A DETAILED STUDY OF EXCLUSIVE AND INCLUSIVE (e^+e^-) INDUCED PROCESSES IN THE ENERGY RANGE 1.2-3.0 GeV†

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We have studied a total of 26,208 events produced in (e^+e^-) reactions in the energy range from 1.2 to 3.0 GeV. All these events had to have at least two charged particles in the final state with an energy cut-off, depending on the nature of the particle: $E_e \geq 100$ MeV; $E_\pi \geq 130$ MeV; $E_K \geq 225$ MeV. The above conditions were imposed by the fast electronic trigger.

The events were of the following nature:

Type of event	Observed Number	
$e^+e^- \to e^+e^-$ (collinear, coplanar)	22,478	1st
$e^+e^- \to e^+e^-$ (acoplanar - $\lvert\phi\rvert \geq 5^\circ$)	1,140	2nd
$e^+e^- \to \mu^+\mu^-$ (collinear, coplanar)	1,120	3rd
$e^+e^- \to \mu^+\mu^-$ (acoplanar- $\lvert\phi\rvert \geq 5^\circ$)	55	4th
$e^+e^- \to h^+h^-$ (collinear, coplanar)	142	5th
$e^+e^- \to h^+h^-$ + anything	1,085	6th
Total	26,208	

All these events have been reconstructed in space ($\Delta\theta = \pm 1^\circ$), and their identification in terms of particle nature (e, μ, π, K) has been done in an unambiguous way through direct calibrations with beams of known particles (e, μ, π) and momenta. The K -meson signal was identified by range. The results are as follows:

1. - Check of QED - the analysis of the first two processes, gives the most accurate check of QED in the range of space like and time like values from $-(0.241$ to $7.49)$ GeV^2 and $+ (2.4$ to $9.0)$ GeV^2, respectively. In fact the energy dependence of the process ($e^+e^- \to e^+e^-$) follows the expected QED behaviour within ±2%;

$$\sigma(e^+e^- \to e^+e^-) = A.s^n$$

with $n = -(0.99 \pm 0.02)$. It should be emphasized that this test is practically independent from systematic errors in our small angle monitor; it however depends on the validity of QED at very small q^2-values (i.e. $\langle q^2 \rangle = 2 \times 10^{-3}$ GeV^2). Moreover the overall fit to all our data (allowing ±5% systematic uncertainty at each energy) gives A within ±2%,

$$\frac{A_{exp}}{A_{QED}} = 1.00 \pm 0.02$$

These data include 1st order radiative corrections. In this connection it is instructive to note that our $|\phi|$ distribution(*) agrees well with the theoretical expectations of Kessler and collaborators for all values of ϕ.

2. - (μe) EM universality and check of crossing symmetry. The analysis of the 3rd and 4th reactions allows us to check the electromagnetic μ-e universality to a level of ±4%. For these $\mu\bar{\mu}$ events we have done the same analysis as for the e^+e^- events. If we assume μe universality, the same data produce a nice check of crossing symmetry for QED, to a level of ±1%.

3. - $|F_\pi|$ and $|F_K|$. The study of the 5th reaction yields the values of the electromagnetic form factors for the charged pseudoscalar mesons in the timelike region 1.44-9.00 GeV^2. In Fig. 1, $|F_\pi|$ is compared with three theoretical models, due to Renard (top curve), Gounaris-Sakurai (middle curve) and Bonneau-Martin (bottom curve). It is this theoretical

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* $|\phi|$ is the angle between the two planes, each one containing one of the final state leptons and the beam axis

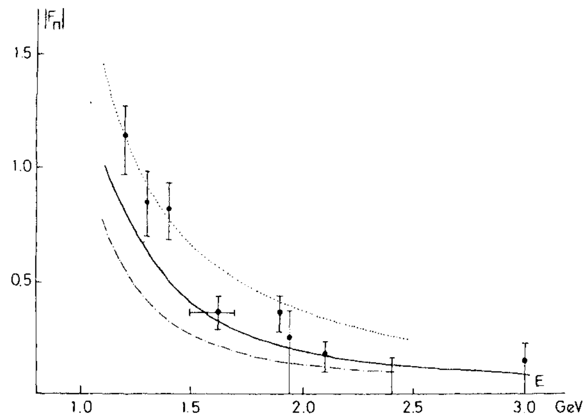

Fig. 1: The electromagnetic form factor of the pion, $|F_\pi|$, compared with 3 theoretical predictions.

