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THE INCLUSIVE HADRON SPECTRUM IN e^+e^- ANNIHILATION AS A TEST FOR THE PRODUCTION AND DECAY OF HEAVY LEPTONS*

K. J. F. Gaemers and Risto Raitio†
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

ABSTRACT

The production and subsequent decay into a neutrino and hadrons of a heavy lepton in e^+e^- colliding beams gives a contribution to the inclusive hadron spectrum $s\,d\sigma/dx$. We calculate this contribution assuming the usual V-A structure for the weak hadronic current and assuming that the "hadronic" decays of the heavy lepton are dominated by the π, ρ, A_1 and ρ' mesons. Due to the decay into a single pion and a neutrino the inclusive energy spectrum of hadrons has a distinct maximum. The position of this maximum is directly related to the heavy lepton velocity. Experimental determination of the position of this maximum will therefore determine the heavy lepton mass. Our calculation also shows that the inclusive hadron spectrum decreases with increasing x less rapidly than the total measured inclusive hadron spectrum. Measuring the spectrum of a hadron in $e^+e^- \rightarrow$ hadron + e/μ + anything and determining the position of the maximum offers a test for the existence of heavy leptons and a way of determining their mass.

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†On leave from the University of Helsinki, Helsinki, Finland.

I. INTRODUCTION

A quantity which has been measured extensively in e^+e^- colliding beam experiments is the inclusive momentum spectrum of single hadrons.[1] If the anomalous $e\mu$ events, detected at SPEAR,[2,3] indicate the production of a pair of new fermions, which are called heavy leptons further on, the decays of these heavy leptons into a neutrino and hadrons, will give a contribution to the inclusive hadron spectrum. Since the measured spectra show a "bulge" at c.m. energies between 4 and 4.4 GeV[1] it is worthwhile to calculate how much of this effect could be due to hadronic decay products of heavy leptons. More important, it is possible to look at this distribution by itself if one considers events where only one muon or electron is present, together with one or more hadrons. The detected lepton then serves as a possible indicator for the production of a heavy lepton pair, one decaying leptonically the other decaying into a neutrino and hadrons. (We will call this latter mode hadronic decay from now on.)

It is to be noted, however, that if at energies above 4 GeV, heavy leptons as well as a new type of hadrons (charm?) are produced, and if these hadrons have an appreciable leptonic and semileptonic branching ratio, these will contaminate the inclusive hadronic spectrum from the heavy leptons even if a lepton is detected along with hadrons. However, the calculations in this paper indicate that the hadron spectrum from heavy leptons has several distinct features, which should help to disentangle possible background effects.

Measuring the inclusive hadron spectrum from the decays of heavy leptons, will establish the existence of hadronic decay modes. It is necessary to show the existence of hadronic decay modes if one wants to explain the observation of $e\mu$ events by heavy leptons.

The general differential cross section for the reaction

$$e^+e^- \to h + X, \qquad (h=\pi, K, N, \ldots) , \tag{1}$$

can be written as[4]

$$\frac{d\sigma}{dx\, d\Omega} = \sigma_T + \sigma_L + (\sigma_T - \sigma_L)\left[\cos^2\theta + P^2 \sin^2\theta \cos 2\phi\right] . \tag{2}$$

In this expression $\sigma_{T,L}$ are positive quantities which depend only on $x=E_h/E$ and the beam energy E. The energy of the detected hadron is E_h. The transverse polarization of the beams is given by P. The variables θ and ϕ are the polar and azimuthal angle of the hadron.

Instead of presenting results as a function of E, x, θ and ϕ, we will present the behavior of

$$s\frac{d\sigma}{dx}(x, E) = s\int \frac{d\sigma}{dx d\Omega}\, d\Omega , \quad (s=4E^2) \tag{3a}$$

and

$$\alpha(x, E) = \frac{\sigma_T - \sigma_L}{\sigma_T + \sigma_L} . \tag{3b}$$

We obtain the following results. The spectrum $s\, d\sigma/dx$ shows a clear maximum as a function of x. The position of this maximum is related to the heavy lepton velocity in a simple way. The mass of the heavy lepton can thus be determined from the position of this maximum.

The calculated spectrum due to a heavy lepton falls slower with increasing x than the measured total inclusive spectrum. The average number of charged hadrons in the decay of a heavy lepton is ≈ 1.1; this is less than the expected average charged multiplicity in the decay of charmed hadrons.[7]

The outline of this paper is as follows. In Section II we give a general expression for the inclusive hadron spectrum in terms of structure functions for the weak hadronic current.

In Section III we derive expressions for the decay distributions from specific channels. We assume that these channels are dominated by a single π or a single resonance. For the vector current we assume dominance by the ρ and the ρ'. For the axial current we take contributions from a single π and the A_1. All results are derived retaining the full width of the resonances involved. In Section IV we combine the production cross section of a heavy lepton pair with the obtained decay distributions. We present numerical results on the inclusive π spectrum and discuss briefly the presence of kaons and nucleons.

II. GENERAL FORMALISM

In order to calculate the inclusive spectrum we will first study the decay of an unpolarized heavy lepton at rest. The amplitude for the decay

$$U^- \rightarrow \nu_U + h + X \tag{4}$$

is given by

$$T = \frac{G}{\sqrt{2}} \bar{u}(k)\gamma^\alpha(1-\lambda\gamma^5)\, u(Q) < h(q), X | J_\alpha^{weak}(0) | 0> \quad . \tag{5}$$

Here k and Q are the four-momenta of the neutrino and the heavy lepton, respectively, and q is the momentum of the observed hadron (h). We assume a massless neutrino ν_U. The weak hadronic current is assumed to have the well-known V-A structure. As a consequence the heavy lepton weak current can only be a combination of V and A and we neglect the possibility of S, T and P interactions. We keep the relative strength of V and A as a free parameter, however, V, A interference terms cannot appear in the spectrum.

