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Heavy flavour production and the evidence for $B - \bar{B}$ mixing
in the UA1 experiment

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UA1 - collaboration

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Abstract

The heavy flavour production at the CERN proton - antiproton collider ($\sqrt{s}=630$ GeV) is discussed. The heavy quarks are tagged in UA1 via their semileptonic decays into muons. The production cross-section for beauty particles and the topology of the events are in good agreement with QCD calculations, once higher processes, like flavour excitation and gluon splitting, are taken into account. The large amount of like sign dimuons is interpreted as evidence for beauty oscillations. These data are discussed in detail and compared with similar measurements at e^+e^- colliders.

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Introduction

Inelastic Proton - Antiproton interactions at the CERN Collider represent a prolific source of heavy flavours, which are produced by various QCD processes. Due to its large centre-of-mass energy (630 GeV) the wide-band beam of quarks and gluons is still effective in beauty pair creation down to values of $x=2p_T/\sqrt{s} \approx 0.02$. Fig. 1 shows the increase of the cross-section for heavy flavour production with the centre-of-mass energy. The calculation was done with ISAJET ¹⁾, using only lowest order QCD contributions. It is sensitive to the gluon content in the proton at low x .

QCD calculations become reliable at large transverse momenta, where non perturbative effects can be neglected. As an example, the large transverse momentum cross-section for jets ²⁾ is well described by QCD over 7 orders of magnitude (fig.2). We will demonstrate that QCD also reproduces the beauty production, since the mass of the beauty quark of 5 GeV/c² introduces a natural cut-off. This contrasts the situation at the ISR, where non perturbative effects make a QCD calculation for charm production less certain.

Heavy flavours are tagged via their semileptonic decays into muons, which offer the experimental advantage that they can be identified at low transverse momenta ($p_T > 3$ GeV/c) and even in the presence of hadronic activity. First generation decays of pair produced b - and c - quarks give unlike sign muon pairs where the muons are in general accompanied by hadronic activity from the quark fragmentation and decay.

Muons can also be due to second generation b - decays resulting in same sign dimuons. However, the large amount of like sign dimuons in the UA1 data can only be understood in terms of B - $\bar{B}$ oscillations, analogous to the well-known phenomena in the K - complex³⁾.

It is plausible that the dominant source of dimuons with large p_T is $b \bar{b}$ production rather than $c \bar{c}$. At transverse momenta larger than the quark masses involved, i.e. ignoring threshold effects, b - and c - quarks are produced with an identical p_T spectrum. The harder fragmentation of the beauty quark compared to charm gives, on average, a larger fraction of the original quark momentum to the B - meson. Hence, the harder p_T - spectrum of muons from beauty quarks compared with charm quarks favours $b \bar{b}$ - events over $c \bar{c}$, once a p_T - cut is applied to the muons.

fig. 1
cross section for heavy flavour
production (Isajet, lowest order)

This effect is demonstrated in fig. 3, where the p_t - spectra of the quarks, the mesons, and the resulting muons are plotted. Muon pairs can also arise from the decay of hidden heavy flavours, like J/ψ and Y , and from virtual photons (Drell - Yan). These unlike sign events can be separated from open heavy flavours with the help of the isolation of the muons. In this case no hadronic activity in addition to the underlying event is expected in a cone around the muon.

Detector, Event Selection and Classification

The UA1 detector has been described in detail elsewhere⁴). In brief, a muon from the $p\bar{p}$ interaction traverses the Central Detector, where the momentum is determined by the deflection in the central magnetic dipole field of 0.7 T. After penetrating the electromagnetic and hadronic calorimeters and the additional iron absorber (a total of more than 9 interaction lengths) the muon is finally detected in the muon chambers, which form the outer shell of the UA1 detector and cover 70% of the pseudorapidity range $|\eta| < 2.0$.

