Beauty Production at the CERN Proton-Antiproton Collider
(Paper I)*UA1 Collaboration, CERN, Geneva, Switzerland*

Aachen¹ - Amsterdam (NIKHEF)² - Annecy (LAPP)³ - Birmingham⁴ - CERN⁵ - Harvard⁶ -
Helsinki⁷ - Kiel⁸ - Imperial College, London⁹ - Queen Mary College, London¹⁰ - MIT¹¹ -
Padua¹² - Paris (Coll. de France)¹³ - Riverside¹⁴ - Rome¹⁵ - Rutherford Appleton Lab.¹⁶ -
Saclay (CEN)¹⁷ - Victoria¹⁸ - Vienna¹⁹ - Wisconsin²⁰ Collaboration

C. Albajar⁵, M. G. Albrow¹⁶, O. C. Allkofer⁸, G. Arnison¹⁶, A. Astbury¹⁸, B. Aubert³,
T. Axon⁹, C. Bacci^{5,15}, T. Bacon⁹, N. Bains⁴, J. R. Batley¹⁰, G. Bauer⁶, S. Beingessner¹⁸,
J. Bellinger²⁰, A. Bettini¹², A. Bezaguet⁵, K. Bos², E. Buckley¹⁰, G. Bunce³, G. Busetto¹²,
P. Catz³, P. Cennini⁵, S. Centro¹², F. Ceradini¹⁵, D. G. Charlton⁴, G. Ciapetti¹⁵, S. Cittolin⁵,
D. Clarke¹⁰, D. Cline²⁰, C. Cochet¹⁷, J. Colas³, P. Colas¹⁷, M. Corden⁴, J. A. Coughlan¹⁶,
G. Cox⁴, D. Dau⁸, M. DeBeer¹⁷, J. P. deBrion¹⁷, M. DeGiorgi¹², M. Della Negra⁵,
M. Demoulin⁵, B. Denby¹⁶, D. Denegri¹⁷, A. DiCiaccio¹⁵, L. Dobrzynski¹³, J. Dorenbosch²,
J. D. Dowell^{4,5}, E. Duchovni⁵, R. Edgecock⁴, K. Eggert¹, E. Eisenhandler¹⁰, N. Ellis⁴,
P. Erhard¹, H. Faissner¹, I. F. Fensome¹⁰, M. Fincke-Keeler¹⁸, P. Flynn¹⁶, G. Fontaine¹³,
R. Frey¹⁴, R. Fruhwirth¹⁹, L. Gately¹⁴, J. Garvey⁴, D. Gee¹⁴, S. Geer⁶, A. Geiser¹,
C. Ghesquiere¹³, P. Ghez³, F. Ghio¹⁵, W. R. Gibson¹⁰, Y. Giraud-Heraud¹³, A. Givernaud¹⁷,
A. Gonidec⁵, H. Grassmann¹, G. Grayer¹⁶, W. Haynes¹⁶, S. J. Haywood⁴, H. Hoffmann⁵,
D. J. Holthuisen², R. J. Homer⁴, A. Honma¹⁰, M. Ikeda¹⁴, W. Jank⁵, M. Jimack⁴, G. Jorat⁵,
P. I. P. Kalmus¹⁰, V. Karimäki⁷, R. Keeler¹⁸, I. Kenyon⁴, A. Kernan¹⁴, A. Khan⁹,
W. Kienzle⁵, R. Kinnunen⁷, M. Krammer¹⁹, J. Kroll⁶, D. Kryn¹³, P. Kyberd¹⁰, F. Lacava¹⁵,
J. P. Laugier¹⁷, J. P. Lees³, R. Leuchs⁸, S. Levegrun⁸, S. Li¹⁸, D. Linglin³, E. Locci⁵,
K. Long⁵, T. Markiewicz²⁰, C. Markou⁹, M. Markytan¹⁹, G. Maurin⁵, J.-P. Mendiburu¹³,
A. Meneguzzo¹², J. P. Merlo¹⁴, T. Meyer⁵, M.-N. Minard³, M. Mohammadi²⁰, K. Morgan¹⁴,
M. Moricca¹⁵, H.-G. Moser¹, B. Mours³, Th. Muller⁵, A. Nandi¹⁰, L. Naumann⁵,
P. Nedelec¹³, A. Norton⁵, D. Pascoli¹², F. Pauss⁵, C. Perault³, P. Petta⁵, E. Petrolo^{5,15},
G. Piano Mortari¹⁵, E. Pietarinen⁷, C. Pigot¹⁷, M. Pimiä⁷, D. Pitman¹⁴, A. Placci⁵,
J.-P. Porte⁵, E. Radermacher⁵, T. Redelberger¹, H. Reithler¹, J.-P. Revol¹¹, J. Richman⁵,
D. Robinson⁹, J. Rohlf⁶, P. Rossi¹², C. Rubbia⁵, W. Ruhm⁵, G. Sajot¹³, G. Salvini¹⁵,
J. Sass⁵, D. Samyn⁵, A. Savoy-Navarro¹⁷, D. Schinzel⁵, A. Schwartz⁶, W. Scott¹⁶, C. Seez⁹,
T. P. Shah¹⁶, I. Sheer¹⁴, I. Siotis⁹, D. Smith¹⁴, R. Sobie¹⁸, P. Sphicas¹¹, J. Strauss¹⁹,
J. Streets⁴, C. Stubenrauch¹⁷, D. Summers²⁰, K. Sumorok⁶, F. Szoncs¹⁹, C. Tao¹³,
A. Taurok¹⁹, I. ten Have², S. Tether¹¹, G. Thompson¹⁰, E. Tscheslog¹, J. Tuominiemi⁷,
B. van Eijk², J. P. Vialle³, L. Villasenor²⁰, T. S. Virdee⁹, H. von der Schmitt⁵,
W. von Schlippe¹⁰, J. Vrana¹³, V. Vuillemin⁵, K. Wacker¹, H. D. Wahl¹⁹, P. Watkins⁴,
A. Wildish⁹, J. Wilson⁴, I. Wingerter³, S. J. Wimpenny⁵, X. Wu¹¹, C.-E. Wulz¹⁹, T. Wyatt⁵,
M. Yvert³, C. Zaccardelli¹⁵, I. Zacharov², N. Zaganidis¹⁷, L. Zanello¹⁵ and P. Zotto¹².

