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Observables sensitive to absolute neutrino masses. II

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In this followup to Phys. Rev. D **75**, 053001 (2007) , we report updated constraints on neutrino mass-mixing parameters, in light of recent neutrino oscillation data (KamLAND, SNO, and MINOS) and cosmological observations (WMAP 5-year and other data). We discuss their interplay with the final $0\nu2\beta$ decay results in ^{76}Ge claimed by part of the Heidelberg-Moscow Collaboration, using recent evaluations of the corresponding nuclear matrix elements, and their uncertainties. We also comment on the $0\nu2\beta$ limits in ^{130}Te recently set by Cuoricino and on prospective limits or signals from the Karlsruhe tritium neutrino experiment.

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I. INTRODUCTION

This paper is meant as a followup to the article [1] where, building upon previous work [2], we presented constraints on the neutrino mass-squared differences ($\delta m^2, \Delta m^2$) and mixing angles ($\sin^2\theta_{12}, \sin^2\theta_{23}, \sin^2\theta_{13}$), as well as on three observables sensitive to absolute ν masses: the effective mass m_β in single beta decay, the effective Majorana mass $m_{\beta\beta}$ in neutrinoless double beta ($0\nu2\beta$) decay, and the sum of ν masses Σ in cosmology—see [1–3] for notation and conventions. We update the results of [1] by including several new experimental inputs, largely presented or discussed at the recent *Neutrino 2008* conference [4].

II. NEUTRINO OSCILLATION UPDATES

The Kamioka liquid scintillator antineutrino detector (KamLAND) Collaboration has presented reactor $\bar{\nu}_e$ disappearance and geo-ν results for an exposure of 2.881 kTy [5], a factor $\sim$4 higher than the one we used in [1]. Following [5], the KamLAND spectrum analysis in [1,3] has been upgraded [6] to include the rates of geo-ν events from U and Th decay as low-energy nuisance parameters.

Results from the third phase of the Sudbury neutrino observatory (SNO-III) [7], recently presented at *Neutrino 2008* [4], have been included [6] in the form of two new integral determinations of the charged- and neutral-current event rates [7]. Other solar ν updates, with a minor impact in the global parameter estimate, include the latest Borexino results [8] and reevaluated GALLEX data [9]—see also [10].

The main injector neutrino oscillation search (MINOS) Collaboration has presented accelerator ν_μ disappearance data from 3.36×10^{20} protons on target [11], a factor of $\sim$2.6 larger than previously used in [1]. In the official MINOS data analysis [11], for any given energy profile of the ν_μ survival probability $P_{\mu\mu}(E_\nu)$, a "beam matrix" method is used to map the energy spectrum from near to far, and an independent near-far extrapolation method is used as a cross-check [12]. This approach can be fully implemented only within the Collaboration. For our purposes, we analyze the 18-bin energy spectrum ratio [11] by folding the function $P_{\mu\mu}(E_\nu, \Delta m^2, \sin^2\theta_{23}, \sin^2\theta_{13})$, with empirical energy resolution profiles, which mimic the near-far energy spectrum mapping of [12]. Normalization and energy scale systematics are treated as nuisance parameters.

In the limit $\theta_{13} \to 0$, our effective 2ν parameter fits reproduce very well the official ones as obtained by the KamLAND [5], SNO-III [7], and MINOS [11] Collaborations. In our global analysis, however, we treat θ_{13} as a free parameter.

Figure 1 displays our updated results on the mass-mixing parameters, in terms of standard deviations n_σ from the best fit ($n_\sigma = \sqrt{\Delta\chi^2}$ after χ^2 marginalization). Table I summarizes such results in numerical form. As compared with [1], the Δm^2 uncertainty is almost halved (by new MINOS data), and both the δm^2 and the $\sin^2 2\theta_{12}$ allowed ranges are reduced (by new KamLAND and SNO data). The range of $\sin^2\theta_{23}$ is almost unchanged. As discussed in [10], an intriguing new result is the preference for $\theta_{13} > 0$ at the level of $\sim 1.6\sigma$ (or, equivalently, $\sim$90% C.L.). Such an indication emerges from the combination

