Study of Heavy Flavour Production in Events with a Muon Accompanied by Jet(s) at the CERN Proton-Antiproton Collider.

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ABSTRACT

We present a study of heavy flavour (charm and beauty) production using data collected with the UA1 detector at the CERN Proton-Antiproton collider at a centre-of-mass energy of 630 GeV for an integrated luminosity of 556 nb^{-1} . This follows our earlier study of $b\bar{b}$ and $c\bar{c}$ production in dimuon events and the evidence for mixing between B^0 and $\bar{B}^0$ states.

Properties of an inclusive sample of events containing a muon with $p_T > 6 \text{ GeV}/c$ are compared with QCD predictions for heavy flavour production, using the ISAJET Monte Carlo program. The predicted large p_T muon yield from heavy flavour production and decay agrees with the data to within 30%. For events with a muon of $p_T > 10 \text{ GeV}/c$ and at least one jet with $E_T > 10 \text{ GeV}$, we measure the ratio charm / (charm + beauty) to be $(24 \pm 8 \pm 9)\%$. We also show that the correlations observed between the two heavy quark jets expected by flavour conservation are consistent with the expected mixture of lowest and higher order QCD processes.

We study in detail the topological and kinematic properties of a subsample of events containing a high p_T muon and one or more jets. The good agreement of the theoretical predictions with our data in a region dominated by the production of charm and beauty shows that one of the main background sources to a new heavy quark signature is well understood.

1.- INTRODUCTION

Large p_T heavy flavour production in proton-antiproton collisions at $\sqrt{s} = 630$ GeV can be studied by selecting events with jets containing a large p_T muon. Such a study is interesting in itself to understand the production mechanisms yielding large p_T charm and beauty jets. This understanding is also a necessary step in the search for any new heavy quark. For example, the main background faking the topology of a heavy top semi-leptonic decay comes from $b\bar{b}g$ final states where one of the b-quarks decays semi-leptonically, producing an almost isolated charged lepton [1].

In [2], we reported evidence for beauty production through the observation of non-isolated dimuon events. In this paper we study the properties of single muon events. We first show that the inclusive muon p_T spectrum from $p_T = 6$ GeV/c up to $p_T = 100$ GeV/c is well described by known physics processes. We then demonstrate that our data are consistent with heavy flavour production mechanisms and the relative contributions of beauty and charm predicted by the QCD-inspired ISAJET Monte Carlo program. Finally, we make a detailed study of the topological and kinematic properties of events with a muon having $10 \text{ GeV/c} < p_T < 15 \text{ GeV/c}$ and one or more jets with $E_T > 12 \text{ GeV}$, a kinematic region where heavy flavour production is expected to dominate.

2.- DATA SAMPLE

The analysis uses the inclusive muon data collected by UA1 at the CERN $\bar{p}p$ collider in 1984 and 1985 at $\sqrt{s} = 630$ GeV, corresponding to a total integrated luminosity of 556 nb^{-1} . The UA1 muon detector and triggering system have been described elsewhere [3]. During the 1985 run a muon detection system based on limited streamer chambers (LSC) with analogue read-out [4] was operational in addition to the muon drift chambers (MDC). In the central region the system consists of magnetised (1.3 T), 60 cm thick, iron walls instrumented with three layers of LSCs, having a resolution of 1.2 mm, providing a momentum measurement independent of the central detector (CD). In the forward regions two layers of LSCs were placed outside the calorimeters, before an iron wall (1.2 m thick at the centre) separating the LSCs from the MDCs. To maintain an acceptable trigger rate, the acceptance of the inclusive muon trigger was reduced to a pseudo-rapidity range of typically $|\eta| < 1.5$. A final selection was made off-line of all events containing a muon with $p_T > 6 \text{ GeV/c}$ and passing tight cuts on the muon track reconstruction [5]. The reconstructed track must have at least 20 measured points in the CD with a good fit of the trajectory in the 0.7 Tesla magnetic field; a further algorithm is applied to reject possible π/K decays by detection of kinks along the reconstructed track. Good matching is also required in position and direction between the extrapolated CD track and the track vector measured in the muon chambers after at least 9 nuclear interaction lengths. This procedure selects about 20000 events with a muon candidate with $p_T > 6 \text{ GeV/c}$. These events were fully reconstructed using standard UA1 programs. In the

following analysis we will refer to muon-jet events as the sub-class of events containing both a muon and one or more calorimeter jets. Calorimeter jets are defined using the standard UA1 jet finding algorithm [6] and quoted jet transverse energies are the uncorrected values given by the algorithm.

3.- BACKGROUND TO THE MUON SIGNATURE

The main sources of background to the primary muon signature in UA1 are the following :

- decays of kaons and pions in flight
- non-interacting hadrons
- shower leakage
- leakage through cracks
- cosmic rays
- misassociation of central detector and muon chamber tracks

The probability for a $\pi(K)$ to decay in flight in the rapidity range $|\eta| < 1.5$ is $0.023(0.11)/p_T$. The probability for a hadron to penetrate the nine or more interaction lengths of absorber without interaction is less than 10^{-4} , and test beam measurements [7] have shown that the shower leakage background is also less than 10^{-4} per incident hadron. Leakage through cracks is effectively removed by local fiducial cuts in the muon selection. The background from cosmic rays (clearly identified by software) is negligible. By scanning a sub-sample of events, it has been checked that the background from misassociation (reduced by tight matching between the reconstructed tracks in the CD and muon chambers) is small compared to the direct decay background.

In summary, the dominant background contribution comes from π/K decays in flight. The inclusive charged particle p_T distribution has been measured by UA1 up to $p_T = 25$ GeV/c [8]. Based on UA2 [9] and UA5 [10] measurements at p_T below 5 GeV/c, we infer a charged particle mixture of 58% π and 23% K at all values of p_T . We have used a simulation of π/K decays in the central detector to estimate the fraction of decays which pass the muon selection criteria and to correct for the difference between the measured p_T and the p_T of the parent π/K . This gives, for each possible p_T of the hadron (p_T^h), the probability density $F(p_T^h, p_T^\mu)$ to observe a decay muon with reconstructed transverse momentum p_T^μ . The decay background is then a convolution of this function with the inclusive p_T distribution for hadrons:

$$d\sigma^\mu/dp_T^\mu = \int F(p_T^h, p_T^\mu)(d\sigma^h/dp_T^h)dp_T^h.$$

In practice, the function $F(p_T^h, p_T^\mu)$ is replaced by a two-dimensional table, binned in p_T^h and p_T^μ , and averaged over the rapidity acceptance of the muon trigger.