(Submitted to Physics Letters B)

ABSTRACT

We report evidence for beauty particle production through the observation of dimuon events from proton-antiproton collisions at energies of $\sqrt{s} = 546$ GeV and $\sqrt{s} = 630$ GeV at the CERN collider. Our data indicate that semi-leptonic decays of beauty particles are the dominant source of pairs of high- p_T muons. The beauty flavour creation (gg or $\bar{q}q \rightarrow \bar{b}b$) cross-section needed to explain the dimuon rate is $\sigma\{\bar{p}p \rightarrow \bar{b}b + X; p_T^b > 5 \text{ GeV}/c, |\eta| < 2.0\} = (1.1 \pm 0.1 \pm 0.4) \mu\text{b}$, which is in good agreement with QCD calculations. We also observe clear signals for $\Upsilon \rightarrow \mu^+\mu^-$ (hidden beauty) and high- p_T $J/\psi \rightarrow \mu^+\mu^-$, well above the background of continuum muon pairs from the Drell-Yan mechanism.

1.-Introduction. The CERN $\bar{p}p$ Collider is expected to be a prolific source of beauty particles. The predicted production cross-section is large ($\sim 10 \mu\text{b}$)[1] and at high p_T is not suppressed relative to that for charm as in e^+e^- heavy flavour production (charge $-1/3$ compared to $+2/3$). Semi-leptonic decays of beauty quarks are expected to be the dominant source of high- p_T muon pairs, because of the decay properties and harder fragmentation of b-quarks compared to c-quarks[2]. In this paper we report evidence for beauty production from analysis of dimuon data recorded in the UA1 detector at the CERN $\bar{p}p$ Collider. Since our previous publication on dimuon production[3], we have increased the integrated luminosity seen by the experiment by a factor of almost seven to 692 nb^{-1} . We report on a search for $B^0 \leftrightarrow \bar{B}^0$ oscillations in a separate paper[4].

2.-Detector and Trigger. The UA1 detector has been described in detail elsewhere[5]. In brief, a muon leaving the interaction region first passes through the large volume drift chamber, the Central Detector (CD), where the momenta of charged particles are analysed in a 0.7 T dipole magnetic field to an accuracy of $\Delta p / p = 0.005 (\text{GeV}/c)^{-1} p$ for 1 m long tracks. The muon then passes through the electromagnetic and hadronic calorimeters, and at least 60 cm of additional iron shielding (about 1 m in the forward regions). The calorimeters and additional shielding represent at least 9 nuclear interaction lengths of material. The electromagnetic calorimeters are a sandwich of lead and plastic scintillator. The energy resolution is $\Delta E / E \simeq 0.15 (\text{GeV})^{1/2} / \sqrt{E}$. The hadronic calorimeters are made of iron and plastic scintillator and have an energy resolution of $\Delta E / E \simeq 0.80 (\text{GeV})^{1/2} / \sqrt{E}$. The iron of the hadronic calorimeter in the central region acts as the magnetic field return yoke. Finally, the muon is detected in the muon chambers, which surround the central calorimeters and cover approximately 75% of the solid angle. The muon detector consists of two drift tube chamber layers separated by 60 cm. Each chamber has two planes of drift tubes per projection, staggered to resolve left-right ambiguities and to minimize dead space. The additional iron shielding beyond the hadronic calorimeter is instrumented with planes of limited-streamer tubes.

