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POSSIBLE PRODUCTION OF CHARMED HADRONS IN CONJUNCTION WITH THE $\psi(3100)$ *

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ABSTRACT

If the $\psi(3100)$ is interpreted as a bound state of a $c\bar{c}$ pair, then the dynamical mechanism which suppresses its strong decays should also imply that it is produced copiously in association with charmed hadrons. Model calculations indicate the feasibility of looking for charmed particles in events where there is a ψ.

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I. INTRODUCTION

One popular interpretation of the properties of the $\psi(3100)$ and $\psi(3700)$ resonances[1,2] is that they are bound states of a quark-antiquark pair in which the constituents carry a new additive quantum number.[3] It seems a reasonable hypothesis to identify this new quantum number with "charm", the quality originally proposed to explain anomolies in weak neutral current interactions.[4] Specific models for the new narrow states based on this identification have been proposed which predict further properties of the charmed quarks and, by inference, charmed hadrons.[5]

Supported by the new results, a great deal of experimental effort is currently being expended to detect and study charmed hadrons, that is, hadrons which carry the charmed quark bound to ordinary uncharmed constituents. One way to do such a search relies on theoretical models for the decay modes of the hypothetical particles and consists of looking with high precision for narrow spikes in the mass spectra of the appropriate two-body decay channels. Estimates of the nonleptonic decay channels[6] and of cross sections for the associated production of charmed particles[7] suggest that such searches might face significant problems due to a small signal-to-noise ratio.

In this note we would like to point out that the interpretation of ψ particles as $c\bar{c}$ states and the related dynamical rules which suppress their decays into ordinary hadrons imply a mechanism for the strong production of charmed hadrons <u>in conjunction with</u> ψ's. Simple calculations suggest that a high energy experiment which triggers on the detection of a massive lepton pair is quite likely to have a pair of charmed particles among the final state hadrons. Because this type of experiment would have a large signal in comparison with background it should be possible to detect the charmed particles through their decay into any one of the many possible channels. Even though the cross section for producing a ψ and a pair of charmed particles should be substantially lower than the cross section for producing the charmed particles alone, the lower background may make the detection of charmed particles compensatingly easier.

Section II outlines the origin of the speculation concerning the conjoint production of ψ's and charmed hadrons in terms of an empirical dynamical interpretation known as Zweig's rule. Section III demonstrates the calculation of ψ cross sections, with and without charmed particles, in three simple models. The one-dimensional multiperipheral model, the Drell-Yan[8] model and the independent emission model[9] all suggest that in pp collisions at Fermilab and CERN-ISR energies the production of ψ's in conjunction with $c\bar{c}$ pairs should dominate the production of ψ's alone. In Section IV we indicate how the fundamental assumption underlying this suggestion can be tested independently by measuring the number of strange particles produced in association with the $\phi(1019)$. In Section V we summarize the arguments and draw some conclusions.

II. ZWEIG'S RULE AND THE VIEW OF THE ψ AS A $c\bar{c}$ STATE

To understand the production of ψ's in hadron collisions we need to consider the dynamical implications of Zweig's rule. This empirical rule is a necessary corollary of any attempt to understand the ψ's as bound states of c and $\bar{c}$ quarks. It can be expressed most simply in terms of quark-line diagrams. All diagrams which contain a quark-antiquark line terminating within the same hadron are suppressed. Some examples of forbidden diagrams are shown in Fig. 1. In the quark model this rule is used to explain the small decay rate for $\phi(1019) \rightarrow 3\pi$. The fact that the empirical result can be expected to be valid for exchange diagrams as well as decays can be deduced from the experimental ratio[10]

$$\frac{d\sigma/dt\,(\pi^- p \to \phi n)}{d\sigma/dt\,(\pi^- p \to \omega n)} \cong \frac{1}{280} \tag{2.1}$$

Detailed analysis suggests the dominant contribution to $\pi^- p \to \phi n$ is not from the ρ exchange diagram drawn in Fig. 1b but from K-$\bar{K}$ Regge cuts.[11]

In the charmed-quark model for the ψ's, the rule is used to explain the small decay rates $\psi(3100) \to$ hadrons, $\psi(3700) \to$ hadrons as well as $\psi(3700) \to \psi(3100) + 2\pi$. It can be expected that the rule works better for charmed quarks than for strange quarks in approximately the ratio

$$\frac{\Gamma(\psi \to \text{hadrons})}{m_\psi} \, \frac{m_\phi}{\Gamma(\phi \to 3\pi)} = 0.10 \tag{2.2}$$

The couplings derived from this rule can be shown[12] to give a quantitative understanding of the production of the ψ's in pp collisions at $p_{lab} = 28.5$.

If we assume the empirical validity of Zweig's rule we can deduce that the two types of multiperipheral quark-line diagrams for the production of ψ's in high energy collisions shown in Fig. 2 have vastly different properties. In diagrams 2a, the coupling of a ψ to hadrons through a Zweig-forbidden coupling, h, is indicated schematically. From the arguments above, the coupling constant, h, must be considerably smaller than typical hadronic values. The second possibility, indicated in Fig. 2b, is for the ψ to be produced in conjunction with a pair of charmed particles. Since the quark and antiquark from the ψ can now terminate on different particles this diagram is allowed by Zweig's rule and the mechanism it represents should be strong. However, since the charmed particles are presumed to have large masses (in the range $2 - 2\frac{1}{2}$ GeV for mesons and $2\frac{1}{2} - 3$ GeV for baryons[13]) this contribution to ψ production is suppressed kinematically. For example, at $p_{lab} = 28.5$ GeV/c where the ψ is observed in the process $pp \rightarrow e^+e^-$ + anything this configuration cannot contribute because we are below threshold for the hypothetical process

$$pp \rightarrow p\, C_0^+ D_0 \psi, \quad \sqrt{s_{thresh}} \cong 9.3 \text{ GeV} \tag{2.3}$$

where C_0 is a charmed baryon (udc) and D_0 is a charmed meson ($\bar{c}u$). Another feature of the graph in Fig. 2b indicates a small cross section. The multiperipheral configuration implies the exchange of a charmed Regge trajectory and since we believe this trajectory must have a low intercept we know that the heavy particles must have small subenergies relative to each other. This cuts down the amount of phase space available.

