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Neutrinos: projecting into the future

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Three areas of research are outlined in which substantial progress is expected. 1). Results of measurements of the 1-3 and 2-3 mixing confirm relation between the corresponding angles which follow from the equality $U_{PMNS} = V_{CKM}^{\dagger} U_X$, where U_X is the matrix of special form related to generation of small neutrino masses. The latter implies kind of quark-lepton symmetry or unification (GUT). 2). Future solar neutrino studies will be focused on detailed measurements of the Day- Night effect and upturn of spectrum. In long term perspective the Earth matter effects on the ^7Be line may be accessible with very interesting results. 3). The present-day hint of $\delta_{CP} \sim -\pi/2$ looks very intriguing (indicating certain symmetry). A possibility to measure the CP-phase by multi-megaton detectors of atmospheric neutrinos with low threshold (future upgrades of PINGU and ORCA) should be explored. Preliminary estimations look encouraging. Some guesses about future developments in other directions of neutrino physics are presented.

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1. Introduction: On predictions and CP-phase

It was unusually intense discussion among several members of IAC of the workshop about necessity of a talk on predictions of the CP phase. The argument is that in the past we had a bad experience with predictions of the 1-3 mixing: too much theory emphasis on zero (or very small) θ_{13}. So, predictions were largely misleading. Concerning CP violation, the point of view of experimentalist was that one can not say “model" predicts the phase. Already now all possible values of δ_{CP} from 0 to 2π are predicted. Theorists should wait (20 years?) till δ_{CP} is measured with good enough precision; this may help them to construct a model (not hundreds of models as it is now) which may predict something new. If accepted, this a bit arrogant point of view means complete failure of theory, which looks useless. In fact, the phase δ_{CP} is one of few unknown yet parameters for which predictions still can be done. What we will understand or prove without predictions?

Indeed, zero (small) 1-3 mixing was supported by Tri-bimaximal mixing (TBM) scheme and flavor symmetries. This was highly appreciated by large experimental community that wanted to develop neutrino factories. But even in the past it was spectrum of predictions of θ_{13} [1]. Furthermore, since the flavor symmetry is not exact, non-zero θ_{13} is generated anyway at some level and its exact value depends on specific model.

Then discussion proceeded with issues related to meaning of predictions, the role of input and theory in general. Of course, predictions require certain “input" which includes assumptions, measured values of parameters, etc., and the key point is quality and number of assumptions. Then, model is based on certain concepts, principles, symmetries, and all this goes eventually into predictions.

In this talk I will discuss predictions of the neutrino parameters (1-3 mixing and CP phase) as well as possible future developments. Projecting into the future, i.e. extrapolation of progress and advances we made, previous experience, lessons, etc.) requires at least two reference moments in time. One is obviously present day situation and another one (starting point), say, 7 years ago. 7 years ago in May of 2008 the XXIII Int. Conference on Neutrino physics and Astrophysics took place in Christchurch, New Zealand. I gave a talk "Neutrino -2008: Where are we? Where are we going?" [2] summarizing situation in 2008 and trying to extrapolate it to the future. Reading the paper in proceedings [2] is nice way to check if I can trust myself. Well, various statements made in 2008 are still valid.

This talk includes three stories: about the 1-3 mixing and its impact (sect. 2); about the solar neutrinos (sect. 3), and about the CP-violation (sect. 4). Some guesses about future developments, “Projection” will be described in sect. 5.

2. My story of the 1-3 mixing

At end of 90ies I exchanged of e-mails with L. A. Mikaelyan who was asking if there is any chance/reason that θ_{13} is close to the CHOOZ upper bound, and so it can be measured by the next generation of the reactor experiments? My answer was "Yes, it can be just at the corner” and I gave reference [3] where the relation

$$\sin^2\theta_{13} = A\frac{\Delta m^2_{21}}{\Delta m^2_{32}}, \qquad A = O(1) \tag{2.1}$$

has been obtained from "Naturalness" condition: absence of fine tuning of the elements of mass matrix (precise value is $A = 0.75$). The idea behind (2.1) is that θ_{13} is the parameter connecting the solar and atmospheric blocks of neutrino mass matrix. In both blocks the mixing is large, so, that the elements in the blocks, m_{solar} and m_{atm}, are of the same order (also the spectrum was assumed non-degenerate). Consequently, $\tan\theta_{13} \sim m_{solar}/m_{atm}$. Very small 1-3 mixing would be something special implying symmetry. Here we have typical dilemma: "usual versus special".

This was not the only prediction of large 1-3 mixing. Large θ_{13} follows from similar relations in the quark (usual) and lepton sectors

$$\sin\theta_{13} = q\sin\theta_{12}\sin\theta_{23},$$

where $q \approx 0.4$ [4]. Another idea was that θ_{13} is close or related to the Cabibbo angle θ_C [5].

