Towards an unambiguous determination of the structure of the hadronic neutral current

G. L. Fogli
Dipartimento di Fisica di Bari, Bari, Italy and Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Italy
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The problem of removing the ambiguities from a model-independent determination of the couplings of the hadronic neutral current is considered. It is shown that a residual ambiguity, difficult to be removed, affects previous determinations, due to both the experimental uncertainties and the use of multiparameter numerical best fits. Starting from a recent updated analysis of the deep-inelastic scattering data, inclusive of radiative corrections, and making use of an analytic approach to the problem, it is seen that the comparison with an analysis of the single-pion production data at intermediate energies, not only (i) leads to discarding, with better evidence than previously, the so-called dominantly isoscalar solution, but also (ii) allows the residual ambiguity to be solved. The unique solution so obtained represents a substantial improvement in the determination of the couplings, in particular, as far as the isoscalar piece of the hadronic neutral current is concerned, with a better agreement than in the past with the standard model.

I. INTRODUCTION

To obtain a unique model-independent determination of the hadronic neutral-current (NC) couplings, and possibly to find it in agreement with the Weinberg-Salam (WS) model,[1] represents one of the challenging points of the weak-interaction physics of the last decade, since NC's have been discovered.

Several times in the past[2–4] a unique model-independent determination of the four couplings has been claimed [either in terms of the chiral couplings u_L, d_L, u_R, d_R introduced by Sehgal,[5] or as the isoscalar (isovector), vector (axial-vector) couplings $\alpha,\beta,\gamma,\delta$, proposed by Hung and Sakurai[6]]. In all cases the model-independent analysis was based on specific different ν-induced processes, since each process is sensitive to specific combinations of the couplings, so that an unambiguous determination can be obtained only by collecting the experimental data coming from different kinds of measurements.

The aim of this paper is twofold: (1) to show that all the previous unique solutions actually contain a residual ambiguity, difficult to be removed, which is plausibly responsible for the present discrepancies with the WS model (discrepancies more visible as far as the isoscalar piece of the NC is concerned); (2) to attempt to remove the residual ambiguity, by basing its resolution on the results coming from a recent analysis[7] of the data of deep-inelastic scattering (the process whose theoretical understanding is by far the most firm) and through the use, on a qualitative basis, of a less recent approach[8] to the single-pion production data at intermediate energy.

Strong support to this attempt, as it will be seen in the following, comes from (i) the high accuracy reached in the sector of deep-inelastic scattering,[7] (ii) the peculiar analytical approach followed in the present analysis, and (iii) the sensitivity of the single-pion production data at intermediate energy to the isoscalar piece of the neutral current.[8]

II. WHY A RESIDUAL AMBIGUITY

The most refined model-independent analysis performed in the past is that of Kim, Langacker, Levine, and Williams.[4] In determining the structure of the hadronic weak neutral current, they make use of the data (those available at the end of 1979) coming from the following different processes: (i) elastic scattering from protons (including measurements of the differential cross section for both ν and $\bar{\nu}$); (ii) semi-inclusive pion production through the measurements of the π^+/π^- ratio in both ν- and $\bar{\nu}$-induced reactions; and mainly (iii) deep-inelastic scattering of ν and $\bar{\nu}$ on isoscalar and n,p target. Moreover, (iv) the results coming from the analysis of single-pion production experiments are considered, on a qualitative basis, in order to exclude the so-called dominantly isoscalar solution [at 90% C.L. (confidence level)].

The solution obtained in Ref. 4 (in which radiative correction effects are not taken into account) shows some slight discrepancies if analyzed within the standard-model scheme, in particular, as far as the isoscalar piece of the NC is concerned: γ and δ differ by more than one standard deviation from the values expected with currently accepted values of $\sin^2\theta_W$. Similarly, β differs from the expected value, very near to one, by about one standard deviation.

In the present analysis, the constraints imposed by the first two processes mentioned above, elastic scattering and semi-inclusive pion production, are not considered. Let us briefly justify this choice.

Elastic scattering from protons is, in principle, simple to interpret theoretically, and relevant in providing additional information about the isospin structure. However, experimental data [the two most relevant experiments are those performed by the Harvard-Pennsylvania-Brookhaven (HPB) and Columbia-Illinois-Brookhaven (CIB) groups[9]] are still affected by large errors, and the theoretical approach suffers large uncertainties, in particular in the estimate of the axial-vector form factors, for which there are no independent experimental measurements [the uncertainties arise from the use of SU(3) in estimating G_A^0, from the treatment of strange and heavy quarks, from possible problems with anomalies[10]]. To these theoretical uncertainties, the systematic uncertainties, estimated about 15% (Ref. 9), must be added. In particular, the inadequacy of elastic scattering in solving the residual ambiguity concerning the sign of d_R can be verified in two ways: (i) by looking at the results of Ref. 4 (in particular Fig. 20); (ii) directly, by verifying the large compatibility of both solutions (7) and (8) of the next section with the estimate of the form factors as performed in the first of Refs. 9. It is worthwhile to note that even more refined measurements would not modify the conclusion, which is mainly inherent in the specific structure of the three form factors in terms of the couplings.

Semi-inclusive pion production data,[11] firstly considered by Sehgal[5] in the analysis of the NC structure, are very sensitive to the couplings. The process depends, however, only on the squared chiral couplings and does not give information about their signs. Moreover, from a theoretical point of view, it is affected by large uncertainties, concerning not only fragmentation functions or a re-

