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OPEN PROBLEMS IN (e^+e^-) HADRON PRODUCTION BELOW 3 GeV

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The e^+e^- annihilation into hadrons in the center of mass total energy region 1÷3 GeV is shortly reviewed.

The quark model and the color as quark internal number were strongly supported when the multihadronic production at these energies was discovered. The J/ψ properly defines an upper limit opening a new kind of physics but, just for its different nature and for the high production cross section (~50 μb radiative corrections included), it is also the best factory for the light quark spectroscopy.

In the following the most relevant features of e^+e^- annihilation at these energies are summarized from the point of view of conservation laws and theoretical expectations.

Published data are reviewed with some anticipation on the DM2 new results. Open problems are emphasized, also if few chances exist they will ever be solved.

THEORETICAL SUMMARY

The oddness of the e^+e^- annihilation into hadrons, independently of its deep physical meaning, is shown in Fig. 1, where the striking feature of the total cross section is sketched: only narrow peaks are visible, being the J/ψ resonance by far the most relevant phenomenon. On a more physical scale, normalizing the cross section to the muon pair production at the same energy, regular steps also appear which connect these narrow peaks.

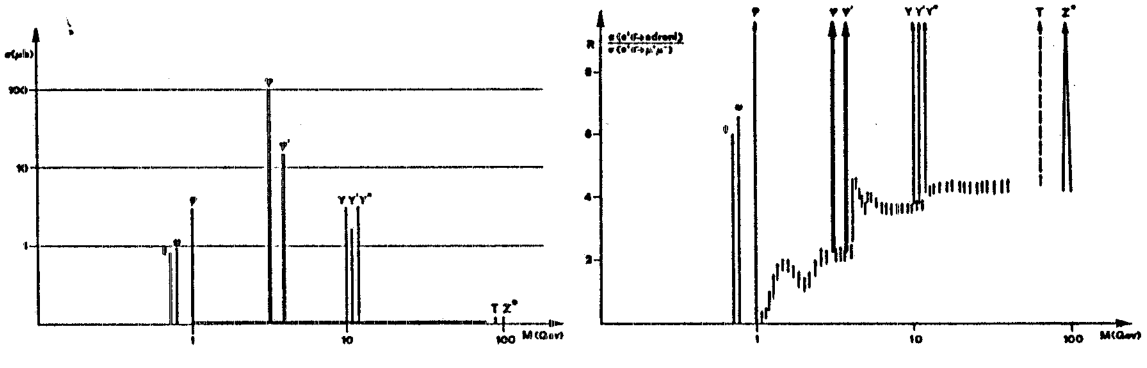
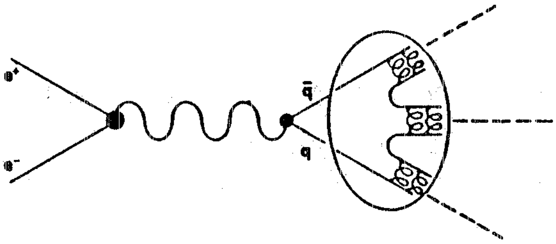


FIGURE 1
$e^+e^- \rightarrow$hadrons versus c.m. total energy M.

The general features of e^+e^- annihilation are summarized in Fig. 2, with the standard assumption that strongly interacting particles are produced mainly at the first electromagnetic order, that is via a virtual photon. Immediate consequences of this assumption can be deduced from the conservation laws: total angular momentum, parity and total charge conjugation.

FIGURE 2
$e^+e^- \rightarrow$hadrons according QCD



Total angular momentum and parity are $J^P = 1^-$. Furthermore in the limit of high center of mass (c.m.) energy 2E, respect to the lepton mass m_e, the longitudinal component along the beam axis z becomes negligible, like for a real photon. In fact in the center of mass the positron u_+ and electron u_- spinors are just solutions of the same Dirac equation with opposite energy $u\,(p, \mp E)$. Therefore the electromagnetic current, which generates the intermediate virtual photon, has components, for unpolarized beams:

$$J_o \propto u^\dagger_+ u_- = 0$$

$$\left.\begin{aligned} J_z &\propto u^\dagger_+ \alpha_z u_- = 0 \left\{1-\left(\frac{p}{|E|+m}\right)^2\right\} \chi^\dagger_+ \sigma_z \chi_- \\ J_z &\propto u^\dagger_+ \alpha_z u_- = 0 \left\{1+\left(\frac{p}{|E|+m}\right)^2\right\} \chi^\dagger_+ \sigma_z \chi_- \end{aligned}\right\} \Rightarrow \frac{J_z\,(S_z^{TOT}=0)}{J_x+iJ_y\,(S_z^{TOT}=\pm 1)} = \frac{m_e}{E}$$

where u and α or χ and σ are, respectively, 4 or 2 dimensional spinors and matrices.

As a consequence the two body annihilation angular distribution can be deduced. For instance:

- Spin 0, bosons pairs: $e^+e^- \rightarrow \pi^+\pi^-, K^+K^-, K_S^o K_L^o$
  $(d\sigma/d\Omega^*) \propto |Y^1{}_1| \propto \mathrm{sen}^2\vartheta^*$

The angular distribution must vanish at 0 degree because only the spin of the produced particles can contribute to the total angular momentum.

- Spin 1/2, fermions pairs: $e^+e^- \rightarrow \mu^+\mu^-, B\bar{B}$.

$$|L-S| \leq J_\gamma \leq L+S$$

$\Rightarrow$ only S=1 and L=0,2, that is S and D waves.

$$P_\gamma = -1 = (-1)\cdot(-1)^L$$

The angular distribution is more transparent if the total angular momentum state $|1, \pm 1>$ is projected with respect to the outgoing particles direction ϑ^*:

$$|1, \pm 1> = \frac{1 \pm \cos \vartheta^*}{2} |+> - \frac{\mathrm{sen}\, \vartheta^*}{\sqrt{2}} |0> + \frac{1 \mp \cos \vartheta^*}{2} |->$$

$$(d\sigma/d\Omega^*) = |A_\pm|^2 (1 + \cos^2 \vartheta^*) + |A_o|^2 \mathrm{sen}^2 \vartheta^*$$

where $|\pm>$ and $|0>$ are the angular momentum eigenstates with respect to the new z* axis.

