Recent OPAL measurements in non-perturbative QCD

G. Giacomelli
Dipartimento di Fisica dell'Universita' di Bologna and INFN, Sezione di Bologna,
Viale B. Pichat 6/2, 40127 Bologna, Italy

for the OPAL Collaboration

Abstract. Using multihadronic Z^0 decays recorded in 1991 - 1995 by the OPAL detector in e^+e^- collisions at LEP1, experimental analyses were made of the following subjects: (a) Bose-Einstein correlations; (b) Intermittency and correlations; (c) ρ and ω spin alignments; (d) A search for the tensor glueball candidate $f_j(2200)$.

1 Introduction

The large sample of multihadronic (MH) Z^0 decays recorded by the OPAL detector at LEP1 offers the possibility to study several aspects of non perturbative QCD.

Bose-Einstein correlations (BEC) give an estimate of the size and shape of the identical bosons emitting region; more recently BEC have been used to yield information on the hadronization process.

Intermittency and multiparticle correlations are studied in terms of the scaled normalized factorial moments and of cumulants vs rapidity y, azimuthal angle ϕ, and transverse momentum P_t. Intermittent behaviour is seen in y and ϕ as an increase of the moments with decreasing bin size. Genuine multiparticle correlations exist. They are contained in the used Monte Carlos.

Little is known on the role of spin in the hadronization process. At LEP, this can be investigated by studying the properties of vector mesons produced in hadronic Z^0 decays. New results are presented on the helicity density matrix elements for the $\rho(770)^\pm$ and $\omega(782)$ mesons.

QCD predicts the existence of glueballs; lattice gauge theories predict the mass of the ground state glueball (two leading gluons with antiparallel spins) to be $\simeq$ 1.5 GeV. Some glueball candidates have been reported; the interpretation of data in this mass region is difficult because of mixing with conventional mesons. This difficulty is less pronounced for the tensor glueball, expected with $m \simeq 2.2$ GeV. A search for this state is here reported.

The OPAL data at LEP1 concern 4.1 million MH events. The analyses use charged particles detected by the tracking chambers in the magnetic field. Standard quality cuts are applied to each track and to each multiparticle event. Photons are detected in the electromagnetic calorimeter, or as $\gamma \to e^+e^-$.

2 Bose-Einstein Correlations

Bose-Einstein correlations (BEC) between identical bosons lead to an enhancement of the number of identical bosons when they are close in phase space. LEP1 data allowed to study: (i) correlations for $\pi^\pm\pi^\pm$, K^0K^0, $K^\pm K^\pm$, (ii) the multiplicity dependence of the 2π emitting region, (iii) multi-pion BECs, (iv) two-dimensional $\pi\pi$ BEC [1]. LEP2 data allowed to study (v) BEC in $e^+e^- \to W^+W^-$ for identical charged pion pairs. For two pions we use the notation in terms of $Q^2 = -(P_1 - P_2)^2 = m^2_{\pi\pi} - 4m^2_\pi$. The distribution in Q of the like-charge pairs has to be normalized to a Q-distribution which does not contain BEC, for instance the distribution of unlike-charge pairs or to a Monte Carlo prediction [2]:

$$C'(Q) = (N^{++} + N^{--})/N^{+-} \quad , \quad C(Q) = (N^{++} + N^{--})/(N^{++} + N^{--})_{MC} \tag{1}$$

Various parametrizations are used in the literature to interpret the data. We use the Goldhaber parametrization:

$$C(Q) = N(1 + \lambda\ e^{-Q^2R^2})(1 + \epsilon Q + \delta Q^2) \tag{2}$$

N is a normalization factor, λ is the chaoticity parameter ($0 \le \lambda \le 1$) and R estimates the radius of the emitting region; $(1 + \epsilon Q + \delta Q^2)$ accounts for the long range correlations arising form charge and energy conservation and phase space constraints. The Q-dependence, corrected for Coulomb effects, of $C(Q)$ or $C'(Q)$ for $\pi^\pm\pi^\pm$ shows an enhancement at small Q value. Fits of $C(Q)$ to Eq. 2, eliminating the regions where there could be hadron resonance effects, yields $R \simeq 0.793 \pm 0.007_{st} \pm 0.015_{sys}$ and $\lambda \sim 0.58$ [2]; R and λ seem to be energy independent [1].

