OBSERVATION OF VECTOR MESON PRODUCTION IN INCLUSIVE pp REACTIONS

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Received 22 November 1973

We have measured cross sections, rapidity and transverse momentum distributions, and vector meson polarization for the reactions $pp \to \rho^0$ + anything, $pp \to \omega$ + charged particles, and $pp \to K^{*\pm}$ + anything at incident laboratory momenta of 12 and 24 GeV/c. We discuss various consequences of our results as well as possible connections with lepton pair production

Virtually nothing is known about inclusive production of vector mesons in high energy collisions, although this process may tell us more than inclusive pseudoscalar meson production does. Not only do we have polarization as an additional observable, but we can study the basic question to what extent the observed pions and kaons are secondary products from primarily produced clusters of well-defined spin and isospin, among which the ρ, ω and K^* may be prominent. V mesons may actually be primarily produced in a kind of hadronic bremsstrahlung process [1]. Furthermore, ρ^0 and ω production implies production of lepton pairs and is therefore possibly connected with lepton pair production at other effective masses or energies.

Measurements carried out so far only concern ρ^0 and K^* production in γp and Kp collisions respectively [2, 3]. In these cases the V mesons are leading particles, sharing some of the quantum numbers with one of the primary particles. It is harder but more interesting to study V mesons produced in pp collisions where we expect them to come off centrally. Since ρ production in high-energy pp collisions has not been observed before, it seems to be a widely accepted belief that the cross section for this process is only a few tens of microbarns.

We therefore have investigated V meson production in an experiment with the 2m hydrogen bubble chamber at CERN. We measured and analyzed 360 000 pp interactions at 12 and 24 GeV/c incident momentum. Details of the experiment and the analysis, as well as an investigation of vector meson production in the exclusive reactions $pp \to ppV^0$, are reported elsewhere [4, 5].

For inclusive ρ^0 production, we consider the distribution of the effective mass of all $\pi^+\pi^-$ combinations, shown in fig. 1. Because of the forward-backward symmetry, it suffices to take the π^+ from the cms backward hemisphere, where the pions have sufficiently low laboratory momenta to be distinguished from protons by ionization In fig. 1, the total distribution is also broken down into various ranges of cms rapidity y^* of the $\pi^+\pi^-$ system. The effective mass distributions have their maximum at about 400 MeV and show no structure except the ρ^0. In order to determine ρ^0 production cross sections, P-wave Breit–Wigner functions together with second order polynomials for the background are fitted to the mass distributions in the range from 500 MeV to 1000 MeV†1. A second order polynomial is sufficient to describe the background because (i) it leads to statistically acceptable fits, and (ii) the $\pi^-\pi^-$ mass distribution is, in the same mass range, fitted well by such a polynomial alone. The ρ^0 cross sections obtained from the fits

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†1 To make sure that what we fit is really the ρ^0, the resonance mass (and in some of the fits, also the width) was a free parameter It always came out within ± 15 MeV of the nominal ρ^0 mass The fits were also done using the π^+ from both cms hemispheres, in which case there is more background due to pion-proton ambiguities, the results were consistent with the ones from the backward π^+.

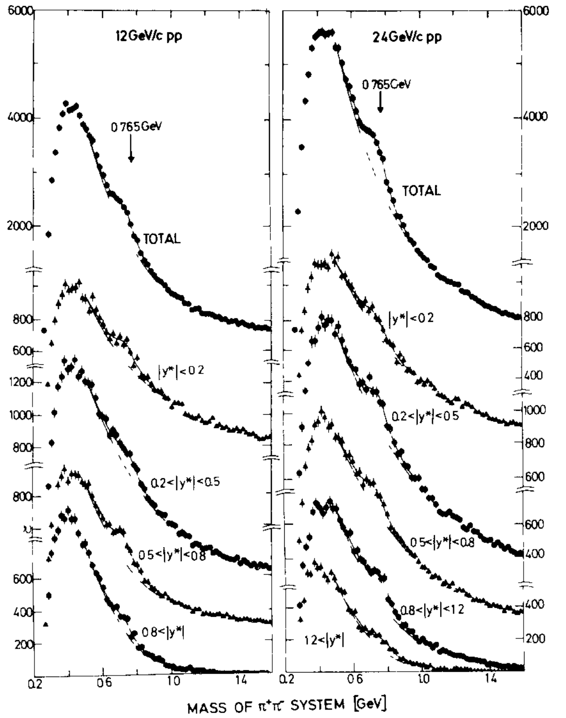

Fig 1. Effective mass distributions of the $\pi^+\pi^-$ systems in the reaction $pp \to \pi^+\pi^-$ + anything at 12 and 24 GeV/c incident laboratory momentum y^* is the longitudinal rapidity of the $\pi^+\pi^-$ systems in the cms.

