Confidence regions for neutrino oscillation parameters from double-Chooz data

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In this work, an independent and detailed statistical analysis of the double-Chooz experiment is performed. In order to have a thorough understanding of the implications of the double-Chooz data on both oscillation parameters $\sin^2(2\theta_{13})$ and $\Delta m^2_{31}$, we decided to analyze the data corresponding to the Far detector, with no additional restriction. This differs from previous analyses, which only aim to estimate the mixing angle $\theta_{13}$, without mentioning the effects on $\Delta m^2_{31}$. By doing this, confidence regions and best fit values are obtained for ($\sin^2(2\theta_{13}), \Delta m^2_{31}$). This analysis yields an out-of-order $\Delta m^2_{31}$ minimum, which has already been mentioned in previous works, and it is corrected with the inclusion of additional restrictions. With such restrictions it is obtained that $\sin^2(2\theta_{13}) = 0.084^{+0.030}_{-0.028}$ and $\Delta m^2_{31} = 2.444^{+0.187}_{-0.215} \times 10^{-3} \text{eV}^2/c^4$. Our analysis allows us to study the effects of the so-called “spectral bump” around 5 MeV; it is observed that a variation of this spectral bump may be able to move the $\Delta m^2_{31}$ best fit value, in such a way that $\Delta m^2_{31}$ takes the order of magnitude of the MINOS value. In other words, if we allow the variation of the spectral bump, then we may be able to determine both oscillation parameters using Far detector data only, with no further restrictions from other experiments. Finally, and with the intention of understanding the effects of the preliminary Near detector data, we performed two different analyses, aiming to eliminate the effects of the energy bump. As a consequence, it is found that unlike the Far detector analysis, the Near detector data may be able to fully determine both oscillation parameters by itself, resulting in $\sin^2(2\theta_{13}) = 0.095 \pm 0.053$ and $\Delta m^2_{31} = 2.63^{+0.98}_{-1.15} \times 10^{-3} \text{eV}^2/c^4$. The later analyses represent an improvement with respect to previous works, where additional constraints for $\Delta m^2_{31}$ were necessary.

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I. INTRODUCTION

The double-Chooz experiment estimated the reactor neutrino flux of the Chooz-B nuclear plant by means of its operating parameters. This flux, when interacting with the detector target, induces a number of inverse $\beta$ decays (IBD). This experiment was designed to run with two detectors located at $L_F \approx 1000 \text{m}$ (Far), and $L_N \approx 400 \text{m}$ (Near). But the current collaboration results report only far observations. The double-Chooz Near detector was finished in 2016, and only preliminary data have been published until now.

In particular, the double-Chooz Far detector reports fewer IBDs than those expected. If a neutrino oscillations model explains this deficit, then the oscillation parameters can be obtained from double-Chooz data.

In the simplified two-flavor oscillation model, the survival probability of a $\bar{\nu}_e$ with energy $E_{\nu}$ (MeV) after traveling a distance $L$ (m) is given as

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \sin^2\left(1.27 \frac{\Delta m^2_{31} L}{E_{\nu}} \right).$$

The main objective of the double-Chooz experiment is the precise measurement of the mixing angle $\theta_{13}$ [1]. Table I shows some results for $\sin^2(2\theta_{13})$. In particular, the double-Chooz collaboration determined $\sin^2(2\theta_{13}) = 0.090^{+0.032}_{-0.029}$, without showing confidence regions and using the value obtained by MINOS of $2.44^{+0.09}_{-0.10} \times 10^{-3} \text{eV}^2/c^4$ for $\Delta m^2_{31}$ [2].
In this paper we use the double-Chooz data in $\chi^2$ tests to determine the best fit for $\sin^2(2\theta_{13})$ and $\Delta m_{21}^2$ without assuming an *a priori* value for the last one to get both parameters as well as their confidence regions.

Consequently, double-Chooz data may be used for a unified analysis with other experiments where both oscillation parameters are obtained simultaneously by means of their corresponding data.