For 2π, OPAL analyzed the dependence of R on the average charged multiplicity of MH events, and it found an increase of R with n_{ch} (from 0.86 to 1.0 fm) and a decrease in the parameter λ [3]. Similar values of R and λ were found for $\pi^0\pi^0$ [3], $K^0_sK^0_s$ [4] and $K^\pm K^\pm$ [5] BECs. For 3π BECs, OPAL [6] considered the ratio

$$R_3(Q_3) = N^{+++}(Q_3)/N^{+++}_{MC}(Q_3) \qquad (3)$$

corrected for Coulomb effects; the Monte Carlo is JETSET7.4. The effects of 2π correlations must be removed to obtain the genuine 3π correlation function:

$$C_3(Q_3) = R_3(Q_3) - R_{1,2}(Q_3) = \frac{N^{+++}}{N^{+++}_{MC}} - \frac{\delta^{++-}}{N^{+++}_{MC}} \langle \frac{n^{+++}}{n^{++-}} \rangle \qquad (4)$$

$R_{1,2} = \delta_2^{+++}/N^{+++}_{MC}$, δ_2^{+++} is the three-pion enhancement due to the two-pion BEC; $Q_3^2 = -(q_1-q_2)^2 - (q_1-q_3)^2 - (q_2-q_3)^2$

The experimental distribution (4) was fitted to an expression similar to (2). One obtains: $R_3 = 0.580 \pm 0.004_{st} \pm 0.029_{sys}\ fm$; $\lambda_3 = 0.504 \pm 0.010_{st} \pm 0.041_{sys}$ Notice that two-pion BEC yield $R_2 = 0.793 \pm 0.015\ fm$; assuming that $R_3 \simeq R_2/\sqrt{2} = 0.793/\sqrt{2}$ one has $R_3 \simeq 0.561 \pm 0.011\ fm$ which agreees with the measured $R_3 = 0.558\ fm$.

BECs have been measured for 2π in the reaction $e^+e^- \to W^+W^-$ at $\sqrt{s} = 172$ and 183 GeV [7]. Three data samples are available: (i) the four-jet hadronic sample, $W^+W^- \to q\overline{q}\prime\ q\overline{q}\prime$: here final state interactions (FSI) can occur within a single W decay or between the two different W bosons. (ii) The two-jet (semileptonic) sample, $W^+W^- \to q\overline{q}\prime\ l\overline{\nu}_l$; FSI can only occur within a single W. (iii) The leptonic sample, $W^+W^- \to l^+\nu_l\ l^-\overline{\nu}_l$. From the point of view of the M_W measurements, FSI are of consequence if they occur between the two W's in the same hadronic event. At LEP2 energies the two W-bosons decay within a distance of about $0.1\ fm$, which is smaller than the hadronization scale of $\simeq 1\ fm$. Thus the fragmentation processes for hadrons coming from different W-bosons could be interconnected. OPAL demonstrated the existence of BEC in W decays, Fig. 1. An attempt was made to determine BEC for two pions originating from the same W-boson and from different W-bosons, as well as for pions from $(Z^0/\gamma) \to q\overline{q}$ events [7]. Fitting these samples together, assuming a common source radius R, we find $\lambda^{same} = 0.63 \pm 0.19 \pm 0.14$, $\lambda^{diff} = 0.22 \pm 0.53 \pm 0.14$, $\lambda^{Z^*} = 0.47 \pm 0.11 \pm 0.08$, $R = 0.92 \pm 0.09 \pm 0.09\ fm$ (the first error is statistical and the second one is systematic). At present it is not established whether BECs between pions from different W bosons exist or not.

Two-dimensional, two-pion BECs are being studied; preliminary results indicate a non spherical di-pion emitter shape [8].