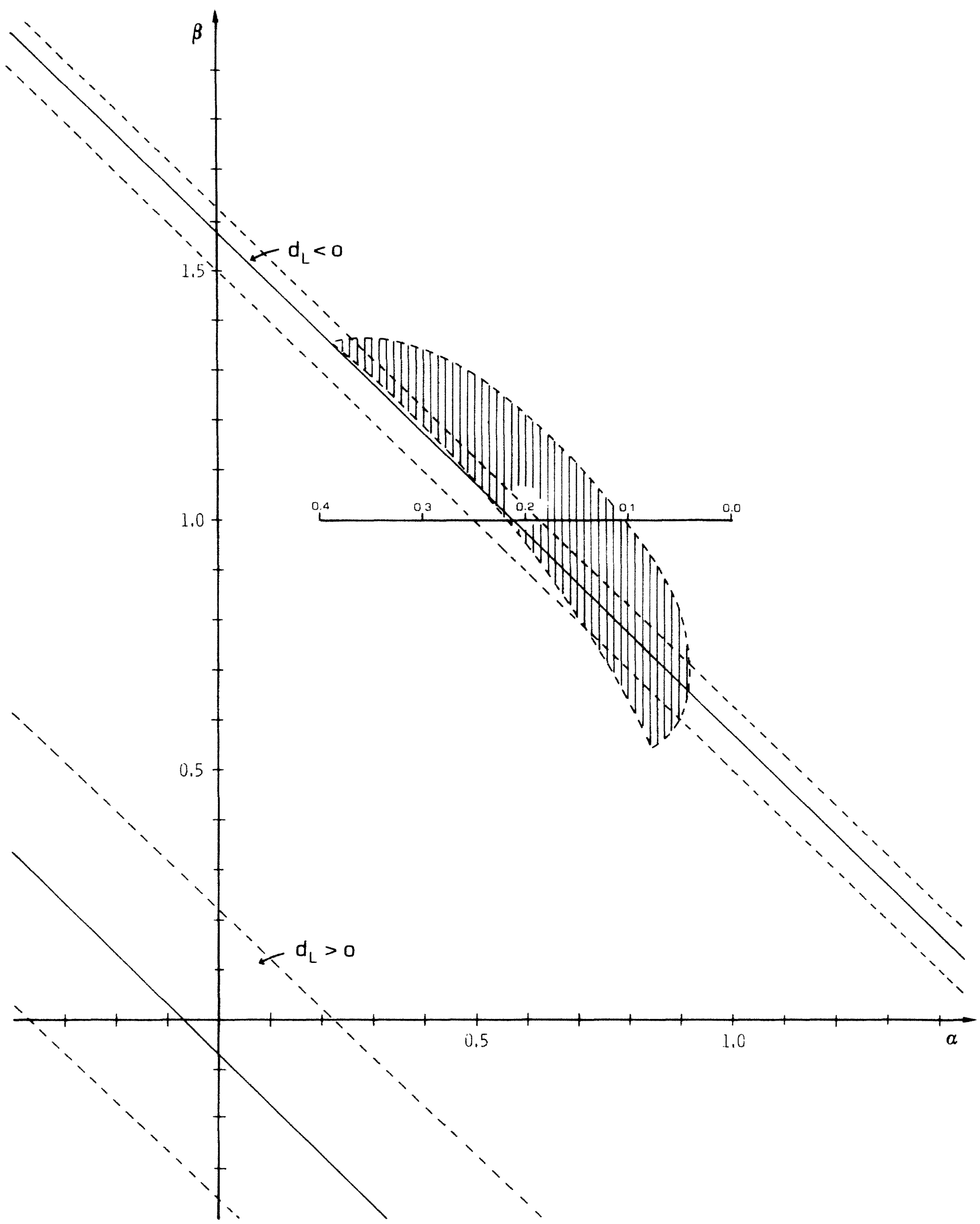

FIG. 1. Three-standard-deviation bands relative to the value of $(\alpha+\beta)$ derived from the estimate of the squared chiral couplings of Ref. 7 and corresponding to the two possible signs of d_L. The dashed contour is the domain allowed by the analysis of the single-pion production data or Ref. 8. Also shown, the prediction of the standard model ($\sin^2\theta_W$ with $\rho=1$).

liable QCD treatment of such complicated reactions, but the assumption itself that these (low-energy) reactions are dominated by current fragmentation: in Ref. 4 these effects are simulated by including (in the fit) a 25% uncertainty in the fragmentation functions.

It follows that the contribution to the determination of the chiral couplings, and in particular of their relative signs, coming from elastic scattering and semi-inclusive pion production is either rather poor or affected by large theoretical uncertainties.

Deep-inelastic inclusive scattering appears therefore as the only process able of inducing striking constraints on the NC couplings without relevant effects coming from the present theoretical uncertainties. Remembering that it is sensitive only to the squared chiral couplings, it follows that the uncertainty concerning the relative signs of the chiral couplings remains essentially unsolved. Only the use of exclusive pion production data allows one to exclude the so-called dominantly isoscalar solution in favor of that dominantly isovector: in the case of Ref. 4, the one-pion data available at that time, analyzed[2,12] within the Adler model[13] [even if compatible with the WS model only if a large (30%) theoretical uncertainty for the matrix elements is assumed] allow, within 90% C.L., to fix the signs of d_L and u_R, once conventionally u_L is assumed positive. But no specific indication about the sign of d_R can be drawn.

A further difficulty in deducing the sign of d_R can be related to the use of an overall multiparameter numerical best fit (this being one of the problems arising from this kind of statistical approach, as discussed in Ref. 7). Since d_R is very near to zero, the two solutions corresponding to the two possible signs overlap, and caution must be taken in avoiding that the minimization procedure leads to something similar to the mean of the two possible solutions (d_R practically zeroed).

As will be shown in the next section, the most accurate data coming from $\overset{(-)}{\nu}$-induced deep-inelastic scattering together with the possibility of making use of a more recent and refined analysis of the single-pion production, allow at present, avoiding the use of a multiparameter best fit, to overcome some of the difficulties of the earlier analyses, towards an attempt of an unambiguous determination of the structure of the hadronic NC.

III. SOLVING THE AMBIGUITIES

The starting point of the approach is represented by the analysis performed in Ref. 7. Accordingly

(a) Only the updated deep-inelastic scattering data, on both isoscalar and n,p target, are considered, with the result of minimizing the theoretical uncertainties.

