η and η' Production in e^+e^- Annihilation at 29 GeV. Evidence for the $D_s^{\pm}$ Decays into $\eta\pi^{\pm}$ and $\eta'\pi^{\pm}$

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η production has been investigated by the Mark II collaboration at the SLAC e^+e^- storage ring PEP. η particles are reconstructed by their $\gamma\gamma$ decay mode. The η fragmentation function has been measured and found to be in good agreement with the Lund-model prediction. η' production has been measured for the first time in high-energy e^+e^- annihilation. There is evidence at the 3σ level for $D_s^{\pm}$ decay into $\eta\pi^{\pm}$ and $\eta'\pi^{\pm}$.

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This Letter presents a measurement of inclusive η and η' production in e^+e^- annihilation using the 208-pb^{-1} data sample collected with the Mark II detector at the SLAC e^+e^- storage ring PEP. The measurements of these two fragmentation functions provide interesting insights into the fragmentation mechanism. Since the η and the η' share the same quantum numbers, their relative yield is mainly related to the mass-suppression mechanism involved in the fragmentation chain. This mechanism differs from model to model and thus, this measurement could provide interesting tests of the fragmentation models in regions where, because of the lack of experimental data, they have not yet been tuned.

We also present evidence for exclusive decays of the $D_s^{\pm}$ involving η and η'. These decay modes are predicted to be rather large by various models but little experimental information has been available up to now.

The Mark II detector is described in detail elsewhere.[1] Since the η particles are reconstructed via their $\gamma\gamma$ decay mode, the liquid-argon electromagnetic calorimeter is of primary importance for this analysis. The calorimeter covers 65% of 4π. Its energy resolution has been measured to be $14\%/\sqrt{E}$ and its angular resolution is 8 mrad. Charged tracks are measured in a cylindrical-drift-chamber system placed in a 2.3-kG solenoid magnet. The momentum resolution is given by $\sigma_p/p = [(0.025)^2+(0.011p)^2]^{1/2}$ (p in GeV/c). Particle identification is provided by a time-of-flight system with a 400-ps resolution.

Inclusive η production.— Hadronic events are selected by our requiring a minimum number of five charged tracks with a minimum total energy of 7 GeV. The event is divided into two hemispheres about the sphericity axis. Events with at least two neutral tracks in the same hemisphere are considered, where a neutral track is defined as an energy cluster of at least 200 MeV in the liquid-argon calorimeter with a distance to the closest charged track greater than 7 cm. Since the photon detection efficiency is rapidly rising at 200 MeV, we repeated the analysis with a 300-MeV cut, without noticeable change.

To reduce the combinatorial background generated by photons coming from π^0 decays, all photons having an invariant mass with any other photon between 50 and 200 MeV are rejected. The resulting $\gamma\gamma$ invariant-mass distribution is shown in Figs. 1(a) and 1(b), for $z > 0.2$ and $z > 0.3$, respectively, where z is the energy of the $\gamma\gamma$ pair divided by the beam energy. Clear evidence for η production is seen in both regions.

The number of η mesons in each z bin is extracted from a fit of the measured $\gamma\gamma$ mass spectrum. The fitting function consists of a quadratic polynomial back-

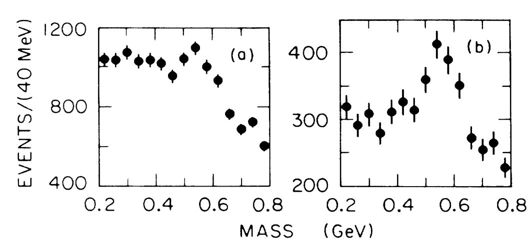

FIG. 1. $\gamma\gamma$ mass spectrum for (a) $z > 0.2$ and (b) $z > 0.3$, where z is the $\gamma\gamma$ pair energy divided by the beam energy.

ground and a Gaussian of fixed mass and free width.[2] This allows the same fitting procedure to be applied on both data and Monte Carlo samples. The efficiency is measured on a sample of Monte Carlo hadronic events by the ratio of observed η's obtained in the way described above to the number of produced η's. In this way, the systematic effects associated with the fitting procedure are reduced. The π^0 removal procedure reduces the η signal by only 20% and thus does not introduce significant systematic uncertainty. The efficiency for detecting η's rises slowly with energy from 3% at 4 GeV to 5% at 10 GeV.

The fragmentation function is plotted in Fig. 2, where the errors include the statistical error on the data, the uncertainty in the detection efficiency, and a remaining systematic error estimated to be 15%, caused by the uncertainty in the width of the η signal. As a result of our imperfect simulation of the liquid-argon calorimeter, the observed width is 15% larger than the predicted one over the whole z range. The quoted systematic uncertainty corresponds to the difference of η yields when we use the predicted width in the fit or when we let it be a free parameter. The width variation in the covered z range is less than 20%.