The organization of this work is as follows. In Sec. I the rate $+$ shape ($R + S$) analysis is presented, aligned with Ref. [2]. The statistics defined there is used for Far detector analysis only. This section shows how the quantities that define the function $\chi^2_{R+S}$ are obtained. A consistent definition of the expected number of IBD is introduced in Sec. II. Both sections are used in Sec. III to estimate the oscillation parameters $\sin^2(2\theta_{13})$ and $\Delta m_{21}^2$ by minimizing the function $\chi^2_{R+S}$. Also the confidence regions for these parameters are obtained from a diagonal covariance matrix (DCM), and a full covariance matrix (FCM). The values obtained for $\Delta m_{21}^2$ are significantly different than those expected. In order to line up our results with the MINOS experiment, a $\chi^2_{R+S+M}$ test is presented.

In Sec. IV a discussion related to the spectral bump of the neutrino spectrum at 5 MeV is included to estimate their effect in the $\chi^2_{R+S}$ function.

Section V is devoted to the Far $+$ Near detector data. With the purpose of determining the oscillation parameters $\Delta m_{21}^2$, $\sin^2(2\theta_{13})$ and their confidence regions from double-Chooz data without using *a priori* the value of $\Delta m_{31}^2$ from another experiment, two convenient $\chi^2$ functions are introduced. These statistics also suppress the spectral bump effects mentioned before. To do this, we use the preliminary data from [8] as input to the formalism presented in the previous sections. The results obtained are promising and can be used when the collaboration releases new data.

Finally, our conclusions are given in Sec. VI.

### TABLE I. Results of the different measurements made by the double-Chooz experiment. The first two (2012) include only reactor-on data and Gd captures. In 2013 the H-captures data were taken into account. From 2014 reactor-off data were included in addition to reactor-on data, only for Gd captures first and including H captures later. In the last one only Gd-captures data are taken into account.

| Parameters | Value |
|------------|-------|
| $\sin^2(2\theta_{13})$ | 0.086 $\pm$ 0.041$^a$ $\pm$ 0.030$^b$ |
| $\sin^2(2\theta_{13})$ | 0.109 $\pm$ 0.030$^a$ $\pm$ 0.025$^b$ |
| $\sin^2(2\theta_{13})$ | 0.097 $\pm$ 0.034$^a$ $\pm$ 0.034$^b$ |
| $\sin^2(2\theta_{13})$ | 0.102 $\pm$ 0.028$^a$ $\pm$ 0.033$^b$ |
| $\sin^2(2\theta_{13})$ | 0.102 $\pm$ 0.043$^c$ |
| $\sin^2(2\theta_{13})$ | 0.090$^{+0.032}_{-0.029}$ |

$^a$Statistical uncertainty.

$^b$Systematic uncertainty.

$^c$Total uncertainty.

### II. RATE $+$ SHAPE ANALYSIS [2]

Neutrinos are detected through the positron kinetic energy, $E_{\text{kin}}$, in the energy range of 0.5 and 20 MeV, which is divided into 40 energy bins, accordingly to Table 15.2 in [9]. The rate $+$ shape analysis is determined by the function

$$
\begin{align*}
\chi^2_{R+S} & = \sum_{i=1}^{40} \sum_{j=1}^{40} (N_{i}^{\text{obs}} - N_{i}^{\exp})M_{ij}^{-1}(N_{j}^{\text{obs}} - N_{j}^{\exp}) \\
& + (\epsilon_a \epsilon_b \epsilon_c) \left( \begin{array}{ccc} \sigma^2_a & \rho_{ab} \sigma_a \sigma_b & \rho_{ac} \sigma_a \sigma_c \\ \rho_{ab} \sigma_a \sigma_b & \sigma^2_b & \rho_{bc} \sigma_b \sigma_c \\ \rho_{ac} \sigma_a \sigma_c & \rho_{bc} \sigma_b \sigma_c & \sigma^2_c \end{array} \right)^{-1} \left( \begin{array}{c} \epsilon_a \\ \epsilon_b \\ \epsilon_c \end{array} \right) \\
& + \sum_{k=1}^{5} \epsilon_k \sigma_k^2 + 2 \left( N_{\text{off}} \ln \left( \frac{N_{\text{obs}}^{\exp}}{N_{\text{off}}^{\exp}} \right) + N_{\text{off}}^{\exp} - N_{\text{off}}^{\text{obs}} \right). 
\end{align*}
$$

In the first term, each energy bin requires $N_{i}^{\text{obs}}$ ($N_{i}^{\exp}$), which is the observed (expected) number of IBD. A covariance matrix $M_{ij}$ is introduced to include the correlation terms among energy bins.

