Beyond the Standard Model?

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HEAVY FLAVOUR PRODUCTION AND WEAK MIXINGS

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ABSTRACT

Heavy flavour production at the CERN $\bar{p}p$ Collider and in e^+e^- annihilation are reviewed in the context of perturbative QCD. We emphasize in particular the dilepton states $p\bar{p} \to \ell^{\pm}\ell^{\pm}x$, $\ell^+\ell^-x$ and $e^+e^- \to \ell^{\pm}\ell^{\pm}x$, $\ell^+\ell^-x$ in view of the theoretical predictions of large weak mixings in the B_s^0-$\bar{B}_s^0$ mesons. It is argued that the large dimuon ratio $(\mu^+\mu^-+\mu^-\mu^-)/\mu^+\mu^-$ measured at the CERN Collider is very likely due to such a mixing. Some consequences of B-$\bar{B}$ mixings for the ongoing e^+e^- and planned LEP experiments are also presented.

1. - INTRODUCTION

It is generally agreed that the processes involving heavy flavour production and decays in e^+e^- annihilation are well described by perturbative QCD and the standard model of electroweak interactions[1)]. Unfortunately, such a statement cannot be made for heavy flavour production in hadronic interactions. The production of charmed hadrons at the ISR-FNAL energies is not under the quantitative control of perturbative QCD, quite apart from the fact that estimates based on different final states in hadronic collisions give different cross-sections[2)]. Since a large fraction of the charm cross-section at the ISR energies is diffractive, and the present UA1/UA2 triggers are not sensitive to such a component, the obvious question is whether the large-p_T and/or central heavy flavour production at the CERN Collider is well described by the purely perturbative QCD component. The first part of the talk is devoted to providing a qualified answer to this question.

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The second part of this talk deals with the issue of heavy flavour mixings among the neutral bottom mesons due to higher order weak interactions. Ever since the discovery of the bottom quark[3], the possibility of measurable weak mixing effects has been entertained in the literature[4]. Though there exist many theoretical suggestions to detect B-$\bar{B}$ mixings[5], the best bets are still the same-sign dilepton final states $e^+e^- \to \ell^\pm\ell^\pm x$ and $p\bar{p} \to \ell^\pm\ell^\pm x$ [6]. Since these final states can also be reached without invoking any mixing, the issue of observing a B-$\bar{B}$ mixing signal is a quantitative matter and requires very detailed analysis. Experimentally, there does not exist at present a single hint on B-$\bar{B}$ mixings from any e^+e^- experiment[7]. The UA1 collaboration[8] at the CERN Collider has observed an excess of $\mu^\pm\mu^\pm$ events in the process $p\bar{p} \to \mu^\pm\mu^\pm x$, $\mu^+\mu^- x$, over the anticipated background mainly from the b cascades, though the excess does not yet have the impeachable 4-5σ character.

The first question is whether the interpretation of the excess $(\mu^+\mu^+ + \mu^-\mu^-)/\mu^+\mu^-$ events at the CERN Collider in terms of B-$\bar{B}$ mixing is compatible with the lack of any such excess in the present e^+e^- experiments. The answer is yes in the standard model! The point is that with the present bound on the Cabibbo-Kobayashi-Maskawa (CKM)[9] suppressed transition, $b \to uw^-$, expressed as $\bar{R} \equiv \left|(b \to u\ell\nu_\ell)/\right|(b \to c\ell\nu_\ell) < 0.03$[2], the mixing in the B_d^0-$\bar{B}_d^0$ mesons is also very much suppressed. Substantial effects of mixing are anticipated only in the B_s^0-$\bar{B}_s^0$ sector. Now, nobody has yet found a B_s^0 meson, let alone the measurement of the cross-sections $\sigma(e^+e^- \to B_s^0 x)$ or $\sigma(p\bar{p} \to B_s^0 x)$. Nevertheless, these cross-sections can be estimated in the continuum if one has measurements of the inclusive bottom cross-sections $\sigma(e^+e^- \to b\bar{b}x)$, $\sigma(p\bar{p} \to b\bar{b}x)$ and the probability of producing an $s\bar{s}$ pair from the vacuum. Both of these quantities have been measured in e^+e^- experiments, with $\Delta R(e^+e^- \to b\bar{b}) = \sigma(e^+e^- \to b\bar{b})/\sigma(e^+e^- \to \mu^+\mu^-) \simeq 1/3$ and Prob. (vac $\to s\bar{s}$) $\simeq$ 0.1-0.15 at the highest PEP/PETRA energies. These measurements would then lead to a cross-section $\sigma(e^+e^- \to B_s^0 x) \simeq 7$ Pb at $\sqrt{s} \simeq 29$ GeV, where most of the PEP data are obtained. It is then easy to understand that the ongoing e^+e^- experiments do not have the sensitivity to detect the process $e^+e^- \to B_s^0 x \leftrightarrow \bar{B}_s^0 x \to$

$\mu^{\pm}\mu^{\pm}x$ with their present statistics. The data from CESR and DORIS are obtained mostly at $\sqrt{s} < \Upsilon(4s)$, where the production $e^+e^- \to B_s^0 x$ is kinematically forbidden. A four-fold increase in the PEP integrated luminosity or the discovery of yet another $(b\bar{b})$ resonance, decaying preferentially into B_s^0 meson at CESR and DORIS, would change this situation for e^+e^- experiments.

The cross-section estimates for $\sigma(p\bar{p} \to b\bar{b}x)$ at the CERN Collider are, however, in a different ball-park compared to the e^+e^- cross-sections. Based on the so-called heavy flavour $\mu\mu$-sample, the UA1 Collaboration has quoted a cross-section, $\sigma(p\bar{p} \to b\bar{b}x) = 2.3 \pm 0.4 \pm 0.4$ μb at $\sqrt{s} = 630$ GeV for $p_T^b >$ 5 GeV and $|\eta^b| < 2$, which is in agreement with theoretical estimates based on perturbative QCD calculations[10]. This would then put the cross-section $\sigma(p\bar{p} \to B_s^0 x)$ in the range of ~300 nb, roughly a factor ~50,000 bigger compared to the inclusive cross-section $\sigma(e^+e^- \to B_s^0 x)$ at PEP! Thus, despite a rather small effective branching ratio for the dimuon final state due to the trigger and $\mu\mu$ efficiency a non-trivial test of the B_s^0-$\bar{B}_s^0$ mixing in the final state $p\bar{p} \to \mu^{\pm}\mu^{\pm}x$ is expected. Though the excess of the $(\mu^+\mu^+ + \mu^-\mu^-)/\mu^+\mu^-$ ratio over the background estimates is at present only at the 2-3 standard deviation level, and I would like to caution about overinterpreting the data, yet there is a very good motivation to take the present excess seriously. We enumerate various possible sources for the $(\mu^+\mu^+ + \mu^-\mu^-)x$ events at the Collider. All of them, except the B-$\bar{B}$ mixings, are rather unlikely.

Interpreting the excess $(\mu^+\mu^- + \mu^-\mu^-)x$ events in the UA1 data as due to B-$\bar{B}$ mixing, we investigate the consequences of such mixings at the planned SLC and LEP energies. Weak mixings in the B-$\bar{B}$ sector, if confirmed experimentally, would open a new window on the realm of $|\Delta F| = 2$ transitions, a field which up until now is the monopoly of the kaon factories. Of course, the overriding interest lies in the investigation of the constraints that the $|\Delta B| = 2$ transitions would impose on the parameters of the standard model. Let us hope that more data and analysis from the CERN bottom factory and elsewhere would soon warrant such an undertaking, thus confronting the standard model with yet another stringent test ... but in the domain of higher order weak interactions.

2. - PERTURBATIVE QCD AND HEAVY FLAVOUR PRODUCTION AT THE CERN COLLIDER

Large-p_T heavy flavour production at the CERN Collider has many sources. The most reliably calculable source is perhaps in the production and decays of the $W^{\pm}$ and Z^0 bosons. Denoting $\sigma_W^e \equiv \sigma(p\bar{p} \to W^{\pm} \to e^{\pm}\nu_e)$ and $\sigma_Z^e \equiv \sigma(p\bar{p} \to Z^0 \to e^+e^-)$, the heavy flavour production cross-sections involving charm, bottom and top quarks in the $W^{\pm}$ and Z^0 decays have the following values (±20%) at $\sqrt{s}$ = 630 GeV.

$$
\begin{aligned}
\sigma(p\bar{p} \to W^{\pm} \to t\bar{b}) &\simeq 1.95\,\sigma_W^e \simeq 1 \text{ nb} \\
\sigma(p\bar{p} \to W^{\pm} \to c\bar{s}) &\simeq 3\,\sigma_W^e \simeq 1.6 \text{ nb} \\
\sigma(p\bar{p} \to Z^0 \to c\bar{c}) &\simeq 3.5\,\sigma_Z^e \simeq 200 \text{ Pb} \\
\sigma(p\bar{p} \to Z^0 \to b\bar{b}) &\simeq 4.5\,\sigma_Z^e \simeq 250 \text{ Pb} \\
\sigma(p\bar{p} \to Z^0 \to t\bar{t}) &\simeq 0.8\,\sigma_Z^e \simeq 45 \text{ Pb}
\end{aligned}
\tag{1}
$$

The numbers in (1) correspond to the following choice of masses and measured cross-sections, compatible with the UA1/UA2 data[11),12)].

$$
\begin{aligned}
m_Z &= 94 \text{ GeV} \\
\sin^2\theta_W &= 0.217 \\
m_t &= 40 \text{ GeV} \\
\sigma_W^e(\sqrt{s} = 630 \text{ GeV}) &= 540 \text{ Pb} \\
\sigma_Z^e(\sqrt{s} = 630 \text{ GeV}) &= 60 \text{ Pb}
\end{aligned}
\tag{2}
$$

Thus, for example, with the present UA1 luminosity ≃ 380 nb^{-1}, one expects ~400 $p\bar{p} \to tx$ events due to the $W^{\pm}$ and Z^0 production.