From the amplitude we get the differential decay rate

$$d\omega = \frac{G^2}{8M(2\pi)^2} \frac{d\vec{q}}{q_0} \int \frac{d\vec{k}}{k_0} W_{\alpha\beta}(q, Q-k)$$
$$\left[(1+\lambda^2)\left\{k^\alpha Q^\beta + Q^\alpha k^\beta - (k\cdot Q)\, g^{\alpha\beta}\right\} - 2i\lambda\, \epsilon^{\alpha\beta\gamma\delta} k_\gamma Q_\delta\right] \tag{6}$$

where M is the heavy lepton mass and the tensor $W_{\alpha\beta}$ is defined by

$$W_{\alpha\beta}(q, Q-k) = \sum_X < 0 | J_\beta^{weak}(0) | h(q), X > \cdot$$
$$< h(q), X | J_\alpha^{weak}(0) | 0 > \delta^4(q + P_X + k - Q) \tag{7}$$

In this expression P_X is the total four momentum of the hadrons recoiling against the neutrino and the observed hadron h.

For the tensor $W_{\alpha\beta}$ we write down a general decomposition into six real structure functions using the variable $\tilde{Q} = Q - k$.

$$W_{\alpha\beta}(q,\tilde{Q}) = -\left(g_{\alpha\beta} - \frac{\tilde{Q}_\alpha \tilde{Q}_\beta}{\tilde{Q}^2}\right) W_1 +$$

$$+ \frac{1}{m_h^2}\left(q_\alpha - \frac{q\cdot\tilde{Q}}{\tilde{Q}^2}\tilde{Q}_\alpha\right)\left(q_\beta - \frac{q\cdot\tilde{Q}}{\tilde{Q}^2}\tilde{Q}_\beta\right) W_2 +$$

$$+ \frac{i}{M^2}\,\epsilon_{\alpha\beta\gamma\delta}\, q^\gamma \tilde{Q}^\delta W_3 + \frac{\tilde{Q}_\alpha \tilde{Q}_\beta}{M^2} W_4 +$$

$$+ \frac{1}{M^2}\left(\tilde{Q}_\alpha q_\beta + q_\alpha \tilde{Q}_\beta\right) W_5 + \frac{i}{M^2}\left(\tilde{Q}_\alpha q_\beta - q_\alpha \tilde{Q}_\beta\right) W_6 \tag{8}$$

The structure functions W_i, $i=1\ldots6$ are functions of $q\cdot\tilde{Q}$ and $\tilde{Q}^2$. W_3 and W_6 are nonzero only if there is V, A interference, W_4 and W_5 are nonzero if the currents contributing are not conserved. If we combine (6) and (7) the expression for the decay rate becomes

$$d\omega = \frac{G^2}{8M(2\pi)^2}\frac{d\vec{q}}{q_0}\int\frac{d\vec{k}}{k_0}\Bigg[(1+\lambda^2)\Bigg\{k\cdot Q\left(2+\frac{M^2}{\tilde{Q}^2}\right) W_1$$

$$+ \frac{1}{m_h^2}\left[2(q\cdot Q)(k\cdot q) - 2(k\cdot q)M^2\delta - (k\cdot Q)m_h^2 + (k\cdot Q)M^2\delta^2\right] W_2$$

$$+ (k\cdot Q)\,W_4 + 2(k\cdot q)\,W_5\Bigg\}$$

$$+ 4\lambda\frac{1}{M^2}\left[(q\cdot Q)(k\cdot Q) + (k\cdot q)(k.Q) - (k\cdot q)M^2\right] W_3\Bigg] \tag{9}$$

where

$$\delta \equiv \frac{q\cdot\tilde{Q}}{\tilde{Q}^2} \quad .$$

Without further information the number of structure functions entering the problem is such that this expression is not very useful. We will show, however, that for the channels we will consider, only one structure function dominates. It is to be noted that the structure function W_6 does not appear in Eq. (9).

III. INCLUSIVE DECAY DISTRIBUTIONS

The eμ data suggest that the mass of the heavy lepton is smaller than 2 GeV.[1] From earlier estimates of the various branching ratios,[5] we see that this implies that the hadronic decay modes are dominated by resonances, and that the continuum is not very important.

We consider three types of hadronic final states in the decay of a heavy lepton. (We will throughout have a negative U in mind.) In decreasing order of importance they are (a) only pions, (b) kaons and pions, (c) baryons and mesons. In general we can say that final states c will have a very small branching ratio due to the limited phase space if they are at all possible. The ratio of final states of type a and type b is set by the Cabibbo angle. From these qualitative arguments we see that final states of type a will be the most important. These final states have the following property: if we assume that the hadronic weak currents are first class an even number of pions can be produced only through the vector current, whereas an odd number of pions will be produced only through the axial current. As a result, in final states of type a there is no V,A interference. For an even number of pions, this means that only W_1 and W_2 contribute; for an odd number there will also be contributions from W_4 and W_5.

The decay rate into a single pion, $U^- \rightarrow \nu_U \pi^-$, can be calculated without reference to the general expression (9).[5] In the heavy lepton rest frame it is

$$d\omega = \frac{G^2 f_\pi^2 (1+\lambda^2)}{8(2\pi)^2} M^3 \left(1 - \frac{m_\pi^2}{M^2}\right) \cdot \delta(M^2 + m_\pi^2 - 2q\cdot Q) \frac{d\vec{q}}{q_0} \quad . \tag{10}$$

Here m_π and f_π are the pion mass and pion decay constant, respectively; f_π includes the Cabibbo angle.