Prediction from "Quark-Lepton Complementarity" [6] was

$$\sin\theta_{13} = \sin\theta_C\frac{1}{\sqrt{2}}(1 - V_{cb}\cos\alpha) + V_{ub}, \tag{2.2}$$

where α is some unfixed CP- phase. (In general, $1/\sqrt{2}$ should be substituted by $\sin\theta_{23}$.) The relation (2.2) is well supported by experiment. Indeed,

$$0.5\sin^2\theta_C = 2.54 \pm 0.02; \tag{2.3}$$

global fit gives [7] $\sin^2\theta_{13} = 2.18 \pm 0.10$; the Daya-Bay result (which dominates in the global fit), $\sin^2\theta_{13} = 2.15 \pm 0.13$ [8], is 15% or 3σ smaller than in (2.3). The latter can be reduced by 1) correction from V_{CKM} (2.2): $2.54 \to 2.11$ for $\alpha = 0$, 2) non-maximal 2-3 mixing: e.g. $2.54 \to 2.28$ for $\sin^2\theta_{23} = 0.50 \to 0.45$.

Prediction has been obtained using the following relation [9], [6], [10]:

$$U_{PMNS} = U^{\dagger}_{CKM}U_X, \tag{2.4}$$

where $U_{CKM} \sim V_{CKM}$, *i.e.* has similar hierarchical structure determined (as in Wolfenstein parametrization) by powers of $\lambda \approx \sin\theta_C$, whereas U_X can be fixed to reproduce correct lepton mixing angles. Since $U_{CKM} \sim I$, we have $U_X \sim U_{TBM}$.

Deeper sense of the relation (2.4) can be obtained in certain theoretical framework. The relation means that quarks and leptons "know" about each other, it implies a kind of quark-lepton unification or common flavor symmetry in the quark and lepton sectors. At the same time some additional physics should be involved in the lepton sector related to neutrino properties. U_{CKM} emerges from the Dirac matrices of charged leptons and neutrinos. U_X is related to mechanism that explains smallness of neutrino mass and its structure can be determined by certain symmetries. So, two types of new physics are involved:

1. The CKM-type new physics, which explains hierarchical Dirac masses and small mixing.

2. The Neutrino new physics, which leads to smallness of neutrino mass and nearly maximal lepton mixing.

The relation (2.4) can be realized in the seesaw type-I mechanism.

Another interpretation of the relation (2.4): $U_X = U_{TBM}$ is the mixing matrix in the flavor symmetry limit, whereas $U_{CKM} = V_{corr}$ is correction due to flavor symmetry breaking. This setup can be realized in the residual symmetry approach. With simple assumptions about V_{corr} various relations among mixing parameters ("sum rules") can be obtained [?]. Here connection to the quark sector is more complicated. and also, in general, there is no relations between mixing and masses.

Prediction of the 1-3 mixing (2.2) has been obtained in the following way. Suppose

$$U_X = U_{23}(\pi/2)U_{12} \tag{2.5}$$

with no (or very small) 1-3 rotation; U_{12} is arbitrary. Then according to (2.4)

$$U_{PMNS} = U_{CKM}^{\dagger} U_{23}(\pi/2)U_{12} \approx U_{12}(\theta_C)^{\dagger} U_{23}(\pi/2)U_{12}. \tag{2.6}$$

Reducing this mixing matrix to the standard parametrization form (essentially, permuting the 1-2 and 2-3 rotation which produces 1-3 rotation) gives (2.2). Various U_X can be taken: U_{BM} as in QLC [6], U_{TBM} as in TBM [13], U_{GR} as in Golden ratio scheme [14].

The fact that prediction agrees with data in the first approximation is in favor of the relation (2.4). The CKM -type corrections and allowed deviation of the 2-3 mixing from maximal lead to perfect agreement.

In this connection the following comment on the quark and lepton mixing is relevant. There is no convincing explanation of quark masses and mixing where information is complete. Can we then resolve the neutrino mass and mixing problem? Do efforts make sense? The answer is Yes, if

1. Neutrino mass generation and charged lepton as well as quark mass generation are independent.

2. We try to explain the difference of masses and mixing of leptons and quarks, and not masses and mixing completely. The relation (2.4) is along with this line.

3. We still hope (as it was in the past) that neutrinos will eventually uncover something simple and insightful which will allow us to solve the quark mass and mixing riddle too.

Finally, let me add remark on θ_{13} from solar neutrinos. At low energies (vaccum dominated part) and at high energies (matter dominated part) the survival probability depends on different combinations of the 1-2 and 1-3 mixing angles. So, degeneracy between them is broken and therefore the angles 1-2 and 1-3 can be determined simultaneously. Using solar neutrino data only an estimation $\sin^2\theta_{13} = 0.017 \pm 0.026$ [15] has been obtained in 2005. It is large and consistent with the present results from reactors.

3. Solar Neutrinos

Two important events have happened in 2014:

1. Direct detection of neutrinos from the primary pp- reaction by BOREXINO [16], where

$$P_{ee} \approx \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2 2\theta_{12}\right). \tag{3.1}$$

2. Statistically significant (about 3σ) observation of the Day-Night effect (D-N) by SuperKamiokande [17]. The significance is even higher if the SNO data are included.

Value of the D-N asymmetry is (almost 2 times) larger than what is expected for Δm^2_{21} determined from the global fit and dominated by KamLAND. Notice however that both zenith angle and energy dependences show fluctuation (clear deviations from what is expected). So, it is possible that large total asymmetry is also fluctuation.