The second and probably the dominant source of heavy flavour production at large-p_T is perturbative QCD (also called here strong production mechanism). The Born diagrams for the perturbative heavy flavour production in hadron-hadron collisions up to $O(\alpha_s)^3$ are shown in Fig. 1. The $2 \to 2$ processes [which have so far been calculated only up to $O(\alpha_s)^2$] are formally finite due to the heavy quark masses and can be integrated down to $p_T^Q = 0$[13]. The $2 \to 3$ processes on the other hand involve the bremsstrahlung of a gluon or scattering involving a light quark (u,d,s)[14]. This necessitates a cut-off on the $2 \to 3$ processes, e.g., on the p_T of the gluon or light quark jet which is produced in association with the $Q\bar{Q}$ pair, to regulate the divergences. In Table 1a we present the inclusive cross-sections $\sigma(p\bar{p} \to Qx)$ for a variety of p_T^Q and pseudorapidity, η^Q, cut-offs at $\sqrt{s}$ = 630 GeV. The numbers correspond to using the Glück-Hoffmann-Reya structure functions[15] with Λ = 0.2 GeV, $Q^2 = s$ in the determination of $\alpha_s(Q^2)$ and in the evolution of the structure functions. To have an idea of the relative importance of the perturbative QCD cross-sections, we note that for $p_T^Q > 5$ GeV and $|\eta^Q| < 2.0$ (i.e., central production) one has[10] (theoretical uncertainties on these cross-sections are typically ±20%)

$$\begin{aligned} \sigma(p\bar{p} \to cx) &\simeq 10\ \mu b \\ \sigma(p\bar{p} \to bx) &\simeq 3\ \mu b \\ \sigma(p\bar{p} \to tx) &\simeq 1.6\ nb \end{aligned} \tag{3}$$

Comparing (1) and (3) makes it evident that the charm and bottom production cross-sections in $p\bar{p}$ collisions at the collider are completely dominated by the strong interaction processes. The production rates of the top quark from the weak and strong sources are comparable at $\sqrt{s}$ = 630 GeV, with $\sigma(p\bar{p} \to tx)_{QCD}/\sigma(p\bar{p} \to tx)_{W,Z} \simeq 1.5-1.7$. It is instructive to compare the cross-sections $\sigma(p\bar{p} \to cx)$, $\sigma(p\bar{p} \to bx)$ in (3) with the cross-sections $\sigma(e^+e^- \to cx)$ and $\sigma(e^+e^- \to bx)$. For $\sqrt{s}$ = 29 GeV, where the highest luminosity e^+e^- data have been accumulated at PEP, one has [note that $\sigma(e^+e^- \to cx) \simeq 2\sigma(e^+e^- \to c\bar{c})$, etc.]

$$\sigma(e^+e^- \to cX) \simeq 275 \text{ Pb}$$
$$\sigma(e^+e^- \to bX) \simeq 70 \text{ Pb} \tag{4}$$

This gives the following ratios (at $\sqrt{s}$ = 630 GeV and 29 GeV for $p\bar{p}$ and e^+e^- respectively)

$$\frac{\sigma(p\bar{p} \to cX)}{\sigma(e^+e^- \to cX)} \left\{ \begin{matrix} P_T^c > 5\text{GeV} \\ |\eta^c| < 2.0 \end{matrix} \right\} \simeq 3.6 \times 10^4$$

$$\frac{\sigma(p\bar{p} \to bX)}{\sigma(e^+e^- \to bX)} \left\{ \begin{matrix} P_T^b > 5\text{GeV} \\ |\eta^b| < 2.0 \end{matrix} \right\} \simeq 4.4 \times 10^4 \tag{5}$$

Thus, the central production ($|\eta^Q| < 2$) of charm and bottom quarks at the CERN Collider are larger by a factor ~40,000 over the e^+e^- production rates at $\sqrt{s}$ = 29 GeV. The cross-sections (3) are in some sense lower bounds since there is yet another source of heavy flavour production in large-p_T jets in $p\bar{p}$ collisions which is almost absent (or small) in e^+e^- annihilation. The clue to this latent heavy flavour component comes from the inclusive $D^{*\pm}$-measurements reported by UA1[16]. Tagging $D^{*\pm}$ via the decay sequence $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$ (and its charge conjugate) in large-p_T centrally produced jets the UA1 collaboration has reported the surprisingly large ratio $N(D^{*\pm})/N(\text{jet}) = 0.65 \pm 0.10$ for D^*'s with fractional momenta $Z > 0.1$. The best that perturbation theory can do is: $N(D^{*\pm})/N(\text{jet}) \simeq 0.05$[14]. The charm cross-section based on perturbative processes given in (3) could then be an underestimate by an order of magnitude. The large D^*-ratio is, however, based on rather small-statistics 1983 data and it would be nice to have the corresponding number for the more luminous 1984 data.

It is conceivable that there is a substantial non-perturbative $c\bar{c}$

component in the fragmentation $g \to c\bar{c}$. A model calculation, whose starting point is the parton (mainly gluon) shower mechanism of perturbative QCD[17)] but which assumes that a large mass scale Q_0 (compared to Λ) plays a role in the fragmentation of a gluon jet at the collider energies, gives a ratio $N(D^{*\pm})/\mathrm{jet} \simeq 0.12-0.15$. This is bigger by a factor ~3 compared to the purely perturbative contributions[14)], but still smaller by a factor ~5 compared to the UA1-data taken at its face value. This non-perturbative component is, however, expected to be much smaller for the $g \to b\bar{b}$ and entirely negligible for the $g \to t\bar{t}$ splittings at the CERN Collider energies. These contributions are expected to remain small at the Tevatron and the LEP-Hadron-Collider energies also, since their relative contributions are governed by Q_0, which is not expected to vary very much with $\sqrt{s}$. If consolidated, the UA1 D^*-data would provide invaluable information about the flavour content of large-p_T gluon jets. At the same time they would render the identification of heavy flavour jets more difficult.

Since the inclusive D^*-analysis based on the 1984 Collider run is still missing, I would not like to emphasize this aspect of the data any more in this talk, except remarking that the soft-nature of the inclusive-D^* spectrum makes only a very marginal contribution to the inclusive lepton rates in both the $p+\bar{p} \to \ell^\pm x$ and the intermediate mass dimuon data. This is a consequence of the rather stringent triggers, in vogue in the UA1 data analysis[10,12)]

and

$$
\begin{aligned}
&p_T^\mu > 12~\mathrm{GeV}, \quad |\eta^\mu| < 1.5 \quad \text{for } p\bar{p} \to \ell^\pm x \\
&p_T^\mu > 3~\mathrm{GeV}, \quad p_T^{\mu_1+\mu_2} > 10~\mathrm{GeV}, \quad |\eta^\mu| < 2.0 \quad \text{for } p\bar{p} \to \mu\mu x
\end{aligned}
\tag{6}
$$

Lowering the p_T^μ cut-off, to say 5 GeV, one should see a sharp rise in the inclusive lepton rate $p+\bar{p} \to \ell^\pm x$ due to the non-perturbative $g \to c\bar{c} \to \ell^\pm x$ contribution. This could serve as an additional consistency check on the UA1-D^* data.

Concentrating on the perturbative processes shown in Fig. 1, we show in Fig. 3 the pseudorapidity distributions $d\sigma/d\eta^Q$ for the inclusive $2 \to 2$ and

$2 \rightarrow 3$ processes leading to the final state $p+\bar{p} \rightarrow Q+x$. The distributions shown correspond to a p_T^{jet} cut-off of 5 GeV on the jet recoiling against the heavy quark. Note that only for the charm quark production is the $2 \rightarrow 3$ process dominant over the $2 \rightarrow 2$. This is a consequence of the heavy quark mass. Further discussion of the role of $2 \rightarrow 3$ processes in heavy flavour production can be found in Refs. 10) and 14).

The inclusive p_T-distributions for the processes (with the indicated kinematic cuts)

$$
\begin{aligned}
&p+\bar{p} \rightarrow Q+x, && Q=c,b,t\,; \quad p_T^Q > 5\ \mathrm{GeV}, \\
& && \qquad\qquad |\eta^Q| < 2.0 \\
&p+\bar{p} \rightarrow \ell^{\pm}+x, && p_T^{\ell} > 3\ \mathrm{GeV},\ |\eta^{\ell}| < 1.5 \qquad (7) \\
&p+\bar{p} \rightarrow (\ell^{\pm}\ell^{\pm}, \ell^{+}\ell^{-})+x, && p_T^{\ell} > 3\ \mathrm{GeV},\ m_{\ell\ell} > 5\ \mathrm{GeV}, \\
& && \qquad\qquad |\eta^{\ell}| < 2.0
\end{aligned}
$$

are shown in Fig. 4. These cut-offs have been selected to match the ongoing UA1-analysis, so that the resulting distributions can be compared directly with the corrected data. Preliminary comparisons of perturbative QCD calculations and the UA1 data in $p+\bar{p} \rightarrow \ell^{\pm}x$ and $p+\bar{p} \rightarrow \mu\mu x$ have already been published[8),12)]. After taking due account of the acceptance and efficiency one finds a fine agreement between the data and the processes shown in Fig. 1 for both the cut-offs (6) and (7)[8),12),18)-20)]. The inclusive cross-sections for $p+\bar{p} \rightarrow \ell^{\pm}x$ at $\sqrt{s}$ = 630 GeV are given in Table 1b and the cross-sections for the dimuons with $p_T^{\mu 1}+p_T^{\mu 2} > 10$ GeV are given in Table 1c. Note that the intermediate mass dimuon cross-section is dominated by the strong process $p+\bar{p} \rightarrow b\bar{b}x$, which accounts for 80% of the total heavy flavour dimuon rate.

