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Sezione di Pavia

INFN/AE-76/3
17 Marzo 1976

M. Cavalli Sforza and G. Goggi : INCLUSIVE MUON PRODUCTION AT SPEAR AND THE HYPOTHESIS OF HEAVY LEPTONS. -

(Presented at the 'International Meeting on Storage Ring Physics', Flaine, February 1976).

ABSTRACT. -

We observe a sizeable production of anomalous two-prong muon events in e^+e^- annihilation at 4.8 GeV. The final state consists of a muon identified at 90^o with momentum $p_\mu > 1.05$ GeV/c and of a charged particle detected over the full solid angle with noncoplanarity $> 20^o$.

This result is discussed in view of the possible production of particles of mass $M \sim 1.8 - 2$ GeV. The data favour the heavy lepton hypothesis and suggest a unified interpretation of these events and SLAC-LBL e-μ events. An estimate of the cross section and of the leptonic branching ratio is given.

The detection of leptonic or semileptonic final states in the e^+e^- annihilation is particularly relevant to the possible production of charmed particles[(1)], heavy leptons[(2)] or to the possible associated production of new quantum numbers. It is expected on theoretical grounds that any such particle or state would indeed decay with a significant leptonic component.

We have been measuring inclusive e^+e^- annihilation at SPEAR I[(3)] with an apparatus consisting of a magnetic spectrometer optimized for particle identification at high momenta, associated with a central detector with full solid angle coverage for charged particles[x]. Events with one track identified as a muon were studied at $\sqrt{s}$ = 4.8 GeV with this apparatus[4].

In the following, after describing muon identification and data normalization through the well understood $\mu\mu$ QED process, we discuss the results and possible implications of μ-inclusive events.

Fig. 1 shows a plan view of the apparatus. The magnetic spectrometer, subtending a solid angle of 0.1 steradians, had a momentum and angular resolution of $\pm$ 1% at 2.4 GeV/c and $\pm$ 0.3^o respectively. Muons were identified in the spectrometer by requiring a signal in a threshold Cerenkov counter, minimum ionizing pulses in a 5-layer shower counter and full penetration of a 3-layer scintillator and iron absorber with a to-

