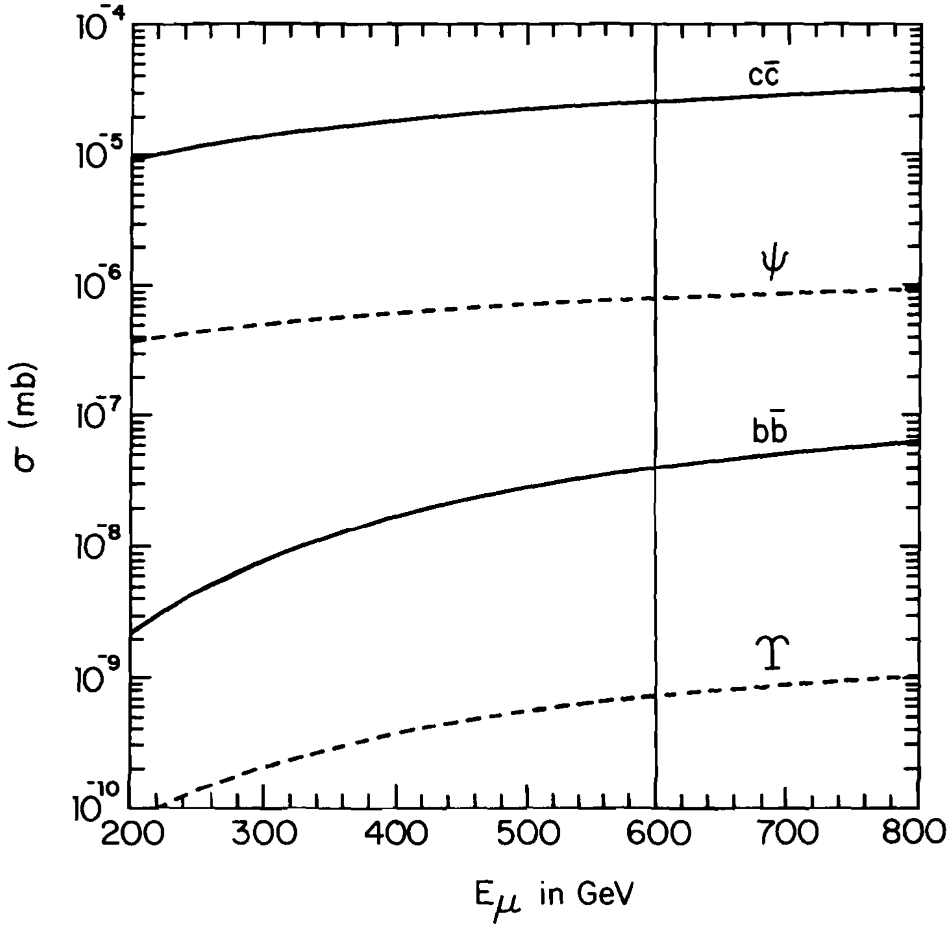


Fig. 2, from Ref. 1. Cross section estimates for muon beams.

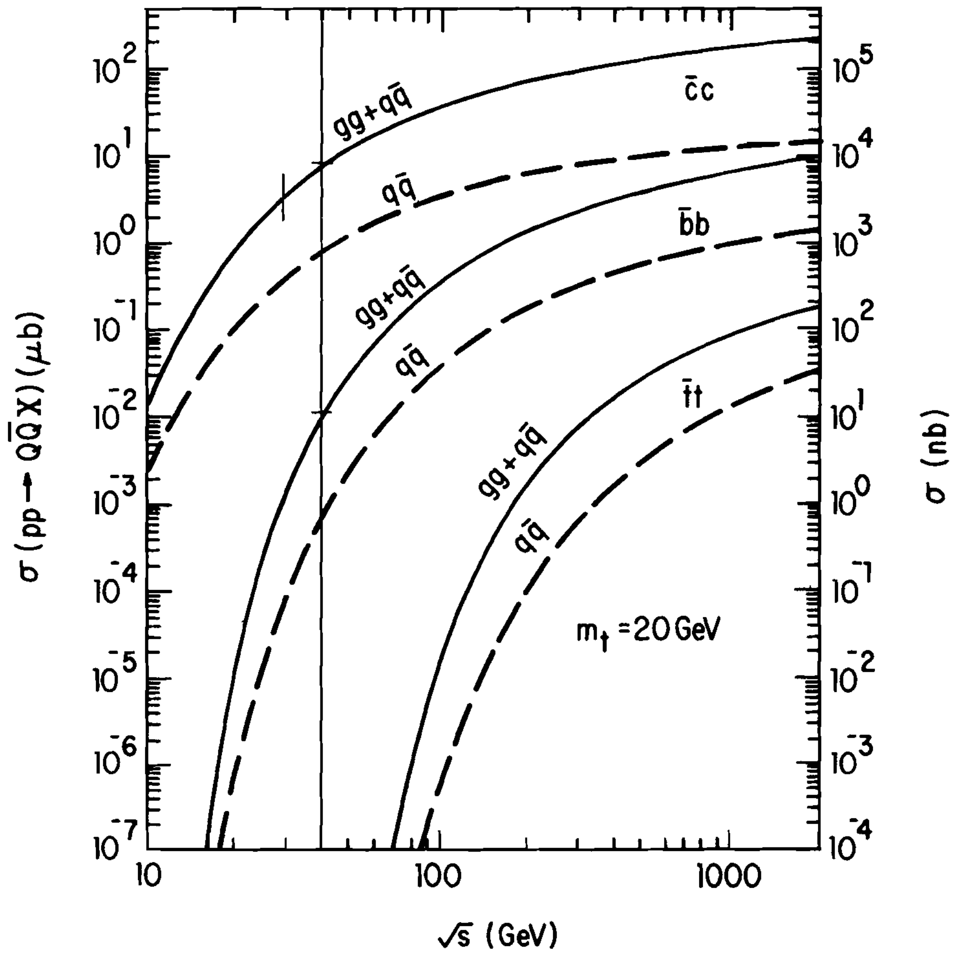


Fig. 3(a). Cross section estimates from naive fusion models (Ref. 5).

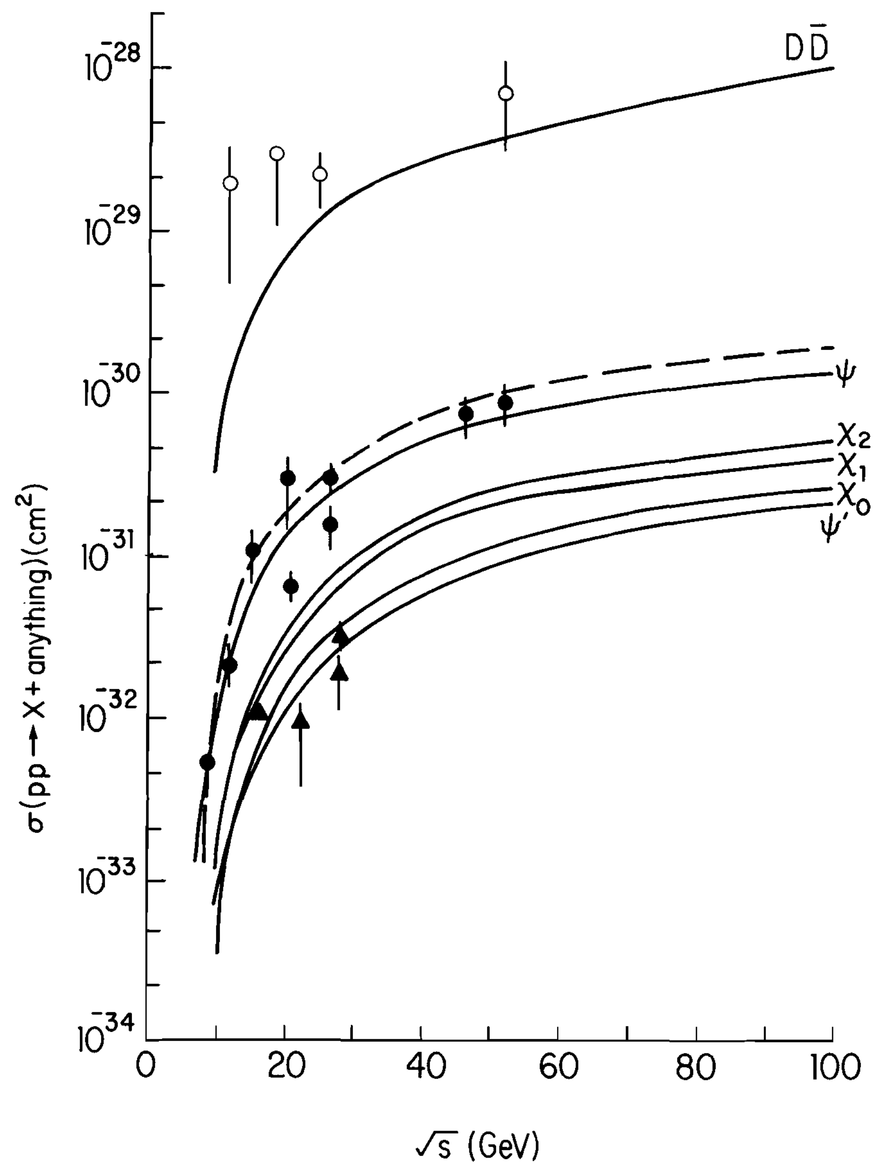


Fig. 3(b). From Ref. 3.

