EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/EP 83-30
23 February 1983

ON THE HADRONIC PRODUCTION OF LEPTON PAIRS FROM HEAVY FLAVOUR DECAY

H.G. Fischer and W.M. Geist
CERN, Geneva, Switzerland

ABSTRACT

The production of dilepton states by semileptonic decay of charm-anticharm and beauty-antibeauty meson pairs is studied for proton-proton collisions. It is shown that the measured features of dilepton production can be well described by this non-electromagnetic process up to masses of at least 5 GeV. Upper limits for hadronic heavy flavour production are derived.

Submitted to Zeitschrift für Physik C

---

1. INTRODUCTION

It is known since some years that hadronic production of charm-anticharm meson pairs ($D\bar{D}$) can give sizeable contributions to the lepton pair continuum via double-semileptonic decays. At ISR energies for instance, it was found [1] that $D\bar{D}$ cross sections of about 100 μb would saturate the measured dilepton continuum up to masses around 1 GeV.

Several experiments [2] at the ISR have since reported charm signals (from hadronic decays) corresponding at least to this level of cross section. The situation remains, however, rather unclear as far as the detailed correlation between charm particles - which governs completely the shape of the resulting dilepton mass spectrum - and their inclusive momentum distributions are concerned. It seems however established that the rapidity distribution of charm mesons and baryons is rather flat [3].

Important new information has recently become available from an experiment at the SPS [4]. Here a total charm cross section in the range 20 to 40 μb was found for pp collisions. Again the observed rapidity distribution is relatively flat, and - most important - the average rapidity difference between charm and anticharm mesons could be sizeable, i.e. about 1.2 units.

Taking into account the known s-dependence of the dilepton continuum, this raises serious doubts about the compatibility of these cross sections with the observed dilepton yields. Also at SPS energies, charm meson pairs must contribute substantially to the high-mass continuum. This would of course be even more true for beauty-antibeauty ($B\bar{B}$) production, should it be present on the nanobarn level of cross section.

We have therefore performed model calculations in order to establish upper limits for hadronic $D\bar{D}$ and $B\bar{B}$ production from lepton pair yields in pp collisions, especially inspecting the dilepton mass range between 1 and 7 GeV. Both opposite and equal charge dilepton cross sections, the average transverse momentum and its mass and s dependence, as well as Feynman x distributions and helicity angle distributions have been investigated.

2. THE MODELS

2.1 Correlated Production

Charm and beauty meson-antimeson pairs are generated via isotropic two body decay of parent flavourless states. The correlation between the decay products and thereby the resulting dilepton mass spectrum are then largely governed by the effective mass distribution of the parent states. An alternative measure is the distribution of rapidity gaps Δy of the meson pairs.

We have used mass distributions reproducing QCD calculations [5] of heavy quark pairs from parton fusion. It turns out that these distributions are approximately of truncated Gaussian shape above the respective $D\bar{D}$ or $B\bar{B}$ threshold m^{thr} (fig. 1). The half width at half maximum (hwhm) follows the scaling law indicated in fig. 2, where the ratio between width and threshold mass is plotted against the ratio of threshold mass and c.m.s. energy.

Several features of fig. 2 are noteworthy:

- (a) The widths of the mass distributions and therefore the average rapidity gaps are s -dependent.
- (b) For small relative threshold masses, the widths (and therefore $\langle \Delta y \rangle$) are expected to approach a constant.
- (c) The absolute value of the width (rapidity gap) can vary according to the uncertainties in the assumed structure functions, especially in the case of gluon fusion.

Rapidity gap distributions for the resulting $D\bar{D}$ and $B\bar{B}$ pairs are also shown in fig. 1. It is seen that rapidity differences of about 1 unit, as suggested by [4] are rather in the tail of the distributions predicted by this "correlated" pair production mechanism.

The parent states were generated according to an exponential transverse momentum distribution with an average value of 1 GeV/c. The resulting distributions for single mesons are shown in fig. 3. The parent rapidity distributions were adjusted to give the inclusive meson rapidity spectra also shown in fig. 3. We believe that this simple choice gives a fair description of the presently available data for charm production in pp collisions.

2.2 Independent production

Sizeable rapidity gaps can be generated by independent emission of heavy flavour particles. This would correspond to the so-called flavour excitation mode predicted to prevail at SPS and ISR energy over the correlated pair production [5], or, experimentally, to the observation of leading charm (or e.g. strange) particles associated with a low momentum partner. We have simulated this mode of "independent" production by uncorrelated $D\bar{D}$ and $B\bar{B}$ pairs where one meson is produced with a flat rapidity distribution and the other one more centrally, with a Feynman-x distribution proportional to $(1-x)^3$. For each meson we use an exponential distribution in transverse momentum with an average value of 1 GeV/c.