From this we get the distribution normalized to one,

$$\frac{d\omega}{\omega} = \frac{1}{\pi}\left(1 - \frac{m_\pi^2}{M^2}\right)^{-1} \delta(M^2 + m_\pi^2 - 2q \cdot Q)\frac{d\vec{q}}{q_0}. \tag{11}$$

The normalized distribution has the advantage that it is Lorentz invariant, which is useful when these distributions have to be combined with the production cross section of a heavy lepton pair.

We now turn to the decay into two pions, $U^- \to \nu_U + \pi^- + \pi^0$. We describe the final state by a Breit-Wigner resonance with the ρ mass (M_ρ) and width (Γ_ρ). The tensor $W_{\alpha\beta}$ now has the form

$$W_{\alpha\beta} = \int \frac{d\vec{p}}{(2\pi)^3 2p_0} \delta^4(q+p+k-Q)(q-p)_\alpha (q-p)_\beta$$

$$\cdot \frac{f_{\nu\rho}^2 f_{\rho\pi\pi}^2}{|(Q-k)^2 - M_\rho^2 + iM_\rho \Gamma_\rho|^2} \tag{12}$$

from which we can see that here only the structure function W_2 is nonzero. The integration variable $\vec{p}$ is the π^0 momentum. The coupling constants $f_{\nu\rho}$ and $f_{\rho\pi\pi}$ describe the couplings of a ρ to the vector current and two pion system, respectively. The resulting decay rate is

$$d\omega = \frac{G^2(1+\lambda^2)f_{\nu\rho}^2 f_{\rho\pi\pi}^2}{8M(2\pi)^5} \frac{d\vec{q}_T}{q_0} \cdot$$

$$\cdot \left[2(2q\cdot Q - M^2)^2 A(q\cdot Q) + (8q\cdot Q - 3M^2 - 4m_\pi^2) B(q\cdot Q)\right]. \tag{13}$$

The functions A and B are defined by

$$[A,B] = \int \frac{d\vec{k}}{k_0} \frac{\delta((Q-k-q)^2 - m_\pi^2)\ [1, k\cdot Q]}{|(Q-k)^2 - M_\rho^2 + iM_\rho\Gamma_\rho|^2}. \tag{14}$$

These functions depend only on the invariant $q \cdot Q$, which in the heavy lepton rest frame reduces to $q_0 M$. In this frame, q_0 can vary between m_π and $M/2$. The bounds on the k_0 integration in (14) are given as a function of q_0 by

$$k_\pm = \frac{M}{2} \frac{(M-2q_0)}{M - q_0 \mp |\vec{q}|} . \tag{15}$$

If we introduce the quantity

$$\mathcal{M} = \frac{M^2 - M_\rho^2 + iM_\rho \Gamma_\rho}{2M} \tag{16}$$

we find for A and B

$$A = \frac{\pi}{4M^2 |\vec{q}|} \cdot \frac{1}{\mathrm{Im}\mathcal{M}} \arctan \frac{k_0 - \mathrm{Re}\mathcal{M}}{\mathrm{Im}\mathcal{M}} \Bigg|_{k_-}^{k_+}$$

$$B = \frac{\pi}{4M|\vec{q}|} \left\{ \ln |k_0 - \mathcal{M}| + \frac{\mathrm{Re}\mathcal{M}}{\mathrm{Im}\mathcal{M}} \arctan \frac{k_0 - \mathrm{Re}\mathcal{M}}{\mathrm{Im}\mathcal{M}} \right\} \Bigg|_{k_-}^{k_+} \tag{17}$$

Combining (13), (15), and (17), we find the single pion spectrum for this channel.

If we now turn to three pions in the final state, we see that because here the axial current contributes we have in general contributions from W_1, W_2, W_4, and W_5. We will now assume that the three pions are always coming from the cascade decay

$$U \to \nu_U + A_1 , \quad A_1 \to 3\pi . \tag{18}$$

As can be seen,[5] the matrix element of the axial current between the vacuum and the A_1 state has the form

$$\langle A_1 | A^\mu(0) | 0 \rangle \propto \epsilon^\mu . \tag{19}$$

Here ϵ^μ is the A_1 polarization vector. This implies that, although the axial current is not conserved, the particular matrix element (19) may be considered to be conserved. We therefore restrict ourselves to the structure functions W_1 and W_2. Since the decay of the A_1 proceeds via a $\pi\rho$ s-wave state, the pions from the A_1 will be distributed isotropically, independent of the A_1 polarization. We therefore take for the A_1 only a W_1 contribution to account for the isotropic pion distribution. In analogy with Eq. (12) for the ρ, for the A_1 contribution we get:

$$W_{\alpha\beta} = \int \frac{d^4p}{(2\pi)^3}\, \delta^{(+)}(p^2 - M_x^2)\delta^4(p + q + k - Q) \cdot$$

$$\cdot \left[- q_{\alpha\beta} + \frac{(Q-k)_\alpha\, (Q-k)_\beta}{(Q-k)^2} \right] \cdot \frac{F_A^2}{|(Q-k)^2 - M_{A_1}^2 + iM_{A_1}\Gamma_{A_1}|^2} \tag{20}$$

Here M_x is the average mass recoiling against the $\nu\pi$ system.. We integrate over the recoil momentum p. This leads to a decay rate of the form

$$d\omega = \frac{G^2(1+\lambda^2)\, F_{A_1}^2}{8M(2\pi)^5} \frac{d\vec{q}}{q_0} \cdot$$

$$\cdot \int \frac{d\vec{k}}{k_0} \; \frac{\delta((Q-q-k)^2 - M_x^2) k\cdot Q}{|(Q-k)^2 - M_{A_1}^2 + iM_{A_1}\Gamma_{A_1}|^2} \cdot \left(2 + \frac{M^2}{(Q-k)^2}\right) . \tag{21}$$

