Detecting Heavy Flavors at CBA.

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Fig. 6

Fig. 7

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INFORMAL REPORT

Detecting Heavy Flavors at CBA

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I. Introduction

In the CBA luminosity range ($L=10^{32}-10^{33}\text{cm}^{-2}\text{sec}^{-1}$) the expected rate of bare heavy flavor production is high enough to allow for detection schemes which rely on relatively small leptonic branching ratios. (Figure 1 illustrates the cross-sections for producing $Q\bar{Q}$ pairs.) As we discuss in detail below, these provide a clean separation of the signal from the gluon plus light quark background, while retaining sufficient statistics for further study.

In Section II we present the current status of our investigation of lepton-related triggers and cuts. In Section III we discuss the jet topologies of events (both signal and background) with high- P_T leptons. While these studies have been carried out with samples of high- P_T $q\bar{q}$ and gluon jets generated with ISAJET,¹ we survey in Section IV other sources of heavy flavor production at CBA.

II. Leptons from Heavy Quarks

We concentrate here on strategies for detecting heavy flavors which are only accessible with CBA-like luminosities, namely trigger schemes

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relying on the lepton(s) from decays of the type

$$Q \rightarrow q l \nu$$

where Q is the heavy quark under study and q is an accessible lighter quark. Lower luminosity hadron colliders probably will not be able to afford the cost of these ($<10\%$) branching ratios, and electron-positron colliders will have access only to those flavors whose mass M_Q is

$$2M_Q < \sqrt{s}.$$

We have found that lepton-based triggers can be devised which are both reasonably efficient for heavy flavors and quite selective against known states (b and lighter). The method, studied with ISAJET (modified to allow secondary decays), uses a very straightforward central region detector. It is based on a segmented 4-walled calorimeter with solid angle $(\Delta\eta, \Delta\phi) \approx (\pm 2, 2\pi)$, and rms resolutions $0.15/E$ ($e-m$) and $0.35/E$ (hadronic). The inner region is filled with a 10kG field and tracking chambers. The whole is surrounded by sufficient steel and counters to cleanly and efficiently identify and measure muons above a P_T threshold of at least 2 GeV/c in all our studies. With relatively coarse segmentation (approx. 700 towers total), and charged particle tracking, we constructed the following quantities:

a. $\vec{P}_T^{\text{miss}} = -\vec{P}_T$, using measured P_T for charged tracks and E_T from the calorimeter for neutrals.

b. P_T^L , the transverse momentum for each leptons, including secondaries from π and K decays.

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c. H_T^H , the sum of the transverse hadronic energy in the 3×3 cell cluster centered on the muon with the largest transverse momentum (P_T^H). For leptons from heavy quarks, which are often well-separated from their hadronic jet, this quantity is usually $\lesssim 2$ GeV.

The following example of a trigger based on these quantities indicates that events from high- P_T quark-antiquark scattering can be very enriched in heavy quark content, without sophisticated (i.e., offline) analysis. We used $M_Q = 50$ GeV and made the following trigger requirements:

1. At least 2 leptons in an event, at least one having $P_T^L \geq 10$ GeV/c for the region $50 \text{ GeV/c} < P_T < 100 \text{ GeV/c}$ studied here.

2. $H_T^H < 2$ GeV

3. $|\vec{P}_T^{\text{miss}}| > 20$ GeV

Imposition of these on-line cuts alone removes all or all-but-one of the background events (at the present statistical level), with a signal-to-background ratio higher than 0.1. Details are given in Table 1. Moreover, any one of the on-line requirements may be removed without increasing the trigger rate beyond a level which is easy to accommodate off-line. In the worst case, the trigger rate increases by a factor of 20.

Our studies of the present sample of events indicate that substantial improvements in the signal-to-background ratio can be made off-line by applying cuts based on the following variables:

1. The transverse mass² M_T , where $M_T^2 = (|\vec{P}_T^L| + |\vec{P}_T^{\nu}|)^2 - (P_T^L + P_T^{\nu})^2$. The neutrino transverse momentum is taken as $\vec{P}_T^{\text{miss}}$, as in the UA1 analysis.

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2. K_T^L , the transverse momentum of each lepton relative to the direction of the jet. The jet direction is taken as the center of the largest 3×3 cell transverse energy cluster in the same quadrant as the lepton.