If, however, we are to take Zweig's rule seriously we would expect that diagrams of the type 2b will dominate at ultra-high energies since broken SU(4) would indicate that all the coupling constants are the same order of magnitude. At high energy, events which contain ψ's should usually contain charmed particles. An experiment which triggers on ψ's should be able to detect charmed particles by looking for bumps in various possible leptonic and nonleptonic decay channels. It is notable that we would expect on simple statistical grounds a more or less random assortment of charmed baryons and of charmed and anticharmed mesons. This contrasts with experiment where, by focusing with high sensitivity at one particular decay mode it is possible to detect only one type of charmed particle.

It is an extremely attractive idea that the mechanism which prohibits the strong decay of the ψ's in a $c\bar{c}$ model should also remove unwanted hadronic background in the search for actual charmed particles.

III. MODELS FOR THE PRODUCTION OF ψ'S AND CHARMED PARTICLES

The problem considered here is to demonstrate the application of Zweig's rule to explicit model calculations for the production of ψ's and charmed particles.

The goals of the calculations are to estimate the asymptotic ratios of the appropriate cross sections and to gain some understanding of the kinematic constraints. Since the kinematics involved in producing three massive states, a ψ and two charmed hadrons, in the same event indicate a substantial suppression even at Fermilab and CERN-ISR energies it is important to consider the interplay of dynamic and kinematic effects. The models calculated here necessarily involve unknown constants and assumptions involving the properties of the hypothetical charmed particles. No single model is completely reliable so we will estimate cross sections in three different ways.

One-Dimensional Multiperipheral Model

We first consider a simple multiperipheral model. The treatment of kinematics in this approach is highly over-simplified but the calculation does illustrate directly the application of Zweig's rule and has many features in common with more realistic models. In a multiperipheral model[14] we can write the cross section for producing a ψ at rapidity y and n+2 other hadrons involving the repeated exchange of a meson trajectory $\alpha \cong 1/2$, as

$$\frac{d\sigma(\psi, n+2)}{dy} \cong \frac{\sigma_0 h^2}{s^2} (g^2)^n \exp\left[2\alpha(Y-Y_0)\right] \sum_{j=1}^{n} \frac{y^j}{(j)!} \frac{(Y-Y_0-y)^{n-j}}{(n-j)!} \tag{3.1}$$

where g is an ordinary hadronic coupling constant, h is the Zweig-forbidden coupling constant, and $Y = \ell n\, s$. The kinematic constraint of making a heavy ψ is input by making $(Y-Y_0)$ the amount of one-dimensional phase space available for particle production in the presence of a massive ψ. The parameter Y_0 is then a "pseudo-threshold" for ψ production in rapidity space which, for illustrative purposes, we fix

$$Y_0 \cong 2 = \ell n\left(m_\psi^2\right) \tag{3.2}$$

In the limit where at most one ψ is produced per event we can write the integrated cross section

$$\sigma(\psi,\text{alone}) \cong h^2(Y-Y_0)\exp\left[(2\alpha-2+g^2)(Y-Y_0)\right]\exp\left[-2Y_0\right] \tag{3.3}$$

With the values $\alpha \cong 1/2$ and $g^2 \cong 1$ we have $(2\alpha-2+g^2) \cong 0$ and $\sigma_{inel}(Y)$ is approximately energy independent. Comparison of the model with BNL data[2] on ψ production gives

$$\frac{\langle n_\psi \rangle}{\langle n_\pi \rangle} \cong \frac{h^2(Y-Y_0)\exp\left[-2Y_0\right]}{g^2 Y} \tag{3.4}$$

so that

$$h^2 \cong 10^{-6} \tag{3.5}$$

This is in line with the kind of numbers we might expect from Zweig's rule[12] and gives us confidence that, in spite of the oversimplified kinematics, the model may be valid for order of magnitude estimates.

In order to generalize the one-dimensional model to the production of charmed particles we need input some additional parameters. One new parameter is the intercept of a typical charmed trajectory. In this we follow Field and Quigg[7] and use

$$\alpha_c \cong -0.62 \tag{3.6}$$

For convenience, we denote the associated pair of charmed particles $D\bar{D}$ even though we expect all types of charmed mesons and baryons. The cross section for producing a ψ and the $D\bar{D}$ can be approximately written

$$\frac{d\sigma(\psi;D\bar{D})}{dy_D\, dy_\psi\, dy_{\bar{D}}} \cong 2\, g_c^2\, 3\, \frac{\sigma_0}{s^2} \exp\left[(2\alpha+g^2)(Y-\Delta)\right] \exp\left[\left(2\alpha_c+g_c^2\right)\Delta\right] \tag{3.7}$$

where $y_D < y_\psi < y_{\bar{D}}$ and $y_{\bar{D}} - y_D \equiv \Delta$. The coupling constant g_c when normalized this way is expected by approximate SU(4) to be the same order of magnitude as g but we allow for the fact that t_{min} effects along the multiperipheral chain may make it slightly smaller. The kinematic suppression due to the mass of the heavy particles in input by requiring a minimum rapidity gap between the two charmed particles,

$$\Delta > \Delta_{min}$$

with

$$\Delta_{min} \cong \ell n \left((2m_D + m_\psi)^2 \right) \cong 4.2 \tag{3.8}$$

We again use the approximation $(2\alpha - 2 + g^2) \cong 0$ and integrate over rapidities to get

$$\sigma(\psi; D\bar{D}) \cong 2\left(g_c^2\right)^3 (Y - \Delta_{min}) \frac{\left[1 + \left(2 - 2\alpha_c - g_c^2\right)\right]}{\left(2 - 2\alpha_c - g_c^2\right)^2} \times$$

$$\times \exp\left[-\left(2 - 2\alpha_c - g_c^2\right)\Delta_{min}\right] \sigma_{inel}(Y - \Delta_{min}) \tag{3.9}$$

Comparing the cross section for the production of a ψ in conjunction with a pair of charmed particles, (3.9), with its production along, Eq. (3.3), we get

$$\frac{\sigma(\psi; D\bar{D})}{\sigma(\psi; \text{alone})} \cong A\left(g_c^2\right) \frac{(Y - \Delta_{min})}{(Y - Y_0)} \tag{3.10}$$

where $A\left(g_c^2\right)$ is a rapidly-varying function of g_c^2 plotted in Fig. 3. We see that the ratio becomes large for g_c^2 near g^2. In the same model the cross section for producing a $D\bar{D}$ pair without a ψ can be written

$$\sigma(D\bar{D}) \cong 2\left(g_c^2\right)^2 (Y - \Delta_{min}) \frac{\exp\left[\left(2\alpha_c + g_c^2 - 2\right)\Delta_{min}\right]}{\left(2 - 2\alpha_c - g_c^2\right)} \sigma_{inel}(Y - \Delta_{min}) \tag{3.11}$$

where $\Delta_{min} \cong 3.2$ represents here the pseudothreshold for producing a charmed pair. The ratio $\sigma(\psi; D\bar{D})/\sigma(D\bar{D})$ at large Y is plotted as a function of g_c^2 in Fig. 4.