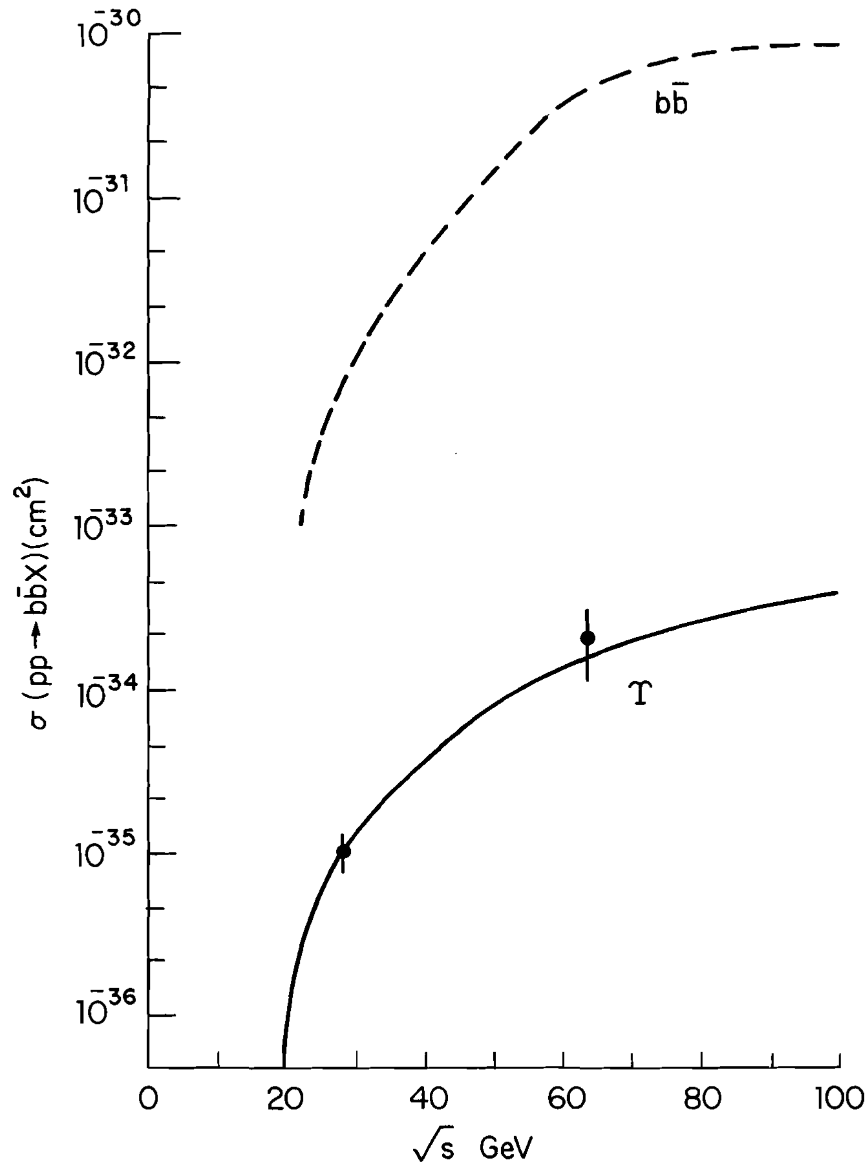


Fig. 3(c). From Ref. 3.

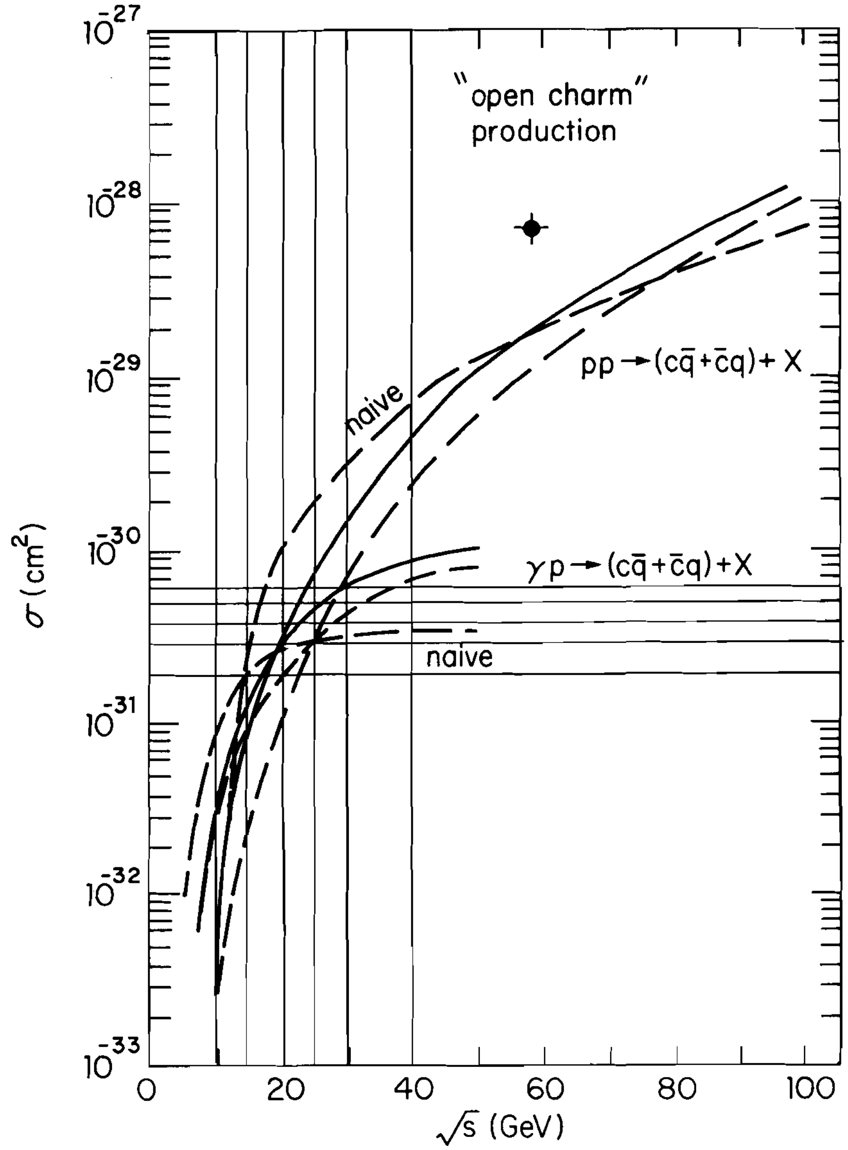


Fig. 3(d). "Open" charm production in proton and photon beams.

differences will appear in the various theoretical predictions for bottom production. In this respect the cross sections obtained from the naive models should be considered optimal. Caution should be applied when using any prediction so close to the threshold. Our experience in charm revealed that the naive models predicted a slower rise than the observed data.

References

1. See e.g. J. P. Leveille in the **Proceedings of the Topical Workshop on the Production of New Particles in Super-High Energy Collisions**, Madison, WI, 1979 and references therein.

2. M. Gluck and E. Reya, Phys. Lett, **79B** 453, (1978); Phys. Lett. **83B**, 98, (1978).

3. B. Margolis et al., Phys. Rev. **D22**, 86, 93 (1980).

4. See, e.g., E. Reya, Perturbative Quantum Chromodynamics, DESY Preprint 79/88, December 1979, and references therein. See also Margolis et al., Ref. 3.