$N_{i}^{\text{obs}}$ were directly obtained from Fig. 21 in [2]. In this analysis we considered the 17 351 IBD candidates, $N_{\text{tot}}$, that occurred during 460.67 days, $T_{\text{on}}$. The first thirty-one readings are consistent with previous double-Chooz collaboration data [10].

$N_{i}^{\exp}$ is proportional to the expected number of antineutrinos without oscillations, $N_{i}^{\exp\text{stat}}$, and to the average survival probability in the $i$th energy bin, $P_{i}$, closely related to the flavor-oscillation model (1). In the following section the explicit form of these quantities is given. For now we can write $N_{i}^{\exp}$ as follows:

$$
N_{i}^{\exp} \sim N_{i}^{\exp\text{stat}} P_{i}(\theta_{13}, \Delta m_{31}^2). 
$$

The diagonal matrix elements $M_{ii}$ contain information on statistical and systematic uncertainties in each energy bin. The bin-to-bin correlations correspond to the off diagonal elements. $M_{ij}$ is discussed in more detail in [2] and is written as

$$
M = M_{\text{stat}} + M_{\text{flux}} + M_{\text{eff}} + M_{\text{li/He(shape)}} + M_{\text{acc(stat)}}. 
$$

The matrix elements $M_{ij}$ have been taken from Fig. 15.3 in [9]. In this figure there are five matrices that define the $M_{ij}$ numerical value. Since the information is presented through a color code, a basic software was necessary to decode it. We verified that the diagonal elements $M_{ii}^{\text{stat}}$, $M_{ii}^{\text{flux}}$, and $M_{ii}^{\text{eff}}$ previously published in [10] were found in the matrices of [9].

In addition to the uncertainties involved in the covariance matrix, eight systematic uncertainties are considered in the second and third terms of $\chi^2_{R+S}$, using $\epsilon_x$ parameters.
considered through five parameters \( P \) of visible energy variation, \( \epsilon_{\text{vis}} \).

These are explicitly introduced in the second term of Eq. (2) by means of a matrix that contains uncertainties \( \sigma_{a}, \sigma_{b}, \sigma_{c} \) and correlations \( \rho_{ab}, \rho_{bc}, \rho_{ac} \) (Table II).

The other sources of systematic uncertainties are considered through five parameters \( \epsilon_{i} \), whose standard deviations are given in Table III.

The fourth term in (2) or \( \chi^{2}_{\text{off}} \) is the contribution of two reactors off (2-off) data, in which \( N_{\text{off}}^{\text{obs}} \) (\( N_{\text{off}}^{\text{exp}} \)) is the observed (expected) number of IBD candidates.

According to Ref. [2], \( N_{\text{off}}^{\text{obs}} = 7 \) and \( N_{\text{off}}^{\text{exp}} \) is determined by the residual \( E_{\nu} \)'s (\( \epsilon_{i} \)), and the background (\( n^{\text{bg}} \)), as

\[
N_{\text{off}}^{\text{exp}} = c_{4} P_{\text{off}}(\theta_{13}, \Delta m_{31}^{2}) + n^{\text{bg}},
\]

where \( n^{\text{bg}} = B \cdot T_{\text{off}} \).

\( B = 1.56 \) events/day is the total background rate provided by \( T_{\text{off}} = 7.24 \) days of reactor-off data, [9].

For IBD events with neutrons captured on Gd, \( P_{\text{off}}(\theta_{13}, \Delta m_{31}^{2}) \) denotes the average survival probability on all the spectrum of antineutrinos with the reactor off, and is written as [9,11],

\[
P_{\text{off}}(\theta_{13}) = 1 - \sin^{2}(2\theta_{13}) \left| \frac{\sin^{2}(1.27\Delta m_{31}^{2}L/E_{\nu})}{E_{\nu}} \right|.
\]

Table III. Miscellaneous uncertainties. Each one of them is related to its own pull parameter by means of the third term of Eq. (2). The pull parameters \( \epsilon_{1}, \ldots, \epsilon_{5} \) are corrections to the predicted antineutrino spectrum. These are as follows: \( \epsilon_{1} \), antineutrino spectrum error due to \( \beta \) decays of \( ^{8}\text{He} \) and \( ^{4}\text{Li} \); \( \epsilon_{2} \), error due to \( n + \mu \); \( \epsilon_{3} \), accidental; \( \epsilon_{4} \), residuals; \( \epsilon_{5} \), uncertainty of the squared mass differences \( \Delta m_{31}^{2} \). The last one is removed later, [2].

