INCLUSIVE PRODUCTION OF VECTOR MESONS ρ^0 AND $K^{*\pm}$ IN e^+e^- ANNIHILATION AT $\langle\sqrt{s}\rangle = 35$ GeV

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The production of vector mesons ρ^0 and $K^{*\pm}$ has been studied in e^+e^- annihilation at an average CM energy of 35 GeV. The production rate per event, extrapolated to the full x_E range was found to be 0.98 ± 0.09 ± 0.15 for ρ^0 and 0.87 ± 0.16 ± 0.08 for $K^{*\pm}$. The scaled differential cross section $s/\beta(d\sigma/dx_E)$ for both ρ^0 and $K^{*\pm}$ production has been measured. The ratio of pseudoscalar to vector meson production has been determined for ρ^0, $K^{*\pm}$, η and D^* production. Its mass dependence has been investigated.

Vector mesons in multihadron final states from e^+e^- annihilation are produced both directly during the fragmentation and also in the decay of higher mass particles. Using the simple argument of counting the number of possible spin states, the ratio of direct production of vector to pseudoscalar mesons should be 3 : 1. This ratio could be modified, however, by the fact that vector and pseudoscalar mesons do not have equal masses.

In this letter, the production of ρ^0 and $K^{*\pm}$ is investigated. The analysis was carried out on multihadron events obtained with the JADE detector [1] at the PETRA e^+e^- storage ring at center of mass energies between 33 and 37 GeV, with an average of 35 GeV. The event sample considered consists of 15 378 events corresponding to an integrated luminosity of 61 pb^{-1}. The trigger and event selection criteria have been described elsewhere [2].

ρ^0 production. The invariant mass $M(\pi^+\pi^-)$ was calculated for oppositely charged tracks assuming both were pions. In order to reduce the combinatorial background, tracks were considered only if they satisfied the following cuts (cylindrical coordinates with the z-axis along the positron beam direction are used):

(1) The distance of closest approach R_{min} of the track to the event vertex as determined from Bhabha events, in the xy-projection satisfied $R_{min} < 7$ mm.

(2) The momentum component of each track transverse to the beam direction satisfied $p_{xy} > 0.1$ GeV/c.

(3) The polar angle ϑ of the track relative to the beam-direction satisfied $|\cos\vartheta| < 0.87$.

(4) The two tracks had to be emitted into the same hemisphere relative to the thrust axis.

(5) ϑ^* the CM decay angle between the π^+ and the $\pi^+\pi^-$ flight direction evaluated in the $\pi^+\pi^-$ rest frame was required to be $|\cos\vartheta^*| < 0.9$. For events excluded by this cut one pion is produced backwards in the rest frame resulting in a low energy pion in the laboratory. The combinatorial background for this configuration is high.

(6) At least one of the tracks should have a momentum transverse to the thrust axis, $p_T(\text{thrust}) > 0.15$ GeV/c.

The $\pi^+\pi^-$ mass distribution obtained using tracks selected in this way is still dominated by combinatorial background and in order to reduce this background further, we restricted the analysis to events with fractional energy of the $\pi^+\pi^-$ system $x_E = 2[E(\pi^+) + E(\pi^-)]/\sqrt{s}$ in the range $0.1 < x_E < 0.7$. Below $x_E = 0.1$ the combinatorial background is overwhelming, whereas above $x_E = 0.7$, smearing effects due to the finite momentum resolution cause a deterioration of the mass resolution. To get a first estimate of the combinatorial background, the distribution of mass m for track pairs with equal charge is analysed in the same way and fitted with the empirical function, taking into account the threshold at 0.28 GeV as well as the fall off at large masses,

$$N(\pm\pm) = A_1|m - 0.28|^{A_2} \exp(-A_3 m - A_4 m^2),$$

the A_n's being free fit parameters. This fitted curve was then subtracted from the opposite charge distribution; the result is shown in fig. 1. There is a peak in the ρ region above a still considerable background. One way to obtain the fraction of ρ^0 production would be to make a fit to the distribution with a resonance plus a smooth background. The situation is somewhat more complicated, however. The background is not only of combinatorial nature but contains reflections from the decay $\omega^0 \to \pi^+\pi^-\pi^0$ as well as from $K^{*0} \to K^\pm\pi^\mp$ with the pion hypothesis taken for the $K^\pm$. These effects were taken into account in the following way: A simultaneous fit was made to the mass-distribution of fig. 1 using the function

$$N(m) = B_1[N(\rho^0) + C_1 N(\omega^0) + C_2 N(K^{*0})] + B_2 N(\mathrm{BG}).$$

