VECTOR MESON AND ψ CONTRIBUTIONS
TO SINGLE LEPTON SPECTRA

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ABSTRACT

The data on the dilepton spectra in a forward cone are used to predict the ρ^0 , ω^0 , and ψ production at $\theta_{\text{cm}} \simeq 90^\circ$ and their contributions to the single lepton spectra. The π , $(\rho^0 + \omega^0)$, and ψ inclusive cross-sections are well fitted over the entire p_T range by a simple expression.

Combined contributions from ρ^0 , ω^0 , and ψ are found to account for about 30% of the observed lepton spectra. The contribution from the dilepton continuum is also discussed.

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1. INTRODUCTION

The inclusive production of high transverse momentum leptons has been observed in several experiments¹⁻³⁾ in proton-proton interactions at high energy ($\sqrt{s} > 20$ GeV). Their surprising abundance, corresponding to a ratio $2/\pi \approx 10^{-4}$ almost independent of p_T and $\sqrt{s}$, has raised much speculation about their origin. In particular, this rate is much larger than the usual parton model predictions. Contributions from leptonic decays of kaons and hyperons have been estimated for the various experiments. They can only account for 10% at the most of the observed signal, even with a generous allowance for hyperon production (hyperon/pion = 1). Other obvious sources of leptons are the leptonic decays of vector mesons (ρ^0, ω^0, ϕ^0). A favourite candidate was the ϕ^0 meson because of its relatively high leptonic branching ratio ($\sim 3 \times 10^{-4}$). A ϕ^0/π^0 ratio of approximately 3 at high transverse momentum was required to explain the single lepton spectrum. The ϕ^0 production has been measured to be much lower in direct ϕ^0 searches^{3,4)}. For $2.05 \text{ GeV}/c < p_T < 3.33 \text{ GeV}/c$ the Columbia-Fermilab group has found upper limits at 95% confidence level which vary between 5 and 10% for the ratio ϕ^0/π^- ⁴⁾.

The discovery of the ψ particle^{5,6)} with its large branching ratio into lepton pairs has prompted various attempts to relate that particle, and possibly other similar states as yet undiscovered, to the observed high transverse momentum single lepton rate. In the experiment of Knapp et al.⁷⁾, the entire dilepton mass spectrum has been measured in the ($\mu^+\mu^-$) mode for neutron-beryllium interactions at $\sqrt{s} \approx 20$ GeV, with clear ρ^0 and ψ peaks (Fig. 1). It is obviously desirable to infer from the measured dilepton cross-section the contribution of the entire mass spectrum (particles and continuum) to the observed single lepton distributions. But, as shown in Fig. 2, the kinematical regions in which the experiments have been performed are unfortunately well separated. For $\sqrt{s} \gtrsim 20$ GeV, the single lepton spectra have been measured at values of $p_T \gtrsim 1.5 \text{ GeV}/c$ and around 90° in the centre-of-mass system, which means very low values of $x_{||} \approx 2p_{||}^{\text{cm}}/\sqrt{s}$. On the contrary, the dimuon data of Knapp et al. correspond to parents with $p_T \lesssim 1.5 \text{ GeV}/c$ and $x_{||} \gtrsim 0.25^*)$. Even for high masses corresponding to large decay Q values there is no overlap between the two experimental regions. Thus to obtain any quantitative estimate of the dilepton contribution to the single lepton spectra one needs to extrapolate from one region to the other.

2. PARAMETRIZATION OF THE INCLUSIVE CROSS-SECTIONS

The inclusive pion cross-section at large $\sqrt{s}$ has been measured in a wide ($p_T, x_{||}$) domain and can provide a bridge between the two above-mentioned regions [see, for example, Alper et al.⁸⁾, Capiluppi et al.⁹⁾, and Cronin et al.¹⁰⁾]. We assume that a parametrization of the pion invariant cross-section will be valid

*) Knapp et al. use $x_{||}^{\text{lab}} = p_{||}^{\text{lab}}/p_{\text{inc}}$ related to $x_{||}$ by $x_{||}^{\text{lab}} = \frac{1}{2}x_{||} + \beta E_{\text{cm}}/\sqrt{s}$ with $\beta \approx 1$ at that energy.