Muon candidates are selected with a fast hardware trigger that requires a track pointing to the interaction region within a cone of aperture $\pm 150 \text{ mrad}$. For this trigger, only the pattern of hit

tubes is used (no drift-time information). The decision time is less than the beam-crossing period so that no dead-time is introduced by the trigger. Data were recorded using inclusive muon and dimuon triggers with typical pseudo-rapidities of $|\eta| \leq 1.5$. For data taken in 1985 (330 nb^{-1}) the acceptance for muon pairs was extended to $|\eta| \leq 2.0$ for both muons.

3.-Event selection. The data presented in this publication were collected during three collider running periods. In 1983, data were recorded at a centre-of-mass energy of $\sqrt{s}=546 \text{ GeV}$, and an integrated luminosity of 108 nb^{-1} was achieved. In 1984 and 1985 a further 584 nb^{-1} were accumulated at $\sqrt{s}=630 \text{ GeV}$. The events were triggered using an inclusive muon or dimuon trigger as described in Section 2. Following this, an inclusive $p_T > 3 \text{ GeV}/c$ muon selection was made using fast filter programs, and the selected events were fully reconstructed. We define p_T as the component of the momentum of the muon transverse to the beam direction. Dimuon events were then selected requiring both muons to have $p_T > 3 \text{ GeV}/c$. This yielded 1175 dimuon candidates, which were scanned by physicists on a high resolution interactive graphics facility: 9 events were identified as having cosmic rays as the source of the muons, 56 as leakage through cracks, 63 as visible kaon decays, 3 as double interactions and 164 as cases of wrong association between the muon chamber and CD tracks (mainly for low mass dimuon candidates). These were removed from the sample leaving 880 scan-validated events. The observed dimuon mass distribution, uncorrected for acceptance, is shown for 235 isolated, unlike-sign events in Fig.1 (isolation is defined in Section 5); 17 events cluster at high masses and are interpreted as $Z^0 \rightarrow \mu^+\mu^-$ decays. These are excluded from the analysis in this paper. Note that $J/\psi \rightarrow \mu^+\mu^-$ and $\Upsilon \rightarrow \mu^+\mu^-$ decays are clearly visible.

The following discussion is based on the 512 events with $m_{\mu\mu} > 6 \text{ GeV}/c^2$, for which the two muons cannot originate from a single beauty-charm cascade. A detailed account of the $m_{\mu\mu} < 6 \text{ GeV}/c^2$ analysis will be given in ref. [6].

4.-Background sources. Potential sources of background to the dimuon sample have been considered in detail:

(1) The pion and kaon decay background has been estimated directly from experimental data. This was done using an inclusive sample of events containing single $p_T > 3 \text{ GeV/c}$ muon candidates, about 80% of which are background, mainly due to pion and kaon decays in flight. Events were considered for the background calculation if they contained a second high- p_T track, presumably a hadron; the decay of this high- p_T hadron into a muon was then simulated. Assuming charged particle fractions of 58% $\pi^\pm$ (f_π) and 21% $K^\pm$ (f_K) [7], the probability for decay in flight is about $0.04 / p_T \text{ (GeV/c)}$ per incident hadron. Each artificially generated event contributes to the background if it passes the same cuts and selection criteria applied in the analysis of the data, including scanning. Momentum mismeasurement due to the sharp change in the track direction at the point of a kaon decay was taken into account in the simulation. The background estimate allows both for decays in the CD and inside the material of the calorimeters. The different acceptances for single muon and dimuon triggers are included in the calculation. We estimate a background of $116 \pi \rightarrow \mu\nu$ or $K \rightarrow \mu\nu$ decays in the $m_{\mu\mu} > 6 \text{ GeV/c}^2$ data sample, with a systematic error of 25%, which is due mainly to the uncertainty on f_π and f_K .

(2) Noninteracting hadrons are indistinguishable from muons. This background has been estimated, taking into account details of the detector geometry and the different interaction probabilities for $\bar{p}$, p , π^- , π^+ , K^- and K^+ particles[8]. This sail-through background is typically two orders of magnitude smaller than the background from pion and kaon decays in flight and we estimate 2 such events in the $m_{\mu\mu} > 6 \text{ GeV/c}^2$ data sample.