Still, considering the e.m. current of the outgoing particles, it is expected $|A_o/A_\pm| \propto M\mu/E$ in case of pointlike fermions. In the barion case this ratio must also be weighted with the relative form factors. Considering the crossed e B → e B scattering channel, the spin of the crossed $\bar{B}$ must be reversed, therefore A_o or $A_\pm$ correspond, respectively, to non spin-flip (purely electric) or spin-flip (purely magnetic) form factors:

$$(d\sigma/d\Omega^*) (e^+e^- \rightarrow B\bar{B}) \propto (1 + \cos^2 \vartheta^*) |G_M|^2 + \mathrm{sen}\, \vartheta^* (M_E/E)^2 |G_E|^2$$

At the threshold, $E=M_B$, the D wave vanishes, therefore it is expected $G_E(2 M_B) = G_M(2 M_B)$.

Total charge conjugation is $C = -1$. As a consequence of this selection rule, at the first e.m. order, the annihilation into all particles with definite C is forbidden: $e^+e^- \not\rightarrow N\pi^\circ, N\rho^\circ$.

Another consequence is, for instance, the rather peculiar Φ decay:

$$|\Phi> = 1/\sqrt{2} \{ |K^\circ(p)> |\bar{K}^\circ(-p)> - |K^\circ(-p)| \bar{K}^\circ(p)> \}$$

$$|K^\circ> = \frac{|K_S> + |K_L>}{\sqrt{2}}$$

$$\Rightarrow |\Phi> = 1/\sqrt{2} \{ |K_S^\circ(p)> |K_L^\circ(-p)> - |K_S^\circ(-p)> |K_L^\circ(p)> \}$$

$$|\bar{K}^\circ> = \frac{|K_S> - |K_L>}{\sqrt{2}}$$

The G parity $G = C \cdot (-1)^I = (-1)^{N_\pi}$ allows to associate directly the isospin to the number of produced pions $N\pi$.

The theoretical prejudice in the Fig. 2 scheme is that the starting point for producing hadrons is the e.m. creation of a pointlike pair of quarks. Then the quark color is the source of the strong interaction, which will generate in some way the hadrons in the final state, according to the quantum chromodynamics (QCD). There is now a widespread acceptance of QCD as the theory of strong interactions and in particular there is hope that lattice QCD will produce all the mesons paramenters just from one parameter, Λ_0, and the quark masses. At present this program is not fulfilled and quantitative predictions are trusted only in some limiting cases, where perturbative calculations would be allowed like high energies or high momentum transfers.

Furthermore the ambiguous meaning of a confined quark mass allows quantitative predictions only at energies much higher than the possible quark mass range.

Predictions are, for instance:

The ratio among different quark flavours produced:

$$|\rho>_n \propto 1/\sqrt{2}\,\{\,|u\,\bar{u}> - |d\,\bar{d}>\} \Rightarrow \Gamma_{ee} \propto |A(e^+e^- \rightarrow \quad \rho_n)|^2 \propto (1/2)|Q_u - Q_d|^2 \propto 9$$

$$|\omega>_n \propto 1/\sqrt{2}\,\{\,|u\,\bar{u}> - |d\,\bar{d}>\} \Rightarrow \Gamma_{ee} \propto |A(e^+e^- \rightarrow \quad \omega_n)|^2 \propto (1/2)|Q_u + Q_d|^2 \propto 1$$

$$|\Phi>_n \propto |s\,\bar{s}> \Rightarrow \Gamma_{ee} \propto |A(e^+e^- \rightarrow \quad \phi_n)|^2 \propto |Q_s|^2 \propto 2$$

The ratio between the total hadronic and μ pair cross sections $\left(R = \dfrac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \right)$

At very high energies:

$$R_o = 3 \sum_{q=1}^{N_q} Q_q^2$$

where N_q is the number of flavours which can be produced. Actually virtual quark pairs and gluon production would spoil this prediction, unless the correction at the first order is already small:

$$R_1^{(w)} = R_0\left(1 + \frac{\alpha_s(w)}{\pi}\right)$$

This would be the case already at energies rather smaller than the J/ψ mass, where[1] $\alpha_s(J/\psi) \simeq 0.2$.

This predictions would be properly tested at any energy if the interaction at t=0 is selected, that is averaging the cross section on the energy according to the uncertainty relations. Therefore vector meson excitation or direct pair production are dual representation of the same process. To be coherent this duality would be local, that is valid for each produced vector meson. Bell and Bertlmann[1] have proved that in the non-relativistic limiting case, when the quark interaction is assumed to be a coulombic potential plus a confining one.

The U-spin invariance holds at energies high enough, where the strange quark mass can be neglected too. In other words mesons, in the same octet with the same electric charge, belong to U-spin multiplets meanwhile the photon is a U-spin singlet. Therefore, concerning the form factors:

$$F_{\pi^\pm} = F_{K^\pm}$$

Besides a $K^o\,K^o$ pair with $C = -1$ has a vanishing U-spin singlet component, therefore

$$(F_{K^o} / F_{K^\pm}) \simeq 0$$

Extended Vector Dominance Model[2] (EVDM, the old orthodoxy) was the phenomenological theory of e^+e^- annihilation, before the J/ψ discovery contemporary with the advent of QCD (the new orthodoxy).

According EVDM the total hadronic cross section is built up by the excitation of a sequence of vector mesons, mainly the ρ_n family. On the other hand, these vector mesons would be the various radial excitations of $q\bar{q}$ pairs. The ρ_n mass rule $M^2\rho_n = M^2\rho + \alpha \cdot n$, $\alpha \simeq 1$ GeV^2 was foreseen by the Veneziano model[3], which suggested the existence of daughter Regge trajectories to have an amplitude for π–π interaction in agreement with analyticity, crossing symmetry and linear Regge trajectories.

It was demonstrated[4] that simple and reasonable rules on mass and widths behaviours:

$$\Gamma^{e+e-}_{\rho_{(n)}} \simeq \Gamma_\rho \, (M_{\rho_{(n)}} / M_\rho)$$

$$\Gamma^{e+e-}_{\rho_{(n)}} \simeq \Gamma_\rho^{e+e-} \, (M_\rho / M_{\rho_{(n)}})$$

can provide a total cross section decreasing just like $1/W^2$, with the c.m. total energy W and an asymptotic value of $R_\infty \simeq 2.5$ not far from the quark model prediction $R_\infty \simeq 2$.

DATA SUMMARY

In the energy range W=1÷3 GeV, which is considered in this short review, data are poor if not lacking. The up to now published data concern incomplete apparata. New data will come very soon from DM2, which is a complete detector, with large solid angle, magnetic field and photon detection[5]. Few anticipations concerning DM2 results will be presented here, anyway DM2 is no more running and its data leave large energy intervals unexplored.

Many risen questions remain still unsolved and probably will never be solved: no e^+e^- storage ring, equipped with a magnetic detector, is planned to run in this energy range in the future. Only the ADONE e^+e^- storage is scheduled to come back in operation in the 1988 with a specialized detector, FENICE, to determine essentially the neutron time-like form factor, never measured before[6].