Solar versus KamLAND data: About 2σ discrepancy has been found between Δm^2_{21} extracted from the solar neutrino data and from the global fit of all the data dominated by KamLAND. This is due to absence of the "spectral upturn" in the solar neutrino spectrum and larger D-N asymmetry. Possible solutions are (i) very light sterile neutrino whose parameters can be adjusted in such a way that it can produce a dip in the ν_e survival probability at 3 MeV, and (ii) non-standard interactions (NSI). Recall that the survival probability P_{ee} obeys scaling: It depends on the combination $\Delta m^2_{12}/V$, and no distance is involved. So, increase of V by factor 1.6 (which can be due to contribution of the diagonal NSI, V^d_{NS}) can bring Δm^2_{21} to agreement. Non-diagonal potential V^{nd}_{NS} leads also to distortion of the energy profile of the effect, P_{ee}, and not just to relative shift of the neutrino spectrum and the profile. This can produce flattening of the spectrum and also increase of the day-night asymmetry.

Even more exotic explanation is related to non-local interactions in the $\nu-$ portal which leads to CPT violation and shows up as $\nu - \bar{\nu}$ mass splitting [18]. Surprisingly the expected mass difference is just what is needed to reconcile the solar (neutrino) and the KamLAND (antineutrino) values of Δm^2_{21}.

Projecting to the far future one can imagine that exploration of oscillations of Be neutrinos in the Earth may become possible [19]. Recall that the present BOREXINO null result on the D-N asymmetry of the Be-neutrinos: $A_{DN} = 0.001 \pm 0.012(stat) \pm 0.007(syst)$ [20], is in agreement with the LMA expectations.

The features of these oscillations are related to narrow width, $\Gamma_{Be} = 1.6$ keV, and low energy: $E = 862.27$ keV, so that $\Gamma_{Be}/E = 1.86 \cdot 10^{-3}$. There is interesting coincidence of the width and the oscillatory period in the energy scale:

$$\Gamma_{Be} \sim \Delta E_T, \tag{3.2}$$

where

$$\Delta E_T = E\frac{l_\nu}{L} = E\frac{l_\nu}{2R_E \cos\eta}. \tag{3.3}$$

The observed signal is determined by oscillations averaged over the line. According to (**??**) with decrease of η ΔE_T decreases and the averaging of oscillations becomes stronger (see Fig. 1).

The main characteristics of the oscillations are the following:

1) here the mass eigenstates oscillate, which is pure matter effect, so that the oscillation effects are proportional to matter potential;

2) the oscillation depth is determined by

$$\varepsilon = \frac{2VE}{\Delta m^2_{21}} = 2.4 \cdot 10^{-3}\left(\frac{\rho}{2.7\text{g cm}^{-3}}\right); \tag{3.4}$$

3) the oscillation length equals $l_m \approx l_\nu[1 + c^2_{13}\cos 2\theta_{12}\varepsilon] = 28.5$ km.

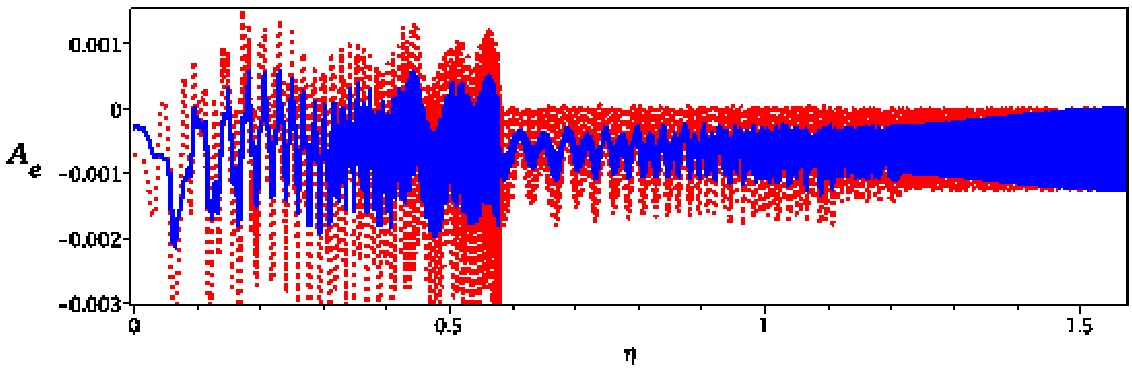

Figure 1: The relative variations of the electron neutrino flux as function of the nadir angle of the neutrino trajectory. Dotted (red) line shows A_e^0 without averaging; solid (blue) line is A_e which corresponds to the variations averaged over the energy spectrum of the ^{7}Be neutrinos.

The day - night variations of the ν_e-flux equal [19]

$$A_e = (P - P_D)/P_D = c_{13}^2 f(\Delta m_{21}^2, \theta_{12}, \theta_{13}) \frac{1}{2} \int_0^L dx V(x) \sin\phi^m(x \to L), \tag{3.5}$$

where $f = 0.43$. Here $\phi^m(x \to L)$ is the phase in matter acquired on the distance from a given point x to a detector. In the case of constant density we have

$$A_e = -c_{13}^2 \varepsilon f \sin^2\left(\frac{1}{2}\Delta_m L\right), \tag{3.6}$$

where $\Delta_m \equiv 2\pi/l_m$.

Variations of the Be-neutrino flux with nadir angle (time) are shown in Fig. 1. Important results of future studies may include

- establishing oscillations due to matter effect;
- detection of quasi-periodic variations of signal during night,
- determination of the Be-line width,
- precision measurements of Δm_{21}^2,
- tomography of the Earth interior.

