ν oscillations at low energy LBL experiments in the presence of NSI & parameter degeneracy

arXiv:2002.01616 [hep-ph]

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June 22 - July 2, 2020
poster@ν 2020

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- Main issue: Can we determine (ε_D, ε_N) by long baseline accelerator experiments?

Result1: $P(\nu_\mu \to \nu_e)$ & $P(\nu_\mu \to \nu_\mu)$ at low energy (<1GeV) involve only (δ, ε_D, ε_N, ε_I), ($\varepsilon_I := \varepsilon_{11} + \varepsilon_{22}$) .

Result2: T2HK+T2HKK can determine (δ, ε_D, ε_N, ε_I) if the experimental errors are small.

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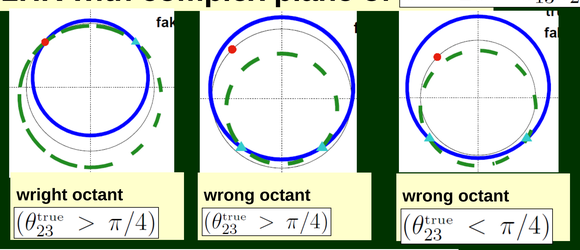
T2HK with complex plane of $z \equiv 2e^{-i\delta} s_{13} s_{23}$



W/o errors, T2HK solves degeneracy of MH & θ_{23}

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3.3 Disappearance of T2HKK

Disappearance probability at T2HKK has little dependence on ε_N : $P_{\mu\mu} \fallingdotseq P_{\mu\mu}(\theta_{23},\delta,\varepsilon_D,\varepsilon_I)$ for ν and $\bar{\nu}$

W/o errors, T2HKK disappearance channel determines ε_D & ε_I using information from T2HK & T2HKK $P_{\mu e}$

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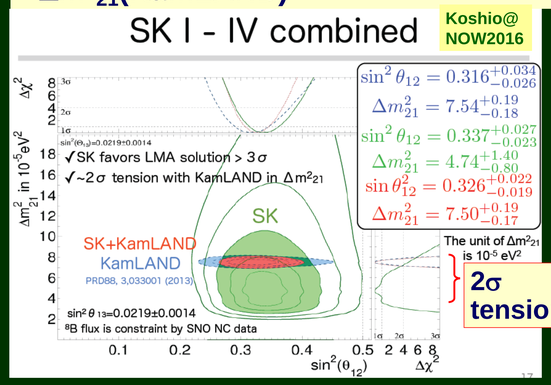
- Tension between Δm^2_{21}(solar) & Δm^2_{21}(KamLAND)



2σ tension

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2. Appearance probability w/ NSI at low energy (E ~< 1GeV)

Oscillation probabilities are expressed by (ε_D , ε_N , ε_N) only

ν experiments on Earth see only the sum:

$\varepsilon_{jk} := \varepsilon^e_{jk} + 3\varepsilon^u_{jk} + 3\varepsilon^d_{jk}$

$\varepsilon_D := (\varepsilon_{22} - \varepsilon_{11})/2$

$\varepsilon_N := \varepsilon_{12}$

$\varepsilon_I := (\varepsilon_{22} + \varepsilon_{11})/2$

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3.2 Appearance of T2HKK

Appearance probability at T2HKK has little dependence on ε_D, ε_I : $P_{\mu e} \fallingdotseq P_{\mu e}(\theta_{23},\delta,\varepsilon_N)$ for ν and $\bar{\nu}$

W/o errors, T2HKK appearance channel determines ε_N using information from T2HK

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$P_{\mu\mu}(\varepsilon_I, \varepsilon_D) = P_{\mu\mu}(0, 0)$

$|Q + \epsilon_I + P\epsilon_D|^2 = |Q|^2 \Rightarrow \epsilon_I + \mathrm{Re}\,[P]\,\epsilon_D = 0$

$P_{\bar{\mu}\bar{\mu}}(\varepsilon_I, \varepsilon_D) = P_{\bar{\mu}\bar{\mu}}(0, 0)$

$|Q' + \epsilon_I + P'\epsilon_D|^2 = |Q'|^2 \Rightarrow \epsilon_I + \mathrm{Re}\,[P']\,\epsilon_D = 0$

$\Rightarrow \epsilon_I = 0 \quad \epsilon_D = 0$

In our approximation, we get a unique solution for ε_I , ε_D

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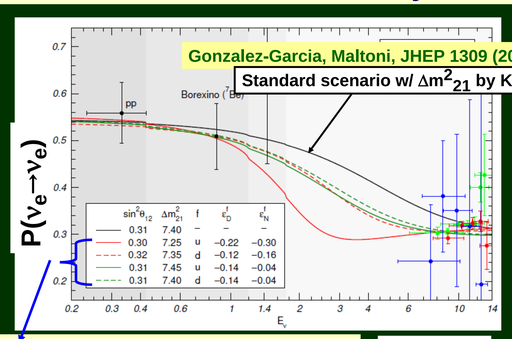
Tension between solar ν & KamLAND data can be accounted for by NSI



NSI gives a better fit!

E_ν/MeV

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3. Parameter degeneracy w/ NSI at low energy

We assume true values for unknown: NH, θ_{23}= 16π/60, δ=-3π/4, ε_D=0, ε_N=0, ε_I=0

Do we have a unique solution of MH, octant, δ, ε_D, ε_N, ε_I to a set of eqs.?