5. Y. Keung, private communication.

I.B. LIFETIME OF HEAVY PARTICLES

Within the last year measurements of charmed particle lifetimes[1] have surprised the theoretical community. The theoretical picture for heavy particle decays had previously followed the conventional dogma: heavy particle decay = heavy quark decay. The other constituent quarks in the charmed mesons or baryons were mere spectators to the decay (the spectator model). Experiments however reveal

$$\tau\,(D^+) \simeq 10.3\,^{+10.5}_{-\,4.1} \times 10^{-13}\ \text{sec}$$

$$\tau(D^0) \simeq 1.0\,^{+0.45}_{-0.28} \times 10^{-13}\ \text{sec}$$

$$\tau(\Lambda_c^+) \simeq 1.14\,^{+0.62}_{-0.36} \times 10^{-13}\ \text{sec}$$

$$\tau(F^+) \simeq 2.2\,^{+\,2.8}_{-\,1.0} \times 10^{-13}\ \text{sec}$$

It was recently discovered[2] that gluon interactions can explain these effects. Indeed although annihilation diagrams for 0^- decays are helicity suppressed (i.e., suppressed by powers of the light quark masses just like $\pi^+ \to e^+\nu_e$ is suppressed relative to

$\pi^+ \rightarrow \mu^+ \nu_\mu$), radiation of a gluon before the interaction allows the constituents to interact in a spin one state thereby avoiding the helicity suppression. This is illustrated in Fig. 1, for the D_0 case.

helicity suppressed — Non-helicity suppressed

Fig. 1

For the case of the Λ_c^+ non-spectator annihilation diagrams[3] also increase the decay rate as shown in Fig. 2.

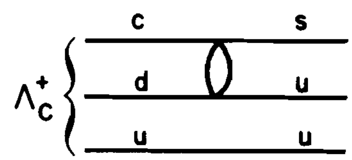


Fig. 2.

Non-helicity suppressed non-spectator contributions of Λ_c^+ decay

The gluon enhanced contributions in the meson case and the diagram of Fig.2 in the Λ_c^+ case give rates which are comparable to the spectator rate, or larger than the latter. One can easily account[4] for the observed lifetime pattern (although **exact** calculations are difficult).

$$\tau(D^+) \gg \tau(F^+) > \tau(D^0)$$

$$\tau(D^+) \gg \tau(\Lambda_c^+).$$

It is expected that the D^+ lifetime will be well studied before the fixed-target Tevatron era, but one may easily be convinced that the F^+, D^0, and Λ_c^+ lifetimes will not be easily measured at other existing machines. Solid state detectors, vertex detectors, or mini-bubble chambers could help the situation tremendously at the Tevatron due to the large rates expected (see later).

Of much more interest for the Tevatron program is the measurement of B particle lifetimes. The current theoretical estimates are surely uncertain but it has been argued that this ambiguity is small. A calculation in the one gluon model gives the lifetime predictions

$$\begin{aligned}
\Gamma(B_d) &= \gamma_b^{-1}[10.4|U_{bu}|^2 + 5|U_{bc}|^2] \\
\Gamma(B_s) &= \gamma_b^{-1}[8.7|U_{bu}|^2 + 3.8|U_{bc}|^2] \\
\Gamma(B_u) &= \gamma_b^{-1}[9.7|U_{bu}|^2 + 3.1|U_{bc}|^2] \\
\Gamma(B_c) &= \gamma_b^{-1}[7.7|U_{bu}|^2 + 5.2|U_{bc}|^2],
\end{aligned} \tag{1}$$

where $\gamma_b = 192\ \pi^3/G_F^2\ m_b^5 \approx .16 \times 10^{-13}$ sec, and where U_{bu} (U_{bc}) are the $b \to u$ and $b \to c$ KM parameters. The assumptions implicit in the derivation of Eq. 1 as follows: Total rates are obtained from parton diagrams integrating over parton phase space. The quark masses used in the phase space were: $m_b = 4.5$ GeV, $m_c = 1.5$ GeV, $m_u = m_d = m_s = 0$. For annihilation diagrams, $f_{Bc} = f_{Bd} = \frac{1}{2}$ GeV, $\alpha_s = 0.34$.

The rates in Eq. (1) should be compared with rates from the spectator picture, where all B mesons and baryons have the same lifetime

$$\Gamma(B) = \gamma_b^{-1}[7.7|U_{bu}|^2 + 3.1|U_{bc}|^2]. \tag{2}$$

We see that annihilation contributions and gluon corrections have not drastically modified the spectator prediction. The main reason for this fact is numerical suppression of gluon-enhanced diagrams by color and strong correction factors.[5]

For numerical estimate of the lifetimes of B mesons we can therefore use Eq. (2). The remaining ambiguity is in the KM parameters U_{bu}, U_{bc}. These parameters are constrained however by a theoretical analysis of the K_L-K_S system.[6] For all allowed values of the mixing angles, we find the important result

$$10^{-14}\ \text{sec} < \tau(B) \lesssim 5 \times 10^{-13}\ \text{sec}. \tag{3}$$

As will be described in the sequel, lifetimes of this magnitude can in principle be measured at Tevatron energies.

References

1. See, e.g., J. Trischuk, **Proceedings of the XVth Recontre de Moriond**, Les Arcs, France, 1980.

2. M. Bander, D. Silverman, A. Soni, Phys. Rev. Lett. **44**, 4 (1980) and H. Fritszch and P. Minkowski, Phys. Lett., **90B**, 455 1980. (E). V. Barger, R. N. Cahn, Y. Kang, J. P. Leveille, S. Pakvasa, M. Suzuki (unpublished).

3. V. Barger, J. P. Leveille, and P. M. Stevenson Phys. Rev. Lett. **44**, 226 (1980).

4. See, e.g., V. Barger, J. P. Leveille, and P. M. Stevenson, Phys. Rev. **D22**, 693 (1980).

5. See, e.g., J. P. Leveille, Invited talk at the XXth International Conference on High Energy Physics, Madison, Wisconsin.

6. V. Barger, W. F. Long, and S. Pakvasa, Phys. Rev. Lett. **42**, 1585 (1979); R. E. Shrock, S. B. Treiman, and L. L. Wang, Phys. Rev. Lett. **42**, 1589 (1979).

I.C. BRANCHING RATIOS FOR B DECAYS

We estimate various branching ratios for B mesons. The parton model with strong corrections are assumed along with the one gluon model as described in the section of B meson lifetimes. Since we expect that B_s and B_c will be harder to produce than B_u and B_d (production of $s\bar{s}$ and $c\bar{c}$ pair along with the $b\bar{b}$ pair should reduce the production rate by roughly one and two orders of magnitude respectively) we only concentrate on the latter two mesons. All our results (see Tables I and II) will be expressed in terms of the KM mixing angles $|U_{bu}|$ and $|U_{bc}|$. The absolute width will be given exactly along with the limit $|U_{bu}| = 0$. We note that the latter limit is only given for pedagogical purposes, since although $b \to c$ transitions will dominate, a small $b \to u$ (say $b \to u \simeq \frac{1}{2} - \frac{1}{4}\, b \to c$) is not presently ruled out by CESR data. We also give the same branching ratios for $b \to u = \frac{1}{2}\, b \to c$ for comparisons. The absolute width is taken from the one gluon model given in the lifetime section. Finally, we have attempted to give an idea of the various final states that evolve from the parton states. It should be remembered that present electron-positron annihilation data indicate an average multiplicity of six charged particles per B meson.

Neutral B Meson $B_d \equiv (b\bar{d})$ $|U_{bu}|^2 \equiv u^2$ $|U_{bc}|^2 \equiv c^2$

Parton Final State	Width Units of $G_F{}^2 m^5{}_b/192\pi^3$	Branching Ratio (%) with $\lvert U_{bu}\rvert=0$,	and $u^2=c^2/4$	Expected Hadrons
$ce^- \bar{\nu}_e$	$0.45c^2$	9%	6%	D+ pions
$c\mu^- \bar{\nu}_\mu$	$0.45c^2$	9%	6%	K+ pions +
$c\tau^- \bar{\nu}_c$	$0.06c^2$	1%	1%	leptons
$ue^- \bar{\nu}_e$	u^2	0	3%	pions + leptons
$u\mu^- \bar{\nu}_\mu$	u^2	0	3%	
$u\tau^- \bar{\nu}_\tau$	$0.32u^2$	0	1%	
$u\,\bar{u}\,d$	$3.52u^2$	0	12%	pions
$u\,\bar{u}\,s$	$0.19u^2$	0	1%	π's,K
$u\,\bar{c}\,s$	$1.58u^2$	0	5%	π's,K's,D
$u\,\bar{c}\,d$	$0.08u^2$	0	2×10^{-3}	π's,D
$c\,\bar{u}\,d$	$1.58u^2$	34%	21%	D,π's
$c\,u\,s$	$0.08c^2$	2%	1%	D,K,π's
$c\,\bar{c}\,s$	$0.42c^2$	8%	6%	D,D̄,K,ψ(?)
$c\,\bar{c}\,s$	$0.02c^2$	0.4%	3×10^{-3}	D,D̄,π's
$u\,\bar{c}$	$10^{-5}u^2$	0	0	D,π's
$c\,\bar{u}$	$2.5 \times 10^{-4}c^2$	≈0	0	D,π
$c\,\bar{c}$	$2.5 \times 10^{-5}c^2$	≈0	0	D's,π's
$u\,\bar{u}\,g$	$2.77u^2$	0	9%	π's
$u\,\bar{c}\,g$	$0.10u^2$	0	3×10^{-3}	D,π's
$c\,\bar{u}\,g$	$1.92c^2$	39%	25%	D,π's
$c\,\bar{c}\,g$	$0.06c^2$	1%	1%	D's,π's,K's