A fast hardware muon trigger, based on the hit information in the drift tubes of the muon chambers, selects muon candidates by requiring a track pointing to the interaction region within a cone of aperture ± 150 mrad. Data were recorded using an inclusive muon trigger with a pseudorapidity acceptance of $|\eta| < 1.5$ and a dimuon trigger within $|\eta| < 2.0$.

The data presented in this paper were collected during three collider periods from 1983 to 1985⁵). The total integrated luminosity amounts to 659 nb^{-1} , 108 nb^{-1} at $\sqrt{s} = 546 \text{ GeV}$ (1983) and 551 nb^{-1} at $\sqrt{s} = 630 \text{ GeV}$ (1984/85). Muon events were selected with the following cuts:

single muons:	$p_t > 6 \text{ GeV}/c$
muon pairs:	$p_t > 3 \text{ GeV}/c$ for each muon

fig. 2
 $d\sigma/dp_t$ for jets at 630 (546) GeV
(UA1 data)

fig. 3: p_t spectra of quarks, mesons and muons, a) $c \bar{c}$, b) $b \bar{b}$ (Isajet, lowest order)

The background to the muon sample has been studied extensively and is discussed in detail elsewhere⁶⁾. The probability that a hadron simulates a muon either by penetrating the absorber without interaction or by leakage of the induced hadron shower was found to be small ($\ll 10^{-4}$). Severe background arises from pions (kaons) which decay in flight in the central detector with a probability of $0.02/p_t$ ($0.11/p_t$). The number of events for the different data samples and their estimated background is listed in Tab. 1.

		data	background
single μ	$p_t > 6 \text{ GeV/c}$	22000	65 %
	$p_t > 10 \text{ GeV/c}$	1733	38 %
dimuons	$p_t > 3 \text{ GeV/c}$	847	22 %
	$M^{\mu\mu} < 6 \text{ GeV/c}^2$	335	17 %
	$M^{\mu\mu} > 6 \text{ GeV/c}^2$	512	26 %

Table 1

Inclusive muon and dimuon samples and estimated background

The muon pairs are classified according to their charge (neutral or double charged) and the degree of muon isolation. Since the muon momentum is rather low the particle sign is well measured. The isolation is characterized by the transverse energy around the muon, i.e. the sum ΣE_t of the transverse energy of all calorimeter cells within a cone of $\Delta R < 0.7$ about the muon in the pseudorapidity η – azimuth ϕ – space (ϕ about the muon axis). The expected energy deposit of the muon itself is subtracted.

$$\Sigma E_t \text{ in a cone of } \Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.7$$

$$S = (\Sigma E_t^{(1)})^2 + (\Sigma E_t^{(2)})^2$$

The isolation quantities are added in quadrature for both muons. They are considered as isolated, if $S < 9 \text{ GeV}^2$. 82 % of the muons from W and Z decays, which should be isolated, survive this cut. For the low mass events the isolation cut has been modified. If the two muons are so close together that the respective cones overlap, a 3 GeV cut on the transverse energy in a single cone around the common dimuon axis is applied instead.

We observe 256 isolated unlike sign events. Their mass distribution - not corrected for acceptance - is plotted in fig. 4. The mass peaks due to the vector particles decaying into muon pairs are clearly visible. J/ψ particles can also occur non isolated in jets and furthermore their acceptance is difficult to calculate, since they cluster near to our p_t - cut. Therefore a mass cut of $6 \text{ GeV}/c^2$ was applied in the following analysis. The classification of these events according to the dimuon charge and the isolation is given in table 2.

	unlike sign	like-sign
isolated	99	17
non-isolated	256	140

Table 2

Classification of the dimuon events ($M^{\mu\mu} > 6 \text{ GeV}/c^2$) in terms of sign and isolation

fig. 4

*Dimuon mass distribution for unlike-sign isolated events
(Background not subtracted, not corrected for acceptance)*