$N(\rho^0)$ was taken to be a relativistic Breit–Wigner [3] with mass dependent width. $M(\rho^0)$ and Γ_0 were fixed to the table values [4], the width Γ was folded with the detector resolution as determined from the observed width of the K^0_S peak [5]. The values for C_1

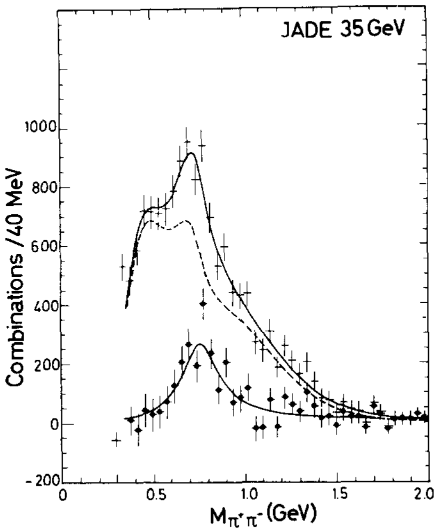

Fig. 1. The invariant mass spectrum for pairs of oppositely charged particles with the pion mass assumed for each particle. The distribution for equal charge pairs is subtracted. The full curve is the result of a fit with a relativistic Breit–Wigner plus background as described in the text. The dashed curve was the fitted background contribution alone. The data with background subtracted, together with the resonance fit, are also shown.

and C_2, the respective numbers of ω^0 and K^{*0} relative to ρ^0, depend on SU(3) mixing as well as on γ_s, the production rate of $s\bar{s}$ pairs relative to that of $u\bar{u}$ pairs in the fragmentation scheme, determined previously from K^0 production [5]. Note that C_1 and C_2 only depend weakly on the details of fragmentation models. C_1 and C_2 were obtained from the Lund model [6] ‡1 and empirical forms for $N(\omega^0)$ and $N(K^{*0})$ were taken as follows:

$$N(\omega^0) = \exp(C_3 m + C_4 m^2)$$

$$\times \{1 + \exp[C_5(m - C_6) + C_7(m - C_8)^2]\}^{-1} ,$$

$$N(K^{*0}) = \exp(C_9 m + C_{10} m^2)$$

$$\times \{1 + \exp[C_{11}(m - C_{12})]\}^{-1} .$$

The specific forms chosen result in sharply cut off distributions typical of kinematic reflections. The coefficients C_3–C_{12} were determined by analysing mass distributions obtained from pure samples of ω^0 and K^{*0} generated with the Lund model, with detector resolution included. For the additional combinatorial background, the same functional form was taken as that used above for $N(\pm\pm)$, i.e.

$$N(\mathrm{BG}) = |m - 0.28|^{B_3} \exp(B_4 m + B_5 m^2) .$$

There are five free parameters in the fit of $N(m)$ to the distribution of fig. 1, namely B_1–B_5. The relative proportions obtained in the fit to the mass distribution are about 20% for the ρ signal, 20% ω-, 20% K^{*0}-, and 40% additional background contribution. The resulting fitted curve as well as the background contribution are shown in fig. 1. The data are described very well by the fit, within the errors. The ρ^0-contribution alone with background subtracted is also shown in fig. 1. In order to obtain the total number of ρ^0's produced per multihadron event, two corrections have to be made both of which were determined using the Lund model [6] ‡1. The first is for the detection efficiency ϵ_1 due to the finite detector acceptance and the selection criteria applied. It was determined to be $\epsilon_1 = 0.310 \pm 0.008$. The second correction ϵ_2 concerns the extrapolation to the x_E regions not covered in the analysis, $x_E < 0.1$ and $x_E > 0.7$. For the second correction $\epsilon_2 = 0.594 \pm 0.046$ was obtained resulting in an overall efficiency of $\epsilon = 0.184 \pm 0.015$. The errors come from the statistics of the Monte Carlo simulation and the uncertainty of ϵ from the variation of the model parameters. Radiative corrections were taken into account. The corrected value for the total number of ρ^0's per event, extrapolated to the full x_E-range, is

$$\rho^0/\text{event} = 0.98 \pm 0.09\ (\text{stat.}) \pm 0.15\ (\text{syst.}) .$$