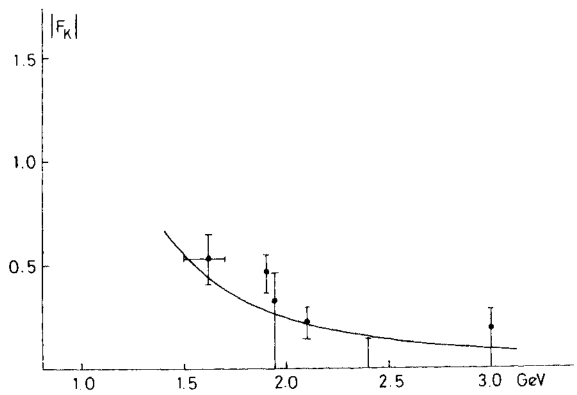

Fig. 2: The electromagnetic form factor of the K-meson, $|F_K|$, compared with the (ρ,ω,ϕ) tail.

uncertainty which prevents us from deriving a definite conclusion on our lowest three points, where the number of observed $\pi^+\pi^-$ events exceed the expectation based on the Gounaris-Sakurai extrapolation of the ρ-tail, with the $\omega\rho$ interference as measured at ORSAY and NOVOSIBIRSK. Fig. 2 shows $|F_k|$, compared with the ρ,ω,ϕ tails, based on naive SU_3 and zero width approximation (Cabibbo prediction).

Two definite conclusions can be derived from our data:

$$|\gamma_{\rho'}\cdot g_{\rho'\pi\pi}|^2 \leq 10^{-2}\, |\gamma_\rho \cdot g_{\rho\pi\pi}|^2 \quad \text{for } m_{\rho'} \simeq 1{,}200 \text{ MeV}$$

$$|\gamma_{\rho''}\cdot g_{\rho''\pi\pi}|^2 \leq 10^{-3}\, |\gamma_\rho \cdot g_{\rho\pi\pi}|^2 \quad \text{for } m_{\rho''} \simeq 1{,}600 \text{ MeV}$$

Namely, the product of the coupling constants ($\gamma_\rho \equiv$ photon vector meson) times ($g_{\rho\pi\pi} \equiv \rho\pi$), for the 1st and the 2nd Veneziano vector mesons (indicated by the mass-values $m_{\rho'} \simeq 1{,}200$ MeV and $m_{\rho''} \simeq 1{,}600$ MeV) are two and three orders of magnitude lower than those of the standard ρ-meson, respectively

4. - Angular distribution of the produced hadrons

Taking all data at all energies for the last reaction, we get 2,806 tracks, which can be used to study possible correlations. Having found no evidence for any type of correlation (multiplicity, angles, range) we look at the same data to extract the angular distribution of the produced particles. If we call θ the angle of the emitted hadron, with respect to the beam line, we expect a distribution

$$f(\theta) = 1 + \alpha \cos^2 \theta$$

If we divide all events into 3 energy intervals, the values of α are, within ±20%, always compatible with zero; more precisely:

Weighted Energy (GeV)	Luminosity $(\text{nbr})^{-1}$	α
$\langle E\rangle_I = 1.45$	98.33	-0.3 ± 0.2
$\langle E\rangle_{II} = 1.95$	414.14	0.0 ± 0.2
$\langle E\rangle_{III} = 2.75$	439.75	0.1 ± 0.2

5. - Energy distribution

Having established the lack of any possible correlation in our data we have taken all events, with more than two tracks, at all machine energies and analysed their range distribution. We can do this for three range intervals. The results are shown in Fig. 3 where the full line is the best fit to the data; assuming that all hadrons are π's we get