Drell - Yan and Upsilon

The 99 isolated unlike sign events should be mainly caused by the Drell - Yan process and by Upsilon decays with some contamination from open heavy flavour decays and from background. Their mass distribution is dominated by the Upsilon peak above the Drell - Yan continuum and the heavy flavour decays (fig.5). After subtracting the background and taking into account the different shapes of the mass and isolation distributions we obtain the following cross-sections for Drell - Yan and Upsilon (we assumed that $N(Y) : N(Y') : N(Y'') = 1 : 0.1 : 0.15$):

$$\sigma(\text{DY}, m^{\mu\mu} > 11 \text{ GeV}/c^2) = 0.26 \pm 0.08_{\text{stat}} \pm 0.05_{\text{sys}} \text{ nb}$$

$$\partial^2 \sigma / \partial m \partial y (y = 0, m^{\mu\mu} = 10 \text{ GeV}/c^2) = 15 \pm 5_{\text{stat}} \pm 3_{\text{sys}} \text{ pb/GeV}/c^2$$

$$(\text{BR}) \sigma(p \bar{p} \rightarrow Y, Y', Y'') = 1.0 \pm 0.2_{\text{stat}} \pm 0.2_{\text{sys}} \text{ nb}$$

$$\partial \sigma / \partial y (p \bar{p} \rightarrow Y, Y', Y'', y = 0) = 0.20 \pm 0.04_{\text{stat}} \pm 0.04_{\text{sys}} \text{ nb}$$

The results are compared with extrapolations from low energy data in fig. 6 and show approximate scaling behaviour, i.e. independence of $\sqrt{s}$, if plotted versus the scaling variable $\sqrt{\tau} = m/\sqrt{s}$.

fig. 5

$\partial\sigma/\partial m^{\mu\mu}$ of the isolated unlike-sign events. The fitted contributions from Drell-Yan, Upsilon, heavy flavour and background are indicated

fig. 6

a) UA1 cross section for Drell Yan compared with data at lower energies⁸⁾.

b) UA1 cross section for Upsilon compared with data at lower energies⁷⁾.

The solid line represents a theoretical calculation from ref.⁹⁾

Production of heavy flavours.

The non isolated dimuon events and all like sign events are expected to come from open heavy flavour decays. Various QCD processes contribute to the associated production of heavy flavours. In lowest order heavy quark pairs are mainly created by gluon - gluon fusion and less important by quark - antiquark annihilation:

$$\text{Flavour creation : } gg \rightarrow Q \bar{Q}, q \bar{q} \rightarrow Q \bar{Q}$$

Higher order processes ($\approx \alpha_s^3$) have not yet been completely calculated. However, it was shown, that some of the $2 \rightarrow 3$ processes contribute a sizeable fraction to the heavy flavour cross-section and can be dominant for selected topologies. Besides initial and final state gluon radiation the following $2 \rightarrow 3$ processes were considered:

$$\text{Flavour excitation : } Qg \rightarrow Qg \text{ and } Qq \rightarrow Qq$$

$$\text{Gluon splitting : } g \rightarrow Q \bar{Q}$$

In the case of flavour excitation the heavy quark already exists in the sea. Heavy quark pairs can also result from the QCD evolution of a large p_t gluon jet via gluon splitting into quarks. Fig. 7 shows the calculated ¹⁰⁾ fraction of gluons splitting into heavy quark pairs. Our measured point was determined by the number of D^* inside jets. Splitting into beauty pairs is mass suppressed, whereas charm pairs can still be created in cascade processes with gluons splitting into other gluons in the first step.