In these expressions F_{A_1} is a combination of the couplings of the A_1 to the axial current and the A_1 decay constant. If we approximate $2+M^2/(Q-k)^2 \approx 2 + M^2/M_{A_1}^2$, the integral can be performed analytically and the resulting expression is

$$d\omega = \frac{G^2(1+\lambda^2)F_{A_1}^2}{8M(2\pi)^5} \frac{d\vec{q}}{q_0} \left(2 + \frac{M^2}{M_{A_1}^2}\right) B' . \tag{22}$$

Here B' is the same expression as B in (17) except for a change in integration limits. Instead of (15) we now have

$$k_{\pm} = \frac{M}{2} \frac{M - 2q_0 + \Delta}{M - q_0 \mp |\vec{q}|} \;, \quad \Delta = \frac{m_\pi^2 - M_x^2}{2M} \;. \tag{23}$$

The case of four pions in the final state can be treated in the same way. We now assume that the four pions come from a ρ'. Because the ρ' decay goes via an s-wave $\rho\epsilon$ state, we use the same argument as for the A_1 to restrict ourselves to a pure W_1 contribution. This means that (22) will also describe the four pion case after the appropriate modifications of masses, width, and coupling constant. As can be seen from the estimates in Ref. 5, the contribution from more than four pions will be negligible. We will therefore not include effects of more than four pions in the inclusive distribution.

As far as decays of type b are concerned we will consider only the decays

$$U \to \nu_U K \tag{24}$$

$$U \to \nu_U K^* \;, \quad K^* \to K\pi \tag{25}$$

The expression for inclusive single K production is the same as for single pions, (10) and (11), provided we change the masses and coupling constants. In the same way we use expression (13) for the decay (25).

IV. NUMERICAL RESULTS AND DISCUSSION

In order to calculate the inclusive hadron spectrum from heavy leptons in an e^+e^- colliding beam experiment, we have to combine the distributions from Section III with the production cross section of heavy lepton pairs. The production cross section of a heavy lepton of mass M is

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16E^2}\left(1 - \frac{M^2}{E^2}\right)^{\frac{1}{2}}\left[1 + \cos^2\theta + \frac{M^2}{E^2}\sin^2\theta\right] . \qquad (26)$$

In order to get $d\sigma/dx\, d\Omega$ for a particular hadron, we proceed as follows. From the expressions derived in Section III we can form the distributions normalized to one for each channel (π, ρ, A_1, ρ', K, K*) and each particle type. We multiply this normalized distribution in each channel with the corresponding branching ratio and the average number of observable hadrons in that channel. For instance, the A_1^- decays with equal probability in $\pi^-\pi^0\pi^0$ and $\pi^-\pi^-\pi^+$; in this case we therefore have $\langle N_{\pi^-}\rangle = 1.5$. For each channel we multiply the obtained expression by the production cross section and integrate over all angles of the heavy lepton, keeping in mind that due to kinematical restrictions this integration is not always over 4π.

The branching ratios are determined using the expressions from Ref. 5, with the modification that we replace the continuum contribution with the ρ' contribution.

Having obtained $d\sigma/dx\, d\Omega$, the quantities in Eqs. (3a) and (3b) can now be deduced. In Table I we list the branching ratios (B. R.), average multiplicities $\langle N\rangle$, and recoil masses (M_x) used in the calculations.

We now discuss the structure of $s\, d\sigma/dx$. In Fig. 1 we plot this as a function of x for beam energy E = 1.9 GeV and heavy lepton mass M = 1.8 GeV. In the same figure we plot the separate contributions from the channels π, ρ, A_1, and ρ'. For comparison we also plot the inclusive spectrum due to ρ if its width is taken to be zero.[5] It is seen that treating the ρ in a zero width approximation changes the spectrum considerably. It is also seen that the spectrum due to the decay $U^- \to \nu_U \pi^-$ has a different structure from the other contributions due to the fact that this is a two body decay as opposed to three (and more) body decays for the other channels. As a consequence of the sharp rectangular shape of the single pion spectrum the total spectrum shows a sharp maximum at the lowest x value where the decay $U^- \to \nu_U + \pi^-$ is kinematically possible. If we call the x value where this maximum occurs x_{max}, we have the following relation (up to corrections of order m_π^2/M^2),

$$x_{max} = \frac{1}{2}(1 - \beta_U) . \tag{27}$$

Here β_U is the velocity of the heavy lepton. The fact that this maximum is very sharp and the fact that its position is in a simple way related to the heavy lepton velocity may provide an alternative way to determine the heavy lepton mass. If the beam energy is E, the mass is given by

$$M^2 = 4E^2 x_{max} (1-x_{max}) . \tag{28}$$

From Fig. 1 we also see that the parts of the spectrum due to the A_1 and ρ' have a smooth behavior.

In Fig. 2 we plot s $d\sigma/dx$ at a beam energy E = 2.2 GeV. Here and in all the following figures the heavy lepton mass is taken to be 1.8 GeV. Besides the spectrum we also plot the variable α which describes the angular behavior of the inclusive hadrons. The function $\alpha(x)$ shows some structure at low x correlated with structure in s $d\sigma/dx$. Experimentally at this energy a "bulge" is seen in the x region between x = .3 and x = .5. From the published data we estimate an increase of .25 μb GeV^2 at x = .35. Our calculation gives .19 μb GeV^2.