In the rest of this section, I will concentrate on the UA1 dimuon data. First, the overall rate of the cross-section $\sigma(p+\bar{p} \rightarrow \mu\mu x)$. To get an idea of the event rate we quote the following cross-sections at $\sqrt{s}$ = 630 GeV[21)]:

$$\sigma(p\bar{p} \to \mu\mu x) \simeq 350 \text{ Pb for cuts (6)}$$
$$\sigma(p\bar{p} \to \mu\mu x) \simeq 1.25 \text{ nb for cuts (7)} \tag{8}$$

For the UA1 integrated luminosity ≈ 380 nb^{-1} and a dimuon detection efficiency $\varepsilon(\mu\mu) = 0.25$ they lead respectively to ~35 and 120 $\mu\mu x$ events ... in good agreement with the UA1 data[10),12),18)-20)]. The shape of the normalized distributions in the transverse momentum of the muons, the dimuon invariant mass and the azimuthal angle between the muons are shown in Figs. 5a-5c and compared with the UA1-data[8),19)]. Again, the agreement is quite satisfactory. Note the almost back to back nature (in the transverse plane) of the $p\bar{p} \to b\bar{b} \to \mu\mu x$ events ... a feature also present in the so-called isolated same-sign dimuon UA1-data sample[8)].

Let us now discuss the isolated same-sign dimuons. Based on the dimuon cuts (6), the UA1 collaboration has reported 67 $\mu\mu x$ events after subtracting the $Z \to \mu\mu$ events, out of which 34 are classified as the heavy flavour sample, in which at least one of the muons is not isolated. There are 7 same-sign dimuon events where both muons are isolated in a cone $\Delta R = \sqrt{\Delta\phi^2+\Delta\eta^2} < 0.7$ centred on the muon (i.e., the hadronic activity in these cones is consistent with the minimum bias events). Some of these isolated $\mu^\pm\mu^\pm x$ events do have associated jet activity but not in the muon-cone. For detailed properties of these events see Ref. 8).

Based on the 34 $\mu\mu x$ events one has $R(\pm\pm/+-) = 8/26 = 0.3 \pm 0.1$. Including the 7 so-called isolated same-sign dimuons this ratio becomes $15/26 \approx 0.55 \pm 0.1$, to be compared with 0.24 ± 0.02 expected from the processes $p\bar{p} \to c\bar{c}, b\bar{b}, t\bar{t} \to \mu\mu x$ without B-$\bar{B}$ mixing[21)]. Thus, the heavy flavour sample with the cuts (6) is consistent with no B-$\bar{B}$ mixing, though the ratio obtained after including the 7 $\mu^\pm\mu^\pm x$ events would be about 3σ away from the no-mixing case. It is tantalizing to identify the $\mu^\pm\mu^\pm$ excess with B-$\bar{B}$ mixing, though one has to understand the isolation first.

Let me briefly summarize the kinematics of the 7 $\mu^\pm\mu^\pm x$ events[8)]. The p_T^μ-distribution of these events is very similar to the heavy flavour $\mu\mu x$

sample. In this respect the 1984 data have eased one of the difficulties in the interpretation of these events as due to $b\bar{b}$ production, since the 1983 data had harder p_T^μ-spectra. The same is true about $(p_T)_{\mu\bar{\mu}}$ distribution, the azimuthal angular distribution $d\sigma/d\phi_{\mu\mu}$, and the presence of strange particles (K_s^0,Λ,etc.) with the charge correlation $\ell^-\ell^-\bar{\Lambda}^0$ and $\ell^+\ell^+\Lambda^0$ ... all these features are compatible with $b\bar{b}$ production and B_s-$\bar{B}_s$ mixings[22]. On the problematic side are the isolation and the invariant mass distribution $d\sigma/dm_{\mu\mu}$, which are features not quite in line with the $b\bar{b}$ interpretation. However, if the isolation criterion is relaxed then the dimuon invariant mass distributions for both the $\mu^+\mu^-$ and $\mu^\pm\mu^\pm x$ events are quite compatible with the ones expected from heavy flavour production.

The processes which give rise to isolated opposite-sign dimuons are well known. Drell-Yan $\mu^+\mu^-$, as well as production and decays of vector mesons $p\bar{p} \to (J/\psi,\ \Upsilon,\ Z^0)x \to \mu^+\mu^- x$ are some examples. There are no doubly charged vector bosons in the mass range 10-14 GeV, where the 7 $\mu^\pm\mu^\pm$ events seem to be produced. A doubly charged meson in this mass range could not have been missed by the PETRA/PEP experiments. Non-diagonal neutral weak currents $c \to (u)+\mu^+\mu^-$, $b \to (d,s)\mu^+\mu^-$ could give rise to the processes $p\bar{p} \to b\bar{b},\ c\bar{c} \to \mu^\pm\mu^\pm x$, but there already exist very stringent bounds on these transitions from e^+e^- data[1]. It has been suggested by Halzen et al.[14] that the non-perturbative process $g \to c\bar{c} \to D^{*\pm}$ could give rise to both $\mu^\pm\mu^\pm x$ and $\mu^-\mu^+x$ events. However, it can easily be checked that with the proper kinematics in production and decays taken into account, the non-perturbative contribution due to the processes $gg \to gg \to (c\bar{c})(c\bar{c})x \to (\mu^\pm\mu^\pm,\ \mu^-\mu^+)x$ is negligible with the UA1 dimuon trigger, (6). In any case, the isolation of so produced $\mu^\pm\mu^\pm$events is even harder to understand than that of the $p\bar{p} \to b\bar{b} \to \mu^\pm\mu^\pm x$ events[22]. The production of a pair of J/ψ in the process $p+\bar{p} \to J/\psi \to \mu^+\mu^-$, $J/\psi \to \mu^+\mu^-+x$ could give rise to $\mu^\pm\mu^\pm x$ events if the other two muons are missed. However, realistic calculations with the p_T^μ and η^μ trigger condition (6) included render the cross-sections minuscule. It would be nice to have an example of a well-constructed double J/ψ production event!

Thus, it seems that the process $p+\bar{p} \to b\bar{b} \to \mu^{\pm}\mu^{\pm}x$ due to B_s^0-$\bar{B}_s^0$ mixing, despite the isolation problem, remains the only viable explanation. Of course, the isolated $\mu^{\pm}\mu^{\pm}$ data could also turn out to be a statistical fluctuation! The encouraging sign is that the relaxed $\mu\mu$ cuts (7) have resulted in a larger dimuon data sample[20]. The preliminary UA1-data have now 127 (both sign) dimuon events in the "non-isolated" category and 15 $\mu^+\mu^+ + \mu^-\mu^-$ events in the "isolated same-sign" sample. The quoted ratios[20]

$$\begin{aligned} R(\pm\pm/+-)_{\text{all events}} &= 0.56 \pm 0.09 \\ R(\pm\pm/+-)_{\text{non-isolated}} &= 0.53 \pm 0.10 \end{aligned} \qquad (9)$$

are to be compared with a perturbative QCD model prediction[21] 0.32±0.02 without B-$\bar{B}$ mixings. It seems that the heavy flavour sample by itself is now indicating the presence of excess $\mu^{\pm}\mu^{\pm}x$ events thus strengthening the B-$\bar{B}$ mixing hypothesis. More data and better analysis should clinch this issue in a not too distant future.

3. WEAK MIXINGS IN THE B-$\bar{B}$ SECTOR

In the standard three-family $SU(2)_L \times U(1)$ model the charged weak currents are governed by a unitary 3×3 matrix, first written down by Kobayashi and Maskawa[8]

$$J_\mu^{\pm} \sim g\, \bar{u}_j V_{ji} \gamma_\mu (1-\gamma_5) d_i + h.c. \qquad (10)$$

with g the gauge coupling constant. The matrix V involves three-angles and a complex phase. In a symbolic form one can write V as

$$V \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{us} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \tag{11}$$

The present information on weak decays of mesons and baryons[1] gives the following values for the entries in the KM matrix

$$\begin{aligned} |V_{ud}| &\simeq 0.974 \\ |V_{us}| &\simeq 0.23 \\ |V_{cb}| &\simeq 0.05 \pm 0.01 \\ |V_{ub}| &\leqslant 0.12\,|V_{cb}| \end{aligned} \tag{12}$$

where the numbers for $|V_{cb}|$ and $|V_{ub}|$ are from the bottom lifetime measurements[1]

$$\tau_B = (1.4 \pm 0.3 \pm 0.3) \times 10^{-12}\ s \tag{13}$$

and the bound

$$\bar{R} \equiv \frac{\Gamma(b \to u \ell \nu_\ell)}{\Gamma(b \to c \ell \nu_\ell)} \leqslant 0.04 \tag{14}$$

The relative magnitudes of the elements $|V_{ij}|$ in (12) are in the ratio 1: λ : λ^2 < $\frac{1}{2}\lambda^3$, where $\lambda = \sin\theta_c \simeq 0.23$. One could expand V in λ getting[23]

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \tag{15}$$

The information (12) can now be translated as

$$\begin{aligned} \lambda &= \sin\theta_C \simeq 0.23 \\ A &= 1.0 \pm 0.2 \\ \rho^2+\eta^2 &< 0.3 \end{aligned} \tag{16}$$

Note the following pattern

$$\begin{aligned} |V_{bc}| \simeq |V_{ts}| &= \lambda^2 \\ |V_{td}|,\ |V_{ub}| &\sim \mathcal{O}(\lambda^3) \\ \cancel{CP} &\sim \mathcal{O}(\lambda^3) \end{aligned} \tag{17}$$

We shall concentrate on B-$\bar{B}$ mixing. For further discussions of flavour-mixings, see Refs. 4), 5), 10) and 24).