Charged B Meson $B_u \equiv (b\bar{u})$ $|U_{bu}|^2 \equiv u^2$
$|U_{bc}|^2 = c^2$

Parton Final State	Width Units of $G^2_F m^5_b/192\pi^3$	Branching Ratio with $U^2 = 0$, and $u^2 = c^2/4$		Hadronic Final States
$ce^- \bar{\nu}_e$	$0.45c^2$	15%	8%	D, Leptons, π's
$c\mu^- \bar{\nu}_\mu$	$0.45c^2$	15%	8%	D, Leptons, π's
$c\tau^- \bar{\nu}_\tau$	$0.06c^2$	2%	1%	D, Leptons, π's
$ue^- \bar{\nu}_e$	u^2		5%	π's, Leptons
$u\mu^- \bar{\nu}_\mu$	u^2	0	5%	π's, Leptons
$u\tau^- \nu_\tau$	$0.32u^2$		1%	π's, Leptons
$u \bar{u} d$	$3.52u^2$		16%	π's
$u \bar{u} s$	$0.19u^2$	0	1%	π's, K
$u \bar{c} s$	$1.58u^2$		7%	π's, K, D
$u \bar{c} d$	$0.08u^2$		~0%	π's, D
$c \bar{u} d$	$1.58c^2$	51%	29%	D, π's
$c \bar{u} s$	$0.08c^2$	3%	1%	D, π's, K
$c \bar{c} s$	$0.42c^2$	14%	8%	D, $\bar{D}$, K
$c \bar{c} d$	$0.02c^2$	1%	~0%	D, $\bar{D}$, π's
$\tau^- \bar{\nu}_\tau$	$0.42u^2$		2%	τ^-, $\bar{\nu}_\tau$
$\bar{c}$ d	$0.05u^2$	0	~0%	π's, $\bar{D}$
c^- s	$1.02u^2$		5%	K, D, π's
$d \bar{u} g$	$0.27u^2$		1%	π's, (K)
$d \bar{c} g$	$0.01u^2$	0	0%	π's, D
$s \bar{c} g$	$0.19u^2$		1%	K, D, π's
$s \bar{u} g$	$0.01u^2$		0%	K, π's

I.D. PHOTOPRODUCTION AT THE TEVATRON

The higher energy photon beams that will be available at the Tevatron allow one to do very high statistics studies of "charm" and begin to study b-quarks. Photon beams are especially useful for these studies because, in the photon, $c\bar{c}$ and $b\bar{b}$ quarks appear as valence quarks. The heavy quark signal is a factor of 10 higher relative to the total interaction rate than it is in hadron beams. Topics that can be studied at the Tevatron are:

1) Charm and b spectroscopy, lifetimes, and production mechanisms

2) ψ and Υ photoproduction

3) Primakoff production of η_c and η_b.

4) τ production and τ lifetime (e-μ-τ universality)

5) Jet related issues,[1] QCD Compton, etc.

Typical rates that can be expected for these processes are given below.[2]

1. Photon Beam Rates Charm and Beauty

The broad band beam flux that has been proposed[3] can achieve a photon flux of 7.5×10^6 photons (E_γ > 200 GeV) per 10^{12} incident protons

A typical experiment, E1, might use the equivalent of a 400 cm liquid deuterium target and run at 6×10^{12} incident protons/pulse. The rates at the target obtained in such an experiment are

Y_h (Total hadronic final states) ≈ 15000/minute

Y_c (Total charm final states) ≈ 150/minute ($\sigma_c = 1\mu b$)

Y_b (Total b-quark final state) ≈ 0.15/minute (σ_b = 1 nb, γ-gluon fusion model)

In a 1000 hour exposure, such an experiment would produce at the target

$$Y_c = 9 \times 10^6$$

$$Y_b = 9 \times 10^3.$$

For charm

$$Y_{D^0} \approx 3.6 \times 10^6$$

$$Y_{\Lambda_c} \approx 1.0 \times 10^6 \ .$$

For a decay mode with a branching fraction of 1%

$$Y_{b(D^0)} \approx 3.6 \times 10^4$$

$$Y_{b(\Lambda_c)} \approx 1.0 \times 10^4 \ .$$

The charm yields are sufficient to do precision comparisons with production models as well as to measure lifetimes and rare decay modes.

There is widespread agreement that a track sensitive target or "vertex" detector is necessary to extract b-quark signals from the rather formidable backgrounds. If events can be "tagged" as B events, many sources of background can be eliminated. In addition, useful physics can be done with these detectors even if it proves to be impossible to actually reconstruct complete final states.

For lifetime measurements, the B sample is probably adequate. The expected numbers of B-induced tri-leptons and quadri-leptons are 30 and 5, respectively. The situation with respect to the reconstruction of particular final states is not too promising. A typical branching fraction to some particular final state, $D\pi^n$ or $\psi K\pi$ for example, may be as high as a few per cent. However, the probability of reconstructing the D or ψ may only be of order 10%. The branching fraction into particular final states may therefore be 0.18-0.5%. Thus, of order 10-50 events in a typical reconstructable final state will be produced in such an exposure. Recall that we have not included the effects of acceptances, triggering efficiency, etc., nor have we considered backgrounds. In fact, backgrounds from "direct" charm production may be a severe problem.

One can imagine improving the sensitivity of the photoproduction experiment described above by an order of magnitude by running twice as long, using 2-2 1/2 times as many photons, and perhaps using longer targets or multiple target schemes. This high sensitivity exposure will be referred to as E2. Under these conditions, lifetime and multi-lepton measurements become quite good and the reconstruction of individual final states begins to look possible.

2. ψ and Υ Production

ψ photo-production provides an important test of production models and should be measured accurately at the highest available energies. Inelastic ψ production may be especially interesting. The ψ-nucleon (no additional charged tracks) cross section is ~ 30 nb/nucleon in the 100-GeV range. The cross section times branching ratio into 2 leptons is 4 nb/nucleon. For the experiment described above, assuming a constant cross section,

$$Y_{\psi} > 30/\text{minute},$$

so that 40,000 ψ's $\to \ell\bar{\ell}$ will be produced. The energy dependence can be measured with high statistics up to 500 GeV.

The upsilon rate is expected to be a factor of 1000 lower and the branching fraction into $\ell\bar{\ell}$ is only ~ 4% so that twenty examples of the process

$$\gamma + p \to \Upsilon + p$$
$$\qquad\qquad \hookrightarrow \mu^+\mu^-$$
$$\qquad\qquad\quad e^+e^-$$

can be obtained. This is sufficient to check the γ-gluon fusion model, to get a crude idea of the energy dependence and $p_\perp$ dependence, and to get an estimate of the Υ-nucleon total cross section. In the longer, higher intensity exposure, E2, one could perhaps increase this number by one order of magnitude.

3. Coherent Photoproduction of η_c and η_b in the Coulomb Field (Primakoff Effect)

The cross section for η_c production by this mechanism increases by a factor of 4 for the high-energy photons available at the Tevatron. The width $\Gamma(\eta_c \to \gamma\gamma)$ which gives the strength of this process is not known. Theoretical estimates vary from 300 KeV to 1 KeV. The total integrated cross section on lead taking $\Gamma(\eta_c \to \gamma\gamma)$ = 10 KeV is

$$\sigma_{\eta_c}{}^{coh} = 38 \text{ nb}, \; E_\gamma = 100 \text{ GeV}$$

$$\sigma_{\eta_c}{}^{coh} = 160 \text{ nb}, \; E_\gamma = 250 \text{ GeV}.$$

Assuming a 20% radiation length target one gets

$$Y_{\eta_c} = 1600 \quad (E1)$$

$$Y_{\eta_c} = 16000 \quad (E2).$$

Any final state which is $\gtrsim$ 1% of the total decay rate is potentially accessible. These states may be very hard to study in e^+e^- collisions.

The cross section for η_b production assuming a 10 KeV width into $\gamma\gamma$ is ~ 1 nb. One would only have a chance at seeing the η_b if the width were significantly larger than 10 KeV. This is possible as the width is expected to increase with mass. The final state is obviously going to be complicated.

