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LIMITS ON NEUTRINO OSCILLATIONS DERIVED FROM THE RATIO
OF NEUTRAL- TO CHARGED-CURRENT CROSS-SECTIONS OF NEUTRINOS
MEASURED AT THE CERN SPS NBB

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ABSTRACT

We present an analysis, in terms of neutrino oscillations, of the recent measurements of the ratio R of neutral-current to charged-current neutrino cross-sections performed by the CDHS and CHARM Collaborations at the CERN Super Proton Synchrotron narrow band beam. The measurements were aimed at the determination of $\sin^2 \theta_w$. Our analysis is based on the observation that ν_μ oscillations would decrease the number of interactions with a muon in the final state. The effect of oscillations on R can be studied, comparing the actual measurements with the value of R predicted by an independent measurement of $\sin^2 \theta_w$. Limits on $\nu_\mu - \nu_e$, $\nu_\mu - \nu_\tau$, and $\nu_\mu - \nu_x$ oscillations are presented. They refer to a region of high mass squared difference of the two oscillating neutrinos ($\Delta m^2 > 3 \text{ eV}^2$). For high Δm^2 the limits on the mixing angle θ are very restrictive. In particular, for the transition $\nu_\mu - \nu_x$ ($x \neq e, \tau$) they represent the best available results for large intervals in Δm^2 .

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Two Collaborations, CDHS [1] and CHARM [2], have recently performed precise measurements of R , the ratio of the neutral-current (NC) to charged-current (CC) cross-sections of neutrinos using a 160 GeV/c neutrino narrow band beam (NBB) at the CERN Super Proton Synchrotron (SPS). The electroweak mixing parameter $\sin^2 \theta_w$ has been determined via the relation

$$R = NC/CC = 1/2 - \sin^2 \theta_w + 5/9 \sin^4 \theta_w (1 + r), \quad (1)$$

where r is the ratio of $CC \bar{\nu}$ to $CC \nu$ cross-sections. In this paper we will use a value of $\sin^2 \theta_w$ independent of neutrino oscillations (e.g. the one determined at the CERN $p\bar{p}$ Collider) to predict, through relation (1), the value of R . The experimental definition of the NC and CC samples relies on the difference between interactions with or without a muon in the final state. Oscillations of ν_μ , the main constituent of the NBB, would decrease the number of interactions with a muon in the final state, therefore affecting the value of R . The measured values of R can then be used to set limits on neutrino oscillations. This method differs from the usual techniques adopted to search for neutrino oscillations [3], i.e. appearance or disappearance of a given neutrino flavour. Owing to the high precision of the measurements of R , it allows the setting of limits which are comparable, and in some cases better, than the ones obtained with dedicated experiments. We note straight away that no evidence for oscillations is found as follows from the agreement, within errors, between the value of $\sin^2 \theta_w$ extracted from the measurements of R and those measured at the $p\bar{p}$ Collider [4].

We consider two-component admixtures with the probability of a ν_μ of energy E (GeV) oscillating to a neutrino of a different type (ν_a) after a distance L (km) given by

$$P(\nu_\mu \rightarrow \nu_a) = \sin^2 2\theta \times \sin^2(1.27 \Delta m^2 L/E), \quad (2)$$

where θ is the mixing angle and Δm^2 (eV^2) is the mass squared difference between the two types of neutrino. Our analysis is sensitive to values of P of the order of a few per mille for high Δm^2 . Since the NBB has $\langle L \rangle \approx 0.6$ km and $\langle E \rangle \approx 50$ GeV, the sensitivity on Δm^2 is limited to $\Delta m^2 > 3 \text{ eV}^2$.

To extract limits on neutrino oscillations one has to evaluate the change $\delta R(\Delta m^2, \sin^2 2\theta)$ induced on R by an oscillation with parameters Δm^2 and $\sin^2 2\theta$ and to compute R_p , the value of R predicted by an independent measurement of $\sin^2 \theta_w$.