The average rapidity gap in this case is 1.4 units for $D\bar{D}$ and 0.8 units for $B\bar{B}$ production, at $\sqrt{s} = 27$ GeV, as compared to 0.48 and 0.23 respectively, in the correlated model.

2.3 Semileptonic decays

The semileptonic decay of D mesons into $eK^{(*)}_\nu$ with an average branching fraction of 8% [6] follows three-body phase space. The resulting electron momentum distribution in the D rest frame is compared to the data [7] in fig. 4; the deviation from calculations using a weak decay matrix element [8] is very small.

B mesons are assumed to decay, with 12.5% branching fraction [9], via three-body phase space into $D^{*+}e^- \nu$ (66%) or $D^0 e^- \nu$ (33%). The resulting lepton spectrum in the B rest frame is also shown in fig. 4. It agrees with first experimental results from CESR [10].

In addition to simultaneous semileptonic decays of heavy flavour pairs ($D\bar{D}$, $B\bar{B}$) into e^+e^- pairs, also cascade semileptonic decays of B mesons into equal and opposite charge lepton pairs from e.g. the processes

$$B \rightarrow e^- D^{(*)}_\nu \rightarrow e^- e^+ K^{(*)}_\nu$$

and

$$B\bar{B} \rightarrow e^- D^{(*)}_\nu \bar{D}^{(*)}_X \rightarrow e^- e^+ K^{(*)}_\nu$$

are taken into account. They give sizeable relative contributions to the dilepton yields due to the fact that B mesons are assumed to decay with practically 100% via D mesons. The D momentum distribution in the B rest frame was assumed to be the same for hadronic and semileptonic B decays.

3. THE LEPTON PAIR MASS SPECTRUM

Invariant mass distributions of opposite charge lepton pairs from semileptonic decay of $D\bar{D}$ and $B\bar{B}$ states are presented in fig. 5(a) for the correlated production model described above, together with data [11,12] for SPS and ISR energies. The corresponding charm and beauty cross sections are adjusted such that their dilepton yield saturates the measured lepton pair cross sections. Several conclusions can be drawn from this plot.

- (a) The mass spectrum from charm decay peaks at a dilepton mass of about 0.5 GeV, the one from beauty decay at about 1 GeV.
- (b) The mass spectra develop considerable tails at large masses and become similar in shape to the measured distributions at about 2 GeV for charm and 4 GeV for beauty production. The corresponding cross section limits are therefore effectively determined in this critical mass range rather than in the low-mass region.
- (c) A modification of the model parameters, such as the introduction of a larger tail at the high end of the parent mass spectrum, would suffice to reproduce the measured dilepton spectra up to even larger values of mass. One should note here, that at a dilepton mass of 5 GeV one is typically sensitive to a fraction of a few per mille of the total heavy flavour cross section. On the other hand, a softer dilepton mass spectrum can be achieved, if the parent system decays into $D\bar{D} + n\pi$, $n \geq 1$.
- (d) A suitable combination of charm and beauty production can fit - in the specific model chosen - the measured lepton pair yield up to about 4 GeV at SPS and 6 GeV at ISR energies.
- (e) The upper limits for $D\bar{D}$ production obtained from fig. 5(a) are 7 μb at $\sqrt{s} = 27$ GeV and 25 μb at $\sqrt{s} = 63$ GeV. The corresponding values for $B\bar{B}$ production are 55 nb and 450 nb respectively. This has to be compared with experimental $D\bar{D}$ cross sections of about 20 μb at $\sqrt{s} = 27$ GeV and several hundred μb at ISR energies.

We have tested the sensitivity of the above statements to the parameters of our model by changing the width of the parent mass distributions and thereby the average rapidity gap from $D\bar{D}$ and $B\bar{B}$ pairs. Fig. 5(b) shows as an example the shape of the dilepton mass spectra and cross section limits obtained by reducing the width of the parent mass distributions by a factor of 2. This manipulation steepens up the mass spectrum and therefore allows for higher charm and beauty cross sections.

The dependence of the cross section limits on the average rapidity gap is given in fig. 7. We conclude that for the specific correlated pair production mechanism considered here, charm and beauty cross sections are sharply limited, especially if the large rapidity gaps found at the SPS are taken into account.