3 Intermittency and multiparticle correlations

Local multiparticle fluctuations have been studied in final hadron states. With the word Intermittency one refers to the rise of the factorial moments with decreasing bin size. Analyses in terms of the factorial cumulant moments reveal "genuine multiparticle" correlations. The modified factorial moments (FM)

$$F_q^c = N^q \overline{\langle n_m^{[q]} \rangle} / \overline{N_m^{[q]}} \qquad (5)$$

are used by OPAL to avoid biases in the normalization [9]. The q-th order factorial moment is $n_m^q = n_m(n_m - 1)...(n_m - q + 1)$; n_m is the number of particles in the m-th bin of the phase space divided into M equal bins, N_m is the number of particles summed over all the N events, $N_m = \sum_{i=1}^{n}(n_m)_i$ The bar stands for "horizontal" averaging over the bins in each event, $(1/M)\sum_{m=1}^{M}$; the angle brackets denote "vertical" averaging over the events. The phase space is considered in terms of the rapidity y, azimuthal angle ϕ and transverse momentum P_t. Non-statistical fluctuations lead to increasing FMs with increasing M, $F_q(M) \approx M\varphi_q$, $0 < \varphi_q < q-1$, $M \to \infty$ (power dependence, scaling law). The FMs of order $q = 2 \div 5$ have been plotted vs the number of bins M for the one-dimensional rapidity, azimuthal angle, and transverse momentum. The y and ϕ distributions increase with M up to $M \sim 20$ and then flatten; the P_t distribution is essentially independent of M. Thus there is an intermittency in y and ϕ and not in P_t. This behaviour is reasonably well predicted by the used Monte Carlos. The same behaviour, with stronger increase with M, is exhibited in two phase space dimensions, in particular by $y \times \phi$, and in three dimensions by $y \times \phi \times P_t$. The modified factorial cumulant (FC) moments are

$$K_q^c = N\overline{K_q^{(m)}}\ /\ \overline{N_m^{[q]}} \qquad (6)$$

The multipliers $K_q^{(m)}$ are the unnormalized factorial cumulants (Mueller moments), and represent genuine q-particle correlations. This leads to

$$F_2 = K_2 + 1\ ,\ F_3 = K_3 + 3K_2 + 1\ ,\ F_4 = K_4 + 4K_3 + 3\overline{(K_2^{(m)})^2} + 6K_2 + 1\ , ... \qquad (7)$$

Two-particle contributions $F_q^{(2)}$ can be expressed as $F_3^{(2)} = 3K_2+)1$, $F_4^{(2)} = \overline{3(K_2^{(m)})^2} + 6K_2 + 1$, $F_5^{(2)} = \overline{15(K_2^{(m)})^2} + 10K_2 + 1$, ... These equations can be used to search for multiparticle correlation contributions to local fluctuations. Fig. 2 shows the FCs in one, two and three dimensions for $q = 4$ and 5. the FCs are positive, which indicates that multiparticle correlations exist. The FCs exhibit stronger power-law behaviour than for FMs. Addition of phase space dimensions, from y to $y \times \phi$ and to $y \times \phi \times P_t$, enhances the manifestation of multiparticle genuine correlatons [9]. The results agree with the QCD jet formation dynamics, but additional contributions from other mechanisms cannot be excluded.

4 Spin alignment of $\rho(770)^{\pm}$ and $\omega(782)$ mesons

The helicity density matrix elements for the $\rho(770)^{\pm}$ and $\omega(782)$ mesons produced in Z^0 decays have been measured by OPAL [10]. Since $\rho^{\pm} \to \pi^{\pm}\pi^0$, we can use as a spin analyzer the angle in the $\pi^{\pm}\pi^0$, rest frame between one of the pion momenta and the $\rho^{\pm}$ boost direction. The distribution of this angle, θ_H, is:

$$W(\cos\theta_H) = \frac{3}{4}[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta_H] \tag{8}$$

ρ_{00} is the helicity density matrix element corresponding to the probability that the spin of the $\rho^{\pm}$ meson be perpendicular to its momentum direction. Because of unitarity and parity conservation, the probabilities that the spin be parallel or antiparallel, ρ_{11} and ρ_{-1-1}, are equal $\rho_{11} = \rho_{-1-1} = (1-\rho_{00})/2$.

