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# The weak mixing angle from low energy neutrino measurements: A global update

B.C. Cañas<sup>a</sup>, E.A. Garcés<sup>b</sup>, O.G. Miranda<sup>a,\*</sup>, M. Tórtola<sup>c</sup>, J.W.F. Valle<sup>c</sup><sup>a</sup> Departamento de Física, Centro de Investigación y de Estudios Avanzados del IPN, Apdo. Postal 14-740, 07000 Ciudad de México, Mexico<sup>b</sup> Instituto de Física, Universidad Nacional Autónoma de México, Apdo. Postal 20-364, 01000 Ciudad de México, Mexico<sup>c</sup> AHEP Group, Institut de Física Corpuscular – C.S.I.C./Universitat de València, Parc Científic de Paterna, C/Catedratic José Beltran 2, E-46980 Paterna (València), Spain

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## ABSTRACT

Taking into account recent theoretical and experimental inputs on reactor fluxes we reconsider the determination of the weak mixing angle from low energy experiments. We perform a global analysis to all available neutrino–electron scattering data from reactor antineutrino experiments, obtaining  $\sin^2 \theta_W = 0.252 \pm 0.030$ . We discuss the impact of the new theoretical prediction for the neutrino spectrum, the new measurement of the reactor antineutrino spectrum by the Daya Bay collaboration, as well as the effect of radiative corrections. We also reanalyze the measurements of the  $\nu_e - e$  cross section at accelerator experiments including radiative corrections. By combining reactor and accelerator data we obtain an improved determination for the weak mixing angle,  $\sin^2 \theta_W = 0.254 \pm 0.024$ .

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## 1. Introduction

The weak mixing angle is a fundamental structural parameter of the Standard Model (SM) and it has been measured with great precision at high energies [1]. At low energies, except for atomic physics measurements [2], its determination has always been a difficult task, especially in neutrino experiments. On the one hand reactor antineutrino scattering off electrons reported results indicating a relatively large value of the weak mixing angle [3,4], without a strong statistical significance. The importance of a new measurement of this fundamental parameter in the low energy region has been stressed in various works and several proposals have been discussed in this direction [5–7]. On the other hand, the interaction of neutrinos with quarks at NuTeV energies gave measurements that appeared to be in disagreement with the SM [8], although a recent evaluation of the sea quark contributions suggests agreement with the Standard Model predictions [9,10].

Reactor neutrino experiments have provided a useful tool for measuring antineutrino scattering off electrons over at least four decades [11] and more recent studies of this process have led to

improved measurements [4,12–14]. On the other hand one expects that new results may be reported in the near future, for instance by the GEMMA experiment [15] which would help improving the current determinations of the weak mixing angle. Moreover, the MINERVA Collaboration has reported first neutrino–electron elastic scattering measurement, providing an important restriction on the relevant neutrino flux, useful to future neutrino beams operating at multi-GeV energies [16].

Recently, a reevaluation of the reactor antineutrino energy spectrum [17,18] has revived the issue of the possible existence of a light sterile neutrino [19]. In this work, we study the impact of the new predicted reactor spectrum on the evaluation of the weak mixing angle. In order to have a more reliable result we will also include the effect of radiative corrections upon the neutrino–electron scattering. We will discuss the interplay between the impact of the new reactor spectrum and the radiative corrections, showing that the overall effect is a shift towards the Standard Model prediction for the weak mixing angle. In order to reach this conclusion we analyze the available neutrino–electron scattering data from the reactor experiments based at the Kuo Sheng (TEXONO) [4,20], Bugey (MUNU) [21,12], Rovno [13] and Krasnoyarsk [14] sites.<sup>1</sup> We have also included accelerator experiments

\* Corresponding author.