(3) Incorrect association of a muon chamber track to an unrelated CD track may occur and is especially important when the latter has high p_T . We have examined the events in the $m_{\mu\mu} > 6 \text{ GeV/c}^2$ dimuon sample for possible matching ambiguities of this type. After selection by program and scanning we are left with 25 events in which the wrong CD track may be associated to the muon chamber track. Of these, 10 like-sign and 10 unlike-sign events would either no longer be selected or would change sign if the other CD track were chosen. This gives an estimated misassociation background of (5 ± 5) like-sign events and (5 ± 5) unlike-sign events.

(4) Test beam measurements[9] show that the background from hadronic shower leakage through material of the calorimeters and the iron can be neglected.

(5) The backgrounds from cosmic rays and from leakage of hadronic showers through cracks in the detector are reduced to a negligible level after scanning.

The total background to the dimuon sample from the above sources is estimated to be 127 ± 32 events.

We have performed a second, independent background calculation based on differences in the central detector - muon chamber track matching χ^2 distributions for prompt muons and for background; background muons tend to match less well. The shape of the matching χ^2 distribution for prompt muons was determined from muons in the $J/\psi \rightarrow \mu^+\mu^-$ sample for which there is negligible background. The shape of the distribution for background muon candidates was obtained from an inclusive $p_T > 3$ GeV/c muon sample which is estimated to contain about 80% background. A least squares fit was then performed to determine the background fraction in the dimuon sample by fitting a weighted sum of the prompt muon and background matching χ^2 distributions to the distribution observed for the dimuon sample. The result of this fit is that the dimuon data contain 137 ± 30 background events, where at least one muon is not prompt.

Since the two estimates are independent, we combine the results for the total number of background events in the dimuon sample: 132 ± 21 events.

5.-Evidence for Beauty production. The dimuon data sample is expected to contain events from a variety of sources: the Drell-Yan mechanism, J/ψ and Υ decays, and heavy flavour processes. Muons from semi-leptonic decays of heavy particles will be accompanied by hadrons from the fragmentation and decay of the heavy quark. Thus, it is possible to separate events resulting from the Drell-Yan mechanism and Υ decays from the heavy flavour events by using *muon isolation*; the muon track is not generally expected to be embedded in a jet for Drell-Yan and Υ decays. We define $S = [\Sigma E_T(\mu_1)]^2 + [\Sigma E_T(\mu_2)]^2$ where $\Sigma E_T(\mu)$ is the scalar sum of the transverse energy measured in calorimeter cells in a cone of $\Delta R = (\Delta\eta^2 + \Delta\phi^2)^{1/2} < 0.7$ around the muon, excluding the expected energy deposited by the muons themselves; η is the pseudo-rapidity

and ϕ is the azimuthal angle measured in radians. The distribution of S for the $m_{\mu\mu} > 6 \text{ GeV}/c^2$ unlike-sign pairs (fig. 2a, 355 events) shows a clear enhancement at $S < 9 \text{ GeV}^2$ due to Drell-Yan and Υ decays, which is not observed for the corresponding like-sign events (fig. 2b, 157 events). We therefore classify as *isolated* those dimuon events with $S < 9 \text{ GeV}^2$. Taking pairs of muons at random from a sample of $W \rightarrow \mu\nu$ events where no jet activity is expected around the direction of the muon, we find that 82% of such artificially mixed $W \rightarrow \mu\nu$ events have $S < 9 \text{ GeV}^2$. According to charge and isolation requirement of $S < 9 \text{ GeV}^2$, we divide the data sample of 512 events into four categories: 98 isolated unlike-sign events (8 background) 15 isolated like-sign events (8 background), 257 nonisolated unlike-sign (58 background) and 142 nonisolated like-sign (58 background).

Heavy flavour events are not completely separated from Drell-Yan and Υ decay events by the isolation requirement since (i) from examining $W \rightarrow \mu\nu$ events we estimate that 18% of Drell-Yan events fail the isolation cut and (ii) the presence of isolated like-sign events indicates that some dimuons from heavy flavour decays appear to be isolated. Nevertheless, the nonisolated dimuon events are expected to be largely from heavy particle decays.

The inclusive muon differential cross-section, $d\sigma/dp_T$, for the muons in the nonisolated dimuon events (solid circles) is compared to QCD predictions from the ISAJET Monte Carlo[10] in Fig 3. Muons are included only for events in which both muons have $|\eta| < 2.0$ and at least one muon has $|\eta| < 1.3$; this approximately describes the acceptance of the most restrictive muon trigger condition. We also show the inclusive $d\sigma/dp_T$ distribution for single muon events measured in the UA1 experiment for $p_T > 6 \text{ GeV}/c$ and $|\eta| < 1.5$ (open circles). These distributions are corrected for acceptance and are background subtracted; for the single muon data, the level of background falls from $\approx 65\%$ at $p_T = 6 \text{ GeV}/c$ to less than 30% at 15 GeV/c. For the first four bins, the error bars shown for the single muon cross-section are dominated by the background subtraction. The cross-section is not shown above 15 GeV/c where $W \rightarrow \mu\nu$ decays affect the distribution.