The systematic error is given by the uncertainties in

‡1 The parameters used in the Monte Carlo simulation (Lund Monte Carlo version 4.3 with first order QCD) are: the first order QCD scale parameter $\Lambda(\mathrm{QCD}) = 0.3$ GeV leading to $\alpha_s = 0.17$ at 35 GeV; the mean transverse momentum of secondary quarks $\sigma_q = 0.35$ GeV/c; the probability of producing an $s\bar{s}$ pair relative to $u\bar{u}$ pair $\gamma_s = 0.3$; the fraction r of pseudoscalar relative to the sum of pseudoscalar and vector mesons and the parameter β defining the fragmentation function for light quarks are varied simultaneously as described in the text. For c and b quarks, we use the fragmentation function proposed by Peterson et al. [7] with $\epsilon_c = 0.25$ and $\epsilon_b = 0.04$. Radiative corrections are applied in all model calculations.

Table 1
Differential cross section $(s/\beta)(\mathrm{d}\sigma/\mathrm{d}x_E)$ for ρ^0 and $K^{*\pm}$.

	x_E	$(s/\beta)(\mathrm{d}\sigma/\mathrm{d}x_E)$
ρ^0	0.10 – 0.20	1228 ± 203
	0.20 – 0.30	455 ± 114
	0.30 – 0.40	191 ± 67
	0.40 – 0.70	90 ± 27
$K^{*\pm}$	0.05 – 0.10	3402 ± 356
	0.10 – 0.20	1174 ± 376
	0.20 – 0.40	268 ± 365

the efficiency and background subtraction. It is dominated by the latter. The number of ρ^0's per event for the x_E-range used in the analysis $0.1 < x_E < 0.7$, is $0.58 \pm 0.05 \pm 0.09$ [‡2]. The number of ρ^0's observed after background subtraction was about 2800. For the calculation of the invariant differential cross section $s/\beta(\mathrm{d}\sigma/\mathrm{d}x_E)$ the data were divided into four bins in x_E and the analysis described above was repeated for each bin. The luminosity was obtained using barrel Bhabha events [2]. The measured values for $s/\beta(\mathrm{d}\sigma/\mathrm{d}x_E)$ are given in table 1 and shown in fig. 3a. The errors given there are the statistical errors from the fit and do not include the systematic errors from background subtraction, the efficiency and the luminosity. The combined systematic error is estimated to be about 15%, independent of x_E. Also shown are data from the TASSO experiment [8]. Except for the first bin where TASSO finds a cross section which is lower than ours, the two experiments agree well.

$K^{*\pm}$ production. A search was made for the decay $K^{*\pm} \to K^0_S\pi^\pm$. The K^0_S was identified through the decay $K^0_S \to \pi^+\pi^-$. The analysis was made for the smaller event sample of 8119 events which had been used previously in the investigation of K^0 production [5]. The details of the K^0_S identification are described in ref. [5]. Essentially, pairs of charged tracks with momentum greater than 0.1 GeV/c were considered if they originate neither from the interaction region nor from the beam pipe material, in order to suppress combinatorial background as well as background from nuclear interactions. All charged tracks were assumed to be pions. Events with a $\pi^+\pi^-$ mass combination in the kaon band $0.425 < M(\pi^+\pi^-) < 0.575$ GeV/c^2 were then selected. A kinematical 1C-fit was made to the K^0_S hypothesis, keeping the K^0_S mass fixed. The K^0_S was then combined with an additional charged particle from the event vertex, using the pion hypothesis. In order to suppress background, the momentum of the additional pion was required to be greater than 0.1 GeV/c and the track had to point into the same hemisphere as the K^0_S, i.e. $\Theta(\pi^\pm, K^0_S) < 90°$, where Θ is the angle in space between the $\pi^\pm$ and K^0_S. The spectrum of the invariant mass $M(K^0_S\pi^\pm)$ thus obtained is shown in fig. 2. There is a prominent peak at about 0.9 GeV/c^2 due to $K^{*\pm}$ production. In order to determine the number of events in the K^* peak, the distribution was fitted with the following form:

$$N(m) = D_1 N(K^{*\pm}) + D_2 N(\mathrm{BG}) .$$

As in the fit for the ρ^0, a relativistic Breit–Wigner was taken for $N(K^{*\pm})$, the mass $M(K^{*\pm})$ is fixed to the table value of 0.892 GeV/c^2 and the nominal K^* width of 0.051 GeV/c^2 was combined in quadrature with the detector resolution of 0.1 GeV/c^2 (full width). For the background $N(\mathrm{BG})$ the empirical form