$P_{\mu e}(\theta_{23},\delta,\varepsilon_D,\varepsilon_N,\varepsilon_I) = P_{\mu e}(16\pi/60,-3\pi/4,0,0)$

$P_{\mu\mu}(\theta_{23},\delta,\varepsilon_D,\varepsilon_N,\varepsilon_I) = P_{\mu\mu}(16\pi/60,-3\pi/4,0,0)$

for ν and $\bar{\nu}$

NH: Normal Hierarchy, MH: Mass Hierarchy

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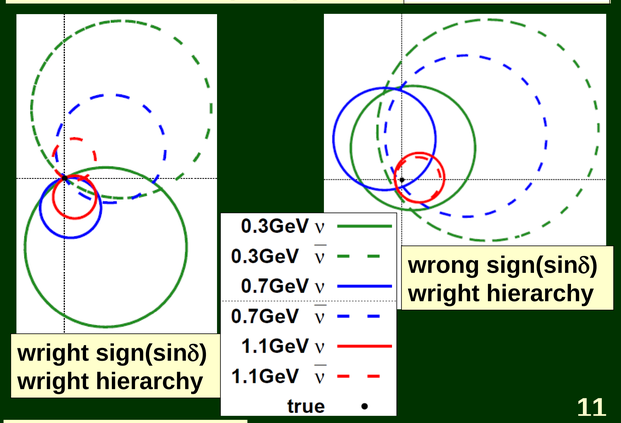
T2HKK with complex plane of $z \equiv (AL/2)U_{\tau 3}\epsilon_N$



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4. Conclusions

- Oscillation probabilities at low energy (E ~<1GeV) w/ NSI involve only ε_D, ε_N and ε_I.
- Assuming $|U_{e3}|\sim|\varepsilon_D|\sim|\varepsilon_N|\sim|\varepsilon_I|\sim$ O(0.1), appearance & disappearance channels for ν & $\bar{\nu}$ at T2HK & T2HKK can resolve parameter degeneracy if experimental errors are small.

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- NonStandard Interaction

$U = R_{23}\,\tilde{R}_{13}\,R_{12}$

$\mathcal{H} = U\,\mathrm{diag}(0, \Delta E_{21}, \Delta E_{31})\,U^{-1} + \mathcal{A}$

$\Delta E_{jk} \equiv \frac{\Delta m^2_{jk}}{2E}$

$\mathcal{A} \equiv \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + A \sum_{f=e,u,d} \frac{N_f}{N_e} \begin{pmatrix} \epsilon^f_{ee} & \epsilon^f_{e\mu} & \epsilon^f_{e\tau} \\ \epsilon^f_{\mu e} & \epsilon^f_{\mu\mu} & \epsilon^f_{\mu\tau} \\ \epsilon^f_{\tau e} & \epsilon^f_{\tau\mu} & \epsilon^f_{\tau\tau} \end{pmatrix}$

- NSI in solar ν flavor basis

$\mathcal{H} = R_{23}\,\tilde{R}_{13}\,\mathcal{H}^{\rm eff}\,\tilde{R}^{-1}_{13}\,R^{-1}_{23}$

Only these parameters appear in low energy ν LBL experiments

$\mathcal{A}^{\rm eff} = A \begin{pmatrix} c^2_{13} & 0 & e^{-i\delta} c_{13} s_{13} \\ 0 & 0 & 0 \\ e^{i\delta} c_{13} s_{13} & 0 & s^2_{13} \end{pmatrix} + A \sum_{f=e,u,d} \frac{N_f}{N_e} \begin{pmatrix} \epsilon^f_{11} & \epsilon^f_{12} & \epsilon^f_{13} \\ \epsilon^f_{21} & \epsilon^f_{22} & \epsilon^f_{23} \\ \epsilon^f_{31} & \epsilon^f_{23} & \epsilon^f_{33} \end{pmatrix}$

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Assumptions:
- $|U_{e3}|\sim|\varepsilon_D|\sim|\varepsilon_N|\sim|\varepsilon_I|\sim$O(0.1)
- Experimental errors are ignored

3.1 Disappearance & Appearance of T2HK

Oscillation probabilities at T2HK have little dependence on ε_D, ε_N, ε_I : $P_{\mu e} \fallingdotseq P_{\mu e}(\theta_{23},\delta)$ $P_{\mu\mu} \fallingdotseq P_{\mu\mu}(\theta_{23},\delta)$ for ν and $\bar{\nu}$

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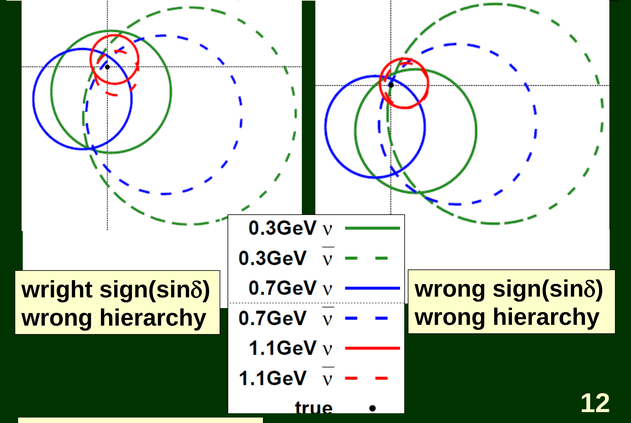
T2HKK with complex plane of $z \equiv (AL/2)U_{\tau 3}\epsilon_N$



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Discussions

- In this work the experimental errors were not taken into account. -> In reality, significance must be considered.
- At high energy (e.g., DUNE), oscillation probabilities depend on all other $\varepsilon_{\alpha\beta}$ parameters, and parameter degeneracy would be impossible to solve.

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