Three mechanisms are contained in ISAJET for heavy flavour production, $\bar{p}p \rightarrow \bar{Q}Q+X$, where $Q = b$ or c : (1) flavour creation $\bar{q}q, gg \rightarrow \bar{Q}Q$, (2) flavour excitation $(q,g) Q \rightarrow (q,g) Q$,

and (3) splitting of any final state gluon $g \rightarrow \bar{Q}Q$. Processes (1) and (2) correspond to direct production of heavy quarks by hard $2 \rightarrow 2$ subprocesses, while (3) is a higher-order process in which heavy quarks result from the QCD evolution of a hard gluon jet. For process (2) heavy quark structure functions are taken from Eichten *et al.* [10]. In calculating the gluon splitting process, ISAJET imposes a cut-off of $6 \text{ GeV}/c^2$ on the mass of the gluon. This cut-off is between the $\bar{c}c$ and $\bar{b}b$ thresholds, and therefore only affects $\bar{c}c$ production. We have checked that this high cut-off value leads to an underestimation of the cross section of the process $\bar{p}p \rightarrow g+X$; $g \rightarrow \bar{c}c$; $c \rightarrow \mu$ ($p_T^\mu > 6 \text{ GeV}/c$) of less than 20%. The cut-off does not affect the cross-section for the dimuon events, for which gluon splitting contributions are significantly suppressed because of the dimuon mass cut.

The solid curves in fig.3 correspond to absolute predictions from ISAJET when all three production mechanisms are taken into account. They agree with the data within a factor of about 1.5, which is well within the uncertainty of the calculation. The dashed lines correspond to predictions from process (1) only (flavour creation). Processes (2) and (3) are needed to explain the single muon yield; they account for 60% ($\approx 30\%$ each) of the single muon cross section but only 25% of the dimuon yield. The relative suppression of processes (2) and (3) for the dimuon yield is a consequence of the mass cut, which suppresses processes in which the two heavy quarks are not back-to-back in the transverse plane. Because of the decay properties and harder fragmentation for beauty compared to charm, beauty decays are predicted to account for about 75% of the single-muon events and 90% of the dimuon events. For t-quark masses greater than $25 \text{ GeV}/c^2$, top decays are predicted to account for less than 7% of the dimuons and less than 3% of the single muons and are therefore neglected in this analysis.

The *relative* transverse momentum, p_T^{rel} , between the muon and its accompanying jet can be used to separate beauty and charm jets on a statistical basis. Since beauty particles are relatively heavy, the decay muon tends to have larger p_T^{rel} than for charm particles. The subsample of 176 nonisolated dimuon events in which a charged particle jet was clearly identified in the CD was used for this work to get the best possible measurement of the jet direction; at least one $p_T > 1 \text{ GeV}/c$ track was required in the jet other than the muon, and the jet axis was required to lie within

$\Delta R < 1.0$ of the muon. For the like-sign events (63 events), only the higher p_T muon, predominantly from first generation decays, was used. The results are shown in fig.4a,b for the unlike-sign and like-sign events respectively. By performing a two parameter fit to the data after background subtraction, using Monte Carlo p_T^{rel} distributions for charm and beauty jets, we find that the fraction of events due to $\bar{c}c$ is $(15 \pm 11)\%$ for the unlike-sign data and $< 18\%$ for the like-sign data at 90% C.L. Note that the $\bar{c}c$ contribution is expected to be absent in the like-sign data because prompt muons come only from first generation decays. Combining the unlike- and like-sign data samples, this gives a global charm fraction $\bar{c}c / (\bar{c}c + \bar{b}b)$ of $\sim 10\%$ for the dimuons coming from heavy flavour processes in agreement with the prediction discussed above.

The distribution of the difference in azimuthal angle between the muons is sensitive to processes (2) and (3). As shown in fig.5, these processes are needed in order to reproduce the data.

Normalizing the predicted number of dimuon events due to heavy flavour pair production to the observed number of dimuons remaining after subtraction of background, Drell-Yan and upilon contributions, yields a cross-section for direct beauty production through flavour creation $\bar{q}q, gg \rightarrow \bar{b}b$:

$$\sigma\{ \bar{p}p \rightarrow \bar{b}b + X ; p_T^b > 5 \text{ GeV}/c, |\eta| < 2.0 \} = (1.1 \pm 0.1 \pm 0.4) \mu\text{b},$$

in agreement with the ISAJET estimate of $1.7 \mu\text{b}$ for the same process. The systematic error of $0.4 \mu\text{b}$ reflects the uncertainties in the Monte Carlo parameters, the luminosity, and the detector acceptance.