(b) In estimating the cross-section ratios, within the usual framework of the parton model with QCD effects, (i) the parameterization suggested by the most recent re-

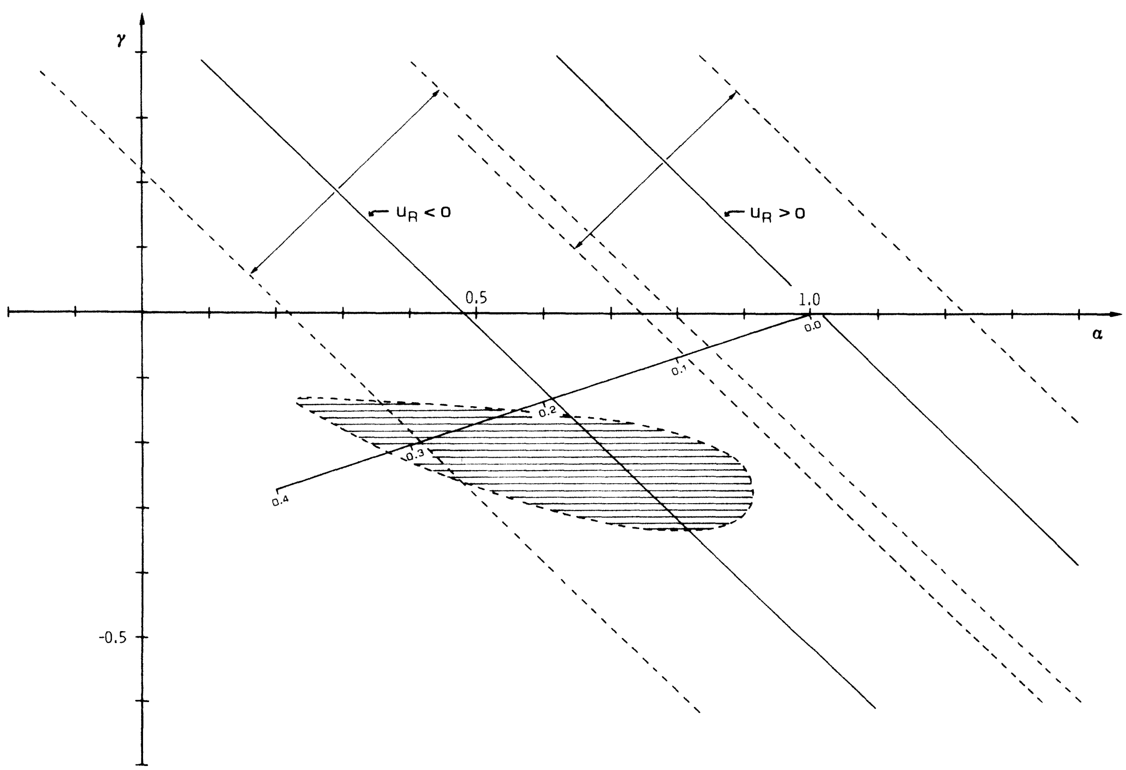

FIG. 2. Three-standard-deviation bands relative to the value of $(\alpha+\gamma)$ derived from the estimate of the squared chiral couplings of Ref. 7 and corresponding to the two possible signs of u_R. The dashed contour is the domain allowed by the analysis of the single-pion production data of Ref. 8. Also shown, the prediction of the standard model ($\sin^2\theta_W$ with $\rho=1$).

sults of deep-inelastic-scattering charged-current (CC) processes is adopted, (ii) the contribution of strange quarks to the scattering on a nonisoscalar target is also included, and (iii) all the theoretical uncertainties are estimated and employed in evaluating the weighted mean of the determinations coming from the different experiments.

(c) The effects induced by radiative corrections are also included, by following closely the approach of Marciano and Sirlin:[14] as stressed in Ref. 7, the effect is nonnegligible and leads, when applied, to a better agreement with the standard model in its minimal version ($\rho=1$).

(d) For the first time the determination of the four squared chiral couplings is accomplished without making use of a multiparameter bestfit: conversely, an analytical iterative procedure is followed, in which the constraints imposed by the physical requirement of positivity of the squared couplings are introduced.

The above analysis (Ref. 7), of course, does not solve the ambiguities due to the relative signs of the chiral couplings. However, the accuracy reached in estimating their squares allows one to distinguish in a rather precise way the different solutions connected to the possible choices of the signs. In order to select among them, they will be