In Fig. 3 we present our s $d\sigma/dx$ for three energies where experimental data are available. From the behavior with increasing E we see that the greater part of the increase takes place at low x. It is to be noted that in all curves presented we plot s $d\sigma/dx$ for negative hadrons (pions) only, whereas the experimental data as presented in Ref. 3 refer to positive and negative charges. The behavior of s $d\sigma/dx$ at PETRA and PEP energies and beyond is indicated in Fig. 4. We see that a scaling limit is reached, as was expected.[8]

In Fig. 5 we show the behavior of α as a function of x at three different energies. At low energies α is close to zero but far above threshold for heavy lepton pair production it approaches unity. This can be understood from the fact that at high energies the heavy leptons have an angular distribution proportional to $(1 + \cos^2\theta)$ and that at these energies the decay products move in the same direction.

A general feature of the calculated spectrum is that the falloff with x is much slower than the falloff in the observed total inclusive hadron spectrum.[6] If we compare at E = 3.7 GeV and take the ratio of s $d\sigma/dx$ at x = .2 and x = .8, the measured hadron spectrum gives $\approx$ 35 as contrasted to 6 in our calculation.

About other final states we mention that although the branching ratio into a nucleon-antinucleon pair and a neutrino will be very small (or zero if $M < 1.86$ GeV), the observation of this decay mode will give a lower bound on the heavy lepton mass. Observation of strange decay modes will also be difficult, due to the small branching ratios involved.

From the various branching ratios and multiplicities in Table I it follows that the average multiplicity of charged hadrons in heavy lepton decay is 1.1. In the leptonic decays the charged multiplicity is exactly one. As a consequence heavy lepton decays (leptonic and hadronic) will almost exclusively show up as events with two oppositely charged particles. Furthermore, since the neutral hadrons in a decay are mainly neutral pions, many events should be accompanied by photons from decaying π^0s.

In summary, we suggest that measuring the inclusive hadron spectrum from the decay of heavy leptons, for instance, by selecting events of the type $e^+e^- \rightarrow \pi + e/\mu$ + anything, can serve as a test of the heavy lepton hypothesis. The position of the maximum of this spectrum will give a determination of the heavy lepton mass.

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TABLE I

	B.R.	$\langle N_{\pi^-} \rangle$	$\langle N_{K^-} \rangle$	M_X in MeV
$\pi^-(137)$	.13	1	0	0
$\rho^-(770)$	.24	1	0	137
$A_1^-(1100)$	.10	3/2	0	700
$\rho'^-(1500)$	.05	3/2	0	900
$K^-(494)$	.01	0	1	0
$K^{*-}(892)$	.02	1/3	2/3	137

FIGURE CAPTIONS

1. The inclusive spectrum for $M = 1.8$ GeV and $E = 1.9$ GeV.

   a) π^- contribution
   b) ρ contribution
   c) A_1 contribution
   d) ρ' contribution
   e) ρ contribution with $\Gamma = 0$
   f) total

2. The inclusive spectrum and $\alpha(x)$ for $M = 1.8$ GeV at $E = 2.2$ GeV.

3. The inclusive spectrum for $M = 1.8$ GeV and energies

   a) $E = 1.9$ GeV
   b) $E = 2.4$ GeV
   c) $E = 3.7$ GeV.

4. The inclusive spectrum for $M = 1.8$ GeV and energies

   a) $E = 5$ GeV
   b) $E = 15$ GeV
   c) $E = 100$ GeV

   Curves b and c are on top of one another.

5. The angular parameter $\alpha(x)$ for $M = 1.8$ GeV and energies

   a) $E = 2.4$ GeV
   b) $E = 5$ GeV
   c) $E = 15$ GeV.