As is by now well known, there are two bottom mesons B_d^0 ($\equiv b\bar{d}$) and B_s^0 ($\equiv \bar{b}s$) which can mix with their charge conjugates due to the $\mathcal{L}_{eff}(\Delta B = 2)$ interactions. The mesons with definite masses and lifetimes we call $B_d^{(1)}$, $B_d^{(2)}$, $B_s^{(1)}$ and $B_s^{(2)}$. The mass differences $\Delta M(B_d^0) \equiv \Delta M(B_d^1 - B_d^2)$ and $\Delta M(B_s^0) \equiv \Delta M(B_s^1 - B_s^2)$ are obtained from the box diagrams[4),5),22)] which give

$$\Delta M(B_d^0) = \frac{G_F^2 f_{Bd}^2 m_{Bd} B}{6\pi^2} F_d(m_b, m_t, \lambda)$$
$$\Delta M(B_s^0) = \frac{G_F^2 f_{Bs}^2 m_{Bs} B}{6\pi^2} F_s(m_b, m_t, \lambda) \tag{18}$$

where B is the bag constant (= 1 in the vacuum insertion approximation), f_{Bd} and f_{Bs} are the pseudoscalar coupling constants for the B_d^0 and B_s^0 mesons respectively, analogous to f_π and f_K, and the functions F_d and F_s are given by

$$F_d(m_b, m_t, \lambda) = (\lambda_c^d)^2 u_1 + (\lambda_t^d)^2 u_2 + 2(\lambda_t^d \lambda_c^d) u_3$$
$$F_s(m_b, m_t, \lambda) = (\lambda_c^s)^2 u_1 + (\lambda_t^s)^2 u_2 + 2(\lambda_t^s \lambda_c^s) u_3 \tag{19}$$

where the CKM angle factors λ_i^j are

$$\begin{aligned} |\lambda_c^d| &\equiv |V_{cb}^* V_{cd}| \sim \lambda^3 \\ |\lambda_t^d| &\equiv |V_{tb}^* V_{td}| \lesssim \tfrac{1}{2}\lambda^3 \\ |\lambda_c^s| &\equiv |V_{cb}^* V_{cs}| \sim \lambda^2 \\ |\lambda_t^s| &\equiv |V_{tb}^* V_{ts}| \sim \lambda^2 \end{aligned} \tag{20}$$

and the quark mass dependent functions u_i are given by

$$u_1 \sim m_c^2/m_W^2$$
$$u_2 \sim m_t^2/m_W^2 \qquad (21)$$
$$u_3 \sim m_t m_c/m_W^2$$

Thus, the dominant contribution in both $\Delta M(B_d^0)$ and $\Delta M(B_s^0)$ is due to the u_2 term. Since in the free-quark decay model the decay widths $\Gamma(B_d^0)$ and $\Gamma(B_s^0)$ are expected to be rather similar and are both determined by the element $|V_{bc}|$, we have

$$\Gamma(B_d^0) \simeq \Gamma(B_s^0) \propto |V_{bc}|^2 \sim \lambda^4 \qquad (22)$$

The phenomenological relevant quantity $\Delta M/\Gamma$ then has the following CKM angular dependence

$$\frac{\Delta M}{\Gamma}(B_d^0) \lesssim \lambda^2$$
$$\frac{\Delta M}{\Gamma}(B_s^0) \propto \frac{\lambda^4}{\lambda^4} = 1 \qquad (23)$$

The mass mixing in the $B_d^0 \leftrightarrow \bar{B}_d^0$ system is <u>Cabibbo suppressed</u> and usual estimates of f_{Bd}, B, etc., then give $\Delta M/\Gamma(B_d^0) < 10^{-2}$. The mixing in the B_s^0-$\bar{B}_s^0$ system is <u>Cabibbo allowed</u>. Theoretical estimates of f_{Bs} give $f_{Bs} \simeq$ 200 MeV[22] and the bag constant B is expected to be close to 1. Using τ_B from (13), estimates of $\Delta M/\Gamma(B_s^0)$ are given in Table 2. Note that for all parameters shown $\Delta M/\Gamma(B_s^0) > 1$. Thus, in the standard model mixing in the B_s^0-$\bar{B}_s^0$ sector is expected to be substantial. The lifetime differences $\Delta\Gamma/\Gamma$ are expected to be small in both the B_d^0-$\bar{B}_d^0$ and B_s^0-$\bar{B}_s^0$ complex and we neglect them here.

Concentrating on B_s^0-$\bar{B}_s^0$ mixing only, one can define the following quantity as a measure of weak mixing[6)]

$$
\begin{aligned}
r(B_s) &= \frac{\Gamma(B_s^0 \to \ell^+ \nu_\ell X^-)}{\Gamma(B_s^0 \to \ell^- \bar{\nu}_\ell X^+)} \\
&= \frac{\left[\left(\frac{\Delta M}{\Gamma}\right)^2 + \left(\frac{\Delta\Gamma}{2\Gamma}\right)^2\right]}{\left[2 + \left(\frac{\Delta M}{\Gamma}\right)^2 \left(\frac{\Delta\Gamma}{\Gamma}\right)^2\right]} \\
&\simeq \frac{(\Delta M/\Gamma)^2}{2 + (\Delta M/\Gamma)^2} \xrightarrow[\left(\frac{\Delta M}{\Gamma}\right) \gg 1]{} 1
\end{aligned}
\tag{24}
$$

the values of $r(B_s^0)$ are also given in Table 2. Note that $r(B_s^0)$ could be large: almost approaching 1. However, since the mixing is expected to be significant in the B_s^0-$\bar{B}_s^0$ sector only, one has to calculate the cross-section $\sigma(e^+e^- \to B_s^0 x)$, $\sigma(p\bar{p} \to B_s^0 x)$ to get observable rates. This probably can be estimated by the perturbative QCD cross-sections $\sigma(e^+e^- \to b\bar{b}x)$, and $\sigma(p\bar{p} \to b\bar{b}x)$ and the fraction of the $s\bar{s}$ pair excitation from the vacuum in the colour field of an excited quark. Denoting symbolically

$$
K \equiv \text{Prob.}\,(\text{vac} \to s\bar{s}) \tag{25}
$$

the ratio of wrong-sign to right-sign lepton in the continuum can be written as[22)]

$$
\begin{aligned}
r_{\text{Cont.}}(B_s^0) &= \frac{b \to B_s^0 \to \ell^+ \nu_\ell X^-}{b \to \ell^- \bar{\nu}_\ell X^+} \\
&= Kr/[1 + r - Kr] \\
&\xrightarrow[r=1]{} \frac{K}{2-K} \xrightarrow[K=1/3]{} 0.2
\end{aligned}
\tag{26}
$$

Thus, $r_{cont}(B_s^0)$ could be as large as 0.2. It is interesting that Mark-II has recently put a limit on the ratio (26) from e^+e^- data at $\sqrt{s}$ = 29 GeV[26)]

$$r_{cont.}^{Mk.\,II} \equiv \frac{b \to \ell^+ \nu_\ell X^-}{b \to \ell^- \bar{\nu}_\ell X^+} < 0.12 \text{ (90\% confidence level)} \tag{27}$$

The interpretation of this result is that it excludes complete B_s-$\bar{B}_s$ mixing (r_s = 1) with a complete SU(3)-symmetric sea (κ = 1/3). However, a realistic number for κ at the PETRA/PEP energies lies in the range 0.1–0.15[27)]. Using the upper value of κ at PEP energies $\kappa \simeq 0.15$, it is easy to determine that

$$r_{cont.}^{th.} \leqslant 0.08 \tag{28}$$

which is lower than the Mark-II limit (27).

From (26), it is straightforward to calculate the ratio of the same-sign to opposite-sign dileptons

$$R_{\ell\ell}(b\bar{b}) \equiv \frac{\sigma(p\bar{p}, e^+e^- \to b\bar{b} \to \ell^+\ell^+ + \ell^-\ell^-)}{\sigma(p\bar{p}, e^+e^- \to b\bar{b} \to \ell^+\ell^-)}$$

$$= \frac{2\kappa r\,[(1+r)(1-\kappa)+\kappa]}{\kappa^2 r^2 + [(1+r)(1-\kappa)+\kappa]^2} \tag{29}$$

$$\xrightarrow[r=1]{} \frac{2\kappa(2-\kappa)}{\kappa^2+(2-\kappa)^2} \xrightarrow[\kappa=1/3]{} 10/26$$

where again the limiting values for complete mixing and an SU(3) symmetric sea are shown. Some representative values of $R_{\ell\ell}(b\bar{b})$ are also shown in Table 2. We must point out that the ratio (29) applies only to primary leptons in the decay $b \to c\ell^-\nu_\ell$. In an actual experiment the ratio R(±±/+–)

would be quite a bit larger than in (29) due to the cascades $\bar{b} \to \bar{c}\ell^+\nu_\ell$, $b \to c \to \ell^+ + \ldots$ which contributes to R(±±/+−) as also noted in the last section. Techniques to remove the cascade leptons from b-decays are well known from e^+e^- experiments and can be used as such in the analysis of the collider data as well. A value $R_{\ell\ell}(b\bar{b}) \simeq 0.15$-$0.20$ at the collider energies would explain the ratios R(±±/+−) measured by the UA1 in a natural way. Note that the values for $R_{\ell\ell}(b\bar{b})$ expected in the standard model are indeed in this region (see Table 2).