| \( \sigma_{i} \) | \( 0.006 \text{ MeV} \) |
| \( \sigma_{b} \) | \( 0.008 \) |
| \( \sigma_{c} \) | \( 0.0006 \text{ MeV}^{-1} \) |
| \( \rho_{ab} \) | \( -0.30 \) |
| \( \rho_{bc} \) | \( -0.29 \) |
| \( \rho_{ac} \) | \( 7.1 \times 10^{-3} \) |

as suggested by Eq. (1). \( L = 1050 \) m is the average distance from the Far detector to both reactors. The term in angle brackets results from averaging the survival probability (1) over all the energy range, \( 0.5 \text{ MeV} \leq E_{\text{vis}} \leq 20.0 \text{ MeV} \),

\[
\left( \frac{\sin^{2}(1.27\Delta m_{31}^{2}L/E_{\nu})}{E_{\nu}} \right) = \frac{1}{\Delta E_{\nu}} \int_{1.282 \text{ MeV}}^{20.782 \text{ MeV}} \sin^{2}(1.27\Delta m_{31}^{2}L/E_{\nu}) \, dE_{\nu},
\]

where

\[
E_{\nu} \approx E_{\text{vis}} + \delta(E_{\text{vis}}) + 0.782 \text{ MeV}
\]

is the energy of the incoming \( \bar{\nu}_{e} \) written in terms of the corrected visible energy or positron kinetic energy, \( E_{\text{vis}} \). The last term of (9) results directly from the observation of the IBD, and depends on the positron and nucleons masses, \( m_{n} - m_{\mu} - m_{e} = 0.782 \text{ MeV}/c^{2} \).

III. EXPECTED NUMBER OF IBD, \( N_{i}^{\text{exp}} \)

As introduced in Eq. (3), the expected number of IBD, \( N_{i}^{\text{exp}} \), is closely related to the oscillation model and is defined as

\[
N_{i}^{\text{exp}} = n_{i}^{\text{exp}} \left( 1 + \frac{\epsilon_{4} T_{\text{on}}}{T_{\text{off}} N_{\text{tot}}} \right) \tilde{P}_{i}(\theta_{13}, \Delta m_{31}^{2})
\]

\[
+ \left( \epsilon_{1} \frac{N_{\nu}^{\text{L+He}}}{n_{i}^{\text{exp}}} + \epsilon_{2} \frac{N_{\nu}^{\text{Other}}}{n_{i}^{\text{exp}}} + \epsilon_{3} \frac{N_{\text{acc}}}{n_{i}^{\text{exp}}} \right).
\]

In this equation the expected neutrino spectrum without oscillations, \( n_{i}^{\text{exp}} \), depends on the operating parameters of the nuclear reactor. These quantities are obtained from Fig. 21 at [2]; a discrepancy between the observed and the expected neutrino spectrum without oscillations between 4 and 6 MeV has been detected. This energy bump will impact the determination of the oscillation parameters. It is discussed in the next section.

The residual neutrinos \( \epsilon_{4} \) are produced by the radioactive elements in the core of the nuclear reactors, even when they are turned off. The term

\[
\epsilon_{4} \frac{T_{\text{on}} n_{i}^{\text{exp}}}{T_{\text{off}} N_{\text{tot}}}
\]

has been included to take into account this contribution to the spectrum.

Both types of events are influenced by the same average oscillation probability over each energy bin, \( \tilde{P}_{i}(\theta_{13}, \Delta m_{31}^{2}) \).

Additionally, the three background sources, \( \epsilon_{1}, \epsilon_{2}, \) and \( \epsilon_{3} \), mentioned in the description of Table III, are taken into account in Eq. (10).
Because we use the double-Chooz data to determine the best fit for \( \sin^2(2\theta_{13}) \) and \( \Delta m_{31}^2 \) without assuming an \textit{a priori} value for \( \Delta m_{31}^2 \), the pull associated with the correction to this parameter, \( e_s \), is not required anymore.