3. P_T^{VL} , the (scalar) component of $\vec{P}_T^{\nu}$ transverse to the lepton three-momentum.³ For Q decays we found $\langle P_T^{VL} \rangle = 11$ GeV/c while for leptons from light constituents the mean value was a factor 3 lower.

As an example, Figure 2 shows scatter plots of M_T vs. K_T^L for the total event sample. The simple cut shown on the plots enhances the signal-to-background by an amount comparable to the factor of 400 improvement due to the on-line cuts, assuming the variables to be uncorrelated. Scatter plots with the variable P_T^{VL} are similarly effective. Examination of scatter plots reveals no large correlation between any of the variables described above. Higher statistics are needed before a more specific set of cuts can be arrived at, but it should not be difficult to obtain a sample with a signal-to-background ratio greater than 1 with $\gtrsim 10^4$ $Q\bar{Q}$ events per year.

III. Event Shapes

We have used the jet classification scheme of Babcock and Cutkosky⁴⁻⁵ to try to discriminate between heavy quark jets and light quark and gluon backgrounds. To simulate approximately the lepton trigger schemes outlined above, yet still retain sufficient background statistics for study, we simply required each event to contain a lepton with $p_T > 5$ GeV/c.

Figure 3 shows the Q-jet effective mass distribution for 50 GeV quarks, and background at two values of $\sqrt{s}$. (Here we have forced a two-jet interpretation on all events.) It is seen that the Q-jet effective mass has a strong peaking in the 20-35 GeV range while the light-constituent background has a flatter shape which is a rather weak function of $\sqrt{s}$. This suggests a subtraction of mass distributions at values of $\sqrt{s}$ which straddle the heavy quark production threshold could be used to see the quark mass in a sample with a stiff lepton trigger.

Figure 4 shows two such subtracted distributions, one with no heavy quark present and one with a $M_Q = 50$ GeV quark present in the $\sqrt{s} = 800$ GeV data ($S/N = 1/2$). In both cases the $\sqrt{s} = 400$ sample has been normalized to the $\sqrt{s} = 800$ sample in the range $0 < M_J < 20$ GeV. It is clear that the ≈ 500 events used in this heavy quark sample would be sufficient to see a signal. In a year of high luminosity running this statistical level can be reached for M_Q in the 130-140 GeV range (see Fig. 1).

Another heavy quark discrimination technique is illustrated if we plot⁶ the sphericity versus $(\sqrt{3}/2)(Q_2 - Q_1)$ for the events (see Fig. 5). One can see the effect of the mass of the heavy quarks in producing aplanar events. The band in the figure contains approximately planar events, which comprise about half of the heavy quark sample and about 80% of the light-constituent background.

More sophisticated analyses⁷ can be applied which make fuller use of the moments of the particle distribution. However, given the cleanliness of the lepton triggers discussed above, it is not likely that we will have to resort to such analyses.

IV. Other Sources of Heavy Quarks

If the t quark is in the mass range $40 < m_t < m_W$ then

$$W \rightarrow t + \bar{b}$$

will be a more copious source of t quarks at CBA than the hard $q\bar{q}$ and gluon processes in ISAJET used as input to the foregoing studies. Since m_W, m_b are known, such events could be used to fit for m_t .⁸ It is also clear that the lepton-based detection schemes discussed in Section II can be used to select this mode.

Another potential source of heavy quarks is via diffractive production. We wish to consider whether lepton-based trigger and analysis schemes are likely to be useful, so we calculate the lepton spectrum from the semileptonic decay

$$Q \rightarrow q l \nu.$$

The lepton spectrum can be easily calculated⁹ if a few simple assumptions are made. The results obtained indicate that such leptons provide a good, clean signal for heavy quark production. Fortunately, the cross sections are fairly insensitive to the phenomenological assumptions made.

Leptons are produced by a two-step process:

- 1) A Q quark is diffractively produced with an invariant cross section

$$E \frac{d\sigma_{diff}}{d^3p}$$

2) The Q decays semileptonically with decay rate

$$k \frac{dN}{d^3k}$$

The semileptonic decay rate is the product of known kinematics and an unknown branching ratio B. The branching ratio, in the standard model, depends on various unknown quantities, but B is given a nominal value of 0.1.