Fig. 1 shows the inclusive p_T distribution, $d\sigma/dp_T$, in the kinematic range $|\eta^\mu| < 1.5$ and $p_T^\mu > 6$ GeV/c for the 20000 muon candidates and for the decay background calculated as described above. The background fraction is shown as a function of p_T^μ and decreases from about

75% to 20% as p_T^μ increases from 6 GeV/c to 20 GeV/c. For $p_T^\mu > 40$ GeV/c, where insufficient statistics are available for the background calculation, a constant fraction of 15% has been assumed. The net systematic uncertainty on the decay background normalization is estimated to be (+20%,-30%), largely due to the uncertainty on the charged particle composition ($\pm 16\%$).

For muon-jet events, the decay background calculation is similar, except that the parent hadron spectrum $d\sigma^h/dp_T^h$ is now taken from an inclusive jet data sample of 0.11nb^{-1} recorded with a hardware trigger threshold of 5 GeV and fully efficient for jets with $E_T > 8$ GeV. Decay background events are generated, starting from a real event from which the energy deposition of the hadron which is required to decay is removed. A decay of that hadron into a muon is simulated, thus superimposing a simulated decay muon on to the initial event, and the calorimeter reconstruction (including jet-finding) is repeated for the modified event. The method provides fake muon events which can be processed in the same way as real data, applying identical selection criteria. Each event is assigned a weight which is the probability for the initial hadron to fake the reconstructed muon, as given by the decay tables. Weighted background events can then be used to provide the background distribution within the actual data for any chosen kinematic variable. The two main uncertainties on the background distributions are the systematic error (+20%,-30%) from the decay tables and the error due to the limited statistics of the low E_T jet sample.

A powerful check of the background calculation was made by applying an independent method to dimuon events [2]. In this second method, the χ^2 distribution for central detector-muon chamber matching for muon candidates in dimuon data is compared to the corresponding χ^2 distributions for samples dominated respectively by prompt muons (J/ψ events) and decay muons (inclusive muon data for $p_T > 3$ GeV/c which contains more than 80% decay background). A two component fit to the χ^2 distribution using the different shapes observed for prompt and decay muons is then performed to estimate the fraction of fake muons in the dimuon sample. The two background estimates agree to better than 10%.

The upgraded muon detection system allows a third evaluation of the background. For muon candidates in the side walls, we considered the difference between the two momentum measurements (in the CD and in the iron wall spectrometer) whose distribution is different for prompt muons and decay background. Fitting the shape of this distribution for the inclusive muon sample as a superposition of those for prompt muons (cosmics with $p_T > 6$ GeV/c) and background (inclusive muons with $p_T > 3$ GeV/c) we obtained a background fraction in agreement with the previous calculations within 10%. In the forward regions we evaluated the background statistically from the multiple scattering in the iron between the LSCs and the MDCs, comparing the distributions of the distance between the impact point on the LSCs and the one extrapolated from the MDCs using similarly defined samples. Again the background estimate agrees with those previously described to within 10%.

4.- MONTE CARLO STUDIES

4.1) General Remarks:

In [2] the measured inclusive muon differential cross-section, $d\sigma/dp_T$, for the process $p\bar{p} \rightarrow \mu^\pm X$ at $\sqrt{s} = 630$ GeV in the kinematic range $6 \text{ GeV}/c < p_T^\mu < 15 \text{ GeV}/c$, $|\eta^\mu| < 1.5$, was compared to QCD predictions from the ISAJET Monte Carlo program [11] for beauty and charm production: $p\bar{p} \rightarrow Q\bar{Q} X$, $Q \rightarrow \mu^\pm X$ where $Q = b$ or c . It was shown that the lowest order QCD calculation for heavy flavour creation:

$$q\bar{q} \rightarrow Q\bar{Q}, \quad gg \rightarrow Q\bar{Q}$$

accounts for only about 1/3 of the observed single muon cross-section. Two other processes contribute to the large p_T single muon yield:

$$\text{flavour excitation:} \quad qQ \rightarrow qQ, \quad gQ \rightarrow gQ$$

$$\text{final state gluon splitting:} \quad g \rightarrow Q\bar{Q}.$$

These two processes account for about 2/3 of the cross-section (1/3 each). Because of the harder fragmentation involved in $b \rightarrow \mu$ as compared to $c \rightarrow \mu$, 75% of the predicted single high p_T muons come from beauty decays.

In this paper, we study the properties of events associated with a large p_T muon: number of associated jets, isolation of the muon and various kinematic quantities. We make a systematic comparison with predictions for the production of heavy flavours $b\bar{b}$ and $c\bar{c}$. In order to understand the significance of such a study it is necessary to describe here in detail the relevant phenomenological assumptions used in the ISAJET Monte Carlo program (version 5.23).

4.2) Phenomenological Assumptions in ISAJET

4.2.a) QCD subprocesses and structure functions --

Hard scattering cross sections are calculated using QCD matrix elements to lowest order in α_s , the strong running coupling constant. A convolution is made with structure functions evaluated at the hard scattering Q^2 defined as: $Q^2 \equiv 2stu/(s^2+t^2+u^2)$, where s , t and u are the Mandelstam variables of the parton-parton scatter. At order α_s^2 , and in the kinematic regime $p_T^Q \gg m_Q$, two subprocesses are considered to produce a large p_T heavy quark: flavour creation and flavour excitation.

In the heavy flavour excitation mechanism, a heavy quark from the sea undergoes a hard scattering with a light quark or a gluon from the other incident hadron. ISAJET uses the heavy quark structure function of Eichten et al. (EHLQ, set I), as recently updated by the same authors [12]. The heavy quark sea at large Q^2 is obtained by evolving initial parton distributions at $Q_0^2 = 5 \text{ GeV}^2/c^4$, without any intrinsic heavy quark component.

4.2.b) Initial and final state gluon bremsstrahlung --

Hard partons participating in the large- Q^2 subprocesses are evolved using the basic QCD branching processes $q \rightarrow qg$, $g \rightarrow gg$ and $g \rightarrow q\bar{q}$. The scattered partons are given a virtual mass with a maximum of order Q . The partons generated during the evolution acquire successively lower virtual masses and the evolution stops when the virtual mass falls below a fixed cut-off $\sqrt{|p^2|} = m_p + 6 \text{ GeV}/c^2$, where m_p is the on-shell mass of the parton. This branching approximation [13] correctly describes the leading-log scaling violations of the structure functions and of the jet fragmentation and also reproduces the observed jet multiplicity in jet data at SPS collider energies [14].