The isolated, unlike-sign data can be used to measure $\Upsilon, \Upsilon', \Upsilon'' \rightarrow \mu^+\mu^-$ and Drell-Yan dimuon production. Allowance must be made for the calculated background and the presence of dimuons from semi-leptonic heavy flavour decays. The dimuon mass distribution for these events is shown in fig.1b, for $m_{\mu\mu} > 6 \text{ GeV}/c^2$. The contributions from the different processes were determined by fitting the sum of their individual mass distributions to the data, after background subtraction. The width of the upilon mass peak is determined allowing for the CD resolution and assuming that decays of $\Upsilon, \Upsilon', \Upsilon'' \rightarrow \mu^+\mu^-$ occur in the ratio $1 : 0.3 : 0.15$ [11]. The highest mass events are consistent with expectations from Drell-Yan production; above $30 \text{ GeV}/c^2$ we

predict 0.8 ± 0.5 events and observe 3 events.

Correcting for acceptance, we obtain cross-section estimates:

$$\sigma.B\{ \bar{p}p \rightarrow \Upsilon, \Upsilon', \Upsilon'' \rightarrow \mu^+\mu^- \} = 0.98 \pm 0.21 \pm 0.19 \text{ nb}$$

$$\sigma \{ \text{Drell-Yan; } m_{\mu\mu} > 11 \text{ GeV}/c^2 \} = 0.25 \pm 0.08 \pm 0.05 \text{ nb.}$$

The acceptance for Drell-Yan events was calculated using the ISAJET Monte Carlo program[10], including a simulation of the detector and muon trigger. For $\Upsilon, \Upsilon', \Upsilon'' \rightarrow \mu^+\mu^-$, the Drell-Yan acceptance calculation was used, for fixed dimuon masses. The acceptance is not strongly mass dependent for $m_{\mu\mu}$ well above $6 \text{ GeV}/c^2$.

The observation of $\Upsilon \rightarrow \mu^+\mu^-$ decays demonstrates the existence of bound $\bar{b}b$ states in the data. The UA1 measured cross-section is shown in fig.6a, compared to lower energy data and an extrapolation based on a gluon fusion model[11]. Good agreement is observed between theory and the data. In order to compare the Drell-Yan result with previous measurements, we plot $m^3 d^2\sigma/dm dy$ at $y=0$ in fig.6b, calculated at $m_{\mu\mu} = 10 \text{ GeV}/c^2$ from the fit of fig.1b, together with earlier data [11], versus the scaling variable $\sqrt{\tau} = m/\sqrt{s}$. The results show approximate scaling over more than an order of magnitude in $\sqrt{s}$.

6.-Conclusions. The *nonisolated* events, having both unlike- and like-sign muon pairs, are in good quantitative agreement with QCD expectations from $\bar{b}b$ and $\bar{c}c$ production where the former is predicted and found to dominate the observed dimuon yield. For muons with $p_T > 3 \text{ GeV}/c$ and $m_{\mu\mu} > 6 \text{ GeV}/c^2$, a global beauty fraction, $\bar{b}b / (\bar{c}c + \bar{b}b)$ of $\approx 90\%$ is deduced from a fit to the unlike- and like-sign p_T^{rel} distributions after background subtraction. The beauty flavour creation (gg or $\bar{q}q \rightarrow \bar{b}b$) cross-section needed to explain the dimuon rate is $\sigma\{ \bar{p}p \rightarrow \bar{b}b + X; p_T^b > 5 \text{ GeV}/c, |\eta| < 2.0 \} = (1.1 \pm 0.1 \pm 0.4) \mu\text{b}$, which is in good agreement with QCD calculations. The *isolated* unlike-sign events, analysed in terms of Υ and Drell-Yan production, are in agreement with extrapolations from lower energy data. The significance of the ratio of the numbers of like-sign to unlike-sign pairs is discussed in a following paper[4].

Acknowledgments

We are thankful to the management and staff of CERN and of all participating institutes for their vigorous support of the experiment. The following funding agencies have contributed to this programme:

Fonds zur Förderung der Wissenschaftlichen Forschung, Austria.

Valtion luonnontieteellinen toimikunta, Finland.

Institut National de Physique Nucléaire et de Physique des Particules and
Institut de Recherche Fondamentale (CEA), France.

Bundesministerium für Forschung und Technologie, Fed. Rep. Germany.

Istituto Nazionale di Fisica Nucleare, Italy.

Science and Engineering Research Council, United Kingdom.

Stichting Voor Fundamenteel Onderzoek der Materie, The Netherland.