for the l^- particles (including the ψ) and for the l^- mass continuum, apart from normalization factors. This hypothesis will be shown to agree with the available data. The experiment of Knapp et al. shows that for low p_T the dN/dp_T^2 distributions become flatter with increasing masses. More precisely they found $dN/dp_T^2 \sim e^{-6p_T^2}$ for ρ^0 's and $dN/dp_T^2 \sim e^{-2p_T^2}$ for ψ 's. This mass dependence suggests that the relevant variable might be $E_T = (m^2 + p_T^2)^{1/2}$ rather than p_T ¹¹⁾.

To make the extrapolation easier to handle we factorize the invariant cross-section as

$$\frac{E}{\pi} \frac{d^2\sigma}{dp_{\parallel} dp_T^2} = \frac{1}{\pi} \frac{d^2\sigma}{dy dp_T^2} = g(E_T) f(y) e^{-2.5 p_T / \sqrt{s}} \quad (1)$$

where we have included a factor $e^{-2.5 p_T / \sqrt{s}}$ to obtain the $\sqrt{s}$ dependence observed for the large p_T pion data. We choose to use as the second variable the centre-of-mass rapidity:

$$y = \frac{1}{2} \ln \left(\frac{E + p_{\parallel}}{E - p_{\parallel}} \right)$$

instead of $x_{\parallel}$, because the pion, kaon, and even antiproton data⁹⁾ show that the cross-sections factorize better with y . The shape of $d\sigma/dy$ deduced from the ISR data^{8,9)} which we have used for the vector mesons is represented in Fig. 2b. It is important to note that, for the extrapolation we wish to perform, the detailed shape of the y distribution is not very relevant. But the ratio between the hatched area which corresponds to the cross-section measured by Knapp et al. and the ordinate at $y = 0$ will determine the absolute normalization of the 90° invariant cross-section.

Initially we parametrize the cross-section at $\sqrt{s} \approx 23$ GeV, where there exist data for π 's, ρ 's and ψ 's.

- i) The 90° pion invariant cross-section is fitted using for $g(E_T)$ the form:

$$g(E_T) = \frac{A}{(E_T + B)^n}.$$

The fit to the π^- data shown in Fig. 3a has been obtained using only the Chicago-Princeton measurements¹⁰⁾ which cover the range $0.76 \text{ GeV}/c < p_T < 6.1 \text{ GeV}/c$. It corresponds to $B = 2.7 \text{ GeV}$ and $n = 16.5$ and is in excellent agreement with the data even in the low p_T region where the British-Scandinavian data⁸⁾ extend down to $p_T = 0.1 \text{ GeV}/c$. There seems to be small systematic disagreements between the two sets of data in the p_T range where they overlap.

- ii) Using the values of B and n determined above and integrating Eq. (1) over y in the range covered by the data of Knapp et al., the dN/dp_T^2 distributions for ρ 's and ψ 's are computed. The experimental resolution is taken into account.

After normalization to the total number of events comparison is made in Figs. 4a and b with the actual ρ^0 and ψ measurements. The excellent agreement indicates the adequacy of a general parametrization in terms of E_T .

iii) A similar comparison can be made for the $x_{\parallel}^{\text{lab}}$ distribution of the ψ 's. Figure 4c shows that the calculated $d\sigma/dx_{\parallel}^{\text{lab}}$ agrees well with the dashed line corresponding to $e^{-10x_{\parallel}^{\text{lab}}}$, the experimental fit of Knapp et al. to their ψ data for $x_{\parallel}^{\text{lab}} > 0.3$.