Notice that with $l_m \sim 30$ km small scale structures at the surface (mountains, oceans, ..), non-sphericity of the Earth, density jumps in the mantle, shape of the core become important and accessible.

Searches for sterile neutrinos, especially for $\Delta m_{01}^2 \sim 10^{-7}$ eV^2 and $\sin^2 2\theta_s \sim 10^{-2}$ will be possible.

4. CP-violation

In 2008 the $e\mu-$ unitarity triangle for $\sin\theta_{13} = 0.15$ (i.e. exactly what we have now) and for $\delta_{CP} = 90^\circ$ has been shown (see Fig. 7 in [2]). This value of θ_{13} was assumed to be established after Double Chooze, Daya Bay, J-PARC - T2K, NOvA. For presently favored $\delta \sim -90^\circ$ the axis z should change the sign. It is still not clear what eventually the triangle will be useful (i) for illustration only (ii) as method to measure δ_{CP}, (iii) for test of unitarity?

Important results on the CP-phase can be obtained in the framework (2.4). If U_{CKM} is the only source of CP violation and no CP violation exists in U_x, we obtain the following relation [21]

$$\sin\theta_{13}\sin\delta_{CP} = (-\cos\theta_{23})\sin\theta^q_{13}\sin\delta^q. \quad (4.1)$$

Here the quark phase equals $\delta^q = -0.2\pi$, when quark mixing is reduced to the same parametrization as in the lepton sector. According to (4.1) $\sin\delta_{CP} \sim \lambda^3/s_{13} \sim \lambda^2$. That is, $\delta_{CP} \approx -\delta$, or $\pi + \delta$, where $\delta \equiv (s^q_{13}/s_{13})c_{23}\sin\delta^q$. There are two important implications of this result:

1. If the observed value of δ_{CP} deviates substantially from 0 or π, new sources of CP violation should exist beyond CKM.

2. New sources of CP violation (CPV) originating from U_x may have specific symmetries which lead to particular values of δ_{CP}, e.g. $-\pi/2$.

In general, any value of the phase can be obtained in the framework (2.4). In contrast to quarks for Majorana neutrinos the RH rotation that diagonalizes m_D becomes relevant and contributes to δ_{CP}.

Let us consider the CP violation from U_R in models with the Left-Right symmetry (which is plausible extension of the Standard Model). In the LR symmetric basis: $U_R = U_L \approx V^*_{CKM}$ and we assume that there is no other CPV in U_x. So, the CP violation in U_R is small ($\sim \lambda^3$). However, the seesaw mechanism itself can enhance this small effect, essentially due to strong hierarchy of mass eigenvalues of m_D [21]. So, the resulting δ_{CP} is large. While the contribution from the left rotation is suppressed, the one from the right rotation is enhanced.

Let us consider perspectives of determination of CP-phase. Presently the global fit gives preference of the phase $3\pi/2$ with respect to 0 at slightly larger than 1 σ. Maximally disfavored value of the phase is $\pi/2$. Genesis of determination of δ_{CP} in the global analysis of oscillation data can be traced from [7]:

1. Solar + Reactors + MINOS disappearance data alone have practically no sensitivity to δ_{CP}.

2. Adding T2K disappearance data does not add much.

3. Adding T2K appearance data yield the main contribution to sensitivity.

4. MINOS-appearance adds a bit, moreover for Normal Ordering (NO) the sign of effect depends on specific values of δ_{CP}.

5. Atmospheric neutrino data add more for NO and a bit for IO.

The expected sensitivity of running experiments has been estimated [22]. J-PARC beam upgrade will provide $7.8 \cdot 10^{21}$ p.o.t. by 2018, i.e. by factor 12 larger than now. (Presently J-PARC runs in the antineutrino mode, and due to smaller cross-section the increase of sensitivity will be modest). With this statistics the sensitivity to δ_{CP} at 90% C.L. or better is expected over $-115° < \delta_{CP} < -60°$ for NH and $50° < \delta_{CP} < 130°$ for IH if $\theta_{23} = 45°$ [22]. In particular, with all available by 2018- 2020 data (J-PARC- SK plus NOvA plus reactors) values of the phase $3\pi/2$ and 0 can be distinguished at $(2-3)\sigma$ level.

Planned dedicated experiment J-PARC- HK [23] , LBNF-DUNE [24], ESS (European spallation source, Lund) [25] can achieve $\approx (5-7)\sigma$ discrimination between $3\pi/2$ and 0 result in 2030 - 2035. In this connection (time, cost) it is worthwhile to consider also other possibilities to measure