4. τ production Lifetimes

The cross section for τ production in beryllium has been calculated[4] at 200 GeV to be

$$\sigma_{\gamma \to \tau^+\tau^-} \approx \begin{matrix} 5 \times 10^{-34}\ \text{cm}^2\ \text{(coherent)} \\ 10 \times 10^{-34}\ \text{cm}^2\ \text{(total).} \end{matrix}$$

For the two exposures, E1 and E2, described in section 1, the yields are 0.5 and 5 τ-pairs/hour, respectively. The number of exclusive μ-e events [using B $(\tau \to \mu\nu\nu) \times$ B $(\tau \to e\nu\nu) = 0.032$] is 15 to 300 total. This final state is simple to trigger on and should allow for an accurate measurement of the τ-lifetime. That lifetime, using the measured branching fraction into $\mu\nu\nu$ or $e\nu\nu$ (0.18) and the calculated rate for $\tau \to \ell\nu\nu$ using τ-μ-e universality is 2.3×10^{-13}s. An accurate measurement ofthe τ lifetime is thus an excellent check of τ-μ-e universality of the weak interaction. Other decay modes, e.g., $3\pi\nu$, will also provide good lifetime measurements if suitable triggers can be found. Rare τ decays at the 10^{-4} level may be accessible.

5. Final Comments

Photoproduction yields for B-production are a factor of 10 below those possibly achievable in a hadron beam. The photon beam, however, offers a better ratio of signal to background and a simpler event topology. The production mechanism for charm has been demonstrated to be fast forward pair production, similar to the properties predicted by the γ-gluon fusion model. Hadron-induced events will be much more complicated.

The detectors required to perform these experiments must have very large acceptance and be able to handle very high interaction rates and rates of e^+e^- pairs. The yields are so low that one must attempt to accept and fully reconstruct every possible event. The simplest approach to triggering may be to exploit the large probability for B-events to produce leptons either directly or through "indirect" charm particle decays. Information from track-sensitive detectors may need to be used at the trigger level. Trigger processors--perhaps with track reconstruction capabilities--are inevitable. Major efforts will be required to develop adequate detectors.

References

1. Jets are discussed elsewhere in this report.
2. Yields for charm and b-quarks production are summarized in a concise and useful way in the article "$B\bar{B}$ and $c\bar{c}$ Pair Event Rates for Proton, Photon and Neutron beams at the Tevatron."
3. Fermi National Accelerator Laboratory Internal Report. Rates for the existing broad band beam with 1-TeV protons incident are comparable.
4. Y.-S. Tsai, Rev. Mod. Phys. **46**, 815 (1974).

I.E. NEUTRINO REACTIONS

The main question is what can be done with a high-energy neutrino beam; for definiteness a neutrino energy $E_\nu \simeq 500$ GeV will be assumed. It may not be overly optimistic. It is useful to quote all results relative to the charged current cross section.

(a) t-quark physics

The situation looks rather difficult. There are three possible ways of producing t quarks at these energies. We shall give cross-section estimates and point out the ambiguities and assumptions inherent in deriving these numbers.

I. Ambiguities

- The mass of the t quark is not known although $m_t \gtrsim 19$ GeV or so from Petra results. We will assume $m_t \simeq 20$ GeV.

- The various mixing angles in the KM matrix are unknown although some constraints exist.

We shall use the following bounds for the coupling of the t quarks to d,s,b

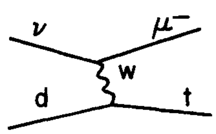
$$|U(\bar{t}d)|^2 = s_1^2,\ s_2^2 < 0.025$$

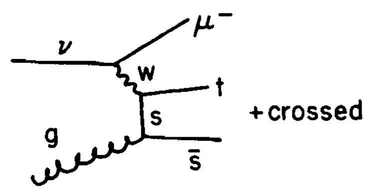
$$|U(\bar{t}s)|^2 < 0.5$$

$$|U(\bar{t}b)|^2 < 1$$

Although all these upper bounds cannot all hold at once[2] we shall use maximal mixing to give numbers. Results are taken from R. J. N. Phillips, Nucl. Phys. **159B**, 418 (1979). His results are calculated as follows:

- production from valence (d) or ($\bar{d}$) sea quarks are calculated using measured sea or valence distribution which evolve with Q^2.
- production of s,b quarks use the W-gluon fusion model[2], with m_s = 500 MeV, m_b = 5 GeV. Similar results could be obtained if one had used a sea content for s. Mass threshold are correctly incorporated in this model.





II. Estimates

Results: at E_ν = 500 GeV; $E_{\bar{\nu}}$ = 500 GeV, M_t = 20 GeV

$\dfrac{\sigma(\nu N \to \mu^- t X)}{\sigma(\nu N \to \mu^- X)}$	≃	2×10^{-4}	$d \to t$	1
		5×10^{-6}	$s \to t$	2
		2×10^{-8}	$b \to t$	3
$\dfrac{\sigma(\bar{\nu} N \to \mu^+ \bar{t} X)}{\sigma(\bar{\nu} N \to \mu^+ \bar{t} X)}$	≃	8×10^{-7}	$\bar{d} \to \bar{t}$	4
		10^{-5}	$\bar{s} \to \bar{t}$	5
		2×10^{-8}	$\bar{b} \to \bar{t}$	6

We emphasize that these rates are optimistic. Two comments must be made immediately.

1. Because of the large mass of the t quark, the cross sections are rising sharply at these energies. A slight increase or decrease in energy would produce deviations by large factors.

2. An increase in the t quark mass could be catastrophic, (decreasing the cross section by factors of ~ 2 for a 20% increase of m_t for $d \to t$, e.g., and $m_t = 17$ GeV $\to m_t = 20$ GeV). See Fig. 1.

An idea of the variations of these cross sections versus energy and t quark mass can be obtained from Fig. 1 and Fig. 2

Let us try to obtain some feelings for the kinds of physics that can be done.

- In a **good** bubble chamber experiment one could obtain ~ 10^5 events. The most optimistic results yield 20 events in ν interactions and no events in antineutrinos. No signal in νN interactions would lead to the conclusion that $|U_{dt}|^2$ is much smaller than the maximal value. It is difficult to estimate what the efficiency for finding 20 events would be. Semi-leptonic branching fraction should not be used. A very large multiplicity trigger might pick out an odd event with n charged > 15-20, but this is really not feasible for bubble-chamber physics.

- In a counter experiment 10^6 events can possibly be obtained. So at most 200 events could be obtained in ν interactions vs 10 events or so in antineutrino reactions. To detect those events one should use a leptonic trigger, i.e., the decay $t \to \mu^+ x$, as the leptons produced would be at extremely large $p_\perp$ with respect to the $(\nu\mu^-)$ plane as illustrated in Fig. 3. However, to separate the hard μ's from t vs μ's from charm one must go to a $p_\perp \sim 6$ GeV. The loss of signal would be tremendous $\gtrsim 90\%$. One must also estimate the semi-leptonic branching ratio of the t quark. A rather simple-minded approach is to count the possible channels and only worry about spectator (t quark decays only) contributions. They are shown in Fig. 4, and we assume $t \to b$ 100% of the time, $c \to s$ 100%; $b \to c$.

This leads to a branching fraction $B(t \to \mu) \approx 1/9$. Assuming the standard lore that strong interactions will enhance the non-leptonic mode an optimistic branching ratio is $B(t \to \mu = 10\%$. This would reduce the number of events to 2 **or less**.