The $\pi^{\pm}$ and π^0 candidates are combined in pairs and three quantities are evaluated: the scaled energy of the pair $x_E = E_{meson}/E_{beam}$, the invariant mass $m_{\pi^{\pm}\pi^0}$, and $\cos\theta_H$ defined between the π^0 and the boost of the $\pi^{\pm}\pi^0$ system. The $\rho^{\pm}$ signal in the $m_{\pi^{\pm}\pi^0}$ distribution is parametrized with a Breit-Wigner convoluted with the experimental mass resolution in x_E. The efficiency-corrected $\rho^{\pm}$ yields are evaluated for ten $\cos\theta_H$ bins and fitted to the formula: $I(\cos\theta_H) = A(1 + B\cos^2\theta_H)$. One has $\rho_{00} = (1+B)/(3+B)$. The parameters A, B are obtained from a linear least square fit. The decay $\omega \to \pi^0\pi^+\pi^-$ has $BR = 88.8\%$. In the rest frame of the $\pi^0\pi^+\pi^-$ system the momenta of the three pions lie in a plane; the appropriate spin analyzer is the angle θ_H between the normal to this plane and the boost direction. The measured values of ρ_{00} as a function of x_E are shown in Figs. 3a and 3b for the $\rho^{\pm}$ and ω mesons, respectively. The measurements are compatible with 1/3, corresponding to a statistical mix of helicity $-1, 0$ and $+1$ states. The DELPHI results for ρ^0 agree with our $\rho^{\pm}$ values [11]. For $0.3 < x_E < 0.6$ one has $\rho_{00} = 0.373 \pm 0.052$ and 0.142 ± 0.114 for $\rho^{\pm}$ and ω, respectively. These results are lower than those for $K^*(890)$ and ϕ mesons [12]. Fig. 3c shows a comparison with previous data.

According to the Monte Carlo, up to 10% of $\rho^{\pm}$ originate from decays of $J^P = 0^-$ mesons into a $\rho^{\pm}$ $(J^P = 1^-)$ and another $J^P = 0^-$ meson (mainly $D^0 \to \rho^+ K^-$, $J^P = 0^- \to 0^- + 1^-$). The effects of the alignment of the $\rho^{\pm}$ from such decays are shown in Fig. 3a as dotted lines.

In conclusion there appears to be a difference in the spin alignment properties of vector mesons, see Fig. 4, possibly depending on their strangeness content.

5 A search for the tensor glueball $f_j(2220)$

In the $K_s^0\ K_s^0$ and $K^+\ K^-$ final states a narrow resonance with $\Gamma \simeq 20$ MeV (denoted $f_j(2220)$ was reported by the MARK III Coll., in J/ψ decays [12], by the BES Collaboration in radiative J/ψ decays [13] and by the L3 Coll. [14] in hadronic Z^0 decays in an enriched three-jet sample (and mainly coming from the lowest energy jet, enriched in gluons). But the DM2 Coll., in J/ψ decays [15] and the CLEO Coll., in $\gamma\gamma$ collisions [16], did not find indications for this state (the DM2 Coll. had indications for a broader structure). The OPAL detector is well suited for a study of the $f_j(2220) \to K_s^0\ K_s^0$ because of its large radius tracking chamber which allows efficient detection of K_s^0 over a large momentum range [17]. The $K_s^0\ K_s^0$ mass spectrum was investigated in the full event sample and, following the L3 analysis, in the three-jet sample and in individual jets of the three-jet sample. Neither in the global event sample nor in gluon enriched samples is there any evidence for a narrow resonance (see Fig. 5). The upper limit for the product of the inclusive production rate per hadronic Z^0 decay $n_{f_J(2220)}$ and the branching ratio $BR_{f_J \to K\overline{K}}$ is $[n_{f_J}(2220) \cdot BR_{f_J \to K\overline{K}}] < 0.0028$, at 95% C.L. for the $f_j(2220)$ with production and decay properties as a 2^{++} meson.