We have seen above that large rapidity gaps can be obtained by independent emission ("flavour excitation" [5]) of heavy flavour particles. The consequences of such a mechanism on the dilepton spectrum are shown in fig. 5(c) for $D\bar{D}$ production. As expected, the mass distributions become very flat indeed and allow - if compared to the measured dilepton spectra - only exceedingly small contributions from this kind of production process. This would be in agreement with the strong decrease of our upper limits with increasing rapidity gap, fig. 7.

At this point however, we have to take into account that most dilepton experiments up to now do not cover the full phase space, especially as far as the lepton angle in the dilepton rest system with respect to the beams (Collins-Soper angle θ^{CS}) is concerned. The typical acceptance coverage is $|\cos\theta^{CS}| \lesssim 0.6$. Usually the total production yield is obtained by extrapolation from this measured region assuming $1 + \cos^2\theta^{CS}$ dependence of the production cross section.

The lepton angular distributions obtained from heavy flavour decays however do not in general follow this expectation. This is shown in fig. 6 where distributions in $\cos\theta_{CS}$ are presented for two mass bins. For correlated production of $D\bar{D}$ and $B\bar{B}$ pairs we obtain rather flat distributions and consequently only little dependence of the integrated cross section on the above-mentioned extrapolation procedure.

Independent emission on the other hand exhibits (as expected) an extremely sharp forward-backward enhancement such that the bulk of this cross section would have escaped present-day lepton pair experiments for masses above, say, the J/ψ region.

In view of this we show in fig. 5(c) also mass spectra from independent emission obtained with a cut at $|\cos\theta^{\text{CS}}| < 0.6$ and extrapolated with a $1 + \cos^2\theta^{\text{CS}}$ dependence. The resulting distributions look rather similar to the ones from correlated production, however allowing now for a sizeable contribution from independent emission (i.e. large rapidity gaps) as indicated by the upper limits of the cross sections shown in fig. 7.

In this context it is amusing to note that a suitable superposition of correlated and independent emission contributions could result in an angular distribution like $1 + \cos^2\theta^{\text{CS}}$.

4. MOMENTUM DISTRIBUTIONS

Given the fact that the measured inclusive dilepton mass distributions can be described reasonably well by heavy flavour decay, it is of course interesting to investigate more detailed features of lepton pair production due to this source which might be hoped to reveal characteristic differences from the data.

This is especially true for the study of the transverse momentum (p_T) distribution of lepton pairs, where the experimental values of $\langle p_T \rangle$ show a very striking dependence on pair mass and c.m.s. energy [11].

For comparison with data we use in this section our correlated $D\bar{D}$ and $B\bar{B}$ production model, with heavy flavour cross sections adjusted to reproduce the measured lepton pair spectra as shown in fig. 10.

The average transverse momentum of lepton pairs, as predicted by this model, is shown in fig. 8 as function of pair mass and c.m.s. energy. It is surprising to note how precisely the well-known features of the data are reproduced by the calculations. This is in part due to kinematics, i.e.

with increasing dilepton mass and increasing $\sqrt{s}$ one selects heavy flavour pairs of increasing effective mass and hence increasing Q-value and relative transverse momentum.

Another distinctive feature is the increase of beauty production relative to charm at higher lepton pair masses and c.m.s. energies, which is mainly responsible for the s-dependence.

As far as longitudinal momentum distributions are concerned, we compare in fig. 9 Feynman-x distributions measured at $\sqrt{s} = 21$ GeV [13] for two mass bins with our model predictions for $\sigma_D = 5$ μb and $\sigma_B = 30$ nb.

Similar results are obtained from independent production.

The fairly reasonable agreement in shape indicates again that lepton-pair production from trivial sources cannot be disentangled easily from the fundamental Drell-Yan process [11] using these inclusive sources of experimental information only.

5. ELECTRON MUON COINCIDENCES AND EQUAL CHARGE CROSS SECTIONS

An absolutely clean distinction between the Drell-Yan mechanism and heavy flavour decay can be provided by the experimentally extremely difficult measurement of electron-muon coincidences over the full mass range. The only experiment performed along this line finds indeed comparable $e\mu$ and e^+e^- yields at masses of about 1 GeV at the ISR [1].

In the absence of more conclusive measurements at other energies and larger masses, a reasonable test at least for the presence of beauty production is provided by the measurement of equal-charge dileptons as they can arise from the cascade decay of beauty particles into charm mesons.

