ERRATUM

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SLAC Report No. 198, "Proceedings of Summer Institute on Particle Physics, pages 220 and 222.

Please note that Figures 16 and 17 have been interchanged in the papers referenced above. The correct figures, with their appropriate captions, are included here.

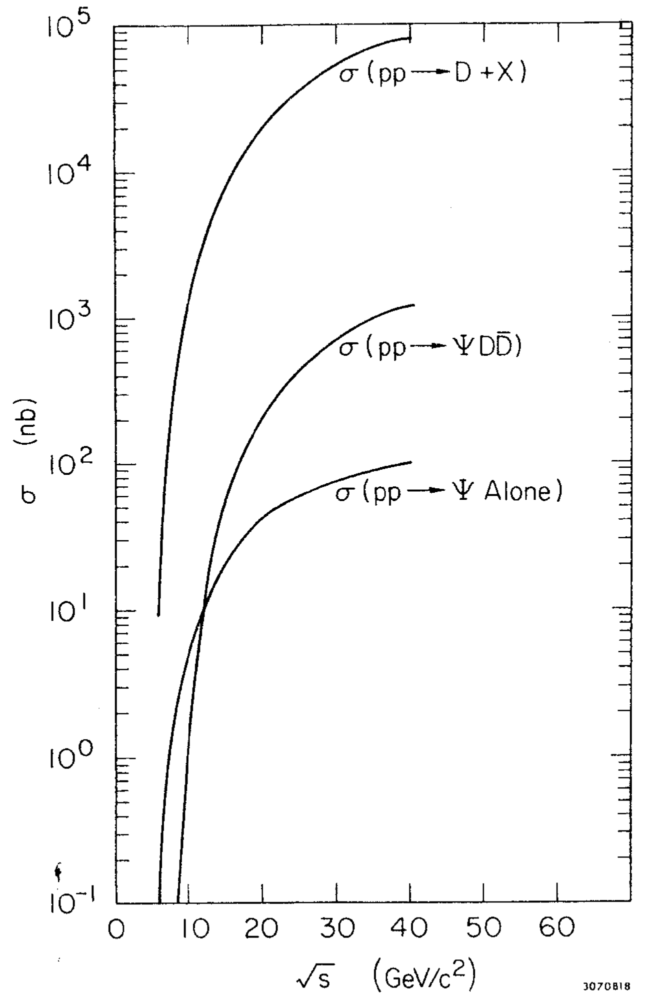

Fig. 16--Predictions of the quark fusion model of Sivers (Ref. 54) for the s-dependence of production by protons of the ψ/J alone, ψ/J in conjunction with charmed particles, and charmed particle pairs.

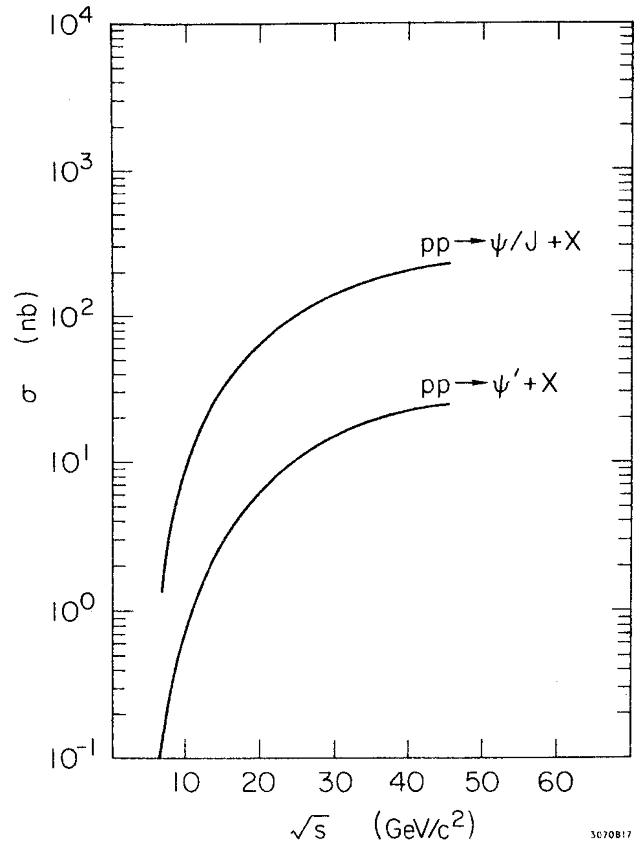

Fig. 17--Predictions of the gluon production mechanism for ψ/J of Carlson and Suaya (Ref. 65) for the s-dependence of production by protons of the ψ/J and ψ'.

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NEW PARTICLE PRODUCTION*

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INTRODUCTION

These lectures deal with several specific topics in the area of new particle production. First, there is charmed particle production in e^+e^- annihilation. Next, photoproduction of ψ and ψ' and implications of these results for the photoproduction of charmed particles are discussed. Hadronic production of ψ and ψ' is then reviewed and again implications of these results for charmed particle production by hadrons are dealt with. Experimental evidence for the operation of the OZI rule in hadronic interactions is then reviewed. The final topic is a discussion of direct lepton production by hadrons and the relevance of this phenomenon to charmed particle production. Frequent reference will be made to results quoted by Jackson in his lectures at the Summer School portion of the Institute, and to material presented by Goldhaber, Glashow, Lederman, Lee, D. Meyer, H. Meyer, Schmüser, and Smith in the Topical Conference.

I. CHARMED PARTICLE PRODUCTION IN e^+e^- ANNIHILATION

While neutrino interactions had yielded several interesting indications of new phenomena which could most readily be explained by the introduction of a new hadronic quantum number,[1] and, indeed, a specific example of a $\Delta S = -\Delta Q$ reaction in the BNL 7-foot bubble chamber,[2] the most striking evidence for the existence of charm has appeared in e^+e^- annihilation.[3,4] The dramatic increase in R in the 4 GeV region[5] had been taken by many to be charm threshold, but characteristic features expected to be associated with the threshold, such as an increase in kaon production,[6] had not, and have not, as of this writing, been seen. Since a large body of data of the SLAC/LBL collaboration existed at 4.8 GeV, these data were examined[7] for narrow mass peaks in the $K^{\pm}\pi^{\mp}$, $K_S^0\pi^+\pi^-$,

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$\pi^+\pi^-$, K^+K^-, $K^\mp\pi^\pm\pi^\pm$, $K_S^0\pi^+$, and $\pi^+\pi^-\pi^\pm$ channels. π,K separation by time-of-flight was not attempted, on the grounds that the K momentum would on average be too high. In this search no significant enhancements were seen, and limits on charmed meson production × branching ratio in the range of a few tenths of a nanobarn were derived. These limits were close to the expected range, but did not exceed them.[8]

The use of time-of-flight information by the SLAC/LBL collaboration to obtain π,K separation in the 4 GeV region improved the signal to noise ratio sufficiently to show the existence of significant mass peaks, first in $K^\pm\pi$ and $K^\pm\pi^\mp\pi^+\pi^-$,[3] and soon thereafter in $K^+\pi\pi$.[4] We will review the features of these decays which lead to the assertion that they are examples of charmed meson decays, will discuss the production mechanism, and will then look at some future experimental prospects. There is a rich spectroscopy of new hadronic states to fill in, and a completely new term in the weak current to understand.

For our purposes, "charm" refers specifically to a new quantum number carried by a fourth quark which has those attributes necessary to implement the GIM mechanism[9] in, for example, the suppression of $K_L^0 \to \mu^+\mu^-$ decay. Other schemes, involving more than four quarks, such as those of Harari,[10] will be dealt with, if at all, only in passing.

Figure 1 shows the behavior of the ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ in the SPEAR/DORIS energy region.[5] The "step" in R, amounting to about two units, is clearly evident in the 4 GeV region. The explanation for the step in the charm scheme is that one has reached charm threshold. The structure at 4.03 GeV appears to be the best place to study charmed meson decays, as the region between phase space suppression on the one hand, and form factor suppression on the other, is relatively small.

Facts are accumulating rapidly, but let us summarize what is

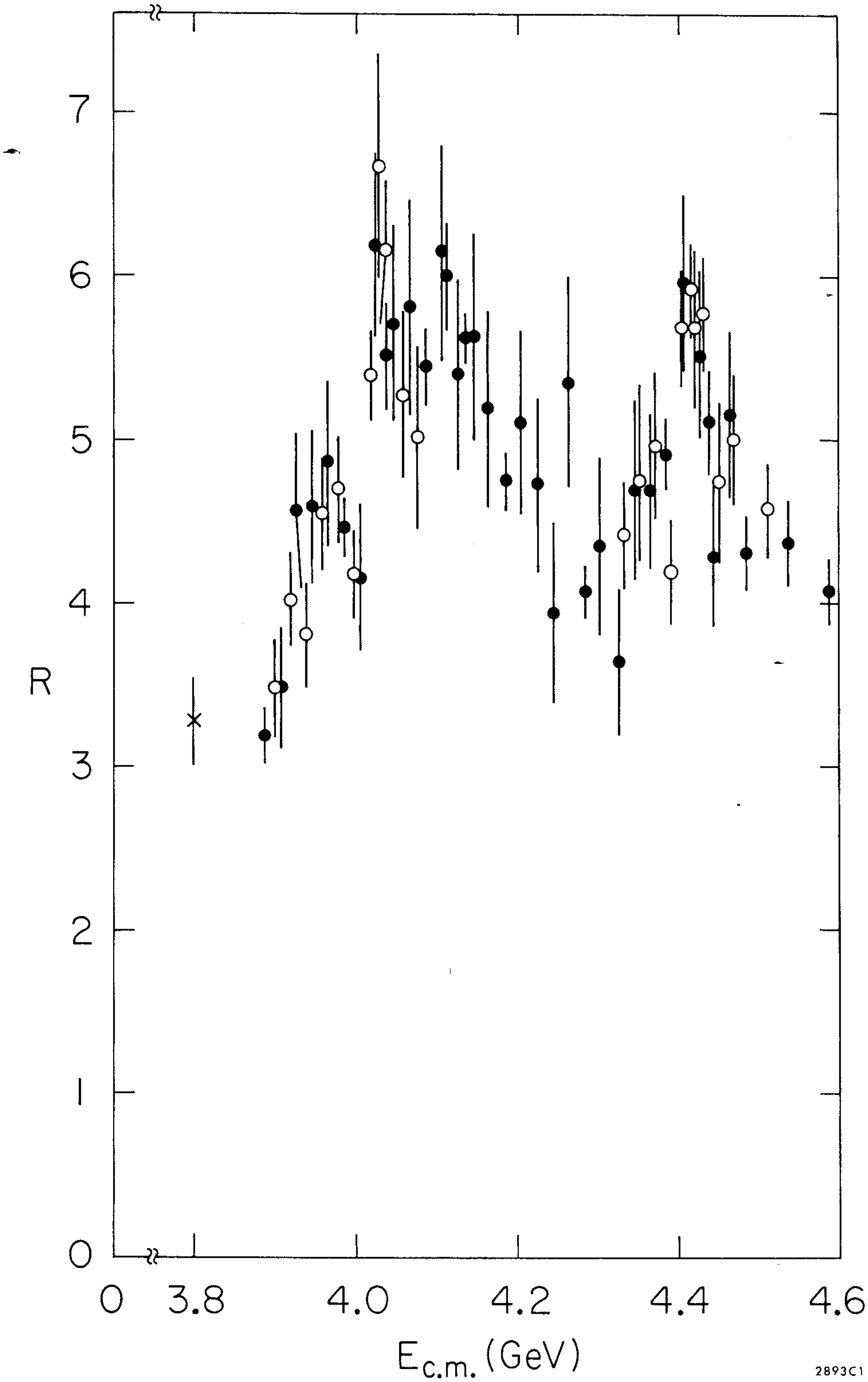


Fig. 1--Structure in $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ observed in the $\sqrt{s} = 4$ GeV region. (Ref. 5.)

experimentally established as of this writing. There is clear evidence for a D^o at a mass of 1865 ± 15 MeV and a D^+ at a mass of 1876 ± 15 MeV. The recoil spectra against these peaks indicates a D^{*o} and a D^{*+}, both with masses of about 2005 MeV. The D^o decays to $K^-\pi^+$ and $K^-\pi^+\pi^+\pi^-$, while the D^+ decays to $K^-\pi^+\pi^+$. Each of these branching ratios amounts to a few percent. Both D's are rather narrow. The decay modes seen thus far are presumably the Cabibbo favored ones; Cabibbo suppressed modes, such as $D^o \to \pi^+\pi^-$ have not been seen. The most likely spin assignment would be zero for the D's, one for the D*'s (see, however, Borchardt and Mathur[11]), but this has not been definitely established. No evidence for F production has yet been obtained.

The states to be expected in the charm scheme and the question of enhanced nonleptonic decays due to <u>20</u> dominance have been discussed in Jackson's lectures. Let us, therefore, discuss several other topics not touched upon there.

1. <u>D, D* Production Ratios</u>. Lane and Eichten[12] and De Rújula, Georgi, and Glashow[13] have shown that in a D production model in which a $c\bar{c}$ quark pair are made in e^+e^- annihilation and then mesons are formed by combining with light quarks from the vacuum with ℓs coupling results in a production ratio, just by counting spins, of $D\bar{D}:D\bar{D}^* + \bar{D}D^*:D^*\bar{D}^*$ of 1:4:7 close to threshold. These ratios may be modified by momentum dependent factors due to effects of the confining potential. Close[14] has shown, using a helicity formalism, that the 1:4:7 ratio is true only if all helicity amplitudes are equal and if one integrates over the polar angle, θ. For devices with particular acceptance, the detected production ratio may differ considerably from 1:4:7. One conclusion which remains unaltered, however, is that D* production in e^+e^- is greater than D production by a factor of 3 or so.

2. <u>Electromagnetic Mass Splittings</u>. The $D^+ - D^o$ and $D^{*+} - D^{*o}$ electromagnetic mass splittings have dramatic effects on the branching ratios of their

decay modes. There have been several calculations of these mass splittings, with predictions ranging from less than 5 to 15 MeV.

The first, and largest, estimate was made by De Rujula, Georgi, and Glashow.[13] Using their nonrelativistic bound state model (see Jackson, these proceedings), they assumed that the Coulomb part of the mass splittings between meson isodoublets was proportional to the product of the quark charges: $\delta \propto q_i q_j = 3{:}2{:}4$ for $\pi^+ - \pi^0 : K^+ - K^0 : D^+ - D^0$. Fitting the π^+-π^0 mass difference implies $\langle \frac{1}{r} \rangle = 1230$ MeV, which they use for all other pairs. It should be noted that this value is much larger than the 410 MeV derived by Schnitzer[15] from charmonium spectroscopy. The non-Coulomb part of the splitting, due to the u-d quark mass difference, is derived by fitting to the K^+-K^0 splitting. Summing these two contributions, DGG find 13 MeV for the D^+-D^0 splitting; they use 15 MeV in their branching ratio calculation.

This calculation has been criticized by several authors. Lane and Weinberg[16] question the applicability of the nonrelativistic atomic model to pions. They use instead Dashen's theorem, which says that the Coulomb contribution to the differences in the mass-squared is the same for K's and π's. After removing the Coulomb contribution to the quark mass difference, they calculate $\langle \frac{1}{r} \rangle = 350$ MeV, leading to a D^+-D^0 splitting of 6.7 MeV, which includes a 10% correction to $\langle \frac{1}{r} \rangle$ for heavy mesons. A similar analysis by Fritzsch[17] derives a similar result.

Celmaster,[18] using a perturbed harmonic potential, finds $M_{D^+} - M_{D^0} <$ 4 MeV. Sanchez Guillen,[19] using a fully relativistic model, finds 3 MeV. The (unweighted) Harvard average is 7 MeV. The D^{*+}-D^{*0} splittings should be comparable.

Because of the very small Q value of $D^* \to D\pi$ decay, relative branching ratios are very sensitive to these mass splittings. For example, with their

15 MeV estimate and with $M_{D^o} = 1.86$ and $M_{D^{*o}} = 2.00$, DGG calculate the branching ratio $D^{*+} \to D^o\pi^+$ to be $\geq 90\%$ of the total width of .5 - 1 MeV, whereas $D^{*+} \to D^+\pi^o$ is $\leq 10\%$ and $D^{*+} \to D^+\gamma \simeq 1\%$. However, if $M_{D^+} - M_{D^o} = 7$ MeV and $M_{\pi^+} - M_{\pi^o} = 4.6$ MeV, the very small Q values involved can change these branching ratios dramatically. Calculations of Ono,[20] shown in Fig. 2, indicate that the relative rates $D^{*+} \to D^+\pi^o$ and $D^o\pi^+$ can vary over several orders of magnitude as the isodoublet mass splitting gets very small. While the recoil spectra seen in the 4 GeV region[21] are in qualitative agreement with the initial predictions of DGG, there are discrepancies in detail, at least some of which are due to this extreme sensitivity to the mass splittings.

3. Recoil Spectra. The spectrum of masses recoiling against a reconstructed D in e^+e^- annihilation is a rich area for studying the production mechanism and for determining the mass of higher D states.[22] These missing mass spectra contain real mass peaks corresponding to the D* mass (or any other meson made in conjunction with a D), and particularly near threshold, kinematic reflections which are artifacts of the details of production and decay. Fig. 3 summarizes the source of real and reflection peaks in the spectrum recoiling against D^o, D^+, and F^+ mesons.[23]

The details of the recoil spectra depend on several factors. First, there is the $D\bar{D}:D\bar{D}^* + \bar{D}D^*:D^*\bar{D}^*$ production ratio, which may depend on the polar angle θ, and thus will be seen differently in different detectors. Then there is an s dependence, due to production threshold effects and form factors. Finally, the relative magnitude of real and reflection peaks depends on the various $D^* \to D$ branching ratios, which are a sensitive function of the D^+-D^o mass splitting.

4. Exotics. A most important piece of evidence supporting the charm interpretation of the 1876 MeV structure seen at SPEAR[4] has been that the peak was found in the exotic channel $K^\mp\pi^\pm\pi^\pm$ and not in $K^\pm\pi^\pm\pi^\mp$ or in doubly charged

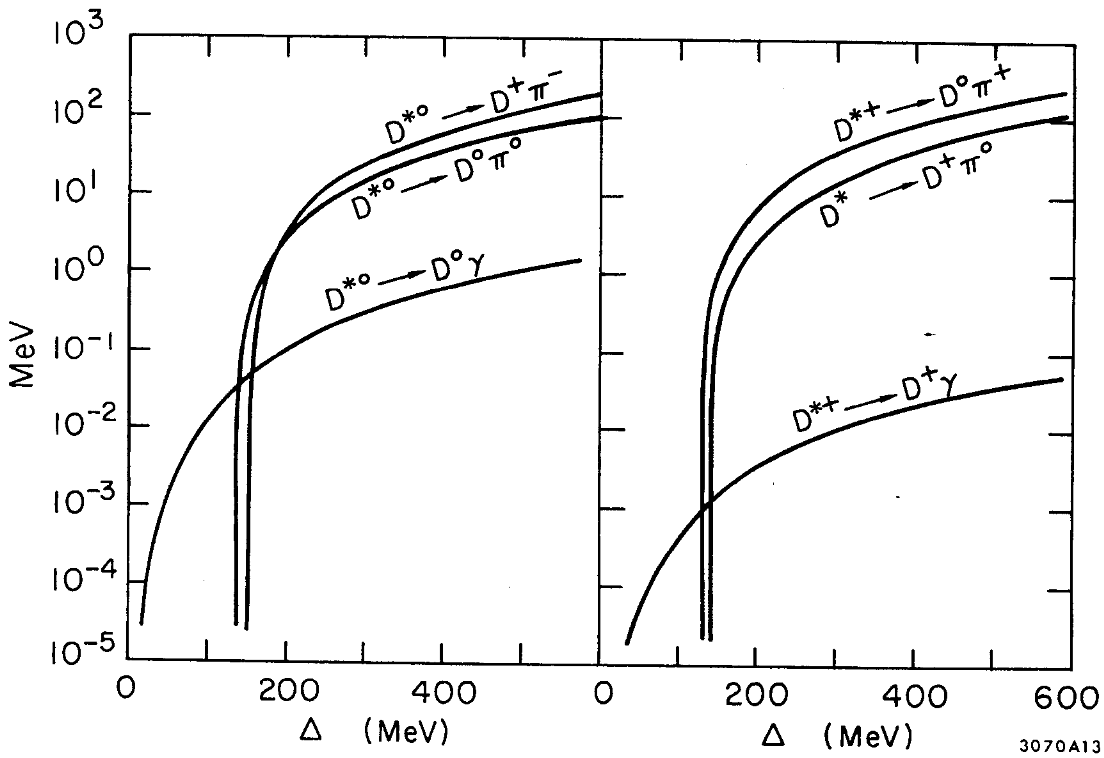


Fig. 2--Dependence of $D^* \to \gamma D$ and $D^* \to \pi D$ decay rates on $\Delta \equiv D^{*0} - D^0$. (Ref. 20.)

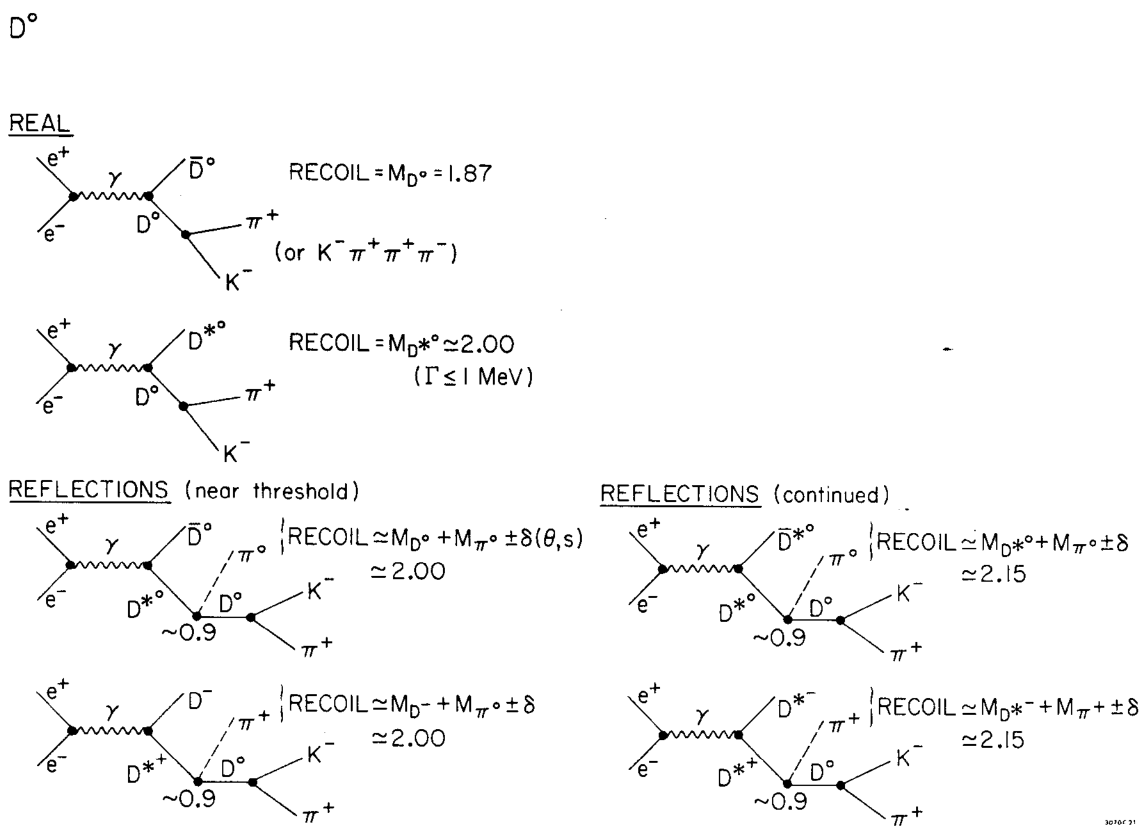


Fig. 3a--Genuine and kinematic reflection peaks expected in D^0 recoil spectra near threshold. (Ref. 23.)