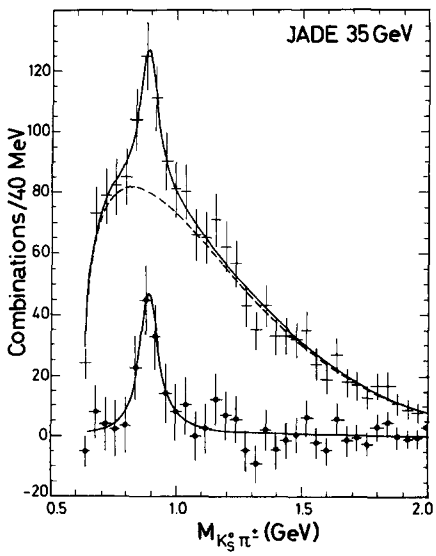

Fig. 2. The invariant mass spectrum $M(K^0_S\pi^\pm)$. The full curve is the result of the overall fit. The dashed curve is the background contribution alone. The distribution with background subtracted, together with the resonance fit, are also shown.

‡2 The number of ρ^0's obtained by making a resonance fit with an empirical smooth background without considering ω^0 and K^{*0} reflections is consistent with this: The value is ρ^0/event = 0.61 ± 0.06 (stat.) for the same x_E range.

$$N(\mathrm{BG}) = |m - 0.637|^{D_3} \exp(-D_4 m - D_5 m^2)$$

was chosen, taking into account the threshold at 0.637 GeV/c^2 as well as the exponential fall off at large masses observed in fig. 2. The parameters D_1–D_5 were left free in the fit which, as shown in fig. 2, describes the data well. Also shown in the figure is the K^*-signal with background subtracted. The detection efficiency for $K^{*\pm}$ due to acceptance and selection criteria was calculated with the Lund model [6] [‡1] to be $\epsilon = 0.083 \pm 0.007$, where the error includes the statistics of the model simulation as well as the effect of a variation of the model parameters. After correcting for the branching ratio of $K^{*\pm} \to K^0_S \pi^\pm$ and for unseen decay modes of the K^0_S, the number of $K^{*\pm}$ mesons produced per multihadron event was determined to be

$$K^{*\pm}/\mathrm{event} = 0.87 \pm 0.16\ (\mathrm{stat.}) \pm 0.08\ (\mathrm{syst.})\,.$$

The errors are the statistical error from the fit as well as the systematic one arising from the uncertainties in the efficiency. Since the K^0_S were identified with relatively little background in the analysis of $K^{*\pm}$ production, it was not necessary to apply a cut in x_E in order to suppress combinatorial background. Due to the more limited statistics, however, the differential cross section $s/\beta(\mathrm{d}\sigma/\mathrm{d}x_E)$ could only be determined for three x_E bins. The values obtained are given in table 1 and shown in fig. 3b. Again only the statistical errors from the fit are given in the figure. The systematic error is about 9%, independent of x_E. Comparing figs. 3a and 3b one notes that the slope of the experimental differential cross section for ρ^0 and $K^{*\pm}$ are compatible with being equal.

The ratio of pseudoscalar to vector meson production. In fragmentation models the number of vector