Since all the computed distributions fit well with the experimental data, we may now determine the ρ and ψ invariant cross-sections at 90° as a function of p_T . The ψ normalization is obtained from the measured product⁷⁾

$$B\sigma(n + \text{Be} \rightarrow \psi + \text{anything}) = 0.5 \times 1.7 \times 10^{-33} \text{ cm}^2/\text{nucleon for } x_{\parallel}^{\text{lab}} > 0.32$$

$$\quad \quad \quad \downarrow$$

$$\quad \quad \quad \mu^+ + \mu^-$$

with $B = 7 \times 10^{-2}$. Obviously the ψ yield includes the contribution due to $\psi'(3.7 \text{ GeV}) \rightarrow \psi + x$. To get the ρ^0 normalization we use the invariant mass distribution of muon pairs given by Knapp et al., taking into account the difference in detection efficiency between the ρ and ψ mass regions because of the limited size of the spectrometer magnet. Since the mass resolution in that experiment does not permit the separation of ρ^0 's from ω^0 's, we have plotted in Fig. 3a the 90° invariant cross-sections of $\frac{1}{2}(\rho^0 + \omega^0)$ and ψ 's. Most theoretical models predict that for large values of $\sqrt{s}$, $\omega^0 \cong \rho^0$. If we adopt that point of view, our extrapolation as drawn in Fig. 3a gives for large p_T :

$$\omega^0 \cong \rho^0 \cong \pi^0,$$

since about 30% of the high p_T pions are due to ρ^0 decays.

An additional experimental check of the validity of our parametrization is given by a recent bubble-chamber experiment which determines the inclusive ρ^0 production in pp interactions at 205 GeV/c¹²⁾. They quote

$$\frac{\rho^0}{\pi^-} = 0.08 \pm 0.02$$

to be compared with a value of 0.06 obtained by integrating Eq. (1) over y and p_T for ρ^0 's and for π^- 's. For the above computations, we have again assumed $\rho^0 = \frac{1}{2}(\omega^0 + \rho^0)$.

A striking point in the dimuon mass distribution of Knapp et al. is the absence of a clear ϕ^0 signal. But assuming that at high p_T the ratio ϕ^0/π^- is smaller than 10%, as indicated by the Columbia-Fermilab measurement⁴⁾ and $\rho^0 \cong \pi^0$, then the ϕ meson leptonic decays produce a peak < 13% of the height of the $(\rho^0 + \omega^0)$ peak in the dimuon spectrum. This is a consequence of the mass dependence of the p_T distributions and a signal of that magnitude is just excluded by the data as indicated in Fig. 1.

3. CONTRIBUTIONS TO SINGLE LEPTON SPECTRA

Using the cross-section parametrization over the entire (p_T, y) phase space for ψ , ρ^0 , and ω^0 , we have computed their contributions to the 90° single lepton spectra. The results for $\sqrt{s} = 23.8$ are shown in the lower half of Fig. 3b together with experimental data. Although the separate contributions of $(\rho^0 + \omega^0)$'s and of ψ 's vary with p_T , their sum represents a rather stable percentage of the single lepton spectrum amounting to about 30% *).

We may be more speculative and consider the contribution of the $\mu^+\mu^-$ continuum from the experiment of Knapp et al. to the single lepton spectrum. A large fraction of the low mass part of that continuum is produced by Bethe-Heitler conversion in the beam dump. Therefore, we have computed the contribution corresponding to the mass spectrum drawn in Fig. 1 together with the data and which includes about $1/3$ of the low mass peak. We assume that the dependence given by Eq. (1) is valid for the continuum and we take into account the variation of detection efficiency with the dimuon mass. The contributions of any dimuon decay of other particles like ρ' , ϕ^0 , ..., are obviously included in the continuum. The corresponding contribution to the single lepton spectrum is given by the dashed curve of Fig. 3b and it amounts to about 15% of the total. This is most likely an overestimate, since the experimental $\mu^+\mu^-$ spectrum probably includes some background. Including more of the low mass μ pairs of Knapp et al. in the continuum induces negligible variation of the single lepton yield for $p_T > 1.5$ GeV/c.

The various contributions to single lepton spectra are summarized in Table 1 for $p_T \sim 2.5$ GeV/c and $\sqrt{s} = 23.8$. It indicates that at most 55% of the observed yield can be attributed to decays of known particles or to the dilepton continuum.