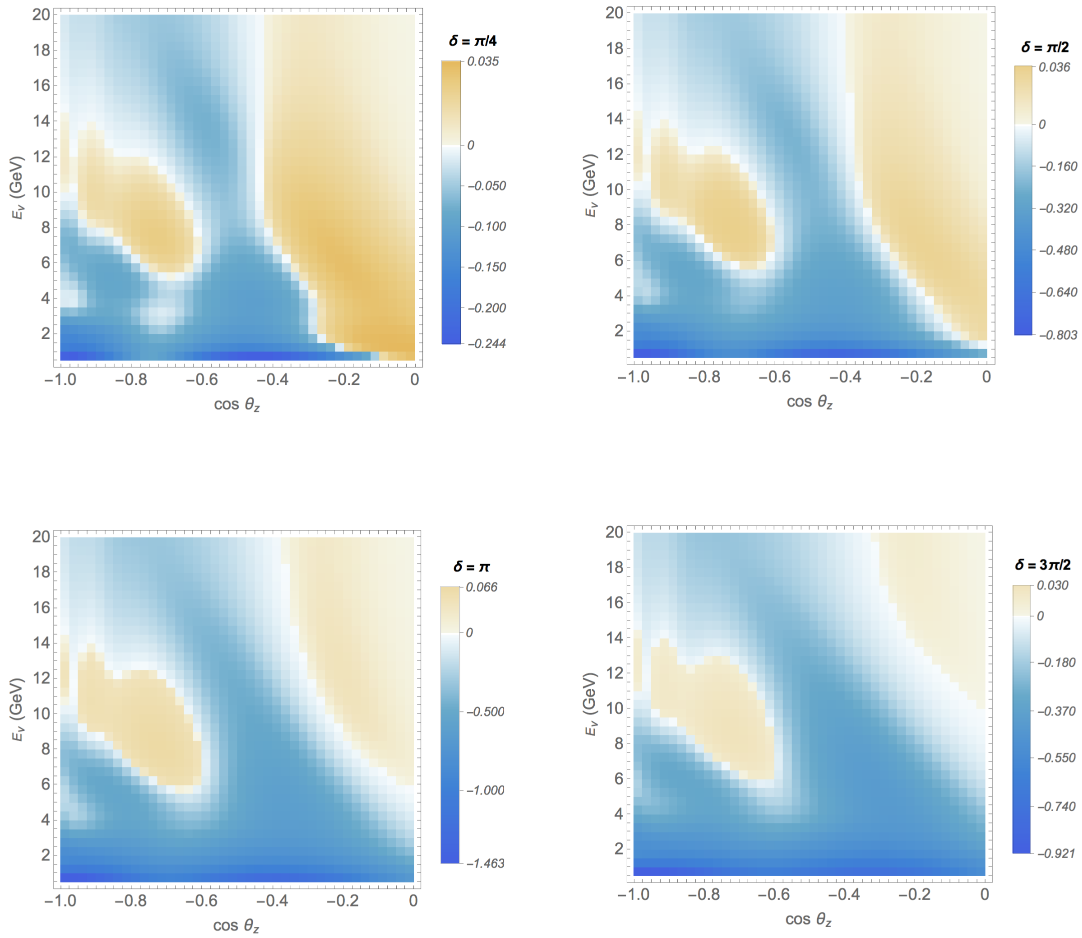

Figure 2: Distribution of the relative CP differences, S_{ij}, for $\nu_\mu + \bar{\nu}_\mu$ events in the $E_\nu - \cos\theta_z$ plane after 1 year of Super-PINGU exposure. The distributions are smeared over the energy and zenith angle of neutrinos. The smearing functions have been taken in the form of the PINGU reconstruction functions with widths reduced by factor $1/\sqrt{3}$.

δ_{CP}. In PINGU [26] and ORCA [27] the CP-violation effects are subleading, which actually helps to identify the mass hierarchy without significant degeneracy with δ_{CP}. Assuming that the hierarchy is known one can explore a possibility to use the atmospheric neutrinos and upgrades of PINGU and ORCA to measure δ_{CP} [28]. The key point is to further reduce the energy threshold down to (0.5 - 1) GeV. Indeed, it has been shown [28] that in spite of averaging over oscillations driven by the 1-3 mass splitting the CP violation effect increases with decrease of energy. With change of δ_{CP} the probabilities change (increase or decrease) in large interval of energies and zenith angles (lengths of trajectories) in the same way. Therefore, even bad angular resolution does not vanish sensitivity to the phase. The CP phase effect has opposite sign for $\nu_\mu - \nu_e$ and $\nu_\mu - \nu_\mu$ transitions. Therefore ,the flavor identification is crucial. The CP effect has also opposite signs for neutrinos and antineutrinos. Consequently, an effective separation of the neutrino and antineutrino signals (use inelasticity [32]) would enhance the sensitivity. Clearly, better energy and angular resolutions will help, also reducing effect of systematics.