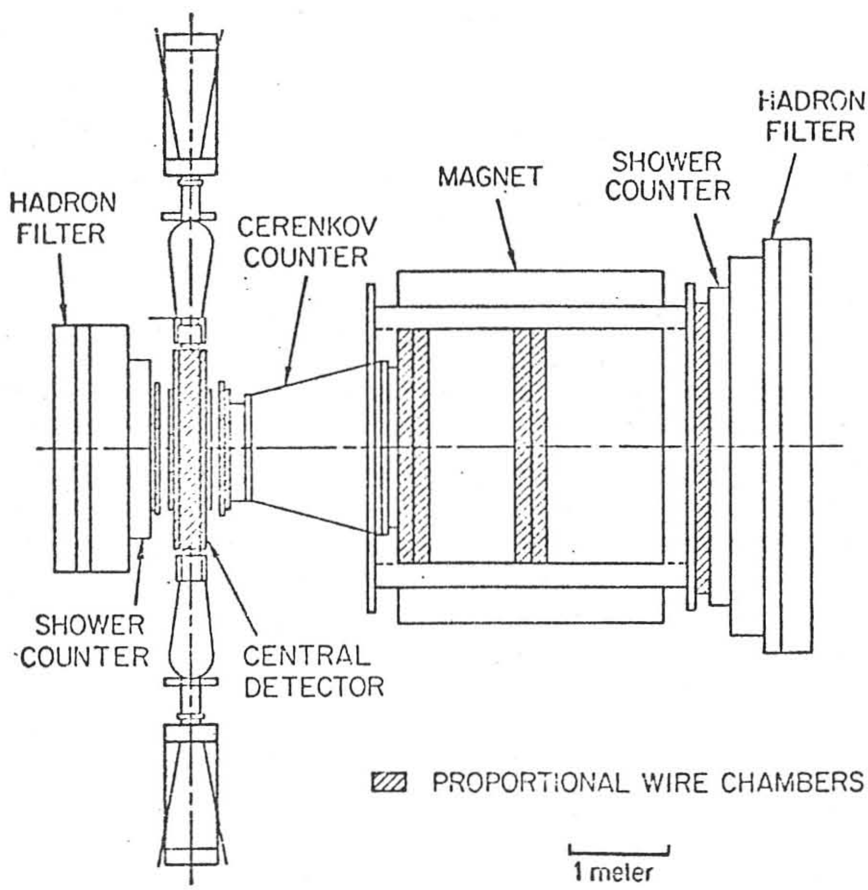

FIG. 1 - Plan view of the experimental apparatus.

(x) - Maryland-Pavia-Princeton collaboration: T. L. Atwood, D. H. Badtke, B. A. Barnett, M. Cavalli-Sforza, D. G. Coyne, G. Goggi, G. C. Mantovani, G. K. O'Neill, A. Piazzoli, B. Rossini, H. F. W. Sadrozinski, D. Scannicchio, V. Trasatti, G. T. Zorn.

tal thickness of 69 cm of iron. The muon momentum required to penetrate all three layers was 1.05 GeV/c.

A similar shower counter and hadron filter covering a much larger solid angle on the opposite side of the interaction region identified back-to-back electron and muons, thus adding to the particle identification capabilities for two-body events.

Charged particles associated to a spectrometer trigger were detected over a solid angle of 99 % by a 3-layer proportional chamber system surrounding the interaction region; for these particles only the azimuthal angle was measured with a precision of $\pm 3^{o}$.

For small noncollinearities[5] muon pair production is known to be well described by QED including radiative corrections. The solid angles of two opposite hadron filters allowed to identify both back-to-back muons within a non collinearity limit of 30^{o}. The noncollinearity distribution of the 190 detected $\mu\mu$ events is shown in Fig. 2. The QED curve, calculated following Berends et al.[6], is normalized to the first bin and is in good agreement with the observed distribution at angles greater than 3^{o} (For the remaining nine bins χ^2/d.f. = 0.86). This sample of $\mu\mu$ events yields an integrated luminosity of $3.84 \pm 0.31\ pb^{-1}$.

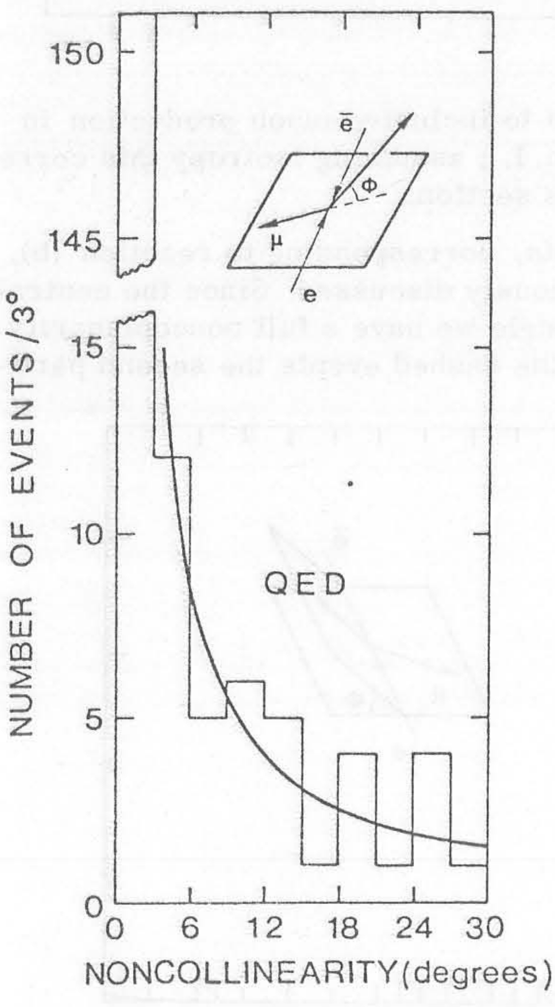

FIG. 2 - Noncollinearity distribution of μ-pairs at $\sqrt{s}$ = 4.8 GeV. Both muons required to penetrate 69 cm of Fe. QED curve from Berends et al.[6].

