THE EVIDENCE FOR \( b \) QUARK PRODUCTION AS THE SOURCE OF HIGH \( p_T \) DIMUON EVENTS AT THE CERN \( pp \) COLLIDER

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The Evidence for $b$ Quark Production as the Source of High $p_T$ Dimuon Events at the CERN $p\bar{p}$ Collider

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High $p_T$ dimuon events produced in $p\bar{p}$ collisions at energies of $\sqrt{s} = 546$ GeV and $\sqrt{s} = 630$ GeV provide the first evidence for beauty particle production at the CERN collider. We find that 90% of the events where each muon has $p_T > 3$ GeV/c and is accompanied by jet activity are due to the semi-leptonic decay of beauty particles. The measured production cross section is $\sigma(pp \rightarrow b\bar{b}X) = 1.2 \pm 0.1 \pm 0.4 \mu b$, where $p_T > 5$ GeV/c and $|\eta| < 2.0$ for both quarks, in good agreement with QCD calculations. We observe a clear signal for $T \rightarrow \mu^+\mu^-$ (hidden beauty) when the muons are relatively isolated from hadronic activity, and observe a large cross section for high $p_T$ $J/\psi$ production, which may be due to $b \rightarrow J/\psi X$ decays.

INTRODUCTION

At CERN $p\bar{p}$ collider energies the production cross section of $b$ and $c$ quarks is expected to be large, on the order of 10 mb for $b$, and approximately equal once the quark $p_T$ (defined as the momentum transverse to the beam direction) is large enough so that $b$ threshold effects are unimportant. These heavy quarks can be identified through their semi-leptonic decay mode, making the experimental problem one of identifying a prompt lepton buried in an accompanying jet. Since muons can be identified by virtue of their penetrating nature, independently of the amount of accompanying energy, they, rather than electrons, are used to select a data sample enriched in $b$ and $c$ quarks. Furthermore, as the fragmentation of $b$ quarks is known to be harder than that of $c$ quarks, we expect that by concentrating on high $p_T$ dimuons we may enhance the production of $b$ quarks while limiting any non-prompt muon background.

APPARATUS

The UA1 apparatus has been described in detail elsewhere. In brief, in order to be identified as a muon, a charged particle must pass through the large central drift chamber, the Central Detector (CD), the electromagnetic and hadronic calorimeters, and at least 80 cm of additional iron shielding before reaching the surrounding muon chambers. Its momentum is measured to within an accuracy of about $0.005p/GeV/c$ for 1 m long tracks, in the 0.7 T dipole field. The material it passes through comprises at least 9 nuclear interaction lengths, resulting as well in a minimum $dE/dx$ loss of at least 3 GeV. The hardware muon trigger requires that muon tracks point back to the vertex within a cone of $\pm 150$ mrad aperture, and an on-line processor refines the cone using drift time information.

DATA SELECTION

The data described here were taken during the collider runs in 1983 (108 nb$^{-1}$ at $\sqrt{s} = 546$ GeV) and 1984-1985 (584 nb$^{-1}$ at $\sqrt{s} = 630$ GeV) using both the inclusive and dimuon triggers. An inclusive $p_T > 3$ GeV/c muon selection was performed offline with loose technical quality criteria (CD track length and $x^2$, and matching $x^2$). Dimuon events were selected requiring both muons to have $p_T > 2$ GeV/c. This yielded 1175 dimuon candidates, which were examined by physicists at an interactive graphics facility where 295 events were removed from the sample. The acceptance un-corrected distribution of $m_{\mu\mu}$ for the isolated unlike-sign events is shown in Fig. 1, where $J/\psi$, $T$, and $Z^0$ clusters are visible.