E-mail addresses: [bcorduz@fis.cinvestav.mx](mailto:bcorduz@fis.cinvestav.mx) (B.C. Cañas), [egarces@fisica.unam.mx](mailto:egarces@fisica.unam.mx) (E.A. Garcés), [OmarMiranda@fis.cinvestav.mx](mailto:OmarMiranda@fis.cinvestav.mx) (O.G. Miranda), [mariam@ific.uv.es](mailto:mariam@ific.uv.es) (M. Tórtola), [valle@ific.uv.es](mailto:valle@ific.uv.es) (J.W.F. Valle).URL: <http://astroparticles.es/> (J.W.F. Valle).<http://dx.doi.org/10.1016/j.physletb.2016.08.047>0370-2693/© 2016 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP<sup>3</sup>.<sup>1</sup> Notice that we are not including the pioneering Reines reactor experiment of Ref. [11]. The lack of detailed publicly available information prevents an improved re-analysis of these data including radiative corrections in the cross section.

in our analysis, such as the measurements from LAMPF [22] and LSND [23]. These are sensitive to the scattering of electron neutrinos with electrons, providing complementary information to reactor experiments. As a result we obtain a more precise determination for the weak mixing angle.

## 2. The neutrino electron scattering measurement

### 2.1. Reactor experiments

In order to perform an analysis of the reactor antineutrino data scattering off electrons it will be necessary to compute the expected number of events and compare it with the experimental results through a statistical analysis. In this section we describe this procedure. The number of events per energy bin for each experiment is, in general, given by

$$N_i = n_e \Delta t \int \int_{T'_i}^{T'_{i+1}} \lambda(E_\nu) \frac{d\sigma(E_\nu, T)}{dT} R(T, T') dT' dT dE, \quad (1)$$

where  $\lambda(E_\nu)$  corresponds to the antineutrino spectrum and  $R(T, T')$  denotes the energy resolution function associated to the detector. This function accounts for possible differences between the observed electron recoil energy  $T'$  and its true value  $T$ , and it is parameterized as

$$R(T, T') = \frac{1}{\sqrt{2\pi}\sigma} \exp\left\{-\frac{(T - T')^2}{2\sigma^2}\right\}, \quad (2)$$

with  $\sigma = \sigma(T) = \sigma_0 \sqrt{T/\text{MeV}}$ . The differential weak cross section for antineutrino–electron scattering, at tree level, can be expressed as

$$\frac{d\sigma(E_\nu, T)}{dT} = \frac{G_F^2 m_e}{2\pi} \left[ (g_V - g_A)^2 + (g_V + g_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (g_V^2 - g_A^2) \frac{m_e T}{E_\nu^2} \right], \quad (3)$$

where  $E_\nu$  is the incoming neutrino energy,  $G_F$  is the Fermi constant,  $m_e$  is the electron mass and  $T$  is the electron recoil energy. At tree level, the coupling constants  $g_V$  and  $g_A$  are given by

$$g_V = \frac{1}{2} + 2 \sin^2 \theta_W, \quad g_A = \frac{1}{2}. \quad (4)$$

Although the tree level expression in Eq. (3) is useful to show the main dependence on the weak mixing angle, we will consider radiative corrections for the scattering of neutrino and antineutrino off electrons in all our calculations. In particular, we will follow closely the prescriptions derived in Refs. [24,25] where the radiative corrections are included taking the value of the weak mixing angle at the  $Z$  peak in the  $\overline{\text{MS}}$ -scheme and some energy-dependent functions to include the effect of running with the scale.

We now proceed to describe the procedure used to re-evaluate the weak mixing angle from reactor antineutrino data including radiative corrections. First of all, in order to calculate the expected number of events for antineutrino electron scattering off electrons as given by Eq. (1), we first need a model that predicts the produced reactor antineutrino flux. Recently, a new evaluation of the reactor antineutrino spectrum has appeared in the literature [17, 18], claiming that the previous predictions were underestimating the total reactor antineutrino flux by approximately 3%.<sup>2</sup> The new

reactor antineutrino spectrum is parametrized by a combination of order five polynomial functions given by

$$\lambda(E_\nu) = \sum_\ell f_\ell \lambda_\ell(E_\nu) = \sum_\ell f_\ell \exp\left[\sum_{k=1}^6 \alpha_{k\ell} E_\nu^{k-1}\right], \quad (5)$$

where  $f_\ell$  is the fission fraction for the isotope  $\ell \equiv {}^{235}\text{U}, {}^{239}\text{Pu}, {}^{241}\text{Pu}$  and  ${}^{238}\text{U}$ , at the reactor under study. The values of the coefficients  $\alpha_{k\ell}$  for energies above 2 MeV can be found at the original references [17,18]. Here we will follow the prescriptions in Ref. [17]. For smaller energies we use the reactor antineutrino spectrum given at Ref. [27].