Inclusive muon processes are defined in this experiment by a muon with $p_{\mu} \geq 1.05$ GeV/c in the spectrometer; we divide the corresponding sample of events into two categories:

(a) $\mu^{\pm} + \geq 2$ charged particles,

(b) $\mu^{\pm} +$ 1 charged particle .

We observe two events of type (a); Table I shows the contributions expected from backgrounds, i.e. hadron misidentification, and from already known physical processes.

The observed hadron momentum spectrum (71 events) was used to calculate both the number of hadrons penetrating the Fe absorbers[7] and the number of decay muons with momentum exceeding our momentum cut.

The other contributions come from virtual $\gamma\gamma$ processes[8] and from the radiative tail of the ψ'. The total number of expected events is 5.3, consistent with 2 events observed.

Table I

Number of events contributing to reaction (a)

hadron penetration	1.3	$e^+e^- \to e^+e^-\mu^+\mu^-$	2.0[9]
π,k decay	1.8	$e^+e^- \to (\gamma)\psi' \to \pi^+\pi^-\mu^+\mu^-$	.2

We therefore set a new limit to inclusive muon production in reaction (a) of 7.5 pb/sr with 95 % c.l. ; assuming isotropy this corresponds to 96 pb total inclusive cross section.

The second category of events, corresponding to reaction (b), obviously includes the μ pairs previously discussed. Since the central detector covers the full azimuthal angle we have a full noncoplanarity distribution, shown in Fig. 3. For the dashed events the second parti-

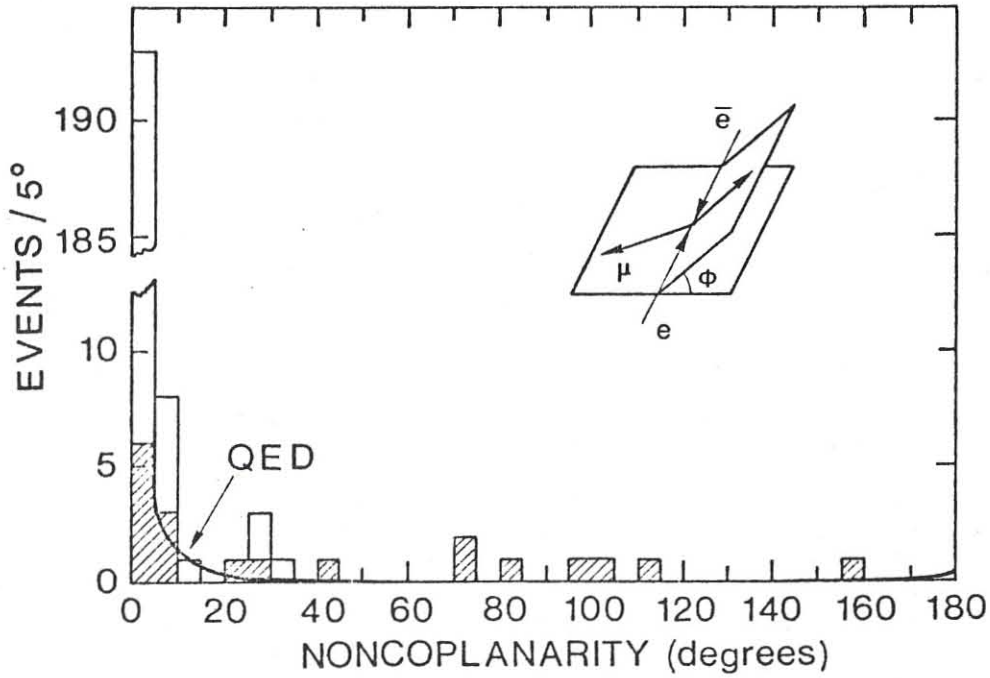

FIG. 3 - Noncoplanarity distribution for reaction (b). For the dashed events the second particle is not identified. QED curve from Berends et al.[6].

cle either did not enter the iron absorber opposite to the spectrometer or did not penetrate them fully. The remaining events are identified as μ pairs. The QED curve was calculated using thresholds of 1.05 GeV and 0.115 GeV for muons detected by the spectrometer and the central detector respectively.