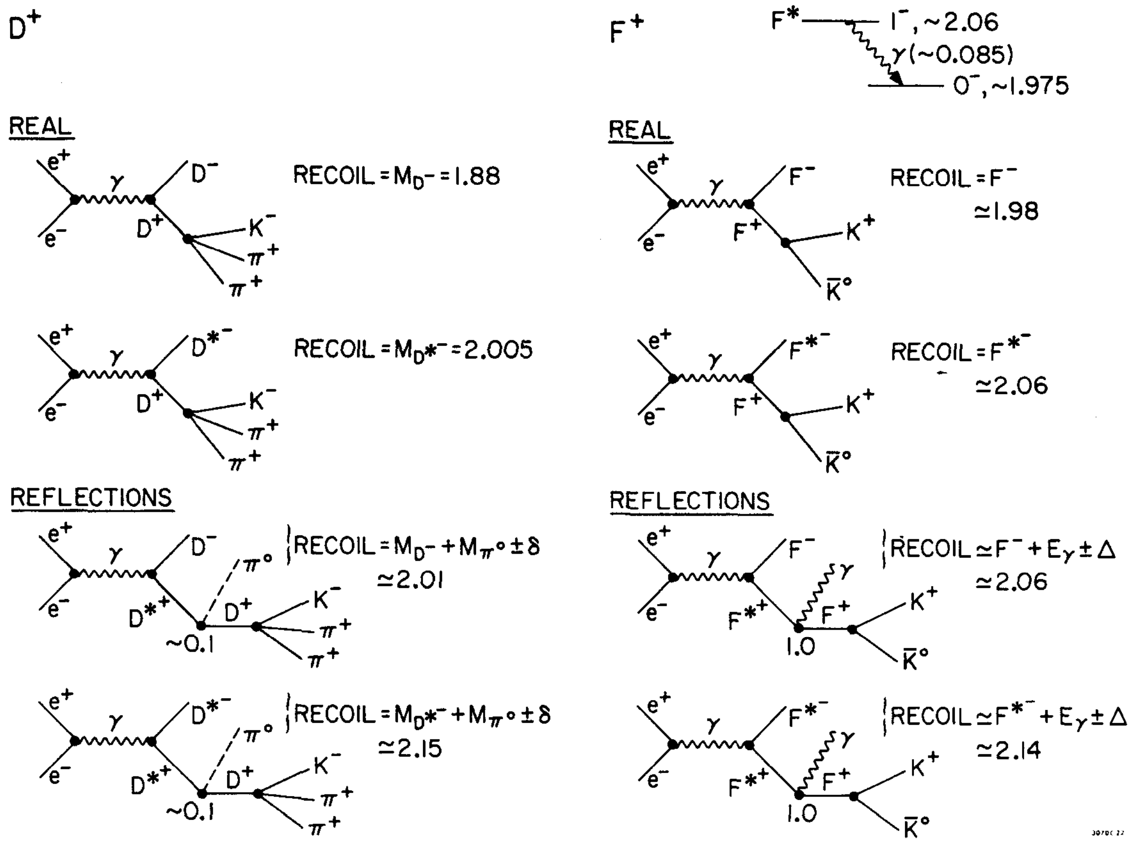


Fig. 3b--Genuine and kinematic reflection peaks expected in D^+ and F^+ recoil spectra near threshold.

modes like $K^{\mp}\pi^{\mp}$, $K^{\mp}\pi^{\mp}\pi^{+}\pi^{-}$, or $K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\pm}$. Since the $\cos\theta_c$ decay of a charmed quark is $c \to s u\bar{d}$, it is expected in the charm scheme that $D^{+}(c\bar{d}) \to K^{-}(s\bar{u})$ and not to $K^{+}(u\bar{s})$. If the new state were a high mass K^*, the existence of the $K\pi\pi$ mode requires $I = 3/2$ or $5/2$. No strange meson with $I > \frac{1}{2}$ has hitherto been observed, and further, the expected doubly charged modes are not seen.

The Λ_c interpretation[24] of the $\bar{\Lambda}\pi^{-}\pi^{-}\pi^{+}$ enhancement seen by the CIHF group[25] is similarly strengthened by the absence of $\bar{\Lambda}\pi^{+}\pi^{+}\pi^{-}$.

5. Parity Violation. There are several rather direct tests of the existence of parity violation in D decay, some of which have already been experimentally verified.

If the $K^{\pm}\pi^{\mp}$ and $K^{\pm}\pi^{\mp}\pi^{\mp}$ mass peaks belong to the same J=0 isomultiplet, then parity is violated since $P\left[(K\pi)_{J=0}\right] = +$, $P\left[(K\pi\pi)_{J=0}\right] = -$. The J^P of the $K\pi$ system is 0^+, 1^-, 2^+, etc., but for $K\pi\pi$ it may be natural or unnatural. For the natural sequence, the $K\pi\pi$ population on the edge of the Dalitz plot must vanish,[26] or parity is violated. Uniform population of the Dalitz plot has been demonstrated (see Goldhaber, these proceedings).

The observation of both $K^{+}\pi^{-}\pi^{-}$ and $K_S^{0}\pi^{-}$ or $K^{+}\pi^{-}$, $K^{-}\pi^{+}\pi^{+}\pi^{-}$ and $K_S^{0}\pi^{+}\pi^{-}$ is a clear manifestation of parity violation.

Parity violation can also, of course, be demonstrated by the existence of pseudoscalars, such as $\vec{p}_{beam} \cdot (\vec{k}_1 \times \vec{k}_2)(\vec{k}_1 - \vec{k}_2) \cdot \vec{p}_{beam}$ in two particle inclusive reactions (not 0^-) or $\vec{k}_1 \cdot (\vec{k}_2 \times \vec{k}_3)$ in three particle exclusive reactions.[27]

6. D^0-$\bar{D}^0$ Mixing. Since D^0 and $\bar{D}^0$ states can be connected by second order weak transitions, it is amusing to recapitulate the well-known $K^0, \bar{K}^0$ formalism.[28] The eigenstates of the system are

$$|D_1^0\rangle = \frac{1}{\sqrt{2}}(|D^0\rangle + |\bar{D}^0\rangle)$$

$$|D_2^o\rangle = \frac{1}{\sqrt{2}}(|D^o\rangle - |\bar{D}^o\rangle).$$

For a state which is initially pure D^o, we have

$$\frac{\Gamma(D^o \to K^+\pi^-)}{\Gamma(D^o \to K^-\pi^+)} = \tan^4\theta_c ,$$

whereas for a mixed state:

$$\frac{\Gamma(D_1^o \to K^+\pi^-)}{\Gamma(D_1^o \to K^-\pi^+)} = \tan^4\theta_c\left[1 + \frac{m_{D_1} - m_{D_2}}{2\lambda\sin^2\theta_c} + \frac{1}{\gamma}\left(\frac{\lambda_{D_1} - \lambda_{D_2}}{\lambda\sin^2\theta_c}\right)^2 + \frac{1}{2}\left(\frac{m_{D_1} - m_{D_2}}{\lambda\sin^2\theta_c}\right)^2\right].$$

It would appear to be very difficult to observe the consequences of $D^o, \bar{D}^o$ mixing, either in these hadronic decay modes or in semileptonic modes, due to the double Cabibbo suppression.

There are other models, however, in which D^o-$\bar{D}^o$ mixing is expected to be much larger.[29] The crucial test is the comparison of the charges of the K's in a sample of completely reconstructed $D^o\bar{D}^o$ events.

7. Semileptonic Decays. The semileptonic decay rate of $D \to K\ell\nu$ is typically estimated by using SU(4) to determine the matrix element of the vector current and assuming constant form factors,[30] or by scaling from $K \to \pi\ell\nu$. However, since the vector and pseudoscalar masses are not very different, the variation of the f_+ form factor may have a substantial effect on the rate. In the pole approximation for f_+, $f_+(t) = \frac{1}{(1-t/M_{F*}^2)}$ varies substantially in the physical region $m_\ell^2 \leq t \leq (m_D - M_K)^2$; the naive rate estimate should be increased by a factor of 1.5.

The lepton spectra resulting from D decay are of some interest, both because of direct lepton signals seen in e^+e^- annihilation, and because of possible contributions to the direct lepton signal in hadronic collisions. Naively, it would appear that $D \to K\ell\nu$ should be the dominant semileptonic decay mode, but there is some evidence that this may not be the case. Fig. 4 shows the

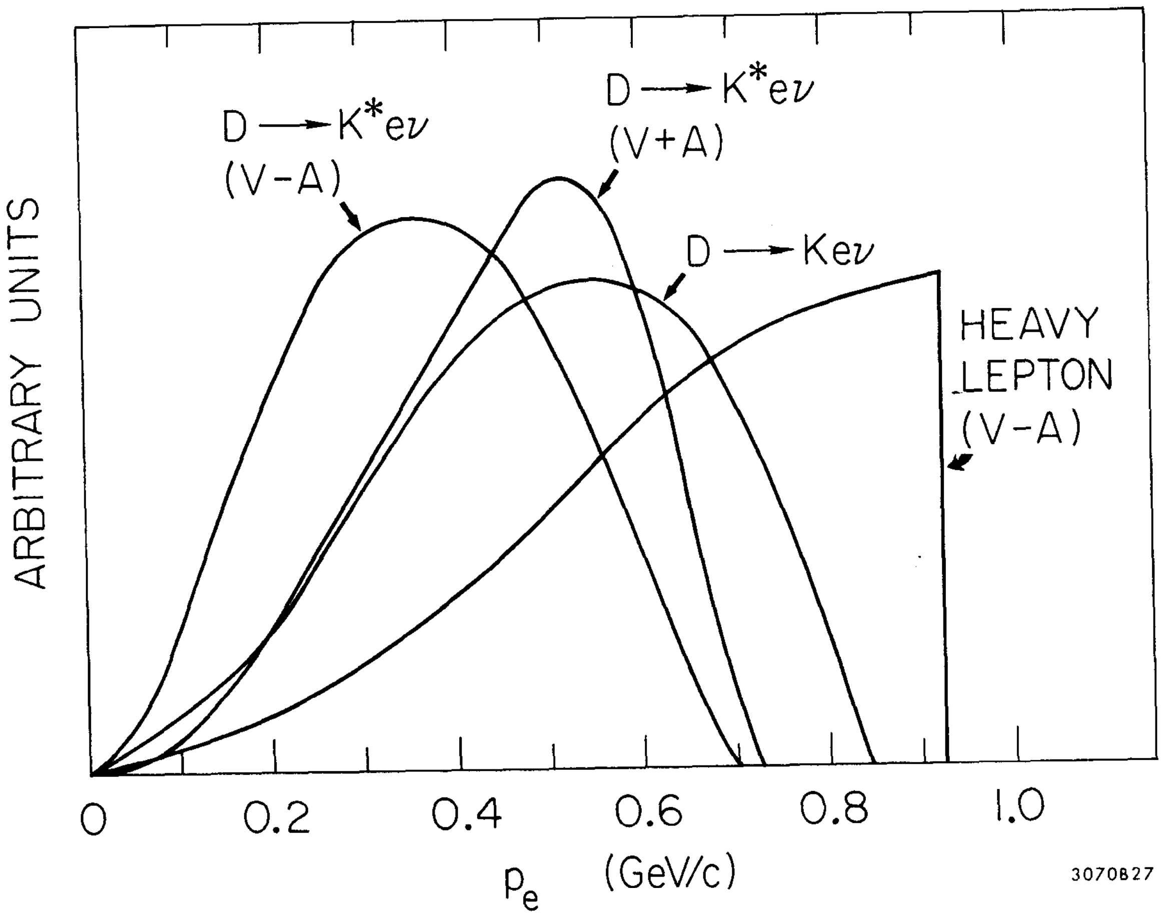


Fig. 4--Electron spectra in the center of mass resulting from D → Keν, D → K*(890)eν for V-A and V+A coupling decays, and from decay of a V-A heavy lepton.

electron spectrum in the D center of mass for $D \rightarrow Ke\nu$ decay with constant form factors. Fig. 5 shows the same spectrum in the laboratory with a $\beta = .3$, a typieal value for D production in the 4 GeV region. The DASP collaboration inclusive e^- spectrum[31] is shown superimposed, and clearly peaks at too low a momentum to be explained by this decay. The PLUTO collaboration has seen the $K_s^o e$ coincidences expected from D decay in the 4 GeV region;[32] their electron spectrum similarly peaks at low values of electron momenta. In order to produce a softer electron spectrum, a natural approach is to consider $D \rightarrow K^*\ell\nu$ or $D \rightarrow K(n\pi)\ell\nu$ decays. There is a great deal of uncertainty in the appropriate values of the four form factors involved in the $K^*\ell\nu$ mode. The matrix element has the general form

$$\langle K^*(q,\epsilon)|(V\mp A)_\lambda|D(p)\rangle = iF_1^V(t)\epsilon_{\lambda\alpha\beta\gamma}p^\alpha q^\beta \epsilon^\gamma \mp \Big(F_1^A(t)\epsilon_\lambda + F_2^A(t)(p\cdot\epsilon)(p+q)_\lambda$$
$$+ F_3^A(t)(p\cdot\epsilon)(p-q)_\lambda\Big) .$$

Just as with the f_- contribution in $K\ell\nu$ decay, the contribution of the F_3^A is proportional to m_e and can be neglected. The F_1^V form factor can be derived from $\Gamma(\omega \rightarrow \pi^o\gamma)$. The other two axial form factors are highly model dependent. Hinchliffe and Llewellyn Smith[33] neglect F_2^A entirely, while Ali and Yang[34] estimate it using a hard pion approach. The center-of-mass electron spectra for $V \mp A$ couplings in $D \rightarrow K^*\ell\nu$ calculated by Ali and Yang are shown in Fig. 4, and the expected spectra in the 4 GeV region in e^+e^- annihilation are compared to the DASP electron spectrum in Fig. 5. An even softer electron spectrum can be generated using $K^*(1420)\ell\nu$ decay.[35] An example is also shown in Figure 5. Uncorrelated $D \rightarrow K\pi\ell\nu$ and $K\pi\pi\ell\nu$ decays, in which the lepton spectra are mainly determined by phase space, also yield such soft e spectra.

Inclusive lepton spectra due to heavy lepton and charm decay can be distinguished by their shape and by the associated hadron multiplicity. For

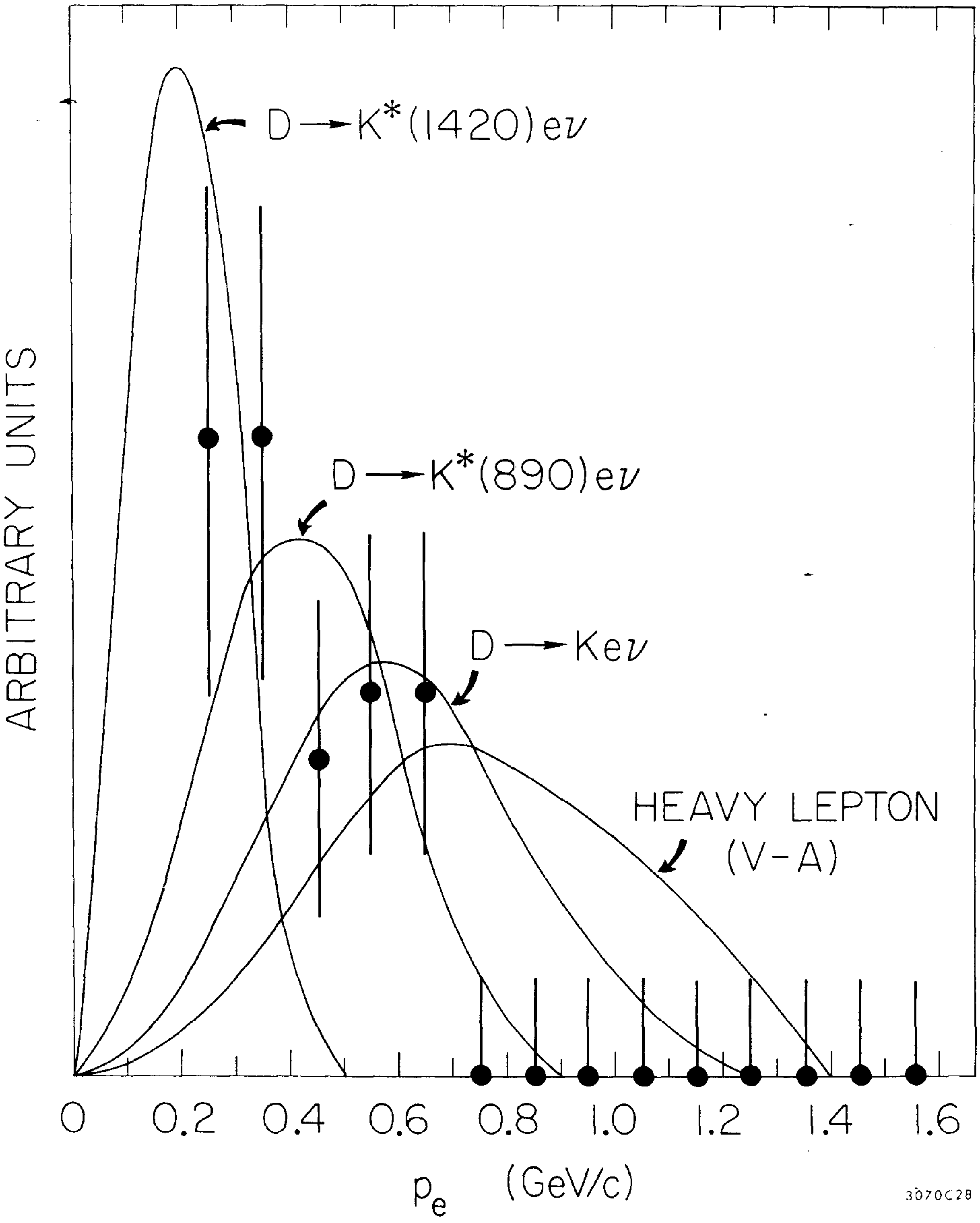


Fig. 5--Electron spectra in the laboratory ($\beta = 0.3$) resulting from $D \rightarrow Ke\nu$, $D \rightarrow K^*(890)e\nu$ (vector coupling), $D \rightarrow K^*(1420)e\nu$, and a V-A heavy lepton. DASP direct electron data shown for comparison (Ref. 31).

comparison V-A heavy lepton electron spectra are also shown in Figures 4 and 5.

The low momentum character of these electron spectra clearly requires the dominance of $K\pi\ell\nu$ (resonant or nonresonant) decay modes over $K\ell\nu$, a surprising result, since soft pion theorems and statistical arguments predict the opposite. A similar conclusion has been reached by Barger[36] in his analysis of ν induced μe events.

In the future, it appears possible to study the details of these weak couplings by a Dalitz plot analysis of the charged lepton-hadron spectra. This should be possible in $D \to K\ell\nu$, $D \to K^*(890)\ell\nu$ and $F \to \eta\ell\nu$ decays. The relative proximity of the higher charmed mesons (F, F*, scalar D) to the physical region for these decays implies substantial variation of the form factors with t. As an example, Fig. 6a shows the Dalitz plot of $D^0 \to K^+e^-\nu$ decay for a vector form factor, f_+, dominated by the F* pole. Fig. 6b shows the sensitivity of a Dalitz plot analysis of this decay to the extraction of the F* mass. The points are the results of a simulation of the decay using an F* mass of 2.1 GeV, for 500 events binned in 100 MeV bins. The curves are the t behavior of the f_+ form factor for several assumed mass values, with $f_+(0) \equiv 1$.

It thus appears to be possible to extract details of the form factors of these decays in much the way K_{ℓ_3} decay has been studied, and to in this way study the breaking of $SU(4) \times SU(4)$ symmetry of the weak hadronic currents.

The semileptonic decays of charmed baryons will also provide information on the structure of the weak current. These decays are likely to have a larger branching ratio than in the strange baryon case,[37] and the details of the spectra are sensitive to the coupling. For example, the mean electron momentum in $\Lambda_c^+ \to \Lambda^0 e^+\nu$ is a sensitive measure of the type of coupling. This can be seen in Fig. 7 from Burwas and Ellis.[38]

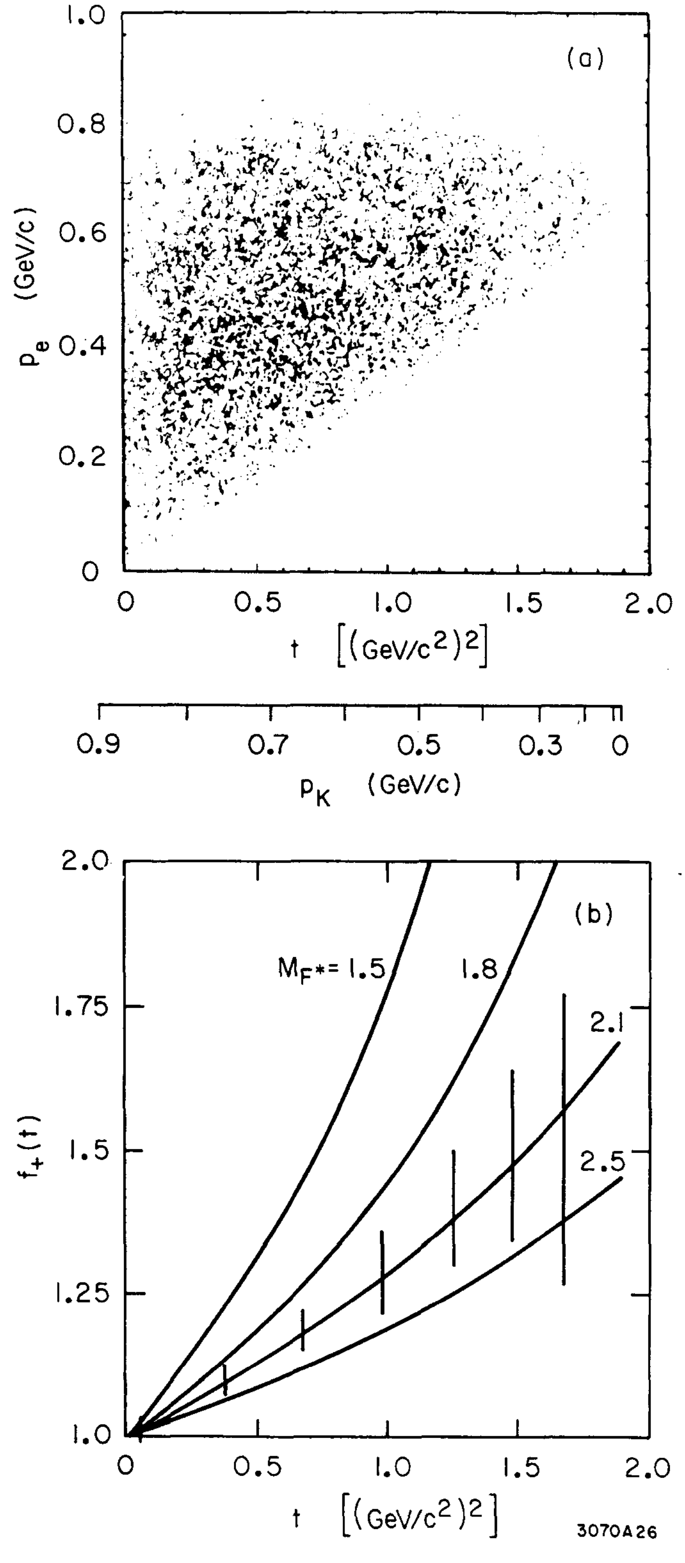


Fig. 6--(a) Dalitz plot for $D^0 \to K^+e^-\nu$ with t-dependence of the vector form factor (f_+) dominated by an F* pole mass of 2.1 GeV. (b) t-dependence of the f_+ form factor for several F* mass values. The "data points" show the sensitivity of a Dalitz plot of 500 events generated by a Monte Carlo calculation for the extraction of the pole mass.

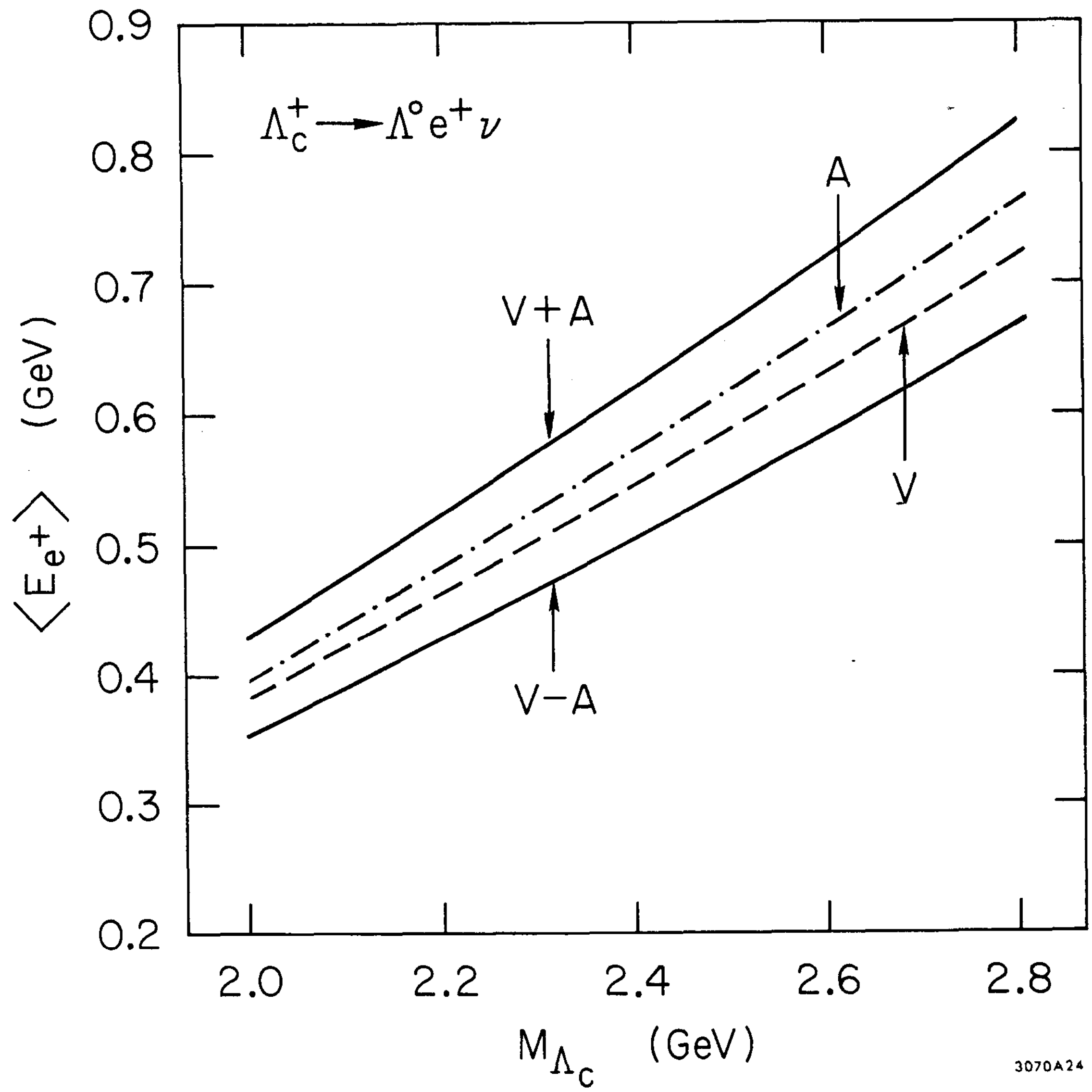
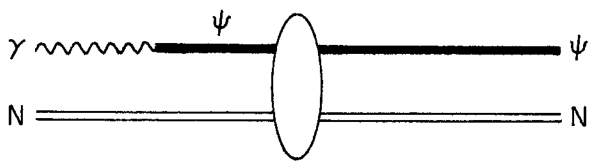


Fig. 7--Dependence of $<E_{e^+}>$ in $C_0^+ \rightarrow \Lambda^o e^+ \nu$ decay on various choices of the form of the decay coupling.