Heavy quark production in gluon jets is a consequence of the evolution of final state gluons. This is an abundant source of heavy quarks at large p_T [15], since the gluon jet cross section is large. For gluon splitting into $b\bar{b}$ and $c\bar{c}$, the cut-off mass of $6 \text{ GeV}/c^2$ below which the gluon is hadronized is between the $c\bar{c}$ and the $b\bar{b}$ thresholds. Consequently the cross section for the reaction $p\bar{p} \rightarrow gX$, $g \rightarrow c\bar{c}$, $c \rightarrow \mu$ is underestimated. However, for $p_T^\mu > 8 \text{ GeV}/c$, the mass distribution of the parent virtual gluon shows a broad spectrum ranging from the cut-off of $6 \text{ GeV}/c^2$ up to a maximum of about $20 \text{ GeV}/c^2$, with a mean value $\langle m(g \rightarrow c\bar{c}) \rangle = 12 \text{ GeV}/c^2$. From this we estimate that the loss is smaller than 10% for the production of muons with $p_T^\mu > 8 \text{ GeV}/c$ from gluons splitting into charm.

In the case of heavy flavour excitation, the incoming heavy quark is evolved backwards [16] until a cut-off of $6 \text{ GeV}/c^2$ is reached. In order to conserve heavy flavour, it is required that, during this evolution, the branching $g \rightarrow Q\bar{Q}$ always occurs. This process leads to a final state where one high p_T heavy quark is produced at large angle and is balanced in momentum by a light quark or gluon. The other heavy quark tends to be produced more in the forward direction. Therefore gluon splitting in the initial state leads to a topology different from that of gluon splitting in the final state. In this approximation, valid only in the kinematic regime $p_T^Q \gg m_Q$, the two processes are considered as independent production mechanisms.

4.2.c) Jet fragmentation --

As a result of the QCD evolution, the final state partons are all on mass shell. They are then hadronized according to the independent fragmentation model of Field and Feynman [17]. This fragmentation model reproduces the measured properties of low energy ($\sim 6 \text{ GeV}$) jets and justifies the use of a 6 GeV cut-off on the parton shower evolution. The combination of the parton cascade and the hadronization model reproduces many features of the measured jet fragmentation properties at SPS collider energies [18]. In particular, the softening of the fragmentation function $D(z)$ observed when going from $13 \text{ GeV } E_T$ jets (ISR or PETRA) to $40 \text{ GeV } E_T$ jets (collider) is a feature of the parton cascade model. In ISAJET a gluon is fragmented at the end of the cascade as if it were a light quark or antiquark. The difference expected between a gluon jet and a light quark jet is therefore only due to the fact that, in the cascade, gluons radiate more than quarks (the branching $q \rightarrow q + g$ is less probable than the branching $g \rightarrow g + g$ by a factor $4/9$). The small

differences seen at the SPS collider between gluon and light quark jets [18] are compatible with the predictions from ISAJET. Gluon jets have a higher multiplicity and are slightly broader than light quark jets.

Charm and beauty quark fragmentation has been extensively measured with e^+e^- colliders [19]. ISAJET has been tuned to reproduce these results. As for ordinary quarks, heavy quarks of large virtual masses initiate a parton shower until a mass cut-off is reached at $\sqrt{|p^2|} = m_Q + 6 \text{ GeV}/c^2$. The resulting heavy quark is then put on the mass shell and fragmented into a leading heavy flavour hadron in the following proportions:

$$Q\bar{U} : Q\bar{D} : Q\bar{S} : Qq = 38.7\% : 38.7\% : 12.6\% : 10\%$$

The ratio of spin 1 to spin 0 (spin 3/2 to spin 1/2 for baryons) is assumed to be $B^*/B = D^*/D \sim 3$. This analysis does not depend strongly on these assumptions as we do not distinguish individual charm or beauty hadrons.

The z distribution of the leading heavy hadron is parameterised with the Peterson *et al.* form [20]:

$$D(z)dz = \frac{N}{z \left[1 - \frac{1}{z} - \frac{\epsilon_Q}{(1-z)} \right]^2} dz$$

where z is the fragmentation variable defined as: $z = (E+p_L)_{\text{hadron}} / (E+p_L)_{\text{quark}}$, and:

- N is a normalization factor.
- p_L is the longitudinal component of the momentum with respect to the quark axis.
- E is the energy evaluated in the same Lorentz frame as p_L , so that z is invariant with respect to Lorentz boosts along the quark axis.
- ϵ_Q is a parameter which depends on the quark mass.

For ISAJET 5.23, ϵ_c was tuned to reproduce the e^+e^- results on $c \rightarrow D^*$ [19], giving $\epsilon_c = 0.30$; for beauty we use $\epsilon_b = 0.02$. The uncertainty on ϵ_Q is the main source of error on the predicted inclusive muon cross-section given the quark cross-section.

The weak decays of heavy hadrons are simulated using V-A matrix elements. The most recent measurements or estimates of the decay branching ratios of charm and beauty hadrons [21] have been incorporated. For beauty hadrons an average semi-leptonic branching ratio is used:

$$\text{Br}(B \rightarrow e) = \text{Br}(B \rightarrow \mu) = 12\%.$$

We have checked that ISAJET reproduces the e^+e^- measurements of charm and beauty decays [22].

4.2.d) The spectator contribution --

The remaining spectator quarks from the proton and the antiproton beams are hadronized in ISAJET such that long range correlations similar to those observed in minimum bias events at SPS collider energies [23] are generated. The global multiplicity distribution was adjusted so that it reproduces the height of the multiplicity plateau in high E_T jet events far away from the jet axes [24]. Similarly the average transverse momentum of primary mesons is adjusted using the same jet data and fixed at $\langle p_T \rangle = 0.45 \text{ GeV}/c$.

The muon isolation is a crucial parameter in the study of heavy quarks including the search for the top quark. In particular a muon from a heavy top quark or from a $W^\pm$ or a Z^0 decay is often isolated. In these processes, the energy flow around the muon reflects the level of activity from the spectator jets. It is therefore important to compare the properties of the simulated underlying event coming from the fragmentation of the spectator jets to measurements using our muon-jet data. Figures 2a, 2b and 2c show the charged multiplicity, the charged track transverse momentum and the transverse energy flow respectively, as a function of $\Delta\eta = \eta(\text{track}) - \eta(\text{muon})$, the pseudo-rapidity difference between the muon and any track (charged track or energy vector) produced in the same azimuthal half-cylinder as the muon (all tracks with $\vec{p}_T^{\text{track}} \cdot \vec{p}_T^{\text{muon}} > 0$). The histograms represent the data and the black dots the Monte Carlo predictions after full detector simulation.

Far away from the muon, for $1 < |\Delta\eta| < 2$, one observes a rapidity plateau which results from two contributions, the dominant one from the spectator jets and a smaller one from initial state gluon radiation.

The transverse energy (E_T) plateau is well described and corresponds to a level of about 4 GeV in $|\Delta\eta| = 1$, $\Delta\phi = \pi$. However, to reach a satisfactory agreement in the charge multiplicity n_{ch} and p_T profiles, the charge multiplicity of the spectator jets in ISAJET 5.23 was scaled down by a factor 0.6. This factor is included in the Monte Carlo predictions of Fig. 2.