My conclusion is that the excess of $\mu^+\mu^+ + \mu^-\mu^-$ events at the collider and its interpretation in terms of B-$\bar{B}$ mixing is not in conflict with the limits from the e^+e^- experiments. The present Mark-II[26] and JADE[25] data lack the statistics to set a meaningful limit on B_s^0-$\bar{B}_s^0$ mixing, given the cross-section estimates for $e^+e^- \to B_s^0 x$. The CLEO data on Υ(4S) have exactly zero sensitivity for B_s^0-$\bar{B}_s^0$ mixing. The values of $R_{\ell\ell}(b\bar{b})$ needed to explain the excess UA1-$\mu^\pm\mu^\pm x$ events are in the right magnitude. Of course, one has still to prove beyond any doubt that the $\mu^+\mu^+ + \mu^-\mu^-$ events are dominantly due to $b\bar{b}$ production $p + \bar{p} \to b\bar{b}x \to \mu^\pm\mu^\pm x$.

In the last part of this section, I would like to examine the prospects of studying B-$\bar{B}$ mixings at the planned LEP experiments. The first step in that direction is to calculate the cross-section $Z^0 \to b\bar{b}$. This is most readily calculable by the following expression. Normalizing the decay widths $\Gamma(Z^0 \to f\bar{f})$ where f is any charged fermion, with respect to the decay width $\Gamma(Z^0 \to \nu\bar{\nu})$, one has in the Born approximation

$$\frac{\Gamma(Z^0 \to f\bar{f})}{\Gamma(Z^0 \to \nu\bar{\nu})} = 2N_c^f \beta \times \left[(g_V^f)^2 \left(1 + \frac{2m_f^2}{m_Z^2}\right) + (g_A^f)^2 \beta^2 \right] \qquad (30)$$

where

$$\beta = (1 - 4m_f^2/m_Z^2)^{1/2}$$
$$N_c^f = 3 \quad \text{for quarks}$$
$$= 1 \quad \text{for leptons}$$

The vector and axial vector coupling constants g_V^f and g_A^f are given by

$$\begin{array}{lcc} & \underline{g^f} & \underline{g_A^f} \\ \nu_e, \nu_\mu, \nu_\tau & 1/2 & 1/2 \\ e, \mu, \tau & -1/2 + 2\sin^2\theta_W & -1/2 \\ u, c, t & 1/2 - 4/3 \sin^2\theta_W & 1/2 \\ d, c, b & -1/2 + 2/3 \sin^2\theta_W & -1/2 \end{array} \qquad (31)$$

and

$$\Gamma(Z^0 \to \nu\bar{\nu}) = \frac{\alpha m_Z}{24 \sin^2\theta_W \cos^2\theta_W} \simeq 0.17 \text{ GeV}$$

for $\sin^2\theta_W = 0.217$ and $m_Z = 94$ GeV. It is straightforward to calculate the branching ratio for $Z^0 \to b\bar{b}$ and one gets

$$BR(Z^0 \to b\bar{b}) \simeq 15\,\% \qquad (32)$$

Since one units of R at $\sqrt{s} = m_Z = 94$ GeV is $87/m_Z^2$ nb $\simeq$ 10 Pb. This leads to the following cross-section per unit of R ($\equiv \sigma(e^+e^- \to \mu^+\mu^-)$)

$$\sigma(Z^0 \to b\bar{b}) \simeq 1.5 \left(\frac{94 \text{ GeV}}{m_Z}\right)^2 \text{Pb} \qquad (33)$$

Since R at LEP (after radiative corrections) is expected to be

$$\mathcal{R}_{peak} \simeq 2.8 \times 10^{3}$$

This would give

$$\sigma(Z^{\circ} \to b\bar{b})_{LEP} \simeq 4.2\ nb$$

For an integrated luminosity of 100 Pb^{-1} which is expected in a year, one would have

$$\#\,(Z^{\circ} \to b\bar{b})_{LEP} \simeq 4.2 \times 10^{5}$$

Using a branching ratio $b \to c\ell\nu_{\ell} \simeq 0.11$ and $R_{\ell\ell}(b\bar{b}) \simeq 0.2$, as indicated by the UA1 experiments, one is expected to get (ℓ = e+μ)

$$\#\,(Z^{\circ} \to b\bar{b} \to \ell^{+}\ell^{+} + \ell^{-}\ell^{-}) \simeq 4 \times 10^{3}$$

Thus, LEP experiments would be able to test $R_{\ell\ell}(b\bar{b})$ down to ~5% level.

In fact, one could make use of correlations ($Z^0 \to \ell^{\pm}\ell^{\pm}F^{\pm}$) expected in the B_s-$\bar{B}_s$ mixing scenario to measure the B_s^0 lifetime[22]. Using realistic $F^{\pm}$ detection efficiency[28] and vertex detector resolution, it seems that this would give a reasonable B_s^0 sample. The experiments at LEP and SLC are potentially capable of testing not only B-$\bar{B}$ mixings but checking that it indeed occurs in the B_s^0-$\bar{B}_s^0$ sector.

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Table 1

Inclusive cross-sections in $p\bar{p}$ collisions at $\sqrt{s}$ = 630 GeV based on $2 \to 2 + 2 \to 3$ processes
(1a) $\sigma(p\bar{p} \to Q\bar{x})$
(1b) $\sigma(p\bar{p} \to \ell^{\pm} x)$
(1c) $\sigma(p\bar{p} \to \ell^{\pm}\ell^{+} x)$ with the additional cut-off $p_T^{\ell 1} + p_T^{\ell 2} > 10$ GeV.

Table 1a

P_T^Q cut-off (GeV)	$\|\eta^Q\|$	$\sigma(p\bar{p} \to cx)$ (μb)	$\sigma(p\bar{p} \to bx)$ (μb)	$\sigma(p\bar{p} \to tx)$ (nb)
0	all	172.0	9.7	1.9
5.0	all	12.2	3.7	1.85
5.0	2	10.0	3.0	1.65

Table 1b

P_T^{ℓ} cut-off (GeV)	$\|\eta^{\ell}\|$	$\sigma(p\bar{p} \to cx \to \ell x)$ (nb)	$\sigma(p\bar{p} \to bx \to \ell x)$ (nb)	$\sigma(p\bar{p} \to tx \to \ell x)$ (nb)	$\sigma(p\bar{p} \to \Sigma Qx \to \ell x)$ (nb)
3.0	1.0	42.0	54.0	0.35	96.35
	1.5	48.0	82.0	0.4	130.4
	1.0	54.0	95.0	0.45	149.45
	all	60.0	107.0	0.50	167.5

Table 1c

$P_T^{\ell_1,\ell_2}$ cut-off (GeV)	$\|\eta^{\ell_1,\ell_2}\|$	$\sigma(p\bar{p} \to cx \to \ell\ell x)$ (Pb)	$\sigma(p\bar{p} \to bx \to \ell\ell x)$ (Pb)	$\sigma(p\bar{p} \to tx \to \ell\ell x)$ (Pb)	$\sigma(p\bar{p} \to \Sigma Qx \to \ell\ell x)$ (Pb)
3.0	1.0	16.0	116.0	10.0	142.0
	1.5	31.0	193.0	15.0	239.0
	2.0	37.0	300.0	19.0	356.0
	all	40.0	320.0	21.0	381.0

Table 2

The ratio $\Delta M/\Gamma$, $r \equiv (B_s^0 \to \ell^+\nu x^-)/(B_s^0 \to \ell^-\nu x^+)$ and the same-sign to opposite-sign dilepton ratio $R_{\ell\ell}(b\bar{b})$ as defined in Eq. (20) for the assumed value of the B_s^0 lifetime, $\tau(B_s^0)$, the bag constant B and the probability of $s\bar{s}$ pair excitation from the vacuum, κ [from Ref. 22)].

$\tau_{B_s} \times (10^{-12}$ sec.)	1.1		1.4		1.7	
Bag constant, B	0.5	1.0	0.5	1.0	0.5	1.0
$\Delta M/\Gamma$	1.13	2.26	1.44	2.88	1.75	3.6
r	0.39	0.72	0.51	0.80	0.6	0.80
$R^{\ell\ell}(b\bar{b})(\kappa = 0.1)$	0.06	0.09	0.07	0.09	0.08	0.1
$R^{\ell\ell}(b\bar{b})$ $(\kappa = 0.2)$	0.12	0.18	0.15	0.20	0.16	0.2
$\ell^{\ell\ell}(b\bar{b})$ $(\kappa = 0.3)$	0.18	0.29	0.22	0.30	0.25	0.32

FIGURE CAPTIONS

Fig. 1 : Feynman diagrams for (a) $O(\alpha_s)^2$ $2 \to 2$ processes for heavy $Q\bar{Q}$ pair production and (b) $O(\alpha_s)^3$ $2 \to 3$ processes where a heavy $Q\bar{Q}$ pair is accompanied with either a gluon or light quark.