We can also compare our model with the electron measurement of the CCRS group³⁾ at $\sqrt{s} = 52.7$. The $\sqrt{s}$ dependence that we have included in Eq. (1) is valid for large p_T . Pion data show that such a dependence sets in at $p_T \sim 1$ GeV/c. For lower transverse momenta the slope is independent of $\sqrt{s}$. Since the pion data are well fitted over the entire p_T range with our formula for $\sqrt{s} = 23.8$, we modify the exponential term as follows

$$\begin{aligned} e^{-2.5p_T/23.8} &= e^{-1.05p_T} & \text{for } p_T \lesssim 1 \text{ GeV/c} \\ e^{-2.5p_T/\sqrt{s}} & & \text{for } p_T \gtrsim 1 \text{ GeV/c} \end{aligned}$$

with a smooth transition around 1 GeV/c. With this modification, all the other parameters being kept identical for the two values of $\sqrt{s}$, we get for $\sqrt{s} = 52.7$ the correct normalization for pions at $p_T = 0$ and the ψ and $(\rho^0 + \omega^0)$ cross-sections are 20% larger than the unmodified Eq. (1) would give. The contributions to the single lepton spectrum from the ψ , ρ^0 's, and ω^0 's are drawn in the upper part of

*) Decay angular distributions of the form $1 + \cos^2 \theta$ have been used. With isotropic decay the 90° lepton yield changes by less than 10%.

Fig. 3b together with the CCRS data. In addition to the single electrons, 9 dilepton events interpreted as $\psi \rightarrow e^+ + e^-$ have been observed in this experiment¹³⁾ at low y ($|y|/y_{\max} \lesssim 0.1$). They quote:

$$B_{ee} \frac{d\sigma}{dy} (p + p \rightarrow \psi + \text{anything}) = (7.5 \pm 2.5) \times 10^{-33} \text{ cm}^2,$$

and a contribution from ψ to the single electron spectrum between 10 and 20% of the observed yield. The procedure described above using our model gives, $B d\sigma/dy = 5 \times 10^{-33} \text{ cm}^2$ and a ψ contribution of 15% at $p_T \approx 2.5 \text{ GeV}/c$. Computing the total inclusive cross-section for ψ production in pp collisions, we find:

$$\begin{aligned} \sigma_{\text{tot}} &= 7 \times 10^{-32} \text{ cm}^2 \text{ at } \sqrt{s} = 23.8 \text{ GeV} \\ \sigma_{\text{tot}} &= 21 \times 10^{-32} \text{ cm}^2 \text{ at } \sqrt{s} = 52.7 \text{ GeV} . \end{aligned}$$

4. CONCLUSIONS

In the process of trying to relate single lepton and dilepton data we have developed a phenomenological model which describes the production of pions, ψ , and vector mesons over the entire p_T range with a simple parametrization of the invariant cross-section:

$$E \frac{d^3\sigma}{d^3\vec{p}} = \frac{A}{(E_T + 2.7)^{16.5}} f(y) e^{-2.5 p_T / \sqrt{s}} .$$

$f(y)$ is a single function of the c.m. rapidity. The normalization constant A varies with the type of particle. To evaluate the dilepton contribution to the 90° lepton spectra, the choice of the relative strength of $f(0)$, with respect to the integral of $f(y)$ for $|y|/y_{\max} > 0.4$, plays a crucial role. The universal shape for $f(y)$ has been taken from the ISR pion data. There are two limited checks of the correctness of our choice. For the ρ^0 we get a good agreement with the measured ratio of inclusive cross-section $\rho^0/\pi^- = 0.08 \pm 0.02$. In the ψ case our model agrees with the CCRS results at $\sqrt{s} = 52.7 \text{ GeV}$. The p_T and E_T dependence have been checked against the π^- , ρ^0 , and ψ experimental distributions. As a result of the extrapolation of the inclusive cross-sections we get that at high p_T our model is consistent with:

$$\rho^0 = \omega^0 = \pi^0 .$$

As indicated in Table 1, for $\sqrt{s} = 23.8 \text{ GeV}$ at most 55% (40% for $\sqrt{s} = 52.7 \text{ GeV}$) of the single leptons can be explained by extrapolating the dilepton data (particles and continuum) and by taking into account kaon and hyperon leptonic decays.