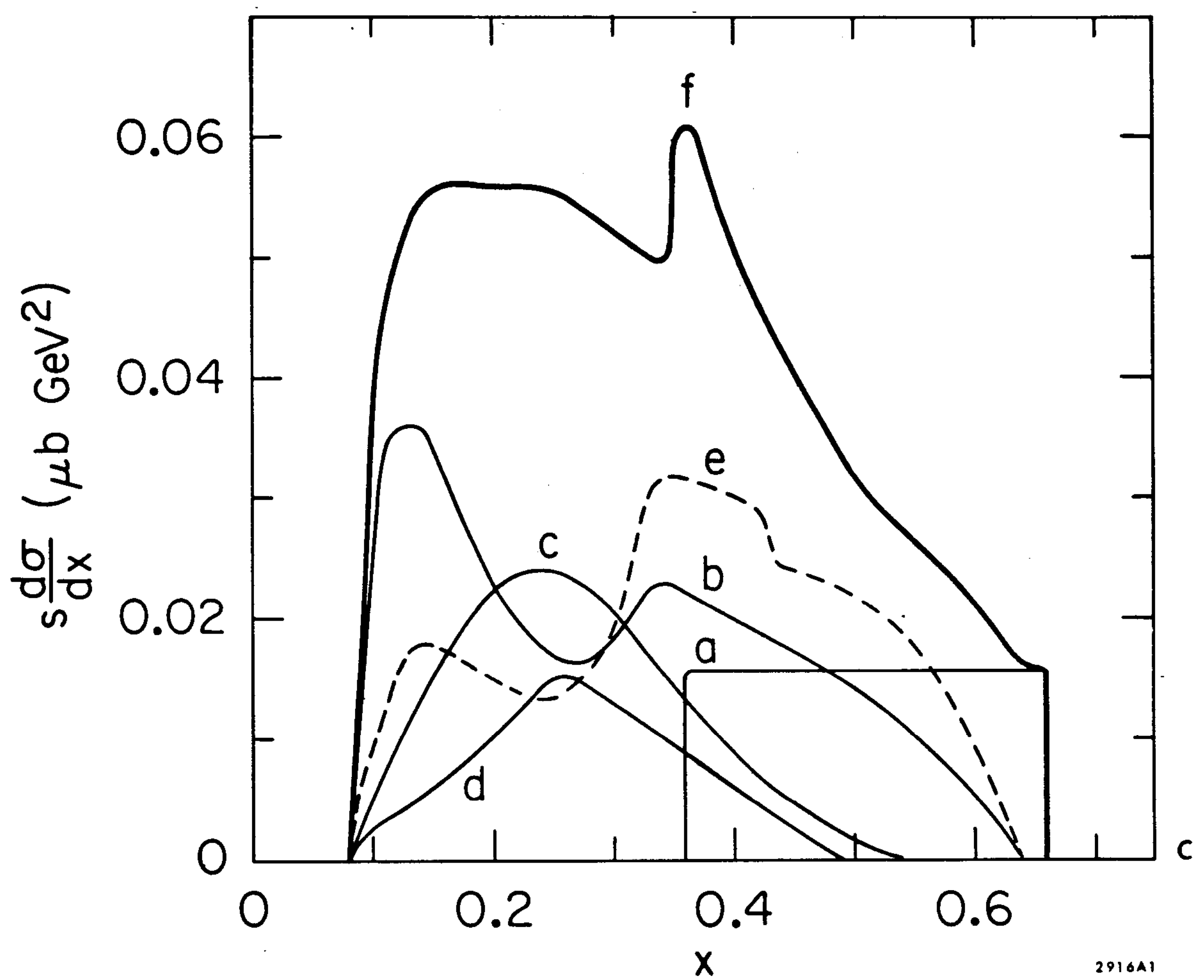
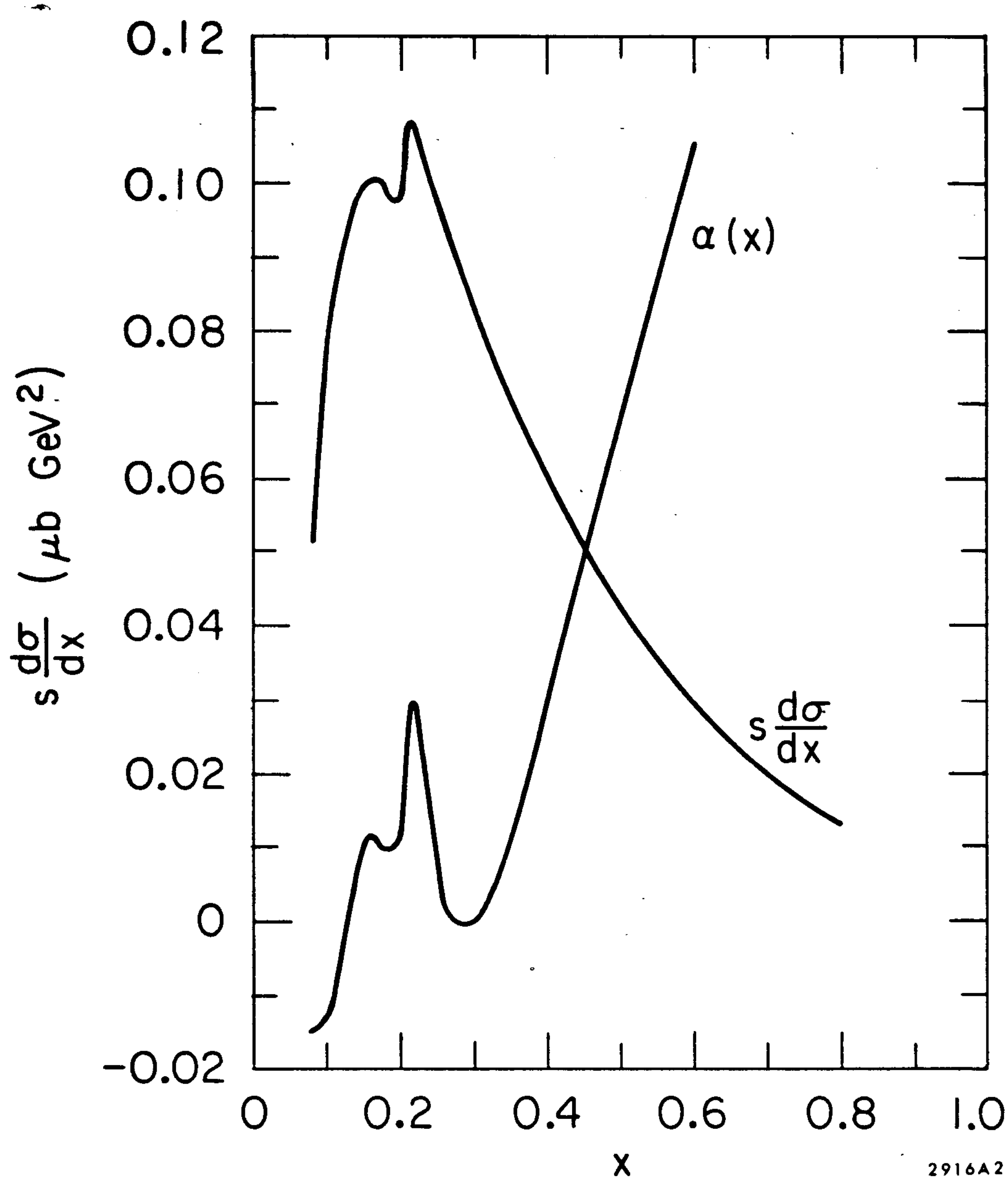