Therefore, the \( \chi^2 \) statistics (2) is a multiparametric function made of two oscillation parameters and seven pulls,

\[
\chi^2_{R+S} = \chi^2_R(\theta_{13}, \Delta m_{31}^2, e_i, e_a),
\]

\( i = 1, \ldots, 4 \) \( \alpha = a, b, c, \) (12)

The \( \Delta \chi^2_{R+S} \) function is defined as the difference between the \( \chi^2_{R+S} \) function and its absolute minimum.

**IV. CONFIDENCE REGIONS OF OSCILLATION PARAMETERS \( \theta_{13} \) AND \( \Delta m_{31}^2 \) WITH FAR DATA ONLY**

We report the minimization of the function \( \chi^2_{R+S} \) and its level curves considering the FCM \( M \) in Fig. 1. Figure 2 takes into account only the diagonal elements of the covariance matrix \( M \) (DCM). In both plots several local minimums are shown.

The absolute minimum (black star) in Fig. 1 has coordinates \((0.087, 27.043 \times 10^{-3} \text{eV}^2/\text{c}^4)\) in the \( \sin^2(2\theta_{13}) - \Delta m_{31}^2 \) plane and the \( \chi^2_{R+S} \) value of 37.17 for the FCM analysis. Another local minimum (white star) is \((0.090, 2.512 \times 10^{-3} \text{eV}^2/\text{c}^4)\) and its \( \chi^2_{R+S} \) value is 41.83. These points share close values for \( \sin^2(2\theta_{13}) \). Nevertheless their corresponding values for \( \Delta m_{31}^2 \) are significantly different. This effect is closely related to the existence of the energy bump of the neutrino spectrum. These points are listed in Table IV.

The absolute minimum obtained implies \( \Delta m_{31}^2 = 27.043 \times 10^{-3} \text{eV}^2/\text{c}^4 \). This value is 1 order of magnitude higher than those reported elsewhere. However, given the quasiperiodic nature of the \( \chi^2_{R+S} \) as a function of \( \Delta m_{31}^2 \), it can be argued that any one of the local minimums may be the right one, and then additional experimental data and/or improved models would be needed to discriminate between minimums. For this reason, in Sec. V we introduce...
TABLE IV. Oscillation parameters found with the $\chi^2_{R+S}$ statistics for FCM and DCM analysis. The local minimums reported for the $\chi^2_{R+S}$ statistics are closer to those reported by double-Chooz [2], and MINOS [12] than the absolute minimums. In all cases, the $\Delta m^2_{31}$ units are $10^{-3}$ eV$^2$/c$^4$.

|          | FCM Fig. (1) | DCM Fig. (2) |
|----------|--------------|--------------|
| Absolute minimum | $\chi^2_{m_3}/$D.O.F. | 37.17/39 | 40.07/39 |
| $\sin^2(2\theta_{13})$ | 0.087$^{+0.047}_{-0.046}$ | 0.091$^{+0.033}_{-0.029}$ |
| $\Delta m^2_{31}$ | 27.043$^{+1.153}_{-1.217}$ | 27.043$^{+1.456}_{-2.534}$ |
| First local minimum | $\chi^2_{m_3}/$D.O.F. | 41.83/39 | 43.34/39 |
| $\sin^2(2\theta_{13})$ | 0.090 | 0.085 |
| $\Delta m^2_{31}$ | 2.512 | 2.422 |

Results of MINOS [12]

$\Delta m^2_{31}$

2.44$^{+0.09}_{-0.10}$ (normal hierarchy)

2.35$^{+0.09}_{-0.10}$ (inverted hierarchy)

Results of double-Chooz [2]

$\sin^2(2\theta_{13})$

0.090$^{+0.032}_{-0.029}$

$\chi^2_{\text{min}}$/D.O.F.

52.2/40

FIG. 3. Confidence regions up to 68.27%, 90%, and 95.45% for $\chi^2_{R+S+M}$, Eq. (14). As a consequence of the addition of $\chi^2_{\text{MINOS}}$ to the statistics, the absolute minimum is discarded. In this way, the best fit is found at $\sin^2 2\theta_{13} = 0.092$, $\Delta m^2_{31} = 2.444 \times 10^{-3}$ eV$^2$/c$^4$ for FCM analysis, and $\sin^2 2\theta_{13} = 0.084$, $\Delta m^2_{31} = 2.444 \times 10^{-3}$ eV$^2$/c$^4$ for DCM analysis. The wider region corresponds to the full analysis, and therefore, this one has greater uncertainties (see Table V). For comparison purposes we introduce the Daya Bay data for the parameters $\sin^2 2\theta_{13}$ and $\Delta m^2_{31}$ up to 95.45% of C.L. [13]. All the analyses are consistent to each other.

we obtain $\sin^2(2\theta_{13}) = 0.084^{+0.030}_{-0.028}$ and $\Delta m^2_{31} = 2.444^{+0.187}_{-0.215} \times 10^{-3}$ eV$^2$/c$^4$, with a $\chi^2_{R+S+M}$ minimum value given as $\chi^2_{\text{min}} = 43.32/40$ d.o.f. for DCM analysis. These results are presented in Table V.