Figs. 2d, 2e and 2f show the comparison between ISAJET and the data for the same profiles as in Figs. 2a, 2b and 2c but around the axis of the highest E_T jet (Jet 1) in each event (with $E_T^{\text{jet1}} > 12$ GeV) and away from the muon ($\Delta R(\mu\text{-jet}) > 1$ where $\Delta R \equiv (\Delta\eta^2 + \Delta\phi^2)^{1/2}$). The jet profiles in charged multiplicity, p_T and E_T are reasonably well described, except that the charged multiplicity is not as well predicted as it is around the muon; in the jet core the charged multiplicity is overestimated by about 30%. It should be noted that, according to ISAJET, jet 1 is produced by gluon fragmentation in 70% of all events, with 23% and 7% respectively from fragmentation of beauty and charm quarks. The peaking of the distributions around the muon direction indicates that most muons are produced inside jets, as expected from heavy flavour production $b \rightarrow \mu(74\%)$, $c \rightarrow \mu(26\%)$. This important point will be discussed in more detail below.

4.3) Monte Carlo Event Samples

A large Monte Carlo production was performed for all processes contributing to the muon-jet data sample [25]:

- $b\bar{b}$ and $c\bar{c}$ production via flavour creation, flavour excitation and gluon splitting.
- Intermediate vector bosons, $W^\pm$ and Z^0 , with all decay channels excluding the top quark.
- J/ψ , Υ , and Drell-Yan production at large p_T .
- Top quark production (discussed in detail in [26]).

In all channels we have generated the equivalent of 10 pb^{-1} of Monte Carlo data, which represents about 18 times the size of our present data sample. The cross section for producing intermediate

vector bosons is taken from measured data [27]. For large p_T $W^\pm$ production, ISAJET uses QCD diagrams of first order in α_s : $q\bar{q} \rightarrow Wg$, $qg \rightarrow Wq$. These contributions diverge as $p_T^W \rightarrow 0$. A cut-off is used at low p_T to reproduce the expected low p_T behaviour. In order to obtain good agreement with the measured $d\sigma/dp_T$ spectrum [28], the high p_T tail produced by ISAJET was weighted with the ratio of the observed value to the generated value in bins of p_T .

The cross sections for Υ and Drell-Yan production are taken from our dimuon data [2]. For Drell-Yan production, large p_T muons are produced in two different regimes:

- high mass pairs at low p_T , where we have measured a cross-section [2] of 0.25nb for $M_{\mu\mu} > 11 \text{ GeV}/c^2$.
- low mass pairs at large p_T , which have been measured [29] in the kinematic range $2m_\mu < M_{\mu\mu} < 6 \text{ GeV}/c^2$, $6 \text{ GeV}/c < p_T^{\mu\mu} < 30 \text{ GeV}/c$.

The ISAJET Drell Yan simulation reproduces the measured cross-section at low p_T for large masses, but the large p_T tail of the low mass pairs was scaled up by a factor 2.5 to fit the data.

J/ψ 's at large p_T have been measured directly in our di-muon data ($p_T^{J/\psi} > 4 \text{ GeV}/c$) and are discussed in a separate publication [30]. Part of the cross section comes from beauty decay, $B \rightarrow J/\psi + X$, and is incorporated as one decay mode in $b\bar{b}$ production, using the measured branching ratio $\text{Br}(B \rightarrow J/\psi) = 1.2\%$ [31]. The other source of J/ψ is direct charmonium production, which can produce isolated J/ψ 's at large p_T and provides, together with $\Upsilon \rightarrow \mu + \mu^-$ and Drell-Yan, isolated large p_T muons when only one of the two muons is observed in the detector.

Local modifications [25] were introduced in ISAJET to allow an efficient and unbiased generation of events containing a large p_T lepton from direct (flavour creation and excitation) and indirect (gluon splitting) heavy quark production. In practice, only events satisfying at least one of the following criteria were kept in the ISAJET generation stage :

- at least one muon with $p_T^\mu > 6 \text{ GeV}/c$.
- at least one electron with $E_T^e > 8 \text{ GeV}$.
- at least one J/ψ decaying into muons with $p_T^{J/\psi} > 3.5 \text{ GeV}/c$.
- at least two leptons, e or μ , satisfying $p_T^e > 5 \text{ GeV}/c$ and $p_T^\mu > 2.5 \text{ GeV}/c$.

All these events were passed through the full UA1 detector simulation and reconstruction programs. They were then selected and analysed with the same programs as the data. The electron Monte Carlo data are discussed in more detail in our publication on the search for new heavy quarks [26]. In this paper only muon events are used, since a muon can be identified even in the proximity of a jet.

A check of the detector simulation quality for muons can be made with $W^\pm$ data in the muon channel. Fig. 3 shows the distribution of ΣE_T , the scalar sum of transverse energies measured in calorimeter cells in a cone $\Delta R = (\Delta\eta^2 + \Delta\phi^2)^{1/2} < 0.7$ around the muon. There are two contributions to ΣE_T , namely the energies deposited by the muon and by the spectator jets. The curve was obtained from fully simulated $W \rightarrow \mu\nu$ events. Fig. 4 shows the distribution of Σp_T , the scalar sum of the transverse momenta of the charged tracks measured in the central detector in a cone $\Delta R < 0.7$ around the muon direction, but excluding the muon track itself. The largest

contribution to this distribution comes from the spectator jets with a small component from gluon bremsstrahlung. Good agreement with the data was obtained after scaling down the ISAJET charged track multiplicity of the spectator system by a factor 0.6, as discussed in section 4.2.d. This was done consistently throughout the analysis described in this paper.

5.- THE INCLUSIVE MUON SPECTRUM

The inclusive muon cross-section $d\sigma/dp_T$ is shown in Fig. 5 and Table 1 for $p_T^\mu > 6$ GeV/c and $|\eta^\mu| < 1.5$, after subtraction of the decay background spectrum shown in Fig. 1. In this figure and in the following analysis, p_T^μ has not been corrected for smearing due to momentum measurement errors in the CD, which typically exceed 10% for $p_T^\mu > 20$ GeV/c. The dashed curve shows the equivalent prediction for the muon cross-section obtained by summing all the physics processes considered in ISAJET, namely charm and beauty production, W and Z decay, Drell-Yan, J/ψ and Υ production. The dash-dotted curve shows the predicted contribution from $W \rightarrow \mu\nu$ alone; the Jacobian peak is spread out due to the limited momentum resolution at 40 GeV/c ($\sim 20\%$). The W contribution increases with p_T from $\sim 10\%$ at 15 GeV/c and exceeds the $b\bar{b}/c\bar{c}$ contribution for $p_T^\mu > 25$ GeV/c.