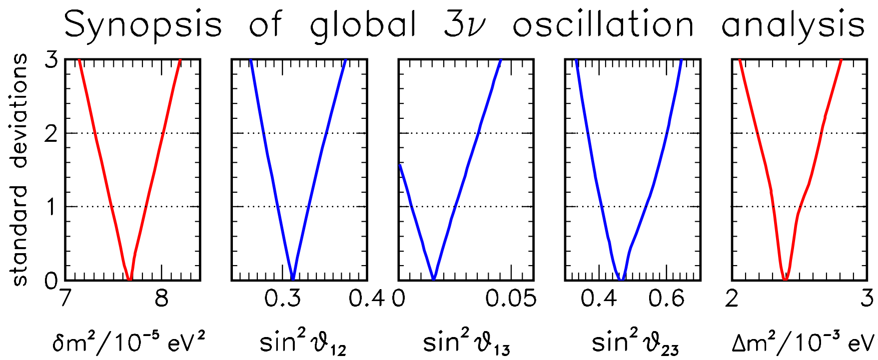

FIG. 1 (color online). Global 3ν oscillation analysis (2008): bounds on the mass-mixing oscillation parameters, in terms of standard deviations from the best fit. Note the 1.6σ preference for $\theta_{13} > 0$.

TABLE I. Global 3ν oscillation analysis (2008): best-fit values and allowed n_σ ranges for the mass-mixing parameters.

Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	7.67	0.312	0.016	0.466	2.39
1σ range	7.48–7.83	0.294–0.331	0.006–0.026	0.408–0.539	2.31–2.50
2σ range	7.31–8.01	0.278–0.352	<0.036	0.366–0.602	2.19–2.66
3σ range	7.14–8.19	0.263–0.375	<0.046	0.331–0.644	2.06–2.81

of two independent hints in favor of $\theta_{13} > 0$, each at the level of $\sim 1\sigma$: an older one, found in the atmospheric ν data analysis of [3], and a newer one, coming from the small difference between the best-fit values of $\sin^2 2\theta_{12}$ in KamLAND [5] and SNO [7]—a difference which is reduced for $\sin^2\theta_{13} \sim$ few%. Hereafter, as in [1,2], we shall show results at a conservative 2σ (95%) confidence level, in which case only an upper bound can be placed on θ_{13}.

Figure 2 shows the 2σ bounds implied by the above ν oscillation parameter constraints (for normal or inverted hierarchy) in the three planes charted by any two among the three observables $(m_\beta, m_{\beta\beta}, \Sigma)$. A measurement of any such quantity, coupled with the bounds in Fig. 2, provides "predictions" for the other two quantities [1–3].

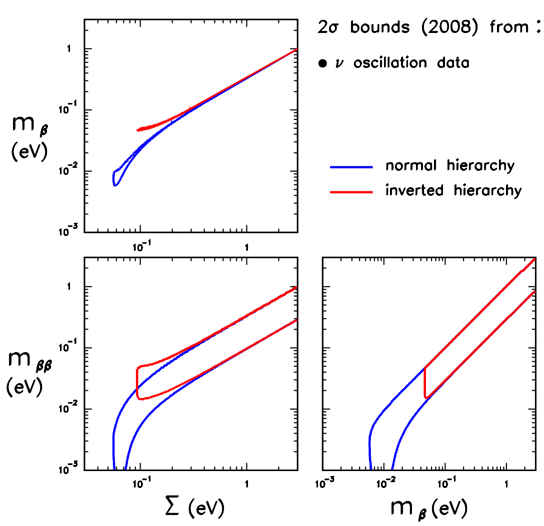

FIG. 2 (color online). Bands allowed at 2σ by neutrino oscillation data, in each of the three coordinate planes of the parameter space $(m_\beta, m_{\beta\beta}, \Sigma)$, for both normal and inverted hierarchy.

III. COSMOLOGY UPDATES

Within the standard cosmological model, the 5-year data recently released by Wilkinson microwave anisotropy probe (WMAP 5y) [13,14] constrain, by themselves, the sum of the ν masses Σ below 1.3 eV at 95% C.L. [13]. This limit can be strengthened in the sub-eV range by adding further cosmological data; for instance, the WMAP Collaboration finds $\Sigma < 0.61$ eV by adding baryonic acoustic oscillation (BAO) and type-Ia supernova (SN-Ia) data [14].