After calculating the expected number of events at a given reactor experiments, we perform a statistical analysis that, comparing the predictions with the actually number of observed events, will give us a determination of the weak mixing angle value. We start the description of the  $\chi^2$  analysis chosen with the treatment of the systematic uncertainties for the antineutrino reactor spectrum. In order to quantify the systematical uncertainties coming from the reactor anti-neutrino flux, we follow the diagonalization method for the covariance matrix discussed in [28]. We take into account the errors of the  $\alpha_{k\ell}$  coefficients,  $\delta\alpha_{k\ell}$ , and their corresponding correlation matrix,  $\rho_{kk'}^\ell$ . The covariance matrix in terms of these quantities can be written as

$$V_{kk'}^\ell = \delta\alpha_{k\ell} \delta\alpha_{k'\ell} \rho_{kk'}^\ell. \quad (6)$$

With this parameterization, the systematic error in the number of events associated to the reactor antineutrino flux is given by

$$(\delta N_\ell^v)^2 = \sum_{kk'} \frac{\partial N_\ell^v}{\partial \alpha_{k\ell}} \frac{\partial N_\ell^v}{\partial \alpha_{k'\ell}} V_{kk'}^\ell. \quad (7)$$

Note that for the numerical analysis it is better to work with the diagonal form of the covariance matrix. To this end, we introduce the new coefficients,  $c_{k\ell}$ , defined as

$$\alpha_{k\ell} = \sum_{k'} \mathcal{O}_{k'k}^\ell c_{k'\ell}, \quad (8)$$

where the rotation matrix  $\mathcal{O}^\ell$  is given by

$$\mathcal{O}^\ell V^\ell (\mathcal{O}^\ell)^T = \text{diag}[(\delta c_{k\ell})^2]. \quad (9)$$

Thus, the new phenomenological parametrization of the flux in Eq. (5) can be rewritten as

$$\lambda_\ell(E_\nu) = \exp\left[\sum_{k=1}^6 c_{k\ell} p_k^\ell(E_\nu)\right], \quad (10)$$

where  $p_k^\ell(E_\nu)$  is a polynomial of  $E_\nu$  given by

$$p_k^\ell(E_\nu) = \sum_{k'=1}^6 \mathcal{O}_{kk'}^\ell E_\nu^{k'-1}. \quad (11)$$

With all these ingredients we can now define the  $\chi^2$  function we will use in our statistical analysis as

$$\chi_{\text{reactor}}^2 = \sum_{ij} (N_i^{\text{theo}} - N_i^{\text{exp}}) \sigma_{ij}^{-2} (N_j^{\text{theo}} - N_j^{\text{exp}}), \quad (12)$$

where the expected number of events  $N_i^{\text{theo}}$  takes into account the contributions from all the isotopes

$$N_i^{\text{theo}} = N_i^{235} + N_i^{238} + N_i^{241} + N_i^{239}, \quad (13)$$

and  $\sigma_{ij}^2$  is given as

<sup>2</sup> See Ref. [26] for a recent review on antineutrino reactor spectra.

**Table 1**

Summary of the measured  $\bar{\nu}_e - e$  scattering cross sections and the corresponding  $\sin^2 \theta_W$  values obtained at the displayed reactor experiments.

Experiment	$E_\nu$ (MeV)	T (MeV)	Published cross-section	Reported $\sin^2 \theta_W$
TEXONO [4]	3.0–8.0	3.0–8.0	$[1.08 \pm 0.21 \pm 0.16] \cdot \sigma_{SM}$	$0.251 \pm 0.031 \pm 0.024$
MUNU [12]	0.7–8.0	0.7–2.0	$[1.07 \pm 0.34]$ events/day	...
Rovno [13]	0.6–8.0	0.6–2.0	$[1.26 \pm 0.62] \times 10^{-44}$ cm <sup>2</sup> /fission	...
Krasnoyarsk [14]	3.2–8.0	3.3–5.2	$[4.5 \pm 2.4] \times 10^{-46}$ cm <sup>2</sup> /fission	$0.22_{-0.8}^{+0.7}$

$$\sigma_{ij}^2 = \Delta_i^2 \delta_{ij} + \sum_{\ell} \delta N_i^{\ell} \delta N_j^{\ell}, \quad (14)$$