On the basis of heuristic arguments (the neutron has no electric charge and a magnetic moment lower than the proton one) one would expect the neutron form factors much lower than the proton ones. On the other hand many fits through the space-like form factors and the measured time-like proton form factor, like for instance assuming ρ, ω and ρ'(1550), ω'(1550) dominance, predict the neutron f.f. much higher than the proton ones[7]. Therefore an uncertainty of two order of magnitude on $e^+e^- \rightarrow n\bar{n}$ cross section strongly demand this measurement.

In principle e^+e^- annihilation can be related to photoproduction on pròton or even better to coherent photoproduction on heavy nuclei at high energies, via the vector dominance model, (Fig. 3) relating that part of the photoproduction amplitude in which the photon converts in the detected hadronic final state, scattering on the target[8]. The unavoidable background and moreover the mass dependence of the vector meson-target scattering strongly limit photoproduction results, which can only be added in proof.

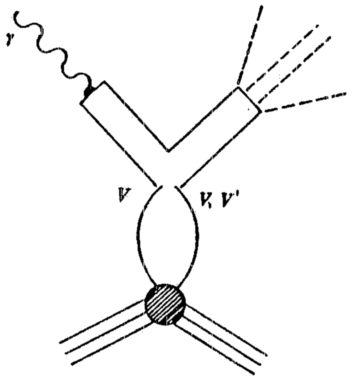


FIGURE 3
"Diffractive" photoproduction according VDM

X(1100), ρ'(1250), X(1440)

An unconfirmed resonance has been claimed in e^+e^- pairs photoproduction[9] with the singular mass of 1100 MeV. The experimental procedure to gain sensitivity in such a measurement is rather peculiar. Two different graphs, with opposite charge conjugation, can contribute to e^+e^- pairs photoproduction: the "Bethe-Heitler" QED amplitude A_{BH} and the "Compton hadronic" amplitude A_V. Therefore in the asymmetry $|A(p_+, p_-)|^2 - |A(p_-, p_+)|^2 = 4\,\mathrm{Re}\,(A^*_{BH} A_V)$ the hadronic contribution is isolated provided the interfering QED graph is not too small. Two peaks have been claimed with the following parameters (Fig. 4):

M (MeV)	Γ (MeV)	$d\sigma/dt(0^\circ)$ (pb GeV $^{-1}$)
1100 ± 20	31 ± 20	14 ± 6
1266 ± 5	110 ± 3	41 ± 20
ρ(770)	150	5900

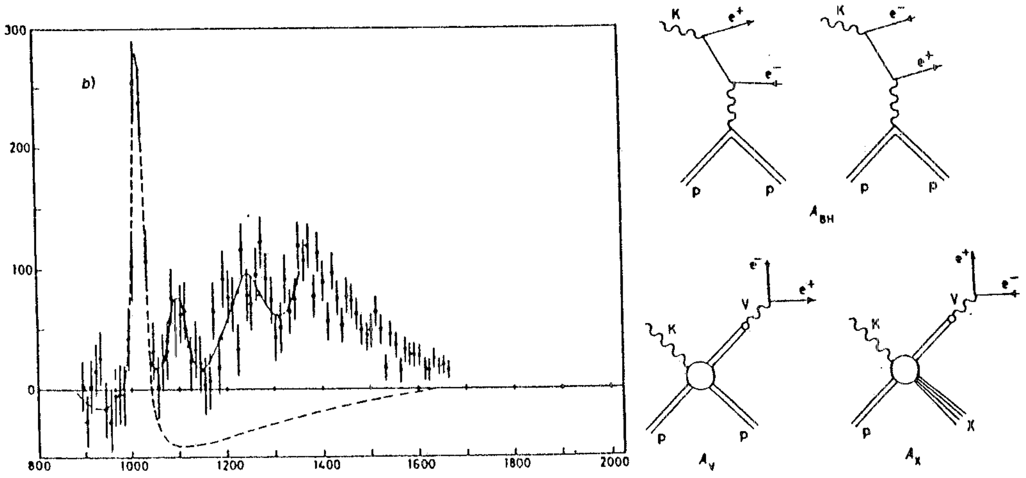


FIGURE 4
Asymmetry in $\gamma p \rightarrow e^+e^-X$

In a naïve vector dominance model:

$$B_x^{\,e\text{-}e+} = B_\rho^{\,e\text{-}e+} \, \frac{M_x \Gamma_\rho}{M_\rho \Gamma_x} \cdot \frac{d\sigma/dt_x(0^\circ)}{d\sigma/dt_\rho(0^\circ)}$$

Therefore:

$$\sigma_{peak}\,(e^+e^- \rightarrow 1100) \simeq \sigma_{peak}\,(e^+e^- \rightarrow 1266) \simeq 30 \text{ nb}$$

In this energy range only exist the VEP2M-OLYA measurement of $e^+e^- \rightarrow 2\,\pi^+\,2\pi^-$, $\pi^+\pi^-\,2\pi^0$, and no evidence for a 1100 MeV resonance is found[10]. Therefore the 1100 resonance remains an open problem. The 1266 bump could be compatible with the Novosibirsk data, once a detailed analysis of the $\pi^+\pi^-\pi^0\pi^0$ channel could disentangle the contributions from the well established ρ'(1550) and the graph in Fig. 5. This graph can be evaluated from the $\omega \rightarrow \rho\pi^0$ decay[11] and contributes for a step of ~10 nb at ~1200 MeV.

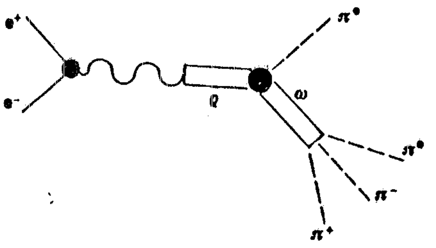
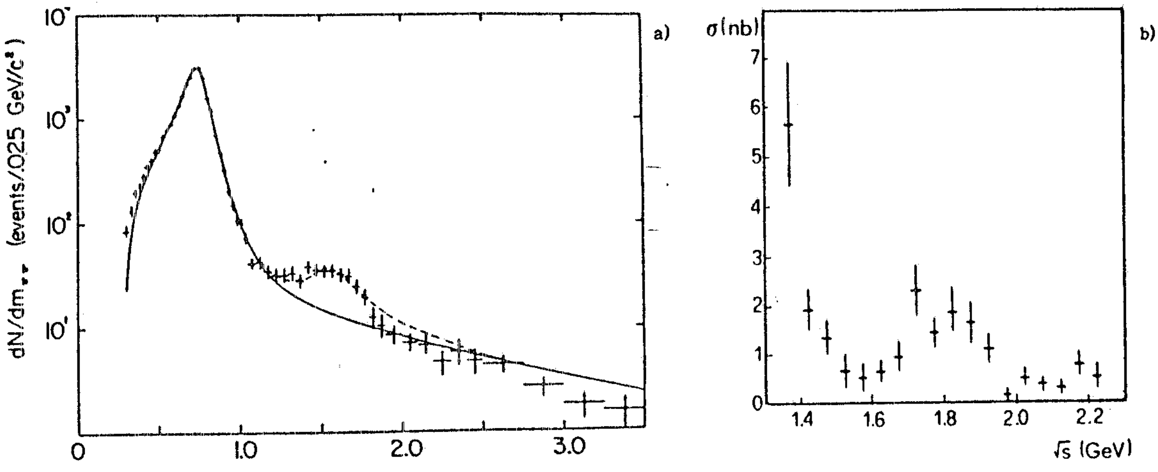