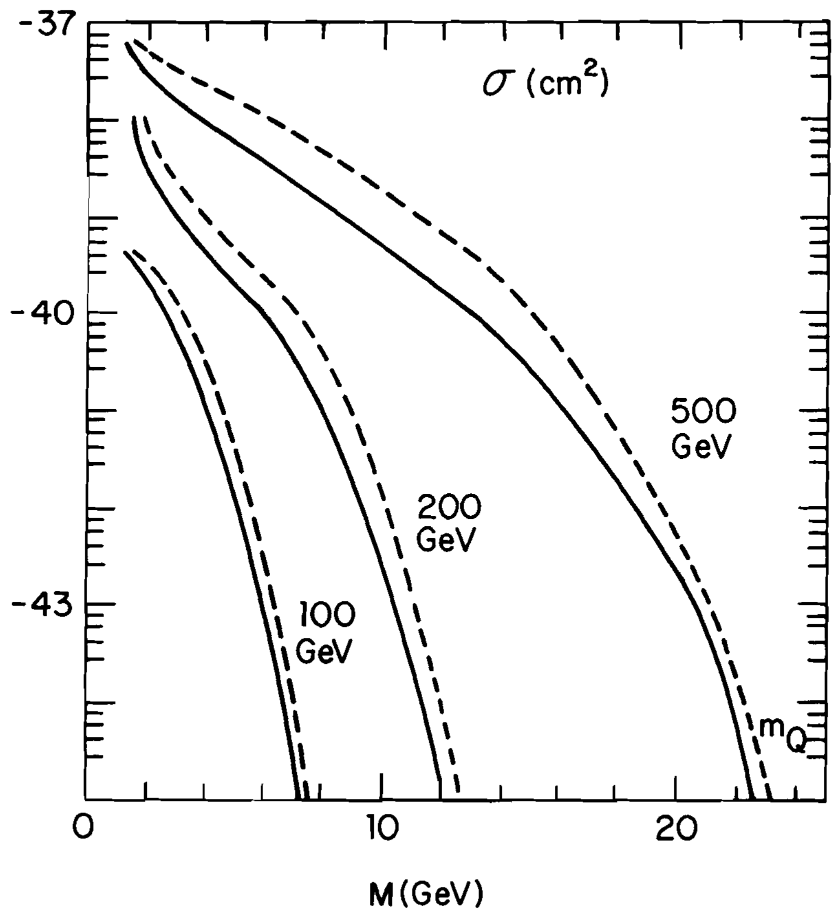
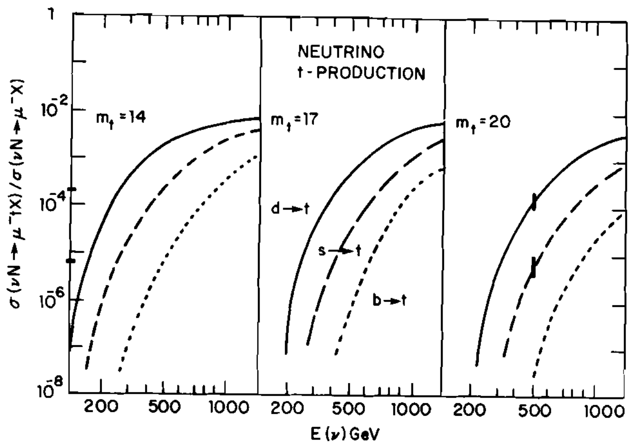
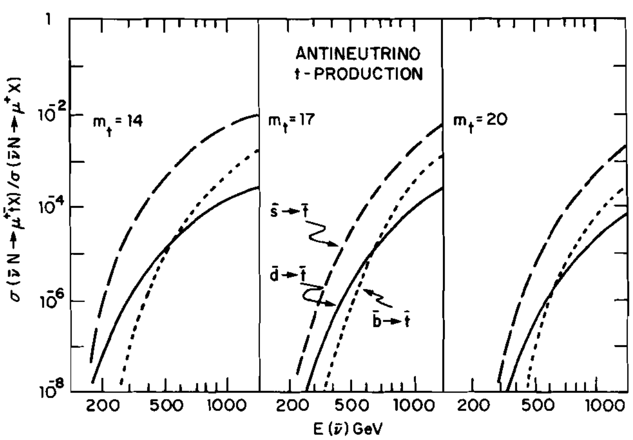


Fig. 1. Total cross section (in powers of 10) for b-quark production by ν or $\bar{\nu}$, plotted vs. the b partner's mass. At each energy the solid (dashed) curve denotes conventional glue $3(1 - x)^{5/5}$ and broad glue (see Ref. 2) respectively.



Upper limits for the neutrino production of t-quarks in the six-quark model. for m_t = 14, 17, 20 GeV.



Upper limits for the antineutrino production of t-quarks in the six-quark model, for m_t = 14, 17, 20 GeV [from R. H. N. Phillips, Nucl. Phys. **B159**, 418 (1979)].

Fig. 2.

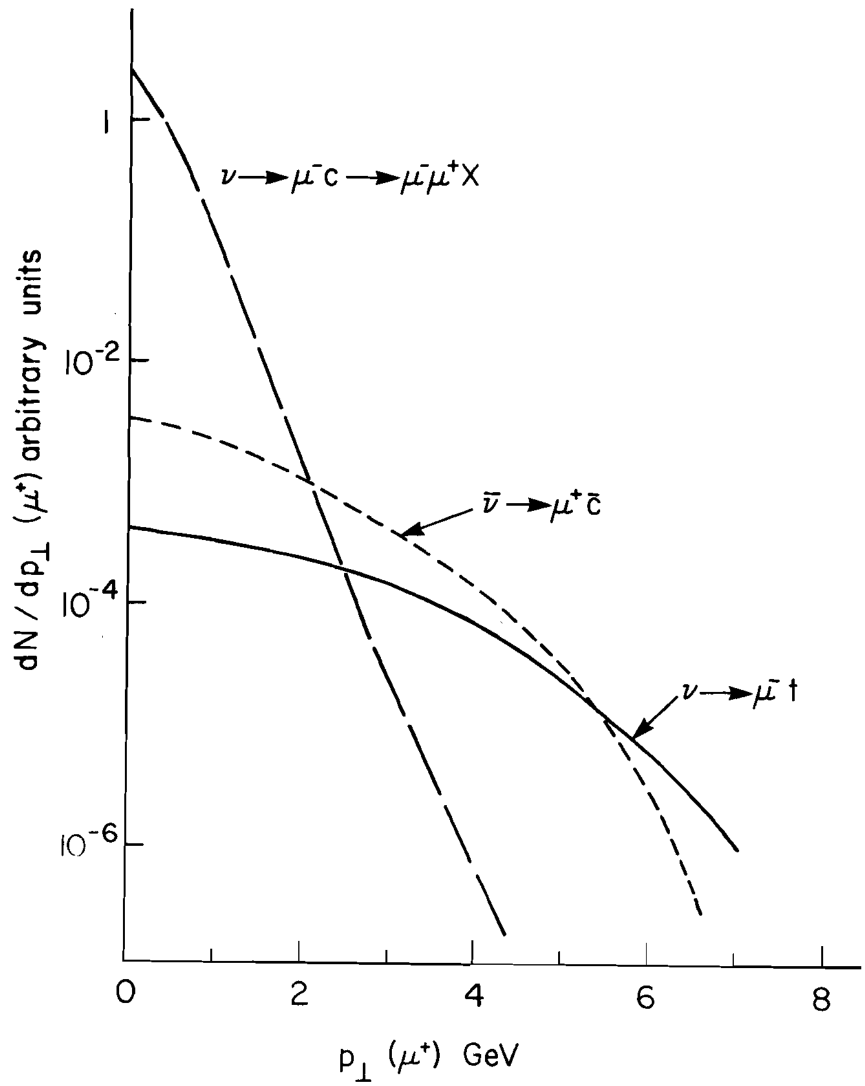


Fig. 3. Distribution of μ^+ momentum transverse to the $\nu-\mu^-$ plane for neutrino dimuons. The calculated signal from t-decay (solid curve) is compared with backgrounds from c-decay (dashed curve) and $\bar{\nu}$-produced $\bar{c}$-decay (dotted curve). The relative normalizations assumed are 1:1000:5 respectively: the $\bar{\nu}$ case assumed $E(\bar{\nu})$ = 200 GeV (from Ref. 1).

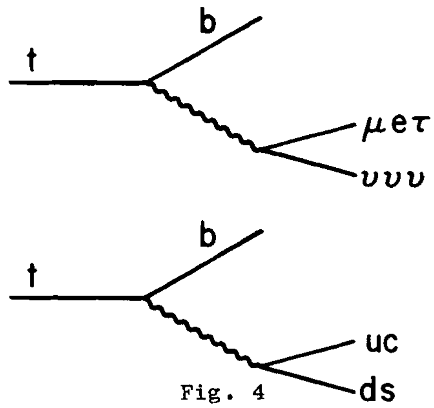


Fig. 4

Conclusion for t-Physics

The situation looks rather hopeless. All the estimates were **very optimistic** and led to a very few events which would be very difficult to pull out of the large background. Bubble-chamber events with extremely large multiplicity might be an indication of t quarks, but it is not an easy trigger. A search for t quarks at Tevatron energies does not seem fruitful in neutrino events.

(b) **b-quark physics**

The mixing angles are not well known but the upper limits are

$$|U_{bu}| \simeq 0.1 \qquad |U_{cb}| \simeq 0.7$$

Again for definiteness the couplings will be assumed maximal, (although this is not a consistent procedure) the model assumptions are the same as for the t-quark. The c,b quark mass is fixed and is set at

$$\begin{matrix} m_c \simeq 1.87 \\ m_b = 5.1 \end{matrix} \ \text{GeV.}$$

The results quoted are from R. J. N. Phillips, Nucl. Phys. **153B**, 475 (1979).[1]

$$\frac{\sigma(\nu N \to \mu^- \bar{b} x)}{\sigma(\nu N \to \mu^- x\ )} = \begin{cases} 2 \times 10^{-4} & \bar{u} \to \bar{b} \\ 3 \times 10^{-3} & \bar{c} \to \bar{b} \end{cases}$$

$$\frac{\sigma(\bar{\nu}N \to \mu^+ bX)}{\sigma(\bar{\nu}N \to \mu^+ X)} = 5 \times 10^{-3} \qquad \begin{matrix} u \to b \\ c \to b \end{matrix}$$

Production associated with t quarks is negligible as already discussed. Variations of the cross sections with energy is shown in Fig. 5.

We may again consider the two cases of bubble chamber vs counter experiments, assuming 10^5 and 10^6 events respectively in these experiments.