We have an additional piece of experimental information which is particularly informative. The measurement of NN $\rightarrow \psi$ + anything at Fermilab[15] can be estimated to be

$$\sigma(\psi) \cong 200 - 800 \text{ nb} \tag{3.12}$$

where the main uncertainty involves an extrapolation into the central region. Based on the simple model and the BNL data we estimate the contribution of the Zweig-forbidden configuration to be at these energies

$$\sigma(\psi;\text{alone}) \cong 6 - 10 \text{ nb} \tag{3.13}$$

In spite of the simple kinematics we see that the energy dependence of the inclusive cross section is suggestive that there are two mechanisms in operation. In terms of our interpretation of Zweig's rule we would suggest that the contribution of the mechanism with a pair of charmed particles in the final state is 20 - 130 times bigger than the cross section for producing a ψ alone.

In the simple one-dimensional model this fixes

$$g_c^2 \in (0.33 - 0.48) \tag{3.14}$$

and indicates that the cross section for producing charmed particles

$$\sigma(D\bar{D}) \cong 10^{-3}(Y-\Delta_{min}) \times \sigma_{inel}(Y-\Delta_{min}) \tag{3.15}$$

It is hard to estimate just how reliable these figures are due to the many assumptions and parameters in the model but the conclusion that triggering on a ψ dramatically improves the background in a charm search seems valid.

The Drell-Yan Model

The alternative to the one-dimensional multiperipheral model which shares the advantage of being easy to calculate is the Drell-Yan model for ψ production. The application of the Drell-Yan quark-antiquark annihilation contribution to ψ production has been discussed in more detail elsewhere.[12,16] In this approach the assumptions concerning Regge trajectory intercepts, couplings, etc. are replaced by assumptions on quark coupling constants and distribution functions in the proton. In principle, these can be determined separately from other experiments. We write the integrated cross section for pp $\rightarrow \psi$ + anything

$$\sigma(\psi) = \frac{8\pi^2}{3m_\psi^2} \left\{ \tau \int_\tau^1 \frac{dx}{x} \sum_i \left(\frac{h_i^2}{4\pi}\right) \left[f_i(x)\, \bar{f}_i(\tau/x) + \bar{f}_i(x)\, f_i(\tau/x) \right] \right\} \tag{3.16}$$

where $\tau = m_\psi^2/s$, $f_i(x)$ are the quark distribution functions for the proton and h_i is the coupling of the ψ to a $q\bar{q}$ pair. We can divide this contribution if the ψ is interpreted to be a $c\bar{c}$ bound state naturally into two parts. The coupling of the ψ to ordinary u, d, s quarks is assumed small by Zweig's rule whereas the coupling to a $c\bar{c}$ quark pair should be large. Examining the quark-antiquark annihilation diagram we see that removing a c from one hadron and a $\bar{c}$ from the other leaves traces of the charm quantum number in the kinematic region of the parton hole. In the spirit of the parton model we should neglect the probability that these parton holes annihilate each other and we should therefore interpret the production of a ψ from a $c\bar{c}$ pair to imply that it is accompanied by the associated production of a pair of charmed particles. Again the parton model would suggest that the charmed quark would combine with other quarks or anti-quarks in a statistically independent manner to produce an assortment of charmed particles.

In the context of this model we can calculate the coupling constants $h_{u,d,s}$ under the assumption that the ψ couples equally to all of them and the hadronic decay of the ψ is dominated by the process $\psi \rightarrow q\bar{q} \rightarrow$ hadrons,

$$\Gamma_{\psi \rightarrow \text{had}} \cong \frac{1}{(2J+1)} \left(\sum_{i=u,d,s} \frac{h_i^2}{4\pi} \right) m_\psi \tag{3.17}$$

Plugging in the direct width 50 keV,[3] we get

$$\left(\frac{h_i^2}{4\pi}\right)_{i=u,d,s} \cong 1.6 \times 10^{-5} \tag{3.18}$$

Note that one difference in these coupling constants and the coupling constant, h Eq. (3.1) in the previous section, is that h represented the coupling of ψ to a specific 2-hadron channel and is expected to be correspondingly smaller. In accordance with our interpretation of the ψ as a $c\bar{c}$ state we assume

$$\left(\frac{h_c^2}{4\pi}\right) \cong 1 \tag{3.19}$$

The one step remaining in order to use (3.16) is to parametrize the quark distribution functions. For the u, d, s quarks these can be approximately determined from fits to deep inelastic lepton scattering. For definiteness we use the distribution functions of Farrar,[17] which are consistent with dimensional counting rules[18]

$$\begin{aligned} f_u(x) &= \frac{.2(1-x)^7}{x} + \frac{1.89(1-x)^7}{x^{1/2}} + 5(1-x)^3 \\ f_d(x) &= \frac{.2(1-x)^7}{x} + \frac{1.03(1-x)^7}{x^{1/2}} + 5(1-x)^3 \\ \bar{f}_u(x) &= \bar{f}_d(x) = f_s(x) = \bar{f}_s(x) = \frac{0.2}{x}(1-x)^7 \end{aligned} \tag{3.20}$$

These distributions functions and the couplings (3.17) have been shown to give an order of magnitude estimate for the production of ψ's.[12,16]

Dimensional counting rules suggest the distribution of charmed quarks should have the same general behavior as that of the strange quarks. If we allow for considerable SU(4) breaking in the amount of charm, we might write

$$f_c(x) = \bar{f}_c(x) = \epsilon f_s(x) \tag{3.21}$$

where ϵ is a parameter to be determined. Purely on the basis of the Drell-Yan model for the production of ψ's in pp collisions, the ϵ can be absorbed into the normalization of the ψ $c\bar{c}$ coupling constant but the comparison of other experiments, γp, πp, etc., removes this ambiguity. The ratio of the $c\bar{c}$ annihilation contribution to the ψ production process to that of the noncharmed quarks for various values of ϵ is shown in Fig. 5 as a function of energy. An interpretation of $\gamma p \to \psi$ + anything has been used to estimate a bound on the charm quark distribution.[19] In this figure we see that there is expected to be considerable energy dependence in the Fermilab range but that a reasonable amount of charmed quark suppression in the proton will allow the associated production of charmed particles.