where  $\Delta_i$  corresponds to the statistical uncertainty for the energy bin  $i$  and  $\delta N_i^{\ell}$  is the contribution from the isotope  $\ell$  to the systematic error in the number of events at the same bin. This is calculated as follows

$$\begin{aligned} \delta N_i^{\ell} &= \sum_k \delta c_{k\ell} \frac{\partial N_i^{\ell}}{\partial c_{k\ell}} \\ &= \sum_k \delta c_{k\ell} \int \int_{T'_i}^{T'_{i+1}} \lambda_{\ell}(E_\nu) p_k^{\ell}(E_\nu) \frac{d\sigma(E_\nu, T)}{dT} \\ &\quad \times R(T, T') dT' dT dE_\nu. \end{aligned} \quad (15)$$

Once we have set all the necessary tools for our analysis we will describe in the next section the particular features of each reactor experiment and we will present our results for the re-evaluation of the weak mixing angle.

## 2.2. Accelerator experiments

Besides the reactor data, in this analysis we will include the observation of neutrino scattering off electrons in accelerator experiments. In particular, we will use data from the LAMPF [22] and LSND [23] experiments. In this case, we will use as observable to fit the average cross section at the experiment, given by

$$\sigma^{theo} = \int \int \lambda(E_\nu) \frac{d\sigma(E_\nu, T)}{dT} dT dE_\nu, \quad (16)$$

where  $\lambda(E_\nu)$  is the electron neutrino flux coming from pion decay [22,23] and the differential cross section for neutrino electron scattering is calculated as

$$\begin{aligned} \frac{d\sigma(E_\nu, T)}{dT} &= \frac{G_F^2 m_e}{2\pi} \left[ (g_V + g_A)^2 + (g_V - g_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 \right. \\ &\quad \left. - (g_V^2 - g_A^2) \frac{m_e T}{E_\nu^2} \right]. \end{aligned} \quad (17)$$

The statistical analysis of the neutrino accelerator data will be performed by using the following  $\chi^2$  function

$$\chi_{\text{accel}}^2 = \sum_{i=1}^2 \frac{(\sigma_i^{theo}(\sin^2 \theta_W) - \sigma_i^{exp})^2}{(\Delta_i)^2}, \quad (18)$$

where the subindex  $i = 1, 2$  stands for the LAMPF and LSND experiment, respectively. For the uncertainties we have included the statistical and systematic errors on the reported cross section, added in quadrature, as an uncorrelated error,  $\Delta_i$ . To test our simulation, we have checked that the reported  $1\sigma$  region for  $\sin^2 \theta_W$  is well reproduced with our simulation once we ignore radiative corrections, as it was done at the original references.

## 3. Antineutrino–electron scattering at reactors

### 3.1. Summary of reactor data

In this section we summarize the main features of the reactor antineutrino experiments relevant in our analysis.

- **TEXONO.** The latest experimental data from TEXONO were reported as a set of ten energy bins ranging from 3 to 8 MeV in electron kinetic recoil energy [20]. The fuel proportion at the reactor ( $^{235}\text{U}$ : $^{239}\text{Pu}$ : $^{238}\text{U}$ : $^{241}\text{Pu}$ ) was taken as (0.55:0.32:0.07:0.06) and the energy resolution function width equal to  $\sigma = 0.0325\sqrt{T}$  [20]. The data analysis of the TEXONO collaboration adopted the reactor antineutrino spectrum reported in Ref. [29].
- **MUNU.** In the case of the antineutrino electron scattering measurements performed by the MUNU collaboration [21], the reactor fission fractions were reported to be (0.54:0.33:0.07:0.06). The antineutrino spectrum originally considered for neutrino energies above 2 MeV was the one reported in Ref. [29] as well, while the reactor antineutrino spectrum in Ref. [27] was adopted for lower energies. The uncertainty in the electron kinetic recoil energy reconstruction was parameterized with a resolution width given by  $\sigma(T) = 0.08 T^{0.7}$  [30]. Experimental measurements of the antineutrino–electron reaction were presented in one single bin with electron recoil energy from 0.7 to 2 MeV, with a total of  $1.07 \pm 0.34$  counts per day (cpd) observed, in agreement with the expectations of  $1.02 \pm 0.10$  cpd.
- **Rovno.** The Rovno experiment [13], measured the electron–antineutrino cross section at low recoil electron energies, in the range from 0.6 to 2 MeV. For low energy antineutrinos they also used the theoretical prescription for the antineutrino spectrum reported in Ref. [27] while for energies above 2 MeV, the resulting antineutrino spectrum for  $^{235}\text{U}$  was taken from [31]. No information was given about the energy resolution function. The Rovno experiment reported a measured cross section for neutrino scattering by electrons equal to  $\sigma_W = (1.26 \pm 0.62) \times 10^{-44}$  cm<sup>2</sup>/fission [13].
- **Krasnoyarsk.** This experiment observed the scattering of reactor antineutrinos with electrons for an electron recoil energy window in the range between 3.15 and 5.175 MeV, with a reported weak differential cross section given by  $\sigma_W = (4.5 \pm 2.4) \times 10^{-46}$  cm<sup>2</sup>/fission for  $\sin^2 \theta_W = 0.22$  [14]. As in the case of the Rovno experiment, the initial neutrino flux coming from the  $^{235}\text{U}$  chain, as given in Ref. [31], was considered as the only antineutrino source.