Fig. 2 : Distributions in the variable $Z = \vec{p}\cdot\vec{p}_{jet}/p^2_{jet}$. The data points (with statistical errors only) are the $D^{*\pm}$ spectrum reported by UA1[16]. The dotted curves give the result of exact QCD matrix elements for $p\bar{p} \to c+x$ to order α_s^2 ($2 \to 2$ processes) and α_s^3 ($2 \to 3$ processes) combined with the fragmentation $c \to D^{*\pm}$. The dashed curves are the charm quark and $D^{*\pm}$ spectra obtained from shower model, and the full curves the result when combined with a non-perturbative model of Ali and Ingelman [Ref. 14)].

Fig. 3 : The pseudorapidity distribution $d\sigma/d\eta^Q$ in the inclusive heavy quark production process $p+\bar{p} \to Q+x$ at $\sqrt{s}$ = 630 GeV for Q = c,b and t quarks. The distributions are based on the diagrams on Fig. 1 with $p_T^{jet} > 5$ GeV for the jet recoiling against a heavy quark jet.

Fig. 4 : Inclusive $-p_T$ distributions based on the $2 \to 2$ and $2 \to 3$ processes in Fig. 1 for the final states $p+\bar{p} \to Q+x$, $p+\bar{p} \to \ell^{\pm}x$ and $p\bar{p} \to (\ell^{\pm}\ell^{\pm}+\ell^{+}\ell^{-})x$ at $\sqrt{s}$ = 630 GeV. For $2 \to 3$ processes a cut $p_T^{jet} > 5$ GeV is used to regulate the cross-section.

Fig. 5 : A comparison of the normalized distributions based on the $2 \to 2$ and $2 \to 3$ processes in Fig. 1 (solid line) with the inclusive dimuon data from the UA1 collaboration[8];

(a) $d\sigma/dp_{2T}^{\mu}$ distribution with $p_T^{\mu} > 3$ GeV, $p_T^{\mu_1}+p_T^{\mu_2} > 10$ GeV and $|\eta^{\mu_1,\mu_2}| < 2.0$;

(b) $d\sigma/dm_{\mu\mu}$ with the same cuts as in (a);

(c) $d\sigma/d\phi_{\mu\mu}$ where $\phi_{\mu\mu}$ is the azimuthal angle between muons with the cuts as in (a).