Below 10 GeV/c the errors on the measured cross-section are dominated by the uncertainties on the decay background subtraction. In Table 2 we give a summary of the contributions to the inclusive cross-section in the region $10 \text{ GeV/c} < p_T^\mu < 15 \text{ GeV/c}$, $|\eta^\mu| < 1.5$. After subtraction of $\sim 36\%$ decay background, the measured cross-section is:

$$\sigma_{\text{DATA}}(10 \text{ GeV/c} < p_T^\mu < 15 \text{ GeV/c}, |\eta^\mu| < 1.5) = 4.33 \pm 0.20^{+0.83}_{-0.56} \text{ nb.}$$

where the first error is statistical and the second is systematic, dominated by the error on the background subtraction. The main contribution comes from semi-leptonic decays of charm and beauty particles. If we subtract all contributions not arising from heavy quarks from the measured cross-section, we get a ratio:

$$N = \text{DATA} / \text{ISAJET} = 1.24 \pm 0.06^{+0.24}_{-0.16}$$

for beauty and charm production, consistent with unity.

In the region $10 \text{ GeV/c} < p_T^\mu < 15 \text{ GeV/c}$, the ratio $b\bar{b}/(b\bar{b}+c\bar{c})$ is predicted to be 74%, due to the harder fragmentation for $b \rightarrow \mu$ compared to $c \rightarrow \mu$. The lowest order flavour creation process accounts for only $\sim 39\%$ of the total muon yield from heavy flavour at large p_T ; the higher order processes of flavour excitation ($\sim 34\%$) and gluon splitting ($\sim 27\%$) are needed to explain the measured muon cross-section. This result implies that the different topologies predicted for the three production mechanisms may be observable in the data.

In our previous analysis [2] in the range $6 \text{ GeV/c} < p_T^\mu < 15 \text{ GeV/c}$, the ISAJET prediction was a factor 1.5 below the data; the present factor 1.24 is more accurately determined. The decay background calculation at large p_T has been improved by extending our measured charged hadron

spectrum up to 25 GeV/c using jet data [8]. We also now subtract small but non-negligible contributions from Drell-Yan, J/Ψ and Υ .

6.- SEPARATION OF CHARM AND BEAUTY DECAYS

In a previous paper [2], we reported a statistical separation of dimuons from $c\bar{c}$ and $b\bar{b}$ production using the muon transverse momentum (p_T^{rel}) relative to the jet axis (jet defined by the charged track activity around the muon). The same technique can be used in the single muon sample, but is complicated by the larger fraction of events from higher order processes and, in particular, from gluon splitting which was suppressed by the dimuon mass cut ($M_{\mu\mu} > 6 \text{ GeV}/c^2$) in the previous analysis. Gluon splitting may distort the muon-jet measurement when the second heavy flavour jet is close to the muon. As in the dimuon case, we work in the central detector because it has a spatial resolution far superior to that of the calorimeter.

For this study we use events with a muon of $p_T^\mu > 10 \text{ GeV}/c$ produced with at least one calorimeter jet with $E_T > 10 \text{ GeV}$; the axis of this jet must be outside a cone of $\Delta R = 1$ around the muon and the jet must contain at least one charged track with $p_T > 0.5 \text{ GeV}/c$ in a cone of $\Delta R = 0.4$. This sample contains 1188 events. To reduce distortions from gluon splitting we first require that the muon be contained in a central detector jet whose cone size is small enough that the probability of significant contamination from a second heavy flavour jet is small. By studying both the data and the Monte Carlo $b\bar{b}$, $c\bar{c}$ samples, a cone size of $\Delta R = 0.6$ was found to contain fully the heavy flavour jet associated with the muon. By requiring a central detector jet found with a jet algorithm cone size of $\Delta R = 0.6$ and containing at least one track with $p_T > 1 \text{ GeV}/c$ in addition to the muon, the sample is reduced to 797 events. A second cut [32] is then made to exclude jets with a lot of transverse activity in addition to the muon; for such jets the muon may acquire a large p_T^{rel} irrespective of its source. The level of transverse activity, m_T , is defined as the sum of the transverse momenta of the charged particles other than the muon with respect to the vector sum of their momenta. Events are rejected if m_T exceeds 2 GeV/c, reducing the sample from 797 to 727 events. This cut has the additional advantage of removing events dominated by systematics on the decay background calculation. After both cuts, ISAJET shows that the distortion from gluon splitting is reduced to a negligible level.

The measured p_T^{rel} distribution is shown in figure 6, along with fitted contributions from $b\bar{b}$, $c\bar{c}$ and background. The $c\bar{c}$ and decay background curves are similar, but the $b\bar{b}$ curve extends to higher p_T^{rel} , and a clear $b\bar{b}$ signal is seen in the data. A two parameter fit was made, fixing the decay background contribution at 33% and fitting the $b\bar{b}$ and $c\bar{c}$ contributions, and then propagating the decay background uncertainty into systematic errors on the fit results. This gives a contribution from $b\bar{b}$ production of $(51 \pm 6)\%$ and a ratio $c\bar{c}/(c\bar{c}+b\bar{b})$ of $(24 \pm 8 \pm 9)\%$ (the first error is statistical, the second systematic) to be compared with the ISAJET prediction of 26% for the same data sample.

7.- EXPERIMENTAL CHECK OF $b\bar{b}$ AND $c\bar{c}$ PRODUCTION MECHANISMS

ISAJET predicts that a substantial fraction ($\sim 2/3$) of heavy flavour production at large p_T comes from the flavour excitation and gluon splitting mechanisms. The main topological difference between these processes and the lowest order flavour creation process is the angular separation of the two heavy quarks. In order to test the prediction of ISAJET, we have selected events with a second muon in order to tag the second heavy quark. We require one muon with $p_T > 7$ GeV/c, a jet with $E_T > 12$ GeV and a second muon with $p_T > 3$ GeV/c. The resulting 64 events were further reduced to 46 by requiring $\Sigma E_T > 6$ GeV in a cone of 0.7 around the first muon; this cut reduces the contribution from Drell-Yan (and J/ψ 's from χ decays) to a negligible level. It is assumed that the contribution from p decays may also be neglected and we note that only two events have a dimuon mass below 1 GeV/c². The distribution of $\Delta\phi$, the azimuthal angle difference between the two muons, is plotted in Fig. 7, together with the fitted contributions from gluon splitting, flavour excitation and flavour creation. The decay background contribution is also shown. For flavour creation, the two heavy quarks are produced back-to-back in the transverse plane and hence $\Delta\phi$ peaks near 180° ; a small contribution is expected near $\Delta\phi = 0^\circ$ from cascade decays ($b \rightarrow \mu\nu c$, $c \rightarrow \mu\nu s$) and from $b \rightarrow J/\psi \rightarrow \mu\mu$. For gluon splitting $\Delta\phi$ peaks near 0° , partly because the two quarks are produced in the gluon direction and partly because of cascade or J/ψ decays (45%). For flavour excitation, one quark is produced at large p_T and the other is uncorrelated in ϕ , giving a mainly flat $\Delta\phi$ distribution. A three component fit has been made of these three shapes to the data, with the background contribution fixed. The result of the fit as percentages of the data after background subtraction are:

$$\begin{aligned} (45^{+16}_{-13})\% & \text{ flavour creation} \\ (33^{+31}_{-17})\% & \text{ flavour excitation} \\ (22^{+20}_{-17})\% & \text{ gluon splitting} \end{aligned}$$

compared to the ISAJET prediction for this selection of 33%, 39% and 28% respectively. The statistical errors are large, with no real distinction between the strongly correlated flavour excitation and gluon splitting components; nevertheless it is clear that flavour creation alone cannot explain the $\Delta\phi$ distribution.