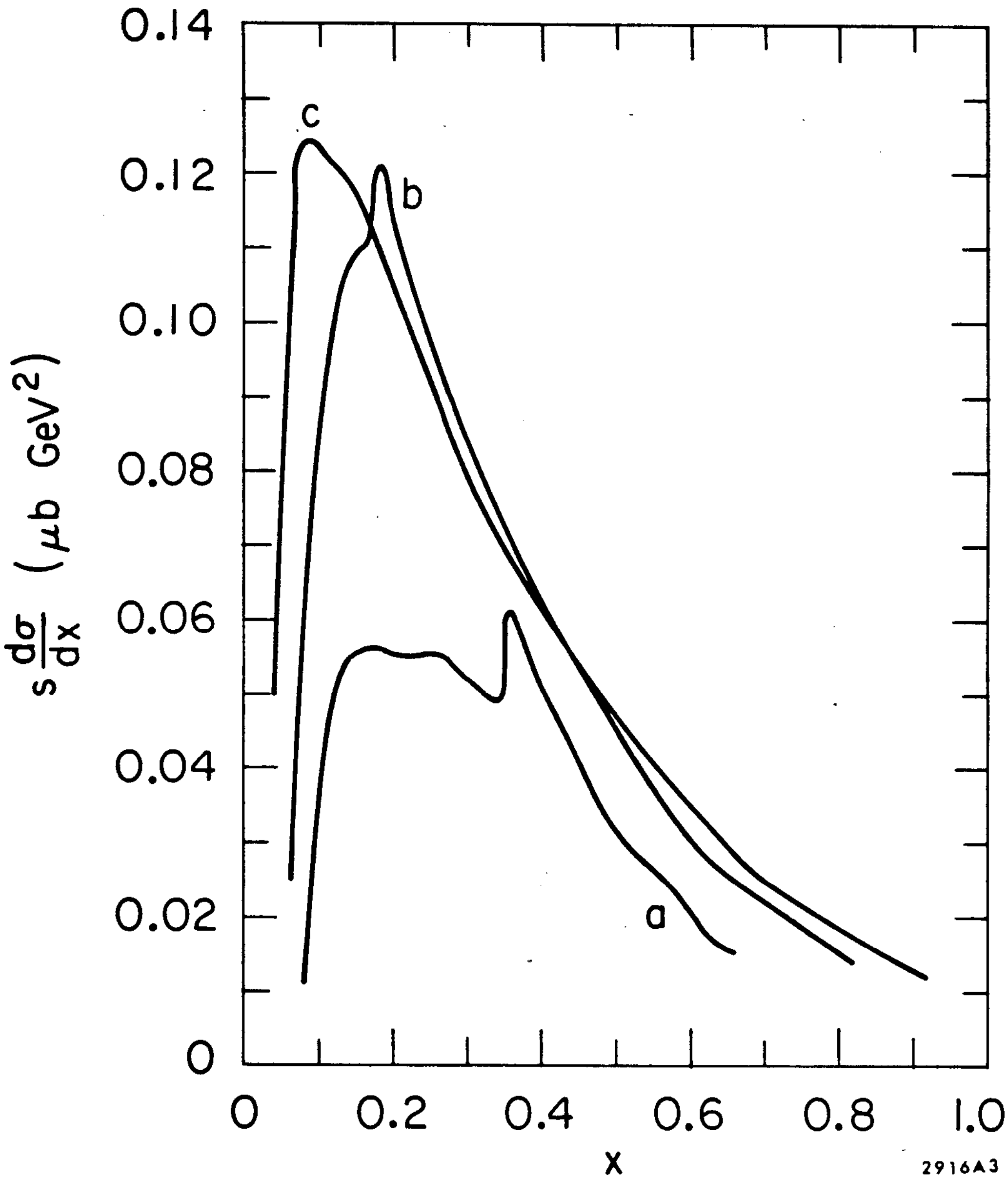