6 Conclusions

Many measurements related to multihadronic non perturbative QCD have been performed by OPAL. In particular: (i) The studies of BEC is yielding a number of interesting informations; (ii) Intermittency and multiparticle correlations are present in multihadron events; (iii) More precise experiments are needed to understand the role of spin in the hadronization process; (iv) OPAL found no confirmation for the proposed $f_j(2220)$ tensor glueball candidate.

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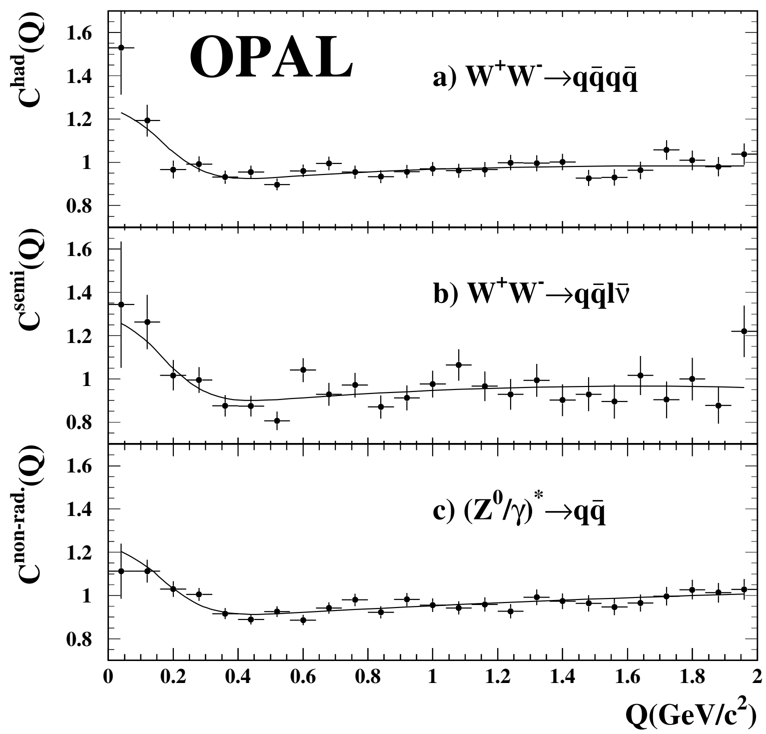

FIG. 1. The BEC for like-charge pairs relative to unlike-charge pairs for three event selections: a) $C^{had}(Q)$ for the fully hadronic, b) $C^{semi}(Q)$ for the semileptonic, and c) $C^{non-rad.}(Q)$ for the non-radiative events. The Coulomb-corrected data are shown as solid points with statistical errors. The lines are the result of the simultaneous fit [7].

