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Inclusive production of heavy particles: $\bar{p}$, D, ψ†

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The average multiplicities as functions of energy are calculated for $\bar{p}$, D, and ψ (where D is a charmed pseudoscalar) in the context of a phenomenologically motivated parameter-free peripheral model.

The hadronic interactions[1] of the new particles promise to give information on both the nature of these particles and the response of hadronic processes to very-high-mass states. In previous papers[2] we have analyzed the total cross sections within a peripheral production model. Our main conclusion is that the "measured"[3] value, $\sigma_{\psi p}^{\text{tot}} \approx 1$ mb, is what one would expect for a conventionally strongly interacting particle. In this note we shall, within the same hadronic framework, make predictions for the average ψ, D, and F multiplicities as functions of energy [where D and F are the charmed pseudoscalars in SU(4), or, more generally, are the particles that act as intermediaries between the ψ and the usual hadrons, enabling ψ to have a "strong" total cross section]. The success or failure of these predictions will further test the hypothesis that these new particles possess normal strong interactions, and will also test the widely held view that multiperipheral models provide a realistic description of hadronic amplitudes. Several studies[4] have shown how multiperipheralism can be made to naturally accommodate the observed energy dependence of inclusive $\bar{p}$, $\bar{K}$ production; we go an essential step further and make parameter-free predictions.

The specific model used (see Ref. 2 for details) has pseudoscalar exchanges and vector particle production [which brings it close to the original Amati-Fubini-Stanghellini (AFS) model[5]]. The production of a particle A, such as D or $\bar{p}$, proceeds via pair production as shown in Fig. 1. To a good approximation the average A multiplicity will equal the average number of *A links*, so we can just sum Fig. 1 over the relevant variables to obtain

$$\langle n_A\rangle\sigma_{pp}^{\text{tot}} = \frac{L}{16\pi^3(2p_{\text{c.m.}})^2 S}\int dM_1^2 dM_2^2 dt\, \frac{M_1^2 M_2^2 \sigma_{Ap}(M_1^2,t)\sigma_{Ap}(M_2^2,t)}{(t-M_A^2)^2}\,, \tag{1}$$

where $\sigma_{Ap}(M^2,t)$ is the off-shell inelastic Ap cross section and L is a factor that takes account of the different ways A can be produced (e.g., $L=2$ counts A or $\bar{A}$ exchange). Following Ref. 2 we take

$$\sigma_{Ap}(M^2,t) = \sigma_{Ap}F_A(t) \tag{2}$$

with

$$F_A(t) = \zeta/(1-t/m_{A^*}^2)\,, \tag{3}$$

where ζ ensures the on-shell normalization of F_A. Since the only justification for (3) is for $t<0$ there is some uncertainty in the determination of ζ. We shall usually evaluate ζ in two ways: first by extrapolating (3) blindly onto the mass shell, and second by using for $t>0$ the "analytic form factor" (AFF) of Ref. 2. This gives us a theoretical uncertainty in the predicted normalizations which we denote by the shading in Fig. 2. Note that the first way of determining ζ breaks down for $A=D$ (since $m_D \approx m_{D^*}$), and so the limits of the shaded area correspond to $\zeta=1$ and $\zeta=\frac{1}{3}$ (the AFF value), and the same procedure is adopted for $\langle n_\psi\rangle^c$ (see below).

We take experimental values for the various cross sections in Eq. (1), and obtain predictions for $\langle n_{\bar{p}}\rangle$ [A = nucleon, $A^* = \Delta(1236)$] as shown in Fig. 2(a). We have also shown the energy dependence using a caricature fermion propagator, $(t-m_A^2)^{-1/2}$. The agreement with the data[6] is more than reasonable. Here two remarks should be made. First is the obvious one that the treatment of the fermion

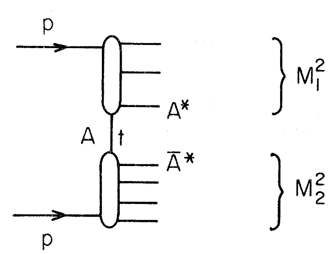

FIG. 1. The production of an $A^*\bar{A}^*$ pair in a pp collision with the A exchange (momentum transfer t) shown explicitly. M_1^2, M_2^2 are the invariant masses squared of the particles produced in the upper and lower blobs, respectively.