The confidence regions generated from the $\chi^2_{R+S+M}$ statistics are consistent with those published in [9] and shown in Fig. 3.

V. SPECTRAL BUMP EFFECTS

Figure 4 shows $\Delta \chi^2_{R+S}$ as a function of $\Delta m^2_{31}$ where $\sin^2(2\theta_{13})$ has been fixed at 0.087 and 0.091. These values correspond to the $\sin^2(2\theta_{13})$ coordinate of the absolute minimum obtained from the FCM and DCM analyses, respectively (Table IV). A succession of $\Delta \chi^2_{R+S}$ local minimums appear and are denoted as

$$\chi^2_{m_j} = \chi^2_{m_1}, \chi^2_{m_2}, \chi^2_{m_3}, \ldots$$

$$\chi^2_{m_j} = \Delta \chi^2_{R+S}(\Delta m^2_{31}|_{j}).$$

In the DCM analysis, the separation between two consecutive minimums of Fig. 4 is given as
Besides, we can identify the absolute minimum with $\chi^2_{m_3} = 0$ at $\Delta m^2_{31} = 27.043 \times 10^{-3} \text{ eV}^2/c^4$ and $\chi^2_{m_1} = 3.27$, with $\Delta m^2_{31} = 2.422 \times 10^{-3} \text{ eV}^2/c^4$, which is closer to the currently accepted $\Delta m^2_{31}$ value.

A weighted average of the neutrino energy can be defined as

$$\bar{\bar{E}}_\nu = \frac{1}{40} \sum_{i=1}^{40} \omega_i E_{\nu,i} = 4.232 \text{ MeV}, \quad (18)$$

where $\omega_i$ is the percentage of the observed IBD in each energy bin.

Substituting this value into the term $\sin^2(1.27 \Delta m^2_{31} \bar{\bar{E}}_\nu)$, we found that it vanishes when $\Delta m^2_{31} = 0.012 \text{ eV}^2/c^4$. This value is approximately equal to the average of $\lambda_1, \lambda_2, \text{ and } \lambda_3$. The small variation of these values may be attributed to the complex dependence of the $\chi^2_{R+S}$ on the squared sine function and to the average value of $\bar{\bar{E}}_\nu$ used.

The Far detector results alone can be used to discuss how the spectral bump around 5 MeV in the neutrino spectrum affects the $\Delta m^2_{31}$ fit and how the distribution of $\chi^2_{m_j}$ might change.
The origin of the energy bump is still undetermined, as discussed by [2,14]. The distortion seems to be hardly correlated to the reactor flux. This hypothesis was tested by the double-Chooz collaboration finding that the number of reactors on has influence on the distortion rate.

The pattern of minima $x^2_{m}$, is sensitive to the energy bump changes. As an example, we introduce a hypothetical source of rector neutrinos, given by $\eta_i \approx x_i^{-1}$ added to the prediction in the energy bump. As a consequence, the oscillatory behavior of the $\chi^2$ functions remains, but the $\Delta m_{31}^2$ can diverge 2 order of magnitude higher than expected or even fall into the order set by MINOS Fig. 5. Note that when $\xi = 5\%$, the $\Delta m_{31}^2$ is still 1 order of magnitude higher than expected, and diverges 2 orders of magnitude when $\xi = 10\%$, but when $\xi = 20\%$ the difference of squared masses falls into $8.2 \times 10^{-3} \text{eV}^2/\text{c}^4$.

Thus, the effect of the spectrum distortion is relevant but its source is unknown. If we want to obtain both parameters simultaneously, it is necessary to change our point of view, suppressing the energy bump as is discussed in the next section. This is encouraging to perform a unified analysis with other experiments.