In fig. 10, we plot, in addition to the opposite-charge mass spectra, our predictions for equal-charge yields from this source. At $\sqrt{s} = 27$ GeV they reproduce well the measured equal-charge distribution [14]. One finds however considerable experimental uncertainties in this quantity, especially when comparing different experiments, in the lower mass range (beam halo,

π -decays, etc.). The only measurements available at the ISR [15] indicate a very sizeable rate of equal-charge electron pairs, of order one half of the opposite-charge yield.

6. CONCLUSIONS

We have shown for the case of proton-proton collisions, that the semi-leptonic decay of charm and beauty particles can give contributions to the dilepton production also at large effective masses. At very large masses the predictions are rather sensitive to our model assumptions.

In addition to the mass spectrum, the main inclusive features of lepton pair production such as Feynman-x distributions, the mass- and s-dependence of average transverse momentum as well as the lepton angular distribution can be reproduced by this non-electromagnetic process.

In adjusting the total charm and beauty cross sections to the measured lepton pair mass distributions below 4 GeV, upper limits for heavy flavour production have been derived. These limits turn out to be rather low and more restrictive than the ones derived so far e.g. from lepton to pion ratios. The latter ones are, of course, insensitive to correlation phenomena.

As far as charm cross sections are concerned, we find for reasonable assumptions on the correlation length for $D\bar{D}$ pairs, upper limits of less than 10 μb at SPS and less than 100 μb at ISR energies. If one allows for a contribution to the measured spectrum from the Drell Yan process according to the basic diagram, the upper limits are reduced by about a factor 2. The problem posed by the limited angular acceptance of most lepton pair experiments in view of the independent emission of charm and beauty pairs with large rapidity gaps, should be noted.

We estimate the uncertainties in these upper limits to be less than about a factor of 2, mostly given by the uncertainties in the semileptonic branching fractions (due to a possible prevailing $D^0\bar{D}^0$ production from $D^{*-}\bar{D}^{*-}$

decay). Contributions from associated $\bar{D}\Lambda_c$ production, with lower semi-leptonic branching ratio of Λ_c [16], have been neglected as well. On the other hand we do not believe that all lepton pairs, even below the J/ψ region, could come from charm decays.

Measured $D\bar{D}$ and Λ_c^+ cross sections of $\sim 20 \mu\text{b}$ at SPS and of several hundred μb at ISR are therefore - in spite of large errors - already touching the limits of possibilities, or necessitate more exotic production mechanisms than the ones investigated here.

It should be added that the atomic number dependence measured for dilepton pairs seems also to hold for charm production [4,17].

As far as beauty production is concerned, our limits are 50 nb at SPS and 600 nb at ISR energies or 25 nb and 300 nb, if there is a 50% contribution to the measured dilepton cross section from the Drell-Yan process. They rule out present experimental indications by several orders of magnitude [18].

It is interesting to note that the different limits for charm and beauty production which were obtained from fits to the measured dilepton spectra and therefore scale approximately in $\sqrt{s} = M/\sqrt{s}$, also yield a strong s -dependence of heavy flavour production as expected in many models.

Dilepton production by π beams has not been studied here since it is expected to be less affected by the above problems:

- (a) The dilepton cross section from π beams is much larger than from proton beams [11], whereas the charm cross sections are very similar [4,19].
- (b) The difference of dilepton cross sections from π^- and π^+ beams incident on isoscalar targets does not contain contributions from hadronic sources; this is not necessarily so for proton-antiproton differences.

Finally we want to stress that the reproduction of nearly all measured inclusive features of dilepton production (with disconcerting ease) by the "trivial" conspiracy of charm and beauty production and decay presented above, indicates the necessity of much more detailed investigations in both heavy flavour and lepton pair experiments in order to quantify the contribution of the fundamental Drell-Yan process to dilepton production in pp collisions.

Acknowledgement

We want to thank D. Treille (CERN) for suggestions and discussions.