Above 20^o noncoplanarity angle an excess of events above the QED prediction is evident. As for reaction (a) the possible contributions are listed in Table II. Out of 13 events observed above 20^o, only 3.9 events can be accounted for on the basis of already known processes.

Table II

Number of events contributing to reaction (b) for noncoplanarity angles greater than 20°

hadron penetration	.4	QED μ-pairs	3.0
π,k decay	.5	$e^+e^- \to e^+e^-\mu^+\mu^-$	-

The probability that the 13 events observed are due to a statistical fluctuation is 2×10^{-4}. The inclusive cross section for channel (b) corresponding to the remaining 9 events is $(d\sigma/d\Omega)_{90^o} = 23^{+12}_{-9}$ pb/sr.

Several questions arise at this point; in particular what statements can be made on their cross sections. The question also arises of the comparison of these anomalous muons with the e-μ events observed(10) at SPEAR.

A first statement can be made on the expected number of e-μ events in this experiment. The shower counters opposite to the spectrometer would have identified those events for noncollinearities $\leq 40^o$. By applying our cuts to the distributions of e-μ events we find that our apparatus should have detected 0.3 events, consistent with the fact that none were observed.

Any attempt to interpret jointly both anomalous lepton processes addresses directly the problem of the production mechanisms. Among the many possibilities the production of a heavy lepton with a new leptonic quantum number or a heavy boson have been proposed(11). The possible decays contributing to our anomalous events would therefore be:

$$e^+e^- \to L\bar{L} \qquad\qquad e^+e^- \to B\bar{B}$$

$$L \to \mu\bar{\nu}_\mu\nu_L \qquad\qquad B \to \mu\bar{\nu}_\mu \qquad (1)$$

$$\to e\bar{\nu}_e\nu_L \qquad\qquad \to e\bar{\nu}_e\,.$$

$$\to h\nu_L$$

Following both hypotheses we calculate the acceptance of the apparatus requiring a muon in the spectrometer and a muon, an electron or a single hadron in the central detector. For pair production of heavy bosons we assume no spin-spin correlation and P-wave threshold behaviour of the cross section. The cross section for production of a heavy spin 1/2 lepton pair is:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\beta((1+\cos^2\theta) + (1-\beta^2)\sin^2\theta)) , \tag{2a}$$

$$\sigma(e^+e^- \rightarrow L^+L^-) = 10.88 \;\frac{\beta(3-\beta^2)}{E^2}\; \mathrm{nb} . \tag{2b}$$

We assume V-A decay with universal coupling, in the limit of negligible final state masses. The decay angular distributions depend strongly on the spin orientation of the decaying lepton, as well known for μ decay. Since S wave is expected to dominate near threshold, the spins of the heavy leptons will tend to be aligned and parallel to the beams. Therefore the angular asymmetry due to the parity violating term in the decay does not contribute at 90^o, where muons are detected. The decay muon momentum spectrum reduces to:

$$f(p_\mu/p_{max}) \sim (p_\mu/p_{max})^2(3-2p_\mu/p_{max}) . \tag{3}$$

The calculated momentum spectra and coplanarity distribution can be compared under this set of assumptions with the experimental results.

The momentum distribution of the 13 anomalous events (b) is shown in Fig. 4. An upper limit to the mass of the decaying particle can be directly derived from the observed momentum spectrum. From Fig. 4, where momentum limits for different masses are shown, one gets $M_L^{max} = 1.8 - 2$ GeV. The momentum acceptance of the spectrometer above the 1.05 GeV/c cut is almost flat up to the beam momentum, as shown in Fig. 5. We therefore choose for subsequent calculations a lepton or boson mass of 1.8 GeV.