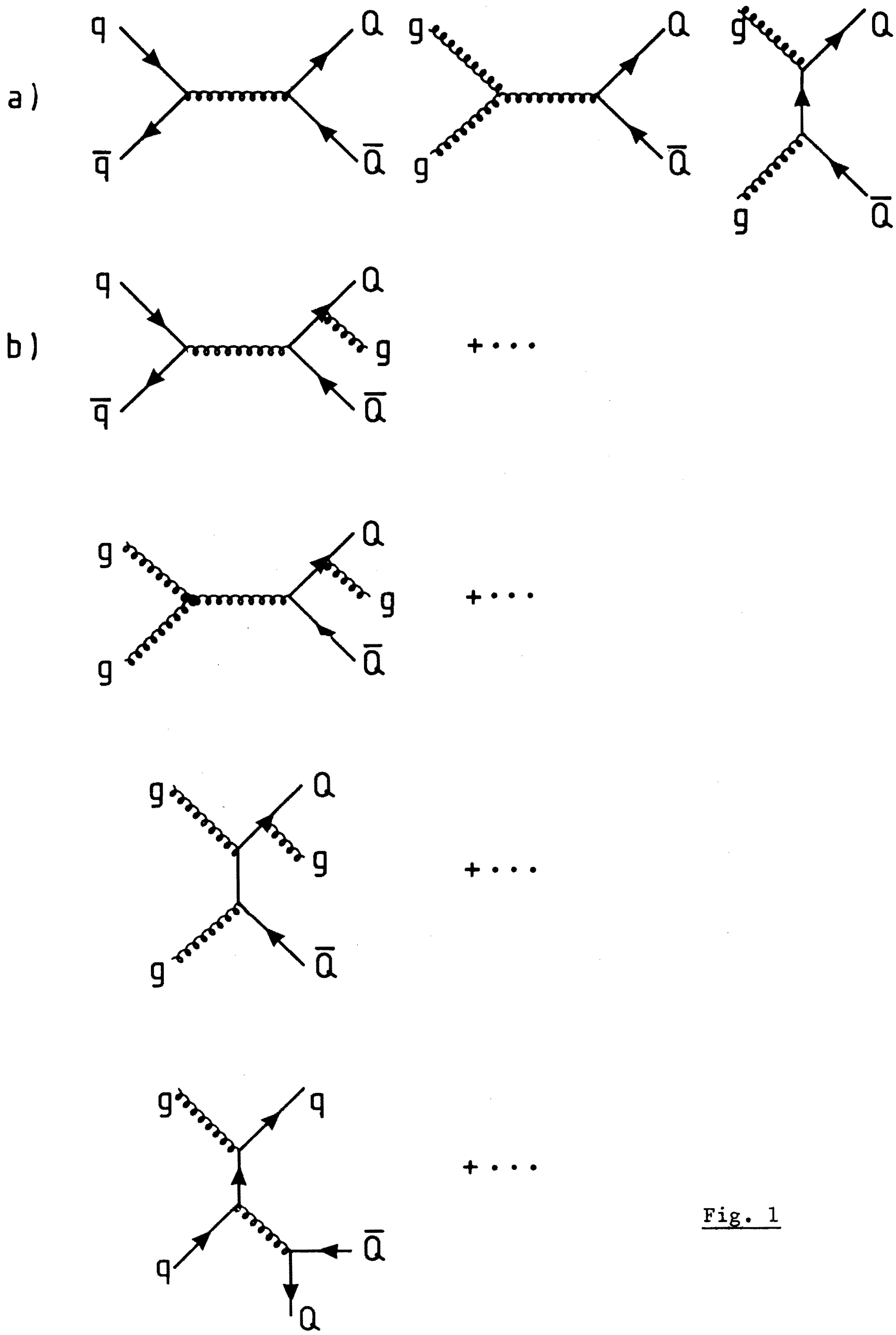


Fig. 1

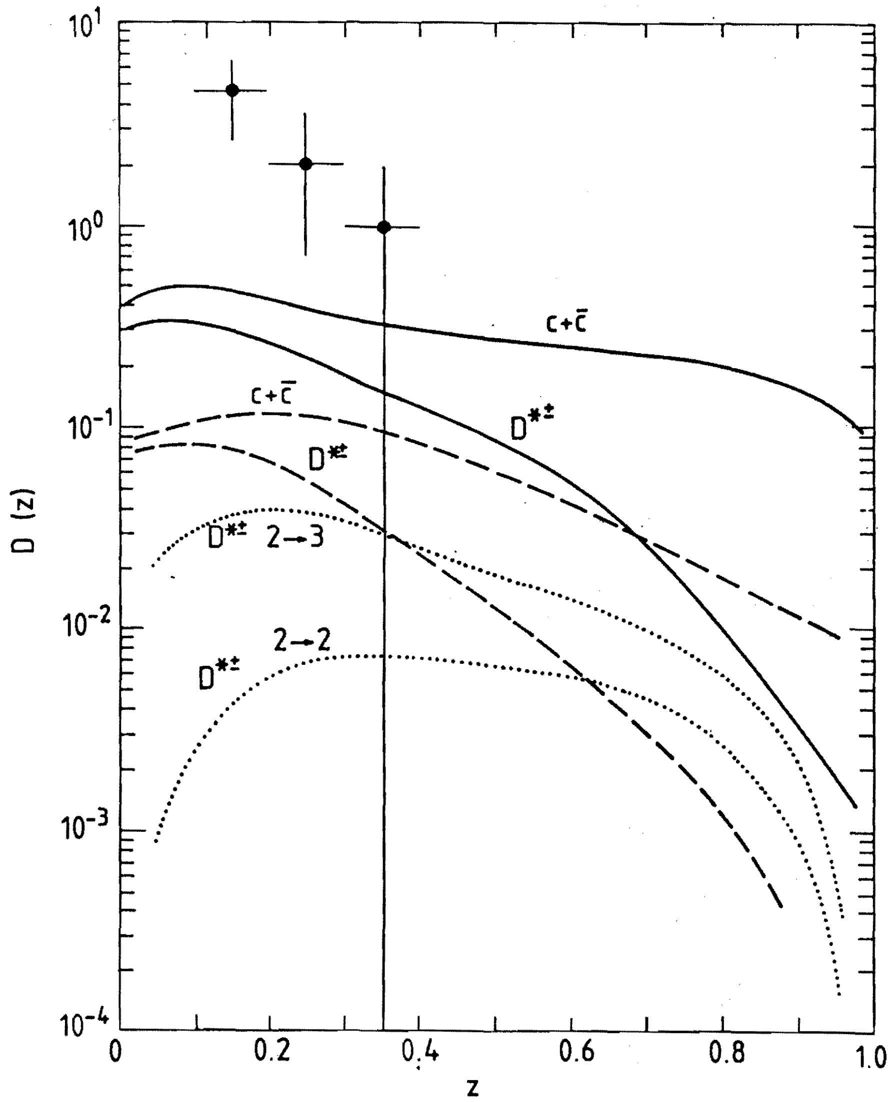
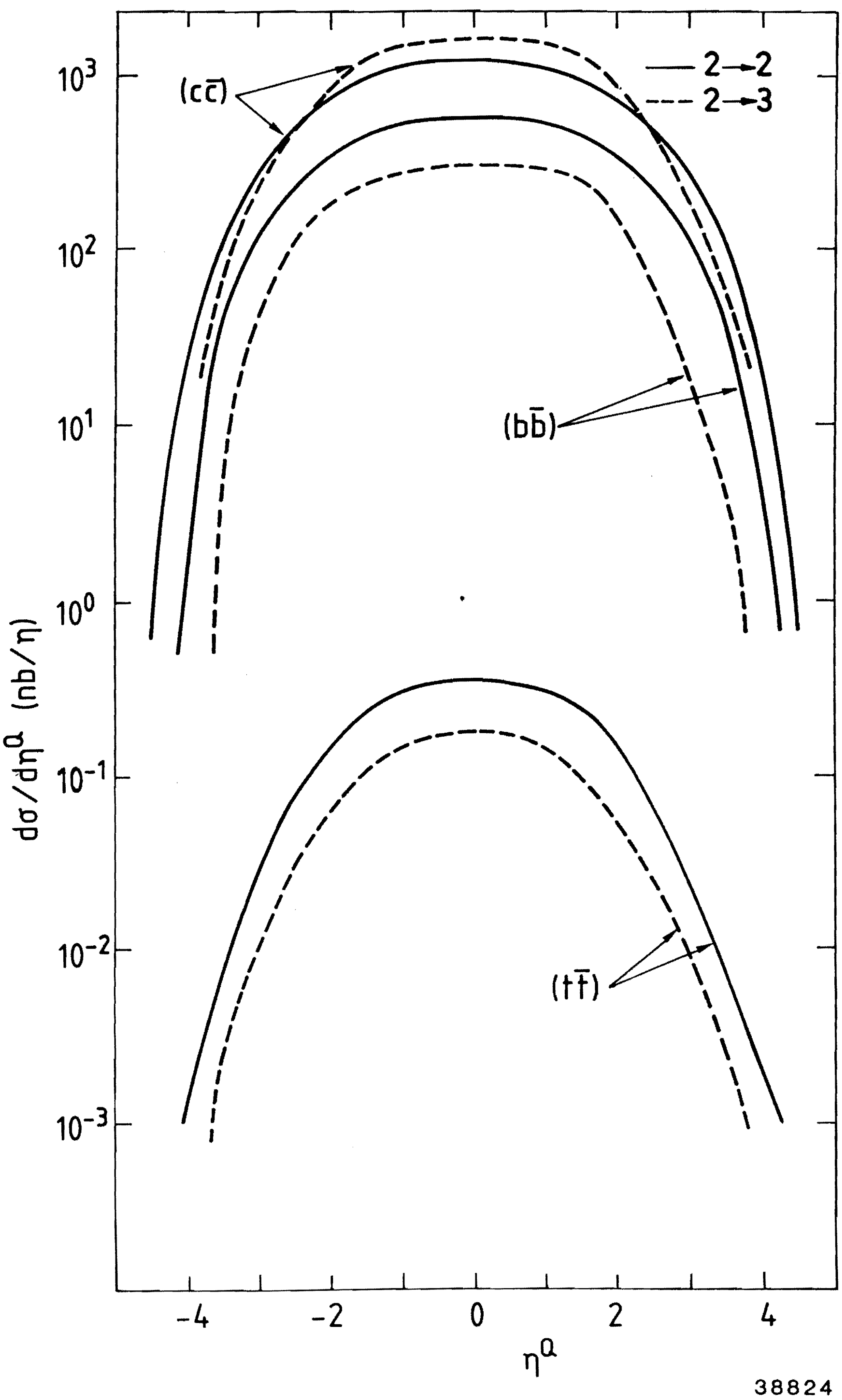


Fig. 2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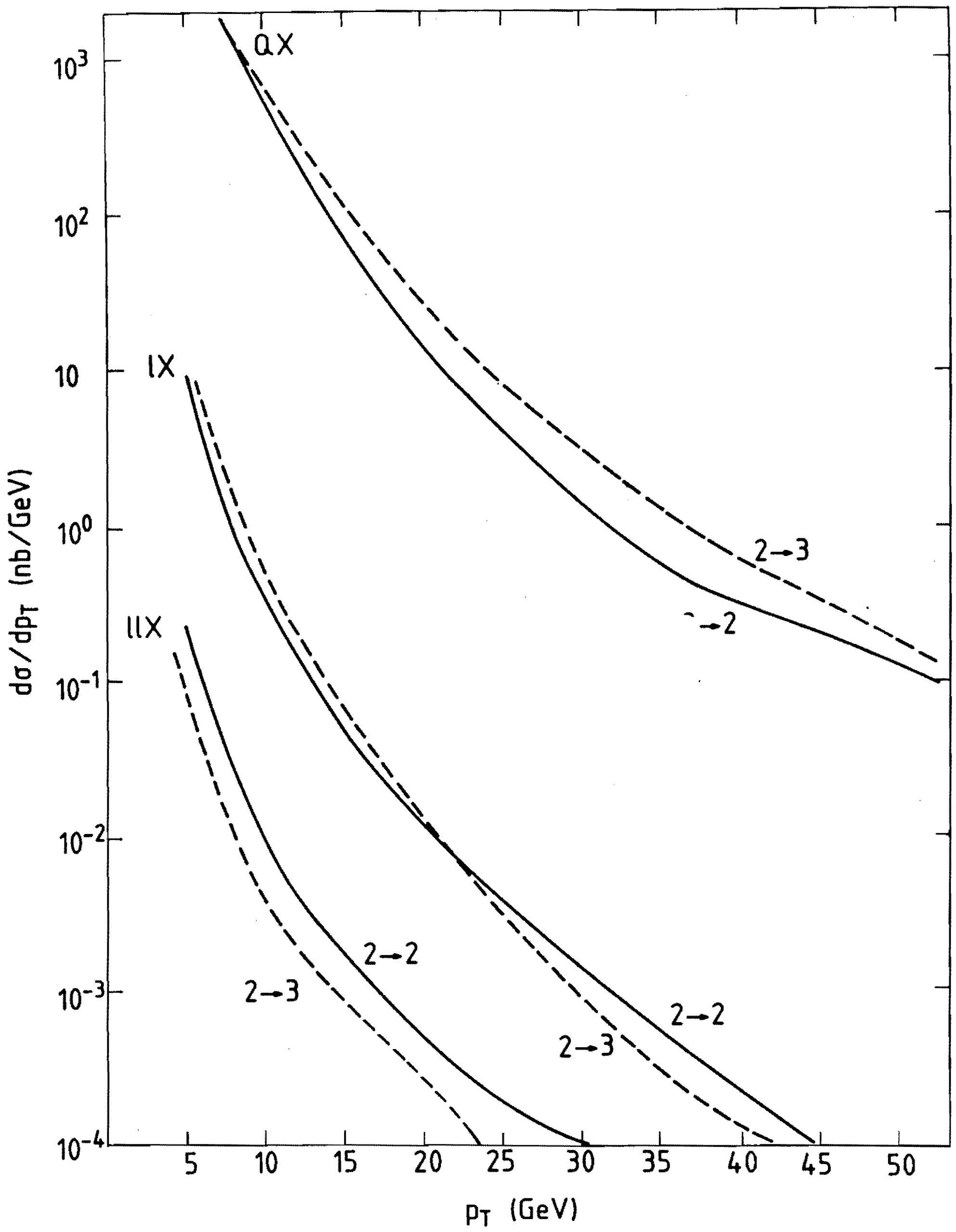
10^2
10^1
10^0
10^-1
10^-2
10^-3
dσ/dη^Q (nb/η)
(cc̄)
2→2
2→3
(bb̄)
(tt̄)
-4
-2
0
2
4
η^Q
38824

Fig. 3


QX
IX
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$d\sigma/dp_T$ (nb/GeV)
10^3
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10^{-2}
10^{-3}
10^{-4}
5 10 15 20 25 30 35 40 45 50
p_T (GeV)