We consider five representative combinations of cosmological data, which lead to increasingly stronger upper limits on Σ: (i) cosmic microwave background (CMB) anisotropy data from: WMAP 5y [14], arcminute cosmology bolometer array receiver (ACBAR) [15], very small array (VSA) [16], cosmic background imager (CBI) [17], and BOOMERANG [18] experiments; (ii) the above CMB results plus the large-scale structure (LSS) information on galaxy clustering coming from the luminous red galaxies Sloan digital sky survey (SDSS) [19]; (iii) the above CMB results plus the Hubble space telescope (HST) prior on the value of the reduced Hubble constant $h = 0.72 \pm 0.07$ [20], and the luminosity distance SN-Ia data of [21]; (iv) the data in (iii) plus the BAO data from [22]; (v) the data in (iv) plus the small-scale primordial spectrum from Lyman-alpha (Lyα) forest clouds [23,24].

TABLE II. Representative cosmological data sets and corresponding 2σ (95% C.L.) constraints on the sum of ν masses Σ.

Case	Cosmological data set	Σ (at 2σ)
(i)	CMB	<1.19 eV
(ii)	CMB + LSS	<0.71 eV
(iii)	CMB + HST + SN-Ia	<0.75 eV
(iv)	CMB + HST + SN-Ia + BAO	<0.60 eV
(v)	CMB + HST + SN-Ia + BAO + Lyα	<0.19 eV

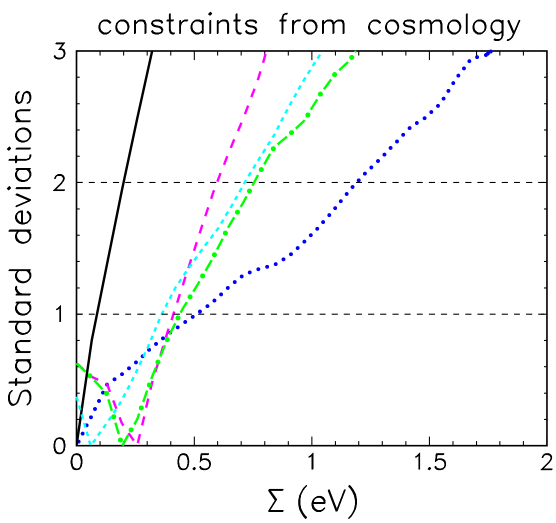

FIG. 3 (color online). Cosmological constraints on the sum of neutrino masses (Σ). Standard deviation curves for the five data sets in Table II: (i) (dotted line), (ii) (dashed line), (iii) (dotted-dashed line), (iv) (long-dashed line), and (v) (solid line).

Adopting the same procedure described in [1], based on the publicly available COSMOMC code [25], we find the upper limits on Σ summarized in Table II and in Fig. 3. The bound in Table II for case (i) is dominated by WMAP-5y data. The results for cases (i) and (iv) are in agreement with similar constraints presented in [13,14], respectively, even if the data sets considered here for BAO and SN-Ia are different. In Fig. 3, the slight preference for $\Sigma \neq 0$ at best fit for case (iv) [and case (i)], also found in [14], is not statistically significant. As in Ref. [1], we find that Lyα data have a strong impact on Σ, but their inclusion in global fits is debated [14] due to systematics still under scrutiny. The upper limits from cases (i)–(iv) (namely, $\Sigma <$ 0.6–1.2 eV) should be considered as more conservative. Including LSS data would not significantly modify case (v), which is dominated by Lyα data. In the following, we shall focus on the two extreme cases (i) and (v).

IV. $0\nu2\beta$ DECAY UPDATES

The final analysis of part of the Heidelberg-Moscow (HM) Collaboration reports a $0\nu2\beta$ signal in ^{76}Ge with half-life $T^{0\nu}_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ y (1σ errors) at a claimed C.L. $> 6\sigma$ [26]. The previously estimated $T^{0\nu}_{1/2}$ [27], as used in [1], was a factor of ~ 2 smaller. The claim is controversial, but the experimental sensitivity to the signal (if real) is no longer questioned [28].

From a theoretical viewpoint, the $0\nu2\beta$ nuclear matrix elements (NMEs) C_{mm} and uncertainties estimated via quasiparticle random phase approximations (QRPA) in [29] (as used in [1]) have been recently revised [30,31], especially to improve the so-called short-range correlations. We adopt for C_{mm} the central values and errors of [31], which agree with independent QRPA [32,33] and shell model [34] evaluations within $\sim 2\sigma$ (see Fig. 11 of [31] and related comments therein).