The muon momentum spectra in the decay of a lepton or a boson are significantly different, as shown in Figs. 6 and 7; the acceptance cuts of the spectrometer further enhance the difference of the detected momentum spectra.

In spite of the low statistics the experimental points seem to agree better with the lepton hypothesis.

In the framework of heavy lepton production the events observed are due to the sequential processes:

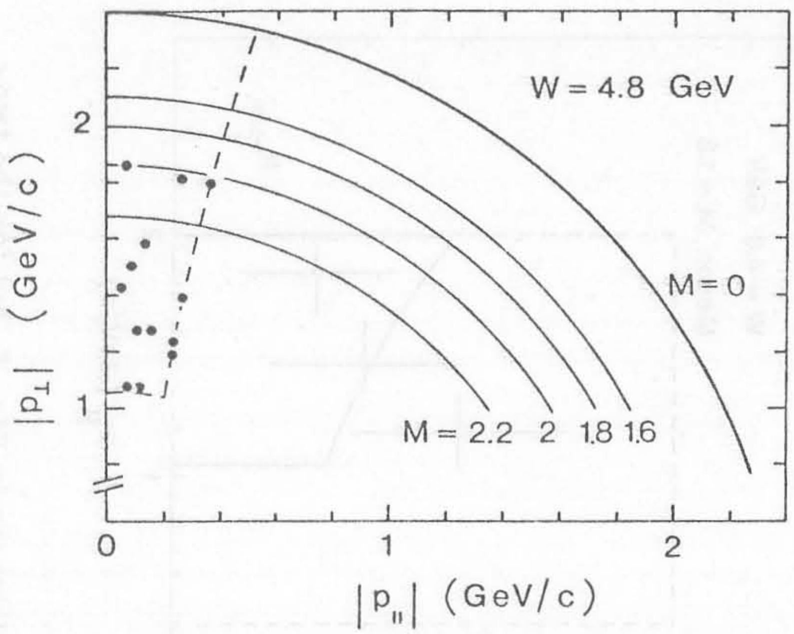

FIG. 4 - Distribution of $p_\perp$ vs $p_\parallel$ for the 13 anomalous events. The dashed line indicates the spectrometer acceptance. Momentum limits for different produced masses are shown.