These data are in good agreement with the previous measurements of the JADE[3] and HRS[4] groups. The agreement with the LUND prediction,[5] as represented by the solid curve, is also good. The η fragmentation in the Webber model[6] is very similar to that in the Lund model. The η multiplicity per event for different z cuts is summarized in Table I.

The total η multiplicity per event is obtained by extrapolation of the measured multiplicity for $z > 0.1$ using the Lund fragmentation function. This is justified by the good agreement observed at low z between JADE data and the Lund model. The result, $N_\eta = 0.62 \pm 0.17 \pm 0.15$, where the systematic error includes the uncertainty in the extrapolation is in good agreement with the JADE and HRS measurements of 0.64 ± 0.15 and 0.58 ± 0.10, respectively, and the LUND and Webber prediction of 0.70.

TABLE I. η multiplicities per event.

z cuts	Multiplicity per event
$z > 0.1$	$0.30 \pm 0.07 \pm 0.05$
$z > 0.2$	$0.12 \pm 0.03 \pm 0.02$
$z > 0.3$	$0.09 \pm 0.02 \pm 0.02$

Inclusive η' production.—The $\eta\pi^+\pi^-$ mode is used to search for η'. The two pions are required to be in the same hemisphere as the η candidate. A pion is any track compatible with the pion hypothesis according to the time-of-flight system. An η candidate is defined as follows: With photon pairs selected as above, a kinematical fit is performed on both photons with the assumption that the angles are perfectly measured. The energy of each photon is thus rescaled with use of the nominal η mass as a constraint. Only pairs with an unconstrained mass between 450 and 650 MeV and with a χ^2 for the kinematic fit less than 6 are retained. In order to ensure the best possible signal-to-noise ratio for the η peak, further cuts are applied.

(1) To reject clusters formed by two merged photons coming from an energetic π^0 decay, the electromagnetic shower is required to be compatible with the presence of a single photon in the first layer of the liquid-argon calorimeter. The efficiency of this cut is measured in different ways: from the η spectrum, from a sample of pure single photons coming from $e^+e^-\ \gamma$ events, and from the Monte Carlo simulations. The three methods agree within 10% and yield an efficiency of 65%.

(2) $\cos\theta^*$ has to be less than 0.7, where θ^* is the angle between one of the photons and the η line of flight in the η rest frame. The background tends to peak at $\cos\theta^* = 1$, corresponding to asymmetric photon pairs.

A clear η' signal of 45 ± 11 events can be seen in Fig. 3, where $z_{\gamma\gamma}$ is required to be above 0.2. This is the first

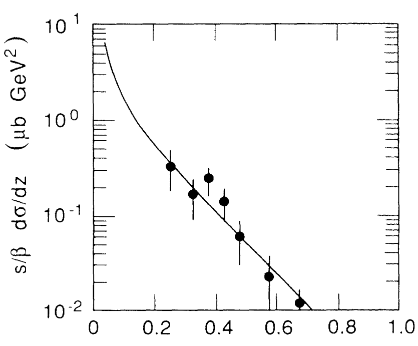

FIG. 2. η fragmentation function. The solid curve is the LUND prediction for the η fragmentation function.

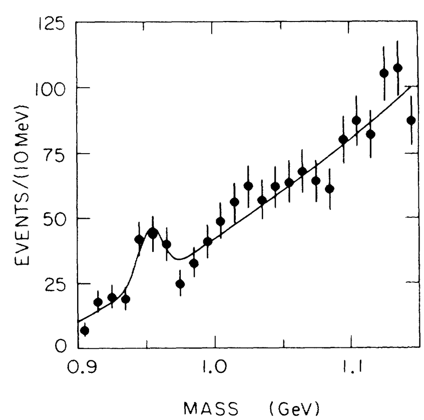

FIG. 3. $\eta\pi^+\pi^-$ mass spectrum. The solid curve is a fit with a polynomial background and a Gaussian (see text).

measurement of η' production in high-energy e^+e^- annihilation.

The reconstruction efficiency varies from 2% at 2 GeV to 7% at 7 GeV (if we do not take into account the 17% branching ratio for the decay $\eta' \rightarrow \gamma\gamma\pi^+\pi^-$). The number of η' with $z > 0.2$ is

$$N_{\eta'}(z > 0.2) = 0.09 \pm 0.03 \pm 0.02 .$$

Extrapolation to $z = 0$ on the basis of the η' Lund fragmentation function, whose shape is very similar to the η fragmentation shown in Fig. 2, leads to a number of η' per event of $0.26 \pm 0.09 \pm 0.05$.

As mentioned above, the η'/η production ratio in e^+e^- jets provides an interesting test of fragmentation models. As an example, the η'/η ratio is predicted to be 0.56 in the Lund model, 0.2 in the Webber model, and 0.30 in the model of Buchanan and Chun.[7] Our data sample is not large enough to enable us to distinguish between these different models.