FIGURE 5
$e^+e^- \rightarrow \rho \rightarrow \omega\pi$

In any case a big resonance[4] like the expected first ρ daughter foreseen by the Veneziano formula just at ~1250 MeV has been theoretically questioned[13] and it is unlike, considering the multihadronic cross section and the pion form factor (Fig. 6) at these energies. The $\pi^+\pi^-\,2\pi^0$ photoproduction data[12] also, which show a big bump at ~1250 MeV interpreted almost completely as $J^P = 1^+$, do not have room for such a ρ'(1250).



$e^+e^- \rightarrow \pi^+\pi^-$ cross section vs $\sqrt{s}$.

FIGURE 6
a) $\gamma p \rightarrow \pi^+\pi^- p$; b) $e^+e^- \rightarrow \pi^+\pi^-$

Recently a $J^P=1^-$ resonance G(1440) has been observed[14] in the channel $\Phi\pi^0$ with M = 1480±40 MeV and Γ= 130±60 MeV in the reaction (Fig. 7):

$\pi p \to G n$
|
$\to \Phi\pi^0$

Such a state is not expected in the standard quark model and, if confirmed, would be a very important proof for the existence of exotic states. Unfortunately no simple argument provides the expected e^+e^- cross section.

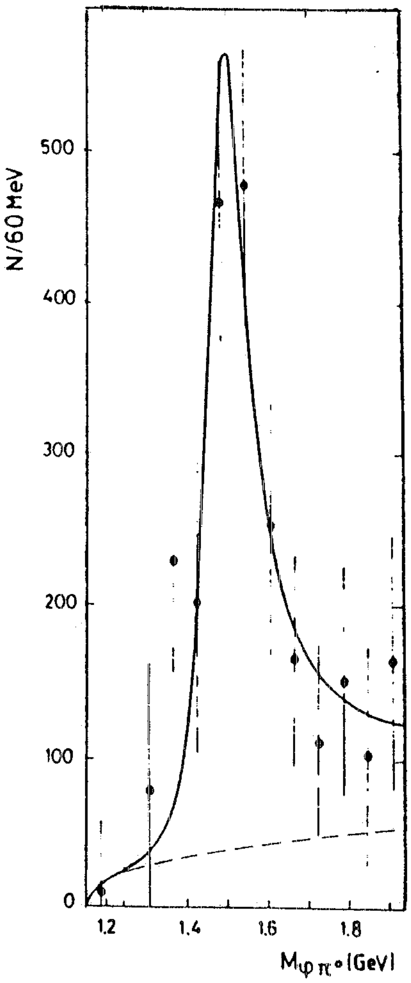


FIGURE 7
$\pi^- p \to (\Phi\pi^0)n$

ρ'(1550), φ'(1650), ρ"(2100), φ"(2000)

Two resonances are clearly observed in the DM2 data[15] (Fig. 8) in the reaction

$e^+e^- \to 2\,\pi^+ 2\pi^-$
$e^+e^- \to K^* K$
$e^+e^- \to K^+ K^-$

and are in fair agreement with the previous measurements[16].

The ρ'(1550) is also evident in $e^+e^- \to \pi^+\pi^-\, 2\pi^0$ with a cross section similar to $2\pi^+\, 2\pi^-$ one. This result is in agreement with the suggested decay dynamics:

$\rho \to A_1(1100)\,\pi$
|
$\to \rho\pi$

and rules out definitively the 'a priori' more natural $\rho' \to \rho\varepsilon_{\to\pi\pi}$, being ε some state with vanishing spin and isospin.

The ρ'(1550) has also been observed in photoproduction[17] (Fig. 9), but the mass spectrum is not exactly the same, clearly confirming the aforementioned problems in comparing photoproduction and e^+e^- data.