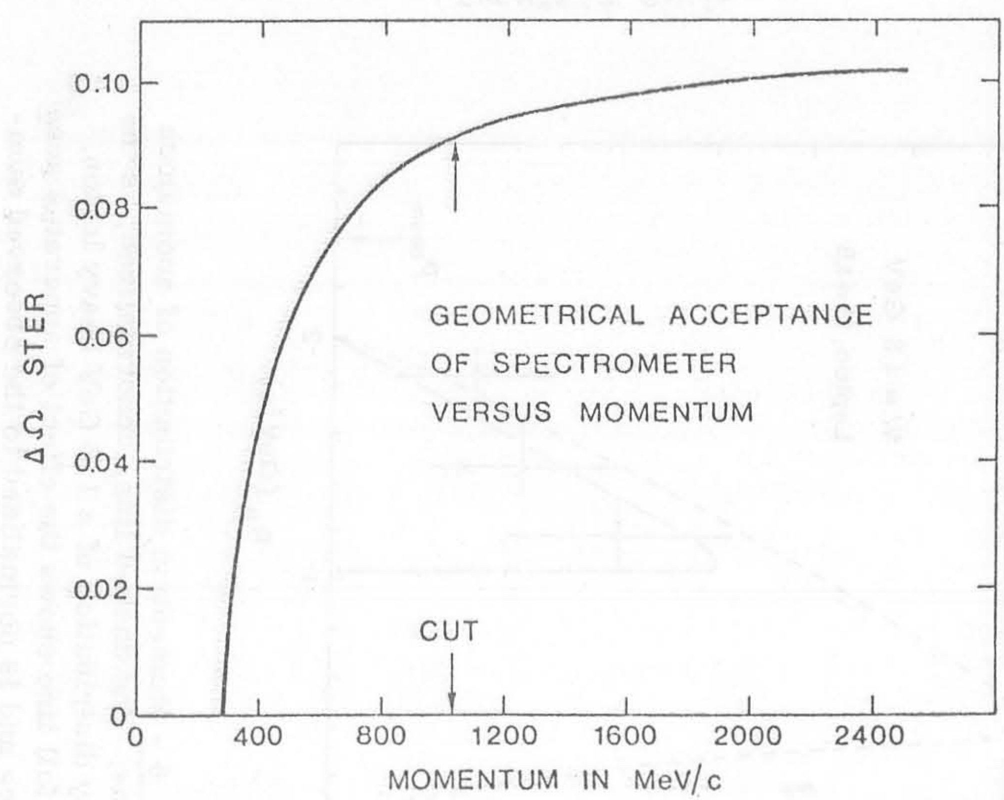

FIG. 5 - Acceptance of the spectrometer as a function of the momentum. The muon momentum cut is shown.

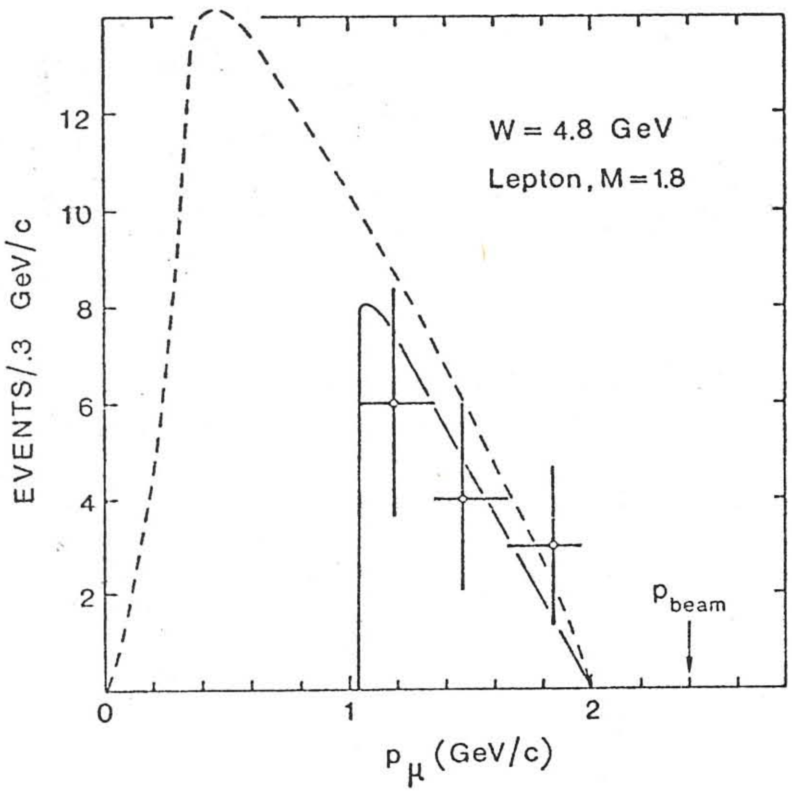

FIG. 6 - Momentum distribution of anomalous muons. The dashed line, unnormalized, is the decay distribution of a 1.8 GeV heavy lepton. The full line shows the effect of apparatus acceptance and is normalized to the observed number of events.