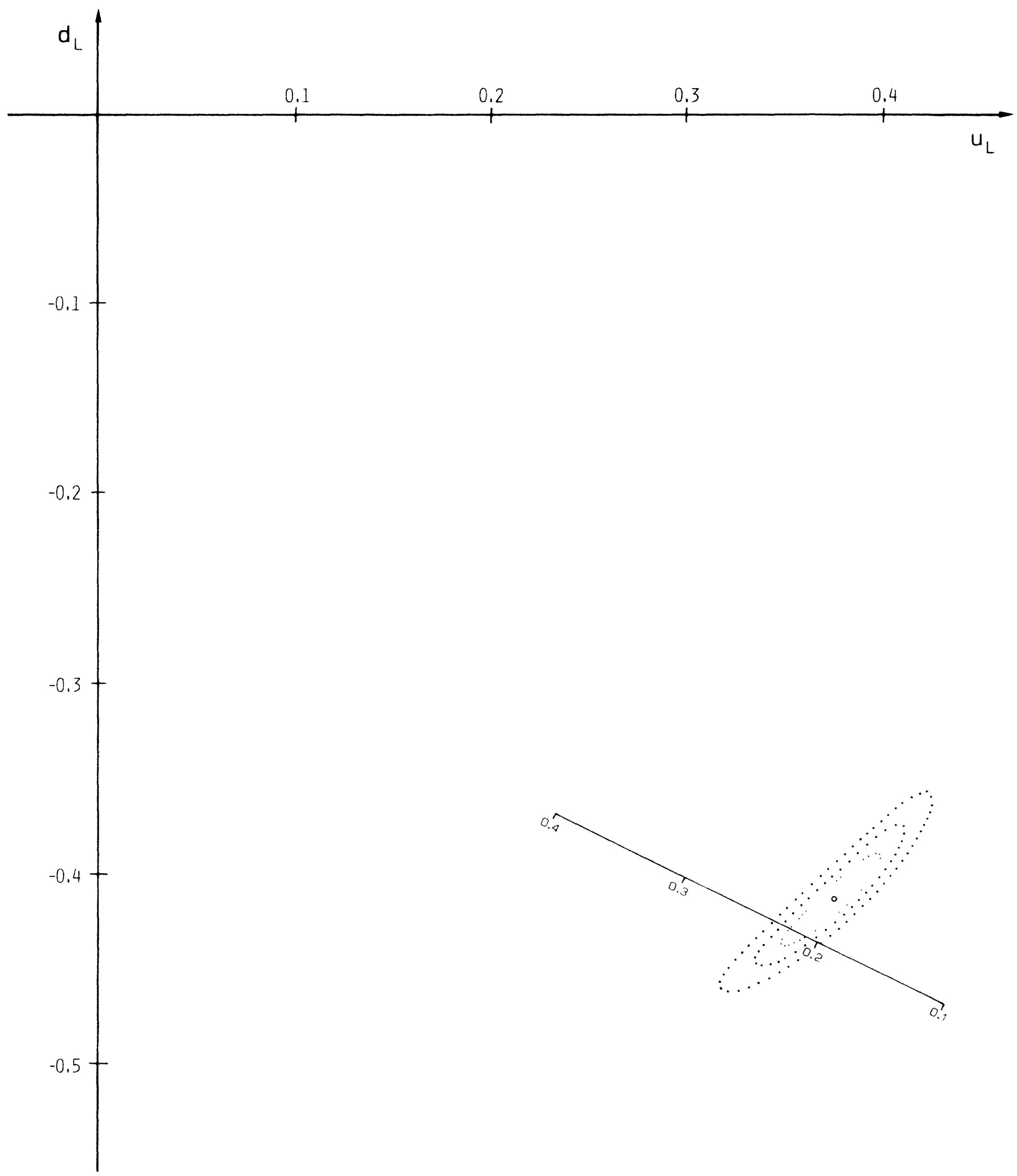

FIG. 3. Central value and regions of assigned C.L. (39.3%, 68.3%, 90% inside the dotted contours, respectively) in the plane (u_L,d_L), derived from the estimate of the squared chiral couplings (see Ref. 7), when d_L is assumed negative. Also shown, the prediction of the standard model ($\sin^2\theta_W$ with $\rho=1$).

compared with a recent analysis[8] of the single-pion production data obtained in Gargamelle with ν and $\bar{\nu}$ beams at intermediate energy,[15] within the framework of a new approach to the ν-induced single-pion production.[16] It is worthwhile to note that the peculiar approach to the single-pion production mechanism, where not only the contributions of background and resonant states are considered, but also the corresponding interference contributions, leads to a considerable agreement in the CC sector, remarkable also in reproducing the πN invariant-mass spectra in the $I=\frac{1}{2}$ first resonant region.[17] Moreover, the intermediate energy typical of the experiments performed in Gargamelle (ν and $\bar{\nu}$ beams peaked at few GeV) tends to enhance the contribution of the $I=\frac{1}{2}$ first resonant region and allows a rather convincing estimate of the isoscalar piece of the weak NC (the theoretical uncertainty, mainly related to the axial form factors as estimated in Ref. 16, is far less then the experimental error).