8.- DETAILED PROPERTIES OF MUON-JET EVENTS

We now define a reference sample of muon-jet events and make a systematic comparison of the properties of these events with the Monte Carlo predictions for heavy flavour production. The muon is required to have a transverse momentum in the interval:

$$10 \text{ GeV/c} < p_T^\mu < 15 \text{ GeV/c}.$$

In this region the decay background is relatively small ($\sim 36\%$) and W and Z contributions are negligible. The jet requirement is that at least one calorimeter jet in the event has $E_T > 12$ GeV, outside a cone of $\Delta R=1$ around the muon direction. The jets are defined using the standard UA1 jet

algorithm [6]. The jet E_T value used in this paper is the uncorrected value from the jet algorithm. The same definition is used for the data and the Monte Carlo samples. Jet 1 is defined as the highest E_T jet satisfying the above cut. These cuts leave us with a sample of 658 events. In Fig. 5 we show the corresponding muon p_T spectrum for events with a jet with $E_T > 12$ GeV.

The predicted contributions to this sample from decay background, $b\bar{b}$ and $c\bar{c}$ production, and residual processes are given in Table 3. The quoted errors for the Monte Carlo predictions are statistical; the first error on the decay background is statistical, the second reflects the systematic uncertainty in the decay tables and the third represents the $\pm 15\%$ uncertainty in the luminosity of the low jet E_T threshold data sample. Adopting a similar procedure to that used for the purely inclusive muon selection, we find a normalization factor: $N = 1.05 \pm 0.09^{+0.21}_{-0.15}$ for the heavy flavour Monte Carlo contributions.

Additional jets in each event are considered above a jet E_T threshold of 7 GeV. A Monte Carlo study of the origin of such low E_T jets revealed that the reconstructed jet quality and matching to partons can be significantly improved by requiring some associated activity in the central detector. An additional jet is therefore counted only if there is a CD track with $p_T > 0.5$ GeV/c which matches the direction of the calorimeter jet axis within a cone $\Delta R = 0.4$; this track must also satisfy loose quality and vertex association criteria. Jets are not considered if their axes lie within a cone $\Delta R = 1$ about the muon direction.

The measured and predicted jet multiplicity distributions are shown in Fig. 8 and Table 3. The absolute numbers of muon events with 1,2,3,4 and even 5 jets are reproduced to $\sim 20\%$. This agreement is surprisingly good, given that the ISAJET QCD radiation was not tuned to our data and depends on only one a priori parameter, the 6 GeV mass cut-off on the parton shower evolution. Similar good agreement has been observed for multijet events with $\Sigma E_T > 200$ GeV [14].

The ISAJET parton shower model is an approximation to the exact $O(\alpha_s^n)$ QCD matrix elements ($n = 3, 4, \dots$). We select distributions of various kinematic quantities which are sensitive to some of the properties of these matrix elements. These distributions are shown in Figs. 9 to 12. The heavy flavour Monte Carlo contributions have been multiplied by the muon-jet N-factor of 1.05. In each case the full prediction, shown as a solid curve, is the sum of the decay background contribution (dotted curve) and the Monte Carlo processes (dashed curve), dominated by beauty and charm production, but also including residual W/Z , Υ , J/ψ and Drell-Yan contributions.

Fig. 9 shows the E_T spectrum of jet 1, the most energetic jet recoiling against the muon. The distribution peaks at the 12 GeV threshold and falls steeply as E_T increases. The decay background falls more steeply than the $b\bar{b}/c\bar{c}$ contribution, but the full prediction reproduces the slope of the data. Fig. 10 shows the azimuthal separation around the beam axis between the muon and jet 1: $\Delta\phi(\mu\text{-jet 1})$. The distribution peaks at $\Delta\phi$ near to 180° , but shows a tail of acoplanar configurations as expected from the substantial content of higher order QCD processes. The full prediction includes these processes and agrees with the data.

Higher order QCD processes imply the presence of at least a second jet; 283 events (43%) of the muon-jet sample have a second jet with $E_T > 7$ GeV and validated by a CD track of

$p_T > 0.5 \text{ GeV}/c$. The E_T spectrum of the second jet is shown in Fig. 11 and is well described by the prediction. $\theta_{\text{jet } 2}^*$ is the angle between the antiproton beam direction and the axis of jet 2 in the centre of mass of the system consisting of the muon, jet 1, jet 2 and the missing transverse energy ("neutrino"). Since jet 2 is produced mainly by initial state QCD radiation, we expect $\theta_{\text{jet } 2}^*$ to peak in the forward direction. This is confirmed in Fig.12, which shows the distribution of $|\cos\theta^*(\text{jet } 2)|$. The fact that the properties of jet 2 are well described by the Monte Carlo indicates that ISAJET contains a good approximation for $O(\alpha_s^3)$ heavy flavour QCD processes.

The semi-leptonic decay, $b \rightarrow \mu\nu c$, produces a neutrino preferentially in the same direction as the muon. However this neutrino is not expected to be energetic because of the trigger bias introduced by the requirement of a large p_T muon. The missing transverse energy spectrum (E_T^V) is shown in Fig. 13. The distribution peaks at $E_T^V \sim 5 \text{ GeV}$, which corresponds to the expected mean value from the calorimeter resolution combined with the muon momentum measurement error. Therefore the bulk of the events show no significant evidence for presence of neutrinos. Fig. 14 shows the azimuthal angle difference, $\Delta\phi$, between the muon and the missing transverse energy vector. The strong correlation near $\Delta\phi = 180^\circ$ is mainly due to muon momentum resolution and is well described by the decay background distribution (dotted curve); because of the falling p_T spectrum the muon momentum is systematically over-estimated, giving rise to a fake missing transverse energy opposite to the muon. However an enhancement is also seen near $\Delta\phi = 0^\circ$, as expected for $b\bar{b}/c\bar{c}$ but not for the decay background. Fig. 15 shows the $\Delta\phi$ distribution for events where the missing transverse energy exceeds 12 GeV. A significant peak is observed for $\Delta\phi < 30^\circ$ which cannot be explained by decay background. According to the Monte Carlo calculation, more than 50% of the events in this peak contain genuine neutrinos with $E_T^V > 5 \text{ GeV}$, coming from the semi-leptonic heavy flavour decay: $b \rightarrow \mu\nu c$ ($c \rightarrow \mu\nu s$).