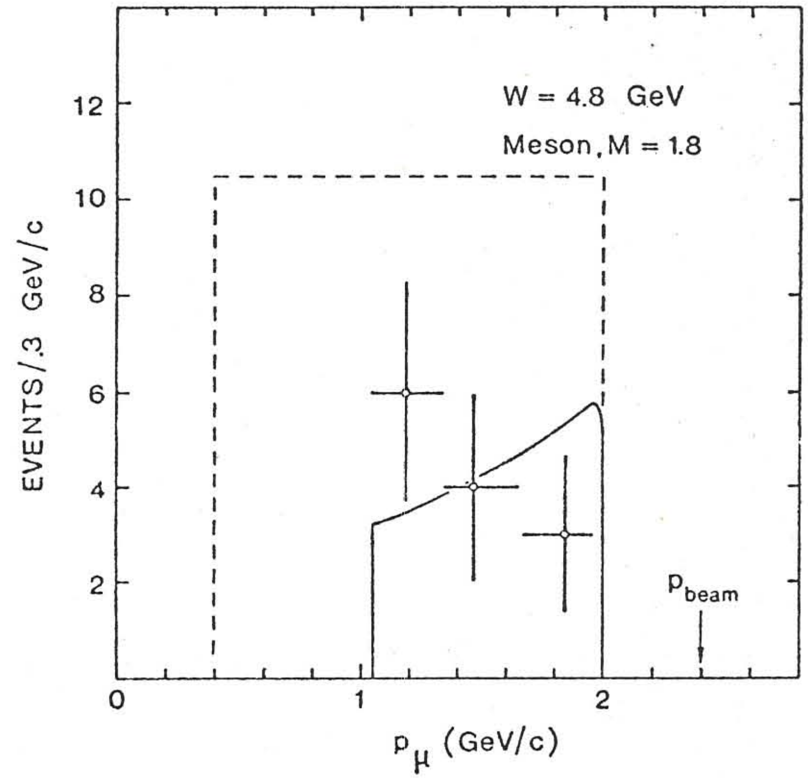

FIG. 7 - Same as in Fig. 6, but for the two-body decay of a 1.8 GeV heavy boson.

$$e^+ e^- \to L + \bar{L}$$
$$\hookrightarrow \bar{\mu}\nu\bar{\nu}_L \text{ (spectrometer)} \qquad (4)$$
$$\hookrightarrow \mu\bar{\nu}\nu_L, \ e\bar{\nu}\nu_L, \ h\nu_L$$

where h denotes a single charged hadron.

In order to calculate cross sections and branching ratios we evaluate the correction due to the 20^o coplanarity cut, first introduced to select the anomalous events. In Fig. 8 the expected noncoplanarity distribution is seen to be consistent with the experimental points and the effect of the cut is shown.

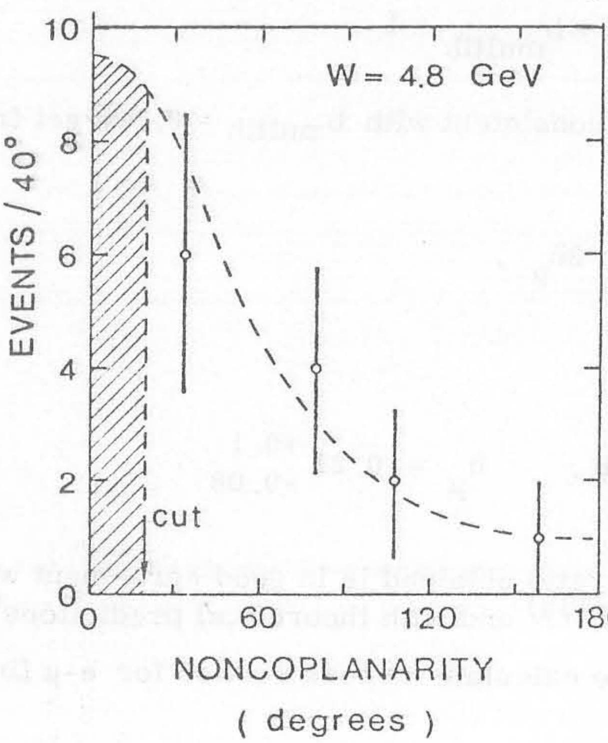

FIG. 8 - Distribution of the noncoplanarity angle for the anomalous muon events. The expected distribution for lepton decay is also shown, together with the 20^o noncoplanarity cut.

We get for reaction (4)

M	σ_{LL}	εx10^{-3}	$\sigma_{\mu x}$
1.6	3.44	1.86	1.26
1.8	3.20	1.71	1.37
2.	2.81	1.69	1.39

where σ_{LL} is the expected heavy lepton cross section(2b) in nanobarn, ε the apparatus acceptance and $\sigma_{\mu x}$ is the cross section for the sum of final states (4) derived from our data at 4.8 GeV. It can be seen that the values of $\sigma_{\mu x}$ depend only slightly on the mass assignement.