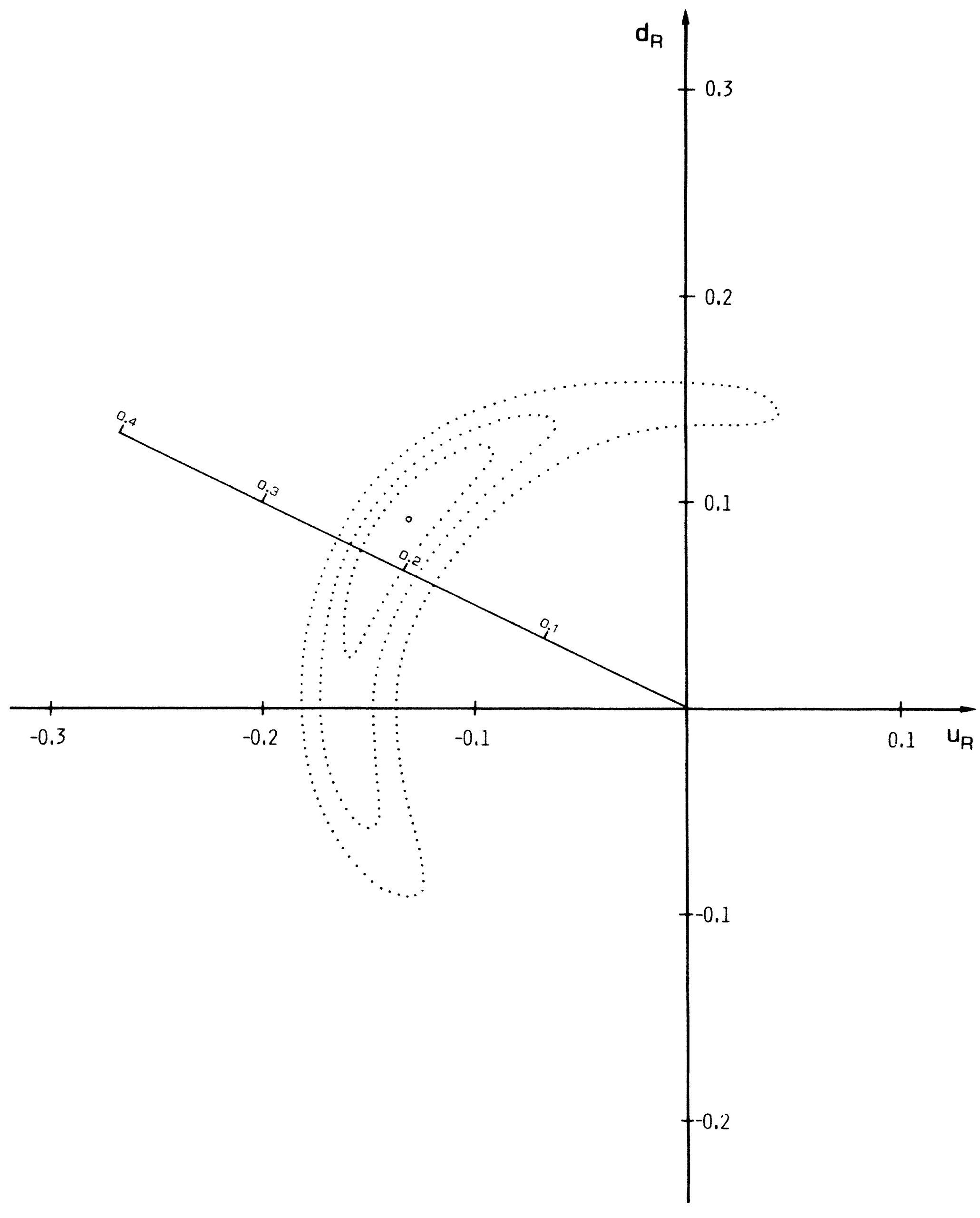

FIG. 4. Central value and regions of assigned C.L. (39.3%, 68.3%, 90% inside the dotted contours, respectively) in the plane (u_R,d_R), derived from the estimate of the squared chiral couplings (see Ref. 7), when u_R is assumed negative and d_R positive. It corresponds to the solution (+) in the text (d_R positive): Solution (−) is symmetric with respect to the u_R axis. Also shown, the prediction of the standard model ($\sin^2\theta_W$ with $\rho=1$).

According to the results given in Ref. 7, the overall analysis of the deep-inelastic scattering leads to

$$\begin{aligned} u_L{}^2 &= 0.1413 \pm 0.0189(\pm 0.0020) , \\ d_L{}^2 &= 0.1697 \pm 0.0200(\pm 0.0024) , \\ u_R{}^2 &= 0.0173 \pm 0.0089(\pm 0.0022) , \\ d_R{}^2 &= 0.0084 \pm 0.0078(\pm 0.0017) , \end{aligned} \tag{1}$$

where, together with the error coming from experimental uncertainties (statistical and systematic errors added quadratically), in the parentheses the (small) error due to the present theoretical uncertainty concerning the parametrization is also reported (but will not be considered here). The matrix of the correlation coefficients between the experimental errors is given by

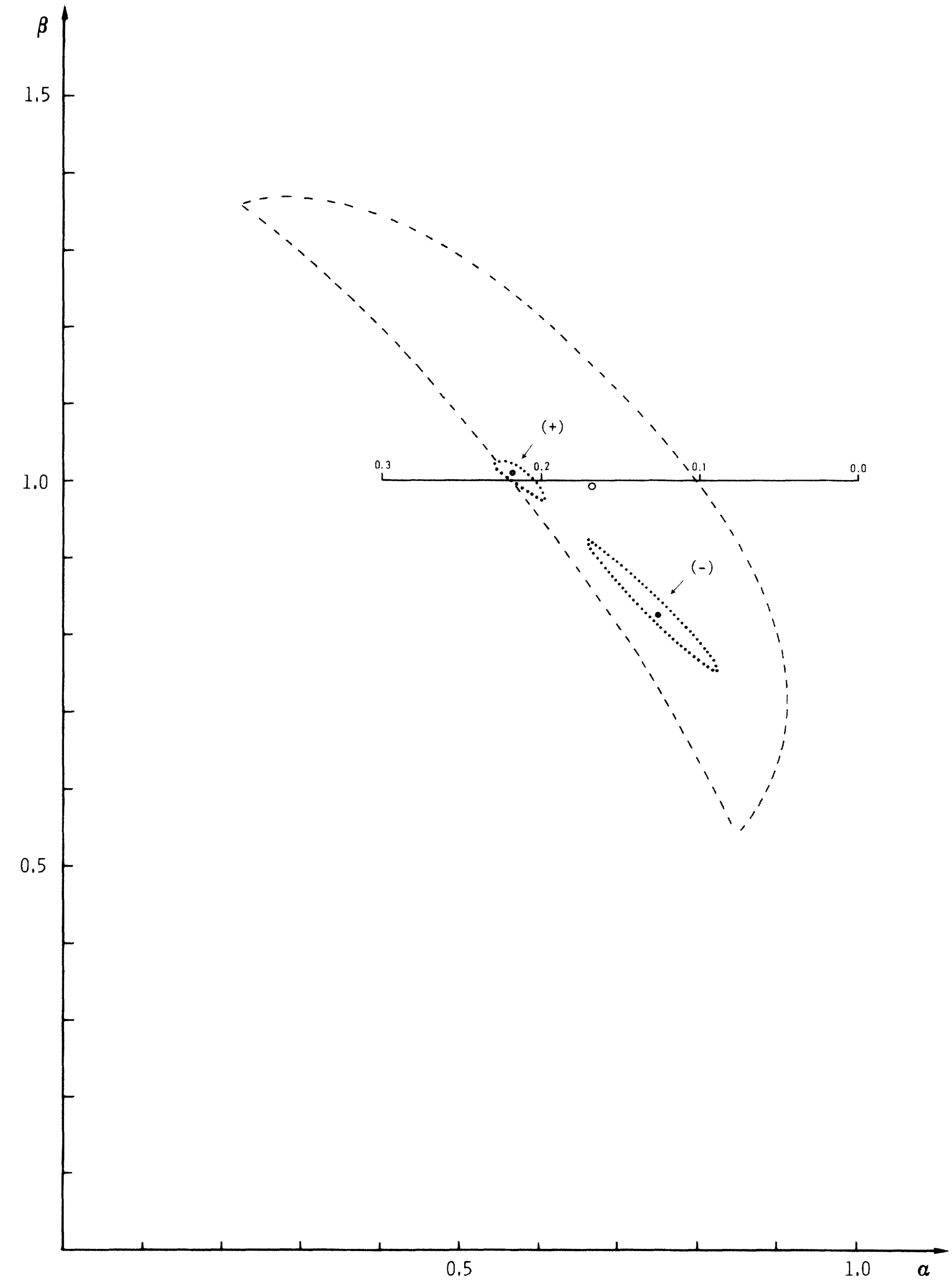

FIG. 5. Comparison in the plane (α,β) of the two solutions $(+)$ and $(-)$ [see Eqs. (6) and (7), respectively] with the domain (dashed contour) allowed by the analysis of the pion production data of Ref. 8. Also shown, the prediction of the standard model ($\sin^2\theta_W$ with $\rho=1$).