II. PHOTOPRODUCTION OF NEW PARTICLES

Important evidence on the hadronic nature of the ψ comes from photoproduction experiments. These also provide data which can be interpreted to place limits on the photoproduction of charmed particles. There is now data on the s and t dependence of ψ photoproduction from threshold out to 240 GeV.[39]

1. Psi Production. Since the ψ is clearly established as a vector meson,[10] it is natural to adopt the language of vector meson dominance to describe the photoproduction process. Let us follow Sivers, Townsend, and West (SWT),[40] who develop a formalism which explicitly allows for corrections to the VMD model. While the corrections can be calculated,[41] let us see how we can extract them from the experimental data itself. In the vector meson dominance model, ψ photoproduction is a diffractive process related to ψN elastic scattering:



$$\frac{d\sigma}{dt}(\gamma N \to \psi N) = \lambda^2 \frac{3\Gamma_{\psi\to e^+e^-}}{\alpha M_\psi} \frac{d\sigma}{dt}(\psi N \to \psi N) .$$

Here λ is a parameter defined by STW describing the breakdown of VMD:

$$\lambda = \frac{\gamma_\psi(m_\psi^2) A(\psi N \to \psi N)\Big|_{q^2=0}}{\gamma_\psi(0)\, A\, (\psi N \to \psi N)\Big|_{q^2=m_\psi^2}} ,$$

λ clearly being unity in the VMD limit. $\Gamma_{\psi\to e^+e^-}$ is the partial rate of ψ into leptons measured in e^+e^- annihilation: $\Gamma_{\psi\to e^+e^-} = 4.8$ keV. Using the optical theorem, we can relate the differential cross section at t=0 to the total cross section:

$$\left.\frac{d\sigma}{dt}(\psi N \to \psi N)\right|_{t=0} = \frac{\sigma^2_{tot}(\psi N)}{16\pi}(1+\rho^2) ,$$

where ρ = Re A/Im A $\to$ 0 as s $\to \infty$. We can then write the ψN total cross section in terms of measurable quantities:

$$\sigma_{tot}(\psi N) = \frac{1}{\lambda(1+\rho^2)^{\frac{1}{2}}}\left[\frac{\alpha M_\psi}{3\Gamma_{\psi\to e^+e^-}} 16\pi e^{-bt_{min}} \left.\frac{d\sigma}{dt}(\gamma N\to\psi N)\right|_{t_{min}}\right]^{\frac{1}{2}}$$

where

$$\frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_{t=0} e^{-bt} , \quad b = b(s).$$

Figure 8 shows the t dependence at 19 GeV measured by the SLAC-Wisconsin collaboration.[42] $\frac{d\sigma}{dt}$ has now been measured by four groups. Their results are summarized in Fig. 9. Note that $\left.\frac{d\sigma}{dt}\right|_{t=0}$ rises with s to a high energy value of about 40 nb/GeV^2. If we assume that $\rho = 0$ and $\lambda = 1$ at high s, we can conclude that $\sigma_{tot}(\psi N) \simeq 1$ mb. This is certainly large enough to qualify the ψ as a member of the hadron family, but we have yet to ascertain the size of corrections to VMD.

A second experiment by the SLAC-Wisconsin collaboration[43] allows a test of the VMD assumption, by deriving $\sigma_{tot}(\psi N)$ from the A dependence of $\left.\frac{d\sigma}{dt}\right|_{t=0}$ using a procedure which is independent of VMD. We can define an effective A value for a nucleus which takes account of the possibility of multiple scattering within the nuclear volume:

$$A_{eff} = \frac{1}{\sigma_{tot}(\psi N)} \int_0^\infty [1-\exp(-\sigma_{tot}(\psi N)T(r'))]dr' .$$

T(r') depends on the details of the nuclear model chosen, but a simple hard sphere model with radius $R = r_0 A^{1/3}$ suffices. In this model

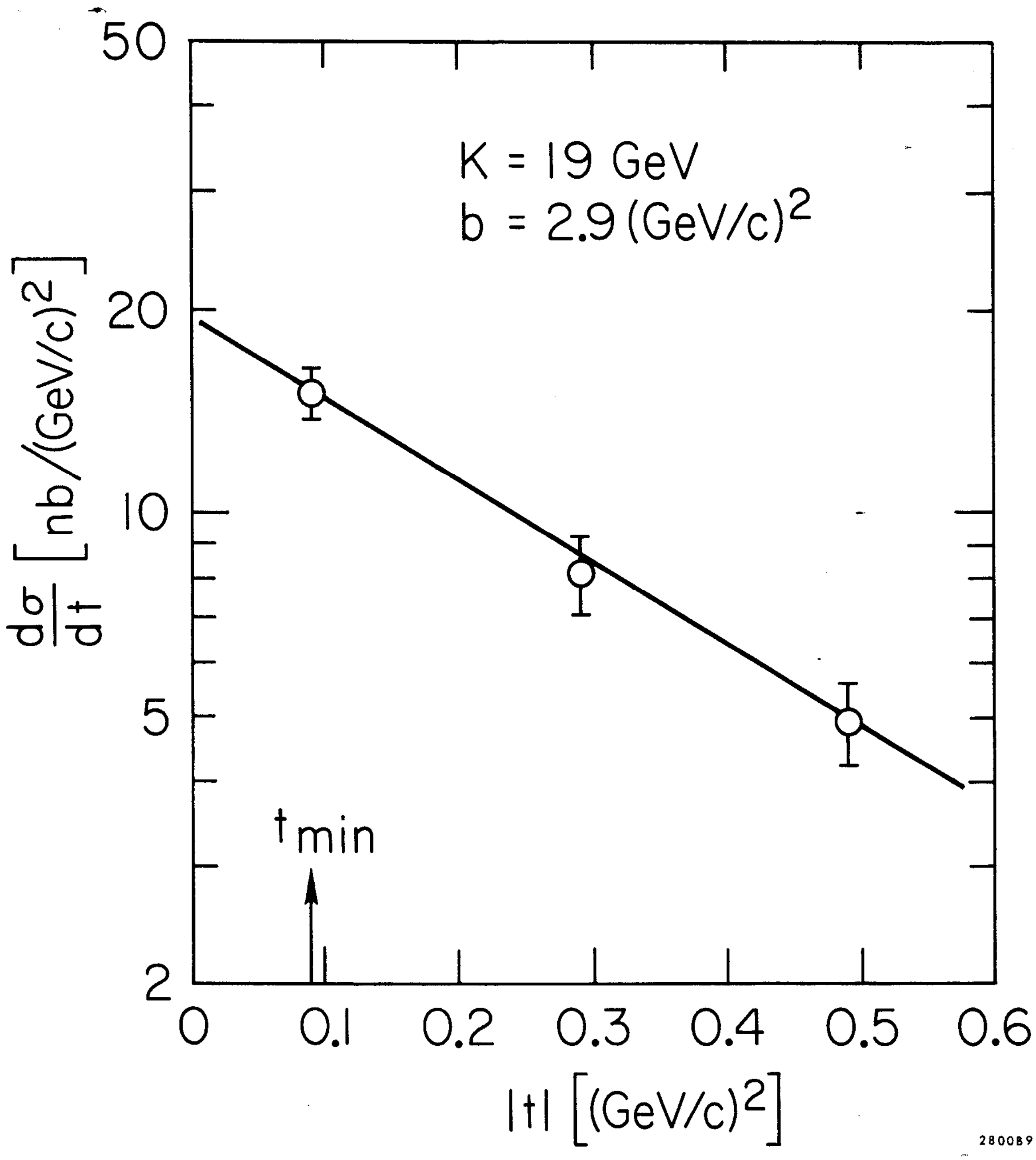


Fig. 8--The t-dependence of the ψ photoproduction cross section (Camerini et al., Ref. 42).

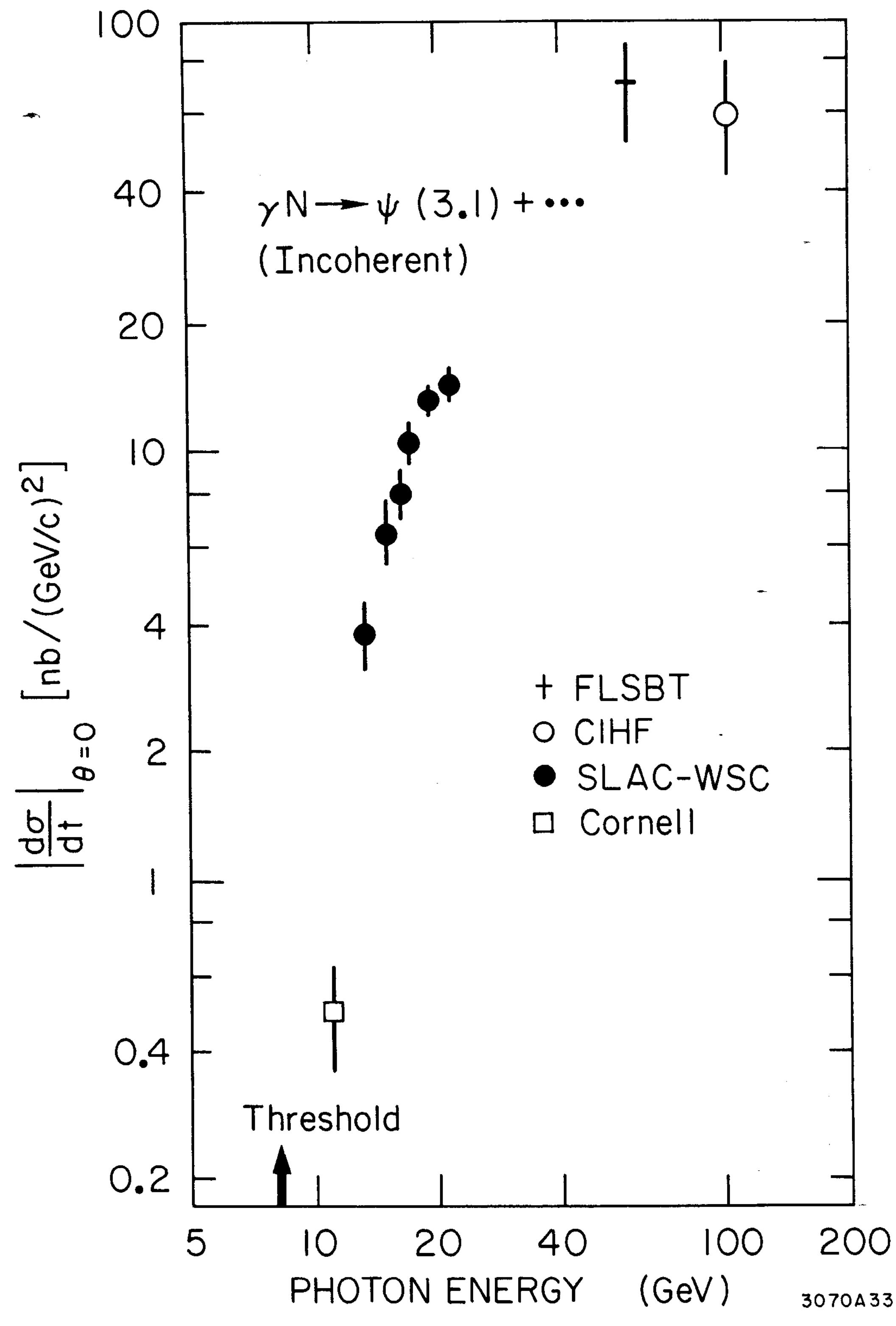


Fig. 9--The s-dependence of $d\sigma/dt$ at $\theta = 0$.

$$T(r') = \frac{3A}{2\pi R^3}(R^2 - r'^2)^{\frac{1}{2}} \qquad r' \leq R$$

$$= 0 \qquad r' > R\,.$$

Then

$$\frac{A_{eff}}{A} = 1 - \frac{9}{16\pi r_0^2}\,\sigma_{tot}(\psi N)A^{1/3} + \text{small corrections.}$$

Measurements on Be and Ta can then be interpreted to yield[43]

$$\sigma_{tot}(\psi N) = 3.48 \pm .79 \text{ mb}\,,$$

a value substantially larger than the VMD estimate. We can then calculate λ:

$$\lambda = \frac{\sigma_{tot}(\psi N)_{VMD}}{\sigma_{tot}(\psi N)_{A\ \text{dependence}}} = .29\,.$$

This value is in reasonable agreement with the corrections to VMD calculated by Aviv et al.[41] The larger value of $\sigma_{tot}(\psi N)$ establishes even further the hadronic behavior of the ψ. Fig. 10 compares σ_{tot} vs s for ρ, ϕ, and ψ.[44] It is interesting to note that the threshold behavior of $\sigma_{tot}(\psi N)$ is known in more detail than the others.

2. <u>Relation to Charmed Particle Production</u>. We can use these data to draw some conclusions about photoproduction of charmed particles. If we assume that $\rho \to 0$ at high energy, we can calculate

$$\frac{\sigma_{elastic}(\psi N)}{\sigma_{tot}(\psi N)} = \frac{1}{b\lambda}\left[\frac{\alpha M_\psi}{3\Gamma_{\psi\to e^+e^-}}\,\frac{e^{bt_{min}}}{16\pi}\,\frac{d\sigma}{dt}(\psi N \to \psi N)\bigg|_{t_{min}}\right]^{\frac{1}{2}} \simeq (4.5 \pm 1.4)\%\,.$$

This is somewhat smaller than the elastic production of other hadrons at high energy, which tends to fall in the range of 10-20%.

Further, at photon energies of 20 GeV, the inelastic cross section for ψ production is less than 20-30% of the elastic ψ production cross section. We can therefore conclude that the bulk of the inelastic cross section does not

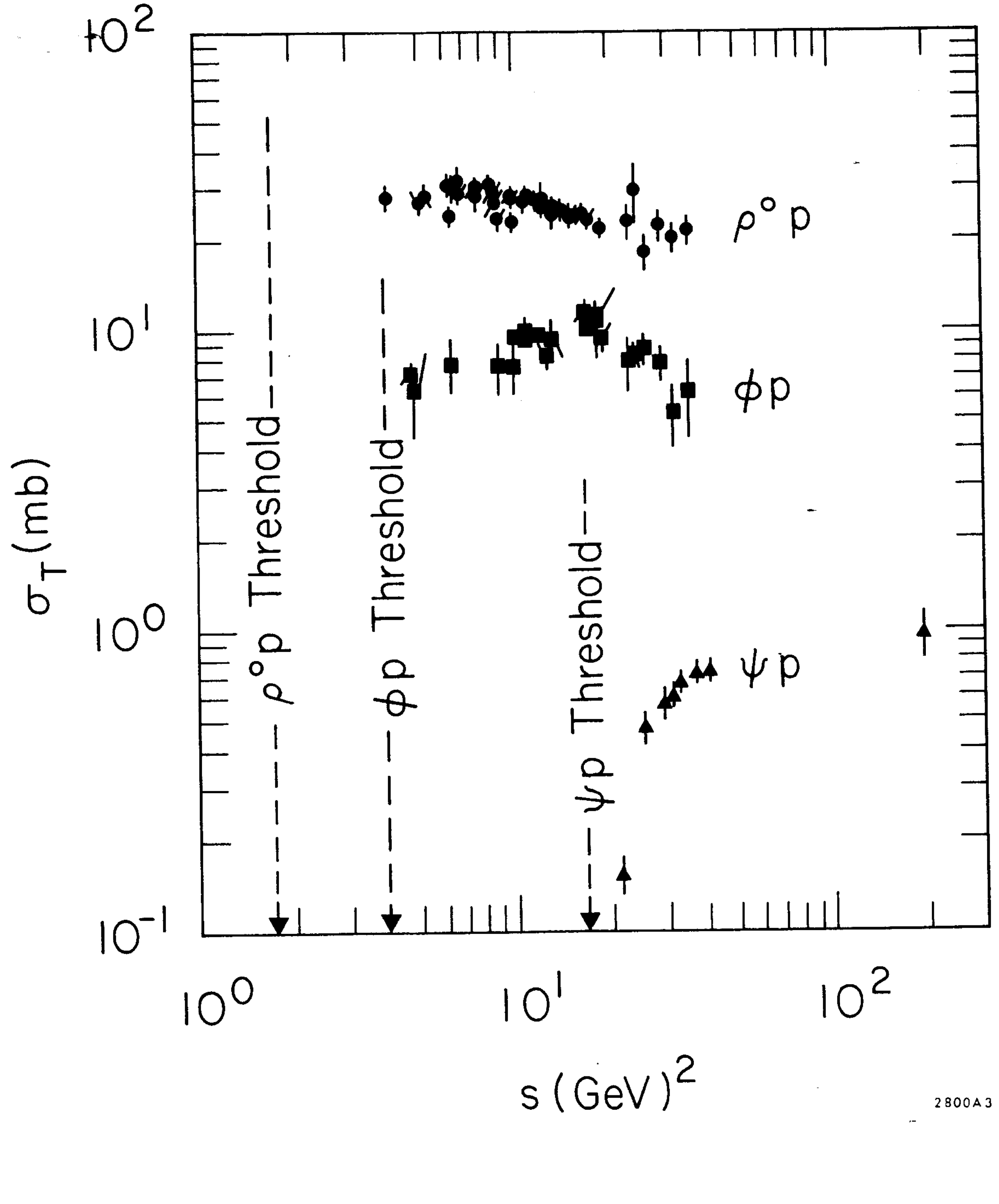


Fig. 10--The s-dependence of the total vector meson-nucleon cross sections. (Ref. 44.)

involve the ψ.[40] However, the $c, \bar{c}$ quarks carried by the ψ must appear in the final state, and they presumably do so in combination with uncharmed quarks. We may therefore conclude that

$$\sigma_{tot}(\psi N) \simeq \sigma(\psi N \to D\bar{D} + X) \; !$$

Here $D, \bar{D}$ mean any state of nonzero charm. This conclusion is made even more tantalizing by the mysterious threshold behavior of $\frac{d\sigma}{dt}(\gamma p \to \psi p)$, which is shown in Fig. 11, since, for a D mass of 1.86 GeV, $D\bar{D}$ threshold in photoproduction is at $E_\gamma = 12$ GeV.

We can pursue this course a little further, noting that in the context of (corrected) VMD we can write

$$\sigma(\gamma p \to D\bar{D} + X) \simeq \frac{\sigma_{tot}(\psi N)}{\sigma_{elastic}(\psi N)} \sigma(\gamma p \to \psi p) \simeq \lambda \times 500 \text{ nb} \simeq 150 \text{ nb} ,$$

whereas $\sigma_{tot}(\gamma p) = 120\ \mu b$ for $E_\gamma > 20$ GeV. This conclusion is compatible with the observation at FNAL of a charmed baryon[25] (to be discussed below)(see also W. Y. Lee, these Proceedings), but is at odds with another result of the SLAC-Wisconsin experiments.

2.1 Experimental Information on Photoproduction of Charm. Fig. 12 shows the single arm inclusive muon yield at $E_\gamma = 8$, 12, and 20 GeV in the second experiment.[45] The extrapolation to zero decay path to remove the effect of normal hadronic decays results in an excess muon signal only at E_γ = 20 GeV. With $\langle p_\perp \rangle = 1$ GeV, the ratio $\mu/\pi = 1.4 \times 10^{-4}$. This implies, if D mesons are the source of the muons, that

$$\sigma(\gamma p \to D\bar{D} + X) \times BR(D \to \mu) \simeq 2 \text{ nb}.$$

However, if the branching ratio is taken to be 10%, then our previously derived result of 150 nb for D photoproduction implies a $\sigma \times BR$ of $\simeq$ 15 nb. These two results are incompatible, but uncertainties in muon acceptance calculations due to unknown production mechanisms, coupled with unknown leptonic decay rates,

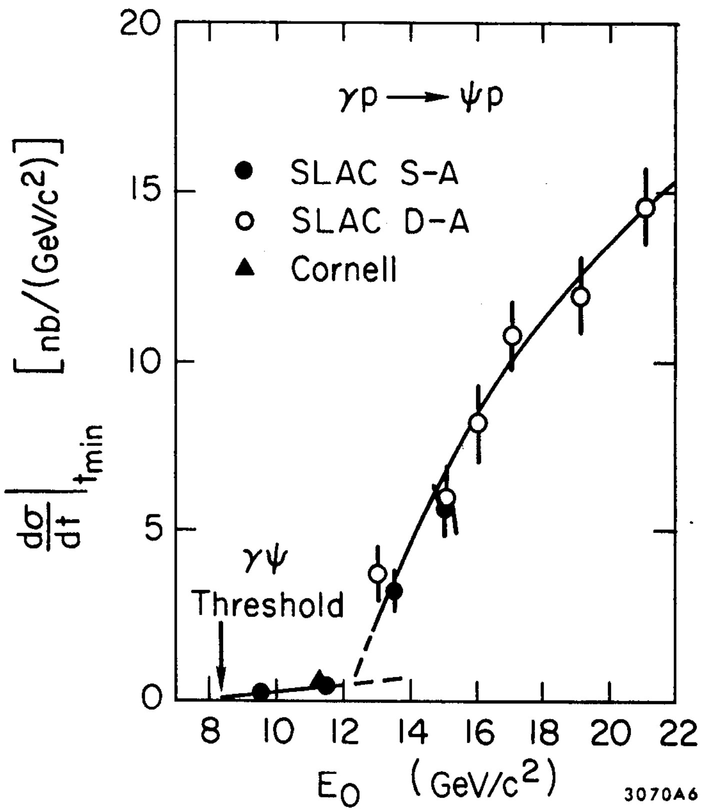


Fig. 11--The threshold behavior of the ψ photoproduction cross section.

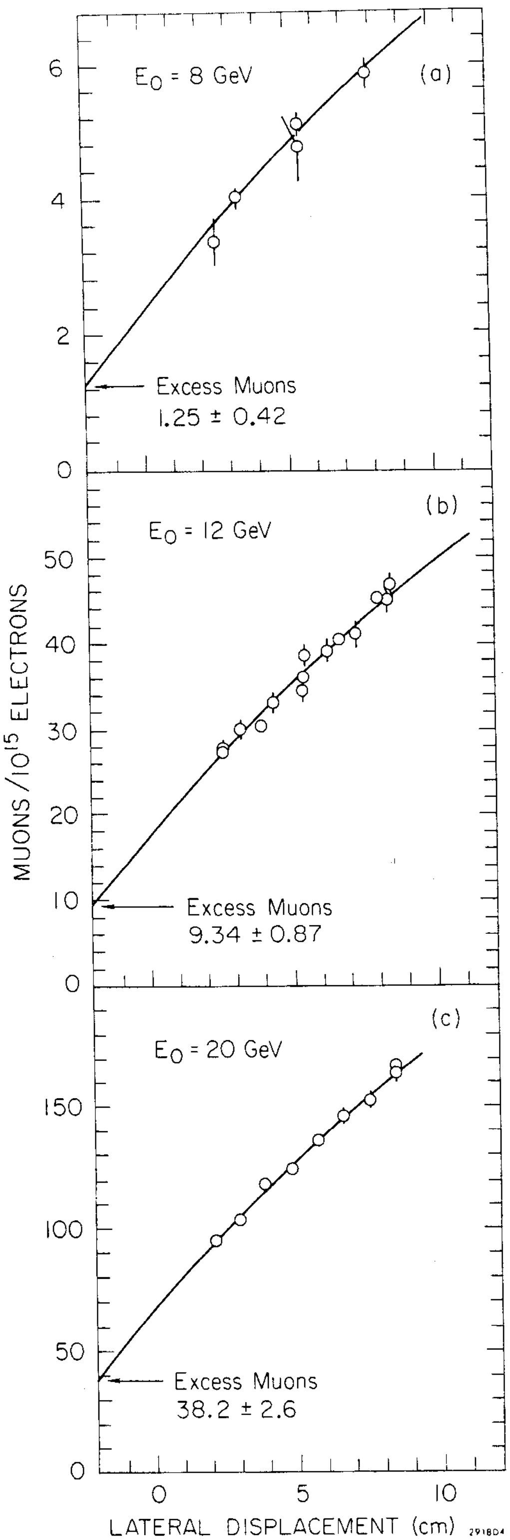


Fig. 12--Single arm inclusive muon yields in the SLAC-Wisconsin photoproduction experiment (Ref. 45).

are most likely responsible for the discrepancy.