Department of Energy, USA.

The Natural Sciences and Engineering Research Council of Canada.

Thanks are also due to the following people who have worked with the collaboration in the preparations for and data collection on the runs described here: L.Baumard, F.Bernasconi, D. Brozzi, R.Conte, L.Dumps, G.Fetchenhauer, G.Gallay, J.C. Michelon and L.Pollet.

REFERENCES

- [1] B. L. Combridge, Nucl. Phys. **B151** (1979) 429.
- [2] A. Chen *et al.* Phys. Rev. Lett. **52** (1984) 1084; J. Green *et al.*, Phys. Rev. Lett. **51** (1983) 347; S.E. Csorna *et al.*, Phys. Rev. Lett. **54** (1985) 1894; W. Bacino *et al.*, Phys. Rev. Lett. **43** (1979) 1073; R. Schindler *et al.*, Phys. Rev. **D24** (1981) 78; R. Baltrusaitis *et al.*, Phys. Rev. Lett. **54** (1985) 1976; S. Bethke, DESY preprint 85-067 (1985) and references therein.
- [3] G. Arnison *et al.*, Phys. Lett. **155B** (1985) 442.
- [4] C. Albajar *et al.*, "Search for B^0 - $\bar{B}^0$ Oscillations at the CERN Proton-Antiproton Collider" CERN EP-86/209, submitted to Physics Letters.
- [5] A. Astbury *et al.*, UA1 Proposal CERN/SPSC 78-06 (1978); M. Barranco Luque *et al.*, Nucl. Instrum. Methods **176** (1980) 175; M. Calvetti *et al.*, Nucl. Instrum. Methods **176** (1980) 225; C. Cochet *et al.*, Nucl. Instrum. Methods **A243** (1986) 45; M.J. Corden *et al.*, Nucl. Instrum. Methods **A238** (1985) 273; K. Eggert *et al.*, Nucl. Instrum. Methods **176** (1980) 217 and 233; G. Bauer *et al.*, "Upgraded Muon Detection System for UA1 Based on Limited Streamer Tubes", submitted to Nucl. Instrum. Methods.
- [6] C. Albajar *et al.*, "J/ ψ Production at the CERN Proton-Antiproton Collider", in preparation.
- [7] The value of $f_\pi=0.58$ was determined from parameterizations of the inclusive charged particle and inclusive pion p_T distributions of UA2, evaluated at 3 GeV/c. The value of $f_K=0.21$ was determined assuming that the K/π ratio at fixed $m_T=\sqrt{m^2+p_T^2}$ is constant, and extrapolating the low p_T UA2 data to $p_T=3$ GeV/c. This results in a good fit to the collider data: M. Banner *et al.*, Phys. Lett. **122B** (1983) 322; G.J. Alner *et al.*, Nucl. Phys. **B258** (1985) 505.
- [8] S. P. Denisov *et al.*, Nucl. Phys. **B61** (1973) 62.
- [9] R. Leuchs, "Messung des hadronischen Untergrundes bei der Identifizierung von Myonen", Diplomarbeit in Physik, III Physikalisches Institut, Aachen (1982).
- [10] F. Paige and S.D. Protopopescu, ISAJET Monte Carlo, BNL 38034 (1986). Proton structure functions are taken from E. Eichten *et al.*, Rev. Mod. Phys. **56** (1984) 579.

Branching ratios for charm and beauty states are taken from the latest experimental measurements: Review of Particle Properties, Particle Data Group, Phys. Lett. **170B** (1986) 1. For nonleptonic decays of beauty states, which are mostly unmeasured, branching ratios were taken from the Eurojet program: A. Ali, E. Pietarinen, B. van Eijk, "Eurojet, a Monte Carlo Program for Jet Simulations", presented by B. van Eijk, 5th Topical Workshop on Proton-Antiproton Collider Physics, Saint Vincent, Italy, 25 Feb - 1 March, 1985, p165; A. Ali, B. van Eijk, I. ten Have, "Heavy Flavour Production in Large Transverse Momentum Proton-Antiproton Collisions", CERN TH-4523/86.

For both programs we have made a detailed comparison of the results with measured beauty and charm decay properties. Calculations were done using a modified version of the ISAJET Monte Carlo (version 5.21) in which the spectator particle parameters have been adjusted to be consistent with UA1 data. See C. Albajar *et al.*, "Inclusive Production of Low Transverse Momentum Jets at the Proton-Antiproton Collider", in preparation.