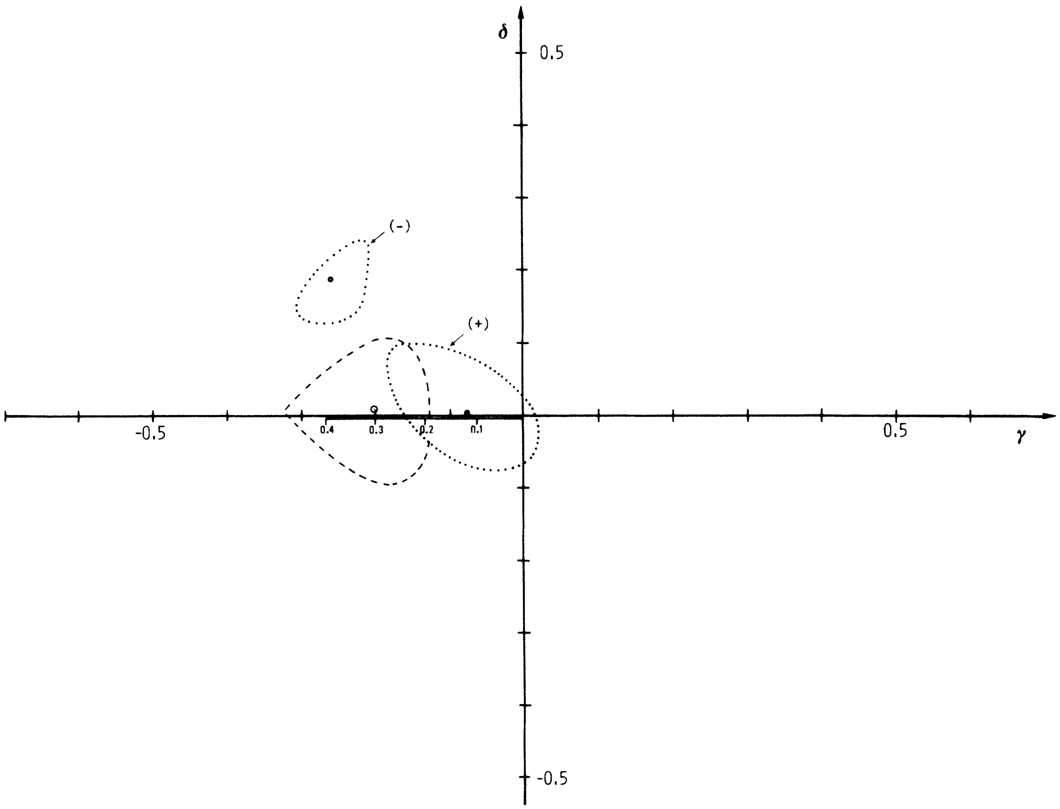

FIG. 6. Comparison in the plane (γ,δ) of the two solutions $(+)$ and $(-)$ [see Eqs. (6) and (7), respectively] with the domain (dashed contour) allowed by the analysis of the pion production data of Ref. 8. Also shown, the prediction of the standard model ($\sin^2\theta_W$ with $\rho=1$).

$$(\tau_{ij})_{\rm expt}\equiv\begin{bmatrix}1 & -0.937 & -0.185 & 0.169\\ & 1 & 0.137 & -0.226\\ & & 1 & -0.902\\ & & & 1\end{bmatrix} \qquad (2)$$

the correlation coefficients between total errors, not reported here, being very similar.

Chosen conventionally u_L positive, as usual, let us first consider the problem of the signs of d_L and u_R with respect to u_L. On the basis of the well-known relations connecting the chiral couplings to the isovector (isoscalar), vector (axial-vector) couplings $\alpha,\beta,\gamma,\delta$,

$$\begin{aligned}\alpha&=u_L-d_L+u_R-d_R\ ,\\ \beta&=u_L-d_L-u_R+d_R\ ,\\ \gamma&=u_L+d_L+u_R+d_R\ ,\\ \delta&=u_L+d_L-u_R-d_R\ ,\end{aligned} \qquad (3)$$

it follows that these signs can be related to the quantities

$$\alpha+\beta=2(u_L-d_L),\ \ \alpha+\gamma=2(u_L+u_R)\ , \qquad (4)$$

respectively. The two above quantities, derived from the estimate (1), are reported in the corresponding planes (α,β) and (α,γ) in Figs. 1 and 2, respectively. In both cases, the two solutions corresponding to the two possible signs are given with their three-standard deviation limits (the two bands in each figure) and compared with the

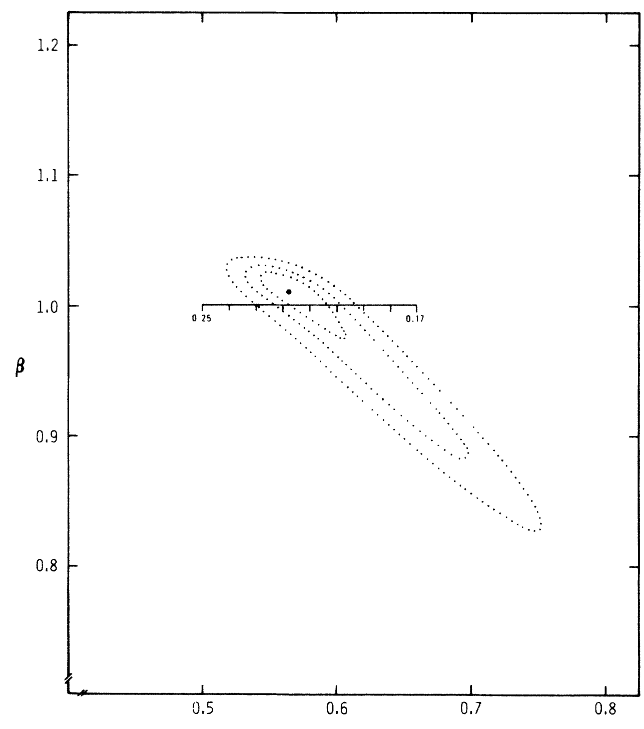

FIG. 7. Central value and regions of assigned C.L. (39.3%, 68.3%, 90% inside the dotted contours, respectively) of the solution $(+)$ in the (α,β) plane. Also shown, the prediction of the standard model ($\sin^2\theta_W$ with $\rho=1$).