The ratio $\sigma_{\mu x}/\sigma_{LL}$ is related to the leptonic and single-hadronic branching ratios by the equation:

$$\frac{\sigma_{\mu x}}{\sigma_{LL}} = 2\,b_\mu(b_\mu + b_e + b_h) \ , \tag{5}$$

where the factor 2 accounts for the symmetry of the inclusive trigger with respect to the decay products. From the identity

$$b_\mu + b_e + b_h + b_{multih} = 1 \tag{6}$$

and our result on reaction (a), consistent with $b_{multih} = 0$, we get from (5) and (6) :

$$\frac{\sigma_{\mu x}}{\sigma_{LL}} = 2b_\mu \ , \tag{7}$$

that for $M = 1.8$ GeV yields:

$$\sigma_{\mu x} = 1.4^{+0.7}_{-0.5}\ \text{nb}\ , \qquad b_\mu = 0.21^{+0.1}_{-0.08} \ .$$

The leptonic branching ratio obtained is in good agreement with the one observed in e-μ events(11a) and with theoretical predictions(2a).

From these numbers we calculate a cross section for e-μ final states:

$$\sigma_{e\mu} = \sigma_{\mu x}\, b_\mu = 0.29^{+0.15}_{-0.11}\ \text{nb}\ .$$

We conclude that the inclusive muon production in two-prong events points, as well as e-μ final states, to the possible production of heavy leptons with leptonic branching ratios in agreement with previous experimental and theoretical results.

Also we observe that under this hypothesis single-hadronic final states seem to account for a large fraction of the heavy lepton decay modes.

REFERENCES. -

(1) - M.K. Gaillard, B.W. Lee and J.L. Rosner, Rev. Mod. Phys. 47, 277 (1975); G.A. Snow, Nucl. Phys. B55, 445 (1973).

(2) - (a) Y.S. Tsai, Phys. Rev. D4, 2821 (1971);
(b) M.L. Perl and P. Rapidis, SLAC-PUB-1496;
(c) J.D. Bjorken and C.H. Llewellyn Smith, Phys. Rev. D7, 887 (1973);
(d) M.A.B. Beg and A. Sirlin, Ann. Rev. Nucl. Phys. 24, 379 (1974).

(3) - T.L. Atwood et al., Phys. Rev. Letters 35, 704 (1975).

(4) - M. Cavalli Sforza, G. Goggi, G.C. Mantovani, A. Piazzoli, B. Rossini, D. Scannicchio, D.G. Coyne, G.K. O'Neill, H.F.W. Sadrozinski, K.A. Shinsky, T.L. Atwood, D.H. Badtke, B.A. Barnett, L. V. Trasatti and G.T. Zorn, Phys. Rev. Letters 36, 558 (1976).

(5) - B. Borgia et al., Lett. Nuovo Cimento 3, 115 (1972); B.L. Beron et al., Phys. Rev. Letters 33, 663 (1974); D. Bollini et al. Lett. Nuovo Cimento 13, 380 (1975).

(6) - F.A. Berends, K.J.F. Gaemers and R. Gastman, Nucl. Phys. B57, 381 (1973).

(7) - P.M. Joseph, Nucl. Instr. and Meth. 75, 13 (1969); A. Buhler et al., Nuovo Cimento 35, 759 (1965).

(8) - G. Grammer, Jr. and T. Kinoshita, Nucl. Phys. B80, 461 (1974).

(9) - This calculation was performed by G. Grammer, Jr. and P. Lepage and was an extension of the exact calculation of Ref. (8) to include all t-channel amplitudes to fourth order.

(10) - M.L. Perl et al., Phys. Rev. Letters 35, 704 (1975).

(11) - (a) M.L. Perl, SLAC-PUB-1592 (1975);
(b) M.L. Perl, SLAC-PUB-1664 (1975).