In order to confront the muon data with QCD calculations elaborate Monte - Carlo programs - ISAJET¹¹⁾ and EUROJET¹¹⁾ - had to be used. These calculations can be factorized into the structure functions, obtained from lepton nucleon scattering data¹²⁾, the hard QCD

fig.7
fraction of gluon jets splitting
into heavy quark pairs
(Q is the mass of the virtual gluon)

process, and the parton fragmentation and particle decay, which were both carefully adjusted to the wealth of the heavy flavour data from e^+e^- colliders¹³⁾. In fig.8 the inclusive muon distribution is compared with QCD calculations for single muons in the pseudorapidity interval $|\eta| < 1.5$ and also for muons from the non isolated dimuon events. Both QCD calculations agree with the single and dimuon data in shape and absolute cross-section to better than a factor 2, which is the uncertainty of these approximate calculations. The dashed curves correspond to lowest order (flavour creation) only, the solid lines include the above mentioned higher order processes. These processes are definitely needed to explain the single muon yield and add less to the dimuons. In these events the higher order

processes, like flavour excitation and gluon splitting, are suppressed by the dimuon mass cut of 6 GeV/c², which forces muons with $p_t \approx 3$ GeV/c to be predominantly back-to-back in the transverse plane. However, a 25% fraction of higher order processes is also present in the dimuon data. This can be best demonstrated with the $\Delta\phi$ - distribution of the two muons (ϕ is the azimuthal angle), which is sensitive to higher orders. Lowest order processes alone cannot explain the events with $\Delta\phi < 100^\circ$ (fig.9). Tab.3 summarizes the contributions of the different processes, as calculated in ISAJET, to the single and dimuon data and also the beauty and charm content. Due to the harder fragmentation of the beauty quark the dimuons arise to 90% and the single muons to 75% from beauty quarks.

	single muons	dimuons
b $\bar{b}$ lowest order	33 %	71 %
b $\bar{b}$ higher order	42 %	19 %
c $\bar{c}$ lowest order	6 %	8 %
c $\bar{c}$ higher order	19 %	2 %

Table 3

Contributions to the single muon ($p_t > 10$ GeV/c) and dimuon ($m^{\mu\mu} > 6$ GeV/c²) samples from different processes. Higher order includes "flavour excitation" and "gluon splitting" (Isajet)

fig. 8: $d\sigma/dp_T$ of inclusive muons

Single muons with $6 \text{ GeV}/c < p_T < 15 \text{ GeV}/c$. For comparison the inclusive p_T distribution of the dimuons with $p_T > 3 \text{ GeV}/c$ is shown, too. Lowest order Isajet calculations are shown as dashed lines, calculations including higher order processes as solid lines.

fig. 9: $\Delta\phi$ between both muons (non isolated events)

Superposed are the contributions from Isajet, separately for lowest order and higher order contributions and the expected background

What are the direct experimental evidences for the large beauty content in the dimuon data ? First of all, the large amount of like sign dimuons can only come from beauty quarks, either by cascade decays or even more important by beauty oscillations. Furthermore, the transverse muon momentum p_t^{rel} w.r.t. the jet axis reflects the mass of the fragmenting quark. A fit to the p_t^{rel} - distribution (fig.10), separate for like and unlike dimuons, results in a charm content in the dimuon data of $8 \pm 6\%$, consistent with the Monte Carlo calculations. We extract from the data the beauty pair production cross-section in lowest order:

$$\sigma(p \bar{p} \rightarrow b \bar{b}) = 1.1 \pm 0.1_{\text{stat}} \pm 0.4_{\text{sys}} \mu\text{b}$$