Finally we investigate the fragmentation properties of beauty (charm) jets when the jet contains a muon from semi-leptonic decay. In Figs. 16 and 17 we show the isolation distributions of the muon for the sample of muon-jet events discussed in this chapter. ΣE_T is formed by adding the E_T contributions from all calorimeter cells within a cone of $\Delta R=0.7$ around the muon. The cone size of 0.7 was found to be optimal considering the calorimeter granularity and the associated spectator activity. Similarly Σp_T is formed by summing the p_T of all CD tracks within a cone of $\Delta R=0.7$, after applying loose quality and momentum cuts to the tracks. These loose cuts minimise the effect of small differences in track reconstruction for very low quality tracks between the Monte Carlo and the data. These two isolation variables are combined into a single variable, $I=(\Sigma E_T/3)^2+(\Sigma p_T/2)^2)^{1/2}$, which is used extensively in the search for new heavy quarks [26]. The relative proportions of ΣE_T and Σp_T were chosen to reflect the average values of these quantities in the underlying event. As shown in Fig. 18a, there is good agreement in the distribution of I between data and prediction. Figures 18b and 18c show the I distributions for events with $7 \text{ GeV}/c < p_T^\mu \leq 8 \text{ GeV}/c$ and $8 \text{ GeV}/c < p_T^\mu \leq 10 \text{ GeV}/c$ respectively, demonstrating that the isolation of muons is also well understood in regions where the decay background is relatively larger.

The effects of systematic uncertainties in the b-quark fragmentation and in the spectator jet fragmentation have been assessed. Varying the ϵ_b parameter of the b-quark Peterson fragmentation function in the range $0.001 < \epsilon_b < 0.05$, allowed by e^+e^- experiments, does not affect the isolation distribution but simply changes the absolute large p_T muon cross-section by $\pm 20\%$ for a fixed b-quark production cross-section. Variation of the spectator jet contribution by a factor two also has little effect on the isolation distribution, even at small values of I . The same is true for variation of the calorimeter energy scale. We conclude that the shape of the isolation distribution is well understood and depends primarily on the semi-leptonic decay kinematics of the heavy hadron which is well known from e^+e^- measurements.

9.- CONCLUSIONS

We have studied the reaction $p\bar{p} \rightarrow \mu + \text{jet(s)} + X$ and find good agreement between our data and QCD predictions for heavy flavour production using the ISAJET Monte Carlo. The predicted large p_T muon yield agrees with the data to within 30%. In events containing a muon with $p_T > 10 \text{ GeV}/c$ and at least one jet with $E_T > 10 \text{ GeV}$, the ratio $c\bar{c} / (b\bar{b} + c\bar{c})$ is measured to be $(24 \pm 8 \pm 9)\%$, in agreement with the Monte Carlo prediction. Our data are consistent with substantial heavy flavour production at large p_T via higher order QCD processes. We find that a range of detailed kinematical and topological properties of muon-jet events are well described by the Monte Carlo. This gives us confidence that the main background source to the signal for any new heavy quark, such as top, is well understood.

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Table 1: Inclusive Muon Cross-section.

$$|\eta^\mu| < 1.5$$

p_T^μ (GeV/c)	$\frac{d\sigma}{dp_T^\mu} \left(\frac{\text{nb}}{\text{GeV/c}} \right)$
6 - 7	11.65 $^{+10.49}_{-7.08}$
7 - 8	7.05 $^{+3.86}_{-2.65}$
8 - 9	4.44 $^{+1.67}_{-1.19}$
9 - 10	2.73 $^{+0.80}_{-0.56}$
10 - 11	1.84 $^{+0.40}_{-0.29}$
11 - 12	1.01 $^{+0.23}_{-0.18}$
12 - 13	0.62 $^{+0.18}_{-0.14}$
13 - 14	0.531 $^{+0.097}_{-0.082}$
14 - 15	0.343 $^{+0.072}_{-0.063}$
15 - 16	0.245 $^{+0.057}_{-0.052}$
16 - 18	0.197 $^{+0.034}_{-0.031}$
18 - 20	0.068 $^{+0.040}_{-0.037}$
20 - 22	0.072 ± 0.018
22 - 24	0.062 ± 0.015
24 - 32	0.0372 ± 0.0058
32 - 40	0.0125 ± 0.0035
40 - 50	0.0105 ± 0.0028
50 - 60	0.0073 ± 0.0023
60 - 70	0.0041 ± 0.0017
70 - 80	0.00136 ± 0.00093
80 - 100	0.00183 ± 0.00079

Note that the smearing due to detector resolution has not been unfolded.

Table 2: Cross-sections for physics processes contributing to the inclusive muon spectrum in the range:

$$10 \text{ GeV}/c < p_T^\mu < 15 \text{ GeV}/c, \quad |\eta^\mu| < 1.5$$

PROCESS	Cross-Section (nb)
Beauty, $b \rightarrow \mu$	2.45 ± 0.03
Charm, $c \rightarrow \mu$	0.83 ± 0.02
Drell-Yan, $J/\Psi, \Upsilon$	0.19 ± 0.009
$W, Z \rightarrow \mu$	0.07 ± 0.005
Total Monte Carlo	3.54 ± 0.04
Data (background subtracted)	$4.33 \pm 0.20^{+0.83}_{-0.56}$

The quoted errors for the Monte Carlo contributions are purely statistical.

Table 3: Classification of Muon + Jet Events:
 $10 \text{ GeV}/c < p_T < 15 \text{ GeV}/c; E_T(\text{jet } 1) > 12 \text{ GeV}$

	MONTE CARLO					DATA
	K / π Decays	W/Z	D.Y. J/ Ψ Υ	b $\bar{b}$ c $\bar{c}$	TOTAL	
$\mu + 1 \text{ jet}$	$147 \pm 18^{+22}_{-44}$ ± 22	3.6 ± 0.4	17 ± 1	176 ± 4	344 ± 18	375
$\mu + 2 \text{ jets}$	$65 \pm 12^{+13}_{-19}$ ± 10	1.1 ± 0.3	2.1 ± 0.3	145 ± 4	213 ± 12	204
$\mu + \geq 3 \text{ jets}$	$23 \pm 7^{+5}_{-7}$ ± 3	0.2 ± 0.1	0.2 ± 0.1	59 ± 2	82 ± 7	79
TOTAL	$235 \pm 23^{+40}_{-70}$ ± 35	4.9 ± 0.5	19 ± 1	380 ± 6	639 ± 23	658