The effect of both the $T^{0\nu}_{1/2}$ and the NME updates for ^{76}Ge is to lower the central value—and to enlarge the errors—of the effective mass parameter $m^2_{\beta\beta} = m^2_e/C_{mm}T^{0\nu}_{1/2}$. By taking logs (in base 10) to linearize error propagation, we have $\log(T^{0\nu}_{1/2}/\mathrm{y}) = 23.35 \pm 0.16$ (2σ) from [26] and $\log(C_{mm}/\mathrm{y}^{-1}) = -12.82 \pm 0.48$ (2σ) from [31], so that

$$\log(m_{\beta\beta}/\mathrm{eV}) = -0.54 \pm 0.26 \qquad (\text{HM claim, } 2\sigma), \tag{1}$$

where the experimental error and the (dominant) theoretical error have been added in quadrature.

The Cuoricino experiment, which does not find $0\nu2\beta$ decay signals in ^{130}Te, quotes $T^{0\nu}_{1/2} > 3.1 \times 10^{24}$ y at 90% C.L. [28], or $T^{0\nu}_{1/2} > 2.5 \times 10^{24}$ y at 95% C.L. [35]. Using the latter limit as $\log(T^{0\nu}_{1/2}/\mathrm{y}) > 24.4$, and the ^{130}Te NME estimate $\log(C_{mm}/\mathrm{y}^{-1}) = -12.27 \pm 0.28(2\sigma)$ from [31], we get

$$\log(m_{\beta\beta}/\mathrm{eV}) < [-0.63, -0.07] \qquad (\text{Cuoricino, } 2\sigma), \tag{2}$$

where the range due to the 2σ uncertainty of the NME is explicitly reported.

A comparison of the corresponding $m_{\beta\beta}$ ranges (2σ)

$$0.16 < m_{\beta\beta}/\mathrm{eV} < 0.52 \qquad (\text{HM claim}), \tag{3}$$

$$0 \leq m_{\beta\beta}/\mathrm{eV} < 0.23 \qquad (\text{Cuoricino, ``favorable'' NME}), \tag{4}$$

$$0 \leq m_{\beta\beta}/\mathrm{eV} < 0.85 \qquad (\text{Cuoricino, ``unfavorable'' NME}), \tag{5}$$

shows that current Cuoricino data may or may not disfavor a fraction of the HM range for $m_{\beta\beta}$ at 2σ, depending on the (still quite uncertain) value of the ^{130}Te $0\nu2\beta$ NME. A similar conclusion (albeit with somewhat different preferred ranges for $m_{\beta\beta}$) has been reached in [28]. Therefore, the $0\nu2\beta$ claim [26] remains an open issue at present, and we shall consider the possibility that it corresponds to a real signal.

V. DISCUSSION

Figure 4 shows the regions allowed at 2σ in normal and inverted hierarchy (slanted bands) by the combination of oscillation results with the first data set in Table II (CMB), in the plane spanned by $(\Sigma, m_{\beta\beta})$. This is the most conservative case, with the weakest limits on Σ, and the largest overlap between the regions separately allowed by oscillation + CMB data and by the $0\nu2\beta$ claim. The results of a global χ^2 fit are shown as a thick black wedge in the upper right part of the figure. [The combination includes the current limit $m_\beta < 1.8$ eV (2σ) [1] which, however, provides only a minor contribution.] Such a global combination would correspond to nearly degenerate masses in the range

$$m_1 \simeq m_2 \simeq m_3 \in [0.15, 0.46]\ \text{eV} \qquad (2\sigma).$$

In this case (degenerate spectrum), the preferred range for effective neutrino mass in β decay would also be $m_\beta \in [0.15, 0.46]$ eV. In the upper half of this range, the Karlsruhe tritium neutrino (KATRIN) β^- experiment could make a 5σ discovery, according to the estimated sensitivity [36]. A 3σ evidence could still be found in KATRIN for $m_\beta \sim 0.3$ eV. Below this value, the sensitivity would be rapidly degraded, and only upper bounds could be placed for $m_\beta \lesssim 0.2$ eV [36]. The possibility of reaching a ~0.1–0.2 eV sensitivity with a different approach to β decay is being discussed [37].

If the cosmological data set (1) were replaced by the data sets (2)–(4) in Table II, the overlap region between the $0\nu2\beta$ band and the oscillation + cosmological bands in Fig. 4 would shrink (not shown) but would not disappear. Therefore, within the standard 3ν framework and the present uncertainties, the $0\nu2\beta$ claim clashes with oscillation + cosmological data only if the latter include Lyα data.