REFERENCES

- [1] A.G. Clark et al., Phys. Lett. 77B (1978) 339;
A. Chilingarov et al., Phys. Lett. 83B (1979) 136;
A. Chilingarov et al., Nucl. Phys. B151 (1979) 29.
- [2] D. Drijard et al., Phys. Lett. 81B (1979) 250;
D. Drijard et al., Phys. Lett. 85B (1979) 452;
K.L. Giboni et al., Phys. Lett. 85B (1979) 437;
W. Lockman et al., Phys. Lett. 85B (1979) 443;
L. Cifarelli, Moriond Workshop on New Flavours, 1982, ed.
J. Tran Thanh Van and L. Montanet, p. 429 and refs therein.
- [3] W.M. Geist, Moriond Workshop on New Flavours, 1982, ed.
J. Tran Thanh Van and L. Montanet, p. 407.
- [4] M. Aguilar-Benitez et al., CERN/EP 82-204.
- [5] B.L. Combridge, Nucl. Phys. B151 (1979) 429.
- [6] G.H. Trilling, Phys. Rep. 75 (1981) 57.
- [7] W. Bacino et al., Phys. Rev. Lett. 43 (1979) 1073.
- [8] I. Hinchliffe and C.H. Llewellyn-Smith, Nucl. Phys. B114 (1976) 45.
- [9] A. Silverman, Proceedings of the 1981 International Symposium on
Lepton and Photon Interactions at High Energies, Bonn, ed. W. Pfeil,
p. 138.
- [10] P. Franzini, Moriond Workshop on New Flavours, 1982, ed.
J. Tran Thanh Van and L. Montanet, p. 159.
- [11] I.R. Kenyon, Rep. Progr. in Phys. 45 (1982) 1261.
- [12] D. Antreasyan et al., Phys. Rev. Lett. 45 (1980) 863.
- [13] K.J. Anderson et al., Phys. Rev. Lett. 42 (1979) 944.
- [14] A.S. Ito et al., Phys. Rev. D23 (1981) 604.
- [15] A.G. Clark et al., Nucl. Phys. B142 (1978) 29;
A.L.S. Angelis et al., Phys. Lett. 87B (1979) 398.
- [16] E. Vella et al., Phys. Rev. Lett. 48 (1982) 1515.
- [17] A. Badertscher et al., Bern preprint LHEP 82/144.
- [18] M. Basile et al., Lett. al. Nuovo Cim. 31 (1981) 97;
D. Drijard et al., Phys. Lett. 108B (1982) 361;
D. Drijard et al., CERN/EP 82-31.
- [19] M. Aguilar-Benitez et al., CERN/EP 82-203.

FIGURE CAPTIONS

- Fig. 1   Distributions of effective mass of parent states and resulting $D\bar{D}$ and $B\bar{B}$ rapidity gap distributions at $\sqrt{s} = 27$ GeV and 63 GeV, for the correlated production model. The arrows indicate $\langle \Delta y \rangle$.
- Fig. 2   Scaling curve for the ratio between width of parent mass distributions and threshold mass, plotted against the ratio between threshold mass and c.m.s. energy. Values for strange (S), charm (C) and beauty (B) pairs are indicated for $\sqrt{s} = 27$ and 63 GeV.
- Fig. 3   Rapidity and transverse momentum distributions for charm (C) and beauty (B) production at $\sqrt{s} = 27$ and 63 GeV, in the correlated model.
- Fig. 4   Generated electron momentum distribution from semileptonic decay in charm and beauty particle rest frame and comparison with data.
- Fig. 5   (a) Lepton pair cross sections from charm and beauty decay as function of pair mass, compared to measurements (solid lines) at $\sqrt{s} = 27$ [11] and 63 GeV [12], for the correlated production model.
- (b) Same distributions from modified model, using half the width of the parent mass distributions (fig. 1).
- (c) Dilepton mass distributions from $D\bar{D}$ decay in the independent emission model. Cross sections for a cut in Collins-Soper angle, correcting with $1 + \cos^2 \theta^{CS}$ assumption, are also presented.
- (d) Same as (c), but for $B\bar{B}$.
- Fig. 6   Angular distributions (Collins-Soper angle) of leptons from correlated and independent emission of $D\bar{D}$ and $B\bar{B}$ pairs.
- Fig. 7   Upper limits for charm and beauty meson pair production as function of average rapidity gap between the heavy flavour particles.

FIGURE CAPTIONS (Cont'd)

- Fig. 8   Average transverse momentum of lepton pairs from heavy flavour decay as function of dilepton mass and c.m.s. energy.
- Fig. 9   Feynman-x distributions of lepton pairs from correlated production of $D\bar{D}$ and $B\bar{B}$ pairs, compared to measurements [13] at $\sqrt{s} = 21$ GeV.
- Fig. 10   Comparison with data (solid lines) of lepton pair cross sections obtained from the combined production of charm and beauty particles, both for equal and opposite charge pairs, in the correlated production model.

fig.1

fig.2

fig. 4

fig. 5a

fig. 5b

fig.6

fig.7

fig.8

fig.9

fig.10