This leads to

# events	experiment	beam
300	Bubble Chamber	ν
3000	Counter	ν
500	Bubble Chamber	$\bar{\nu}$
5000	Counter	$\bar{\nu}$

Before investigating the experimental possibilities with these numbers of events, a comment should be made. As shown in Fig. 5 the event rate comes about entirely from associated production of (bc). The coupling strength for $b \to c$ is likely to be less uncertain than the $b \to u$ coupling. Present experimental measurement at CESR already favors $b \to c$. Theoretical prejudice prefers $b \to c$ maximal and favors $b \to u \approx 0$. So the above numbers may not be too optimistic.

(i) Bubble chamber experiments. How could one detect the B's in bubble chamber ν experiments? Multiplicity does not help in bubble-chamber events. The best signature of b decay will be from hard muons at large transverse momenta with respect to the lepton plane. The relevant distributions are shown in Fig. 6. It has been assumed that the P_t^2 distributions are only a function of the transverse mass $(P_t^2 + m_b^2)^{1/2}$, a fact borne out by the gluon-fusion model calculations (see, e.g., Ref. 2).

Specifically

$$\frac{d\sigma}{dp_t^2} \simeq \exp\{-A(p_t^2 + m_b^2)^{1/2}\}.$$

Figure 6 shows the P_t distributions for A = 5 as observed in hadronic interactions and A = 2.5 as calculated in gluon fusion models.[2] To clearly separate events a cut of 1.5-2 GeV may be necessary. This will result in a loss of signal of about **90%** for A = 5. Of course a trigger with > 1 GeV may also be used if

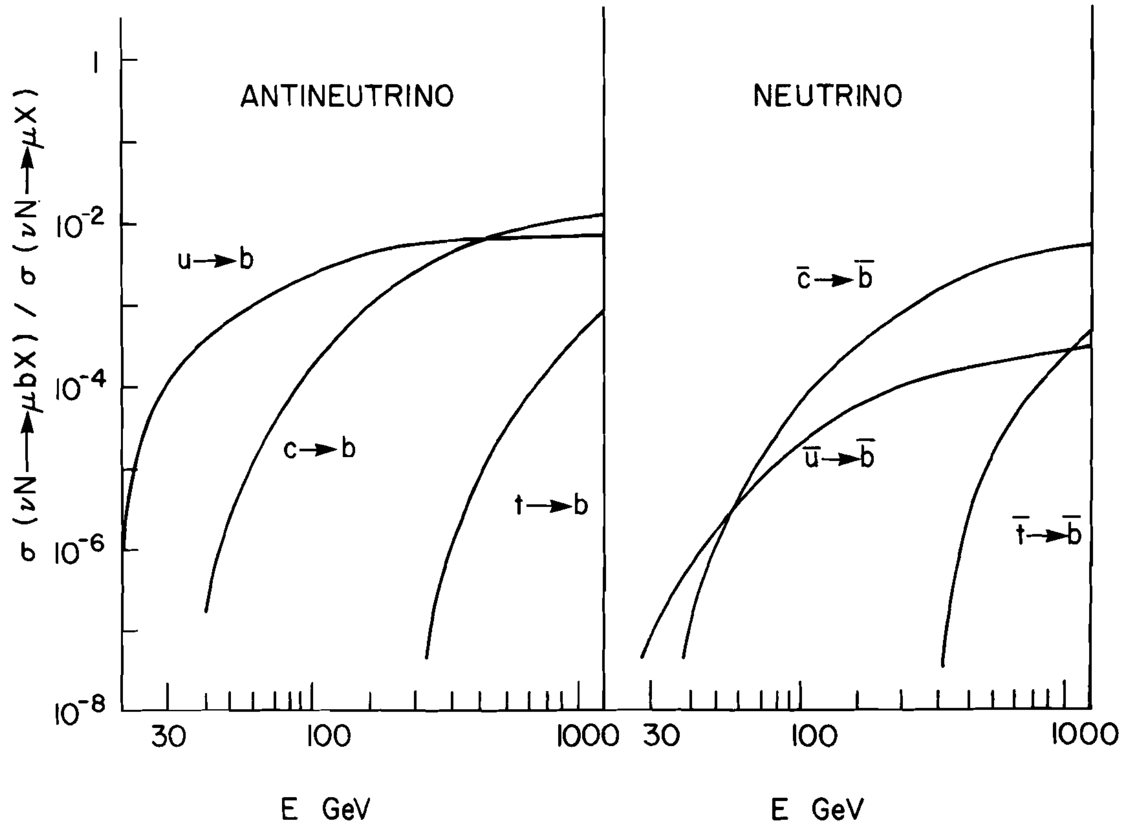


Fig. 5. Charged current b-production from an I-spin averaged nucleon target, as a fraction of the total charged current cross section, for neutrinos and antineutrinos. Maximal mixing angles are assumed for each contribution (from Ref. 1).

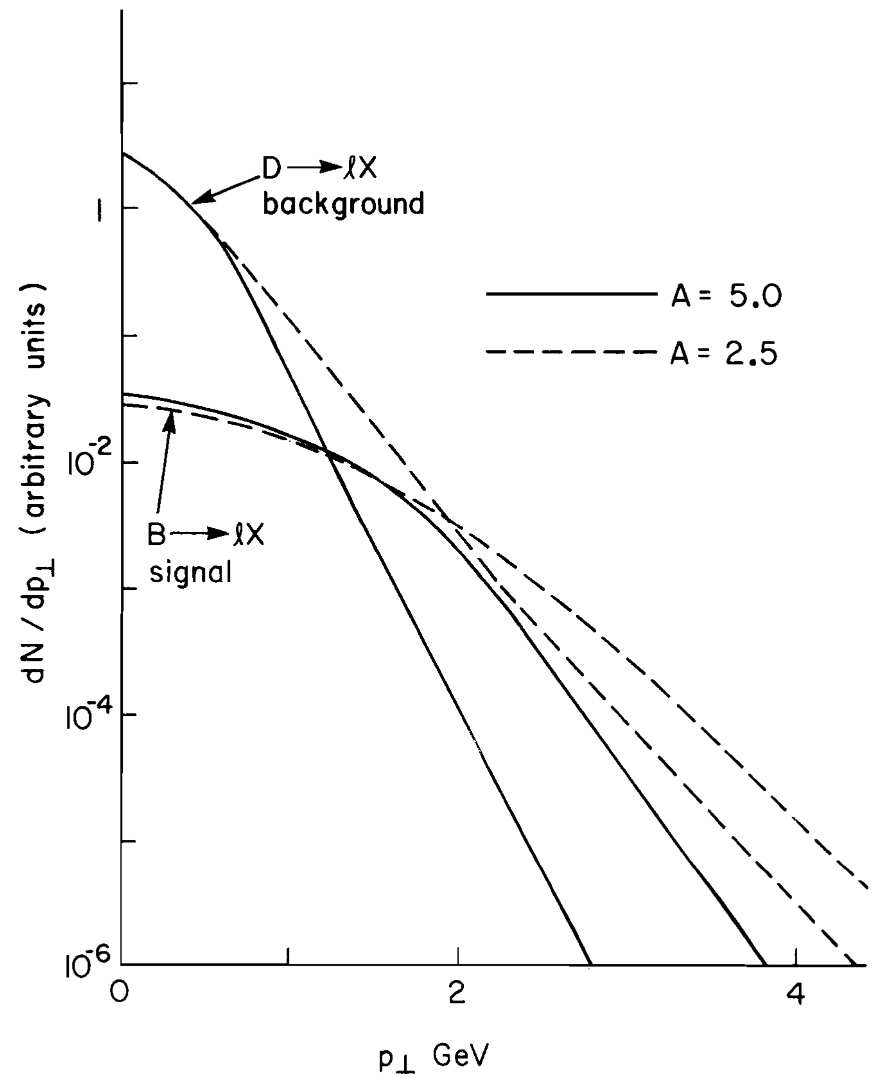


Fig. 6. Opposite-sign dilepton events: dependence on the momentum $p_\perp$ transverse to the production plane for leptons from B → ℓX decay and background leptons from D→ ℓX. Parameter values A = 2.5, 5.0 GeV^{-1} for Eq. (3) are illustrated (from Ref. 1).

one can stand a larger charm background. If A = 2.5 a cut at 2.5 GeV results eliminates all but 1% of the B decays. Folding in a 10% branching ratio for $B \to \mu$ results in a net number of events of about 4 in ν, $\bar{\nu}$ interactions. This does not allow for dilepton triggers. Therefore the situation does not look favorable for conventional bubble chambers. If, however, high spatial resolution bubble chambers (below) are available, then B decays may be separated from the charm background on the basis of kinematic fitting, without the need for p_t cuts. In that case the experiment would be quite feasible.