However, as we wish to concentrate on those events where the two muons cannot originate from a single $b \rightarrow c$ cascade, the discussion of this sample will be limited to those events where $m_{\mu\mu} > 6$ GeV/c$^2$. These comprise 669 of the 1175 events. Events removed by scanning were identified as coming from cosmic rays (9), double interactions (3), leakage through cracks (52), kaon decays with a visible decay vertex in the CD (46), mis-association of the muon and CD tracks (28), and $Z^0 \rightarrow \mu^+\mu^-$ events (19), leaving 512 events in the final sample.

The discussion of $J/\psi$ production is based on an enriched sample which is limited to $2 < m_{\mu\mu} < 4$ GeV/c$^2$ and $p_T > 4$ GeV/c, but where the $p_T$ requirement on the second muon is relaxed to 0.75 GeV/c.

![Fig. 1- Dimuon mass distribution for isolated unlike-sign dimuon events with $p_T > 3$ GeV/c muons on a logarithmic mass scale showing the contribution from $Z^0 \rightarrow \mu^+\mu^-$.](image)

where $\sigma(pp \rightarrow b\bar{b}X) = 1.2 \pm 0.1 \pm 0.4 \mu b$, where $p_T > 5$ GeV/c and $|\eta| < 2.0$ for both quarks, in good agreement with QCD calculations. We observe a clear signal for $T \rightarrow \mu^+\mu^-$ (hidden beauty) when the muons are relatively isolated from hadronic activity, and observe a large cross section for high $p_T$ $J/\psi$ production, which may be due to $b \rightarrow J/\psi X$ decays.
Fig. 2 - Estimated background from $\pi$ and $K$ decay compared to the inclusive muon data sample passing the same loose cuts required of the dimuons.

**BACKGROUNDS**

Because of the thickness of the hadron absorber, in the UA1 detector the major background to the prompt muon signal comes from $\pi$ and $K$ decay in flight. The background from non-interacting hadrons, shower leakage through material, and (after scanning) shower leakage through cracks and cosmic rays is estimated at 2 events in the $m_{\mu\mu} > 6$ GeV/c$^2$ sample. The misassociation of a muon track to an unrelated high $p_T$ charged track in the accompanying jet can occur. This background has been estimated as $10 \pm 10$ events, by counting the events in the sample where a nearby lower $p_T$ track in the CD could possibly form a second valid match to the muon track. Of these, half are like-sign and half are unlike-sign events.

The $\pi$ and $K$ decay background to the dimuon sample has been calculated using the $p_T > 3$ GeV/c inclusive muon sample described earlier, which is itself mainly due to $\pi$ and $K$ decays. Tracks of $p_T > 2$ GeV/c, presumably hadrons, were chosen and their decay to a muon then simulated assuming that the charged particle composition is 58% $\pi^\pm$ ($f_{\pi}$), 21% $K^\pm$ ($f_K$), and 21% $p, \bar{p}$. Each such generated event is passed through the detector simulation and contributes to the background if it passes the same selection criteria applied to the data, including scanning. We estimate a background of 95 $\pi, K \rightarrow \mu\nu$ decays in the $m_{\mu\mu} > 6$ GeV/c$^2$ sample, with a systematic error of 25% due to the uncertainty in the detector simulation, in the trigger and scanning efficiencies, and especially in $f_{\pi}$ and $f_K$.

To check this calculation the exercise was repeated for the inclusive muon data, using the charged particle $p_T$ distribution measured in minimum bias data as the parent sample. The result is shown in Fig. 2, where we find that the estimated background is consistent with and slightly exceeds the observed number of events in the region $3 < p_T < 6$ GeV/c, thus allowing little room for additional background in the dimuon sample.

Fig. 3 - Isolation of $m_{\mu\mu} > 6$ GeV dimuons. The energy seen in the calorimeters in a cone of $\Delta R = 0.7$, where $\Delta R \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$, is plotted for the highest $p_T$ muon on the abscissa and for the lowest $p_T$ muon on the ordinate.