$$\exp\left(-5.5^{+1.5}_{-0.5}\right)\frac{E_\pi}{E_0}$$

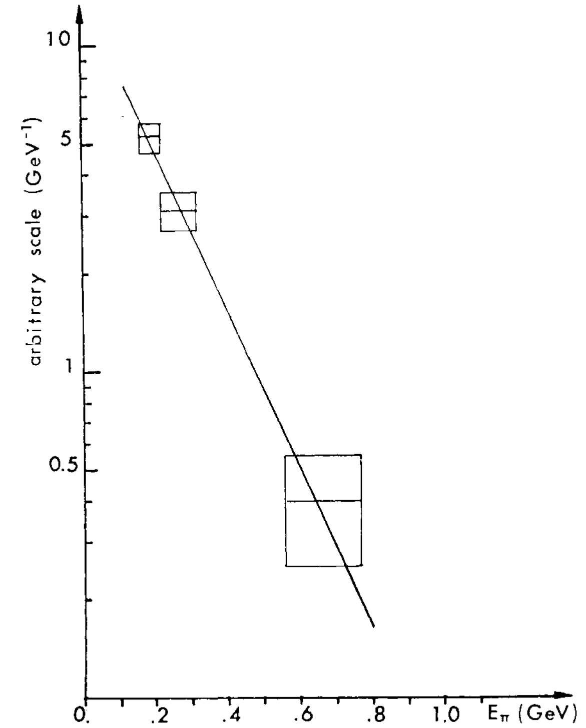

Fig. 3: The energy spectrum of the pions produced in (e^+e^-).

where E_0=1 GeV and E_π is the total π-energy. Notice that the exponent is typical of strong interaction phenomena.

6. - <u>The energy dependence of $\sigma(e^+e^- \to 4\pi^\pm)$ and the problem of $\rho'' \to 4\pi^\pm$</u>

The analysis of the four tracks events yields the exclusive cross-sections

$$\sigma(e^+e^- \to 4\pi^\pm)$$

in the range (1.2 - 3.0) GeV total centre of mass energy. Figure 4 shows the results obtained using not only kinematic closure (as done by previous authors) but also requiring the correct penetration of the 4 track events. The numbers are as follows:

4T → 4TK → 4TKP

128 → 59 → 32

4T ≡ all 4 tracks events

4TK ≡ all 4 track events with kinematic closure

4TKP ≡ all 4 track events with kinematic closure and correct penetration

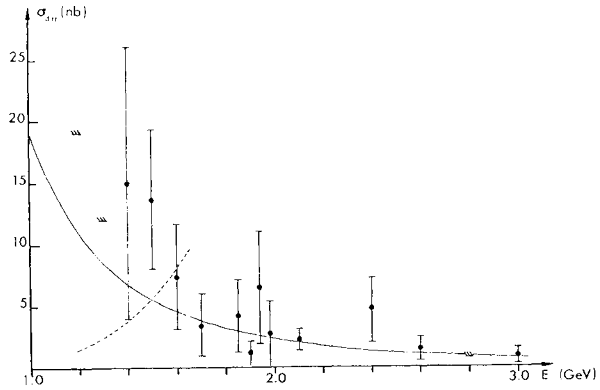

Fig. 4: The energy dependence of $\sigma(e^+e^- \to 4\pi^\pm)$. Dotted line is 4 body phase space. Full curve shows the energy dependence of $e^+e^- \to$ hadrons

The results which are compared in Figure 4 with 4 body phase space (dotted line) plus the fall off of the total annihilation cross section, were tested versus four different hypotheses: i) assuming for the energy dependence the same value we measured for the total hadronic annihilation cross-section ($\underline{P}(\chi^2)$=75%); ii) allowing the fit to choose the best energy dependence for $\sigma(e^+e^- \to 4\pi^\pm)$ ($\underline{P}(\chi^2)$=77%); iii) allowing a B.W. resonance to be present ($\underline{P}(\chi^2)$=76%); iv) using the production of ρ, ϵ, A_1, as advocated by Hirshfeld and Kramer ($\underline{P}(\chi^2)$=72%).
We conclude that it is not possible to discriminate among these possibilities in a statistically significant way. In particular the existence of a ρ'' in this energy region is completely open. It is on the other hand meaningful to determine the energy dependence of $\sigma(e^+e^- \to 4\pi)$, which turns out to be

$$\sigma(e^+e^- \to 4\pi^\pm) = A.s^n$$

with $n = -(1.66 \pm ^{0.76}_{0.44})$. This value is perfectly consistent with the energy dependence of the total hadronic annihilation cross section, to which we go now.