for

$$p_t > 5 \text{ GeV}/c \text{ (both b-quarks)}$$

$$|\eta| < 2 \text{ (both b-quarks)}$$

The Isajet cross-section is $1.7 \mu\text{b}$ for the lowest order beauty production. The good description of the beauty production by QCD gives us confidence in the calculation of the top cross-section. The heavy top mass makes a perturbative QCD estimate even more reliable. If the mass is less than $\approx 80 \text{ GeV}/c^2$, W - decays are an additional source for top. Fig. 11 shows the expected number of semileptonic top decays versus the top mass for an integrated luminosity of 690 nb^{-1} . The needed p_t and topology cuts to separate top from bottom are not yet applied. In the mass range between 50 and $80 \text{ GeV}/c^2$ W - decays are the dominant source. They give rise to spectacular events with two large p_t like sign muons and jet activity. The calculated muon transverse momentum spectra from the different sources is plotted in fig.12 together with the single muon data. For a top mass of $40 \text{ GeV}/c^2$ the signal to background ratio is only 0.1 in the best case at a muon p_t of about $15 \text{ GeV}/c$. Additional criteria like the muon isolation, jet activity, topology, and missing energy have to be applied to single out the top events, but they drastically reduce the number of top events. UA1 has performed a careful top analysis and estimates at a 95% confidence limit a lower top mass limit of about $30 \text{ GeV}/c^2$ from the dimuon data and about $50 \text{ GeV}/c^2$ from the combined single muon and electron data ¹⁴⁾. Similar limits hold for a fourth generation bottom quark. In the future, with ten times increased statistics due to ACOL, top will be found, if the mass is below $100 \text{ GeV}/c^2$. At such a high mass the top decay into a W offers a spectacular signature.

The heavy flavour production and all kinematic distributions are in good agreement with QCD. There is only one exception: the large fraction of like sign dimuons, which can only be explained in terms of substantial B^0 - $\bar{B}^0$ oscillations¹⁵⁾.

fig. 10

p_T of the muon with respect to the jet axis
the curves are the result of a fit of Monte Carlo generated p_T^{rel} distributions for
 $c-\bar{c}$, $b-\bar{b}$ and background
a) unlike sign events b) like sign events

fig. 11: number of muon events at 690 nb^{-1}

fig. 12: $d\sigma/dp_t(\mu)$ for various processes (also shown are the inclusive muon data)

Phenomenology of Beauty-Oscillations

Like in the K^0 - $\bar{K}^0$ system, transitions between a B^0 and a $\bar{B}^0$ meson are allowed by second order weak interaction. Hence B^0 and $\bar{B}^0$ are a linear combination of the mass eigenstates B_H and B_L (assuming no CP violation):

$$B^0 = (B_H + B_L) / \sqrt{2}$$

$$\bar{B}^0 = (B_H - B_L) / \sqrt{2}$$

These states may have different masses and decay widths, m_H , Γ_H and m_L , Γ_L respectively, which results in a time dependent phase difference between the B_H and B_L wave functions. With the present experimental resolution it is not possible to measure this time dependence directly. However it is possible to measure time integrated quantities, like the probability that a B^0 -meson decays into a "wrong" sign muon ($\Delta m = m_H - m_L$, assuming $\Gamma_H = \Gamma_L = \Gamma$):

$$\chi = P(B^0 \rightarrow \bar{B}^0 \rightarrow \mu^-) / P(B^0 \rightarrow \mu^\pm) = (1/2) (\Delta m / \Gamma)^2 / [1 + (\Delta m / \Gamma)^2]$$

In the case of maximal mixing, that is if the decay time $\tau_{\text{decay}} = 1/\Gamma$ is much longer than the oscillation time $\tau_{\text{osc}} = 1/\Delta m$, χ approaches 0.5.

fig. 13

Box diagram for $\Delta B = 2$ weak transitions

The mass difference Δm can be calculated from the Box diagram ¹⁶⁾(fig. 13):

$$\Delta m = (G_F^2 / 6 \pi^2) B f_B^2 m_B m_W^2 F(m_c, m_t)$$

G_F is the Fermi coupling constant, m_B the B mass, m_W the W mass, B is the bag parameter ($0.5 < B < 1.5$, $B = 1$ is the vacuum saturation approximation) and f_B is the B decay constant ($f_B \approx 110$ MeV for the B_d^0 and 150 MeV for the B_s^0 ¹⁷⁾).