Search for $D_s^\pm \rightarrow \eta\pi^\pm$.—The η candidates are combined with any charged track found in the same hemisphere and compatible with a π according to the time-of-flight system. An η candidate is defined as above, with two additional cuts which reduce the background under the η peak: (1) The η momentum is required to be greater than 4.5 GeV (i.e., $z > 0.3$). (2) One photon has to have a p_t relative to the thrust axis greater than 500 MeV. This cut favors photons from $D_s^\pm$ decays compared to those coming from soft π^0 decays.

An excess of events is found in the $D_s^\pm$ mass range [Fig. 4(a)]. The probability that this excess is due to a statistical fluctuation of the background deduced from the observed mass spectrum both in the data and in the Monte Carlo calculation is at the 10^{-3} level. We thus have observed evidence for the decay $D_s^\pm \rightarrow \eta\pi^\pm$ at the 3σ level.

A quadratic polynomial background and a Gaussian of fixed mass and free width are fitted to the data. The fit gives 16 ± 6 $D_s^\pm$, with a width of 40 ± 15 MeV consistent with the 50 MeV expected from our resolution. This corresponds to, after radiative corrections,

$$\sigma(e^+e^- \rightarrow D_s^\pm) B(D_s^\pm \rightarrow \eta\pi^\pm) = 5.2 \pm 2.2 \text{ pb} .$$

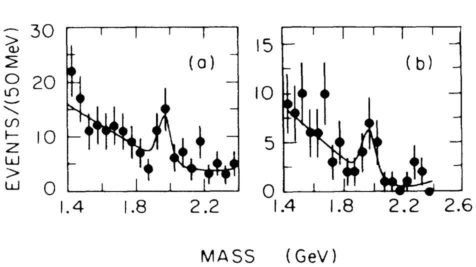

FIG. 4. (a) $\eta\pi^\pm$ and (b) $\eta'\pi^\pm$ mass spectra. The solid curves are fits with polynomial backgrounds and Gaussians (see text).

If we use the standard hypothesis for the $D_s^\pm$ production rate (assuming quark counting and a 15% probability for a c quark to produce a $D_s^\pm$ meson, thus leading to a $D_s^\pm$ cross section around 44 pb or 0.11 $D_s^\pm$ per hadronic event), this result translates into a branching ratio around 12%, about 3 times larger than the world-average value for the $\phi\pi^\pm$ mode.

The Mark III collaboration has presented preliminary evidence[8] for the same decay mode of the $D_s^\pm$, with a comparable branching ratio.

Search for $D_s^\pm \rightarrow \eta'\pi^\pm$.—To search for this decay, η' candidates are combined with any charged track above 1 GeV found in the same hemisphere. An η' candidate is required to have an invariant mass of the $\eta\pi^+\pi^-$ system between 0.9 and 1 GeV. The invariant mass is constrained to the nominal η' mass. Furthermore, $z_{\gamma\gamma}$ has to be greater than 0.2.

An excess of events is found in the $D_s^\pm$ mass region [see Fig. 4(b)], indicating the observation of the decay $D_s^\pm \rightarrow \eta'\pi^\pm$ at a 3σ level. This leads to, after radiative corrections,

$$\sigma(e^+e^- \rightarrow D_s^\pm) B(D_s^\pm \rightarrow \eta'\pi^\pm) = 8.4 \pm 3.7 \text{ pb} .$$

With the same production hypothesis as above, the branching ratio for $D_s^\pm \rightarrow \eta'\pi^\pm$ is around 19%.

The theoretical implications of large branching ratios for both the $\eta\pi^\pm$ and the $\eta'\pi^\pm$ modes have been discussed by several authors.[9,10] The presence of a scalar resonance in the 2-GeV range could lead to such effects without affecting the standard mixture of spectator and annihilation mechanisms in the $D_s^\pm$ decays.

Conclusion.—The η fragmentation function has been measured and the results are in agreement with previous measurements and with the Lund model. The η multiplicity for $z > 0.1$ is found to be $0.3 \pm 0.07 \pm 0.05$. η' inclusive production has been measured for the first time in high-energy annihilation events. The resulting η' multiplicity for $z > 0.2$ is found to be $0.09 \pm 0.03 \pm 0.02$, somewhat lower than the LUND prediction of 0.14.

There is evidence for the decays $D_s^\pm \rightarrow \eta\pi^\pm$ and $D_s^\pm \rightarrow \eta'\pi^\pm$. The $D_s^\pm$ production cross section multiplied by the branching ratio $B(D_s^\pm \rightarrow \eta\pi^\pm)$ is measured to be 5.2 ± 2.2 pb, corresponding to a branching ratio about 3 times as large as $D_s^\pm \rightarrow \phi\pi^\pm$ and in good agreement with a recent Mark III preliminary result. $\sigma(e^+e^- \rightarrow D_s^\pm) B(D_s^\pm \rightarrow \eta'\pi^\pm)$ is measured to be 8.4 ± 3.7 pb, corresponding to a branching ratio of about 19%.

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[6]We have used version 4.1 of the Webber Monte Carlo code, with a cluster mass parameter set to 3.75 GeV/c^2. The resonance decay table is the same one as in our LUND Monte Carlo simulation.

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