Let us now turn to the very (photo)productive Columbia-Illinois-Hawaii-Fermilab (CIHF) experiment. Their most exciting result, of course, is the identification of a probable charmed (anti) baryon. Before briefly describing that result, however, there are several others from this experiment which have bearing on the question of new particle production. The first is a limit:[46]

$$\sigma(\gamma + \mathrm{Be} \rightarrow \underbrace{D}_{\hookrightarrow K_S^0 \pi}\bar{D} + X) \leq 5 \text{ nb} .$$

From the recent SPEAR result, $\mathrm{BR}(D^0 \rightarrow K\pi) \simeq$ 2-3%, we can conclude that

$$\sigma(\gamma + \mathrm{Be} \rightarrow D\bar{D} + X) \leq 150 - 250 \text{ nb} ,$$

which is consistent with our earlier conclusion.

The second is an enhancement in the dimuon spectrum[47] at $m_{\mu\mu} = 4.7$ GeV in the reaction

$$\gamma + \mathrm{Be} \rightarrow \underbrace{(4.7)}_{\hookrightarrow \mu^+\mu^-} + X .$$

The enhancement above the Bethe-Heitler background is statistically significant, but $\sigma \times \mathrm{BR}$ is small:

$$\frac{\sigma \times \mathrm{BR}(4.7 \rightarrow \mu\mu)}{\sigma \times \mathrm{BR}(\psi \rightarrow \mu\mu)} = .015 .$$

The third result is a preliminary one derived from a study of two track events with an identified μ and e.[48] There are two μe events with $M_{\mu e} > 1.1$ GeV, which, if real, imply a $\sigma \times (\mathrm{BR})^2 \times \text{acceptance} = 4 \times 10^{-2}$ nb. This, it should be noted, is not likely to be relevant to the SPEAR μe events, but it could very well be the result of two leptonic decays of charmed particles.

There is now good evidence of photoproduction of charm, in this case a charmed baryon. The CIHF collaboration has observed a resonance decaying to $\bar{\Lambda}\pi^+\pi^-\pi^-$ in photoproduction. This is very likely the $\bar{\Lambda}_c$, the lowest mass charmed baryon and the only one to decay weakly. If the invariant mass of the

$\bar{\Lambda}_c$ and an additional charged π are plotted, there is also evidence for an enhancement near 2.5 GeV, which is probably either the Σ_c or Σ_c^*. The close agreement of these masses with those observed in the Brookhaven neutrino event tends to confirm the conclusion that the 2.244 and 2.426 GeV mass combinations in that picture were indeed charmed states.

At this writing, the production cross section of the $\bar{\Lambda}_c$ has not been determined. For more details on the $\bar{\Lambda}_c$, see the lecture of W. Y. Lee in these Proceedings.

III. HADRONIC PRODUCTION OF NEW PARTICLES

In this section we will review the characteristics of ψ/J and ψ' production by hadrons and the implications of these data for the possibility of observing charmed particle production in hadronic reactions.

The inclusive cross section for ψ/J production by protons is shown in Fig. 13. It is seen to rise very rapidly with $\sqrt{s}$, so rapidly, in fact, that the simplest parton model ideas fail to reproduce the s dependence. The data of Fig. 13 are taken in different kinematic regions and with different targets.[49] In order to place them on a single graph, it is necessary to know the x, $p_\perp$, and A dependence of ψ/J production. The A dependence has been measured by the CIHF experiment[50] in a neutron beam at $\sqrt{s} = 24$ GeV, and found to be $A^{0.93\pm0.04}$, compared to that for $\rho+\omega$ production measured, in the same experiment, as $A^{0.62\pm0.03}$. Data on ψ/J production by pions are shown in Fig. 14.

The $p_\perp$ dependence of ψ/J production has been measured over a wide range of $\sqrt{s}$ and $p_\perp$, using both proton and π beams. These results are summarized in Table I. That the $p_\perp$ dependence is much more gradual than for other hadronic reactions is well established. It has also been shown by the CFSB group[51] that the x dependence of ψ/J production is flat for $\pm$ 0.06 about x = 0. More detailed information on the x dependence of ψ/J production by p and $\pi^\pm$

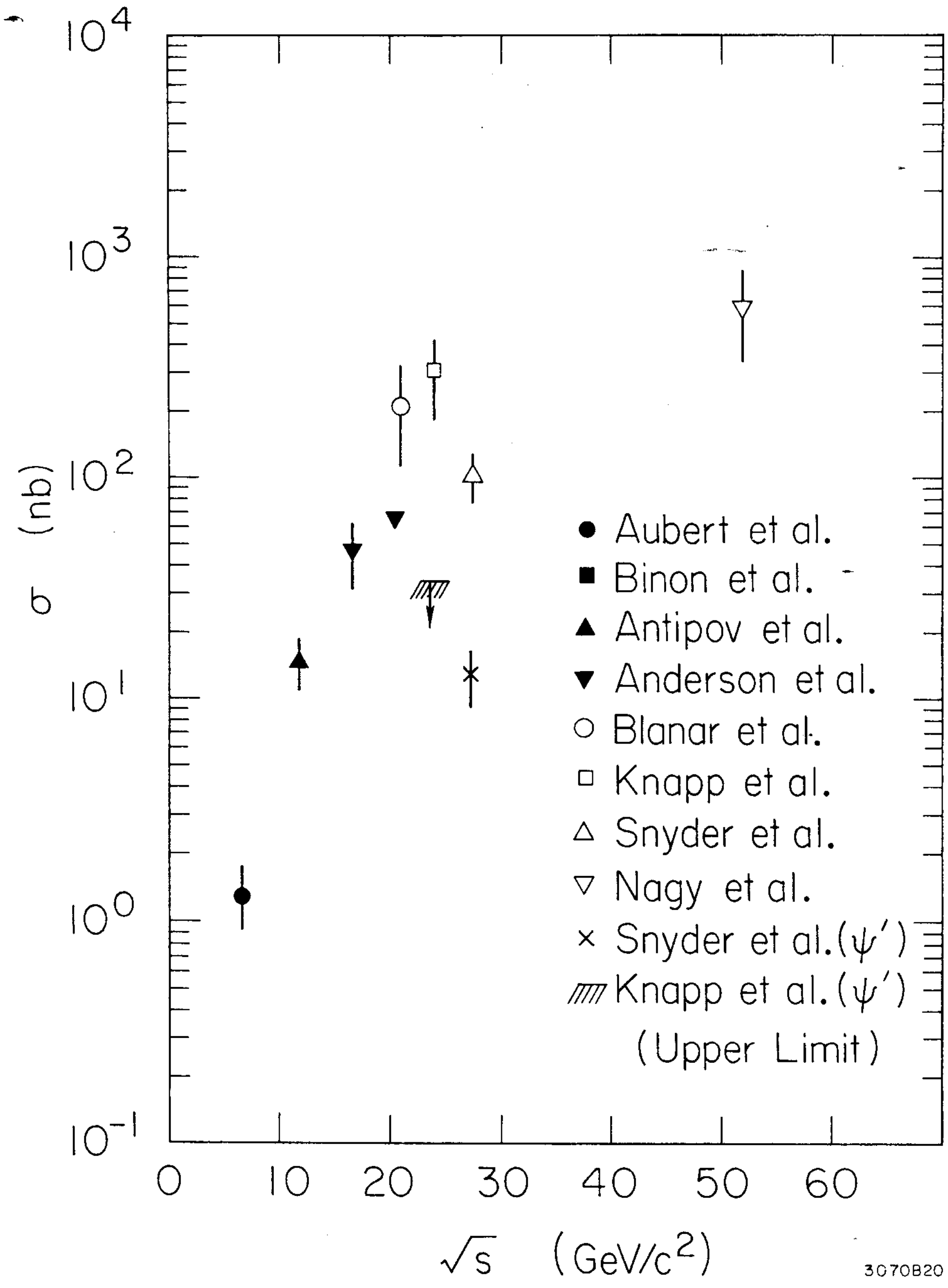


Fig. 13--s-dependence of the total cross section for ψ/J, ψ' production by protons and neutrons.

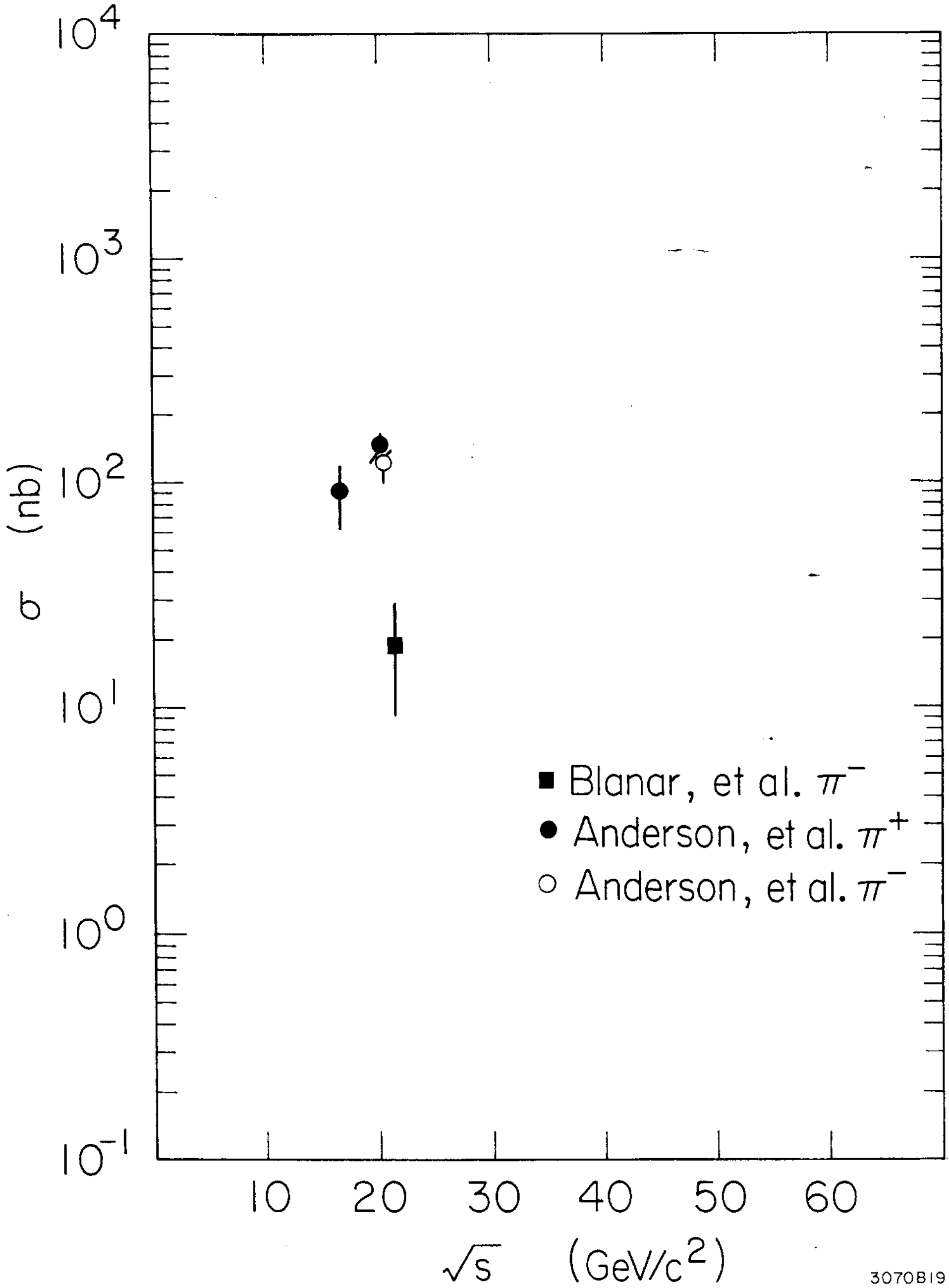


Fig. 14--s-dependence of the total cross section for ψ/J production by pions.

TABLE I

$p_\perp$ dependence of ψ/J production in p, n, and π interactions

exp	$\sqrt{s}$	$p_\perp$ range	$e^{-ap_\perp}$	$e^{-bp_\perp^2}$
p				
BNL-MIT	7.3	0 - 1.2		1.6
CP	16.8	0 - 2	1.97	
	20.5	0 - 2.5	1.97 ± .08	0.80 ± 0.06
NE	21.2	0 - 2	2.2 ± 0.5	1.1 ± 0.3
CIHF (n)	23.8	0 - 3	1.6 ± 0.2	excluded
CFSB	27.4	0 - 2	1.6 ± 0.35	1.1 ± 0.35
π				
CP (+)	16.8	0 - 2	1.7	
CP (+)	20.5	0 - 2.5	2.03 ± .15	0.88 ± 0.12
(-)	20.5	0 - 2.5	1.58 ± .13	0.59 ± .06
NE (-)	19.4	0 - 2	1.6 ± 0.2	0.81 ± 0.14

has recently been presented by the Chicago-Princeton[52] experiment.

The decay angular distribution has also been measured by the CFSB group, and appears to fit $1 + \cos^2\theta$ somewhat better than an isotropic decay. The Chicago-Princeton experiment, however, finds significant deviations from isotropy only in ψ/J production by protons on tin.

ψ' production has now been observed by the CFSB,[51] CIHF,[53] and Chicago-Princeton groups.[52] These data are also shown in Fig. 13.

1. Models of ψ/J Production by Hadrons and the OZI Rule. A successful model for ψ/J and ψ' production should presumably explain the s dependence of the cross section, the large $\langle p_\perp \rangle$, the ratio of cross sections for production by protons and pions, the operation of the OZI rule, and the fact that ψ' production is suppressed relative to ψ/J production. A further useful feature would be any predictions concerning the relation of ψ/J cross sections to charmed particle production cross sections.

1.1 Quark Fusion. One interesting approach to a model is the idea of $q\bar{q}$ fusion of Sivers,[54] Gunion,[55] Donnachie and Landshoff,[56] etc. In this model, to the extent the ψ/J consists of a $c\bar{c}$ pair, the hadronic production of ψ's alone is forbidden by the OZI rule, since the c quark content of the nucleon is presumably small (see Fig. 15a). In this model, the cross section for inclusive ψ/J production is given by

$$\sigma(pp \to \psi + \ldots) = \frac{8\pi^2}{3M_\psi^2} \sum_i \frac{g_{\psi_i}^2}{4\pi} \, \tau \int_\tau^1 \frac{dx}{x}\left[f_i(x)\bar{f}_i\left(\frac{\tau}{x}\right) + f_i\left(\frac{\tau}{x}\right)\bar{f}_i(x)\right] ,$$

where

$$\tau = \frac{M_\psi^2}{s - s_{\text{threshold}}} .$$

The u,d quark distributions $f_i(x)$ are then obtained from the fits of Farrar[57] or Chu and Gunion.[58] The coupling is estimated by Sivers[54] to be

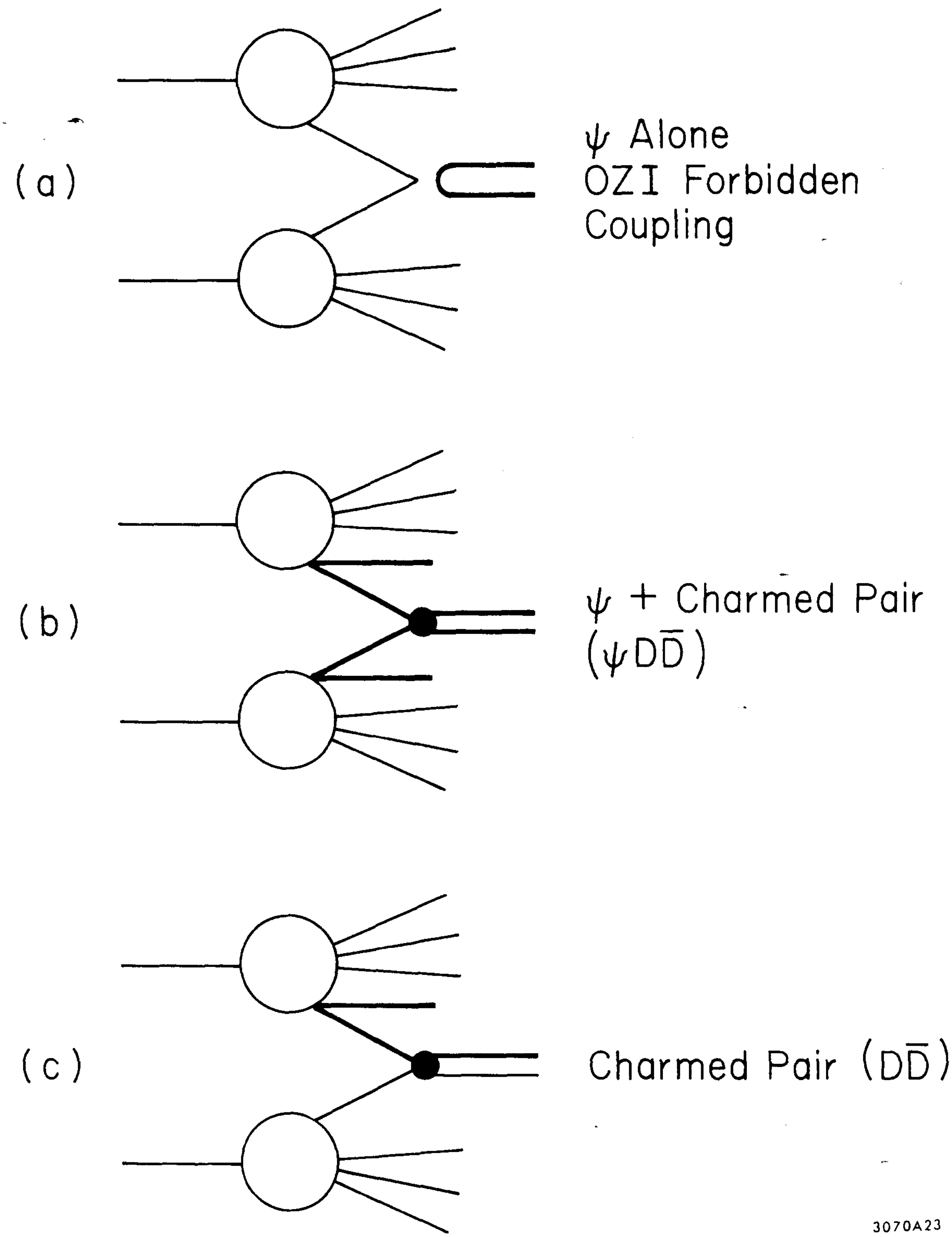


Fig. 15--Quark fusion diagrams for hadronic production of (a) the ψ/J alone, (b) ψ/J in conjunction with charmed particles, and (c) charmed particle pairs.

$$\frac{g^2_{u\bar{u}}}{4\pi} = \frac{g^2_{d\bar{d}}}{4\pi} = \frac{1}{2} R_\psi \frac{g^2_{\psi e^+e^-}}{4\pi} \doteq 1.3 \times 10^{-5} .$$

Alternatively, one can fit the cross section to low energy data. One finds, however, that the s dependence of this mechanism does not rise fast enough, failing by nearly an order of magnitude at $\sqrt{s} = 20$.

In order to boost the cross section, appeal is made to production from c quarks in the sea. Presumably, $g^2_{c\bar{c}}/4\pi$ is of order one. An estimate of the $f_c(x)$ can be made by analogy with strange quark distributions:

$$f_c(x) \simeq f_{\bar{c}}(x) \simeq \epsilon f_s(x) \simeq \epsilon \times 0.2 \times \frac{(1-x)^7}{x} .$$

Sivers obtains $\epsilon = .2$ for $g^2_{c\bar{c}}/4\pi = .5$. This mechanism then implies that $\sigma(pp \to \psi D\bar{D})$ is greater than $\sigma(pp \to \psi + X)$(Fig. 15b) and, further, that charmed particle production alone (Fig. 15c) will be larger than joint production with ψ/J: $\sigma(pp \to D\bar{D}X) > \sigma(pp \to \psi D\bar{D})$, since

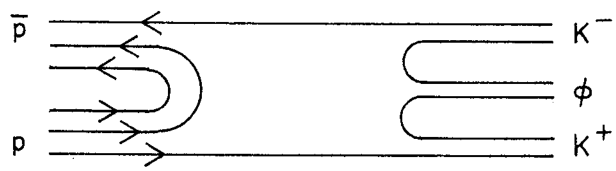
$$\sigma(pp \to D\bar{D}X) \simeq \frac{4\pi^2}{3M_D^2} \frac{\bar{g}^2}{4\pi} \tau \int_\tau^1 \frac{dx}{x} \sum_i \left[f_c(x)\bar{f}_i(\tfrac{\tau}{x}) + \bar{f}_c(x) f_i(\tfrac{\tau}{x}) + f_c(\tfrac{\tau}{x})\bar{f}_i(x) + \bar{f}_c(\tfrac{\tau}{x}) f_i(x) \right] .$$

1.2 Experimental Evidence for the OZI Rule. In this model, Sivers, for example, is able to obtain a reasonable fit to ψ/J inclusive production. A consequence of the model, however, is that inclusive $D\bar{D}$ production is predicted to be about $10^2 \times$ inclusive ψ/J production. Recent emulsion experiments call this prediction into question. This will be discussed further below. An interesting laboratory for testing these ideas is provided by hadronic ϕ production.[54] To the extent that the ϕ is composed of $s\bar{s}$ quarks, we can study the sea quark mechanism by comparing $\sigma(pp \to \phi \text{ alone})$ with $\sigma(pp \to \phi K\bar{K})$ and $\sigma(pp \to \text{strangeness})$. The analogy is inexact, however, since OZI suppression is expected to be less stringent for ϕ's due to ϕ-ω mixing and the possible effect of intermediate states with a real $K\bar{K}$. Further, threshold effects in s are bound to enter differently. With this in mind, we can briefly look at the experimental evidence in ϕ production. There are three relevant experiments. First, Blobel et al.[59] have investigated inclusive ϕ production by protons at $\sqrt{s} = 6.8$, measuring $\sigma(pp \to \phi + x) = 158 \pm 35\ \mu b$, and finding no strange particle enhancement in association with the ϕ. The Omega collaboration[60] has measured ϕ production in $\pi^- p$ at $\sqrt{s} = 6$, finding

$$\frac{\sigma(\pi^- p \to \phi K^+ K^- \pi^- p)}{\sigma(\pi^- p \to \rho^0 K^+ K^- \pi^- p)} = 0.45 \begin{array}{l} + 0.25 \\ - 0.15 \end{array} ,$$

so that the two Zweig-allowed processes are comparable.

The third experiment, by Donald et al.,[61] in $\bar{p}p$ at 3.6 GeV/c, does provide some support for the operation of the OZI rule. To the extent that the ϕ is $s\bar{s}$, the OZI rule predicts an enhancement of ϕ production in $\bar{p}p \to K^+ K^- K^+ K^-$:



but no ϕ production in $\bar{p}p \to K^+ K^- \pi^+ \pi^-$. This statement is, of course, weakened by ϕ-ω mixing. Donald et al. find 12 of 16 $\bar{p}p \to K^+ K^- K^+ K^-$ events are in fact $\phi K^+ K^-$, and that after cuts to remove $K^*(890)$ and ρ^0:

$$\frac{\sigma(\bar{p}p \to \phi\pi\pi)}{\sigma(\bar{p}p \to \omega^0 \pi\pi)} = 0.009 \begin{array}{l} + 0.004 \\ - 0.007 \end{array} ,$$

in agreement with the mixing prediction. It should be noted, however, that $\bar{p}p$ experiments at lower momenta do not show significant enhancements of this type. Thus, while there is some evidence for the operation of the OZI rule in hadronic production, it is far from overwhelming.