The Independent Emission Model

The multiperipheral model and Drell-Yan model discussed previously are mechanisms which give some insight into the implications of Zweig's rule. It is not clear, however, that they correctly implement the kinematic constraints associated with the production of heavy particles. To address this problem separately we consider a simple analytic approximation to phase space integrals weighted to insure the leading particle effect and a reasonable cutoff in transverse momentum.[9]

We write the cross section for the reaction $pp \to pp + n\pi + F$ where F is a massive fireball to be

$$\Omega_n(p) = g_\pi^{2n} g_F^2 \int \left[\prod_{i=1}^{2} \frac{d^3p_i}{2E_i} \exp\left(2\lambda \cdot p_i\, s^{-\frac{1}{2}} - R^2 p_{Ti}^2\right)\right]\left[\prod_{j=1}^{n} \frac{d^3q_j}{2\omega_j} \exp\left(-R^2 q_{Tj}^2\right)\right]$$
$$\left[\frac{d^3q_F}{2\omega_F} \exp\left(-R^2 q_{TF}^2\right)\right] \delta^{(4)}\left(p - \sum_{i=1}^{2} p_i - \sum_{j=1}^{n} q_j - q_F\right) \qquad (3.22)$$

where $s = P^2$, λ is a 4-vector which in the c.m. frame has only a time component. Consistency with the observed leading particle effect in pp collisions requires $|\lambda| = 5$.[9] For convenience, we assume the cutoff in transverse momentum for each type of particle is the same but this assumption can be relaxed without affecting subsequent arguments substantially.

We sum over the number of pions and form

$$\Omega(z, P) = \sum_n z^n \Omega_n(P) \tag{3.23}$$

To estimate the cross section we approximate the phase space integrations by a method due to Lurçat and Mazur.[20] We first take the Laplace transform

$$\begin{aligned} \Omega(z, \alpha) &= \int d^4p \, e^{-\alpha \cdot P} \, \Omega(z, P) \\ &= \left[\psi_N(\alpha)\right]^2 \left[g_F^2 \, \phi_F(\alpha)\right] \exp\left[z g^2 \, \phi_\pi(\alpha)\right] \end{aligned} \tag{3.24}$$

where

$$\begin{aligned} \psi_N(\alpha) &= \pi \int d\left(p_T^2\right) \exp\left(-R^2 p_T^2\right) K_0\left(\left(\alpha - 2\lambda \, s^{-\frac{1}{2}}\right)\left(m_N^2 + p_T^2\right)^{1/2}\right) \\ \phi_N(\alpha) &= \pi \int d\left(q_T^2\right) \exp\left(-R^2 q_T^2\right) K_0\left(\alpha\left(m_\pi^2 + q_T^2\right)^{1/2}\right) \\ \phi_F(\alpha) &= \pi \int d\left(q_T^2\right) \exp\left(-R^2 q_T^2\right) K_0\left(\alpha\left(M_F^2 + q_T^2\right)^{1/2}\right) \end{aligned} \tag{3.25}$$

and the $K_0(x)$ are modified Bessel functions. The inverse transform can be approximated by

$$\Omega(z, P) \cong \frac{\exp(\beta s^{\frac{1}{2}}) \, \Omega(z, \beta)}{(2\pi)^2 \, (\det B)^{\frac{1}{2}}} \tag{3.26}$$

where β is the solution to

$$\frac{2\psi_N'(\beta)}{\psi_N(\beta)} + \frac{\phi_F'(\beta)}{\phi_F(\beta)} + g^2 z \, \phi_\pi(\beta) = s^{\frac{1}{2}} \tag{3.27}$$

and

$$\det B \cong \frac{s^{\frac{1}{2}}}{\beta}\left(\frac{\partial^2}{\partial\beta^2}\ln\Omega(z,\beta)\right)\left(\frac{1}{2R^2}g^2\phi_\pi(\beta)\right) \tag{3.28}$$

The relevance of this exercize for the problem of ψ production or $\psi + D\bar{D}$ production is that we can compare the energy dependence for the cross section as a function of the fireball mass. If we treat the production of a $\psi + D\bar{D}$ as a fireball of mass $M_F \gtrsim 8$ GeV we can compare the ratio of $\sigma(\psi D\bar{D})/\sigma(\psi)$ as a function of energy. For $s^{\frac{1}{2}} \gtrsim 15$ GeV the solution to the equation for β, (3.27) is approximately determined by the first term, and gives

$$\beta \cong 2\lambda/s^{\frac{1}{2}}$$

and the ratio

$$\frac{\sigma(\psi;D\bar{D})}{\sigma(\psi;\text{alone})} \cong \frac{g_F^2}{g_\psi^2}\,\frac{K_0\left(\frac{2\lambda}{s^{\frac{1}{2}}}\,8\right)}{K_0\left(\frac{2\lambda}{s^{\frac{1}{2}}}\,3.1\right)}\left(\frac{\det B\,(3.1)}{\det B\,(8)}\right)^{1/2} \tag{3.29}$$

This approximation of energy dependence has been found reliable in estimating the ratio of $\bar{p}$ to π production.[21] If the interpretation of the implication of Zweig's rule is valid so that the ratio of the cross section for producing a ψ in conjunction with a pair of charmed particles to its cross section for being produced alone becomes large at asymptotic energies, the implication of the IEM as shown in Fig. 6 is that the kinematic limitations are not too severe to suppress the signal at Fermilab energies. This supplements our estimate of kinematics in the Drell-Yan model and multiperipheral model.

IV. THE ANALOGY BETWEEN THE $\psi(3100)$ AND THE $\phi(1019)$

One attractive feature of the suggestions here is that the fundamental assumption underlying the application of Zweig's rule can be tested independently of the model calculations in Section III. The most direct test involves once again the analogy between charm and strangeness.