### 3.2. Reactor data analysis with new antineutrino spectrum prediction

We show in Table 1 a summary with the main details of the reactor experiments described above. Besides the range of energy explored at each experiment, we have also quoted the measured value for the electron–antineutrino cross section, as well as the value for the weak mixing angle, when reported.

**Table 2**

Weak mixing angle determinations obtained from reactor data using different assumptions for the antineutrino spectrum and radiative corrections, as indicated.

	Mueller spectrum	Radiative correc.	TEXONO	MUNU	Rovno	Krasnoyarsk
a)	–	–	$0.256^{+0.032}_{-0.036}$	$0.241^{+0.069}_{-0.088}$	$0.220^{+0.102}_{-0.158}$	$0.220^{+0.068}_{-0.1}$
b)	–	✓	$0.261^{+0.032}_{-0.036}$	$0.248^{+0.069}_{-0.088}$	$0.226^{+0.102}_{-0.156}$	$0.224^{+0.069}_{-0.1}$
c)	✓	–	$0.253^{+0.032}_{-0.036}$	$0.237^{+0.069}_{-0.088}$	$0.228^{+0.102}_{-0.157}$	$0.231^{+0.069}_{-0.1}$
d)	✓	✓	$0.258^{+0.032}_{-0.036}$	$0.244^{+0.068}_{-0.088}$	$0.235^{+0.102}_{-0.157}$	$0.235^{+0.069}_{-0.1}$

In a previous global analysis of reactor and accelerator neutrino-electron scattering data [3], the weak mixing angle value was found to be

$$\sin^2 \theta_W = 0.259 \pm 0.025. \quad (19)$$

Recently, an updated version of this analysis including the reactor data from TEXONO has reported a slightly improved determination of the weak mixing angle [32]

$$\sin^2 \theta_W = 0.249 \pm 0.020. \quad (20)$$

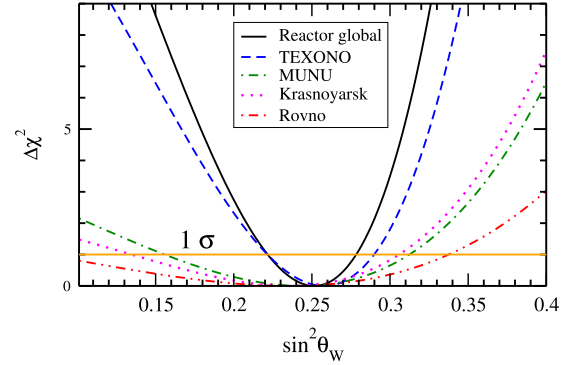
However, the role of radiative corrections in the weak cross section has not been discussed in these references. Both results lie above the theoretical predicted value in the  $\overline{\text{MS}}$ -scheme at the Z-peak [1]