Returning to the ψ,D production case, Fig. 16 shows the result of Sivers' calculations for ψ production in pp collisions.[54] While the sum of ψ alone and $\psi D\bar{D}$ cross sections provides a good fit to the data, the predicted cross section

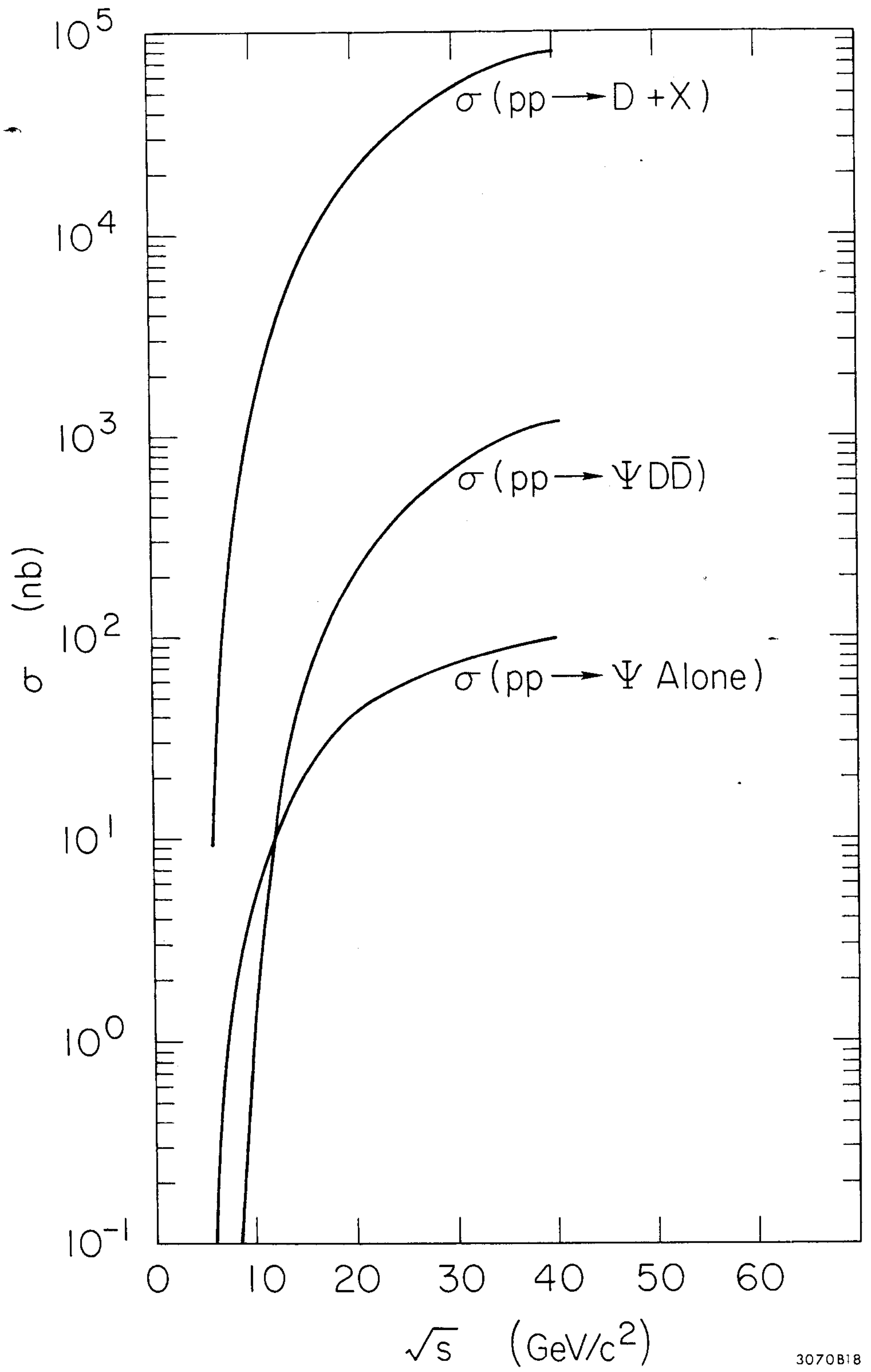


Fig. 16--Predictions of the quark fusion model of Sivers (Ref. 54) for the s-dependence of production by protons of the ψ/J alone, ψ/J in conjunction with charmed particles, and charmed particle pairs.

for inclusive D production is greater than 10 μb. This large a D production cross section would appear to be ruled out by a recent University College, London, emulsion exposure[62] to 300 GeV/c protons in which short tracks emerging from stars with lifetimes $\geq 10^{-14}$ seconds were searched for and not seen to level of less than 1 μb.

Another piece of experimental evidence which bears on the choice of production models comes from the neutron beam part of the CIHF experiment.[63] Events of the type $n + W \to \underbrace{\psi/J}_{\to \mu^+\mu^-} + \underbrace{X}_{\to \mu^\pm} + \ldots$ can, if π or K decay is ruled out as a source of the third muon, be indicative of the semileptonic decay of a charmed particle produced in association with the ψ/J. Two events of this type, which are consistent with π,K decay, were seen, so that a limit at 90% confidence level of

$$\frac{2\sigma(nW \to \psi D\bar{D})\ BR\ (D \to \mu + X)}{\sigma(nW \to \psi)} < 0.006$$

can be set for $x_F > 0.25$. If the semileptonic branching ratio is taken to be .1, we then have

$$\frac{\sigma(nW \to \psi D\bar{D})}{\sigma(nW \to \psi)} < .03,$$

which contradicts the quark fusion model.

1.3 Associated Production. At low energies, associated production of strange particles has a large cross section. For example, at $\sqrt{s} = 5$, $\sigma(\pi^- p \to K^0\Lambda^0) = 10\ \mu b$. By analogy, it should be possible to calculate the associated production of charm, in reactions such as $\pi^- p \to D^-\Lambda_c^+$ or $\pi^+ p \to \bar{D}^0\Sigma_c^{++}$. This has been done by Barger and Phillips[64] in a Regge model. They write

$$\frac{\frac{d\sigma}{dt}(\text{associated charm})}{\frac{d\sigma}{dt}(\text{associated strangeness})} = \left[\frac{\Gamma(1-\alpha_{D^*}(t))}{\Gamma(1-\alpha_{K^*}(t))}\right]^2 (\alpha'_s s)^{-2(\alpha_{K^*}(t)-\alpha_{D^*}(t))} .$$

The K* trajectory is well known:

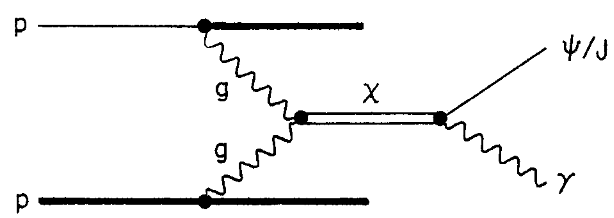
$$\alpha_{K^*}(t) = 1 + .9(t - m_{K^*}^2) = .3 + .9t\ ,$$

but the D* trajectory

$$\alpha_{D^*}(t) = 1 + \alpha^1_{D^*}(t - m_{D^*}^2)$$

is, of course, not known. With different estimates of this trajectory, Barger and Phillips predict a rather small cross section for associated production, e.g., $\sigma(\pi^- p \to D^- \Lambda_c^+)$ is about 1 nb at $\sqrt{s} = 5$, falling to .01 nb at $\sqrt{s} = 20$.

1.4 <u>Psi Production via Gluons</u>. A third approach to hadronic production of ψ/J postulates that it is not directly produced in hadronic collisions, but rather results from the decay of $C = +1$ χ states which are more readily produced by the gluon component of the hadronic wave function.[65] In the charmonium model, the $C = -1$ ψ/J is produced by a three gluon coupling, while the ^3P χ is produced by a two gluon mechanism:



Since $\alpha_g \simeq 0.2$, χ production should dominate ψ/J production. The cross section is then given by

$$\sigma = \sum_n \frac{8\pi^2}{M_{n\,^3P}^3} \sum_J \sum_a \frac{\Gamma(n^3P_J \to gg)\Gamma(n^3P_J \to \psi + a)}{\Gamma_{tot}(n^3P_J)} \times \tau \int_\tau^1 \frac{dx}{x} f_g(x) f_g(\frac{\tau}{x})\ ,$$

where the gluon x distribution is

$$f_g(x) = \frac{n+1}{16}\frac{1}{x}(1-x)^n\ .$$

The only n's which contribute to the sum must be those below charm threshold, or else $\Gamma(n^3P_J \to gg) \ll \Gamma_{total}(n^3P_J)$, since $n^3P_J \to gg$ violates the

OZI rule and is therefore assumed to be suppressed. The predominant χ decay is to $\psi/J + \gamma$ (or ω), since $\chi \to \psi + \pi$ is forbidden by isospin, $\chi \to \psi + 2\pi$ is forbidden by G parity and $\chi \to \psi$ + anything else is energetically forbidden.

This model can provide a good fit to the s dependence of ψ/J production, as shown in Fig. 17. It also explains several features of the reaction and makes other definite predictions. Since the ψ/J results from the decay of another state, the remarkable signal/noise ratio (~ 200 at BNL) can be understood. In a typical charmonium potential n = 3 lies at about 3.9 GeV. Thus only this level can feed the ψ', and the result is that ψ' production is small. Similarly, the hadronic production of ψ'', etc., states should be very small. In this context, the Υ(6 GeV) is not a bound state of standard SU(4) quarks. No joint production of ψ/J and charmed particles is predicted. Finally, some definite predictions about π and K production of ψ/J by this mechanism are possible.[66] For example, since the gluon distribution with $\pi^{\pm}$ are identical, one expects $d\sigma(\pi^+ T \to \chi + \ldots) = d\sigma(\pi^- T \to \chi + \ldots)$, for a target T of arbitrary isospin, whereas, since the $q\bar{q}$ annihilation mechanism is sensitive to valence quarks: $d\sigma(\pi^+ p \to \chi + \ldots) \leq \frac{1}{2}\, d\sigma(\pi^- p \to \chi + \ldots)$. Similar relations also hold for production by $K^{\pm}$. If the gluon distribution is SU(3) symmetric, then K and π production of χ should be equal. Finally, at x = 1, $f_g^N(x) \sim (1-x)^5$, whereas $f_g^{\pi}(x) \sim (1-x)^3$. If the fractional gluon momentum is ~ 50% for π as well as N, then, at high energies, one expects

$$\frac{d\sigma}{dx_L}(\pi N) \simeq \frac{d\sigma}{dx_L}(NN) \text{ at } x_L = 0, \text{ but}$$

$$\frac{d\sigma}{dx_L}(\pi N) \simeq 6\,\frac{d\sigma}{dx_L}(NN) \text{ at } x_L = .6.$$

The recent Chicago-Princeton results lend some support to this picture.[67]

We end this section by noting an interesting scaling relation found by Gaisser, Halzen, and Paschos.[68] They write

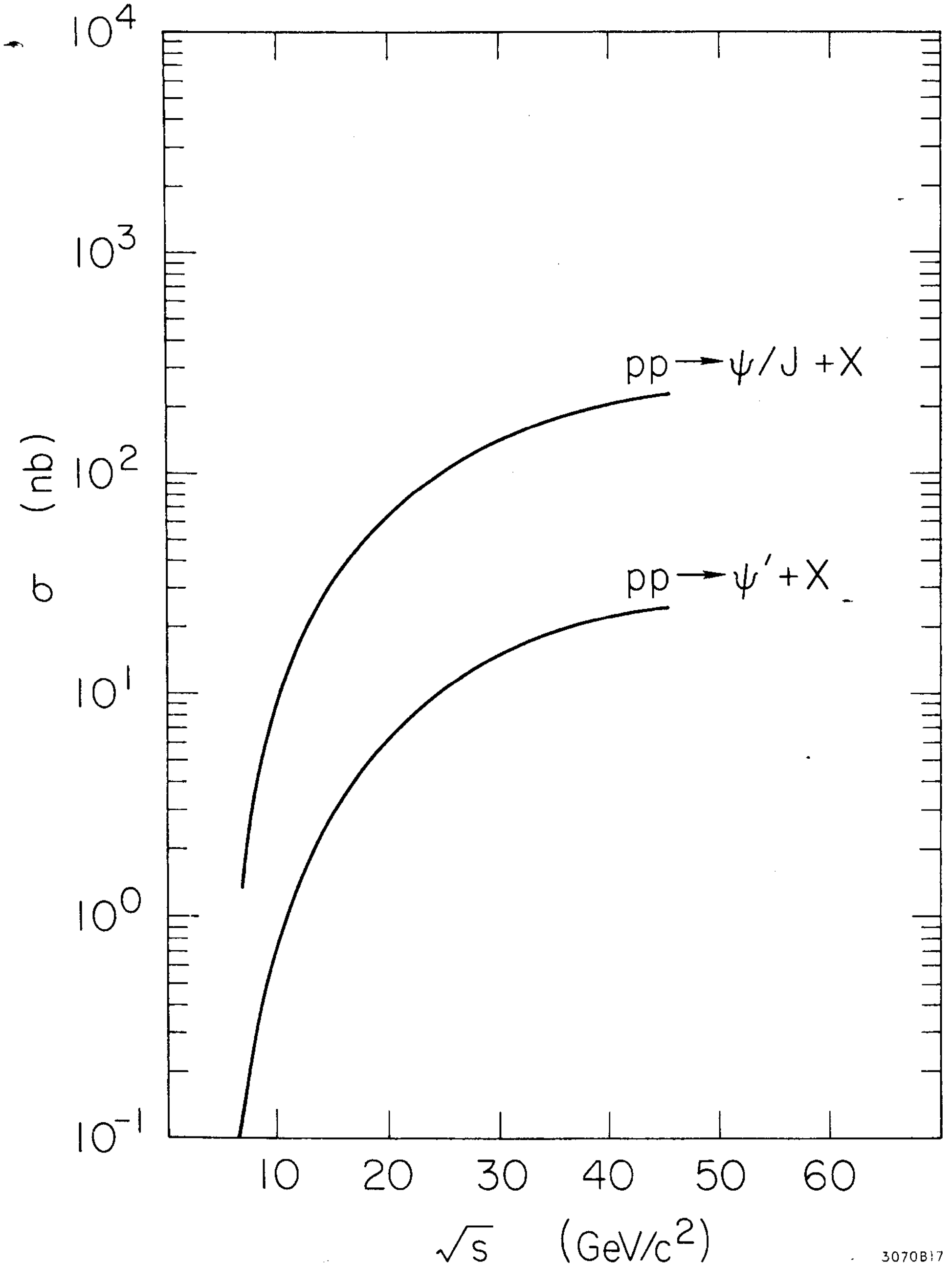


Fig. 17--Predictions of the gluon production mechanism for ψ/J of Carlson and Suaya (Ref. 65) for the s-dependence of production by protons of the ψ/J and ψ'.

$$\sigma(pp \to V + x) \equiv \sigma_V = \frac{\Gamma_V}{M_V^3} F\left(\frac{s}{M_V^2}\right) \quad ,$$

which is valid for Γ_V/M_V small. The notion is that $F\left(\frac{s}{M_V^2}\right)$ is a universal function which describes the manufacture of a mass M_V out of the available energy $\sqrt{s}$. Then all differences between the production of vector mesons are contained in their hadronic widths. Referring to Fig. 18, we see that ϕ, ψ, and ψ' production fall on a universal curve, but note that $\psi' \to \psi\pi\pi$ is excluded from $\Gamma_{\psi'}$. This relation "explains" the small ratio $\sigma_{\psi'}/\sigma_\psi$ without the χ production mechanism and allows one to predict intermediate boson production cross sections at higher energies.

2. Production of the Υ. A narrow resonance in the e^+e^- spectrum produced by 400 GeV protons on Be has been reported by the CFSB collaboration[69] at a mass of 5.97 ± 0.05 GeV. The enhancement consists of 12 events at this mass corresponding to $\sigma \cdot B = (5.2 \pm 2.0) \times 10^{-3}$ nb/nucleon. It is a very narrow resonance with a $\sigma \simeq 70$ MeV. This structure has been given the name Υ. The definite establishment of the Υ awaits further data on the $\mu^+\mu^-$ spectrum and improved e^+e^- data with better resolution, both by the same group.

The SLAC/LBL collaboration has searched the 6 GeV region at SPEAR for signs of the Υ.[70] The search was done in 4 MeV steps with ~ 60 hadron events/point. No enhancement was seen. Limits on Υ production in e^+e^- depend on its width. The cross section for a resonance is given by

$$\sigma(e^+e^- \to f) = \frac{\pi(2J+1)}{s} \frac{\Gamma_{ee}\Gamma_f}{(\sqrt{s}-m)^2 + \frac{\Gamma^2}{4}} \ .$$

At $\sqrt{s} = 6$ GeV, the beam width is ~ 4 MeV. If the resonance is narrow compared to this, then integrating over the resonance determines $(2J+1)\Gamma_{ee}\Gamma_{hadrons}/\Gamma$, while, if the resonance is wide, one determines

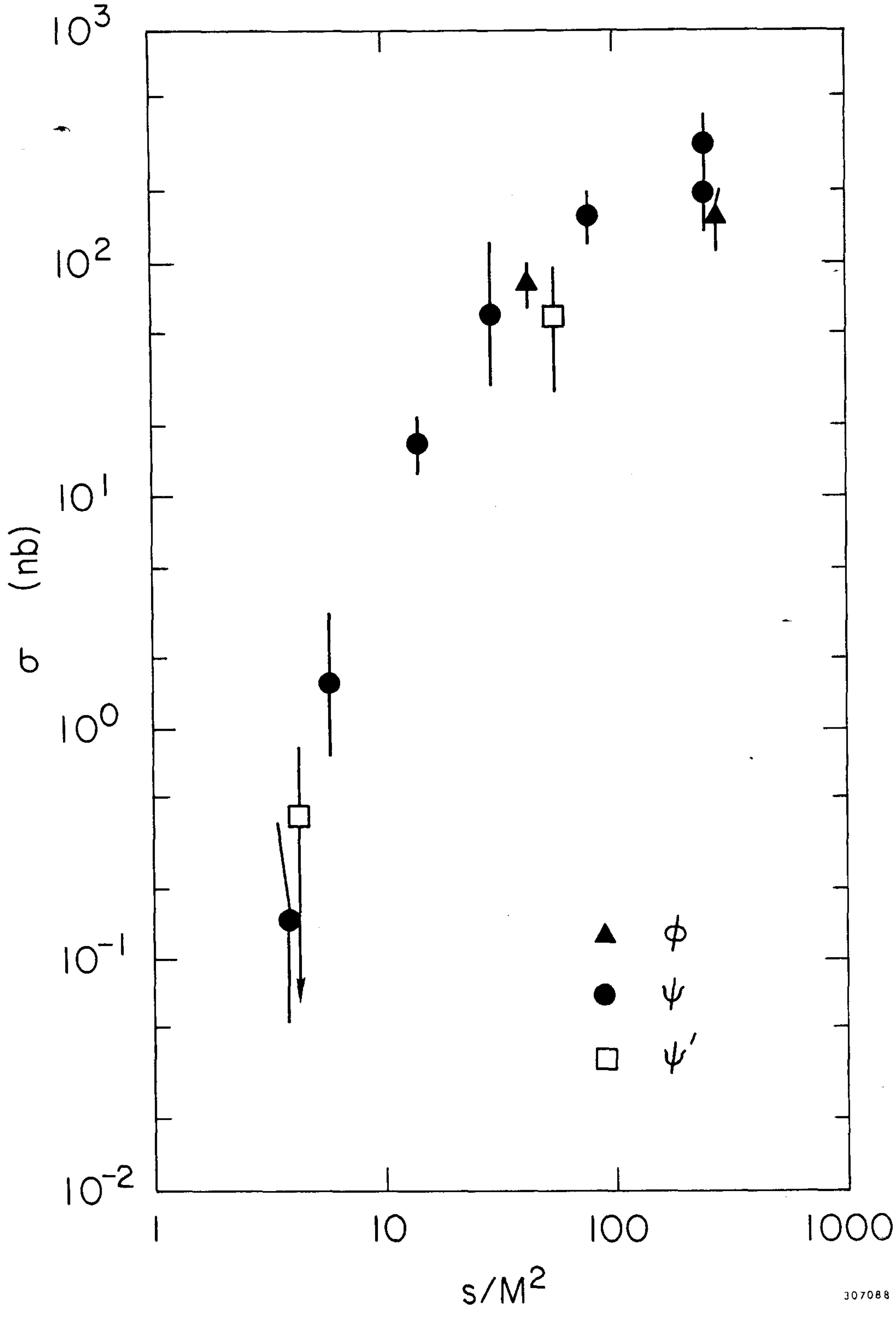


Fig. 18--The scaling relation for vector meson production. (Ref. 68.)

$(2J+1)\Gamma_{ee}\ \Gamma_{hadrons}/\Gamma^2$.

If J=1 is assumed, then the SPEAR search sets the following limits:

$$\text{for } \Gamma \ll 10 \text{ MeV} \quad : \qquad \frac{\Gamma_{ee}\Gamma_{hadrons}}{\Gamma} < 150 \text{ ev (90\% C. L.)}$$

$$10 \leq \Gamma \leq 50 \text{ MeV}: \qquad \frac{\Gamma_{ee}\Gamma_{hadrons}}{\Gamma^2} < 1.5 \times 10^{-5}.$$

Since $\Gamma_{ee}/\Gamma \ll 1$ and $\Gamma_{hadrons}/\Gamma \simeq 1$, these are effectively limits on Γ_{ee} and Γ_{ee}/Γ, respectively. By comparison the known vector mesons have Γ_{ee} equal to several keV. These limits imply that the cross section for Υ production by protons is large. Since $(\sigma \cdot B_{ee})_{\Upsilon} = 5 \times 10^{-4} (\sigma \cdot B_{ee})_{\psi}$, we have $\sigma_{\Upsilon} \geq 3.5\ \sigma_{\psi}$. Two points which potentially weaken these conclusions should be made, however. First, it is known that Γ_{ee} of the $\psi(4.4)$ is only 440 eV, so small leptonic widths of vector mesons are not unprecedented. Second, were the Υ to have J = 0, the limits on production in e^+e^- would be a factor of three weaker, and, in addition, it is known that BR $(\eta \to \mu^+\mu^-) = 2.2 \times 10^{-5}$, so that a small leptonic width of a pseudoscalar meson might be expected.

3. Bump Hunting in Hadronic Reactions. As we have seen, the existence of a substantial body of experimental data on the hadronic production of the ψ/J has shed little light on the problem of charmed particle production by hadrons. Emulsion experiments, however, do constrain the total cross section for charm production to less than $\sim 1\ \mu$b. This leaves the hadronic bump hunter with a formidable task. As of this writing, no statistically significant mass peak has been seen in hadronic reactions.

Most such experiments have concentrated on two body final states.[71] In the conventional charm scheme the only such decay is $D^0 \to K^-\pi^+$ at 1.86 GeV. Nonetheless, it is valuable to search in $\pi\pi$, πp, $\bar{p}p$ (a likely decay mode of the η_c) final states, and most experiments have done this. Three body final states include $D^+ \rightarrow K^-\pi^+\pi^+$, $K_S^o\pi^+$ at 1.87 GeV, $F^+ \rightarrow \pi^+\pi^+\pi^-$ (expected at ~ 2 GeV), $D^{*+} \rightarrow D^o\pi^+ \rightarrow K^-\pi^+\pi^+$ at ~ 2.02 GeV, and $\Lambda_c^+ \rightarrow \bar{K}^o p$, $\Lambda^o\pi$ at 2.25 GeV. If the total charm production cross section is taken as 1 μb and we use the SPEAR branching ratios for $D \rightarrow K\pi$, $K\pi\pi$ of 2-5%, the magnitude of the problem becomes clear: a likely σB of less than 20-50 nb. In typical FNAL two-body experiments performed so far, this corresponds to a peak of about 1% of background or less. The absence of 4σ peaks to this date is therefore not surprising.

There have been several bubble chamber experiments, which have looked for mass peaks in inclusive distributions and for evidence of associated production of charm.[72] These are far from having (what is now known to be) the required sensitivity. Counter experiments at BNL, CERN, and Fermilab have placed limits on σB which come closer to the needed sensitivity. For example, the MIT-BNL experiment[73] at $\sqrt{s} = 7.3$ places two-body limits on σB of as low as 1 nb at $M_{K\pi} = 2.25$ GeV. (No limits are quoted for the 1.8-2 GeV region.) If the s dependence of the charm production cross section is the same as that for ψ/J production, then this is still more than an order of magnitude above the expected σB. The Omega collaboration[74] has looked at two to five body final states in π^-p at $\sqrt{s} = 6$, setting limits as low as 35 nb at 95% confidence. These are summarized in Table II. At FNAL energies, there have been n, p, and π induced experiments.[75] As an example, the limits on σB placed by the MSU-OSU-Carleton collaboration in n+Be initiated final states are summarized in Fig. 19. A tantalizing peak in $M_{K^-\pi^+} = 1.86$ has been found in the Michigan-Purdue-Fermilab experiment,[76] but it is at the 3σ level and no corresponding peak is evident in $M_{K^+\pi^-}$ (see Fig. 20). This experiment differs from most others of this type in that it has its largest acceptance at x = 0.