Figure 5 is analogous to Fig. 4 but refers to the fifth data set in Table II (all cosmological data, including Lyα). In this case, the allowed regions do not overlap and cannot be combined, since the relatively strong cosmological limit $\Sigma < 0.19$ eV implies $m_{\beta\beta} \lesssim 0.08$ eV, in contradiction with Eq. (3). Solutions to this discrepancy would require that either some data or their interpretation are wrong.

In conclusion, important pieces of information are being slowly added to the puzzle of absolute ν masses. In this followup to [1], we have discussed the most recent oscillation and nonoscillation updates in the field, after the recent *Neutrino 2008* conference [4]. Oscillation parameters are robustly constrained, and an intriguing indication for $\theta_{13} > 0$ emerges, as summarized in Fig. 1 and in Table I. Concerning nonoscillation observables, despite some recent experimental and theoretical progress, a coherent picture remains elusive. In particular, the $0\nu2\beta$ claim is still under independent experimental scrutiny, and it may be compatible (Fig. 4) or incompatible (Fig. 5) with the cosmological bounds (Table II), depending on data selection (especially Lyα). A confident assessment of the ν mass scale will require converging evidence from at least two of the three observables $(m_\beta, m_{\beta\beta}, \Sigma)$ within the bands allowed by oscillation data in Fig. 2.

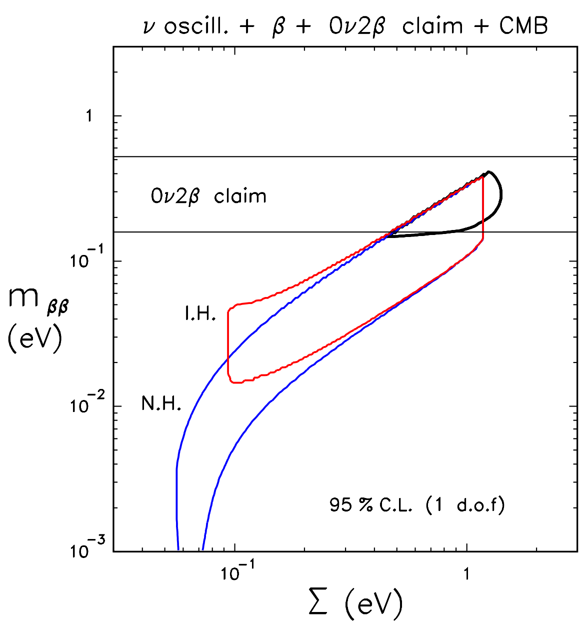

FIG. 4 (color online). Global combination of oscillation plus CMB data [case (i) in Table II] with the $0\nu2\beta$ decay claim, in the plane $(\Sigma, m_{\beta\beta})$.

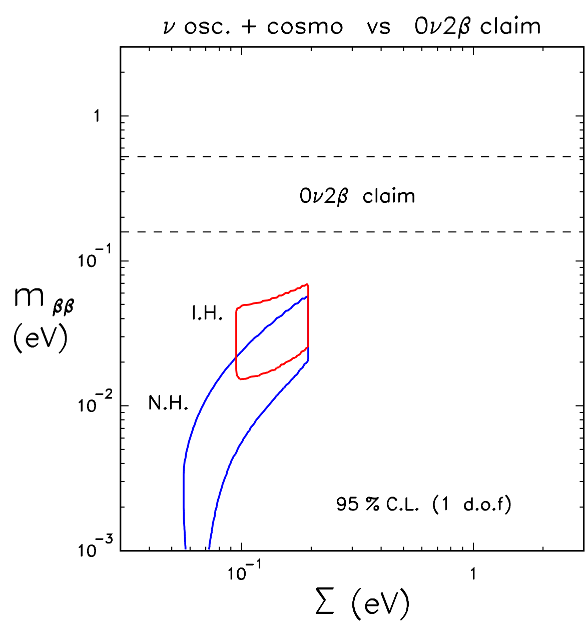

FIG. 5 (color online). Bounds from oscillation plus all cosmological data [case (v) in Table II], contrasted with the $0\nu2\beta$ decay claim, in the plane $(\Sigma, m_{\beta\beta})$.

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