$$\sin^2 \theta_W = 0.23126 \pm 0.00005. \quad (21)$$

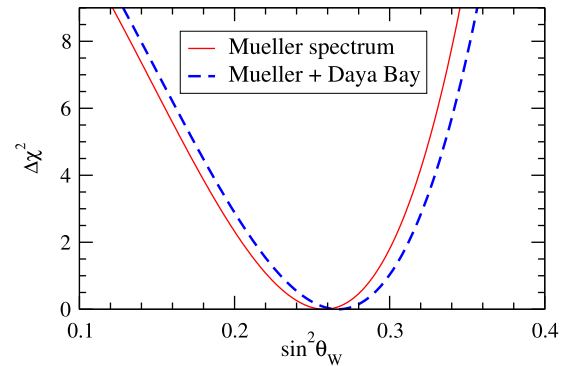
In order to illustrate how sensitive is the weak mixing angle to the presence of radiative corrections in the antineutrino–electron scattering cross section and to the considered reactor antineutrino spectrum, we present in Table 2 the central value of  $\sin^2 \theta_W$  obtained from each reactor antineutrino experiment, under the following assumptions: a) the original antineutrino spectrum considered in the original analysis of the experimental collaboration without radiative corrections, b) the original spectrum including radiative corrections, c) the new reactor antineutrino spectrum without radiative corrections, and d) the new reactor antineutrino spectrum including radiative corrections. In the first row we have reported the fit for the original spectrum used in each experiment without including radiative corrections. For the TEXONO case, notice that the value obtained in the absence of radiative corrections and with the original spectrum is in good agreement with the value reported by the collaboration,  $\sin^2 \theta_W = 0.251$  [4]. The next rows in the table show the separate effect of including either the new antineutrino spectrum or the radiative corrections. Finally, the last row shows our updated analysis with all the improvements included. One can see from this table that the impact of the new analysis is different for every experiment and some experiments give closer values to the expected theoretical predictions than others. For each  $\chi^2$  analysis we have taken into account the systematic error for the antineutrino energy flux and the statistical errors.

We have performed a combined statistical analysis using the data from the four reactor experiments described above. Our global determination for the weak mixing angle is shown in Fig. 1. We also give in the plot the  $\Delta\chi^2$  profiles obtained for each reactor experiment individually. As we can see, the most recent TEXONO data play a dominant role in the combined analysis, although the previous experiments shift the preferred value of  $\sin^2 \theta_W$  towards a slightly smaller central value:

$$\sin^2 \theta_W = 0.252 \pm 0.030. \quad (22)$$



**Fig. 1.** Determination of  $\sin^2 \theta_W$  from the combined analysis of reactor experiments (solid black line). The individual  $\Delta\chi^2$  profiles obtained from each single experiment are also shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

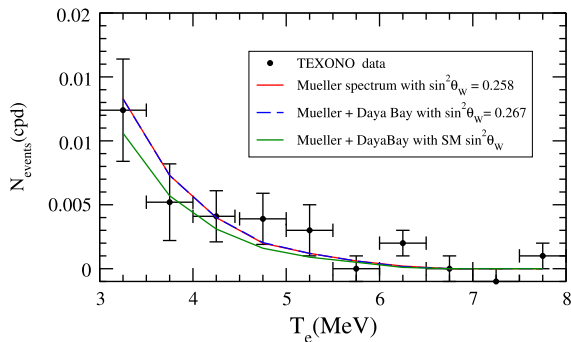


**Fig. 2.** Determination of  $\sin^2 \theta_W$  from TEXONO data using the original Mueller et al. spectrum (solid red line) and the Mueller spectrum corrected by the Daya Bay measurement of the total reactor antineutrino flux (dashed blue line).

### 3.3. Impact of the Daya Bay total reactor flux determination

Recently, the Daya Bay collaboration has published results on the measurement of the antineutrino spectrum using inverse beta decay [33]. There are indications that this measurement is not fully consistent with the recent theoretical predictions for the antineutrino flux produced at reactors [17,18]. Further theoretical developments and experimental measurements will be required in order to settle this point. While this question is solved, here we have estimated the impact of the recent Daya Bay reactor flux measurement on the extraction of the weak mixing angle from reactor data. As a first approximation, we correct the theoretical spectrum predicted by Mueller et al. [17] with the overall normalization factor 0.946, which is the central value for the ratio of measured to predicted flux, as reported by the Daya Bay collaboration [33,34].