(dashed) allowed region coming from the single-pion production analysis.[8] The comparison leads us to discard the two signs, d_L positive and u_R positive, separately, with a better evidence than in previous analyses (and without making use of semi-inclusive pion production and $\overset{(-)}{\nu}p$ elastic scattering data).

Once the signs of d_L and u_R are established to be both negative, we remain with two possible solutions depending on the relative sign, positive or negative, to be assumed for d_R. Let us denote with (+) and (−) the two corresponding solutions, respectively. From (1) follows

$$\text{solution } (+):\ u_L = 0.376^{+0.025}_{-0.026}\,,\quad d_L = -0.412^{+0.025}_{-0.024}\,,\quad u_R = -0.131^{+0.042}_{-0.031}\,,\quad d_R = 0.092^{+0.036}_{-0.071}\,, \tag{5}$$

the solution (−) being obtained by changing the sign of d_R and interchanging the corresponding upper and lower errors.

Errors are asymmetrical and distributions far from being normal. The only significant "measure" is now represented by the allowed regions of assumed C.L. In Figs. 3 and 4 the regions of assigned C.L., allowed by solution (+) in the planes (u_L,d_L) and (u_R,d_R), respectively, are shown: whereas the allowed region in the left-handed plane is not far from being elliptical, the strong asymmetry due to the correlation effects and to the small values of d_R are well evident in Fig. 4. It appears that an estimate of the four linear couplings in terms of symmetric errors and assigned correlation coefficients is relatively reliable because of the highly nonlinear effects.

Solution (−) is not reported: it can be obtained from solution (+) by merely taking its symmetric with respect to the u_R axis in the plane (u_R,d_R).

In order to estimate the sign to be attributed to d_R, we follow the same approach used above, by comparing the two solutions (+) and (−) to that coming from the single-pion production analysis.[8] Going from the chiral couplings to the parameter $\alpha,\beta,\gamma,\delta$, the two following solutions are obtained [from a technical point of view, the solutions are obtained by extracting from the normal distribution (1), (2) the corresponding hypercontour in the hyperspace of the four parameters $\alpha,\beta,\gamma,\delta$, and then by projecting it in the plane of two of them. By leaving the two other parameters free, this allows one to estimate, by definition, the standard deviation of each parameter, separately. In all figures the usual meaning[18] has to be attributed to the contours of the assigned C.L.]:

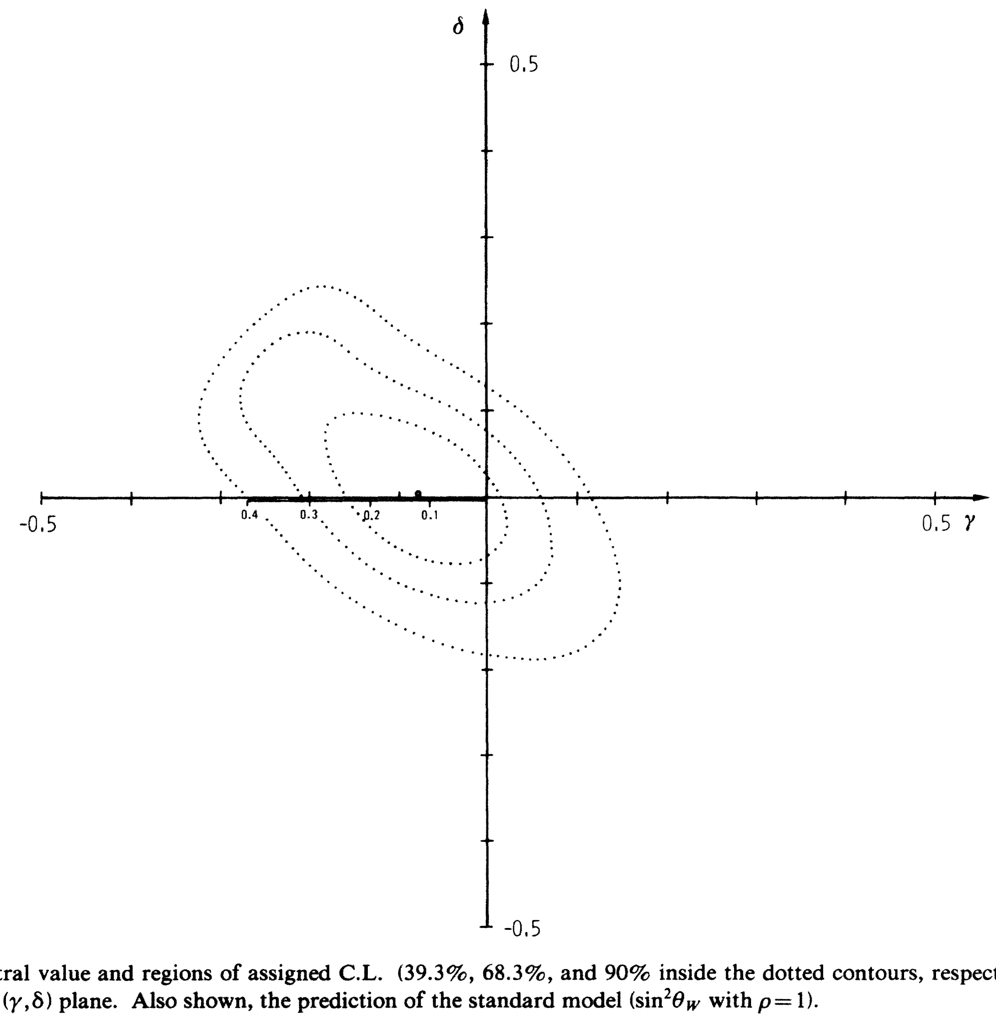

FIG. 8. Central value and regions of assigned C.L. (39.3%, 68.3%, and 90% inside the dotted contours, respectively) of the solution (+) in the (γ,δ) plane. Also shown, the prediction of the standard model ($\sin^2\theta_W$ with $\rho=1$).