Fig. 4

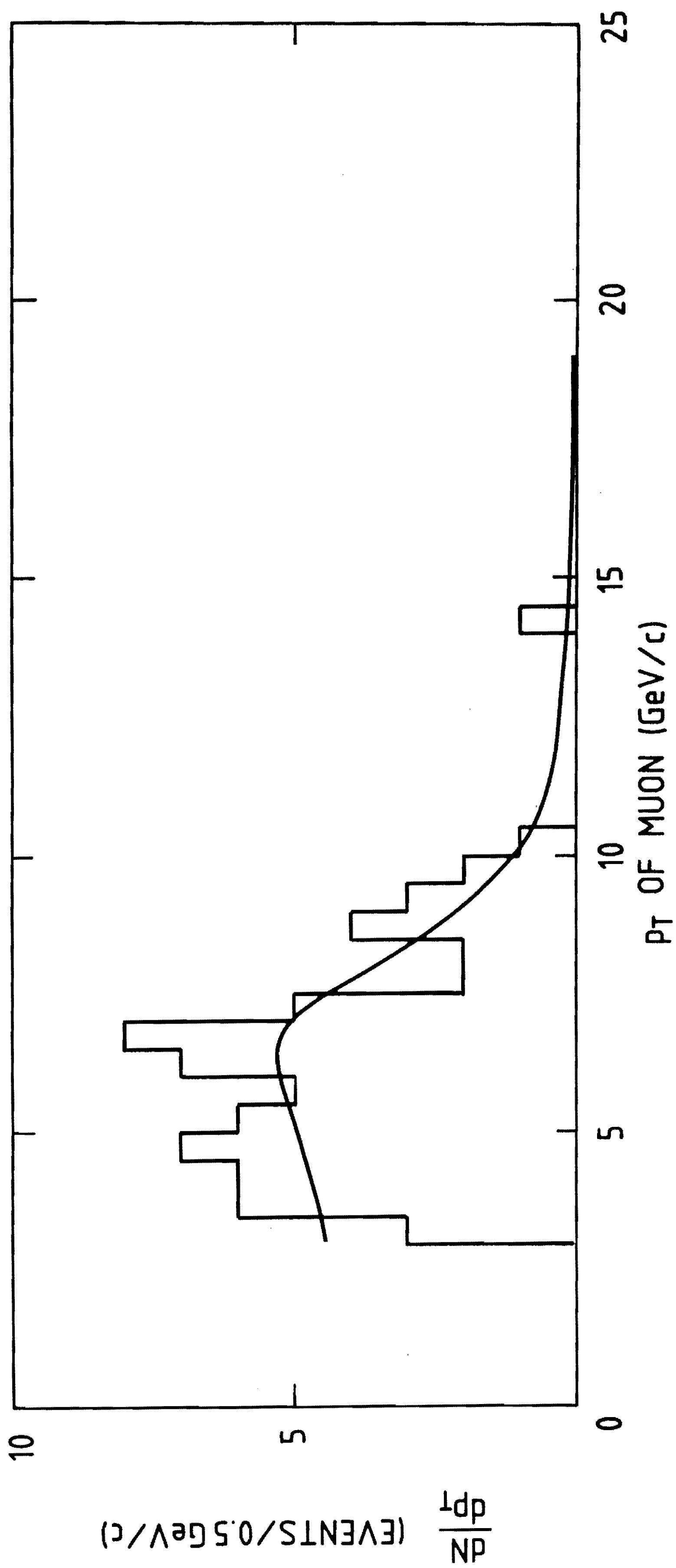
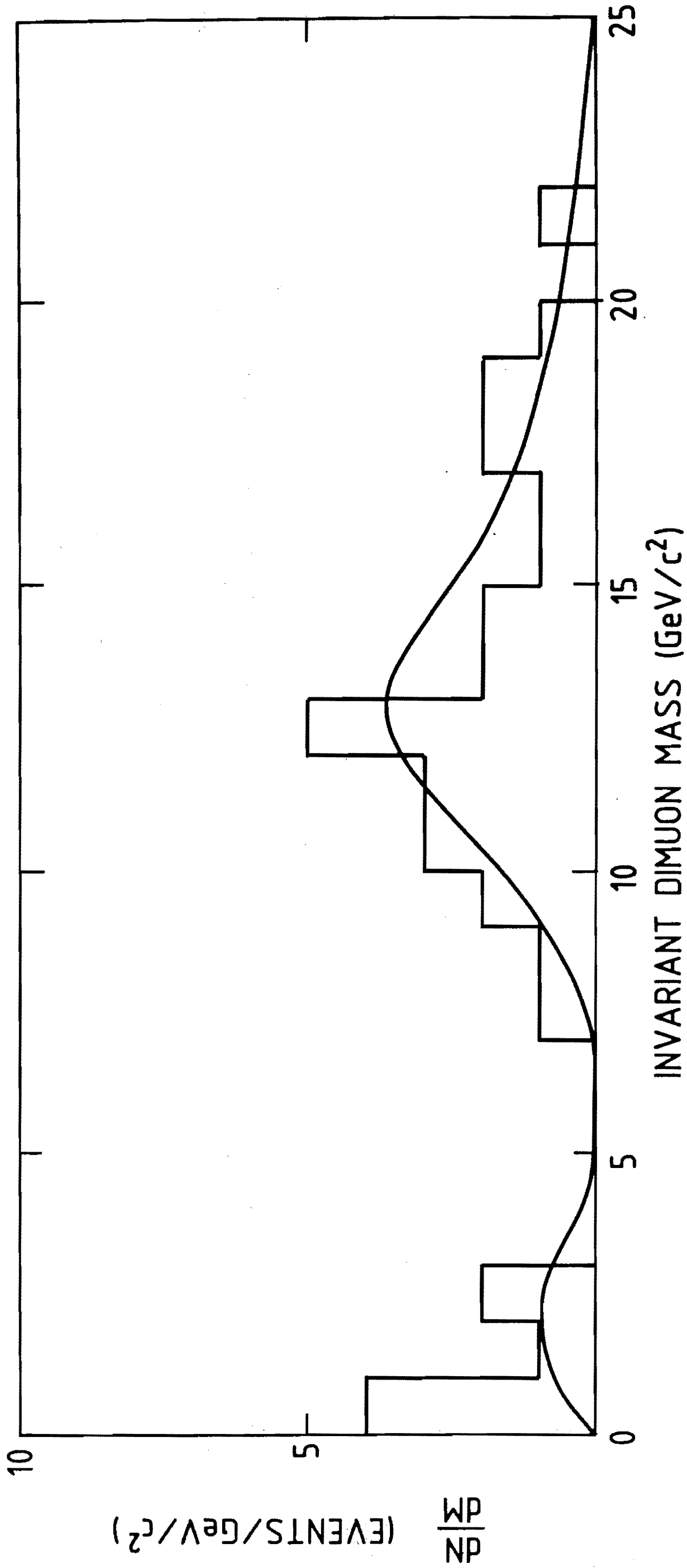


Fig. 5a


0
5
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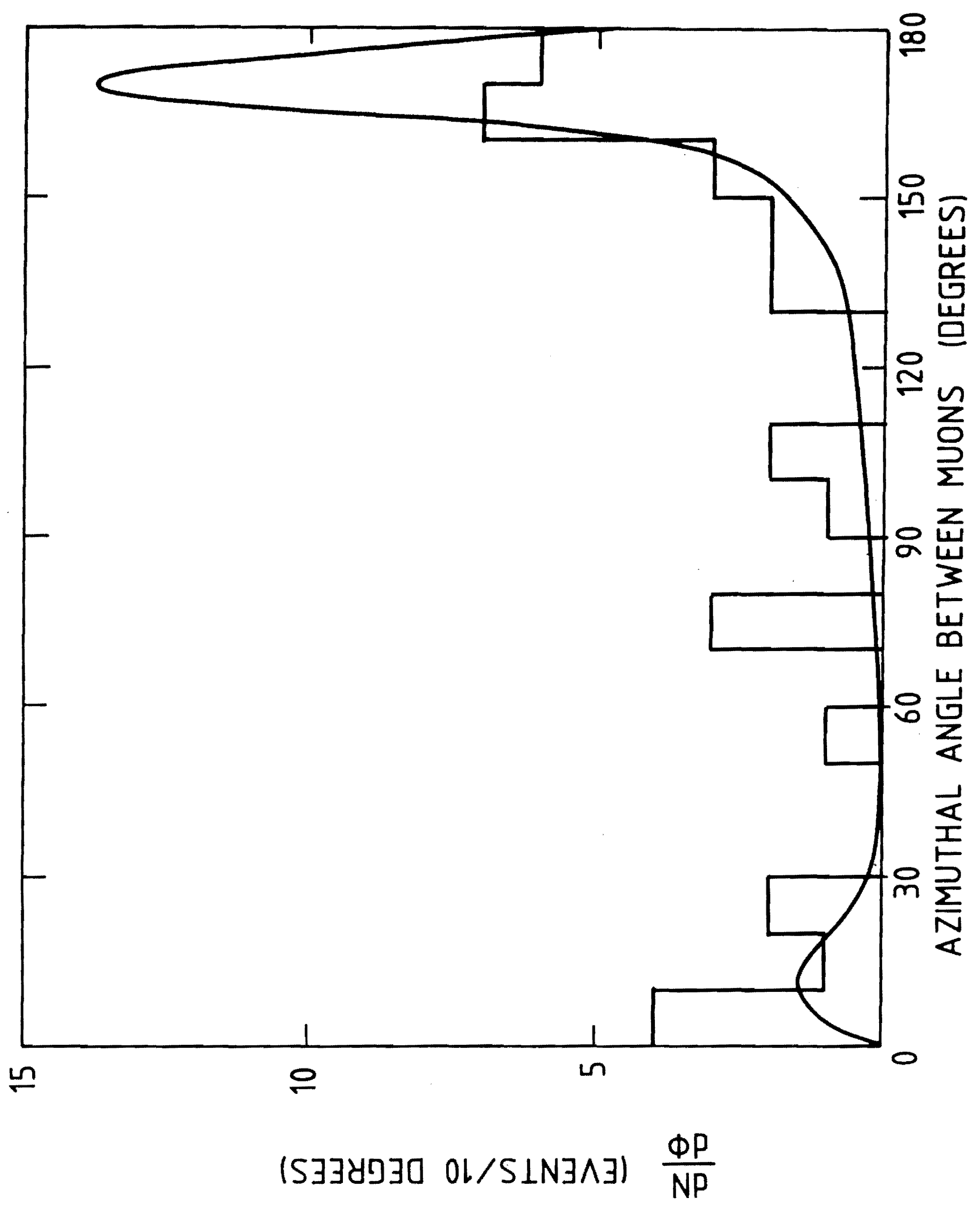
INVARIANT DIMUON MASS (GeV/c^2)
10
5
$\frac{dN}{dM}$ (EVENTS/GeV/c^2)

Fig. 5b



AZIMUTHAL ANGLE BETWEEN MUONS (DEGREES)
0
30
60
90
120
150
180
dN/dΦ (EVENTS/10 DEGREES)
0
5
10
15

Fig.5c