Since the semileptonic branching ratios of charmed mesons are expected to

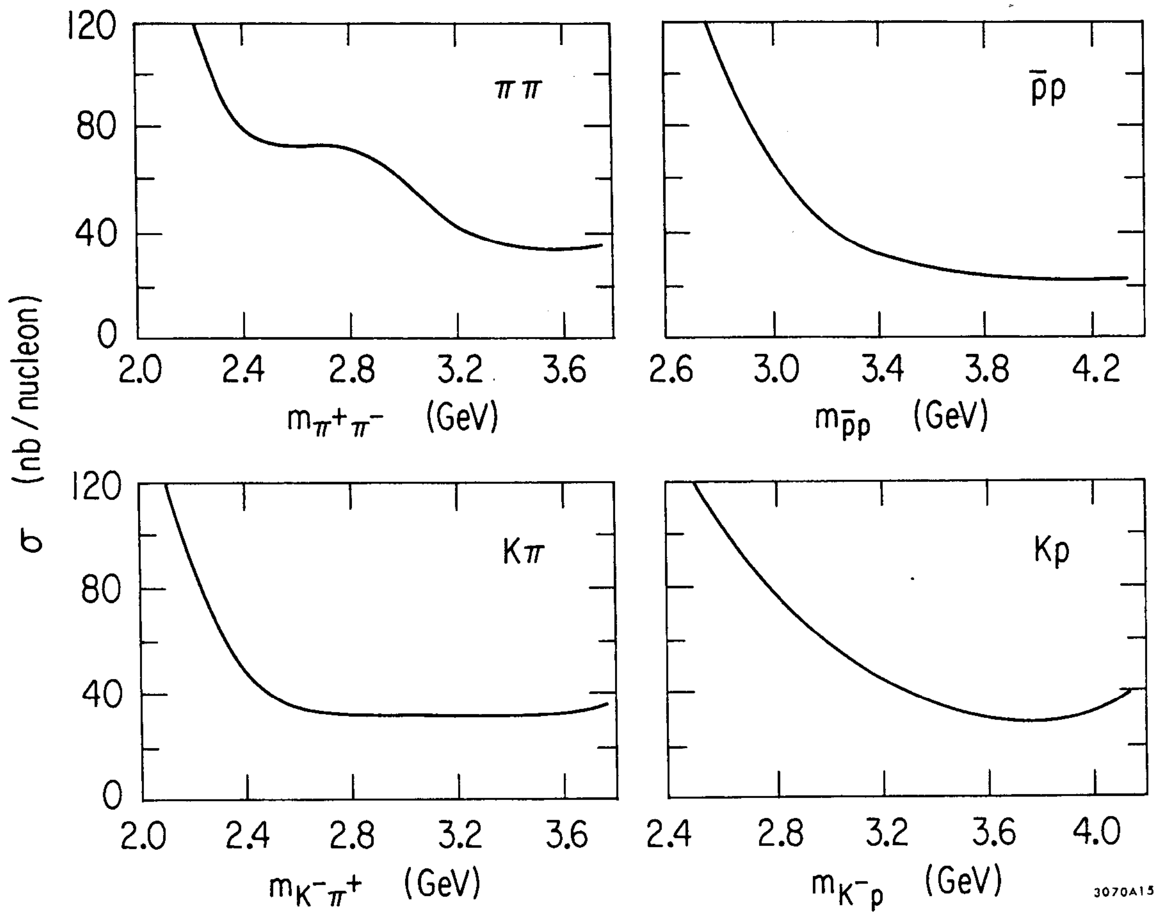


Fig. 19--Limits on hadronic production of two-body final states by 240 GeV/c neutrons (Abolins et al., Ref. 71).

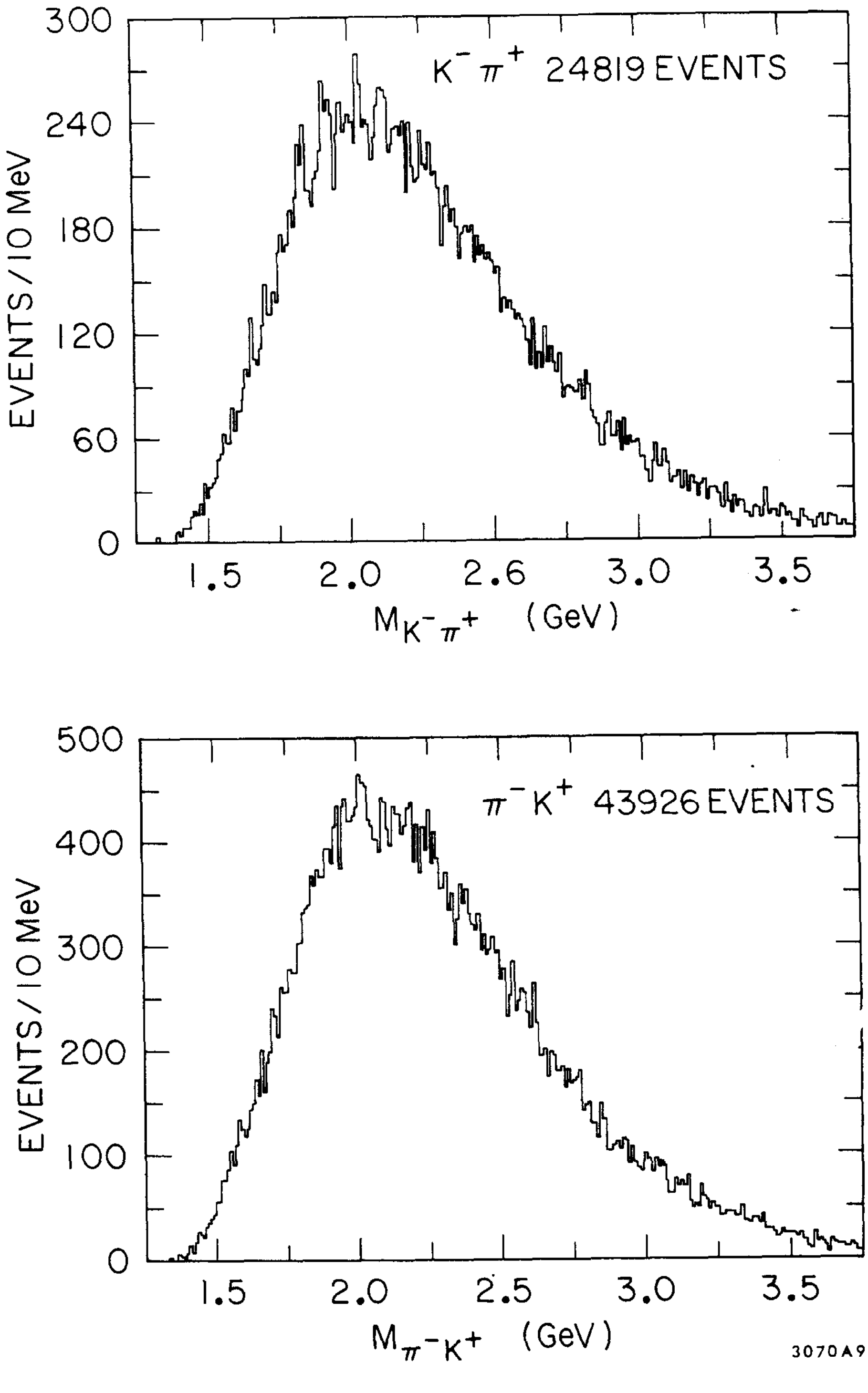


Fig. 20--$K^{\pm}\pi^{\mp}$ invariant mass spectra produced by 400 GeV/c protons (Bintinger et al., Ref. 71).

TABLE II

Limits on production of charmed hadrons in 19 GeV $\pi^- p$ interactions (Ref. 74)

Charm reaction	Charm decays	Cross section upper limits (nb)		
		phase space	forward mesons	forward baryons
$\pi^- p \to D^- D^0 p$	$D^- \to K^+\pi^-\pi^-; D^0 \to K^-\pi^+$	75	50	
$\pi^- p \to \bar{D}^0 D^0 \pi^- p$	$\bar{D}^0 \to K^+\pi^-; D^0 \to K^-\pi^+$	80	60	
$\pi^- p \to D^- C^+$	$D^- \to K^+\pi^-\pi^-; C^+ \to K^- p\pi^+$	65	80	200
$\pi^- p \to \bar{D}^0 C^0$	$\bar{D}^0 \to K^+\pi^+\pi^-\pi^-; C^0 \to K^- p$	75	100	2000[a]
$\pi^- p \to \bar{D}^0 C^0$	$\bar{D}^0 \to K^+\pi^-; C^0 \to K^- p\pi^+\pi^-$	65	1000[b]	55
$\pi^- p \to \bar{D}^0 C^0$	$\bar{D}^0 \to K^+\pi^-; C^0 \to K^- p$	40	200	40
$\pi^- p \to D^- C^0 \pi^+$	$D^- \to K^+\pi^-\pi^-; C^0 \to K^- p$	45	95	60
$\pi^- p \to \bar{D}^0 C^+ \pi^-$	$\bar{D}^0 \to K^+\pi^-; C^+ \to K^- p\pi^+$	55	120	60
$\pi^- p \to \bar{D}^0 C^0 \pi^+\pi^-$	$\bar{D}^0 \to K^+\pi^-; C^0 \to K^- p$	50	70	40

[a] 200 nb for $M_C + M_D > 4.0$ GeV for backward-produced mesons.

[b] 500 nb for $M_c > 2.3$ GeV and 300 nb for $M_c > 2.5$ GeV for backward-produced baryons.

be 15%, it is tempting to try to enrich a sample of hadronic events by requiring a coincident muon or electron. In practice the gain in sensitivity of such an experiment is limited by several factors. The improvement in trigger rate is held to $\sim 10^3$ by π decays, even at high energies, but even this is not realized, because a factor of 2 or 3 must usually be sacrificed in solid angle. The small semileptonic branching ratio and the fact that only one of the pair of D's produced is a candidate cost another factor of 20 or so. Such experiments thus can gain about 3-5 in sensitivity over untriggered experiments. This is sometimes realized in practice, and sometimes it is not.

As examples of this technique, we can cite the SLAC-Santa Cruz streamer chamber experiment[77] which used a 14 GeV π^+ beam on a polyethylene target and a μ trigger, setting limits in the 1-10 μb range on many different multihadron final states (up to five bodies). A similar experiment was performed in the FNAL streamer chamber by the SOD collaboration.[78] In this experiment, which utilized a 225 GeV π^- beam, enhancements in V^0's were searched for in coincidence with one and two high energy μ's. For $M_C = 3$ GeV, they set limits on $\sigma B_\mu^2 < 35$ nb. The MIT-BNL experiment[79] has searched for $K^-\pi^+\mu X$ final states in pBe reactions, seeing about 5 events per 12.5 MeV bin at 1.8-2.0 GeV. This allows them to set a limit on $\sigma B_\mu B_{K\pi} < .2$ nb, corresponding to a production cross section of the order of 100 nb. This experiment has also found that K^-e^+ coincidences in their double-arm spectrometer were 1% of π^-e^+ coincidences (note that this ratio is not $D \to Ke\nu/D \to \pi e\nu$), implying $\sigma_D B_e \leq 1$ nb. The idea of finding a charm signature by two semileptonic decays, resulting in μe coincidences, is currently being pursued in two experiments at the ISR.[80]

IV. DIRECT LEPTON PRODUCTION BY HADRONS

The subject of direct lepton production by hadrons has caused great excitement in recent years and has received many comprehensive reviews.[81] New data at low $p_\perp$, polarization measurements, and pair mass data, however, would seem to warrant a reexamination of the field and, in the context of these lectures, a discussion of the relevance of this phenomenon to the question of new particle production. For the sake of completeness, we will begin at the beginning, with some definitions, will summarize the available data, and will examine some attempts at an explanation of the phenomenon.

1. Definitions. "Direct leptons" are defined as those which are produced at or close to a production target but arise from "nontrivial sources". This far from clear definition must be made more specific by the enumeration of what is direct but trivial and direct yet nontrivial. The conventional classification of triviality is as follows:

Trivial: weak decays of π's, K's, hyperons.

Nontrivial: weak decays of charmed particles, heavy leptons, intermediate bosons.

Trivial: electromagnetic decays of ρ, ϕ, ω. Dalitz decays of π^o, η^o.

Nontrivial: electromagnetic decays of ψ/J, ψ', or new mesons (vector or otherwise).

Trivial: conversions of γ's from π^o.

Nontrivial: conversions of γ's from direct photon continuum.

It would seem that a more adequate definition for "trivial" would be "expected, as of mid-1974".

If the direct lepton is a muon, the background sources are π and K decay. The standard technique for measuring the background is the variation of the decay path before the muon filter and extrapolation to zero decay path. The sensitivity of this approach improves with beam energy and with transverse momentum, such that at FNAL energies and $p_\perp$ of 5 GeV/c or so μ/π ratios of 10^{-6} can be measured. Multiple scattering of the muons in the filter affects target reconstruction accuracy and can cause feeddown problems due to relatively poor $p_\perp$ resolution on a steeply falling spectrum.

If the direct lepton is an electron, the π and K backgrounds are less important than those arising from π^o or η^o Dalitz decays or conversion of photons from π^o decay in the target or surrounding material. This last background is removed by adding converter and extrapolating to zero length of conversion material. Dalitz decay backgrounds are dealt with by calculation. At low energies, electron detection is the more sensitive technique, the intrinsic sensitivity of the method not being a strong function of beam energy. If pairs can be detected, the sensitivity of the approach is extended still further.

2. Data. There is at present a great deal of data on direct lepton production. The kinematic regions covered by the measurements of the ℓ/π ratio are summarized in Figs. 21-23 for the ISR,[82-84] FNAL,[85-89] and lower energy machines,[90-94] respectively. Note that there are now data at low x extending from $p_\perp = .25$ GeV/c to 5.5 GeV/c and high x data at many energies. This extended range of data is quite important in arriving at a coherent explanation, as are the muon polarization measurements from Serpukhov[95] and Yale-FNAL[96,97] and the data on the pair origin of the single leptons from the Yale-FNAL[98] and Chicago-Princeton[99] experiments.

Before evaluating the contribution of trivial and nontrivial sources to the ℓ/π data, let us examine the s, $p_\perp$, and x dependence of the e/π and μ/π data. Figure 24 shows the s dependence of the μ/π ratio for data at $x \simeq 0$ with $p_\perp >$ 1 GeV/c. The s dependence of the e/π ratio for $x \simeq 0$ and $p_\perp > 1$ GeV/c is shown in Fig. 25. These μ/π and e/π data agree fairly well, both showing the threshold in $\sqrt{s}$ which would be characteristic of new particle production. The dominant contribution from the semileptonic decays of charmed mesons to the ℓ/π ratio should occur, as we shall see, just below $p_\perp = 1$ GeV/c. The new particle contributing the most to the ratio, especially beyond $p_\perp = 1.5$ GeV/c, is the ψ/J.

There is now a substantial amount of data at low $p_\perp$. The $p_\perp$ dependence of the e/π data is shown in Fig. 26. A vast range of center-of-mass energies is involved, from LASL energies up to $\sqrt{s} = 53$. No signal was seen at LASL, or in Winter's analysis of 19 GeV data. There does appear to be a signal at low s, low $p_\perp$, however, in the Penn-Stony Brook data. At high s, there is some discrepancy between the CHORMN data at 30° at the ISR and the revised CCRS data (at 90°). The background subtraction of the CCRS results has been changed, resulting in a decreasing e/π ratio with decreasing $p_\perp$, the original version[100] of these data fitted smoothly onto the CHORMN points. In the $p_\perp$ region in which

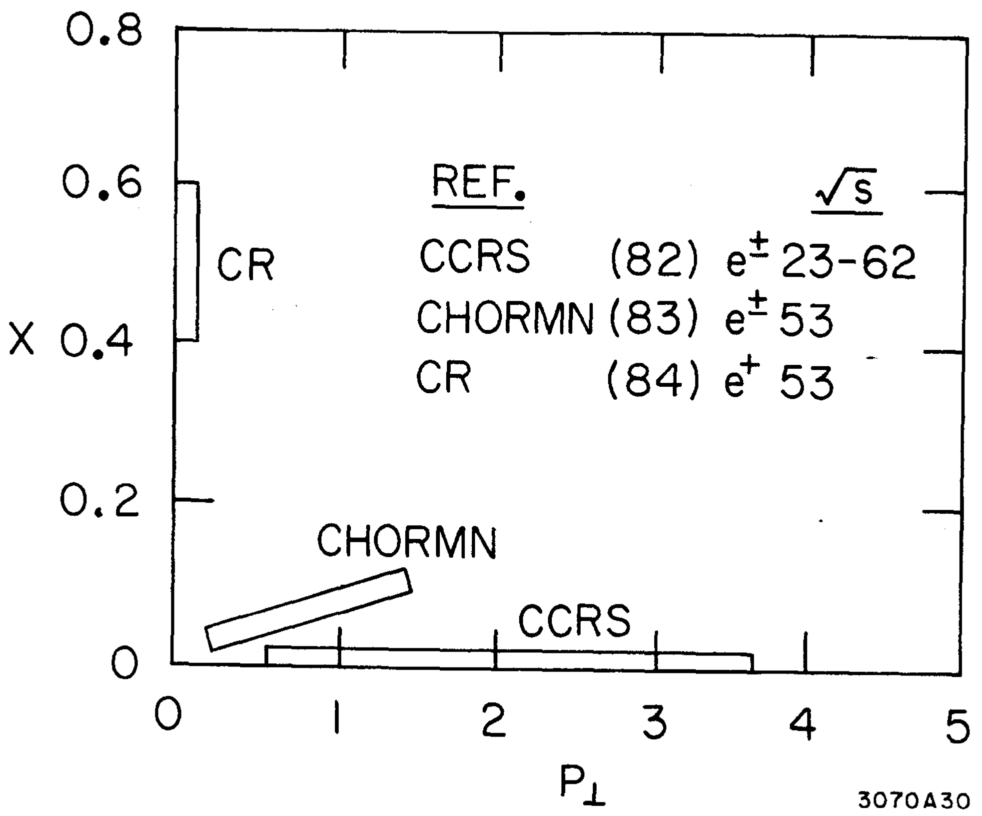


Fig. 21--ISR data on direct lepton production.

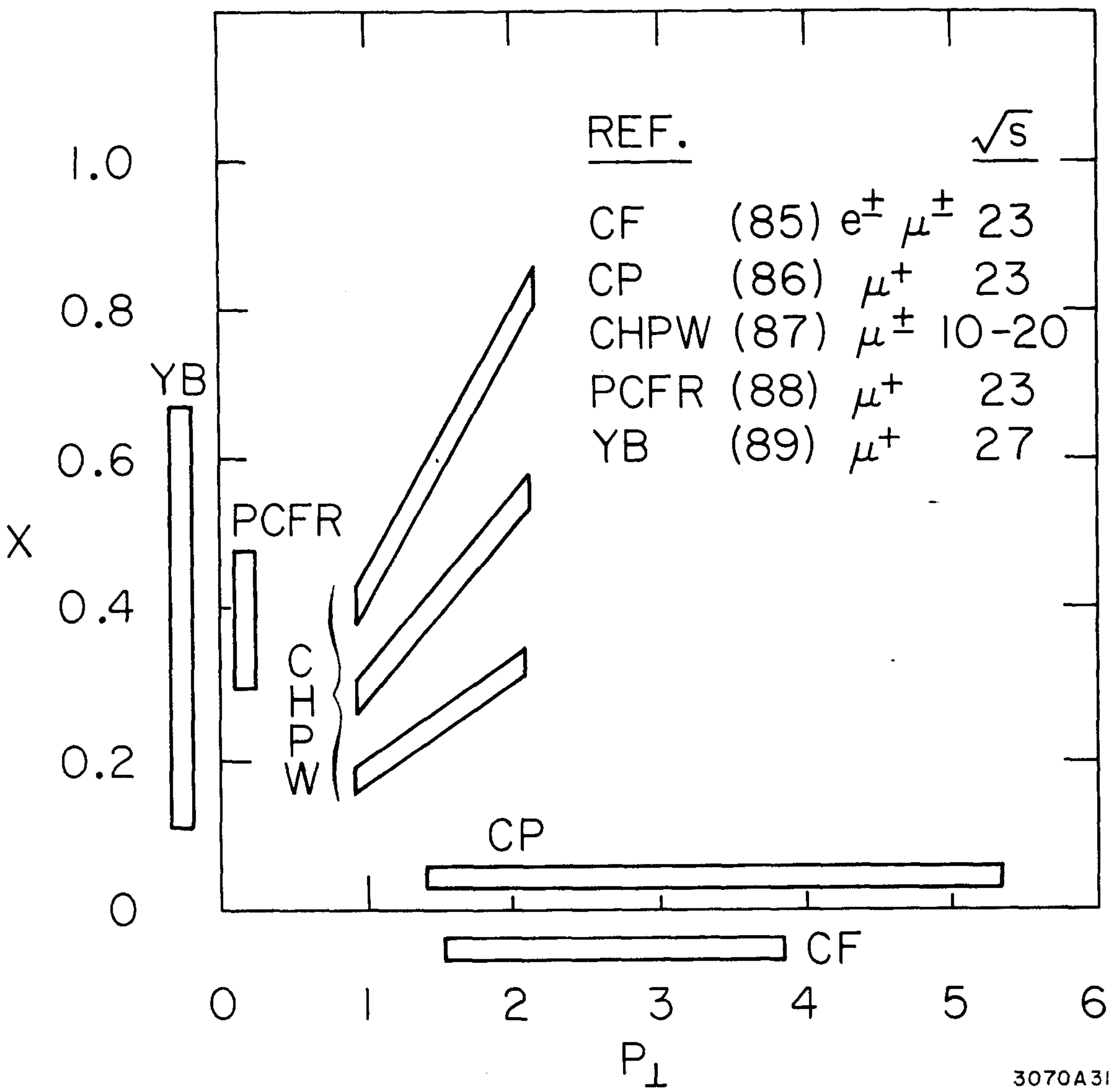


Fig. 22--Fermilab data on direct lepton production.

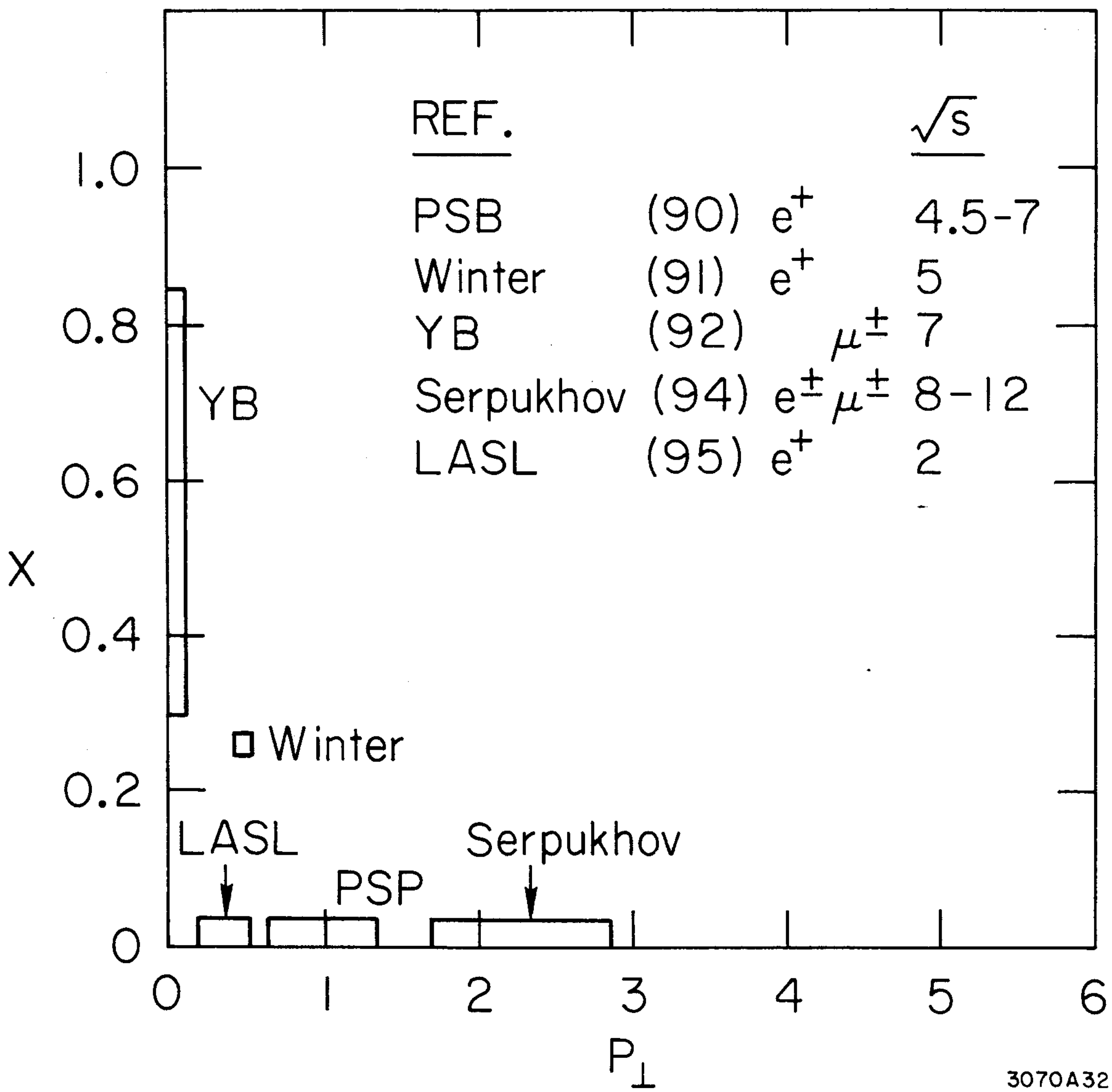


Fig. 23--Data on direct lepton production at machines below 30 GeV.