Solution (+):

$$\alpha=0.565^{+0.041}_{-0.023}\,,\quad \beta=1.011^{+0.011}_{-0.038}\,,\quad \gamma=-0.076^{+0.095}_{-0.110}\,,\quad \delta=0.004^{+0.092}_{-0.080} \tag{6}$$

and

solution (−):

$$\alpha=0.748^{+0.071}_{-0.091}\,,\quad \beta=0.827^{+0.092}_{-0.073}\,,\quad \gamma=-0.259^{+0.049}_{-0.049}\,,\quad \delta=0.187^{+0.054}_{-0.060}\,. \tag{7}$$

In Figs. 5 and 6 the corresponding contours in the planes (α,β) and (γ,δ), respectively, are drawn: together with the two above solutions (dotted contours) the result (dashed) coming from the single-pion production analysis is given, corresponding to[8]

single-pion solution:

$$\alpha=0.677^{+0.242}_{-0.452}\,,\quad \beta=0.993^{+0.372}_{-0.453}\,,\quad \gamma=-0.202^{+0.077}_{-0.123}\,,\quad \delta=0.007^{+0.103}_{-0.102}\,. \tag{8}$$

The comparison leads to a rather clear indication in favor of solution (+), emerging in a more evident way in the plane of the two isoscalar couplings γ and δ, because of the mentioned sensitivity of the single-pion production data to the corresponding piece of the weak NC. However, the above indication is far from being conclusive, since the 90% C.L. contours of the two solutions partially overlap and both become compatible with the solution given by the single-pion production analysis, even though the agreement is more marked if solution (+) is considered.

It is important to observe that the present experimental accuracy does not allow one to distinguish the two solu-

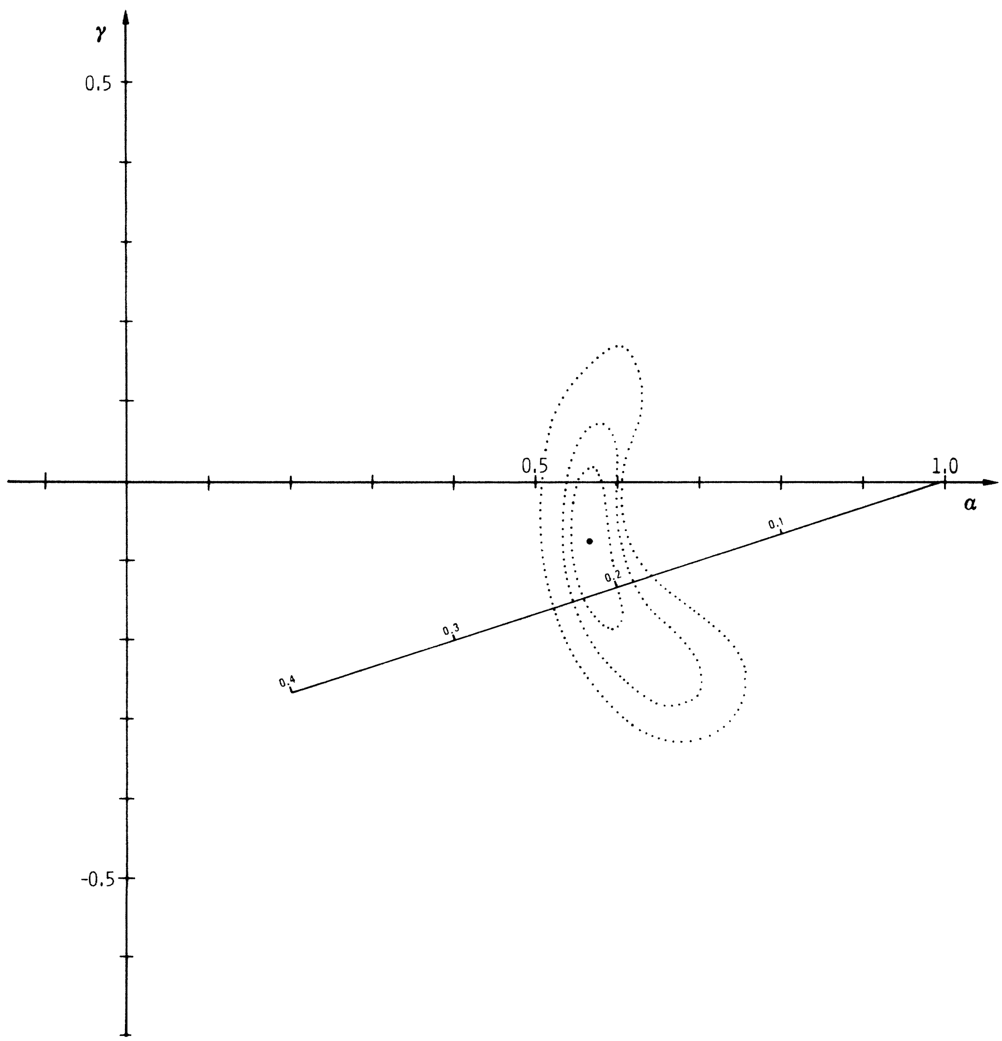

FIG. 9. Central value and regions of assigned C.L. (39.3%, 68.3%, 90% inside the dotted contours, respectively) of the solution (+) in the (α,γ) plane. Also shown, the prediction of the standard model ($\sin^2\theta_W$ with $\rho=1$).

tions without separating them through an analytic approach.

Once solution (+) is chosen (always within the limits discussed above), the discrepancies concerning the isoscalar piece of the weak neutral current are removed, the values found for the couplings $\alpha,\beta,\gamma,\delta$ being very near to those expected in the framework of the standard model. This can be seen in Figs. 7, 8, and 9 where the C.L. contours are drawn in the planes (α,β),(γ,δ), and (α,γ), respectively, together with the predictions of the standard model in its minimal version ($\rho=1$). The comparison with the standard model of the model-independent solution (1), relative to the squared chiral couplings, has yet been performed in Ref. 7: there the strong agreement with the model in its minimal version and the relevance of the radiative correction effects in realizing this agreement have been stressed. Here the agreement is further corroborated, since the model gives a well-defined prescription about the relative signs of the four chiral couplings (or equivalently of $\alpha,\beta,\gamma,\delta$). Solution (+) given in (5) [or in (6)] is that which better agrees with the standard model: the indication about it establishes more firmly the agreement, even though additional evidence against solution (−), related to accurate experimental measurements sensitive to the sign of d_R, is welcome.

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