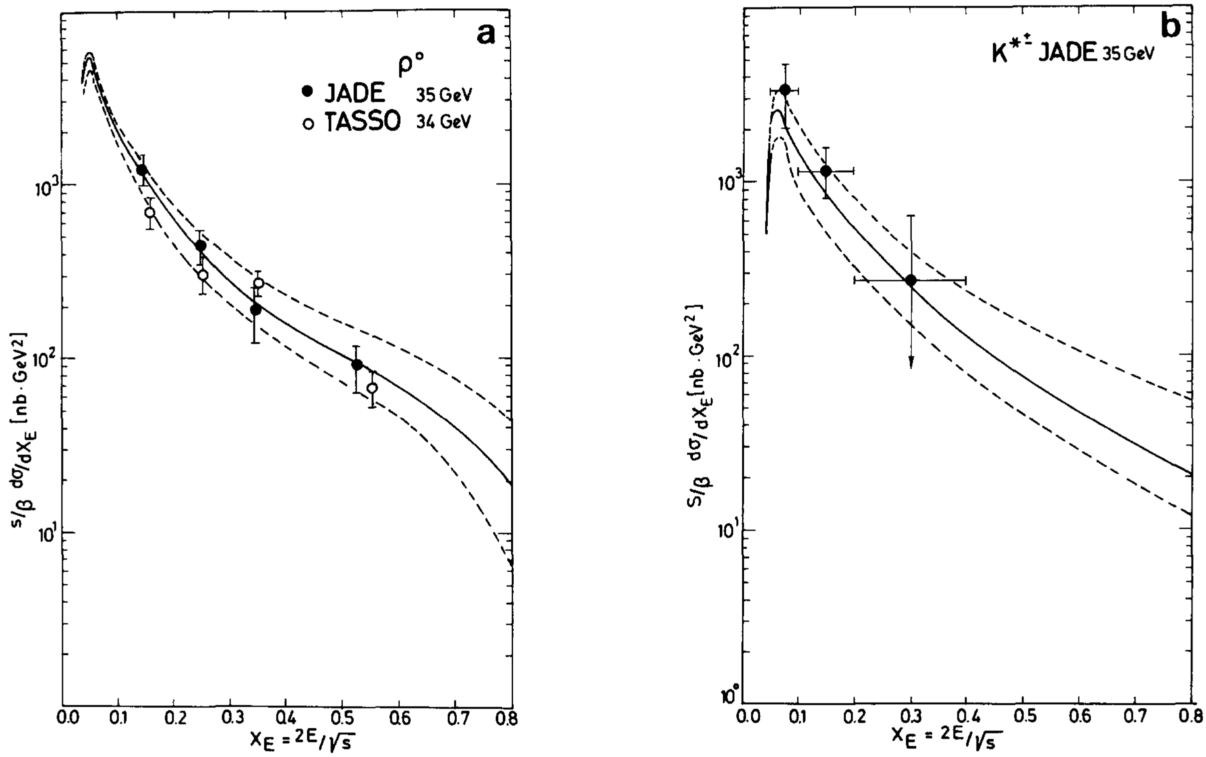

Fig. 3. Differential cross section $(s/\beta)(\mathrm{d}\sigma/\mathrm{d}x_E)$ for ρ^0 production (a) and $K^{*\pm}$ production (b). The TASSO result for ρ^0 is also shown. The errors shown in the figure are statistical only. The solid curve indicates the prediction by the Lund model with parameters $r = 0.49$, $\beta = 0.515$, $\gamma_s = 0.30$. The dashed curves are those with $r = 0.22$, $\beta = 0.0$ and $\gamma_s = 0.30$ (upper one), $r = 0.72$, $\beta = 1.0$ and $\gamma_s = 0.30$ (lower one), respectively.

mesons is determined by a free parameter r, the probability for the production of pseudoscalar mesons in the fragmentation processes relative to that of the sum of pseudoscalar and vector mesons. As discussed in ref. [5], the parameter r is strongly correlated with the form of the primordial fragmentation function $f(z)$, through the charged multiplicity. This ambiguity in the determination of r and the fragmentation function is resolved by the measurement of vector mesons per event. The analysis was again carried out using the Lund model [6] ‡1, since the observed distribution of charged particles between and within the jets favours this model over those with independent jet fragmentation [9,10]. Both the number of vector mesons ρ^0 and $K^{*\pm}$ discussed above, as well as the number of pseudoscalars η^0 per event, previously determined [11], was used to extract a value for r. In order to study a possible dependence of r on the meson mass, it was done separately for ρ^0, K^{*0} and η. For this the measured rate of mesons produced per event was compared with the value predicted by the model as a function of the parameter r. When varying r in the model, care was taken to simultaneously vary β, the parameter defining the fragmentation function $f(z) \propto (1-z)^{\beta}$, such that the charged multiplicity came out to be 13.6, as observed experimentally [5]. The production of mesons both in the fragmentation and as decay products of higher mass resonances was taken into account ‡3. Note, however, that mesons with $J^P = 0^+, 1^+$ or $J \geqslant 2$ are not included in the model. This leads to the following values for r:

$$r = 0.49 \pm 0.10\,(\text{stat.}) \pm 0.15\,(\text{syst.})\,,$$
from ρ^0 production ,

$$r = 0.30 \pm 0.15\,(\text{stat.}) \pm 0.11\,(\text{syst.})\,,$$
from $K^{*\pm}$ production ,

$$r = 0.46 \pm 0.06\,(\text{stat.}) \pm 0.11\,(\text{syst.})\,,$$
from η production ‡4 .