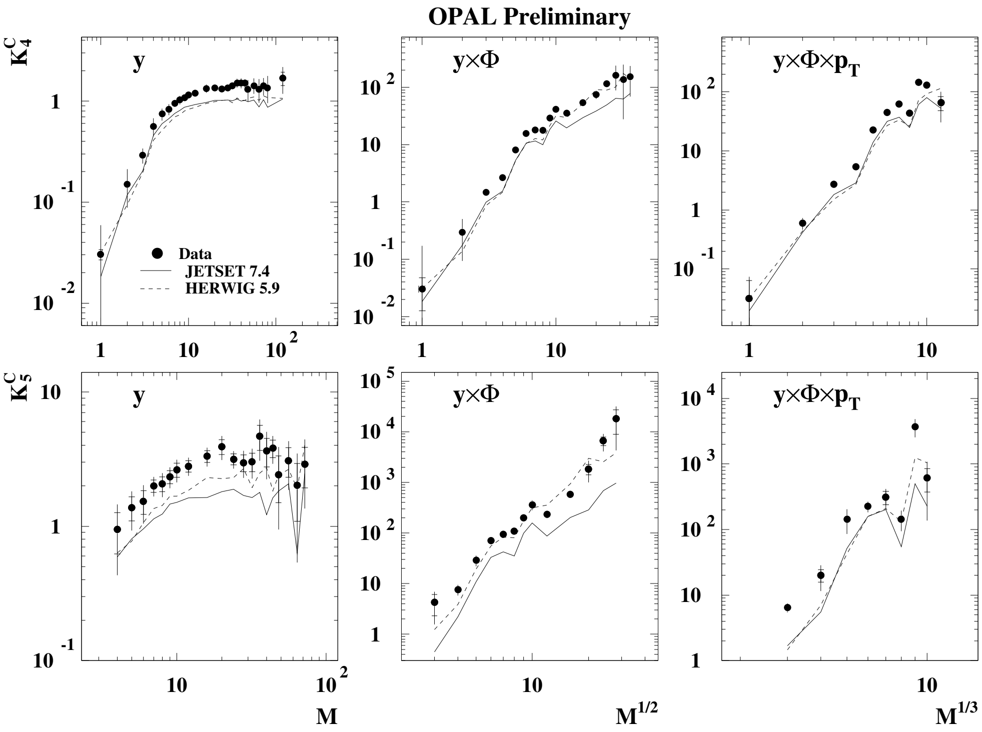

FIG. 2. The 4th and 5th FC in one, two, and three dimensions of rapidity, azimuthal angle and transverse momentum vs the number of bins M [9].

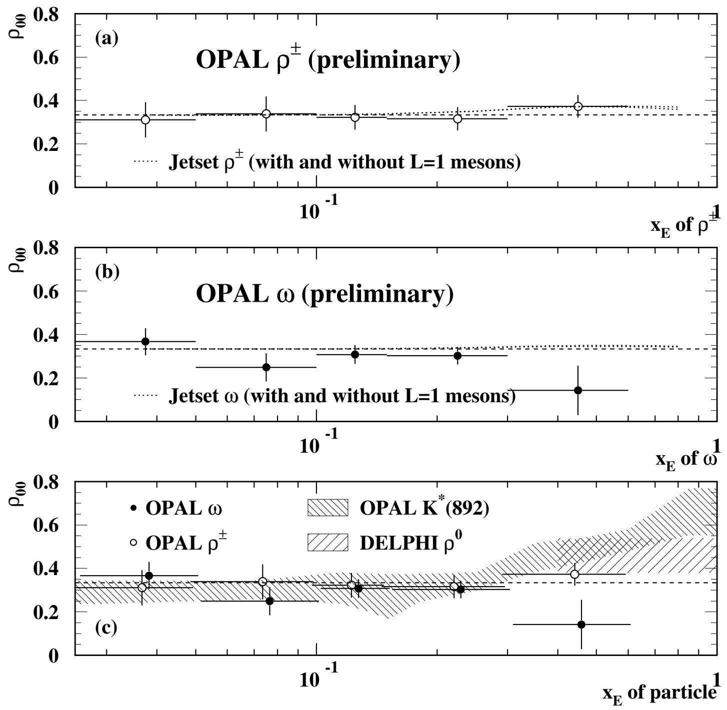

FIG. 3. Measured ρ_{00} values vs x_E for a) $\rho^{\pm}$ mesons and b) ω mesons produced in Z^0 decays [10]. The dotted lines are the ρ_{00} values calculated assuming that $J^P = 0^- \to 0^- + 1^-$ decays are the only source of alignment, and that the number of these decays per hadronic Z^0 decays is as predicted by the Monte Carlo. In c) our data are compared with other measurements.