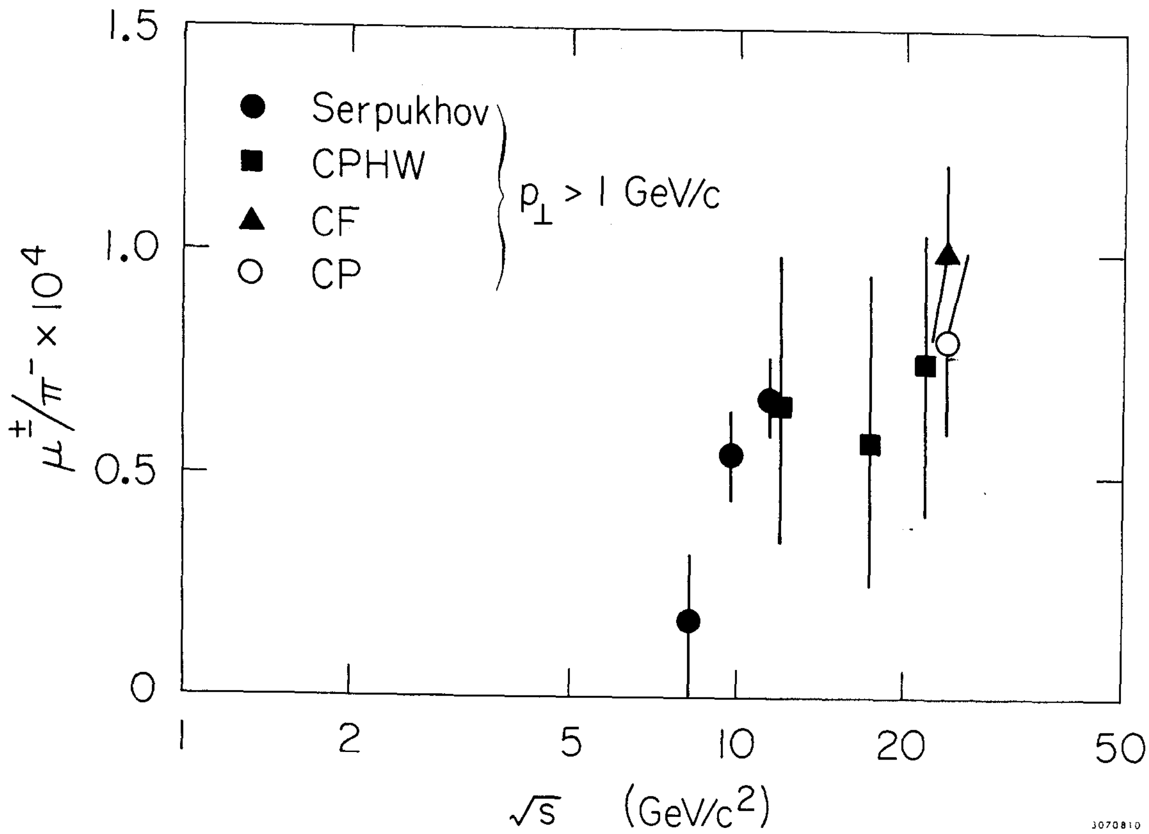


Fig. 24--s-dependence of the μ/π ratio for $p_{\perp} > 1$ GeV/c.

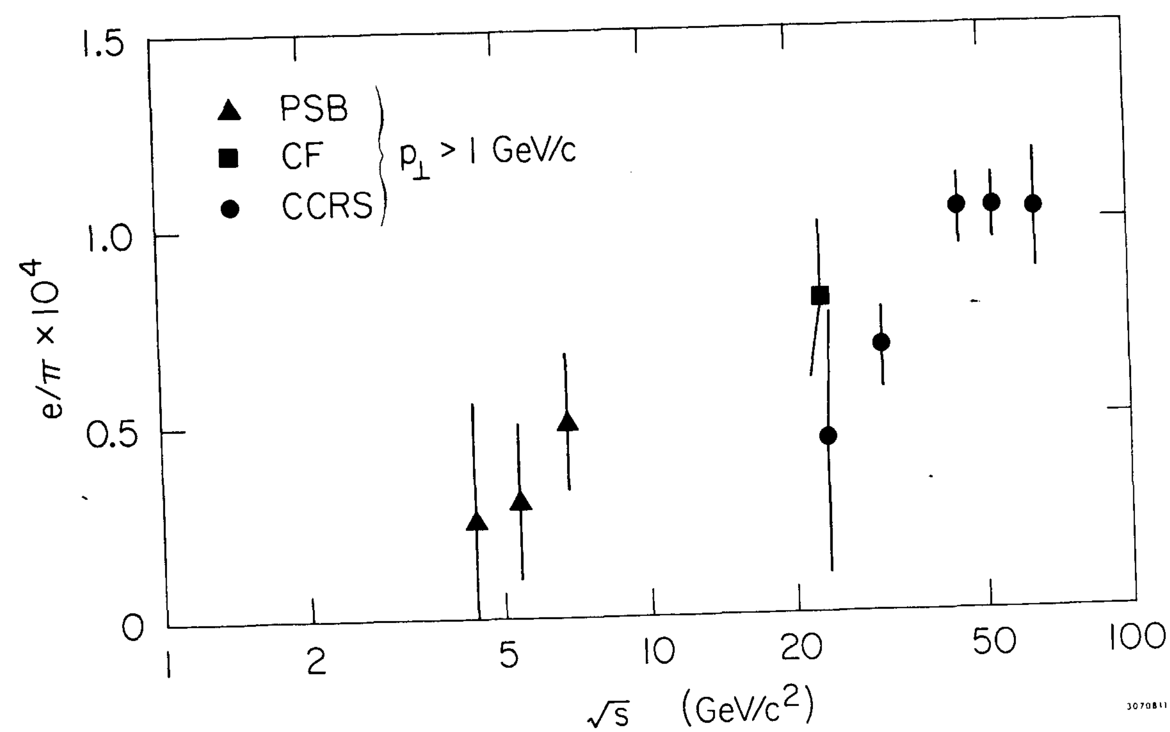


Fig. 25--s-dependence of the e/π ratio for $p_\perp > 1$ GeV/c.

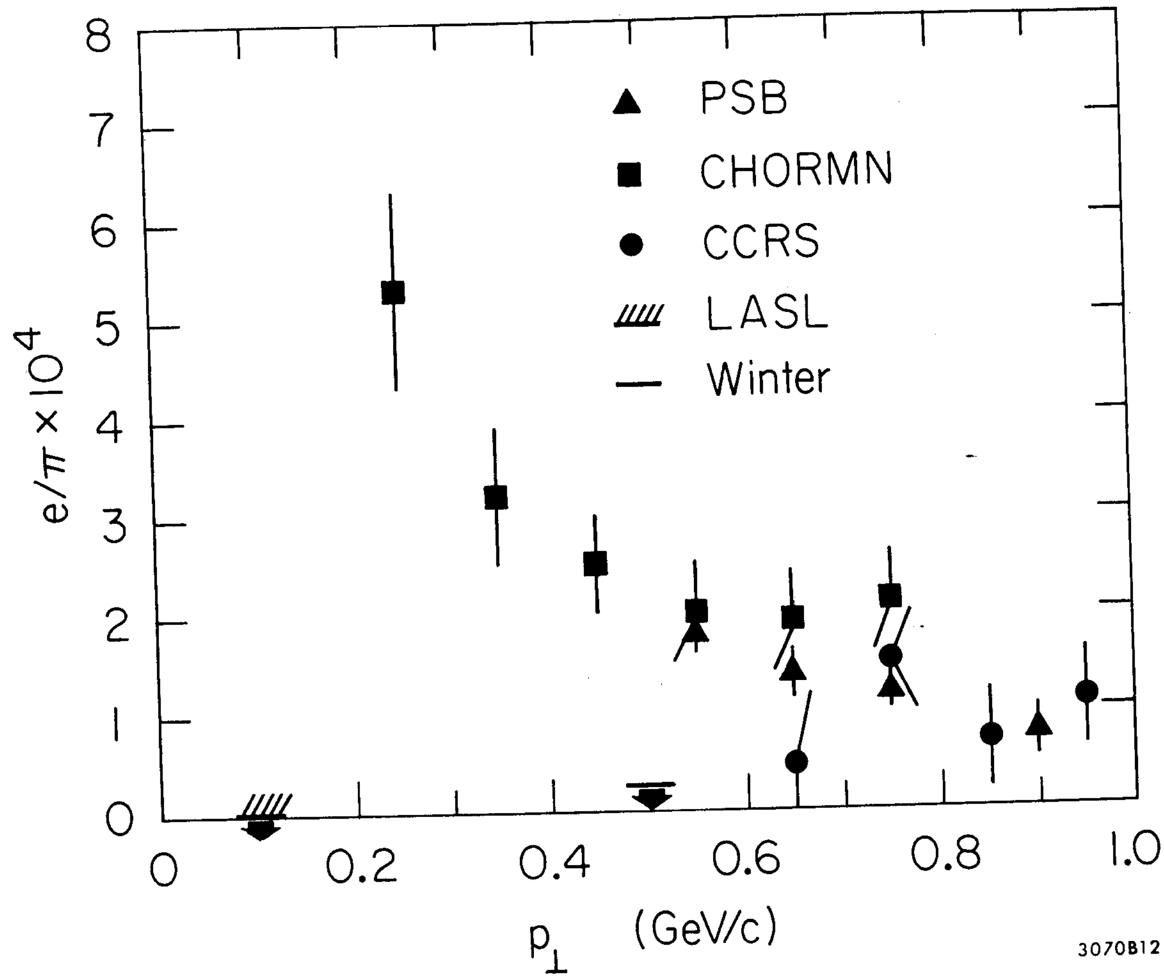


Fig. 26--$p_\perp$-dependence of the e/π ratio for $p_\perp < 1$ GeV/c.

they overlap, the agreement of the CHORMN and PSB data is good.

The measurements of μ/π in the forward direction are shown in Fig. 27. The ratio falls off substantially as x_F approaches 1; this decrease will play an important part in any attempt at a global understanding of the ℓ/π data.

If the origin of the direct lepton signal is the weak decay of a charmed meson or heavy lepton, we would expect the muons to be longitudinally polarized. Since the purely leptonic decay of a pseudoscalar meson is inhibited by angular momentum considerations, semileptonic decay modes are expected to predominate so that V-A couplings produce a μ^+ with positive helicity. Despite the fact that a three body decay produces a yield of leptons which peaks at low $p_\perp$, for typical mass and meson production mechanisms, the ℓ/π ratio actually falls below 1 GeV/c, so that polarized muons are best sought somewhat above a $p_\perp$ of 1 GeV/c. One is faced in these experiments with the necessity to extrapolate the measured polarization to zero hadronic decay length. This has been done by a Yale-BNL group at FNAL[96,97] and in two experiments at Serpukhov,[95] which quote a joint result. The results are shown in Table III. The high energy

TABLE III

Longitudinal polarization of directly produced muons

Group	$\sqrt{s}$	$p_\perp$	p_μ	P
Yale-BNL	27	0 - 1	185	0.0 ± 0.10
	27	2.15	54	-0.15 ± 0.20
Serpukhov	12	2.0 · 2.8	21	-0.85 ± 0.36

results see no significant longitudinal polarization, while the Serpukhov experiments see a significant <u>negative</u> value. The Yale-BNL results are not strong evidence against the contribution of semileptonic decays of charmed particles to

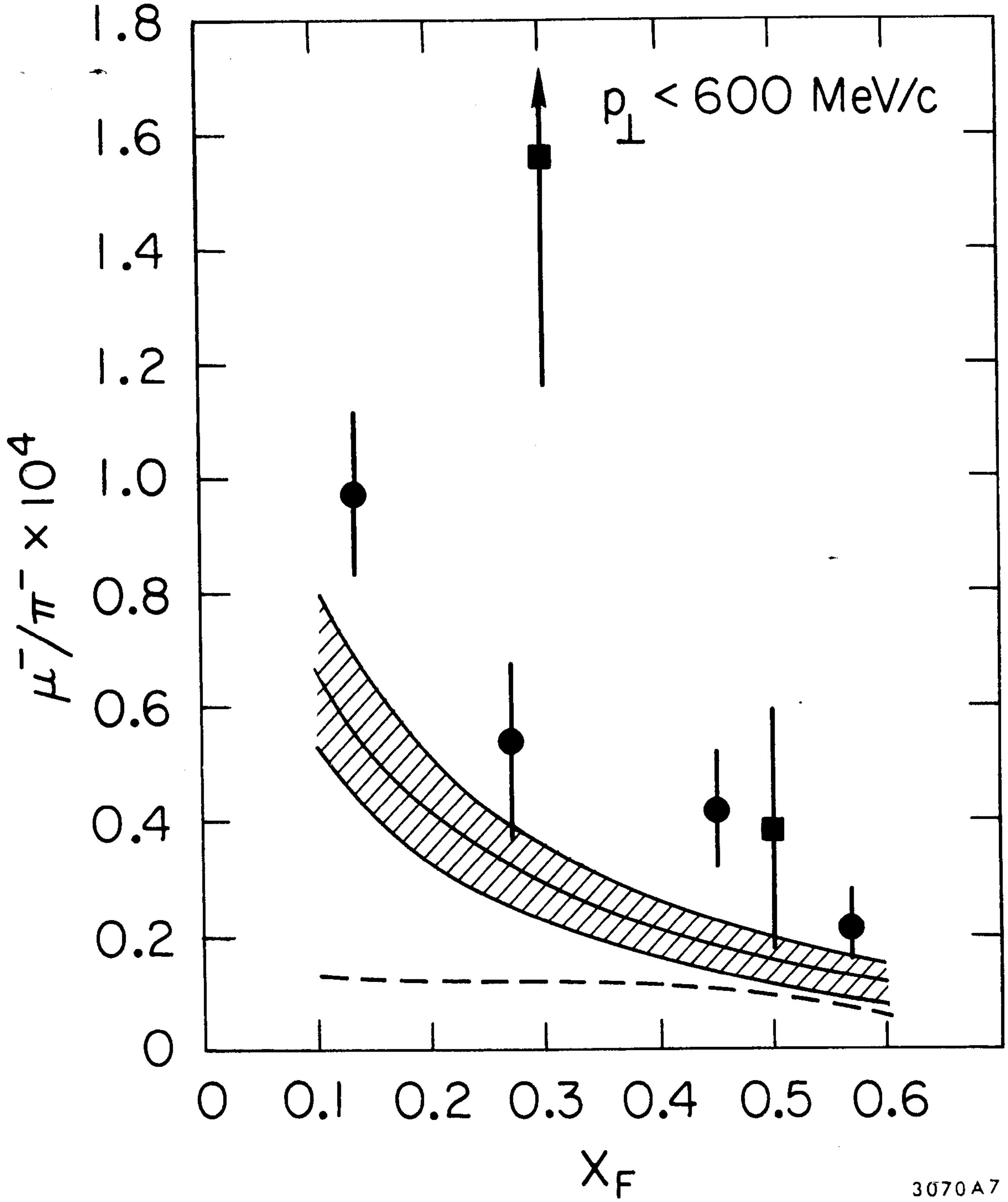


Fig. 27--Measurements of the μ/π ratio at high s as a function of Feynman x. Contribution of muon pairs to the ratio derived by Ref. 99 is shown superimposed.

the direct μ signal, as they bracket the region where the maximum contribution is expected. The Serpukhov result is difficult to interpret. No substantial contribution from charmed particles is expected at this $p_\perp$, even with V+A coupling. π and K decays can yield muons with negative polarization.

There are other features of the direct lepton signal, such as the strange A dependence of the phenomenon, the question of correlations, and the question of charge and lepton symmetry, which have been well summarized by Lederman[101] and will not be dealt with further here.

There have been many attempts to explain the direct lepton signal. It appears reasonably certain that as complex and wide ranging a phenomenon as this will be quantitatively understood in terms of many contributions. As we shall see, new particle production plays a role, but by "new particle" we can only with certainty mean the ψ/J; the contribution of charmed particles remains problematical. The new data at low $p_\perp$ and the large x data cannot be understood in terms of new particle production, but recent experiments on μ pair production may provide the answer here. Let us first find the size of the direct lepton signal due to known sources and then look at the characteristics of the remainder, considering possible sources.

3. Contributions to Direct Lepton Spectra

3.1 Vector Meson Contribution. It has long been clear that the leptonic decays of vector mesons make an important contribution to the direct lepton signal. New data have reinforced this contention and provided better values for cross sections and the $p_\perp$ dependence of production. Bourquin and Gaillard[102] have recently summarized these contributions in an empirical model of production in which the invariant cross section is given by

$$E\frac{d^3\sigma}{dp^3}=A\left(\frac{2}{E_\perp+2}\right)^{12.3} e^{-5.13/Y^{0.38}} \times \begin{cases} e^{-p_\perp}, & p_\perp < 1 \text{ GeV/c} \\ e^{-23(p_\perp-1)/\sqrt{s}}\, e^{-1}, & p_\perp > 1 \text{ GeV/c} \end{cases}$$

with $p_\perp$ in GeV/c, $E_\perp = (m^2+p_\perp^2)^{\frac{1}{2}}$ in GeV/c^2, and

$$Y = \ln\left(\frac{E_{max} + p_{L_{max}}}{E+p_L}\right) .$$

There appears to be reasonable evidence for the factorization assumption. In any case, at $x = 0$ this parametrization works well. The normalization constants A are chosen to fit available data. There is still some disagreement among ρ production cross sections; the suggestion of Bourquin and Gaillard that they could be reconciled by a $1+\cos^2\theta$ decay distribution has not been borne out by experiment. Nonetheless, their choice of $A_\rho = 5.5 \times 10^{-24}$ cm^2/GeV^2 is a decent fit to most data. Based on a single experiment at $\sqrt{s} = 5$ GeV, they choose $A_\omega = A_\rho$. ϕ production mechanisms, as we have seen, should involve the OZI mechanism, for which there is conflicting evidence. Weighing this evidence, Bourquin and Gaillard chose $A_\phi = .15\ A_\rho$, representing the operation of the OZI rule. In their model then, they, as a consequence, predict that, in central collisions at high energy, more than 50% of ϕ's produced should be accompanied by a $K\bar{K}$ pair. ψ/J production is similarly affected by the OZI mechanism, such that the appropriate normalization of the production of ψ/J alone is $A_{\psi/J} = .025\ A_\rho$. This gives a good fit to the data at low s, but is slightly too low at high s (ISR energies). This small discrepancy may be accounted for by the OZI allowed $\psi D\bar{D}$ production mechanism which we have also discussed above. One can set a limit on the $\psi D\bar{D}$ contribution by requiring agreement for $\langle p_\perp \rangle$ at $\sqrt{s} = 23$ and 53 GeV. This limits $\psi D\bar{D}$ to about 20% of ψ alone at $\sqrt{s} = 23$, but $\psi D\bar{D}$ can be a factor of 2 greater than ψ alone at higher s. In this model

$A_{\psi'} = A_{\psi/J}$ provides agreement with the Columbia-Fermilab data on ψ' production. Recently, Craigie and Schildknecht[103] have emphasized that the decays $\omega \to \pi^0 e^+e^-$ and $\eta' \to \gamma e^+e^-$ can make a significant contribution, although in the past this has been neglected with respect to the dominant $V^0 \to \ell^+\ell^-$ decays.

Figure 28 shows the vector meson contributions to ℓ/π at x = 0, .3 and .5 at $\sqrt{s} = 23$ in the Bourquin-Gaillard model. The x = 0 curves are compared to the Columbia-Fermilab and Chicago-Princeton data. The agreement for $2 \leq p_\perp \leq 4$ GeV/c is good, once the substantial contribution of the ψ/J is included. Below $p_\perp = 2$ GeV/c, there is a discrepancy, which may be removed by the semi-leptonic charm decay contribution (see below).

The vector meson contributions at x = .3 and .5 do not account for the Yale-Brookhaven and CCFPR μ/π results shown. Models of the Bourquin-Gaillard type do not fit these data well. No substantial charmed meson contribution is, of course, expected at high x. Modifications of the production assumptions, for example relaxation of the factorization hypothesis, have been made by Hinchliffe and Llewellyn Smith,[33] but the agreement is still poor at high x. The continuum contribution at high x, shown in Figure 27, will be discussed below.

3.2 Charm Contribution. Can leptonic decays of charmed mesons account for the remaining excess at $p_\perp \lesssim 2$ GeV/c? The $p_\perp$ spectra lend some hope to this notion. The decay electron spectra of Fig. 4, for a D meson of mass 1.87 GeV, when folded with a representative D production spectrum, yield the $p_\perp$ distributions shown in Fig. 29 (from Hinchliffe and Llewellyn Smith). With the $D \to K^*e\nu$ spectrum of Yang and Ali,[34] using hard pion form factors and V-A or V+A coupling, it is possible to shift the peak from this decay contribution up or down slightly. The peaking of these distributions below $p_\perp = 1$ GeV/c makes it very attractive to try to fit the CCRS and/or CHORMN data by adding semi-leptonic D decays to the vector meson contribution. This has been done by Bourquin and Gaillard, who considered $D \to Ke\nu$ decay only and by Hinchliffe

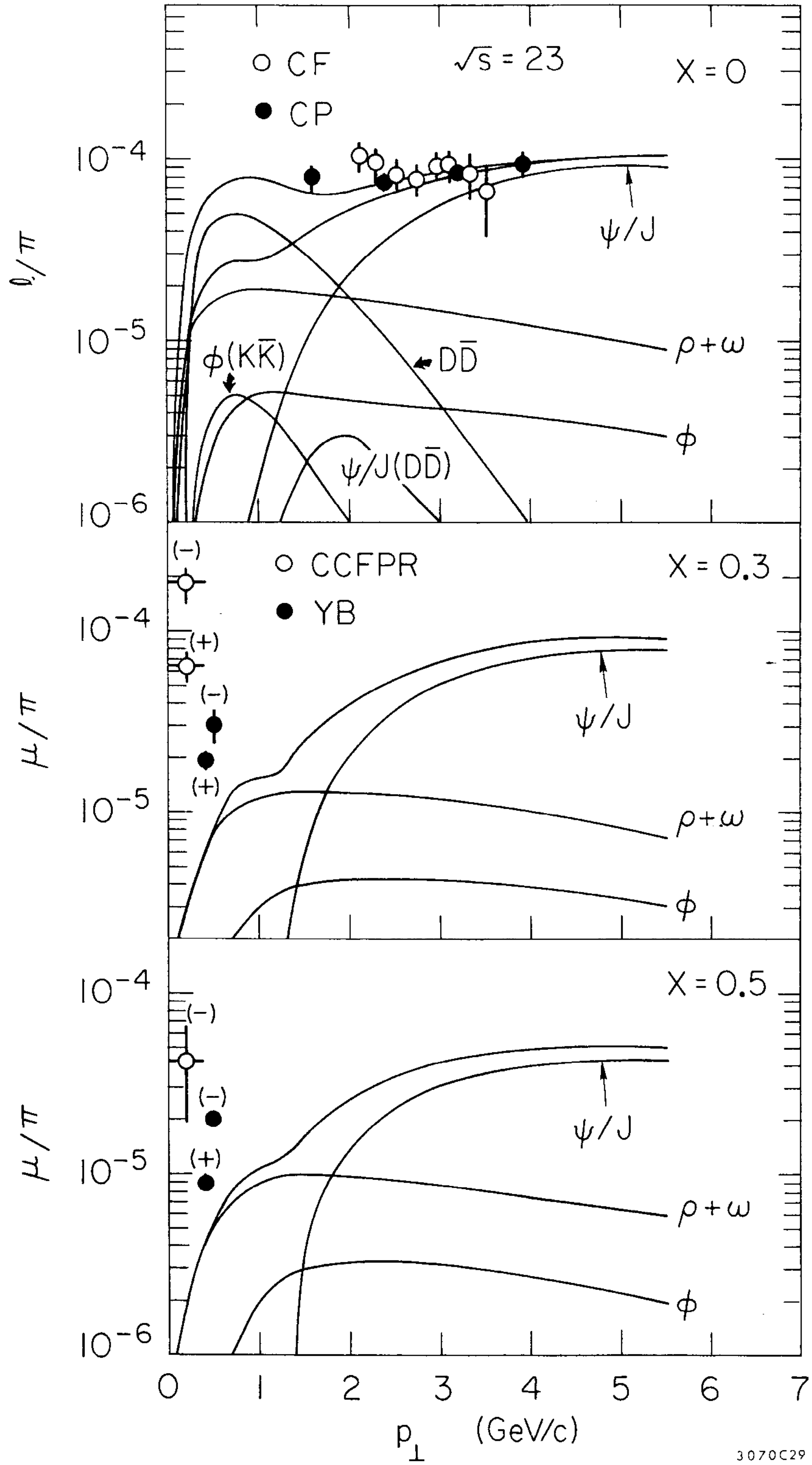


Fig. 28--Vector meson contributions to the ℓ/π ratio as a function of $p_\perp$ at $\sqrt{s} = 23$ for x = 0, x = 0.3, and x = 0.5 (Ref. 102). Data of Refs. 85, 86.