$F(m_c, m_t)$ describes the dependence on the mass of the exchanged quarks. A good approximation is:

$$B_d^0: F \approx \eta_{cc} (V_{cb}^* V_{cd}) m_c^2 / m_W^2 + \eta_{tt} (V_{tb}^* V_{td}) m_t^2 / m_W^2 + 2 \eta_{ct} (V_{cb}^* V_{cd} V_{tb}^* V_{td}) m_c m_t / m_W^2$$

$$B_s^0: F \approx \eta_{cc} (V_{cb}^* V_{cs}) m_c^2 / m_W^2 + \eta_{tt} (V_{tb}^* V_{ts}) m_t^2 / m_W^2 + 2 \eta_{ct} (V_{cb}^* V_{cs} V_{tb}^* V_{ts}) m_c m_t / m_W^2$$

V_{ij} are the respective Kobayashi Maskawa Matrix elements, η_{ij} are QCD corrections (which are close to 1 ¹⁸⁾) and m_i the masses of the involved heavy quarks. The dominant term comes from the top exchange since the transitions are proportional to the mass squared of the exchanged particle.

As many of these parameters are rather unknown, precise predictions of the strenght of $B^0 - \bar{B}^0$ oscillations are not possible. Theoretical estimates of χ are in a range of 0.1 to 0.48 for B_s^0 and less than 0.2 for B_d^0 .

The main difference between B_d^0 and B_s^0 is due to the Kobayashi Maskawa matrix elements V_{td} and V_{ts} , which favours mixing in the B_s^0 channel. In the standard model with three quark families these matrix elements are already constrained by the unitarity of the Kobayashi Maskawa matrix¹⁹⁾:

$$0.002 < |V_{td}| < 0.017$$

$$0.037 < |V_{ts}| < 0.048$$

This can be used to give an upper limit on χ_d as a function of χ_s :

Assuming $(B f_B \tau)_{Bs} = (B f_B \tau)_{Bd}$, we obtain:

$$(\Delta m/\Gamma)_{Bd} / (\Delta m/\Gamma)_{Bs} = |V_{td}|^2 / |V_{ts}|^2 < 0.21$$

This transforms into:

$$\chi_d < 0.21^2 \chi_s / [1 - 2 \chi_s (1 - 0.21^2)]$$

The advantage of this approach is that most of the theoretical uncertainties cancel, especially the dependence on the top mass.

Evidence for Beauty-Oscillations

The experimental signature of B^0 - $\bar{B}^0$ oscillations are like sign dimuons in excess of the expected small number of like sign events from a beauty -charm cascade:

$$b \rightarrow c \rightarrow \mu^+$$

The cascade decays result in a softer p_t spectrum of the second generation muons. Therefore these events can be suppressed by a cut on the muon p_t . First generation decays of the pair produced beauty quarks result in unlike sign events. However, if one b hadronizes into a $\bar{B}_d^0$ or a $\bar{B}_s^0$, which then oscillates and decays into a μ^+ , like sign events can also arise from first generation decays.

We observe 256 unlike-sign non-isolated dimuons and 140 like-sign non-isolated events. After subtracting the background of 58.5 events in either sample, the following ratio is obtained:

$$R = N(++ , --) / N(+-) = (140 - 58.5) / (256 - 58.5) = 0.41 \pm 0.07_{\text{stat}} \pm 0.03_{\text{sys}}$$

where the systematic error reflects the uncertainty of the background subtraction. This number ignores the contribution from Drell-Yan and Ypsilon. Because of the limited efficiency of the isolation cut we expect 15 ± 7 events from Drell Yan and Upsilon in the non-isolated unlike-sign sample. Taking this into account we get:

$$R = 0.45 \pm 0.08 \pm 0.04$$

These numbers have to be compared with the expectations from heavy flavour production in the case of no mixing:

$$R = N_s / (N_f + N_c)$$

N_f is the number of dimuon events with both muons from first generation decays, N_s the number of events with one muon from first and one muon from second generation decay, and N_c is the contribution from $c \bar{c}$ production. Using Isajet to estimate N_f , N_s and N_c we expect:

$$R_{\text{Isajet}} = 0.26 \pm 0.03$$

The error is due to uncertainties from the b and c fragmentation functions and the semileptonic branching ratios. R_{Isajet} agrees well with independent calculations (table. 4).