The evaluation of δR requires a Monte Carlo simulation of the NBB. For this purpose we used a program set up by the CHARM Collaboration (see, for example, Ref. [5]). We also simulated the geometrical and kinematical acceptance of the CDHS and CHARM detectors. The different techniques adopted by the two experiments to define the NC and CC samples were taken into account. Three oscillation channels were considered: 1) $\nu_\mu - \nu_e$, 2) $\nu_\mu - \nu_\tau$, 3) $\nu_\mu - \nu_x$ (x stands for any, possibly unknown, flavour). The couplings to NC and CC were assumed to be independent of the neutrino flavour. The three channels affect R in different ways. A $\nu_\mu - \nu_e$ oscillation reduces the number of interactions with a muon in the final state, simultaneously increasing the number of muonless events because of the CC interactions of the ν_e . For $\nu_\mu - \nu_\tau$ oscillations the change in R is regulated by the ratio of CC cross-sections $\sigma_{\nu_\tau} / \sigma_{\nu_\mu}$ (different from unity because of the τ lepton mass) and by the decay mode of the τ lepton. The effect of $\nu_\mu - \nu_x$ oscillations is calculated, instead, assuming that such a transition only provokes the disappearance of interactions with a muon in the final state, with no increase of the NC sample; the corresponding limits are therefore the most conservative. All the above-described effects were considered in computing δR . For channel 1 the small ν_e component present in the NBB was also taken into account.

To predict R we assumed $\rho = 1$ [$\rho = m_W^2 / (m_Z^2 \cos^2 \theta_w)$] and the radiative corrections to be valid. We used a weighted average of

the $\sin^2 \theta_w$ values measured by the UA1 and UA2 Collaborations at the $p\bar{p}$ Collider: $\sin^2 \theta_w = 0.228 \pm 0.008$ [4]. However, since the measurements of the Z^0 mass at the Stanford Linear Collider (SLC) and at the CERN e^+e^- collider LEP will probably provide a determination of $\sin^2 \theta_w$ with much smaller error, we also computed the effect of using $\sin^2 \theta_w = 0.220, 0.228, 0.236$, with an error of 0.002. This corresponds to the assumption that the dominant error left will be due to uncertainties affecting the evaluation of the radiative corrections needed to extract $\sin^2 \theta_w$ from the measurement of the Z^0 mass^{*}). For a given $\sin^2 \theta_w$, eq. (1) could be used to evaluate R_p . However, small corrections, different for CDHS and CHARM, should be applied. For our needs it is sufficient to consider variations of R . Then one gets from eq. (1) the relation $d(R) = 0.64 \times d(\sin^2 \theta_w)$, which is valid for both experiments and also allows to transform errors on $\sin^2 \theta_w$ into errors on R ; R_p is then computed for each experiment, on the basis of the published measurements which are recalled hereafter:

$$R = 0.307 \pm 0.003 \text{ (exp.)} \quad (3)$$

$$\sin^2 \theta_w = 0.225 \pm 0.005 \text{ (exp.)} \pm 0.005 \text{ (theor.)} \quad (4)$$

for CDHS [1] and

$$R = 0.309 \pm 0.003 \text{ (exp.)} \quad (5)$$

$$\sin^2 \theta_w = 0.236 \pm 0.005 \text{ (exp.)} \pm 0.005 \text{ (theor.)} \quad (6)$$

^{*}) A large part of these uncertainties is due to the unknown mass of the top quark. Current calculations assume m_t in the range 30 to 100 GeV. This might be an underestimate. In this case, however, our limits on neutrino oscillation resulting from the comparison of the predicted and measured values of R would be conservative. This is because, for fixed m_{Z^0} , increasing values of m_t lead to smaller values of $\sin^2 \theta_w$ [4], and hence to higher R_p .

for CHARM [2]. Here we have combined quadratically the statistical and systematic errors on R . The resulting error corresponds to the 0.005 error on $\sin^2 \theta_w$ indicated as experimental. The error on $\sin^2 \theta_w$ indicated as theoretical is obtained combining quadratically the theoretical errors and the error due to the uncertainty on the charm-quark mass reported in refs. [1] and [2]. An error of 300 MeV on the charm-quark mass was assumed.

Having a procedure to compute R_p and δR , the 90% CL limits on the oscillation parameters Δm^2 and $\sin^2 2\theta$ are obtained imposing

$$\chi^2(\Delta m^2, \sin^2 2\theta) - \chi_{\min}^2 = 1.64$$

with the following definitions:

$$\chi^2 = (\Delta^2 R_{\text{CDHS}} + \Delta^2 R_{\text{CHARM}} - 2\rho_c \Delta R_{\text{CDHS}} \Delta R_{\text{CHARM}}) / \sigma^2 (1 - \rho_c^2)$$

$$\Delta R_{(\text{CDHS}, \text{CHARM})} = [R_p + \delta R(\Delta m^2, \sin^2 2\theta) - R]_{(\text{CDHS}, \text{CHARM})}.$$