Fig. 1



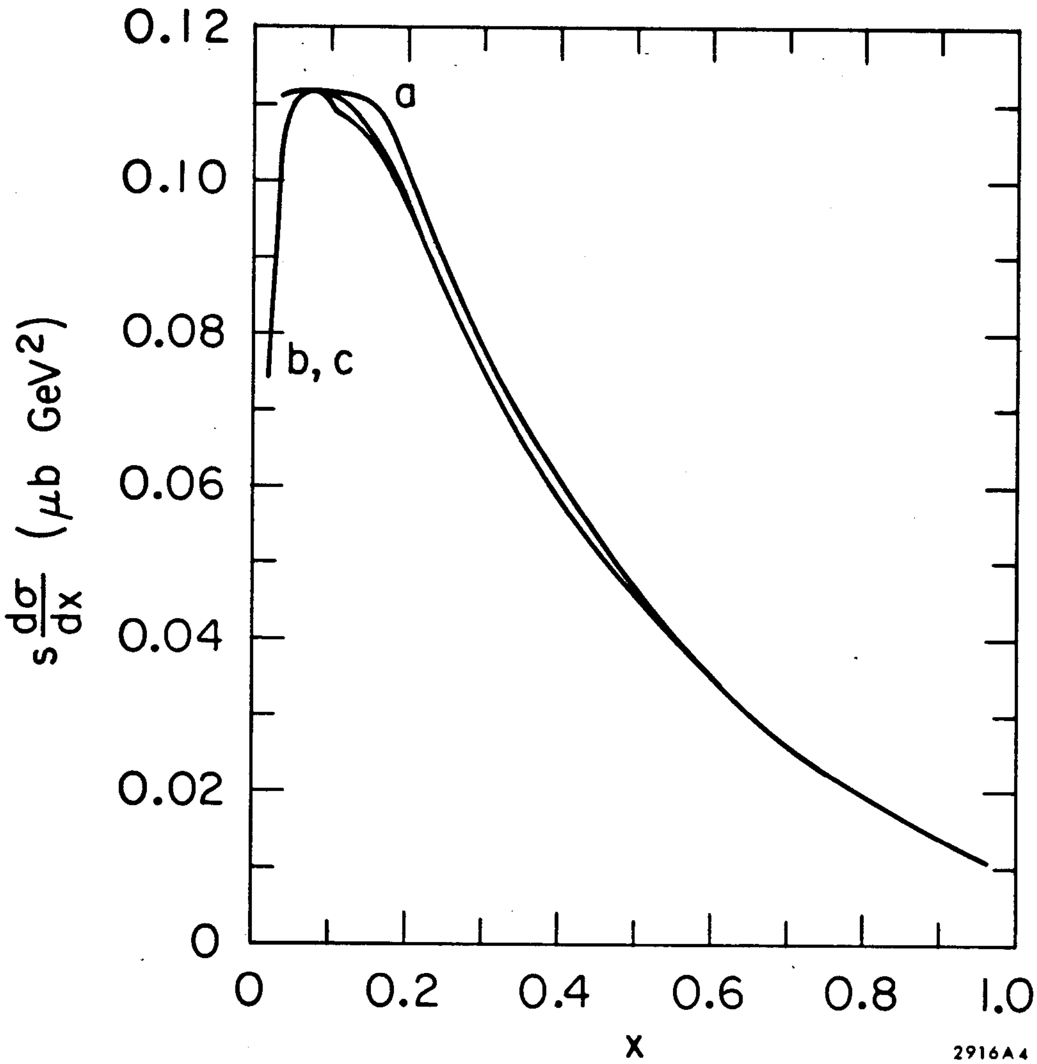
0.12
0.10
0.08
0.06
0.04
0.02
0
−0.02
$s\frac{d\sigma}{dx}$ (μb GeV^2)
$\alpha(x)$
$s\frac{d\sigma}{dx}$
0
0.2
0.4
0.6
0.8
1.0
x
2916A2

Fig. 2



0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
$s\frac{d\sigma}{dx}$ (μb GeV^2)
c
b
a
0
0.2
0.4
0.6
0.8
1.0
x
2916A3

Fig. 3



0.12
0.10
0.08
0.06
0.04
0.02
0
$s\frac{d\sigma}{dx}$ (μb GeV^2)
a
b, c
0
0.2
0.4
0.6
0.8
1.0
x
2916A4

Fig. 4

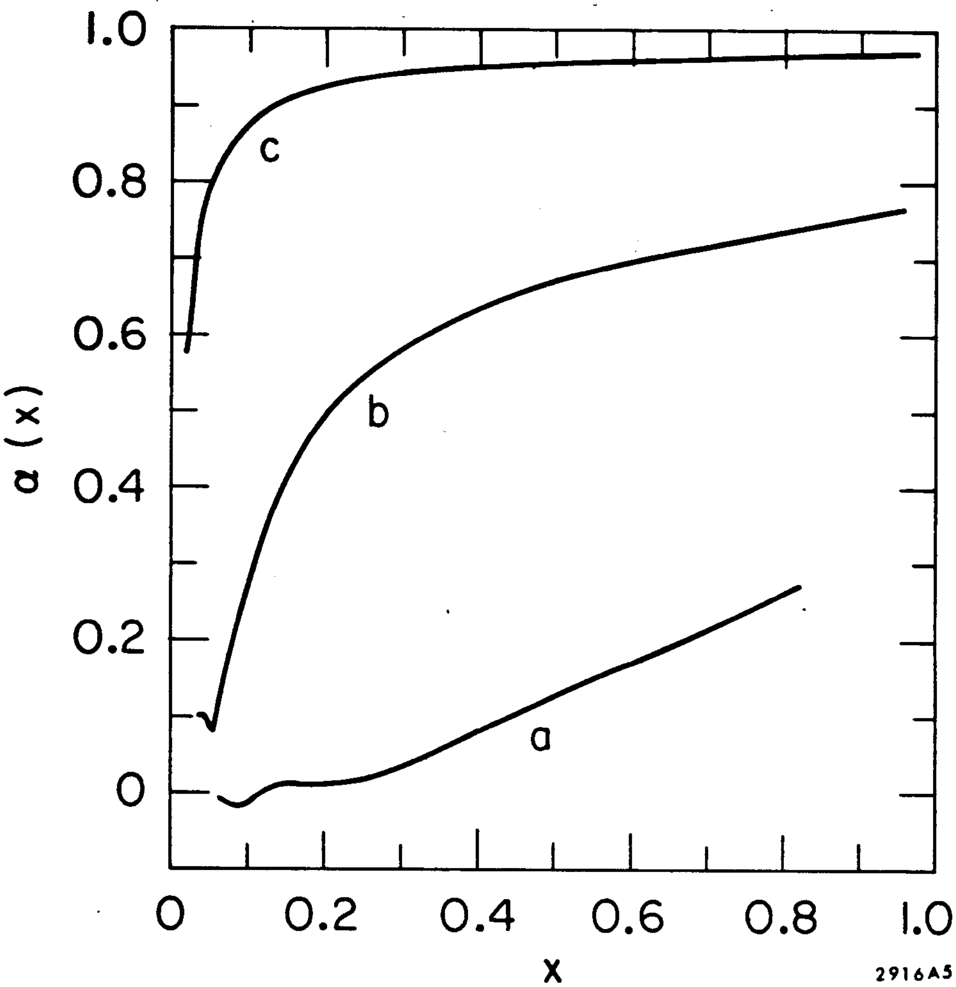


Fig. 5