If we consider $B^0 - \bar{B}^0$ oscillations, the probability of a b ($\bar{b}$) to decay into a "wrong" sign muon becomes (if all B-hadrons have the same semileptonic branching ratio):

$$\chi = P(b \rightarrow \bar{b} \rightarrow \mu^+) / P(b \rightarrow \mu^\pm) = f_s \bar{s} \chi_s + f_d \bar{d} \chi_d$$

where $f_s \bar{s}$ ($f_d \bar{d}$) is the probability that the b picks up a $\bar{s}$ -quark ($\bar{d}$ -quark) and forms a $\bar{B}_s^0$ ($\bar{B}_d^0$) meson. Based on the ratio K^+/π^+ at high p_T , which was measured at the ISR ²⁰, we use (allowing for 10% of B-Baryons):

$$f_s \bar{s} = 0.18$$

$$f_d \bar{d} = 0.36$$

The ratio of like-sign to unlike sign events is related to χ by:

$$R = \{ 2\chi (1 - \chi) N_f + [(1 - \chi^2) + \chi^2] N_s \} / \{ [(1 - \chi^2) + \chi^2] N_f + 2\chi (1 - \chi) N_s + N_c \}$$

The dependence of R on χ is shown in fig. 14 based on Isajet calculations. Table 4 contains the results from several independent calculations. According to these calculations the preferred value of χ is between 0.10 and 0.15.

Reference	$\chi = 0$	$\chi = 0.05$	$\chi = 0.10$	$\chi = 0.15$	charm content
Barger et al. ²¹⁾	0.25	0.31	0.36	0.42	0.23
Halzen et al. ²²⁾	0.25	0.33	0.41	0.48	0.11
Isajet ¹⁾	0.26	0.34	0.42	0.50	0.10
Eurojet ¹¹⁾	0.21	0.28	0.36	0.43	0.15

Table 4

Predictions for R without B^0 - $\bar{B}^0$ oscillations ($\chi = 0$) and for three values of the mixing parameter χ

Muons from second generation decays have a softer p_t spectrum than primary muons. This difference can be used to determine the mixing parameter χ more precisely. The two-dimensional p_t distributions of first - and second generation beauty decays, charm decays and background were fitted to the data. The maximum likelihood fit accounted for errors of the Monte Carlo calculations and of the background determination. The fit results in (fig. 15):

$$\chi = 0.121 \pm 0.047$$

$$\chi > 0.065 \text{ at } 90 \% \text{ confidence level}$$

The alternative of no mixing ($\chi = 0$) is disfavoured by 2.9 standard deviations. Subtracting the contribution from Drell-Yan and Upsilon we obtain:

$$\chi = 0.158 \pm 0.059$$

$$\chi > 0.091 \text{ at } 90\% \text{ confidence level}$$

which is 3.3 standard deviations away from $\chi = 0$.

	$b \bar{b}$ source	$\sqrt{s} / \text{GeV}$	result
CLEO ²³⁾	$Y(4s) \rightarrow B_d^0 \bar{B}_d^0$	10.6	$\chi_d < 0.19 \text{ at } 90 \% \text{ C.L.}$
ARGUS ²⁴⁾	$Y(4s) \rightarrow B_d^0 \bar{B}_d^0$	10.6	$\chi_d = 0.19 \pm 0.07$
MARK II ²⁵⁾	$e^+e^- \rightarrow b \bar{b}$	29	$\chi < 0.12 \text{ at } 90 \% \text{ C.L.}$
JADE ²⁶⁾	$e^+e^- \rightarrow b \bar{b}$	34	$\chi < 0.13 \text{ at } 90 \% \text{ C.L.}$

Table 5

Results on B^0 - $\bar{B}^0$ oscillations from e^+e^- experiments

fig. 14:

Dependence of R on the mixing parameter χ .
(Isajet calculation for different $c\bar{c}$ contributions: 5, 10 and 15 %)

χ = Fraction of Wrong Sign
Beauty Hadron Decays

FIG. 2

fig. 15

Likelihood function of the mixing parameter χ .