The result of such an analysis for the TEXONO experiment is displayed in Fig. 2, where one can see that, if the Daya Bay result is confirmed, the resulting value of weak mixing angle shifts towards higher values.



**Fig. 3.** Expected event numbers in TEXONO using the Mueller et al. spectrum for the TEXONO  $\sin^2 \theta_W$  best fit value (solid red line). The blue dashed line corresponds to the best fit analysis obtained using the Mueller spectrum modified by the Daya Bay flux measurement. The green solid line shows the prediction for the SM weak mixing angle,  $\sin^2 \theta_W = 0.23126$ . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 3**

Published  $\nu_e - e$  scattering cross section and  $\sin^2 \theta_W$  measurements at accelerator experiments. The error combines the systematic and statistical uncertainties in both cases.

Experiment	$E_\nu$ (MeV)	$\sigma^{\text{exp}} [10^{-45} \text{ cm}^2]$	Reported $\sin^2 \theta_W$
LAMPF [22]	7–50	$[10.0 \pm 1.5 \pm 0.9] E_\nu$	$0.249 \pm 0.063$
LSND [23]	20–50	$[10.1 \pm 1.1 \pm 1.0] E_\nu$	$0.248 \pm 0.051$

$$\sin^2 \theta_W = 0.267 \pm 0.033 \quad (\text{Mueller} + \text{DayaBay spectrum}). \quad (23)$$

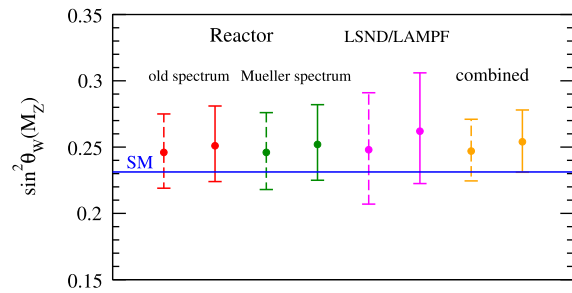
One sees that the TEXONO data correlates the flux normalization with the value of the weak mixing angle, so that a decrease in the total normalization prefers a higher value of  $\sin^2 \theta_W$ .

In Fig. 3 we illustrate how the prediction of this analysis compares with the experimental data from TEXONO. We plot the expected number of counts per day in this experiment for three different assumptions: i) using the Mueller et al. spectrum [17] with the best fit value of the weak mixing angle obtained from the TEXONO data analysis,  $\sin^2 \theta_W = 0.258$ , as in Section 3.2; ii) the reactor antineutrino spectrum predicted by Mueller et al. with the correction factor indicated by the Daya Bay measurements for the obtained best fit value  $\sin^2 \theta_W = 0.267$ ; iii) the Mueller reactor antineutrino spectrum corrected by the Daya Bay result for the SM prediction for the weak mixing angle at the Z-peak in the  $\overline{\text{MS}}$  scheme:  $\sin^2 \theta_W = 0.23126$ . We can see from this figure how TEXONO data are in tension with the SM prediction for the weak mixing angle, favoring higher values for  $\sin^2 \theta_W$ . Further neutrino electron scattering measurements will be necessary in order to have a better understanding both of the neutrino reaction, as well as the reactor spectrum.

#### 4. Neutrino–electron scattering at accelerator experiments

Besides studying electron scattering with electron antineutrinos coming from reactors, in this work we have also analyzed the case of electron neutrino scattering off electrons for two experiments that used a spallation source. In this case the electron neutrino flux came from pion decay and the differential cross section was measured at the LAMPF [22] and LSND [23] experiments. Here we analyze the results on the neutrino–electron scattering cross section reported by these experimental collaborations, given in Table 3, using the procedure described in section 2. After minimizing the  $\chi^2$  function defined in Eq. (18) for both experiments, we obtained a new value for the weak mixing angle without radiative corrections:

$$\sin^2 \theta_W = 0.248 \pm 0.042. \quad (24)$$



**Fig. 4.** Values of the weak mixing angle from the global analysis of reactor experiments using the original (old) or the Mueller reactor spectrum with (continuous error bars) and without (dashed error bars) radiative corrections. The combined result from the accelerator experiments LSND and LAMPF is shown for comparison, as well as the result of combining all the low-energy measurements. The horizontal line corresponds to the Standard Model prediction in the  $\overline{\text{MS}}$  scheme.