The systematic error of r includes the systematic uncertainty of the number of mesons per event as well as the uncertainty in the model prediction coming from the variation of the fragmentation parameters β and γ_s. In the case of ρ^0 production, the experimental number of ρ^0's in the x_E-range $0.1 < x_E < 0.7$ was used, in order to minimize the systematic error. The predictions of the Lund model with the r-values given above are compared with the experimental x_E-distributions for ρ^0's and $K^{*\pm}$'s in figs. 3a and 3b. The agreement is good. A value of r from ρ^0 production of $0.42 \pm 0.08 \pm 0.15$ has been given by the TASSO experiment [8], within the Field–Feynman fragmentation model, for the same range in x_E as that used in this analysis.

In order to study the dependence of vector meson production on the meson mass we include data on D^* production as measured by several experiments [12], [13–15] ‡5. It has been suggested [16] that the ratio of pseudoscalars to vector mesons PS/V should be a function of their mass ratio M_V/M_{PS}. For small values of this ratio the expectation is $PS/V = \frac{1}{3}M_V/M_{PS}$, where the factor $\frac{1}{3}$ is due to spin counting. For $M_V/M_{PS} \gtrsim 5$, the ratio PS/V is expected to level off approaching an asymptotic value of about 2.8 at very high values of M_V/M_{PS}. Hence the above r-values were converted into the ratio PS/V for all data on D^*, $K^{*\pm}$ and ρ^0 production. The pseudoscalars to be compared with D^*, K^* and ρ are D, K and π. The η-result was not considered here because of mixing of the corresponding vector mesons φ^0 and ω^0. Fig. 4 shows the ratio PS/V as a function of M_V/M_{PS}. The production of pseudoscalars relative to that of vector mesons does indeed rise with increasing mass ratio. The ρ/π ratio seems to indicate though that the leveling off sets in earlier than predicted by the relationship given above. A fit to $PS/V = \frac{1}{3}(M_V/M_{PS})^{\alpha}$ with α left free gives $\alpha = 0.5 \pm 0.1$. The result of this fit is also shown in fig. 4.

In conclusion, a substantial production of vector mesons is observed in e^+e^- annihilations. More than

‡3 For $r = 0.5$, about 75% of the ρ^0 mesons are primary ρ^0's from fragmentation, 15% come from η' decay and 10% from other decays. The corresponding numbers are for the $K^{*\pm}$: 75% from fragmentation and 25% from decays and for the η: 53% from fragmentation, 35% from η' decay and 12% from other decays.

‡4 There is some indication that the rate of η-production per event increases as a function of sphericity S [11]. This is possibly due to a higher production rate of isoscalar mesons in gluon jets. In order to estimate the uncertainty in the determination of r due to this effect the analysis was repeated for two-jet events alone, defined by $S < 0.15$. This results in an r-value approximately 20% lower.

‡5 The value of $R(D^*)$ is converted into r with $r = 1 - R(D^*)/R(D + D^*)$.

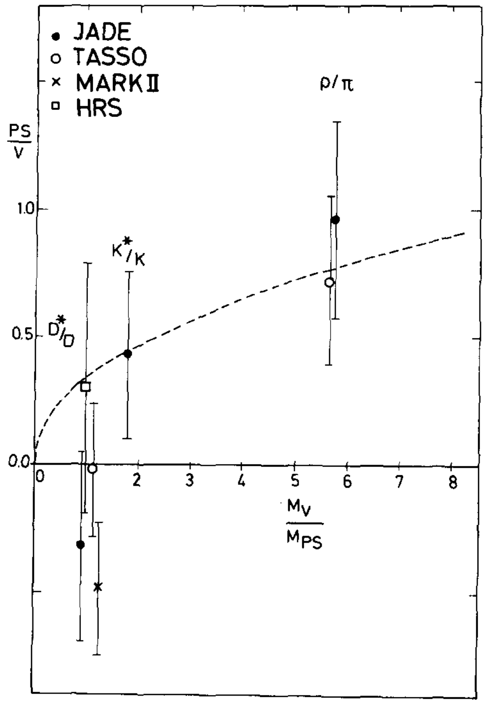

Fig. 4. The ratio of pseudoscalar to vector meson production PS/V as a function of M_V/M_{PS} for D*/D, K*/K and ρ/π. The dashed curve is the result of a fit PS/V = $\frac{1}{3}(M_V/M_{PS})^\alpha$, α_{fit} = 0.5. (● [14], ○ [15], × [12], □ [13].)

15% of all charged particles are due to charged pions from ρ^0 decay alone. About 2/3 of all K^0's produced originate from the decay of charged K^*. The ratio of pseudoscalar to vector mesons PS/V determined independently from D^*, K^* and ρ-production shows a rising behavior as a function of the mass ratio M_V/M_{PS}, as predicted.

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