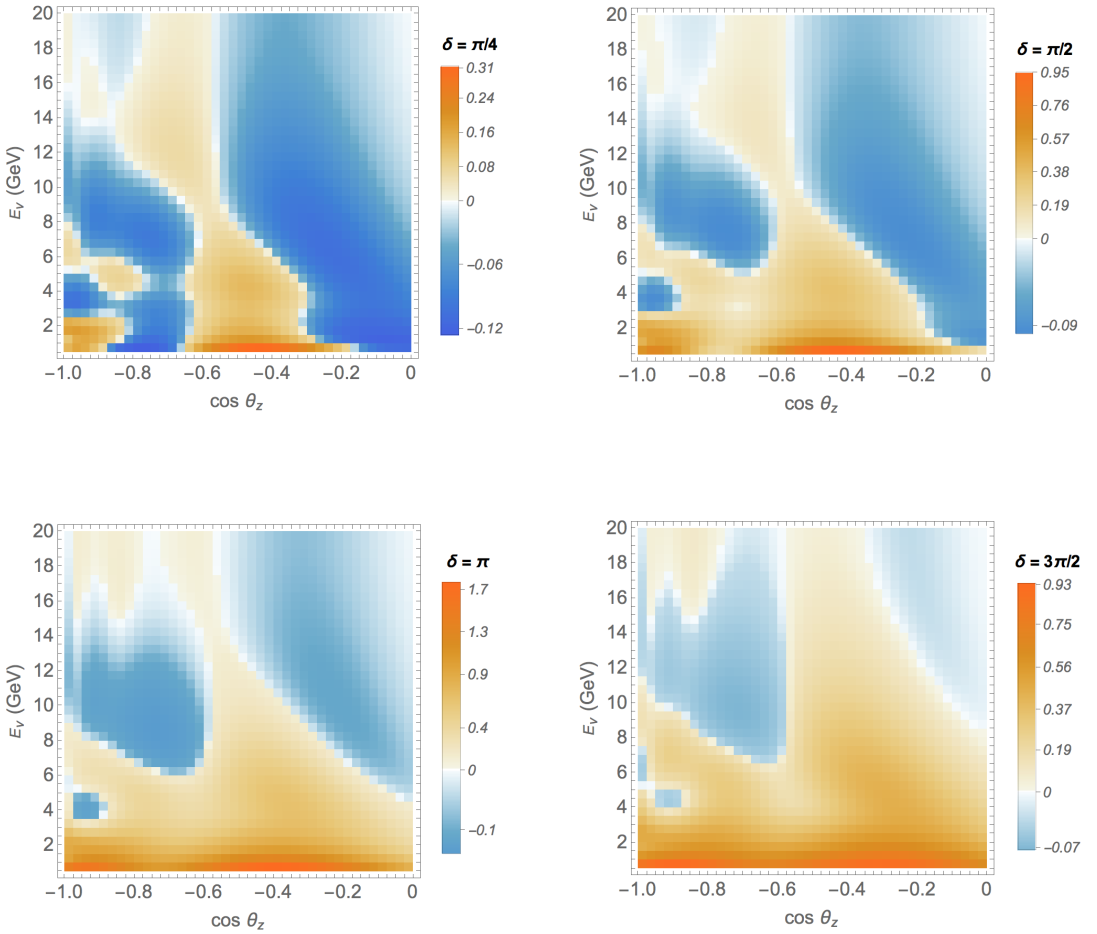

Figure 3: Same as in Fig. 2, but for the $\nu_e + \bar{\nu}_e$ events.

Notice that the Megaton-scale Ice Cherenkov Array (MICA) [29] has been considered as future development of the technique with the effective energy threshold about 10 MeV to detect the supernova neutrinos as well as the high energy part of the solar neutrino spectrum. The "Super" PINGU, ORCA for CP measurements could be an intermediate step between PINGU, ORCA and MICA.

Quick estimator (metric) of discovery potential is provided by the CP distinguishability. For each energy-zenith angle ($E_\nu - \cos\theta_z$) bin, ij, we define the relative CP-difference [31]

$$S_{ij} = \frac{N_{ij}^{\delta_{CP}} - N_{ij}^{\delta_{CP}=0}}{\sqrt{N_{ij}^{\delta_{CP}=0}}}. \quad (4.2)$$

If $\delta_{CP} = 0$ is the true value of the phase, $N^{\delta_{CP}=0}$ can be considered as the "experimental" number of events, whereas δ_{CP} and $N_{ij}^{\delta_{CP}}$ – as the "fit" value and number of events. Then $|S_{ij}|$ is a kind of statistical significance of distinguishing a given value δ_{CP} from $\delta_{CP} = 0$. This quantity does not take into account fluctuations. Still S_{ij} is very useful characteristic which allows one to study dependence of the discovery potential on various parameters. The uncorrelated systematic errors