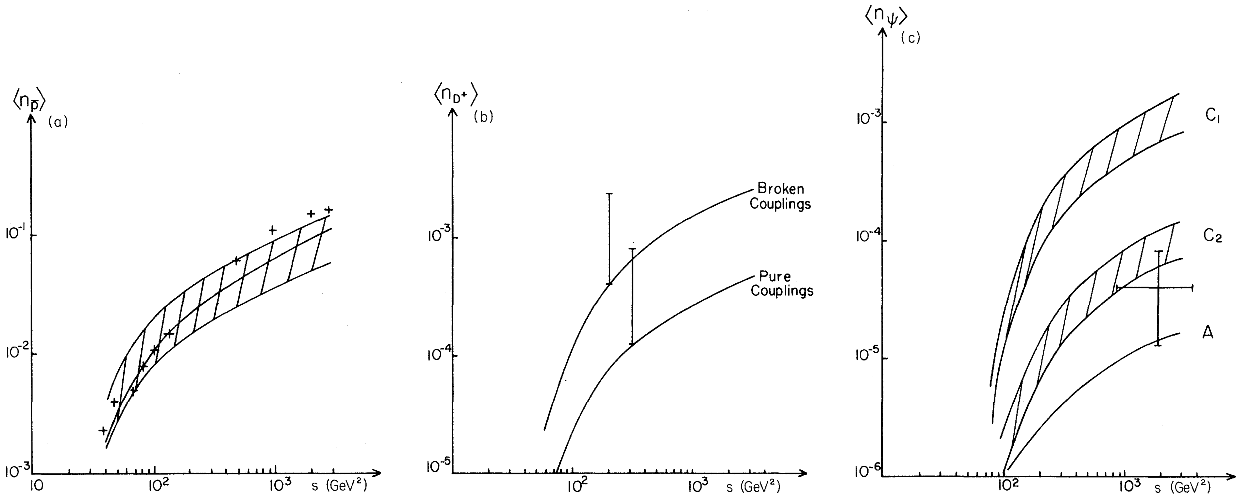

FIG. 2. Predictions of the model for: (a) $\langle n_{\bar{p}}\rangle$; the shaded region corresponds to a boson propagator, the solid line (——) gives the energy dependence with a $(t - m_p{}^2)^{-1/2}$ propagator, and the points with errors (+) are the data (Ref. 6). (b) $\langle n_{D^+}\rangle$; the two curves correspond to predictions obtained with pure and broken SU(4) couplings as labeled. The error bars represent the theoretical uncertainties in the normalizations. The bottom of the error bar is that obtained using the AFF procedure to calculate ξ, the top is for $\xi = 1$. (c) $\langle n_\psi\rangle$ from processes A, $C_{1,2}$ as discussed in the text. $C_{1,2}$ are for broken and pure SU(4) couplings, respectively. The large cross (†) is the ISR data point. The shading represents a theoretical "error" and is discussed in the text.

character of the exchanges has been perfunctory. Second, there have been suggestions[7] that the primary produced $p\bar{p}$ pairs will often annihilate into pions owing to the high annihilation cross section near threshold. We expect such an effect to decrease somewhat with energy since as s increases the constraint on the produced $p\bar{p}$ to be very near threshold also decreases. In such a picture the *primary* experimental $\bar{p}$ production would be even closer in energy dependence to our theoretical curves than is suggested naively by the data; the normalization, however, would change by less than a factor of 2 and would thus still be consistent with our theoretical predictions as shown.

Motivated then by the success of the model in predicting $\bar{p}$ multiplicities, we show in Fig. 2(b) the prediction for D production. In the calculation we use[2] a mass $m_D \approx m_{D^*} \approx 2.2$ GeV and values for σ_{Dp} of 4 mb [pure SU(4) couplings] to 9 mb [obtained with the preferred set of broken SU(4) couplings[2]]. As discussed in Ref. 2 we expect these numbers to be essentially independent of any charm prejudices. It is probable that $m_D \approx 2$ GeV, and the only question, in general, is how many of these D's there are. The F, having the same mass, would have the same energy dependence, but would be lower in normalization by a factor of between 8 [broken SU(4) couplings] and 50 [pure SU(4) couplings]. So we see that a significant supply of D's is predicted at CERN ISR energies—somewhere between $\frac{1}{20}$ and $\frac{1}{100}$ of the $\bar{p}$ multiplicity–and they shoudl be especially visible at larger momentum transfers, say $p_\perp \approx 1$ GeV, owing to their relatively slow $p_\perp$ falloff (which arises from the massive character of the propagator connecting the pair of produced D^*'s).

For the ψ there are, *a priori*, three major types of contribution.