Comparison with other Experiments

We can compare our result with measurements from e+e- experiments. Searches for $B^0 - \bar{B}^0$ oscillations were made by ARGUS²⁴⁾, CLEO²³⁾, JADE²⁶⁾ and MARK II²⁵⁾. Their results are summarized in table 5. CLEO and ARGUS use the $Y(4s)$ resonance, which decays into $B^\pm$ and B_d^0 , thus they are sensitive only to B_d^0 mixing. MARK II and JADE use continuum data well above the B_s^0 threshold and should therefore be sensitive to B_d^0 and B_s^0 . CLEO, MARK II and JADE report upper limits. These limits are shown together with the UA1 result in fig. 16. ARGUS has recently reported a positive signal for B_d^0 oscillations. The ± 1 standard deviation bands of the UA1 and ARGUS measurements are shown together in fig. 17. The two measurements are consistent within a large area in the $\chi_s - \chi_d$ plane. Thus ARGUS is in best agreement with UA1 and confirms our result.

Fig. 18 shows the allowed region in the $\chi_s - \chi_d$ plane for a fit that combines the likelihood function of all measurements. We used the following data:

- UA1: Gaussian distribution: $\chi = 0.121 \pm 0.047$
- CLEO: Gaussian distribution: $\chi_d = 0.096 \pm 0.096$
- ARGUS: Gaussian distribution: $\chi_d = 0.187 \pm 0.069$
- MARK II: Gaussian distribution: $\chi = 0 \pm 0.075$

All experimental results are consistent and allow a large region in the $\chi_s - \chi_d$ plane. Whilst χ_d is restricted between 0.08 and 0.20 (mainly due to ARGUS) there is no restriction on χ_s from experimental data: all values between 0 and 0.5 are possible. We show also the upper limit on χ_d as a function of χ_s , which can be derived from existing limits on the Kobayashi Maskawa matrix elements V_{ts} and V_{td} (i.e. $|V_{td}|^2/|V_{ts}|^2 < 0.21$). If this constraint is combined with the experimental limits, only a small allowed region in the $\chi_s - \chi_d$ plane remains, indicating almost maximal mixing in the B_s^0 channel. Thus a lower limit on $\chi_s > 0.40$ (90 % C.L.) can be derived ($\chi_s > 0.30$ from UA1 alone).

At present the data are consistent with the expectations of the standard model. Future experiments with a more precise determination of χ_s and χ_d are required to test the standard model seriously. With ACOL UA1 is expected to collect about 20000 dimuon events. This will allow to determine χ with an accuracy of 10 %, which will improve the present accuracy by a factor of four.

fig. 16

Limits on χ_d and χ_s from MARK II, CLEO and UA1. The solid lines are the 90 % C.L. limits. The dashed line indicates the UA1 central value of $\chi = 0.12$. The UA1 data were evaluated with $f_s^- = 0.18$ while $f_s^- = 0.15$ was used for MARK II data. This is justified by the lower Q^2 of the e^+e^- data.

fig. 17

± 1 standard deviation bands from UA1 and ARGUS (same values for f_s^- as in figure 16)

fig. 18

Combined Limit on χ_d and χ_s from UA1, MARK II, CLEO and ARGUS (solid lines, 90 % C.L.)

The dashed line indicates the limits on χ_s and χ_d from the Kobayshi Maskawa matrix. The dotted region is allowed by both constraints

("UA1 >" indicates the UA1 lower limit $\chi > 0.065$, 90 % C.L.)

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