There is currently very little published information on the production of ϕ's in high energy pp collisions but a large amount of data could be buried in unanalyzed experiments. Obviously, all the models we have discussed for the production of a ψ which is a bound state of a $c\bar{c}$ pair can be repeated with trivial modification for the ϕ. The classification of the ϕ in the quark model as an $s\bar{s}$ state is quite well founded and the interpretation of Zweig's rule as a mechanism for suppressing decays is obviously similar since it was originally designed for this purpose. In addition we have direct information based on 2-2 reactions[10] which support the generalization of the rule to exchange diagrams. This suggests that in a multiparticle system ϕ's will be more easily produced by K or K* exchange links. For pp or πp collisions we can draw quark-line multiperipheral diagrams for ϕ production just like those of Fig. 2. We conclude that final states containing ϕ's should usually have at least two strange particles (excluding, of course, the $K\bar{K}$ decay products of the ϕ). Since the average number of strange particles produced in inelastic pp collisions at Fermilab energies,

$$\langle n_s \rangle \cong \langle n_{K^+} \rangle + 2 \langle n_{K_0^S} \rangle + \langle n_{K^-} \rangle + \langle n_\Lambda \rangle \cong 1.3 \qquad (4.1)$$

is smaller than 2, the average number of strange particles produced in an event containing a ϕ should be significantly larger than in an ordinary collision,

$$\begin{aligned} \langle n_{K/\phi} \rangle &> \langle n_K \rangle \quad , \\ \langle n_{\Lambda/\phi} \rangle &> \langle n_\Lambda \rangle \quad , \qquad (4.2) \\ &\text{etc.} \end{aligned}$$

This corollary of the interpretation of Zweig's rule which states that events containing ϕ's should contain particularly rich samples of strange particle is subject to immediate experimental test. For example, bubble chamber film from BNL, CERN-PS or Fermilab exposures can be scanned for events containing ϕ's with or without strange particles.

In the event that an experiment triggering on ψ's fails to find any evidence for charmed particles the analog experiment triggering on ϕ's and looking for strange particles would be invaluable in helping to decide what a negative result could mean in terms of charmed particle masses, etc. If the proposal does not work for strangeness we need to substantially modify our understanding of Zweig's rule. This, in itself, should be an important result.

V. SUMMARY AND CONCLUSIONS

The interpretation of the $\psi(3100)$ and $\psi(3700)$ as bound states of a charmed quark-antiquark pair suggests immediately an interesting way to look for charmed particles. The quark-model explanation of the suppression of the strong decays of $c\bar{c}$ ψ's, the Zweig rule, indicates that the new particles should be produced copiously in association with charmed particle pairs. This involves a kind of quasi-associated production which we call conjoint production which is based, not on quantum number conservation, but on dynamical quark-model selection rules. The existence of conjoint production for ϕ's and ψ's has not yet been shown valid but the mechanism deserves consideration as the basis for an experimental search for charm since simple model calculations indicate the possibility of substantially lowering the background of uncharmed hadrons.

The type of experiment envisioned is the triggering of an apparatus, either counters or a hybrid bubble chamber system, on the detection of a massive lepton pair from the decay of a ψ. Models suggest that at Fermilab and CERN-ISR energies most ψ's should be produced in events with a charmed pair. The cross section, on the order of 100's of nanobarns, is significantly smaller than the cross section for the production of charmed particles alone but the high signal-to-background ratio should made it possible to easily recognize charmed particles in many decay modes.

It should be pointed out that this can be done in conjunction with an experiment which triggers on the detection of a single large p_T lepton. The observation of a ratio of $\mu/\pi \cong 10^{-4}$ at Fermilab[22] and the CERN-ISR[23] has lead naturally to speculation that a substantial fraction of these are due to the leptonic decays of charmed particles. If this speculation is true, examination of these final states for further evidence of massive narrow states may also provide a convenient way to search for charm. The two types of triggers are complementary. It should be noted, however, that the experiment involving ψ's also bears directly on the $c\bar{c}$ model for the ψ states. In view of the ambiguous results of photoproduction experiments this is an important conceptual link in the charm scheme.

Although the proposed experiment discussed here is specific to the identification of the $\psi(3100)$ and $\psi(3700)$ as states of hidden charm, other interpretations of these narrow resonances may contain interesting effects in the final states of production experiments.

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FIGURE CAPTIONS

1. Examples of quark-line diagrams forbidden by Zweig's rule:

   (a) The decay $\phi \to 3\pi$.

   (b) The exchange diagram for $\pi^- p \to \phi n$.

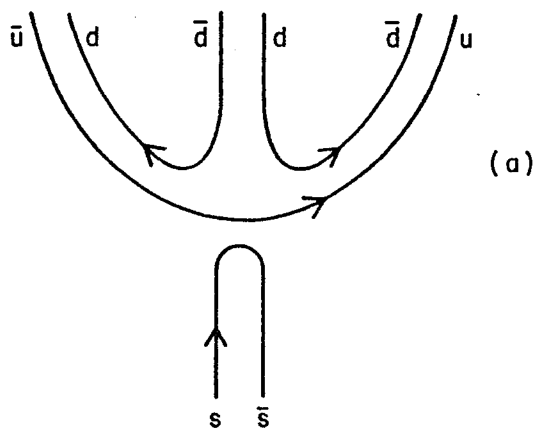
2. Two types of multiperipheral quark-line diagrams for the production of a ψ. The production of a ψ alone necessarily involves a disconnected diagram such as shown in (a). Diagram (b) shows the Zweig-allowed production of the ψ in association with a pair of charmed particles.

3. The ratio $\sigma(\psi;D\bar{D})/\sigma(\psi;\text{alone})$ at large Y in the one-dimensional multiperipheral model using (3.3) and (3.9) is plotted as a function of g_c^2.

4. The ratio $\sigma(\psi;D\bar{D})/\sigma(D,\bar{D})$ at large Y in the one-dimensional multiperipheral model using (3.9) and (3.11) is plotted as a function of g_c^2.

5. The ratio $\sigma(\psi;D\bar{D})/\sigma(\psi;\text{alone})$ vs. s in the Drell-Yan model with a range $\epsilon^2 = 10^{-2} - 10^{-4}$ where ϵ is the ratio of the amount of charmed quark in a nucleon to the amount of strange quark. The coupling constants are fixed as $h^2/g^2 = 10^{-5}$.

6. The ratio $\sigma(\psi;D\bar{D})/\sigma(\psi;\text{alone})$ as a function of $s^{\frac{1}{2}}$ in the IEM. The cross sections are normalized so the asymptotic value of the ratio is 10.