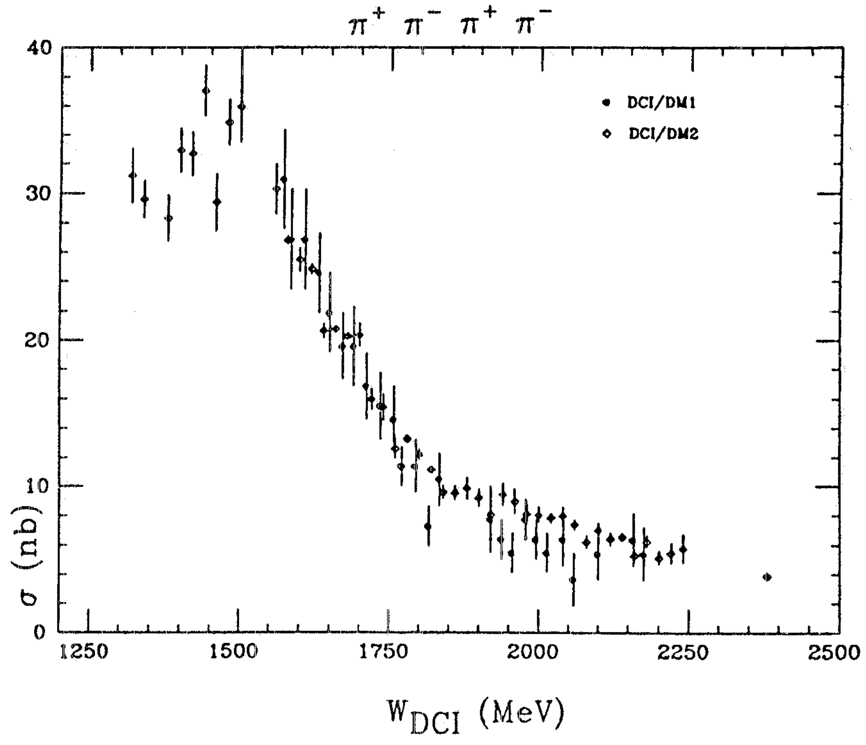


FIGURE 8
$e^+e^- \to 2\pi^+2\pi^-$

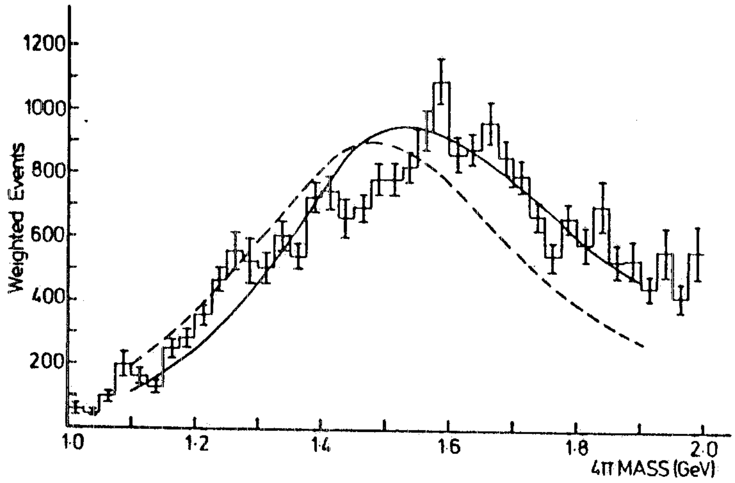


FIGURE 9
Comparison of measured mass spectrum in photoproduction with the $e^+e^- \to 2\pi^+2\pi^-$(dashed curve).

Also the ρ'(1550) is seen[18,19] in $e^+e^- \to \pi^+\pi^-$ and $\gamma p \to \pi^+\pi^- p$, still with different interference patterns respect to the ρ tail (Fig. 6).

It has been suggested that such a large bump is the convolution of more resonances[20]: the new DM2 data have the statistical significance needed to test this hypothesis.

The ϕ'(1650), as a peak in the $e^+e^- \to K^*K$ channel and an interference pattern in $e^+e^- \to K^+K^-$, was already put in evidence by DM1[16] and it is confirmed by DM2 data (Fig. 10). Incidentally it is rather striking that already at these low energies the U-spin predictions $F_\pi \approx F_{\pi\pm} \gg F_{\pi 0}$ are verified.

To establish definitely the ϕ'(1650) parameters as first ϕ excited state, the observation of the ω' also in the channels with odd number of pions would be welcome.

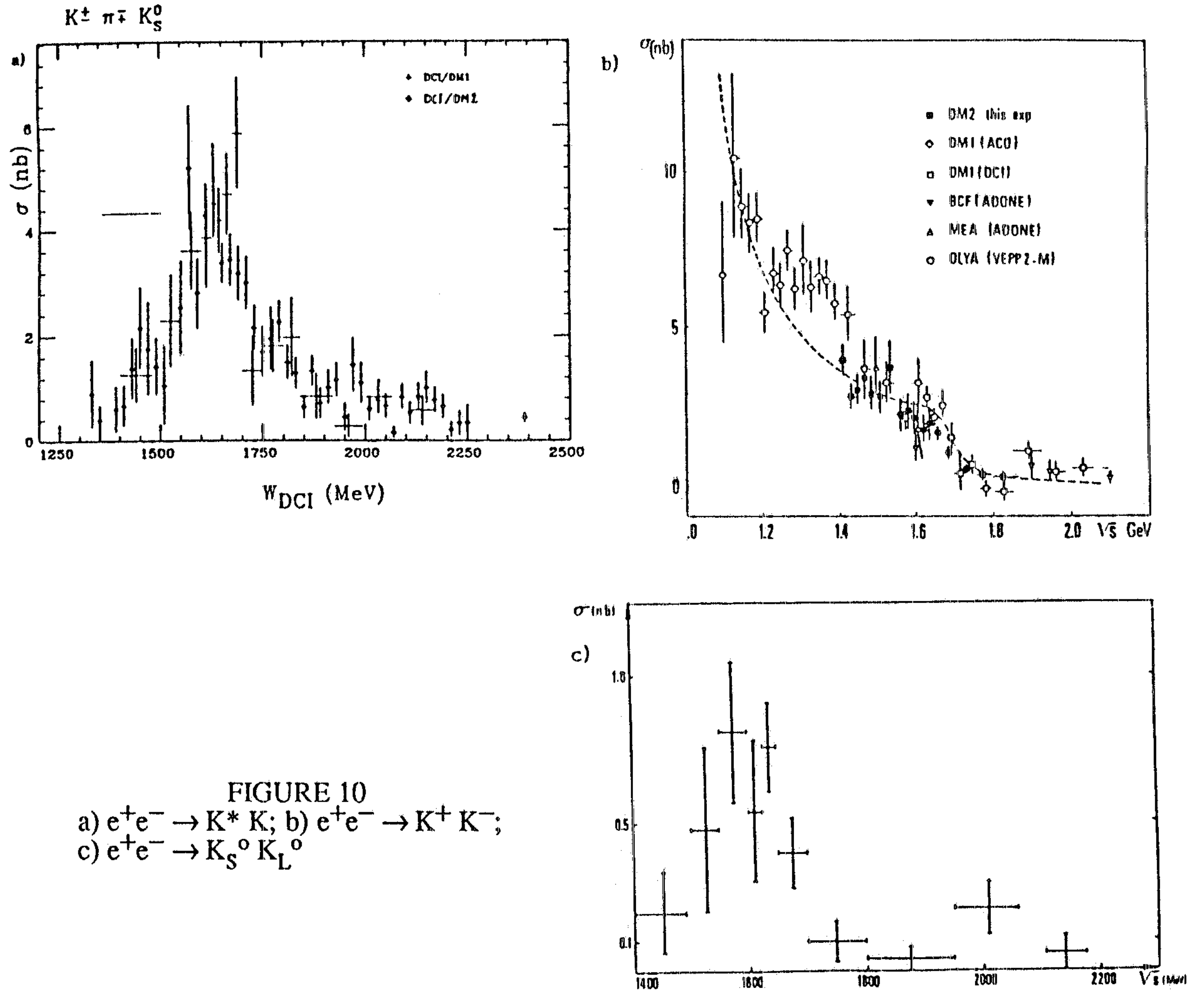


FIGURE 10

a) $e^+e^- \to K^* K$; b) $e^+e^- \to K^+ K^-$;
c) $e^+e^- \to K_S{}^0 K_L{}^0$

The ω' is expected as large as the ρ', the prejudice for the small ω width being the small phase space for its decay $\omega \to \rho\pi^0$. The $\pi^+\pi^-\pi^0$ cross section from DM2 does not agree with this prediction (Fig. 11) but there is a lack of statistics and more data at lower energies are needed.