(A) The ψ may be produced directly off a pair of meson links as in Fig. 3(a). The coupling squared will be $\sim 10^{-4} \times$ usual couplings, and the mass of the ψ is close to the mass of a $\Delta\bar{\Delta}$ pair so we expect

$$\langle n_\psi\rangle^A \sim 10^{-4}\langle n_{\bar{p}}\rangle\,. \qquad (4)$$

(B) A pair of ψ's may be produced as in Fig. 3(b). That this cross section is negligible we see as follows. Compare Fig. 3(b) with the analogous

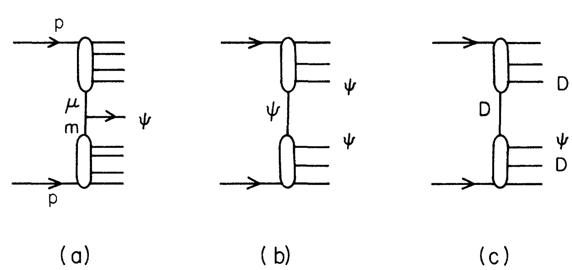

FIG. 3. Three contributions to inclusive ψ production (a), (b), (c), corresponding to the contributions A, B, C, respectively, discussed in the text. μ, m are ordinary mesons.

diagram for $p\bar{p}$ production. A rough estimate gives

$$\frac{\langle n_\psi\rangle^B}{\langle n_{\bar{p}}\rangle} < \frac{\sigma_{\psi p}{}^2 \to \psi X/m_\psi{}^2}{\sigma_{pp}{}^2 \to \Delta X/m_p{}^2} \lesssim 10^{-7}, \quad (5)$$

where we use the apparent experimental fact that[2]

$$\sigma_{\psi p\to\psi X} < \tfrac{1}{2}\,\sigma^{\rm el}_{\psi p} \sim \tfrac{1}{100}\ \text{mb}. \quad (6)$$

(C) In the above two cases the couplings were suppressed. A situation in which the couplings are not suppressed, but in which one pays a price in heavy propagators and produced particles, is shown in Fig. 3(c); the ψ is produced accompanied by two D's. To gain a *very* rough idea of the magnitude of this component we go to asymptotic energies and compare Fig. 3(c) with the $\bar{p}$ production diagram

$$\frac{\langle n_\psi\rangle^C}{\langle n_{\bar{p}}\rangle} \sim \frac{\sigma_{Dp}\sigma_{Dp} \to \psi_{DX}/m_D{}^2}{\sigma_{pp}{}^2/m_p{}^2}$$

$$\sim \frac{\sigma_{Dp}{}^2/(m_D{}^2)^2}{\sigma_{pp}{}^2/m_p{}^2} \sim 10^{-3}, \quad (7)$$

which is somewhat larger than (4). Thus at ISR energies we expect that most events in which a central ψ is observed will contain two central D's. This is then a convenient place to search for D's, particularly at larger transverse momenta, e.g., $p_\perp \sim 1$ GeV.

In Fig. 2(c) we plot the contributions of A and C as calculated numerically. For C we have two shaded curves: C_1 using broken couplings[2] and C_2 using pure SU(4) couplings. In each case the lower edge of the shaded region corresponds to calculating normalizations using AFF continuations for $t > 0$. The data point derives from the ISR data.[8] Observe that it appears consistent with A. It is our expectation, on the basis of the curves shown in Fig. 2(c), that more refined measurements will reveal a substantially higher ψ-production cross section.

We comment finally on the general question of how reliable are the predictions of multiperipheral models with respect to produced multiplicities. It is known that simple multiperipheral models will predict π multiplicities that are much too small if they are made to give reasonable total cross-section values. Our model shows, in fact, the same to be true of K^- multiplicities. However, we have seen that for $\bar{p}$ production our model is accurate. It appears to be the case then—and only if this *is* the case can our predictions be taken seriously—that the model is only inaccurate for the produced multiplicities of *low-mass* particles. A possible—and plausible—reason why this might be so is that the produced particles may in fact include *all* the distinct resonances and not just the ρ, K^*, etc. This would have the effect of increasing the predicted π, K multiplicities (while keeping the π/K ratio roughly correct), but would not alter directly the heavy-particle multiplicities because the distinct resonances are not massive enough to decay into heavy particles.

While the above comments should be borne in mind when considering our predictions, we feel that these predictions are probably as good as can be made with our present understanding of strong interactions, and that they provide a useful criterion for assessing the theoretical significance of the eventual experimental results of D and ψ production.

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