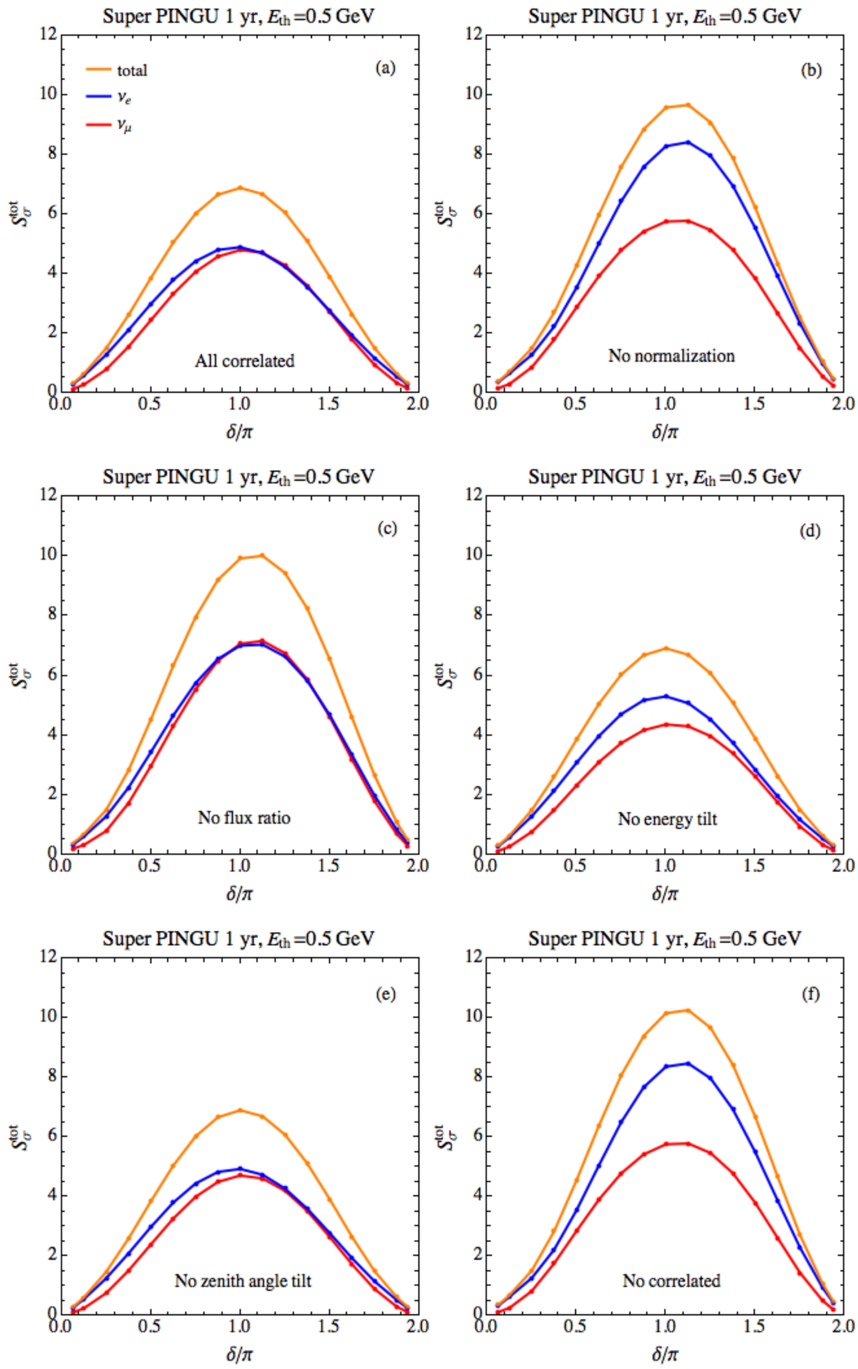

Figure 4: Effects of different correlated systematic errors on sensitivity to the CP-phase. Shown are the total distinguishability as well as integrated Super-PINGU distinguishabilities from ν_μ and ν_e events between a given value of δ and $\delta = 0$ as functions of δ. Different panels correspond to the cases when (a) all errors are included; (b) normalization uncertainty of 20% is removed; (c) flux ratio uncertainty is removed; (d) the energy tilt uncertainty is removed; (e) the angular tilt uncertainty is removed; (f) all correlated systematic uncertainties are removed. The distinguishabilities have been computed after smearing, with 2.5% uncorrelated systematics 1 year exposure, $E_{th} = 0.5$ GeV and for sum of ν and $\bar{\nu}$ signals.

can be added to the denominator of (4.2) as

$$N_{ij}^{\delta_{CP}=0} \to \sigma_{ij}^2 = N_{ij}^{\delta_{CP}=0} + (f N_{ij}^{\delta_{CP}=0})^2, \quad (4.3)$$

where f determines the level of systematic errors. If measurements in each bin are independent the total significance is then given by

$$S_{tot} = \sqrt{\sum_{ij} |S_{ij}|^2}. \quad (4.4)$$

Results of very preliminary study are given in Figs. 2, 3. We show S-distributions of the ν_μ (tracks) and ν_e (cascade) events for different values of δ_{CP} smeared over neutrino energy and direction.

In fig. 4 we present the integrated distinguishability as function of δ_{CP} after 4 years of exposure with various systematic errors included. Flavor misidentification can further reduce distinguishability by factor 1.5 - 2. Still $S_\sigma \approx 3-4$ can be achieved for $\delta = \pi$ after 4 years of exposure.

5. Projecting on to the future

Popular notions are the "Neutrino portal" and "Hidden sector". The latter can communicate to us (Visibles") via this portal. The fermionic operator LH with L being the lepton doublet and H - the Higgs doubled is singlet of the Standard Model symmetry group. Therefore it can couple with other singlets of SM, composed of the SM model fields as well as with fields from the Hidden sector being singlets of SM, thus providing a portal to new physics.

Possible operators which can couple via the neutrino portal include

- (LH), that leads to D=5 Weinberg operator;

- ν_R - which have generation structure and therefore can be considered as RH neutrino,

- S singlet fermions without family structure, their number can be larger or even much larger than 3. Those can include particles of Dark matter,

- F - composite fermionic operator. The coupling is then

$$\frac{1}{\Lambda^{n(F)-3/2}} LHF. \quad (5.1)$$

When H acquires the VEV the fermionic operator F mixes with neutrinos. F can be non-local operator originating from the Planck scale physics [18]. It can lead to CPT violation, difference of masses of neutrinos and antineutrinos. Detailed exploration of the neutrino portal to the Hidden sector and the Dark Universe will be in agenda of theoretical studies.

1. Sterile neutrinos can be components of the Hidden sector which show up via the neutrino portal. Checks of existence of 1 eV steriles with LSND required mixing is the must. This can be done probably by lower cost, with smaller numbers of experiments than planned now. What if all results are negative? The IceCube outcome on searches of steriles is really urgent - it will have strong impact on future studies.