**DRELL-YAN, $T$, and $J/\psi$ SAMPLES**

In order to separate the contributions of the Drell-Yan process and $T \rightarrow \mu^+\mu^-$ from open heavy flavor decay, we measure the degree to which a muon is embedded in a jet, its isolation. The former processes are expected to yield mainly isolated muons. In Fig. 3 the scalar sum of the transverse energy measured in the calorimeter cells in a cone of $\Delta R = (\Delta \eta)^2 + (\Delta \phi)^2)^{1/2} < 0.7$ around the muon, excluding the mean muon $dE/dz$, is plotted for the higher $p_T$ muon, separately for like-sign and unlike-sign events. Here $\eta$ is the pseudorapidity and $\phi$ is the azimuth. We see a clustering of events close to the origin for the unlike-sign events that is absent for the like-sign. This motivates the labelling of the region $(\Sigma E_T(\mu_1))^2 + (\Sigma E_T(\mu_2))^2)^{1/2} < 3$ GeV as isolated and the adjacent region as non-isolated. With this definition there are 98 unlike-sign and 15 like-sign events in the isolated sample, and 257 unlike-sign and 142 like-sign events in the non-isolated sample. The efficiency of this definition was examined using random pairs of $W \rightarrow \mu\nu$ events; 82% of these are isolated by the above definition. The background sample is composed of 90 non-isolated events and 17 isolated events, equally divided into the like and unlike sign categories.
Fig. 4- Dimuon mass distribution for isolated unlike-sign dimuon events with $p_T > 3$ GeV/c having $6 < m_{\mu\mu} < 50$ GeV/c$^2$, with curves showing the result of a three parameter fit for the Drell-Yan, upsilon, and heavy flavour contributions after background subtraction.

The mass distribution of the 98 isolated unlike-sign events is shown in Fig. 4. After subtracting the background, a three parameter fit has been made to determine the level of the Drell-Yan, $\Upsilon$, $\Upsilon'$, $\Upsilon'' \rightarrow \mu^+\mu^-$, and residual heavy flavor decays, using their individual mass distributions and allowing for the CD resolution. After correcting for acceptance, we find

$$\sigma \cdot B(p\bar{p} \rightarrow \Upsilon, \Upsilon', \Upsilon'' \rightarrow \mu^+\mu^-) = 905 \pm 148 \pm 216 \text{ pb}$$
$$\sigma(\text{Drell-Yan}; m_{\mu\mu} > 11\text{GeV/c}^2) = 302 \pm 51 \pm 88 \text{ pb}$$

in good agreement with extrapolations from lower energy data.

The distribution of $m_{\mu\mu}$ for the unlike-sign events in the enlarged $J/\psi$ sample described previously shows a clean peak at $m_{\mu\mu} = 3.116\pm 0.006$ GeV/c$^2$, with a width consistent with the CD resolution, containing 280 $\pm 12$ events. The corresponding cross section is

$$\sigma(p\bar{p} \rightarrow J/\psi X, p_T(J/\psi) > 5 \text{ GeV/c}) = 82 \pm 28 \text{ nb}$$

In Fig. 5 we show the inclusive $J/\psi p_T$ distribution. It is interesting to speculate that the observed $J/\psi$ signal is a result of the process $b \rightarrow J/\psi X$, for which the branching ratio has been measured to be $\sim 1\%$. The curve in Fig. 5 is from a first order QCD calculation, where 70% of the $J/\psi$ is produced by $b$ decay, which has been scaled by the ratio of the measured inclusive $d\sigma/dp_T$ and the (similar) first order ISAJET prediction (see Fig. 7). The good agreement suggests that we might have another handle on beauty production. A search for the presence of a $b$ decay in these events is in progress.

OPEN $b\bar{b}$ PRODUCTION

The direct evidence for open $b\bar{b}$ production in the non-isolated dimuon events is twofold. Firstly, the existence of a significant number of like-sign events (142 $-$ 45 = 97) which cannot come from the direct decays of $c\bar{c}$ events (given no mixing in the $c$ system) implies the presence of $b$ quarks. Secondly, we can use the difference in the relative transverse momentum between the muon and a beauty or charm jet to separate the two cases on a statistical basis.