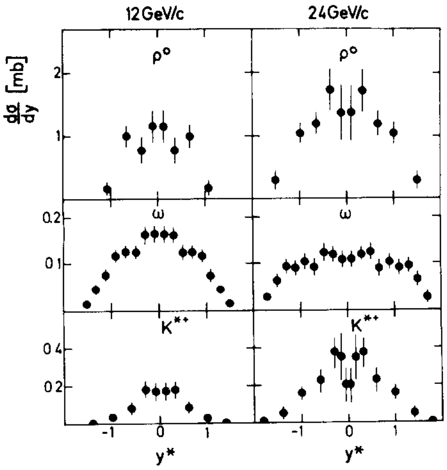

Fig. 2 Symmetrized distributions of the longitudinal rapidity y^* in the cms, for the reactions $pp \to \rho^0$ + anything, $pp \to \omega$ + charged particles, and $pp \to K^{*+}$ + anything at 12 and 24 GeV/c.

are multiplied by 2 to correct for the π^+ going forward in the cms. We find

$$\sigma(pp \to \rho^0 + \text{anything}) = \begin{cases} (1.80 \pm 0.25)\ \text{mb at } 12\ \text{GeV}/c \\ (3.49 \pm 0.42)\ \text{mb at } 24\ \text{GeV}/c \end{cases}$$

These ρ^0 production cross sections are ~1/15 of the π^0 cross sections, and about 50% larger than the K^0 plus $\bar{K}^0$ cross sections at the same energies [4] The rapidity distribution of the ρ^0, as obtained from the resonance plus background fits shown in fig. 1, is presented in fig. 2, the production is mainly centreal (while for the exclusive reaction $pp \to pp\rho^0$, $d\sigma/dy$ has a minimum at zero cms rapidity [5]).

In a similar way as the y^* distributions we have determined transverse momentum and decay angular ($\cos\theta_D$) distributions for the ρ^0. They are shown in figs. 3 and 4. The p_T^2 distribution is compatible with an exponential $d\sigma/dp_T^2 = A\exp(-Bp_T^2)$, with a slope $B = (3.6 \pm 0.4)\ (\text{GeV}/c)^{-2}$. Assuming this exponential shape throughout, it corresponds to an average trans-

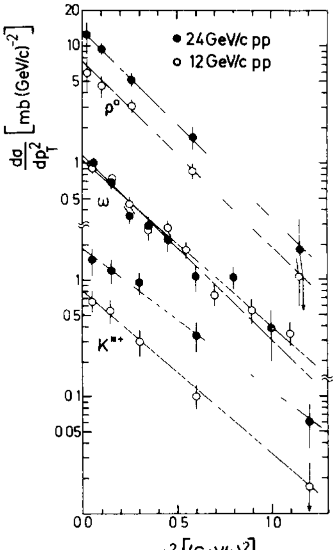

Fig 3. Distributions of the square of the transverse momentum, for the reactions $pp \to \rho^0$ + anything, $pp \to \omega$ + charged particles, and $pp \to K^{*+}$ + anything at 12 and 24 GeV/c. The fitted slopes are 3.6 ± 0.4 (ρ, 12 and 24 GeV/c), 3.4 ± 0 2 (ω at 12 GeV/c), 3.7 ± 0.3 (ω at 24 GeV/c), 3.4 ± 0.4 (K^* at 12 GeV/c), and 2.8 ± 0.3 (K^* at 24 GeV/c), all values being in $(\text{GeV}/c)^{-2}$.

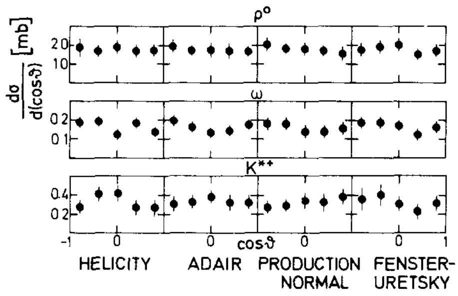

Fig. 4 Decay angular distributions of the vector mesons produced at 24 GeV/c in various coordinate frames

verse momentum of $\langle p_T \rangle \approx 470$ MeV/c of the ρ^0, this is larger than the $\langle p_T \rangle$ of the pions and the neutral kaons (320 and 405 MeV/c respectively at 24 GeV/c incident momentum).