Two large bumps (Figs. 12, 13) are clearly seen in[15]

$e^+e^- \to 2\pi^+2\pi^-\pi^0,\ 3\pi^+3\pi^-$
$e^+e^- \to K^+K^-\pi^+\pi^-$

which allow some conclusions if interpreted simply as the next ρ and ϕ excitations.

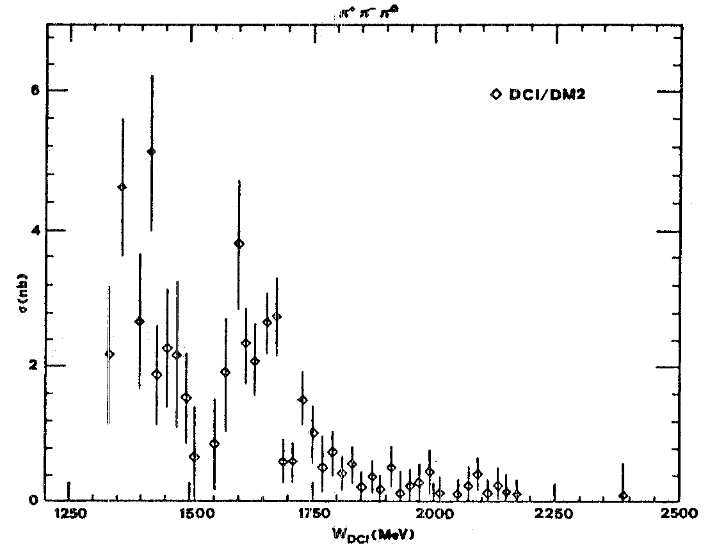


FIGURE 11
$e^+e^- \to \pi^+\pi^-\pi^0$

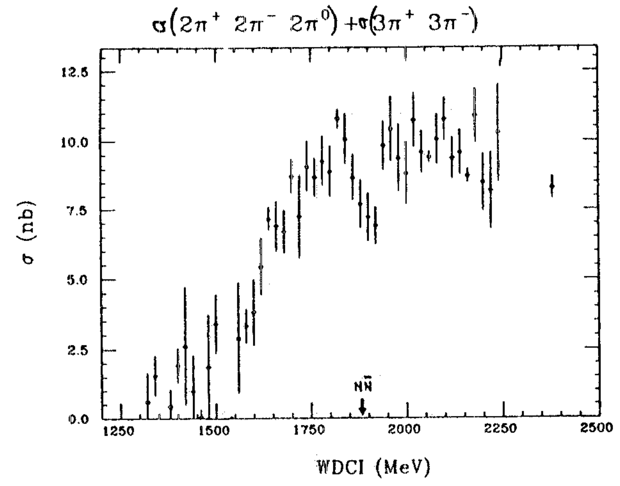


FIGURE 12
$e^+e^- \to 6\pi$

Indeed one could conclude on the present data that ρ excitations follows within larget errors he Veneziano formula but only the even daughters exist.

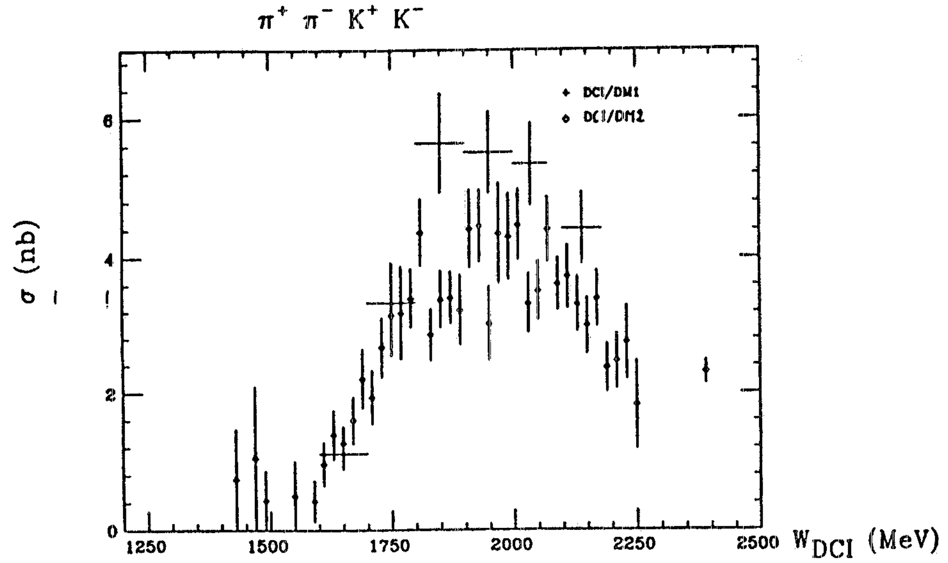


FIGURE 13
$e^+e^- \rightarrow K^+K^-\pi^+\pi^-$

Conversely the ϕ excitations agree with the ψ and γ excitations pattern:

	M_1-M_0 MeV	M_2-M_1 MeV
ϕ	660	~320
ψ	588	345
γ	563	332

In the DM2 data a structure is also evident in the 6π channel just around the $N\bar{N}$ threshold, which is under investigation.

The ratio R

A summary of all the R measurements[21], DM2 excluded is reported in Fig. 14. Only processes are considered where at least 3 hadrons are produced and at low energies Novosibirsk data concerning 4π are assumed to saturate the total cross section.

In Fig. 15 all these data have been averaged, weighted with the relative statistical errors only, and DM2 preliminary data concerning 2 hadron pairs have been added[15]. Many hadrons preliminary DM2 data fairly agree with these averaged values in the energy region 1.4 ÷ 2.2 GeV. A comparison with the theoretical prediction could be meaningless, due to the proximity of the $s\bar{s}$ threshold. Literally interpreting local duality a problem is foreseen, since in the energy region of first excited states (1÷2 GeV) the experimental data are lower than the theoretical prediction:

$$R_1\ (1.5\ \mathrm{GeV}) \simeq 2\ \{\ 1 + (\alpha_s(\psi)/\pi)\frac{\log(M_\psi/\Lambda)}{\log(1.5/\Lambda)}\ \} \simeq 2.3,$$

assuming Λ ~0.1÷0.5 GeV.