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FIGURE CAPTIONS

- Fig. 1** Inclusive muon p_T distribution for single muon candidates (black circles) without background subtraction. The estimated background as a function of p_T^μ is also shown (open triangles). The insert shows the ratio background/data as a function of p_T^μ .
- Fig. 2** Comparison of data and Monte Carlo predictions for muon-jet events with $p_T^\mu > 10$ GeV/c, $E_T^{\text{jet1}} > 12$ GeV. The histograms represent the data. The black dots are the ISAJET predictions including full detector simulation; the charged track multiplicity has been scaled down by a factor 0.6.
- a) Charge multiplicity flow around the muon direction (n_{ch}), as a function of $\Delta\eta \equiv \eta(\text{track}) - \eta(\text{muon})$. η is the pseudorapidity with respect to the incident antiproton direction.
 - b) Transverse momentum flow around the muon direction, as a function of $\Delta\eta$.
 - c) Transverse energy flow around the muon direction, as a function of $\Delta\eta$.
 - d) Charge multiplicity flow around the axis of the highest E_T jet for events with at least one jet of $E_T > 12$ GeV, as function of $\Delta\eta \equiv \eta(\text{track}) - \eta(\text{jet axis})$.
 - e) Transverse momentum flow around the jet axis, as a function of $\Delta\eta$.
 - f) Transverse energy flow around the jet axis, as a function of $\Delta\eta$.
- Fig. 3** Isolation of muons in the calorimeter for $W \rightarrow \mu\nu$ candidates: the scalar sum of transverse energies (ΣE_T) in a cone $\Delta R \equiv (\Delta\eta^2 + \Delta\phi^2)^{1/2} < 0.7$ around the muon direction. The points with error bars are measured data; the histogram is the ISAJET prediction including full detector simulation.
- Fig. 4** Isolation of muons in the CD for $W \rightarrow \mu\nu$ candidates: the scalar sum of transverse momenta (Σp_T) in a cone $\Delta R < 0.7$ around the muon direction. The points with error bars are measured data; the histogram is the ISAJET prediction, including full detector simulation, with the charged track multiplicity scaled down by a factor 0.6.
- Fig. 5** The inclusive muon p_T spectrum (corrected for decay background and acceptance) for all events and for events with at least one jet with $E_T > 12$ GeV. The curves show the sum of the ISAJET predictions. The $W \rightarrow \mu\nu$ contribution is shown as a separate curve.
- Fig. 6** For events with a muon of $p_T > 10$ GeV/c and at least one jet of $E_T > 10$ GeV, the distribution of p_T^{rel} , the muon transverse momentum with respect to the jet axis as measured in the CD. The black dots represent the data, the histograms are the fitted contributions from $b\bar{b}$, $c\bar{c}$ and decay background.

- Fig. 7** The azimuthal angle difference, $\Delta\phi$, between two muons for events with $p_T^{\mu 1} > 7 \text{ GeV/c}$, $E_T^{\text{jet1}} > 12 \text{ GeV}$ and $p_T^{\mu 2} > 3 \text{ GeV/c}$, and with $\Sigma E_T > 6 \text{ GeV}$ in a cone of $\Delta R = 0.7$ around the first muon. The data, the background and the fitted contributions from flavour creation, flavour excitation and gluon splitting are shown.
- Fig. 8** Jet multiplicity distribution for events with at least one jet with $E_T > 12 \text{ GeV}$ and one muon with $10 \text{ GeV/c} < p_T^\mu < 15 \text{ GeV/c}$.
- Fig. 9** E_T of highest E_T jet (jet 1) for events with at least one jet with $E_T > 12 \text{ GeV}$ and one muon with $10 \text{ GeV/c} < p_T^\mu < 15 \text{ GeV/c}$.
- Fig. 10** Azimuthal angle difference between the muon and jet 1 for events with at least one jet with $E_T > 12 \text{ GeV}$ and one muon with $10 \text{ GeV/c} < p_T^\mu < 15 \text{ GeV/c}$.
- Fig. 11** E_T of jet 2 for events with at least one jet with $E_T > 12 \text{ GeV}$, one muon with $10 \text{ GeV/c} < p_T^\mu < 15 \text{ GeV/c}$ and a second jet with $E_T > 7 \text{ GeV}$.
- Fig. 12** $|\cos(\theta^*)|$ for jet 2 for events with at least one jet with $E_T > 12 \text{ GeV}$, one muon with $10 \text{ GeV/c} < p_T^\mu < 15 \text{ GeV/c}$ and a second jet with $E_T > 7 \text{ GeV}$.
- Fig. 13** Missing transverse energy for events with at least one jet with $E_T > 12 \text{ GeV}$ and one muon with $10 \text{ GeV/c} < p_T^\mu < 15 \text{ GeV/c}$.
- Fig. 14** Azimuthal angle difference between the muon and the missing transverse energy vector ("neutrino") for events with at least one jet with $E_T > 12 \text{ GeV}$ and one muon with $10 \text{ GeV/c} < p_T^\mu < 15 \text{ GeV/c}$.
- Fig. 15** As Fig. 14, but for $E_T^V > 12 \text{ GeV}$.
- Fig. 16** Calorimeter isolation, ΣE_T in a cone $\Delta R < 0.7$ for events with at least one jet $E_T > 12 \text{ GeV}$ and one muon with $10 \text{ GeV/c} < p_T^\mu < 15 \text{ GeV/c}$.
- Fig. 17** Central Detector isolation, Σp_T in a cone $\Delta R < 0.7$ for events with at least one jet $E_T > 12 \text{ GeV}$ and one muon with $10 \text{ GeV/c} < p_T^\mu < 15 \text{ GeV/c}$.
- Fig. 18** The isolation variable $I \equiv [(\Sigma E_T/3)^2 + (\Sigma p_T/2)^2]^{1/2}$ for events with at least one jet $E_T > 12 \text{ GeV}$ and one muon with: a) $10 \text{ GeV/c} < p_T^\mu < 15 \text{ GeV/c}$; b) $7 \text{ GeV/c} < p_T^\mu \leq 8 \text{ GeV/c}$; c) $8 \text{ GeV/c} < p_T^\mu \leq 10 \text{ GeV/c}$.

FIG. 1

n_{ch} , p_T AND E_T FLOW

FIG.2

FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

$\Delta\phi$ (μ - jet1) (degrees) FIG. 10

E_T of jet 2 (GeV)

FIG. 12

FIG. 13

FIG. 14
 $\Delta\phi$ ($\mu-\nu$) (degrees)

FIG. 15
 $\Delta\phi$ ($\mu-\nu$) (degrees)

FIG. 16

FIG. 17

FIG. 18a

FIG. 18b

FIG. 18c