Fig. 5- Transverse momentum distribution of $J/\psi$'s. The curve is a first order QCD prediction scaled to the UA1 single muon data.

In Fig. 6 are plotted those 175 non-isolated events in which a charged particle jet is identified in the CD, in order to get the best possible measurement of the jet direction. At least one $p_T > 1$ GeV/c track is required in the jet, and the jet axis must lie within $\Delta R < 1.0$ of the muon. For the like-sign events, in order to look predominately at first generation decays, only the higher $p_T$ muon is used. By performing a two parameter fit to the data after background subtraction, using Monte Carlo $p_T\rightarrow f$ distributions for the charm and beauty jets, we find that the fraction of events due to $c\bar{c}$ is $(17 \pm 11\%)$ for the unlike-sign data and $(0 \pm 11\%)$ for the like-sign data. Combining both like- and unlike-sign samples leads to a global charm fraction of $c\bar{c}/(c\bar{c} + b\bar{b}) \sim 10\%$, which is in good agreement with QCD predictions.

The inclusive muon differential cross section, $d\sigma/dp_T$, for these non-isolated events is plotted in Fig. 7 and compared to a QCD prediction. Also shown is $d\sigma/dp_T$ for the single muon events after more restrictive cuts have been applied. Both distributions are corrected for acceptance and are background subtracted. Good agreement with the data is observed.

We note that for the single muon prediction, higher order processes, due largely to $q \rightarrow b\bar{b}, c\bar{c}$, are important. In calculating this gluon splitting process, a cutoff on the $Q^2$ of the gluon is used, which may account for the fact that the prediction is smaller than the data. In the dimuon events these contributions are suppressed by the dimuon mass cut, but nonetheless account for about 25% of the predicted cross section. $\Delta \phi_{b\bar{b}}$ is sensitive to these processes. Fig. 8 shows that the higher order processes are needed to account for the low $\Delta \phi_{b\bar{b}}$ part of the distribution and that they appear in correct proportion to the lowest order process.

Normalizing the predicted number of dimuon events to the data yields a cross section for direct beauty production of

$$\sigma(p\bar{p} \rightarrow b\bar{b}X) = 1.2 \pm 0.1 \pm 0.4 \text{ pb}$$
Fig. 6—Transverse momentum of muons relative to the axis of jets measured in the CD, for (a) unlike-sign and (b) like-sign dimuon events. The curves are the result of a two parameter fit to the data for the b\bar{b} and c\bar{c} components, after background subtraction. For the like-sign events, only the higher \( p_T \) muon was used.

Fig. 7—Inclusive muon \( p_T \) distributions for single muon and \( m_{\mu\mu} > 6 \text{ GeV/c}^2 \) dimuon events, after acceptance correction and background subtraction. The curves are absolutely normalized QCD predictions from the ISAJET program.

Fig. 8—Azimuthal angle difference between muons for the non-isolated muon pairs. The curves are QCD predictions, normalized to the number of events in the plot.

where \( p_T > 5 \text{ GeV/c}, \ |\eta| < 2.0 \) for both quarks, and the systematic error of 0.4 \( \mu \text{b} \) includes the uncertainty on the parameters in the Monte Carlo, as well as on the luminosity and detector acceptance.

REFERENCES

   The value of \( f_x = 0.58 \) was determined from parameterizations of the inclusive charged particle and inclusive pion \( p_T \) distributions of UA2, evaluated at 3 GeV/c. \( f_K = 0.21 \) was determined assuming that the \( K/\pi \) ratio at fixed \( m_{\mu\mu} \equiv \sqrt{m^2 + p_T^2} \) is constant, and extrapolating the low \( p_T \) UA2 data to \( p_T = 3 \text{ GeV/c} \).