The χ^2 is written so as to take into account differences in sensitivity between the two experiments. The error σ , which is the same for the two experiments, was computed combining quadratically the errors on the determination of $\sin^2 \theta_w$ in neutrino scattering [eqs. (4),(6)] with the error (0.002 or 0.008) affecting the $\sin^2 \theta_w$ value used to predict R . The correlation factor ρ_c was obtained considering that the experimental errors on R are almost independent for CDHS and CHARM, while all other errors affect the two experiments in the same way. One gets $\sigma = 0.0067$ and $\rho_c = 0.78$ when using the $\sin^2 \theta_w$ value of the $p\bar{p}$ Collider ($\sin^2 \theta_w = 0.228 \pm 0.008$), and $\sigma = 0.0046$ and $\rho_c = 0.52$ for the assumed error of 0.002 on the $\sin^2 \theta_w$ determination at the SLC and LEP.

Figures 1, 2 and 3 show the limits in the $\Delta m^2, \sin^2 2\theta$ plane resulting from our analysis for the transitions $\nu_\mu - \nu_e$, $\nu_\mu - \nu_\tau$, and $\nu_\mu - \nu_x$, respectively. In each graph curve (a) represents the

'present' limit, i.e. the one obtained using the results of the $p\bar{p}$ Collider. The 'future' limits, computed on the hypothesis of an error of 0.002 on $\sin^2 \theta_w$, are given by the curves (b), (c), and (d) for $\sin^2 \theta_w = 0.236$, 0.228, and 0.220, respectively [please note that curves (a) and (b) coincide].

Also shown are limits coming from other experiments. For $\nu_\mu - \bar{\nu}_e$ the experimental information is particularly rich [6] and we only show the limits obtained at BNL [7], the most restrictive in the high Δm^2 region. For $\nu_\mu - \nu_\tau$ the best results come from searches in bubble chamber [8] and emulsions [9] at FNAL. They are shown in fig. 2. The ν_μ disappearance, i.e. $\nu_\mu - \nu_x$ oscillations, has been studied in four experiments [10-13]. Their results are shown in fig. 3. All limits shown correspond to 90% CL.

From the results shown in figs. 1 to 3, we draw the following conclusions. The 'present' limits improve the constraints on $\nu_\mu - \nu_x$ oscillations in large intervals of Δm^2 (for this channel: $\Delta m^2 < 8 \text{ eV}^2$ for $\sin^2 2\theta = 1$, and $\sin^2 2\theta < 0.05$ asymptotically in Δm^2). They also give good information in the $\nu_\mu - \nu_\tau$ channel where, for high Δm^2 , only one experiment [9] gives better constraints. The 'future' limits, the ones obtained assuming an error of 0.002 on $\sin^2 \theta_w$, could improve the experimental information for all three oscillation channels, depending on the actual value of $\sin^2 \theta_w$.

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Figure captions

Fig. 1 The 90% CL limits on ν_μ - ν_e oscillations. The solid line (a) represents the results of this analysis obtained using $\sin^2 \theta_w = 0.228 \pm 0.008$. Dotted lines (b) [overlaid by solid line (a)], (c) and (d): limits obtained using $\sin^2 \theta_w = 0.236, 0.228$ and 0.220 ± 0.002 (see text). Dashed line: best result from earlier experiments (BNL [7]).

Fig. 2 The 90% CL limits on ν_μ - ν_τ oscillations. The solid line (a) represents the results of this analysis obtained using $\sin^2 \theta_w = 0.228 \pm 0.008$. Dotted lines (b) [overlaid by solid line (a)], (c) and (d): limits obtained using $\sin^2 \theta_w = 0.236, 0.228$, and 0.220 ± 0.002 (see text). Dashed lines: best results from earlier experiments (FNAL-BC [8] and FNAL-emulsions [9]).

Fig. 3 The 90% CL limits on ν_μ - ν_x oscillations. The solid line (a) represents the results of this analysis obtained using $\sin^2 \theta_w = 0.228 \pm 0.008$. Dotted lines (b) [overlaid by solid line (a)], (c) and (d): limits obtained using $\sin^2 \theta_w = 0.236, 0.228$, and 0.220 ± 0.002 (see text). Dashed lines: results from earlier experiments (CHARM [10], CDHS [11], CCFR [12], and Serpukhov [13]).

Fig. 1

Fig. 2

Fig. 3