The inclusion of radiative corrections to the neutrino–electron cross section results in a somewhat higher value for the weak mixing angle:

$$\sin^2 \theta_W = 0.261 \pm 0.042. \quad (25)$$

These results are given in Fig. 4 and compared with the results obtained from reactor experiments. They are also used to obtain a global determination of the weak mixing angle from the combination of reactor and accelerator data that will be discussed in the next section.

#### 5. Discussion and conclusions

We have performed an updated analysis of the reactor and low-energy accelerator neutrino experiments. In particular, we considered reactor neutrino scattering off electrons. We have studied the impact of the new reactor spectrum on the extracted value of the weak mixing angle. The combined analysis shows an agreement with the theoretical prediction, although more precise measurements in this energy range would be highly desirable. As illustrated in Table 2, using the new spectrum prediction shifts the value for the weak mixing angle differently for each reactor experiment. We show in Fig. 4 the expected value of  $\sin^2 \theta_W$  for a combined analysis of all reactor experiments. We can see that in this case the inclusion of the Mueller spectrum has a mild effect in the determination of  $\sin^2 \theta_W$ .

We have also quantified the role of radiative corrections, both for neutrino and antineutrino scattering off electrons. The importance of radiative corrections can be seen in Fig. 4 where we show the determination of the weak mixing angle with and without radiative corrections from reactor and accelerator measurements of the (anti)neutrino–electron scattering cross section. As one can see from the figure, the inclusion of radiative corrections increases the value of the weak mixing angle. From the combined analysis of all the experiments considered, we obtain an improved determination of the weak mixing angle

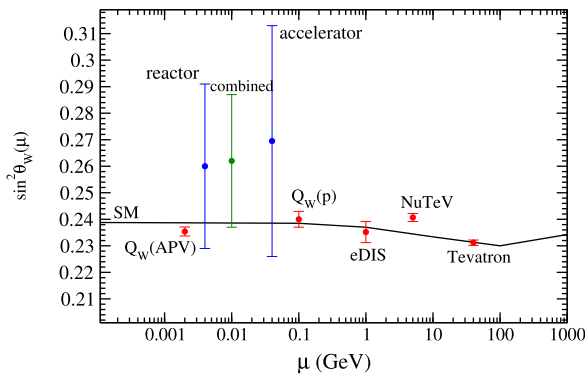
$$\sin^2 \theta_W = 0.254 \pm 0.024. \quad (26)$$

This should be compared with other determinations at different energy ranges, much more precise, as seen in Fig. 5. In order to illustrate how this result compares with other low energy measurements, we can take, as a first approximation, the weak mixing angle at low energies as given as [35]

$$\sin^2 \theta_W(0)_{\overline{\text{MS}}} = \kappa(0)_{\overline{\text{MS}}} \sin^2 \theta_W(M_Z)_{\overline{\text{MS}}} \quad (27)$$

with  $\kappa(0) = 1.03232$  [35]. This approach can give an idea of the level of precision that has been reached by neutrino electron scat-





**Fig. 5.** Values of the weak mixing angle, in the  $\overline{\text{MS}}$  scheme, from various experimental determinations, according to Ref. [1]. For comparison, we extrapolate our results to the low-energy limit as discussed in the text.

tering and it is shown in Fig. 5, where we compile the most important measurements already reported [1].

Beyond the modest improvement we have obtained in our analysis, one should stress the importance of further more refined experiments in electron (anti)neutrino–electron scattering, so as to improve the low energy determination of the weak mixing angle from neutrino experiments. Indeed, proposals such as GEMMA [15] may provide better Standard Model probes at low energies. On the other hand, they could also open a window for important probes of neutrino properties and the structure of the electroweak theory, since the experimental technique itself seems not yet fully optimized [5]. Moreover, they should provide improved reactor antineutrino flux measurements. Indeed, various proposals for improving neutrino electron scattering measurements have been discussed in the literature, either using reactor neutrinos or a proton beam [6]. Another possibility would be the use of an upgraded version of the Borexino detector [36], such as envisaged in the framework of a LENA-like proposal [37], either in combination with solar neutrinos, or with an artificial neutrino source [7].

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