The $\cos\theta_D$ distributions was determined for different coordinate frames in the ρ^0 rest system: (i) Helicity system (quantization axis $\hat{z}$ parallel to the cms momentum of the ρ^0), (ii) Adair system ($\hat{z}$ parallel to the cms beam momentum), (iii) production normal system ($\hat{z}$ normal to the plane of production of the ρ^0), (iv) Fenster–Uretsky system [6] ($\hat{z}$ parallel to $\hat{p}_a - \hat{p}_b$ where $\hat{p}_a$ ($\hat{p}_b$) are unit vectors in the beam (target) directions as measured in the ρ^0 rest (frame). In all frames the $\cos\theta_D$ distributions (fig. 4) are consistent with isotropy. Thus the ρ^0 is apparently not strongly polarized.

The ω can be studied in our experiment only in the decay mode $\omega \to \pi^+\pi^-\pi^0$. Since the π^0 momentum must be calculated from the momenta of the charged final state particles by energy-momentum conservation, we can identify an ω only in final states with no additional undetected neutrals, i.e. in the quasi-inclusive process $pp \to \omega$ + charged particles. The background subtraction was again done by resonance plus background fits. We obtain cross sections (corrected for the unobserved decay modes of the ω) of

$$\sigma(pp \to \omega + \text{charged particles}) = \begin{cases} (0.32 \pm 0.02) \text{ mb at } 12 \text{ GeV}/c \\ (0.32 \pm 0.03) \text{ mb at } 24 \text{ GeV}/c. \end{cases}$$

The analogous quasi-inclusive ρ^0 cross sections $\sigma(pp \to \rho^0$ + charged particles) are (0.32 ± 0.06) mb and (0.30 ± 0.05) mb at the two incident momenta, i.e., the same as the ω cross sections within the measuring errors The y^* and p_T^2 distributions of the ω are shown in figs. 2 and 3 and are similar to those of the ρ^0 (e.g. $\langle p_T \rangle \approx 460$ MeV/c), the $\cos\theta_D$ distributions shown in fig. 4 are consistent with zero polarization of the ω.

Finally, we have identified the $K^{*\pm}(892)$ by the decay into $K_S^0\pi^\pm$. Again subtracting the background by fits, we obtain the inclusive cross sections (corrected for all other decay modes of the K^*)

$$\sigma(pp \to K^{*+} + \text{anything}) = \begin{cases} (0.25 \pm 0.03) \text{ mb at } 12 \text{ GeV}/c \\ (0.64 \pm 0.06) \text{ mb at } 24 \text{ GeV}/c \end{cases}$$

$$\sigma(pp \to K^{*-} + \text{anything}) = \begin{cases} (0.02 \pm 0.02) \text{ mb at } 12 \text{ GeV}/c \\ (0.14 \pm 0.02) \text{ mb at } 24 \text{ GeV}/c \end{cases}$$

Rapidity, transverse momentum and decay angular distributions of the K^{*+} are shown in figs. 2 to 4, from the slope of the p_T^2 distribution we find $\langle p_T \rangle \sim 530$ MeV/c at 24 GeV/c incident momentum

We now discuss various implications of our results. For pions the total inclusive cross section (for $\pi^\pm$ and π^0) is $\sigma(\pi) \approx 3\sigma(\pi^0)$ [4], and therefore it is reasonable to assume the same charged to neutral ratio for rhos, i.e., $\sigma(\rho) \approx 3\sigma(\rho^0) = 10.5$ mb at 24 GeV/c With $\sigma(\pi) = (144 \pm 3)$ mb at 24 GeV/c [4] it follows that only 1/7 of all pions are coming from ρ decay Since the total inelastic cross section of 30.6 mb at 24 GeV/c contains a diffractive component of 6.3 mb [7], we can also state that on the average there are $\lesssim 0.5$ ρ mesons per *non* diffractive event, the average pion multiplicity of the inelastic events, on the other hand is 4.7. Thus up to 24 GeV/c incident momentum, emission of ρ mesons is not a dominant process in multipion production†2. On the other hand, a more than 10 times smaller ρ cross section than observed, as well as strong polarization of the ρ, would have been expected from the dual resonance model [6].