Searches for new neutrino states (sterile, partially sterile, with secret interaction) will continue anyway. The goal is upper bound on mixing as function of mass. For 1 eV mass bound at the level $\sin^2 2\theta < 10^{-3}$ is important to exclude substantial influence on the 3ν paradigm.

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Another high priority issue is the 7 kev sterile and further clarifications of existence of the 3.5 kev X-ray line which can be due to the radiative decay of ν_S. This neutrino does not play any role in generation of masses of light neutrinos. Therefore it is probably not a right handed neutrino but some new fermion from the Hidden sector on the top of 3 RH neutrinos.

Experiments like SHiP [33] can perform searches for new neutral leptons, and first of all those involved in νMSM model.

2. LHC-14. Tests of low scale mechanisms of neutrino mass generation (inverse seesaw, radiative mechanisms, seesaw type III, etc.) via searches for new particles involved in these mechanisms will continue. Actually, discovery of almost any kind on new physics at LHC will have impact on neutrino physics.

Lepton Flavor Violation processes. Any chance to see something at low energies and at high energies (LHC)?

3. Neutrinoless double beta decays searches are and will be of the highest priority in the field.

4. Neutrinos and Dark Universe. Connection "neutrinos - dark matter" will be further explored. Also possible relations between neutrinos and the Dark radiation, Dark energy will remain an important topic. Interaction via neutrino portal can provide such a connection. Inversely, neutrinos will be used as probe of Dark Universe: Properties of high energy cosmic neutrinos, relic supernova neutrinos propagating cosmological distances may encode unique information about the Dark Universe.

Studies of new physics at low (eV - sub eV) energy scales will expand. Very light hidden sector which may include (i) scalar bosons, majoron, axions, (ii) fermions (sterile neutrinos, partially sterile), (iii) gauge bosons (e.g., Dark photons), gravitinos. New experimental techniques for low energy neutrino physics may appear.

5. Determination of the neutrino mass hierarchy (ordering) is the next big in the field. One or another hierarchy exists, and so the discovery is guaranteed. PINGU, ORCA should not miss chance to be first or to be complementary to JUNO, RENO50. Identification of the hierarchy has important implications for SN neutrinos and $\beta\beta0\nu$- decay, for cosmology and atmospheric neutrinos, for theory. Knowledge of the hierarchy facilitates determination of δ_{CP}.

6. The 2-3 mixing: Accuracy of $\sin^2\theta_{23}$ better than 0.05 is required to test various relation between mixing and masses as well as to probe existence of symmetry behind neutrino mass and mixing.

7. Multi-megaton atmospheric neutrino detectors with low (0.5 - 1) GeV thresholds have enormous physics/discovery potential. Apart from mass hierarchy, also searches for sterile neutrinos, non-standard neutrino interactions, violation of fundamental symmetries with high precision will be possible.

8. CP-violation: already J-PARK-SK, NOvA may accumulate evidence for $\delta_{CP} \approx -90^\circ$ and reach 3σ level of discovery of CP-violation. Long term perspectives are related to LBNF-DUNE, HyperKamiokande, ESS. A possibility to measure δ_{CP} using multi- megaton scale atmospheric neutrino detectors super- PINGU, ORCA should be explored.

Specific values of the phase like 0, π , $\pi/2$ may have straightforward and suggestive implications (still not unique) for theory. Values $\pm\pi/2$ can be related (by symmetry) with maximal 2-3 mixing, quasi-degeneracy of mass states, *etc*. Comparison with the quark phase will be interesting.

Even in unification approach they can be very different. Substantial deviation of δ_{CP} from 0, π, will testify for new sources of CP in lepton sector.

9. Solar neutrinos. Here issues to be further studied include

- The Earth matter effect, its energy and zenith angle dependences should be studied with high accuracy.

- Search for and study of the spectral upturn may lead to discovery of the fundamental importance.

- Precise measurements of the pp-neutrino flux will contribute to the global fit, to test of the MSW solution, to searches of new physics.

- Detection of CNO neutrinos is crucial for astrophysics.

In long term perspective one can explore the Earth matter effect on Be neutrinos, seasonal variations of the Boron neutrinos in Antarctica (MICA), etc.

10. Supernova neutrinos: Hopefully a signal will arrive soon. Knowledge of the 1-3 mixing simplifies many things. On the other hand the role of collective neutrino oscillations is far from complete understanding. New features have been realized such as the directional dependence of lepton asymmetry in emission [34].

11. Theory. After the 1-3 mixing measurements the main question is "symmetry or no symmetry" behind the lepton mixing and masses. If symmetry - next question is accidental or real with new structures? Inverted mass hierarchy, degenerate spectrum, special values of CP phase would testify for symmetry. Some new realizations of flavor symmetries are possible.

Appealing scenario is GUT (in particular, SO(10)) with the Hidden sector and the following elements:

- The double seesaw mechanism [35] which produces smallness of neutrino mass.

- It allows also to realize relation $U_{PMNS} = U_{CKM}^{\dagger} U_X$.

- Flavor symmetries at very high scales. Additional symmetries can exist in the Hidden sector.

Other possibilities: scales of new physics, mechanisms of neutrino mass generation, etc. will be further explored. No simple resolution of mass and mixing problem is expected, and different types of new physics (e.g. CKM new physics and neutrino new physics) can be involved. New experimental input is needed for further progress!

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