VI. CONFIDENCE REGIONS OF OSCILLATION PARAMETERS $\theta_{13}$ AND $\Delta m_{31}^2$ WITH FAR + NEAR DATA

Although the Near detector was built in 2016, only preliminary results have been published [8]. These preliminary double-Chooz two-detector results can be used as input to the formalism presented in Secs. II and III.

A direct comparison between two sets of data (a data-data analysis) has been considered to cancel the spectrum distortion for the determination of the oscillation parameters.

In order to perform a data-data analysis we are restricted to compare only the Far II to the Near data from [8]. In particular, we propose a $\chi^2_{1}$ statistics defined as

$$\chi^2_{1} = \sum_{i=1}^{40} \left( \frac{N^{\text{obs}}_{\text{Far},i} - \Omega_i N^{\text{obs}}_{\text{Near},i} \tilde{P}_{i}(\theta_{13}, \Delta m_{31}^2, L_{\text{Far}/\text{Near}})}{\sigma_i^{(1)}} \right)^2,$$

where $N^{\text{obs}}_{\text{Far}/\text{Near}}$ are the observed number of IBD candidates at the Far/Near detector in the bin with energy $E^i$, $\Omega_i$ is a weight factor, and $\tilde{P}_{i}(\theta_{13}, \Delta m_{31}^2, L_{\text{Far}/\text{Near}})$ is the averaged survival probability over each energy bin at the Far/Near detector.

This statistics suppresses the use of the prediction of the unoscillated reactor neutrino signal spectrum $N_{\text{Near/Far}}^{\text{exp}}$ at the Near/Far detector.

Another way to define a data-data analysis is

$$\chi^2_{2} = \sum_{i=1}^{40} \left( \frac{N^{\text{exp}}_{\text{Far},i} - N^{\text{exp}}_{\text{Near},i}}{\Omega_i \sigma_i^{(2)}} \right)^2,$$

where

\begin{equation}
\begin{aligned}
\chi^2_{1} &= \frac{53.4}{40}, \\
\chi^2_{2} &= \frac{42.1}{40}, \\
\sin^2(2\theta_{13}) &= 0.140^{+0.047}_{-0.043}, \\
\Delta m_{31}^2 &= 2.63^{+0.33}_{-0.55} \times 10^{-3} \text{eV}^2/\text{c}^4.
\end{aligned}
\end{equation}

Thus, the effect of the spectrum distortion is relevant but its source is unknown. If we want to obtain both parameters simultaneously, it is necessary to change our point of view, suppressing the energy bump as is discussed in the next section. This is encouraging to perform a unified analysis with other experiments.

TABLE VI. Oscillation parameters found with the $\chi^2_{1}$ and $\chi^2_{2}$ statistics using Far II and Near data from [8]. The $\Delta m_{31}^2$ units are $10^{-3} \text{eV}^2/\text{c}^4$. Notice in this case, the $\Delta m_{31}^2$ values obtained do not differ very much from those expected. The uncertainties are given by the 90\% C.L. regions presented in Figs. 6 and 7. These results can be directly compared with those on Tables IV and V.

| $\chi^2_{1}$  | $\chi^2_{2}$  |
|-------------|-------------|
| Absolute minimum $\chi^2/D.O.F.$ | $\chi^2/D.O.F.$ |
| $\sin^2(2\theta_{13})$ | $\sin^2(2\theta_{13})$ |
| $\Delta m_{31}^2$ | $\Delta m_{31}^2$ |
| 0.140$^{+0.047}_{-0.043}$ | 2.63$^{+0.33}_{-0.55}$ |
| 0.095$^{+0.053}_{-0.053}$ | 2.63$^{+0.98}_{-1.15}$ |

where $N^{\text{exp}}_{\text{Far}/\text{Near},i} = n^{\text{exp}}_{\text{Far}/\text{Near},i} \tilde{P}_{i}(\theta_{13}, \Delta m_{31}^2, L_{\text{Far}/\text{Near}}).$ This results from Eq. (10) when the background sources and the residual contribution are neglected.

The minimization of both data-data statistics leads to $\sin^2(2\theta_{13}) = 0.140^{+0.047}_{-0.043}$ and $\Delta m_{31}^2 = 2.63^{+0.33}_{-0.55} \times 10^{-3} \text{eV}^2/\text{c}^4$ for $\chi^2_{1}$, and for $\chi^2_{2}$, $\sin^2(2\theta_{13}) = 0.095 \pm 0.053$ and $\Delta m_{31}^2 = 2.63^{+0.98}_{-1.15} \times 10^{-3} \text{eV}^2/\text{c}^4$. These results are summarized in Table VI.