(ii) Counter experiments. Assuming 10^6 charged-current events will leave a sample of approximately 30-50 events depending on the beam, and assuming a 1.5-GeV cut, with A = 5. This could lead to a convincing signal. If A = 2.5 the situation is again unfavorable with only a handful of events available. Remembering that the $b \to c$ chosen was the maximally allowed coupling, it appears that although a convincing B signal could be obtained, it would be a formidable experimental task. Doubling the number of events to 2×10^6 produced would help but may not be feasible.

Before closing this subsection, it should be noticed that the p_t distribution for charm has not been measured accurately enough to discriminate between dependence of $d\sigma/dp^2$ on $M_t = (p_t^2 + m_b^2)^{1/2}$ versus p_t^2. If one assumes

$$d\sigma/dp_t^2 \sim \exp(-Ap_t^2)$$

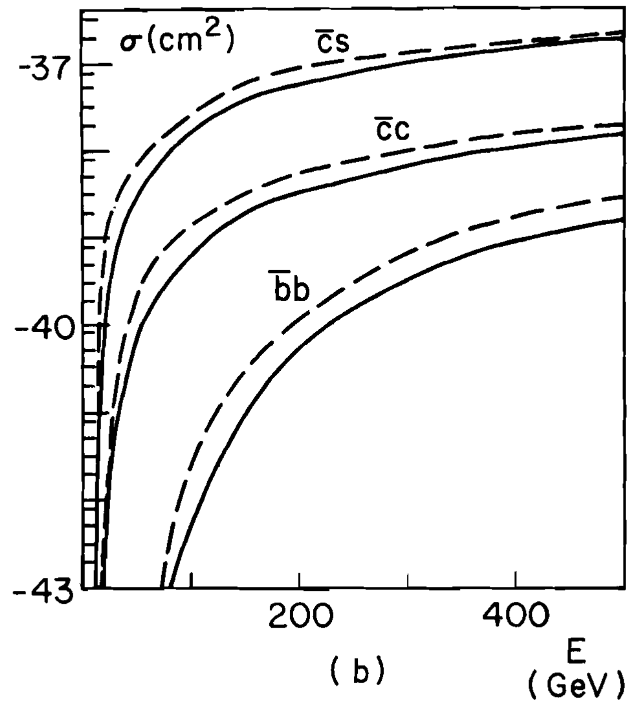
instead of m_t scaling the numbers become much more optimistic.[4]

Conclusion

In the best possible situation a convincing signal for B mesons **may** be detected in a large counter experiment in $\nu,\bar{\nu}$ beams. The signal will be feeble however and the estimates made here are of an optimistic nature, i.e., $E_\nu \sim 500$ GeV, with maximal mixing. A proper folding of the neutrino spectrum would be necessary before any realistic conclusions can be obtained.

(c) Charm Physics

Charm cross sections can be evaluated rather unambiguously using the fusion model. No ambiguity arises, as the mixing angles are definitely known and the gluon distribution is well measured from muoproductions of charm.[5] The calculation of Ref. 2 is shown in Fig. 7. Assuming a beam energy of 500 GeV again for definiteness and assuming the Cabbibo suppressed contribution from valence quarks) or sea contribution to be equal to the fusion cross section leads to the following estimate (see Fig. 1).



(b)

Fig. 7. Charged and neutral current cross sections for $\bar{\nu}$ beams in fusion models. The continuous curve is the only relevant one with counting rule gluon distribution.

$$\frac{\sigma(\bar{\nu}N \to \bar{c}sX)}{\sigma(\bar{\nu}N \to \mu X)} \sim \frac{\sigma(\nu N \to cX)}{\sigma(\nu N \to \mu^- X)} \sim \frac{2 \times 10^{-37}\text{cm}^2}{(0.3)(500)10^{-38}\text{cm}^2} \sim 1/10$$

(We do not differentiate here between neutrinos and antineutrinos. Only a factor of 2 or so will result.) The number is probably best taken as 5×10^{-2} to account for lower beam energy.

This leads to a very large number of charm events. Using 10^5 bubble-chamber events, 10^6 counter events, one has a total number of charm events of order 5000, or 50,000. Again these numbers are optimistic but a sample half that size may be easily possible. Triggering on dimuons (at large p_T or not) leads to a sample size of a few hundred or a few thousands. So models can be easily tested with such production rates, with possible distributions etc.

As can be seen from Fig. 7 neutral current production of $c\bar{c}$ is only about an order of magnitude below charged current cross section. The possibility of detecting bound charm becomes real for a Tevatron neutrino beam. In particular the Ψ production cross section could be observed with a few events. It would be a major contribution if the neutral current couplings of the charmed quark could be measured.

References

1. R. J. N. Phillips, Nucl. Phys. **B153**, 475 (1979); R. J. N. Phillips, Nucl. Phys. **B159**, 418 (1979).

2. V. Barger, W. F. Long, and S. Pakvasa, Phys. Rev. Lett. **42**, 1585 (1979); R. E. Schrock, S. B. Treiman, and L. L. Wang, Phys. Rev. Lett. **42**, 1589 (1979).

3. See, e.g., J. P. Leveille and T. Weiler, Nucl. Phys. **B147**, 147 (1979).

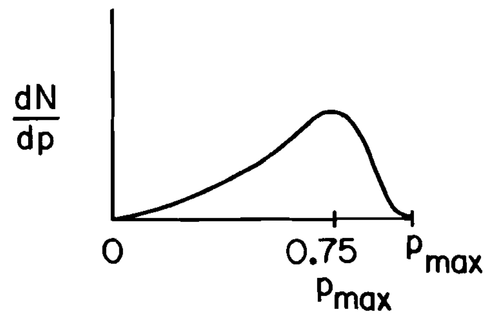
4. C. Albright, and J. Smith, Phys. Rev. **D21**, 711 (1980).

5. T. Weiler, Phys. Rev. Lett. **44**, 304 (1980).

I.F. NEUTRON PRODUCTION OF CHARM AND BEAUTY

Neutron beams have significant advantages for experiments with track-sensitive targets. These targets can typically tolerate some maximum flux of charged particles beyond which their performance degrades. Many of these devices are only a small fraction of an interaction length. In charged hadron beams, the charged particle rate in the device is typically dominated by incident beam tracks which do not interact. If a neutron beam is used instead, only interactions in the device produce charged tracks. The limit is now based on the number of interactions, rather than on the number of non-interacting beam tracks. Roughly speaking, the sensitivity of the experiment is improved by $\ell/\ell(int)$ where $\ell(int)$ is the number of interaction lengths in the target.

Two neutron beams are currently in operation at Fermilab -- one in Proton-East and one in the Meson Area. A third neutron beam will be installed in P-Center for an experiment with a track-sensitive target (E630). The momentum spectrum of these beams peaks at ~ 3/4 of the incident proton beam energy and is approximately triangular



The peak of the neutron spectrum will therefore occur at 750 GeV. Yields for a neutron beam of 400 GeV and 1 TeV incident protons are given in the accompanying table. Spot sizes are calculated from the angular acceptances based on a distance from the production target to the experimental target of 500 ft for 400 GeV and 1000 ft for 1 TeV.

Charm and b-quark rates for neutrons generated by 1-TeV protons are given in the article "$b\bar{b}$ and $c\bar{c}$ Pair Event Rates for Proton, Photon and Neutron Beams at the Tevatron," see contents. The main point is that enough neutrons can be obtained from a rather modest number of incident protons ($< 10^{12}$) to saturate the interaction rate capability of nearly any of the proposed track-sensitive targets. Beam intensity is unlikely to limit the experiment!

Several comments need to be made concerning the desirability of neutron beams relative to pion or proton beams.

1) The average neutron energy is significantly lower than the 1 TeV obtainable with primary protons. Since the cross section rises rapidly with energy, there is a penalty of say a factor of 2-3 in b-quark rate relative to the number of interactions.

2) Neutron beams cost fewer protons than pion beams of equivalent energies. It is likely that one would do

pion experiments at somewhat lower energy, therefore suffering from reduced cross sections. On the other hand, it is rumored that the pion's gluon distribution function is stiffer than the neutron's so that at any given energy the cross section might be higher.

3) Energy constraints in b-quark hadroproduction are not likely to be important. The events will contain so many γ's, neutrons, K_2^0's, and neutrinos that it will be impossible to sum up accurately the observed energy.

Neutron Yields.

Incident Proton Energy	Angular Acceptance (mrad × mrad)	Spot size (in. × in.)	Yield Neutrons Incident Proton
400	0.625 × 0.0313	0.33 × 0.17	7.1×10^{-6}
(present	0.14 × 0.07	0.75 × 0.375	3.5×10^{-5}
beam)	0.167 × 0.167	0.90 × 0.90	9.9×10^{-5}
1000 (new beam)	0.0625 × 0.0313	0.75 × 0.375	4.4×10^{-5}
	0.14 × 0.07	1.50 × 0.75	2.1×10^{-4}
	0.167 × 0.167	2.0 × 2.0	5.9×10^{-4}