An expression for $E d\sigma_{diff}/d^3p$ is also needed. Empirically, one expects this quantity to depend on p_T as $\exp(-b p_T^2)$. In practice, it turns out that the lepton distribution is not sensitive to b. Qualitatively, the enhancement from Q quarks moving parallel to the lepton momentum is compensated by a depletion from Q's moving antiparallel. Thus one can take $p_T = 0$.

A simple and widely used distribution for diffractive production of heavy quarks is

$$\frac{d\sigma}{dx} = \frac{f+1}{2} \sigma_{diff} (1-x)^f$$

Here σ_{diff} is the total diffractive cross section and x is Feynman x. The shape parameter f has been taken to be between 1 and 5 on various grounds, but the results are insensitive to the precise value.

The total diffractive cross section for Q production can be estimated using the phenomenological expression

$$\frac{0.1}{m_Q^2} \ln \frac{\sqrt{s}}{m_Q} \text{ (mb)}$$

This gives neither the most optimistic nor the most pessimistic σ_{diff} . The most pessimistic prediction for σ_{diff} is about an order of magnitude lower.

With this input, the lepton spectrum can be calculated (See Fig.

6). The best place to look for such leptons is at angles of about 20° - 30° with respect to the beam. If too small an angle is chosen, the Q contribution is swamped by the contribution of diffractively produced b and c quarks. At these intermediate angles, one can still anticipate useful quantities of events per year at CBA luminosities, even with the most pessimistic assumptions.

For example, for $m_Q = 60$ GeV a standard year of high luminosity running (10^{40} cm^{-2}) yields 10^6 leptons/steradian from semileptonic Q decay at 25° in the lab. This assumes 1 order of magnitude smaller cross section than what is displayed in Figure 6. The yield from diffractively produced b's is a factor of 100 higher, but a k_T cut at 5 GeV/c removes all of this background (see Fig. 7).

Several points should be made about the lepton spectrum:

- 1) It is insensitive to $\sqrt{s}$. A higher $\sqrt{s}$ increases the forward peak, but this is compensated by a larger total cross section.
- 2) It is insensitive to the value of the shape parameter f.
- 3) The spectrum peaks at a lepton transverse momentum $k_T = m_Q/4$, so unaccompanied leptons at intermediate angles with $k_T > 5$ GeV provide a clean signal. The heavier the Q quark is, the clearer the signal.

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9. See, for example, D.M. Scott, "Getting to the Top," Proton-Antiproton Collider Physics - 1981, p. 151, AIP (1982), and references contained therein.

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Table I.

Event rates for 50 GeV quarks and backgrounds, using the trigger described in the text.

	$P_T = 50 \text{ GeV/c}$		$P_T = 100 \text{ GeV/c}$	
	$\frac{Q\bar{Q}}{25K}$	$\frac{q\bar{q}}{10^3}$	$\frac{Q\bar{Q}}{800}$	$\frac{q\bar{q}}{10^6}$
Total Events per year per GeV/c P_T				
Triggers per year per GeV/c P_T	1.1K	$<10^4$	60	100

Figure Captions

Fig. 1. Cross section for heavy quark production at $L = 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ and $\sqrt{s} = 800$ as a function of quark mass.

Fig. 2. Scatterplots of transverse mass vs. lepton transverse momentum relative to the jet. The cuts are discussed in the text.

Fig. 3. Unnormalized jet mass distributions from ISAJET. The light constituent events contain gluons and $q\bar{q}$ up through the b .

Fig. 4. Subtracted jet mass distributions with and without 50 GeV $Q\bar{Q}$ events at $\sqrt{s} = 800$. The light constituent distribution at $\sqrt{s} = 400$ is normalized to the $\sqrt{s} = 800$ samples in the 0-20 GeV range and then subtracted. The sample including heavy quarks has signal-to-noise = 0.5. All events have a lepton with $P_T > 5$ GeV/c.

Fig. 5. Jet shape distributions for heavy quark and light constituent events with a cut requiring a lepton with $P_T > 5$ GeV/c.

Fig. 6. Differential cross section times leptonic branching ratio for diffractively produced 60 GeV quarks.

Fig. 7. Lepton transverse momentum spectra for diffractively produced b and Q quarks.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5