- [11] For low energy Drell-Yan data see:
A.G. Clark *et al.*, Nucl. Phys. **B142** (1978) 29; C. Kourkouvelis *et al.*, Phys. Lett. **91B** (1980) 475; D. Antreasyan *et al.*, Phys. Rev. Lett. **48** (1982) 302; J. Badier *et al.*, Z. Phys **C26** (1985) 489; A.S. Ito *et al.*, Phys. Rev. **D23** (1981) 604. For a comprehensive list of Drell-Yan experiments see J. P. Rutherford, Proc. Int. Symp. on Lepton and Photon Interactions at High Energy, Kyoto (1985) 695.

For low energy epsilon data see:

A.L.S. Angelis *et al.*, Phys. Lett. **87B** (1979) 398; C. Kourkouvelis *et al.*, Phys. Lett. **91B** (1980) 481; J. Badier *et al.*, Phys. Lett. **B86** (1979) 98; D. Antreasyan *et al.*, Proc. EPS Int. Conf. on High Energy Physics, Geneva (1979) 779 and CERN-EP 79-116; J.S. Yoh *et al.*, Phys. Rev. Lett. **41** (1978) 684.

The QCD prediction is from:

V. Barger and A.D. Martin, Phys. Rev. **D31** (1985) 1051. See also V. Barger *et al.*, Z. Phys. **C6** (1980) 169.

FIGURE CAPTIONS

- Fig.1** Dimuon mass distributions for isolated unlike-sign dimuon events with $p_T^\mu > 3 \text{ GeV}/c$: (a) 235 events on logarithmic mass scale including contribution from $Z^0 \rightarrow \mu^+\mu^-$; for the $m_{\mu\mu} < 6 \text{ GeV}/c^2$ dimuon events, the isolation criterion is $\Sigma E_T < 3 \text{ GeV}$ in a single cone of $\Delta R < 0.7$ around the *dimuon* direction; (b) 98 events with $m_{\mu\mu} > 6 \text{ GeV}/c^2$, excluding $Z^0 \rightarrow \mu^+\mu^-$ events, with curves showing result of a three parameter fit to the background subtracted data, for the Drell-Yan, upilon and heavy flavour contributions.
- Fig. 2** Distribution of the isolation variable S for (a) 355 unlike-sign events and (b) 157 like-sign events. The shaded regions, $S < 9 \text{ GeV}^2$, define the isolated event samples.
- Fig. 3** Inclusive muon p_T distributions for single-muon events with $|\eta| < 1.5$ (open circles) and nonisolated dimuon events with $|\eta| < 2.0$ for both muons, $|\eta| < 1.3$ for at least one muon and $m_{\mu\mu} > 6 \text{ GeV}/c^2$ (solid circles), after correction for acceptance and background subtraction. The curves are absolutely normalized QCD predictions from the ISAJET program[10]; the lowest order dashed curve corresponds to process (1) defined in the text (flavour creation) and the solid line corresponds to the sum of processes (1), (2) and (3) (flavour creation, flavour excitation and gluon splitting).
- Fig. 4** Transverse momentum of muons relative to the jet axis, which is defined by charged particles only (including the muon in the jet), for (a) 226 muons from 113 unlike-sign dimuon events (two entries per event) and (b) 63 muons from like-sign dimuon events where only the higher p_T muon was used. The curves are the result of a two parameter fit of the $\bar{c}c$ and $\bar{b}b$ components, where the background fraction has been fixed at the estimated values of (a) $22 \pm 5\%$ for unlike-sign events and (b) $39 \pm 8\%$ for the like-sign events. After background subtraction, we find that the fraction of events due to $\bar{c}c$ is $15 \pm 11\%$ for the unlike-sign data and $< 18\%$ for the like-sign data at 90% C.L.
- Fig. 5** Azimuthal angle difference between the muons for the nonisolated muon pairs. The curves are QCD predictions from ISAJET[10], normalized to the 399 events observed. The lowest order dot-dashed curve corresponds to process (1) defined in the text (flavour creation), the dashed curve corresponds to the sum of processes (2) and (3) (flavour excitation and gluon splitting), and the solid line corresponds to the sum of processes (1), (2) and (3). Processes (2) and (3) are needed to explain the region of $\Delta\phi < 110$ degrees (insert) where the two muons are not coplanar.

Fig. 6 Cross-section for (a) $\bar{p}p \rightarrow \Upsilon + X$ where the curve is calculated from a gluon fusion model[11] and (b) Drell-Yan dimuon production as a function of the scaling variable, $\sqrt{\tau} = m/\sqrt{s}$. Note that the data at $\sqrt{\tau} < 0.05$ from other experiments are for masses less than $2.5 \text{ GeV}/c^2$ and may contain contributions other than Drell-Yan.

Fig. 1a

Fig. 1b

Fig. 2

Fig. 3

Fig. 4a

Fig. 4b

Fig. 5

Fig. 6a

Fig. 6b