7. - The energy dependence of $\sigma(e^+e^- \to$ hadrons)

As in any other experimental set-up, we do not cover 100% of the solid angle but only 20% of the total. In order to derive the total hadronic annihilation cross-section, a model is therefore needed. We have studied various possibilities and we present here two extreme cases. One is the result obtained assuming that the final states produced in (e^+e^-) annihilation are analogous to those produced in ($\bar{p}p$) annihilation at rest. Figure 5 shows a self-consistent check of this choice; the multiplicity predicted by the ($\bar{p}p$) model (histogram) is compared with experimental results (points with errors). The other is what we call the quasi-model-independent method, where the multiplicity distributions of the final states are obtained directly from our observations. The results are shown in Figure 6. The best fit to the energy dependence of ($e^+e^- \to$ hadrons), including the uncertainty of the models is as follows:

$$\sigma(e^+e^- \to \text{hadrons}) = A.s^n$$

with

$$n = -(1.54^{+0.17}_{-0.29})$$

In the energy region below 3 GeV the total hadronic annihilation cross-section doesn't follow the behaviour observed at CEA and SLAC. From 1.2 to 3.0 GeV the cross section certainly decreases with energy.

For more details we refer the reader to the four papers submitted at the conference from the same authors:

995A) "The energy dependence of $\sigma(e^+e^- \to$ hadrons) in the total centre of mass energy range 1.2 to 3.0 GeV."

995B) "Cross-section measurements for the exclusive reaction $e^+e^- \to 4\pi^\pm$ in the energy range 1.2-3.0 GeV"

995C) "A Study of low energy pions produced in (e^+e^-) from 1.2 to 3.0 GeV."

995D) "A Study of the hadronic angular distribution in e^+e^- from 1.2 to 3.0 GeV".

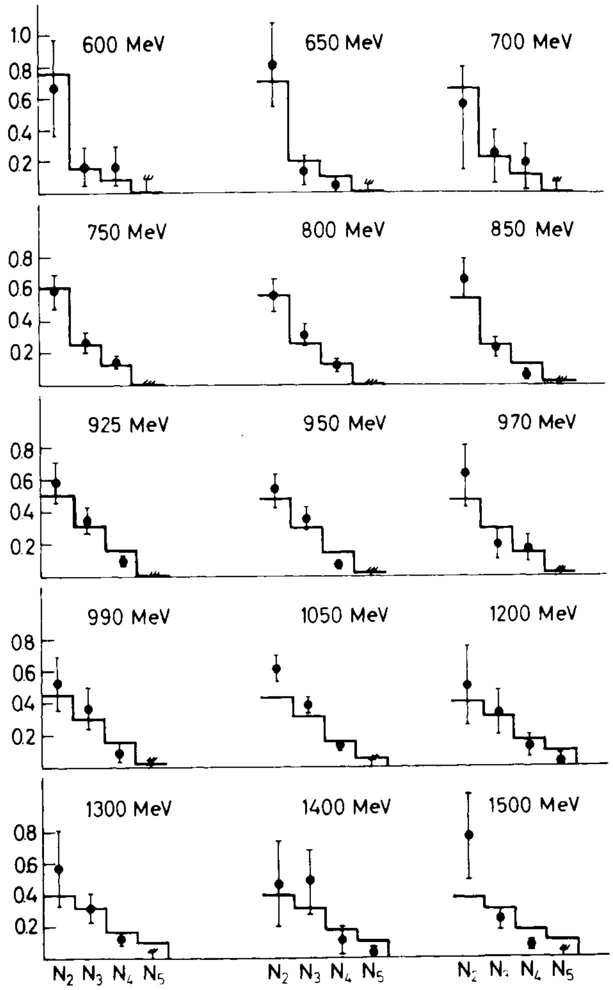

Fig. 5: Observed and expected multiplicities, compared.

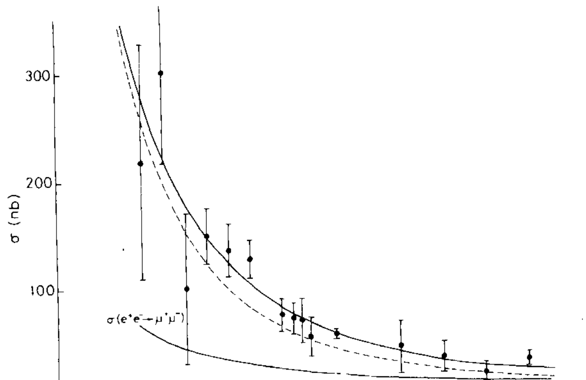

Fig. 6: The energy dependence of $\sigma(e^+e^- \to$ hadrons). The dotted line is our best fit to the data derived on the basis of the $\bar{p}p$ model. The full line is the best fit to the data shown, obtained with the quasi-model-independent method.