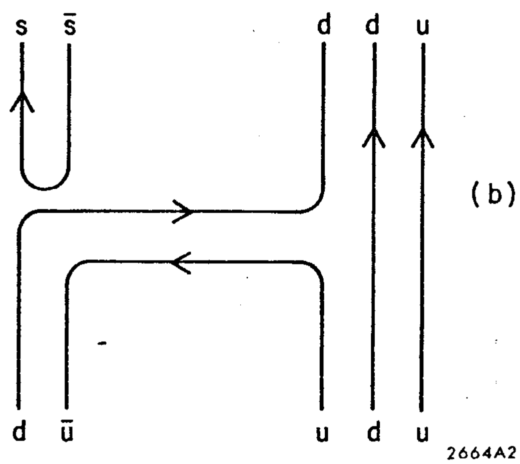
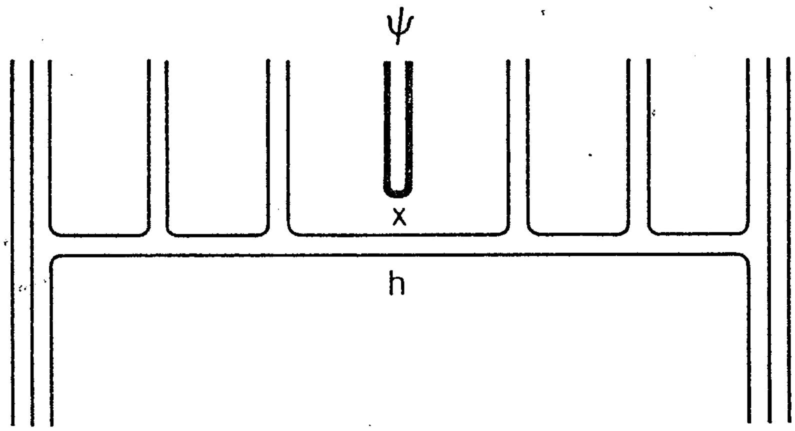
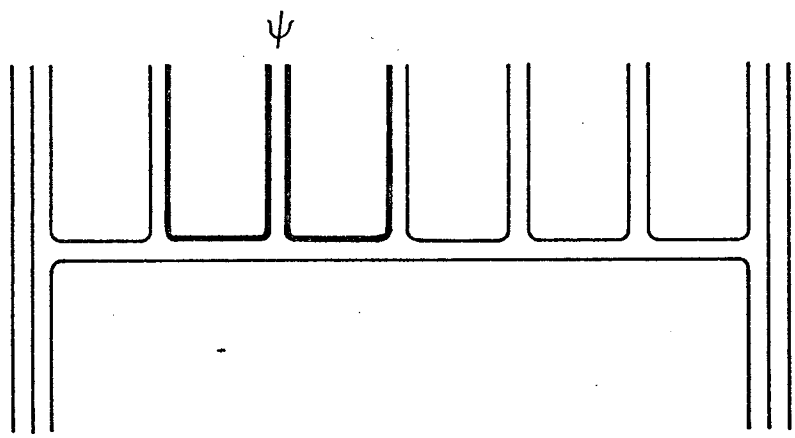


Fig. 1



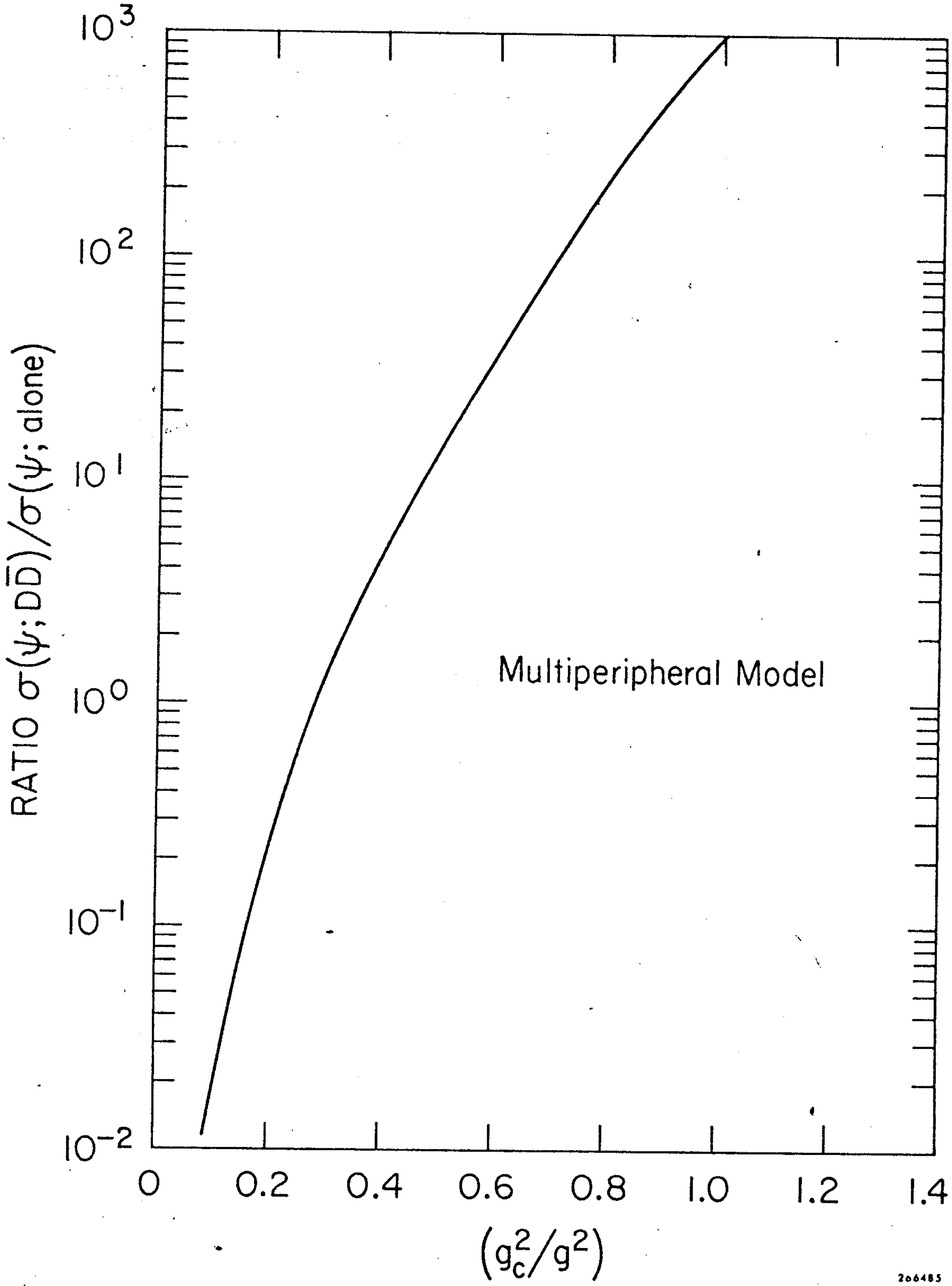
(a)