The p_T dependences of the lepton spectra vary with the mass of the parent (see Fig. 3b), and the combination $(\rho^0 + \omega^0 + \psi)$ gives a smooth contribution to the lepton spectrum in particular with no shoulder around $p_T = M_\psi/2$. In addition,

this contribution as well as the more speculative continuum contribution is parallel to the experimental spectrum. Since our extrapolation could presumably be wrong by a factor ~ 2 , it is rather tempting to increase the contributions of ρ^0 , ω^0 , ψ , and of the continuum by a factor 2 to 3 which would be sufficient to explain the single lepton signal. However, in addition to difficult disagreements with some experimental results, one would have $\rho^0 = \omega^0 = (3 \text{ to } 6) \times \pi^0$ at high transverse momentum since in that case most of the observed pions would be due to $\rho^0_{\pm}$ decays.

Our analysis has dealt only with the contributions to single leptons from pairs of charged leptons and from leptonic decays of kaons and hyperons. One may hope that decays of states to be discovered, involving lepton and neutrino, will extinguish the single lepton deficit.

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- 13) F.W. Büsser et al., Phys. Letters 56B, 482 (1975).

Table 1

Contributions to the single lepton spectrum at $\sqrt{s} \approx 23.8$ GeV
in percentage of the observed signal

Hyperons and kaons	$\leq 10\%$	} at $p_T = 2.5$ GeV/c
ψ	19%	
$\rho^0 + \omega^0$	10%	
Lepton pair continuum	16%	

Figure captions

- Fig. 1 : Muon pair mass spectrum obtained in $n + Be$ interactions at $\sqrt{s} \approx 20$ GeV by Knapp et al. The full curve drawn is used in the computation of the continuum contribution to the single lepton spectrum. The dashed curve is the expected contribution from ϕ^0 if $\phi^0/\pi^- = 10\%$ at high p_T .
- Fig. 2a) : Regions of experimental measurements in the $(x_T = 2p_T/\sqrt{s}, x)$ plane.
- b) : $1/y_{\max} \times d\sigma/dy$ as a function of $|y|/y_{\max}$ for $p_T \approx 0$. $f(y)$ is proportional to $(d\sigma/dy)_{p_T=0}$ and $y_{\max}$ is the maximum value of $|y|$. For $p_T = 0$, $y_{\max} \approx \log(\sqrt{s}/m)$.
- Fig. 3a) : Invariant cross-sections at 90° in the c.m. system for π^- , $1/2(\rho^0 + \omega^0)$ and ψ in proton-nucleon collision at $\sqrt{s} \approx 23.8$ GeV. Squares are data points from the British-Scandinavian Collaboration⁸⁾, black dots from the Chicago-Princeton group¹⁰⁾.
- b) : Electron and muon data at $\sqrt{s} = 23.8$ GeV and $\sqrt{s} = 52.7$ GeV compared to the invariant cross-sections expected from ψ , ρ^0 , and ω^0 contributions with the production cross-sections given in Fig. 3a. The dashed curve corresponds to an estimate of the contribution of the muon pair continuum measured in the experiment of Knapp et al. Data points from Chicago-Princeton¹⁾ (●); Columbia-Fermilab²⁾ (Δ); CCRS group³⁾ (+).
- Fig. 4a) : dN/dp_T^2 distributions for ρ^0 's.
- b) : dN/dp_T^2 distributions for ψ 's. The data of Knapp et al. are compared to the curves predicted by the model.
- c) : $d\sigma/dx_{\parallel}^{\text{lab}}$ distribution for ψ 's. The full curve is computed using Eq. (1). The dashed line is the experimental fit of Knapp et al. for $x_{\parallel}^{\text{lab}} > 0.3$.

1941-1942

The first of the series of reports on the progress of the work of the Committee on the Organization of the United Nations, was presented to the General Assembly on 14 December 1941. It was the first of a series of reports which were presented to the General Assembly on the progress of the work of the Committee on the Organization of the United Nations, from 1941 to 1942.

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Fig. 10

Fig. 2 (GeV/c, 0.02 GeV)

Fig. 3

Fig. 4