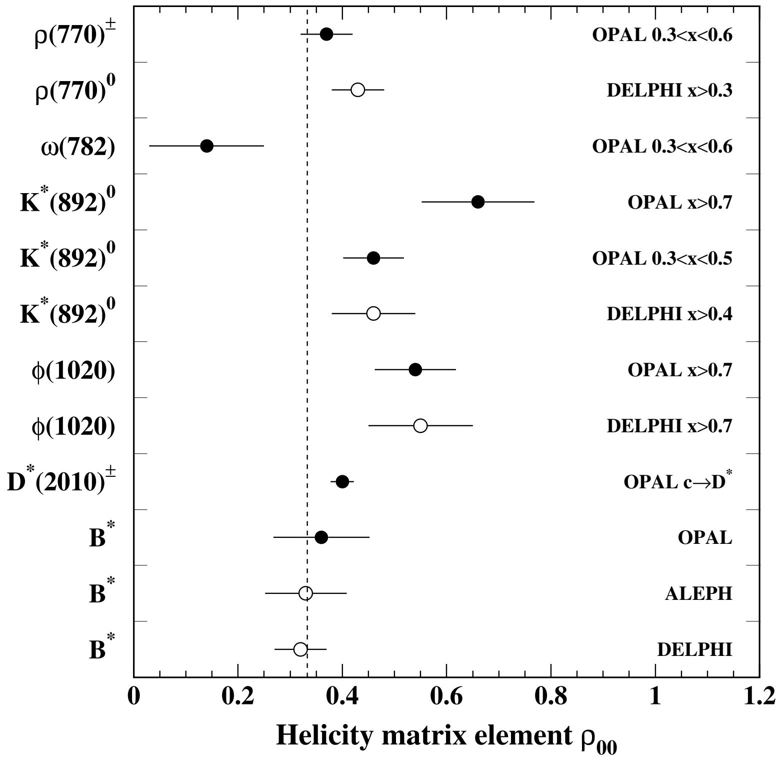

FIG. 4. Summary of ρ_{00} measurements for vector mesons produced in Z^0 decays [10].

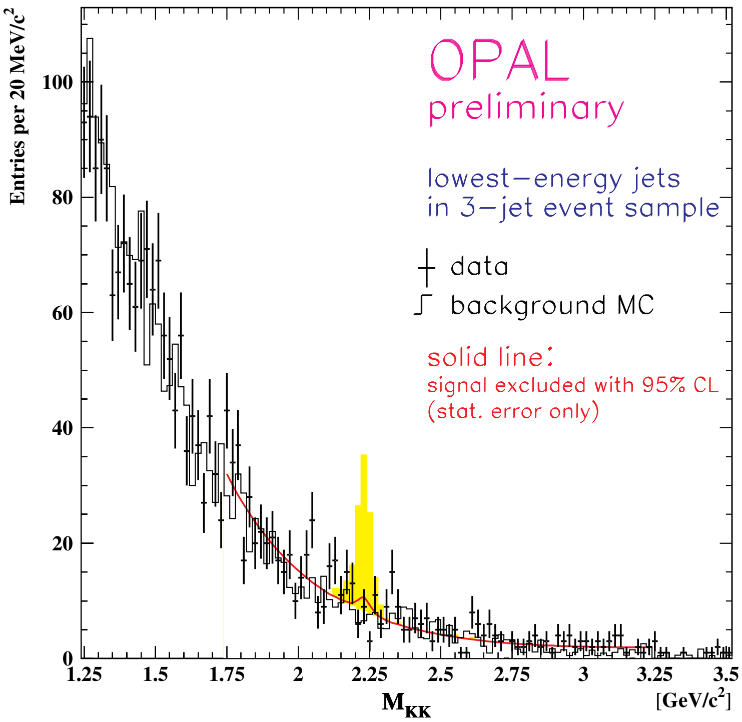

FIG. 5. Invariant mass spectrum of $K_s^0 K_s^0$ pairs for the lowest-energy jet in the 3-jet event sample [17]. The Jetset 7.4 prediction is shown by the open histogram while the lines with error bars are the data. The solid line shows the result of the fit with the 95% confidence upper limit for the signal. The shaded histogram is the expectation based on the preliminary L3 result.