Vector mesons are a source of lepton pairs, and using our cross sections we can predict the vector-

†2 It may be thought that more ρ mesons are produced primarily, but that they are masked in the $\pi^+\pi^-$ effective mass distributions due to final state interactions of the pions If this was significant, however, we would have expected a broadened ρ^0 signal, but in fact it is best fitted, in all our mass distributions, with the width of 135 MeV.

dominance contribution to the reaction $pp \to \ell^+\ell^-$ + anything using the relation [8, 9]

$$d\sigma/dQ^2 = (\alpha^2/12\pi Q^2) \times \sum_{V=\rho^0,\omega,\Phi} \left(\frac{m_V^2}{m_V^2 - Q^2}\right)^2 \frac{4\pi}{\gamma_V^2} \left[2\rho_{11}^{(V)} + \frac{Q^2}{m_V^2}\rho_{00}^{(V)}\right]\sigma(V),$$

where $M_{\ell\ell} = \sqrt{Q^2}$ is the effective mass of the lepton pair, γ_V the V photon coupling constant ($\gamma_\rho^2/4\pi = 4.8$), $\rho_{\lambda\lambda'}^{(V)}$ the helicity density matrix, and m_V the V mass We evaluate this at 24 GeV/c, taking $\rho_{00}^{(V)} \approx \rho_{11}^{(V)} \approx \frac{1}{3}$ and $\sigma(\rho^0) = \sigma(\omega) \approx 3.5$ mb as suggested by our data (the Φ contribution is negligible). The formula probably overestimates the contribution from longitudinal ($\lambda = 0$) rhos, since the Q^2/m_V^2 factor is justified only at small Q^2. To compare with the Columbia–Brookhaven data [10] on the reaction p + (bound nucleon) $\to \mu^+\mu^-$ + anything, we have to correct for the limited acceptance ($p_{lab}(\mu^+\mu^-) > 12$ GeV/c, $\theta_{lab}(\mu^+\mu^-) < 63$ mrad) of the BNL experiment. This correction is model-dependent†3 but with all reasonable assumptions we find that in the lowest Q^2 region of the BNL experiment, $1.1 < Q^2 < 2$ GeV^2, the observed $\mu^+\mu^-$ cross section at 25 GeV/c exceeds the prediction from $\rho\omega\Phi$ dominance by a factor 2 to 3 While part of this factor may come from V mesons being produced by secondary pions in the target nuclei, there is also a strong variation of the $\mu^+\mu^-$ cross section with incident momentum (a factor 5 increase between 22 and 29.5 GeV/c, only part of which seems attributable to the limited acceptance) which appears incompatible with the rather slow increase of the ρ^0 cross section we observed between 12 and 24 GeV/c. Thus, the $\mu^+\mu^-$ pairs observed in the BNL experiment cannot be the Breit–Wigner tails of the ρ, ω and Φ.

Finally, there may be a relation between our ρ^0 production cross section and lepton pair production cross sections at very high energies. Thus, Sakurai is suggesting that the Drell–Yan scaling law [11] for production of heavy lepton pairs $d\sigma/dQ^2 = Q^{-4}F(Q^2/s)$ holds, in an average sense, also in the Q^2 region dominated by vector mesons [12]. Taking the ρ^0 and ω to be the dominant contributors to lepton pair production over the Q^2 region from threshold to $Q^2 = 2m_\rho^2$, one has

$$\frac{d\sigma}{dQ^2}(Q^2 \sim m_\rho^2) \approx \frac{2 \times 3.5\ \text{mb}}{1.2\ \text{GeV}^2}\left(\frac{\Gamma(\rho^0,\omega \to e^+e^-)}{\Gamma_{\rho,\omega}}\right) \approx 2.4 \times 10^{-31}\ \text{cm}^2\ \text{GeV}^2$$

at 24 GeV/c incident momentum ($s = 46.6$ GeV^2), the scaling law then predicts $d\sigma/dQ^2(Q^2 = 36\ \text{GeV}^2) \sim 0.7 \times 10^{-34}$ cm^2 GeV^{-2} at $s = 2800$ GeV^2 This is just equal to the value of a 95% confidence upper limit for e^+e^- production, set by the experiment of the CERN-Columbia-Rockefeller collaboration at the intersecting storage rings at CERN [13].

We gratefully acknowledge the help and support from E. Lohrmann, H.H Nagel, N. Schmitz and M.W. Teucher

†3 One could make the same p_{lab} and θ_{lab} cuts for ρ and ω production, but there are other possibilities, e g to assume that the x and p_T distributions of the $\mu^+\mu^-$ pairs are similar from $Q^2 = m_\rho^2$ to $Q^2 = 2$ GeV^2

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