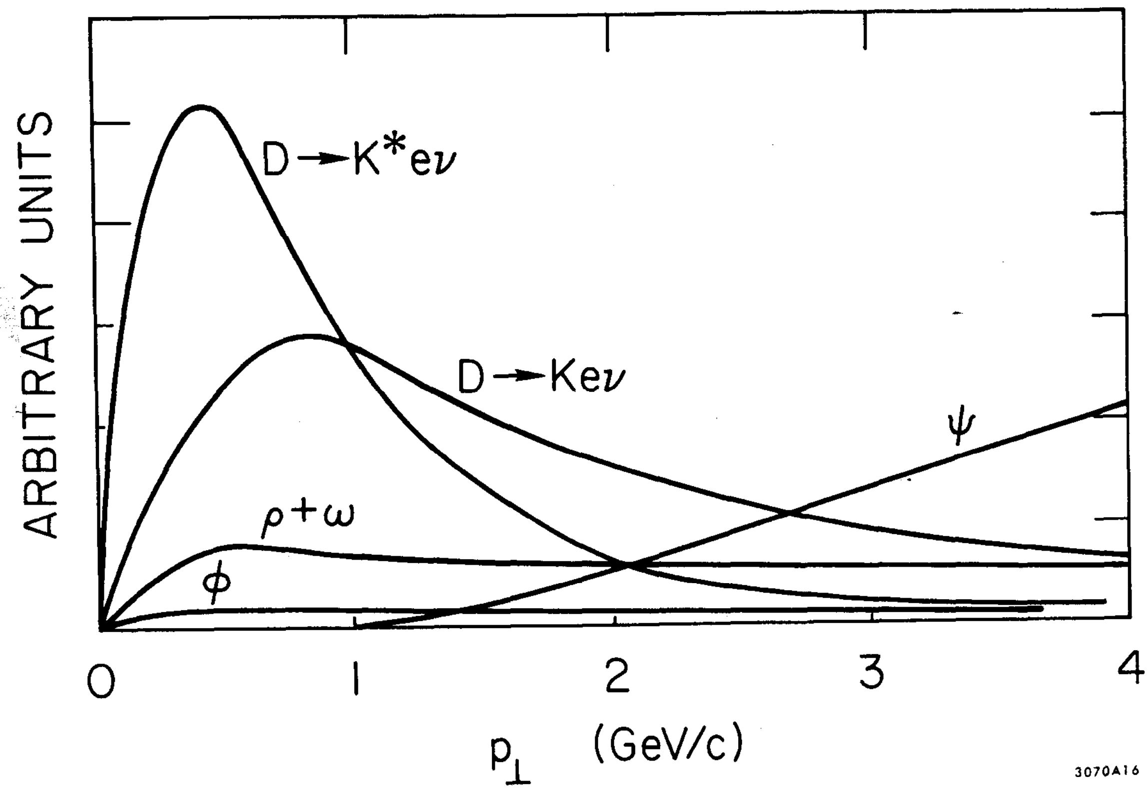


Fig. 29--Contribution to the $p_{\perp}$ dependence of the e/π ratio from D meson decays (Ref. 33).

and Llewellyn Smith, who also calculated the $D \rightarrow K^*e\nu$ contribution, but who did their fit using the CCRS data before it was revised. A fit of this type at $\sqrt{s} = 53$ is shown in Fig. 30. Clearly, neither attempt can account for the lowest $p_\perp$ CHORMN points (or for the high x data, because of the production characteristics).

Bourquin and Gaillard claim success in eliminating the discrepancy for $p_\perp \geq 1$ GeV/c by this mechanism. With a D mass of 1.8 GeV and $D \rightarrow Ke\nu$ only, they require $\sigma B = 3.6 \times 10^{-30} cm^2$ at $\sqrt{s} = 53$ GeV, and $0.8 \times 10^{-3} cm^2$ at $\sqrt{s} = 23$ GeV. For a branching ratio of 10%, this requires a production cross section of 8×10^{-3} cm^2 at $\sqrt{s} = 23$. The University College, London emulsion experiment[62] quoted above, however, sets a limit of $\lesssim 10^{-30}$ cm^2. It is, of course, not possible to claim that this represents a discrepancy until the D semileptonic branching ratio is actually measured. Hinchliffe and Llewellyn Smith find that they can reproduce some of the CHORMN rise at low $p_\perp$ with a $D \rightarrow K^*e\nu$ decay and a $\sigma B = 3 \times 10^{-29}$ cm^2 at $\sqrt{s} = 53$ GeV. This is probably in even worse contradiction to the emulsion experiment, and in addition requires that the $K^*e\nu$ (or $K(n\pi)e\nu$) modes dominate the $Ke\nu$, or else the agreement in the $p_\perp \simeq 1$ GeV/c region is spoiled. It is interesting that the DASP direct electron spectrum[31] also points to the same puzzling dominance of multipion semileptonic decay modes of the D.

Below $p_\perp$ of $\simeq .5$ GeV, neither vector mesons nor semileptonic decays of charmed particles are sufficient to explain the data. This is true of the CHORMN data at $\sqrt{s} = 53$, and of the FNAL μ data at $\sqrt{s} \simeq 23$. The Penn-Stony Brook signal at low s and $p_\perp < 1$ GeV/c is similarly not likely to originate from these sources.

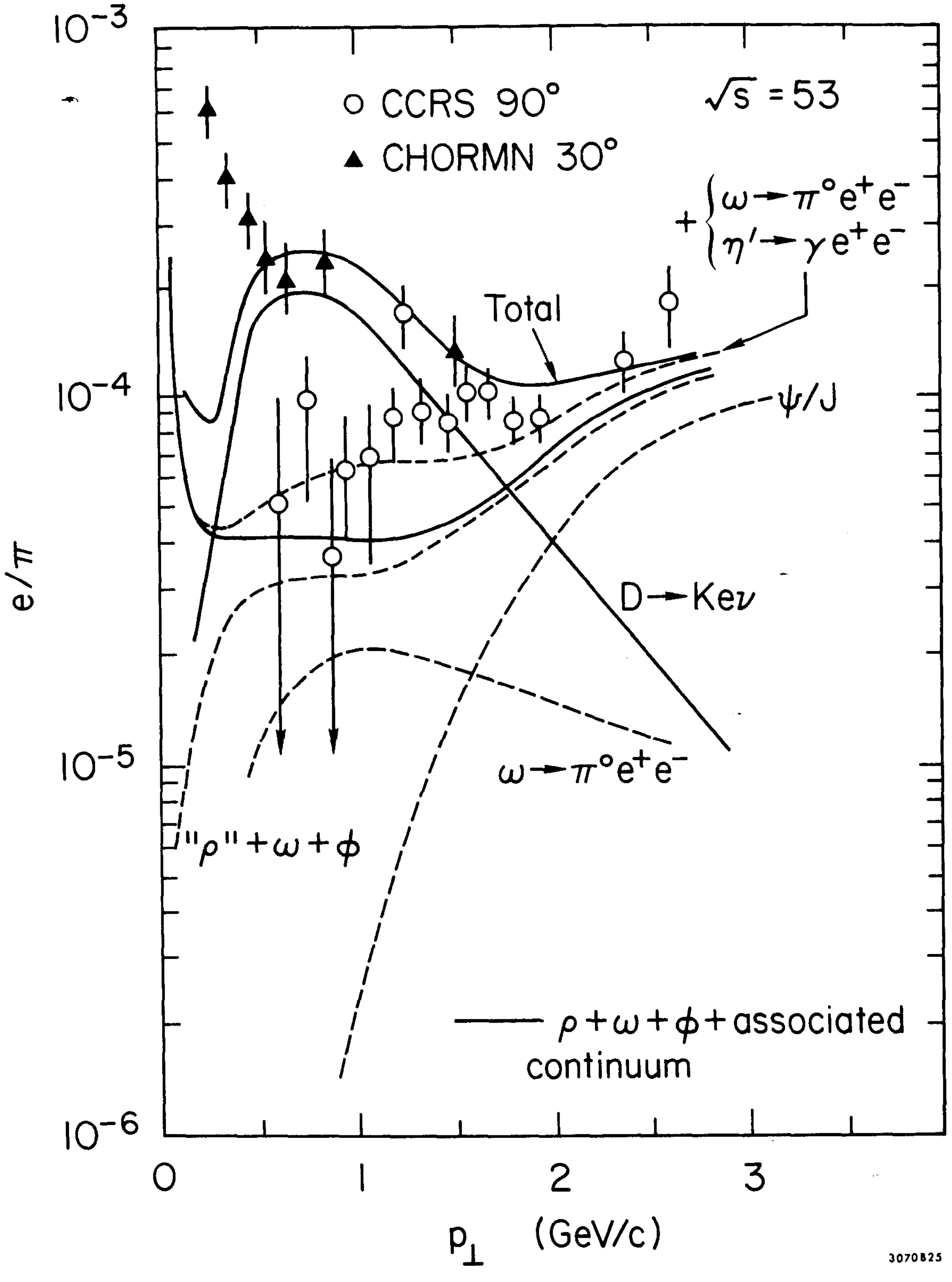


Fig. 30--Vector meson and possible charm contribution to the e/π ratio at $\sqrt{s} = 53$ (Refs. 102, 103). Data of Refs. 82, 83.

Lederman and White[104] have shown that the leptonic decay of a low mass (< 600 MeV) charged meson produced with $\sigma \cdot B = 10^{-3}\sigma_\pi$ can explain many features of the ℓ/π data at low s and low $p_\perp$.

3.3 Continuum Contribution. There is now evidence for the operation of the Drell-Yan mechanism at very high $p_\perp$, although this will not be discussed in detail here. Several modifications have been made to extend these types of calculation to low $p_\perp$. M. Duong-van[105] has included the effect of the transverse momentum of the partons. Bjorken and Weisberg[106] have argued that lepton pairs are produced not only by valence quarks but also by newly produced quarks which have not yet combined to form hadrons. A similar approach by Ranft and Ranft[107] has produced a fit to the CHORMN data. Rückl[108] has been able to reproduce the low $p_\perp$ rise by considering the conversion of soft virtual bremsstrahlung. Several other attempts along these lines have been reviewed by Sullivan.[109]

It now appears that the higher energy anomalies at low $p_\perp$ and high x may be largely explained by the continuum pair mechanism. The Yale-FNAL experiment[98] showed indirectly that most single muons at high x and low $p_\perp$ originate from $\mu^+\mu^-$ pairs. Very recent Chicago-Princeton results[99] (see also A. J. Smith, these Proceedings) make an even stronger case for the pair origin of the single muons in these regions. The Chicago-Princeton group has used their data on $\mu^+\mu^-$ pairs produced by protons on Be at $\sqrt{s} = 16$ GeV to calculate the single muon contribution to the μ/π ratio by Monte Carlo techniques. Their spectrometer has a large acceptance in x_F and $p_\perp$, so that they have been able to make reliable extrapolations to $x_F = 0$. They find that at $x_F = 0$ the continuum contribution is 50% at $p_\perp = 1$ GeV/c and 30% at 2 GeV/c. This does not completely explain the μ/π data: between .75 and 2 GeV/c, about 60% of the total is accounted for. It is in this region that the maximum contribution from $D \rightarrow Ke\nu$ decay is expected. Since D decay is now required to provide only about half as much of ℓ/π contribution as was needed without the measured continuum contribution, the prospects for a contribution due to charm are, if anything, enhanced.

The contribution of $\mu^+\mu^-$ pairs at $x_F > 0$, calculated by the Chicago-Princeton group, is compared with existing data in Fig. 27. The continuum contribution is quite important, and gives a reasonable account of the data.

4. Conclusion. In conclusion, it appears that the direct lepton phenomenon is now largely understood, or soon will be, as certain experimental discrepancies are resolved and measurements of charm production cross sections become available. It appears that the sources are varied, and that, as expected, new particle production does play a role. The dominant contribution at low $p_\perp$, at both low and high s, would appear to be continuum pairs, although low energy pair data are still not available. At intermediate values of $p_\perp$ at high s, there is some room for a contribution from semileptonic D decays. There are upper limits on charmed particle production which place restrictions on this contribution, but it cannot be ruled out that as much as 50% of the ℓ/π ratio in the $p_\perp = .5 - 1.5$ GeV/c region is the result of D decay, and this is, in fact, likely. At higher $p_\perp$, the contribution of the ψ/J is crucial to an understanding of the phenomenon. Recent extensions of the ℓ/π measurements to the $p_\perp = 4\text{-}6$ GeV region, not covered in this lecture, will allow further tests of our understanding of this phenomenon, and may even provide some surprises.

REFERENCES

1. A. Benvenuti et al., Phys. Rev. Lett. 34, 419 (1975), Phys. Rev. Lett. 35, 1199, 1203, 1249 (1975); B. C. Barish et al., Phys. Rev. Lett. 36, 939 (1976); J. von Krogh et al., Phys. Rev. Lett. 36, 710 (1976); H. Deden et al., Phys. Lett. 58B, 361 (1975); J. Blietschau et al., Phys. Lett. 60B, 207 (1976).
2. E. Cazzoli et al., Phys. Rev. Lett. 34, 1125 (1975).
3. G. Goldhaber et al., Phys. Rev. Lett. 37, 255 (1976).
4. I. Peruzzi et al., Phys. Rev. Lett. 37, 569 (1976).
5. J. Siegrist et al., Phys. Rev. Lett. 36, 700 (1976).
6. H. Lynch, SLAC Report No. SLAC-PUB-1750 (1976).
7. A. M. Boyarski et al., Phys. Rev. Lett. 35, 195 (1975).
8. M. Einhorn and C. Quigg, Phys. Rev. Lett. 35, 1114 (1975).
9. S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).
10. H. Harari, Proc. SLAC Summer Inst. in Particle Physics, 1975.
11. S. Borchardt and V. S. Mathur, Rochester Preprint COO-3065-149 (1976).
12. K. Lane and E. Eichten, Phys. Rev. Lett. 37, 477 (1976).
13. A. De Rújula, H. Georgi, and S. L. Glashow, Phys. Rev. Lett. 37, 398 (1976).
14. F. E. Close, Phys. Lett. 65B, 55 (1976).
15. H. Schnitzer, Phys. Rev. D 13, 74 (1976).
16. K. Lane and S. Weinberg, SLAC Report No. SLAC-PUB-1793 (1976).
17. H. Fritzsch, CERN-TH-2191 (1976).
18. W. Celmaster, Phys. Rev. Lett. 37, 1042 (1976).
19. J. Sanchez Guillen, Harvard Preprint HUTP-76/A170 (1976).
20. S. Ono, Phys. Rev. Lett. 37, 655 (1976).
21. G. Goldhaber, these Proceedings.
22. A. De Rújula, H. Georgi, and S. L. Glashow, op. cit.
23. A. De Rújula, Proc. Int. Neutrino Conf. 1976, Aachen, Germany, 8-12 June 1976.

24. B. W. Lee, C. Quigg, and J. L. Rosner, FERMILAB-PUB-76/71-THY.

25. B. Knapp et al., Phys. Rev. Lett. 37, 882 (1976); W. Y. Lee, these Proceedings.

26. B. W. Lee, C. Quigg, and J. L. Rosner, FERMILAB-PUB-76/63-THY.

27. A. De Rújula, S. L. Glashow, and R. Shankar, Phys. Rev. D 14, 752 (1976).

28. R. L. Kingsley et al., Phys. Rev. D 11, 1919 (1975); R. L. Kingsley, Rutherford Laboratory Preprint RL-76-065 (1976).

29. S. L. Glashow and S. Weinberg, Harvard Preprint HUTP-76/A158 (1976); R. L. Kingsley, op. cit.

30. M. K. Gaillard, B. W. Lee, and J. L. Rosner, Rev. Mod. Phys. 47, 277 (1975).

31. W. Braunschweig et al., Phys. Lett. B 63, 471 (1976).

32. J. Burmester et al., DESY 76/50 (1976).

33. I. Hinchliffe and C. Llewellyn Smith, Phys. Lett. 61B, 472 (1976) and Oxford Preprint TP-23/76 (1976).

34. A. Ali and T. C. Yang, DESY 76/39 (1976).

35. V. Barger, T. Gottschalk, and R. J. N. Phillips, Wisconsin Preprint COO-881-569 (1976).

36. V. Barger and R. J. N. Phillips, Phys. Rev. Lett. 36, 1226 (1976).

37. J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. B 100, 313 (1975).

38. A. Burwas and J. Ellis, Nucl. Phys. B 111, 341 (1976).

39. B. Gittleman et al., Phys. Rev. Lett. 35, 1616 (1975); U. Camerini et al., Phys. Rev. Lett. 35, 483 (1975); B. Knapp et al., Phys. Rev. Lett. 34, 1040 (1975); T. Nash et al., Phys. Rev. Lett. 36, 1233 (1976).

40. D. Sivers, J. Townsend, and G. West, Phys. Rev. D 13, 1234 (1976).

41. A. Donnachie and J. Randa, Manchester Preprint 76-0556 (1976); R. Aviv et al., Phys. Rev. D 12, 2862 (1975).

42. U. Camerini et al., op. cit.

43. R. L. Anderson et al., SLAC Report No. SLAC-PUB-1795 (1976).

44. V. Barger, Proc. Canadian IPP Int. Summer School, McGill University, Montreal, June 16-21, 1975.

45. D. M. Ritson, Proc. Vanderbilt Conf. on New Particles: Searches and Discoveries, Nashville, 1976, ed. R. Panvini.

46. W. Y. Lee, Proc. 1975 Int. Symposium on Lepton and Photon Interactions at High Energies, Stanford University, Aug. 21-27, 1975, ed. W. T. Kirk (SLAC, Stanford, 1975).

47. I. Gaines, Proc. Vanderbilt Conf. on New Particles: Searches and Discoveries, Nashville, 1976, ed. R. Panvini.

48. B. Knapp et al., preprint submitted to 18th Int. Conf. on High Energy Physics, Tbilisi, USSR, 15-21 Jul 1976.

49. J. J. Aubert et al., Phys. Rev. Lett. 33, 1404 (1974); Y. M. Antipov et al., Phys. Lett. 60B, 309 (1976); F. W. Büsser et al., Phys. Lett. 56B, 482 (1975); B. Knapp et al., Phys. Rev. Lett. 34, 1044 (1975); K. J. Anderson et al., Phys. Rev. Lett. 36, 237 (1976); G. J. Blanar et al., Phys. Rev. Lett. 35, 346 (1975); E. Nagy et al., Phys. Lett. 60B, 96 (1975); F. Binon et al., CERN Preprint (1975).

50. M. Binkley et al., Phys. Rev. Lett. 37, 571 (1976).

51. H. D. Snyder et al., Phys. Rev. Lett. 36, 1415 (1976).

52. K. J. Anderson et al., preprint submitted to 18th Int. Conf. on High Energy Physics, Tbilisi, USSR, 15-21 Jul 1976.

53. M. Binkley et al., Phys. Rev. Lett. 37, 574 (1976).

54. D. Sivers, Nucl. Phys. B 106, 95 (1976).

55. J. F. Gunion, Phys. Rev. D 12, 1345 (1975).

56. A. Donnachie and P. V. Landshoff, CERN-TH-2166 (1976).

57. G. Farrar, Nucl. Phys. B 77, 429 (1974).

58. G. Chu and J. Gunion, Phys. Rev. D 10, 3672 (1974).

59. V. Blobel et al., Phys. Lett. 59B, 88 (1975).

60. P. L. Woodworth et al. (Omega Collaboration), Phys. Lett. 65B, 89 (1976).

61. R. Donald et al., Phys. Lett. 61B, 210 (1976).

62. D. Davis et al., quoted by D. Sivers, Rutherford Preprint RL-76-026 (1976).

63. M. Binkley et al., Phys. Rev. Lett. 37, 578 (1976).

64. V. Barger and R. J. N. Phillips, Phys. Rev. D 12, 2623 (1975).

65. C. Carlson and R. Suaya, WM-PP 10, PP-12 (1976); S. D. Ellis, M. Einhorn, and C. Quigg, Phys. Rev. Lett. 36, 1263 (1976); F. Halzen, Wisconsin Preprint COO-501 (1976).

66. S. D. Ellis, M. Einhorn, and C. Quigg, op. cit.

67. K. J. Anderson et al., Phys. Rev. Lett. 37, 799 (1976); K. J. Anderson et al., preprint submitted to 18th Int. Conf. on High Energy Physics, Tbilisi, USSR, 15-21 Jul 1976.

68. T. Gaisser, F. Halzen, and M. Paschos, BNL-21489 (1976).

69. D. C. Hom et al., Phys. Rev. Lett. 36, 1236 (1976).

70. H. Lynch, SLAC Report No. SLAC-PUB-1750 (1976).

71. D. Bintinger et al., Phys. Rev. Lett. 37, 732 (1976); E. J. Bleser et al., Phys. Rev. Lett. 35, 76 (1975); J. J. Aubert et al., Phys. Rev. Lett. 35, 416 (1975); M. A. Abolins et al., Phys. Rev. Lett. 37, 417 (1976); N. A. McCubbin, Proc. Vanderbilt Conf. on New Particles: Searches and Discoveries, Nashville, 1976, ed. R. Panvini.

72. For a summary of these results see R. Harris, in Proc. APS/DPF Seattle Meeting, Seattle, 1975, ed. H. J. Lubatti and P. Mochett.

73. J. J. Aubert et al., Phys. Rev. Lett. 35, 416 (1975).

74. B. Ghidini et al., Nucl. Phys. B 111, 189 (1976).

75. M. A. Abolins et al., op. cit.; E. J. Bleser et al., op. cit.; D. Bintinger et al., op. cit.

76. D. Meyer, these Proceedings; D. Bintinger, op. cit.

77. K. Bunnell et al., Phys. Rev. Lett. 37, 85 (1976).

78. V. Cook et al., Washington Preprint VTL-PUB-33 (1976).

79. U. Becker, Proc. Int. Neutrino Conf. 1976, Aachen, Germany, 8-12 June 1976.

80. ISR Experiments R605, R702.

81. J. Cronin, Lectures at the Int. School of Subnuclear Physics, Erice, 1975; L. M. Lederman, Proc. 1975 Int. Symposium on Lepton and Photon Interactions at High Energies, Stanford University, Aug. 21-27, 1975, ed. W. T. Kirk (SLAC, Stanford, 1975); B. Pope, Proc. Int. Conf. on High Energy Physics, Palermo, 1975.

82. F. W. Büsser et al., CERN Preprint 76-0672 (1976).

83. L. Baum et al., Phys. Lett. 60B, 485 (1976).

84. CERN-Rome Collaboration. Quoted by A. Staude, Proc. Int. Neutrino Conf. 1976, Aachen, Germany, 8-12 June 1976.

85. J. A. Appel et al., Phys. Rev. Lett. 33, 722 (1974).

86. J. P. Boymond et al., Phys. Rev. Lett. 33, 112 (1974).

87. D. Bintinger et al., Phys. Rev. Lett. 35, 72 (1975).

88. D. Bucholz et al., Phys. Rev. Lett. 36, 932 (1976).

89. L. B. Leipuner et al., Phys. Rev. Lett. 35, 1613 (1975).

90. E. Beier et al., Phys. Rev. Lett. 37, 1117 (1976).

91. K. Winter, Phys. Lett. 57B, 479 (1975).

92. L. Leipuner et al., Phys. Rev. Lett. 34, 103 (1975).

93. V. V. Abramov et al., Serpukhov Preprint IFVE 76-92 (1976).

94. A. Browman et al., Phys. Rev. Lett. 37, 246 (1976).

95. N. Z. Anisimova et al., Phys. Lett. 65B, 85 (1976).

96. L. Leipuner et al., Phys. Rev. Lett. 36, 1011 (1976).

97. M. J. Lauterbach et al., Brookhaven Preprint BNL-21852 (1976).

98. H. Kasha et al., Phys. Rev. Lett. 36, 1007 (1976).

99. K. J. Anderson et al., Phys. Rev. Lett. 37, 803 (1976).

100. F. W. Büsser et al., Preprint submitted to 1975 Int. Symposium on Lepton and Photon Interactions at High Energies, Stanford University, Aug. 21-27, 1975.

101. L. Lederman, op. cit.

102. M. Bourquin and J.-M. Gaillard, CERN Preprint 76-0393 (1976).

103. N. Craigie and D. Schildknecht, CERN-TH-2193 (1976).

104. L. Lederman and S. White, Phys. Rev. Lett. 35, 1543 (1975).

105. M. Duong-van, Phys. Lett. 60B, 287 (1976).

106. J. D. Bjorken and H. Weisberg, Phys. Rev. D 13, 1405 (1976).

107. J. Ranft and G. Ranft, Phys. Lett. 62B, 57 (1976).

108. R. Rückl, Max Planck Institute Preprint MPI-PAE/PTh 10/76 (1976).

109. J. D. Sullivan, Proc. Vanderbilt Conf. on New Particles: Searches and Discoveries, Nashville, 1976, ed. R. Panvini.