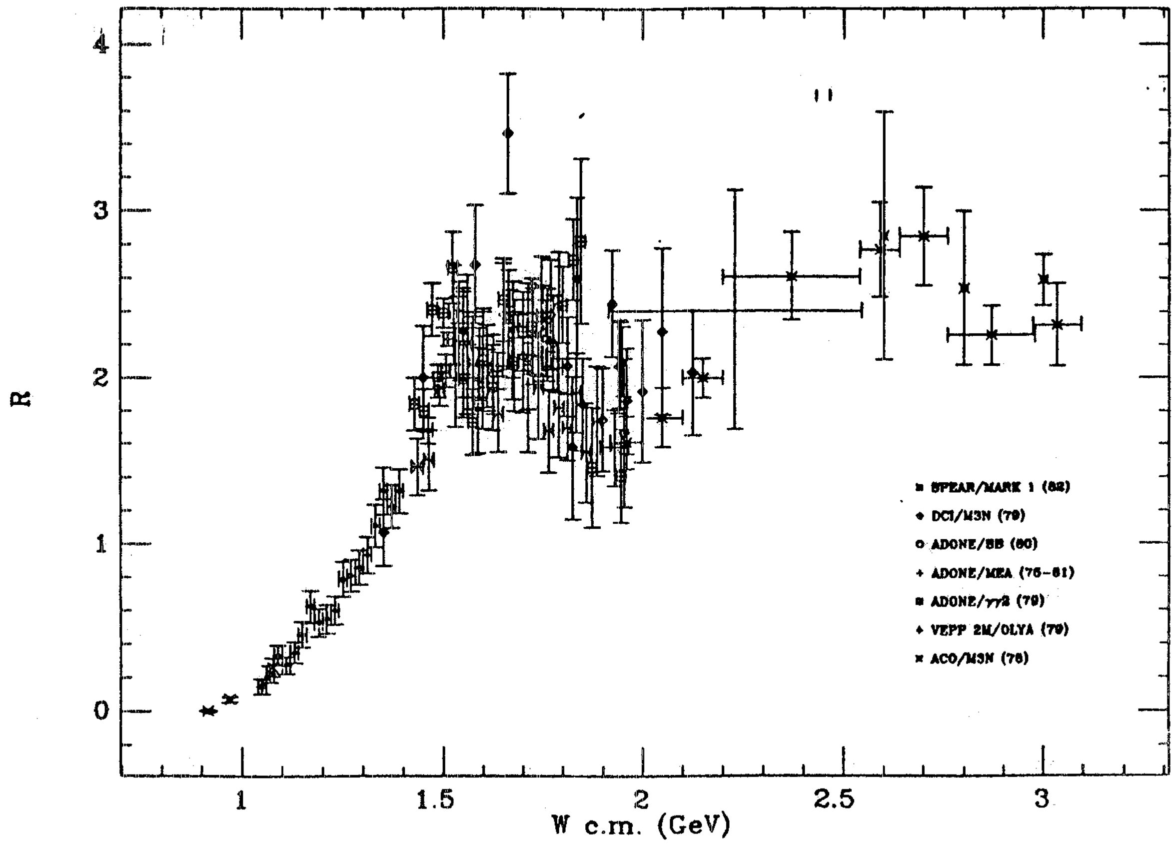


FIGURE 14
R(≥3body)

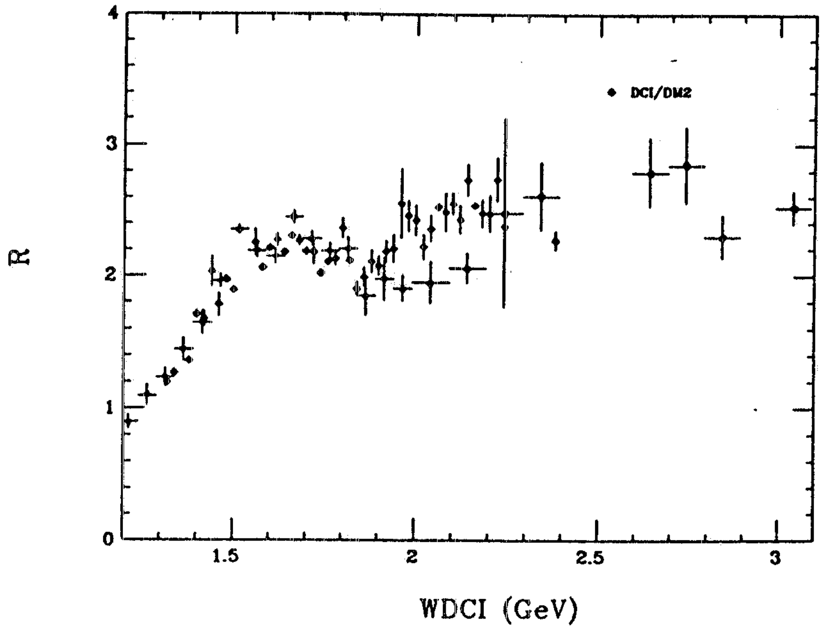


FIGURE 15
R averaged and DM2 preliminary results.

A further correction should be added to take into account the coulombic part of the $s\bar{s}$ interaction near threshold[22]:

$$\bar{R}_2\ (1.5\ \text{GeV}) \simeq \bar{R}_1 + (2/3)\ (\alpha/\pi)\ [(2/3\beta_s) - 1/2 - (1/4\pi^2) - \beta_s\ (1/6 - (1/4\pi^2))\ ] \simeq 2.4$$

where $\beta_s \simeq\ 0.75$ if $m_s \simeq 500$ MeV

A meaningful comparison is possible if the I=1 contribution could be isolated mainly selecting channels with even number of pions, the u and d quarks masses being much smaller than the considered energies.

J/ψ Physics

J/ψ can be considered as the best factory for hadron spectroscopy below 3 GeV. A big campaign had been launched at the storage ring DCI with DM2 and at SPEAR with Mark III, collecting respectively 8.4 and 5.8 millions of hadronic events at the J/ψ mass. The main goal was the glueballs detection looking at the J/ψ radiative decays. If QCD is a meaningful theory, glueballs, that is gluon bound states, are expected: in fact gluons are predicted confined and selfinteracting. An ideal glueball is a I=0 meson strongly enhanced in the J/ψ radiative decays and much less produced associate to an ω or a ϕ. Flavour independent glueball branching ratios are expected too, in the questionable limit of neglecting the strange quark mass.

Controversial candidates have been found, far to be ideal glueballs[23]: i(1440), ϑ(1650) and ξ(2200). But the experimental situation is much more complex than naïvely expected, many states appear lumped together, and at least ten times the collected statistics is needed to disentangle the experimental situation (Fig. 16).

The most intriguing resonance is the ξ (2200), whose existence is controversial too. DM2[24] and MarkIII[25] data do not agree (Fig. 17) and it has not been observed so far in $p\bar{p}$ formation[26]. The ξ(2200), if it exists, has a very small width, ≤ 20 MeV, compared to its mass and it has been interpreted even as a Higgs boson[27], to explain its singular features.