(b)

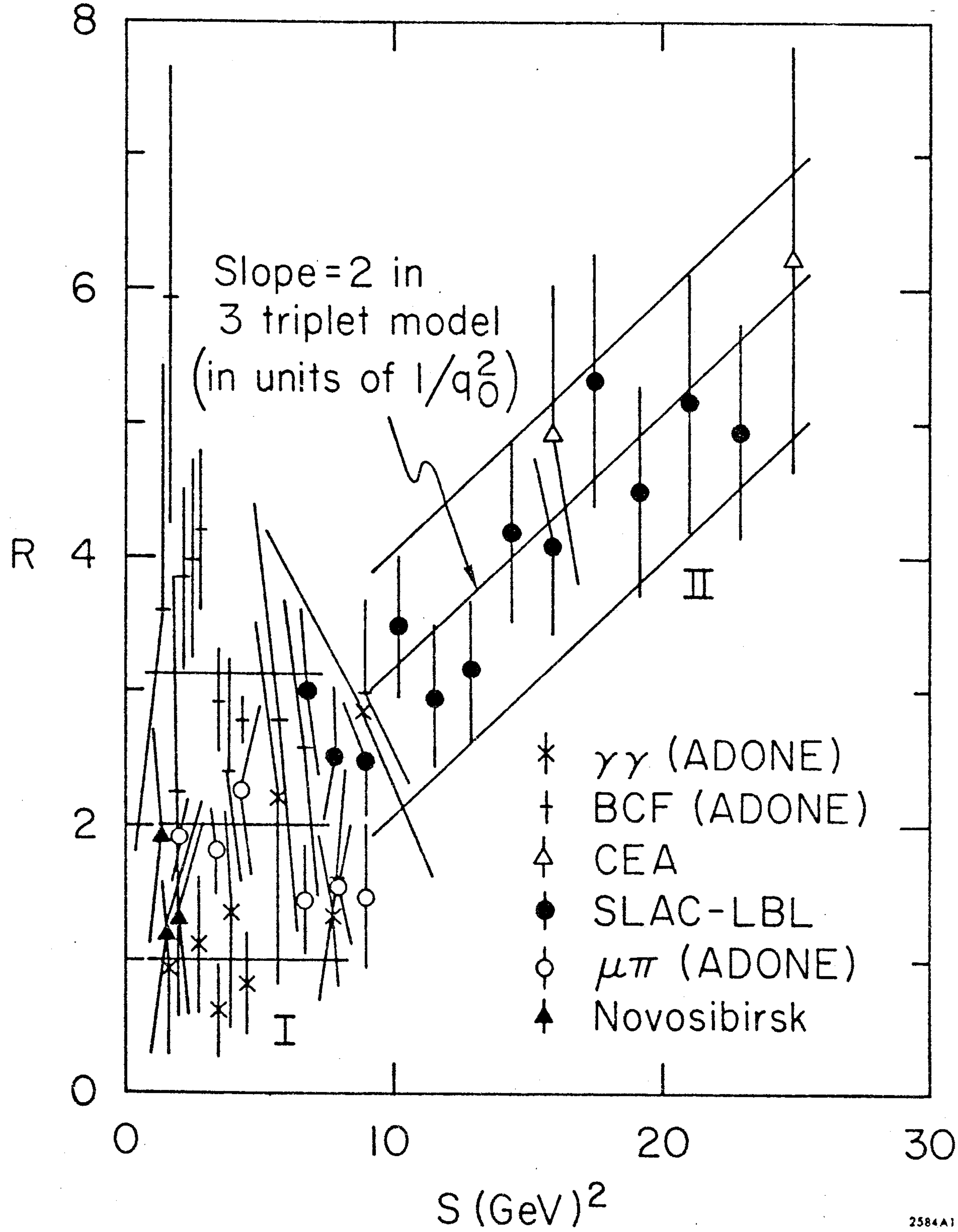
2664A1

Fig. 2



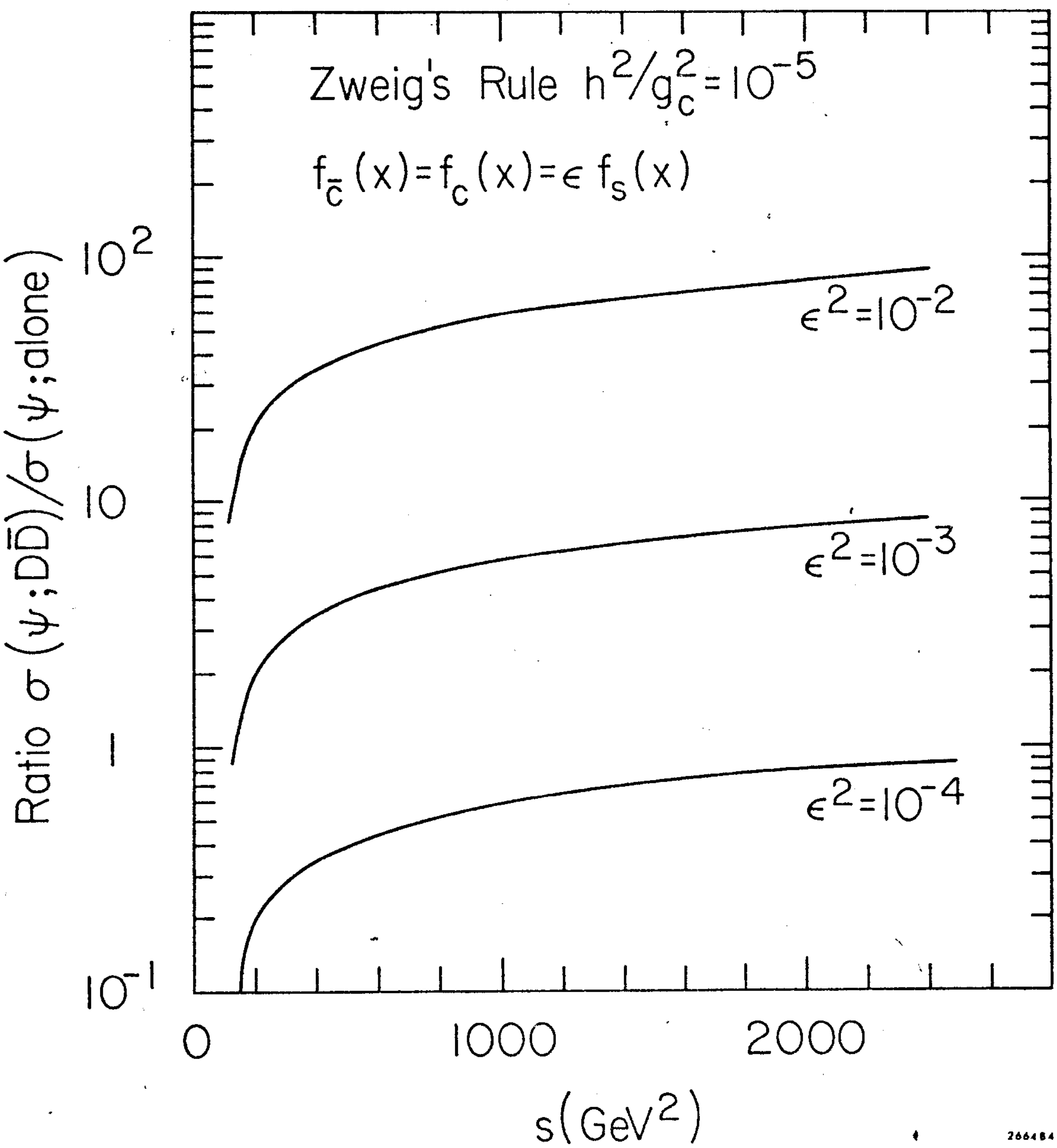
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
RATIO $\sigma(\psi;D\bar{D})/\sigma(\psi;\text{alone})$
Multiperipheral Model
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
(g_c^2/g^2)
266485

Fig. 3



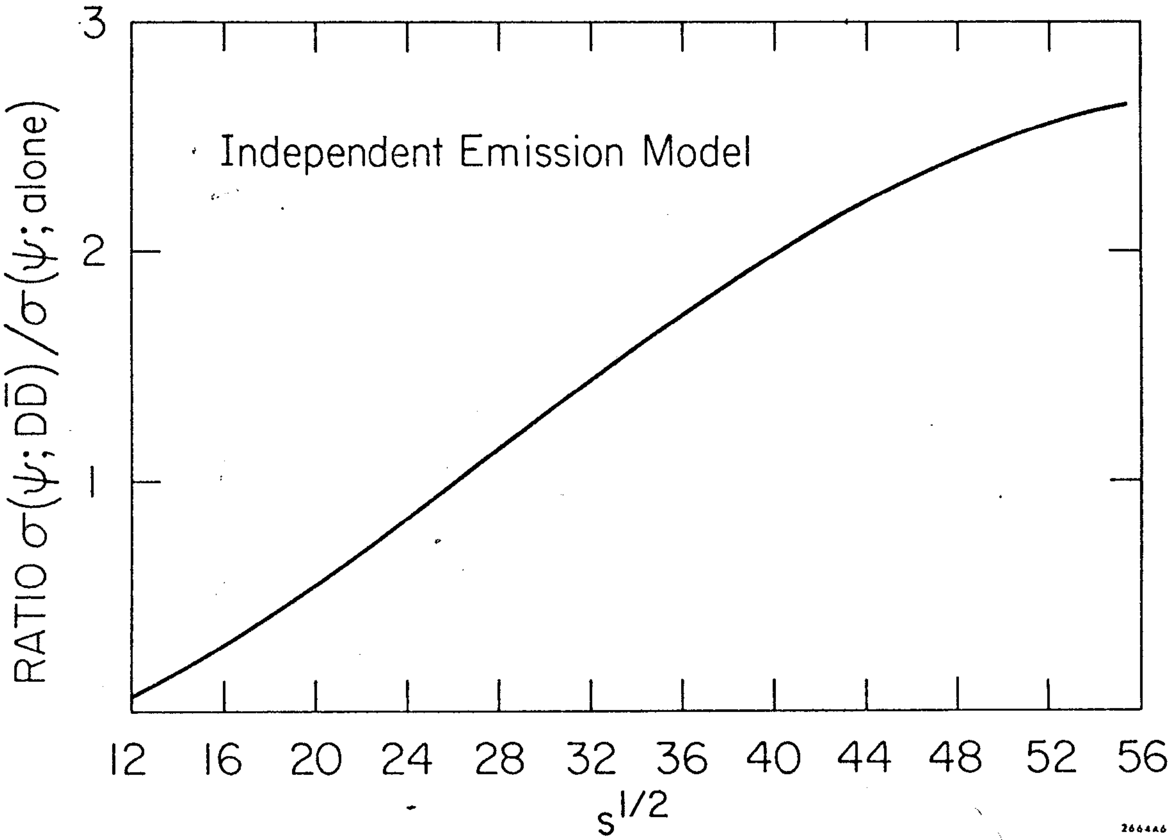
8
6
R 4
2
0
0
10
20
30
S (GeV)^2
Slope = 2 in
3 triplet model
(in units of $1/q_0^2$)
I
II
$\gamma\gamma$ (ADONE)
BCF (ADONE)
CEA
SLAC-LBL
$\mu\pi$ (ADONE)
Novosibirsk
2584A1

Fig. 4



Zweig's Rule $h^2/g_c^2 = 10^{-5}$
$f_{\bar{c}}(x) = f_c(x) = \epsilon f_s(x)$
10^2
10
1
10^{-1}
Ratio $\sigma(\psi;D\bar{D})/\sigma(\psi;\text{alone})$
$\epsilon^2 = 10^{-2}$
$\epsilon^2 = 10^{-3}$
$\epsilon^2 = 10^{-4}$
0
1000
2000
$s(\text{GeV}^2)$

Fig. 5



Independent Emission Model
RATIO $\sigma(\psi; D\bar{D}) / \sigma(\psi; \text{alone})$
$s^{1/2}$
3
2
1
12
16
20
24
28
32
36
40
44
48
52
56
2664A6

Fig. 6