By means of the data-data analyses, the influence of the spectral distortion for the $\Delta m_{31}^2$ determination is highly suppressed. Figure 6 shows the 68.27\%, 90\%, and 95.45\% C.L. regions. Three main points are remarkable.

(i) Data-data analyses no longer show two disjoint regions as the $\chi^2_{R+S}$ in Sec. III,

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{68.27\%, 90\%, and 95.45\% C.L. regions for $\chi^2_{1}$ and $\chi^2_{2}$ for $\Delta m_{31}^2$ and best fit. Through data-data analyses the spectral bump effect in the $\Delta m_{31}^2$ determination is highly suppressed. Even when the oscillatory behavior is still present, the $\Delta m_{31}^2$ is fully defined now; this is shown in Fig. 7.}
\end{figure}
Secs. II and III, in addition to the data-data statistics of this data from [8] were used. In fact, the formalism described in regions are wider in some sense based on the double-Chooz Far detector analysis only.

DCM analysis, which is in some sense a zero statistical error χ for those cases, can be used to analyze the double-Chooz two-minima, as can be seen in Fig. 7. It is important to recall that in this section, preliminary results to those published by the double-Chooz collaboration only.

This work represents a useful tool to build a unified analysis of double-Chooz, Daya Bay, and RENO, as suggested in [15] and [16], even without solving the spectrum bump problem.

VII. CONCLUSIONS

The proposed χR+S statistical analysis yields consistent results to those published by the double-Chooz collaboration using Far data. The approach followed allows us to generate the confidence regions for the oscillation parameters Δm231 and sin2(2θ13) shown in Figs. 1 and 2.

The effect of the nondiagonal elements of the covariance matrix on the oscillation parameters can be compared with DCM analysis, which is in some sense a zero statistical error case based on the double-Chooz Far detector analysis only.

It is observed that in the FCM analysis the confidence regions are wider in sin2(2θ31), and therefore have greater uncertainties.

Each one of the FCM and DCM analyses reports the existence of a Δm231 absolute minimum, corresponding to a Δm231 value, which is inconsistent with the MINOS Δm231 value. In fact, the double-Chooz Far data do not provide by themselves enough evidence to perform a squared mass difference Δm231 estimation with the data available before 2016. However the first local minimum agrees with MINOS Δm231 value, as shown in Fig. 4.

In order to force the first local minimum to become the absolute minimum we introduced the additional term (13), in χR+S. Hence by minimizing the χR+S+M we got the best fit parameters, sin2(2θ13) = 0.084 ± 0.030 and Δm231 = 2.444 ± 0.187 × 10−3 eV2/c2, as can be seen in Table V.

In Fig. 3 we have established the confidence regions for neutrino oscillation parameters θ13 and Δm231 from double-Chooz Far data.

In Sec. IV we have introduced a hypothetical source of reactor neutrinos to show how the spectrum distortion affects the oscillatory behavior of the χ2 functions and the Δm231 value. We found that a correction of 20% in the expected spectrum distortion, independently of its source, corrects the order of magnitude of Δm231, as indicated in Fig. 5.

To cancel the spectrum distortion in the determination of the oscillation parameters, we performed two data-data analyses, using preliminary two-detector data. In both cases, the Δm231 values obtained are not so different than those currently accepted by the community as shown in Figs. 6 and 7 and Table VI.

Data-data analyses no longer show two disjoint regions as the χR+S in Sec. III. Also the value of Δm231 found does not differ by 1 or more orders of magnitude with respect to MINOS and the whole analysis is independent of external information.
The formalism described in Secs. II and III in addition to the data-data statistics from Sec. V can be used to analyze the two-detector double-Chooz data to determine both $\sin^2(2\theta_{13})$ and $\Delta m^2_{31}$ without any restrictions from other experiments. In this way, this work extends the facilities of the double-Chooz experiment by allowing us to measure two oscillation parameters, $\Delta m^2_{31}$ and $\sin^2(2\theta_{13})$.

This work might contain elements of a future unified analysis with other experiments, such as Daya Bay and RENO even with the spectrum bump problem.

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