CONCLUSIONS

After almost fifteen years from the e^+e^- multihadronic production and J/ψ discoveries, this energy range still contains many enigmas and open questions. In particular, if hadronic spectroscopy has any meaning, a new high luminosity storage ring is needed, optimized in the center of mass total energy region 1÷3 GeV.

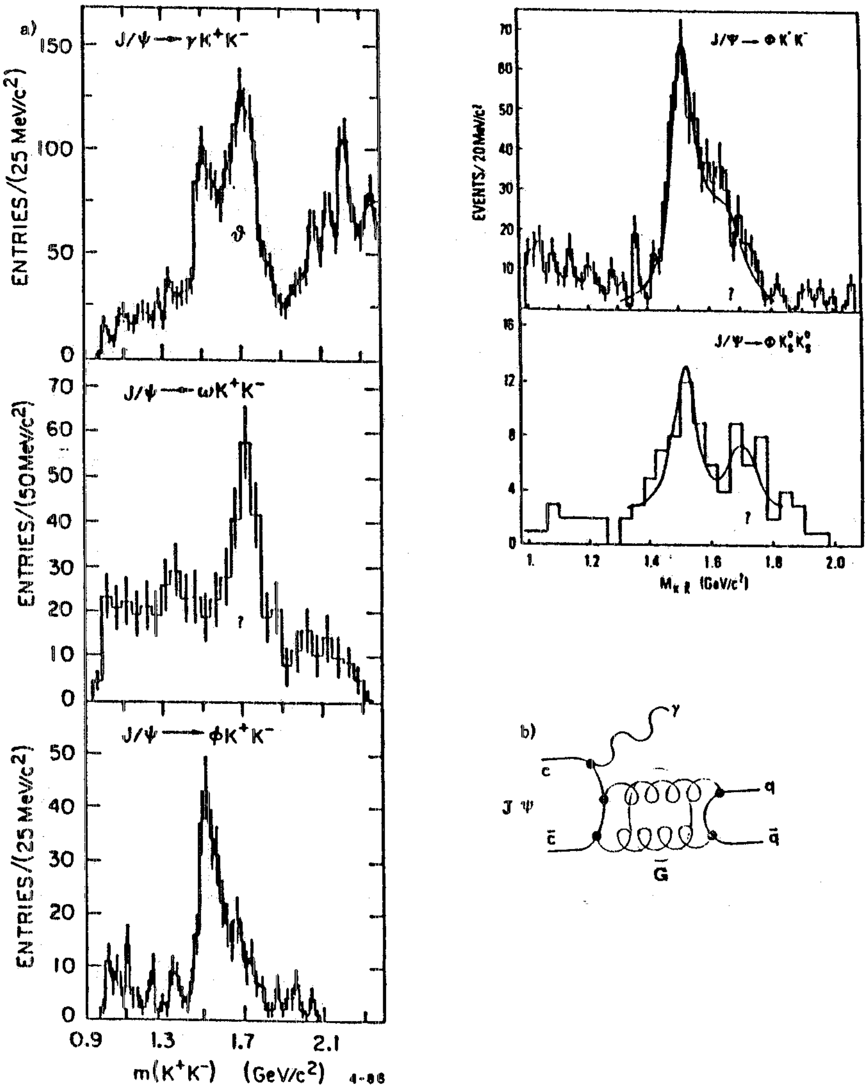


FIGURE 16
a): Glueball hunting via J/ψ radiative decay, b): The ϑ(1650) puzzle.

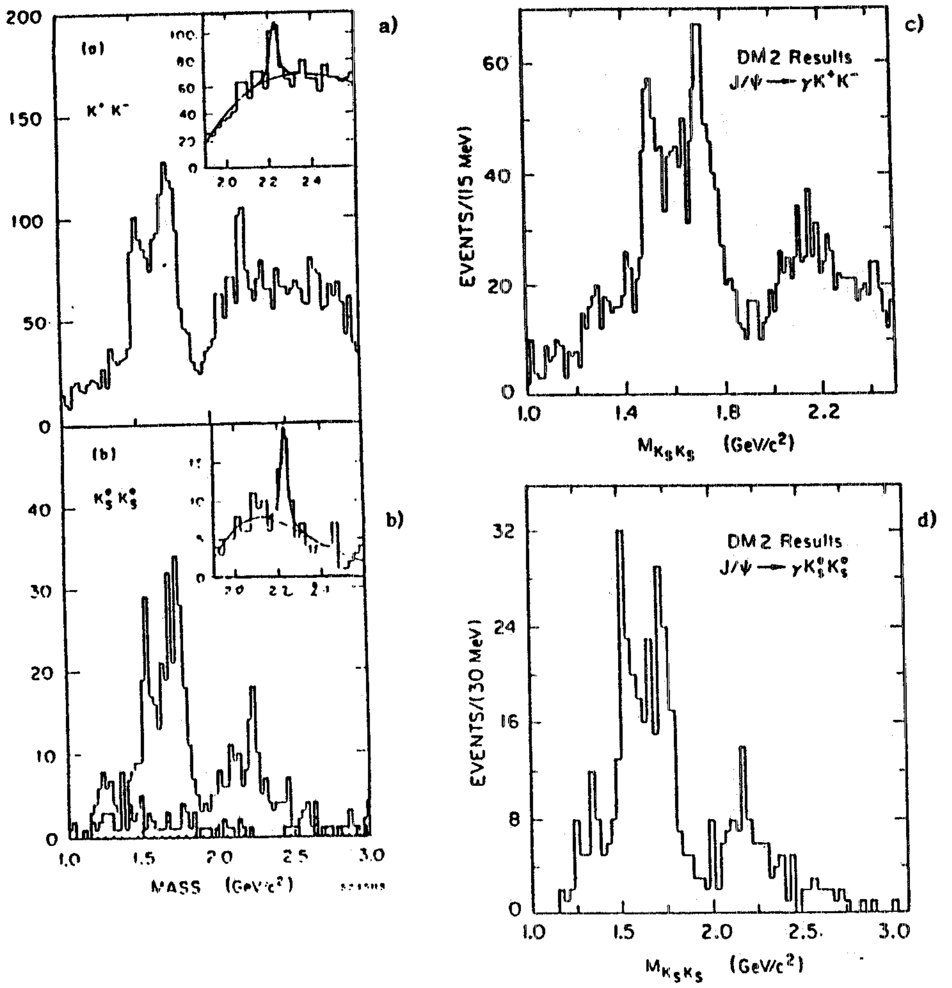


FIGURE 17
The ξ (2200) puzzle: a, b): MarkIII; c,d): DM2.

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