非標準相互作用がある場合の低エネルギー長基線実験のニュートリノ振動とパラメーター縮退

都立大理・安田修

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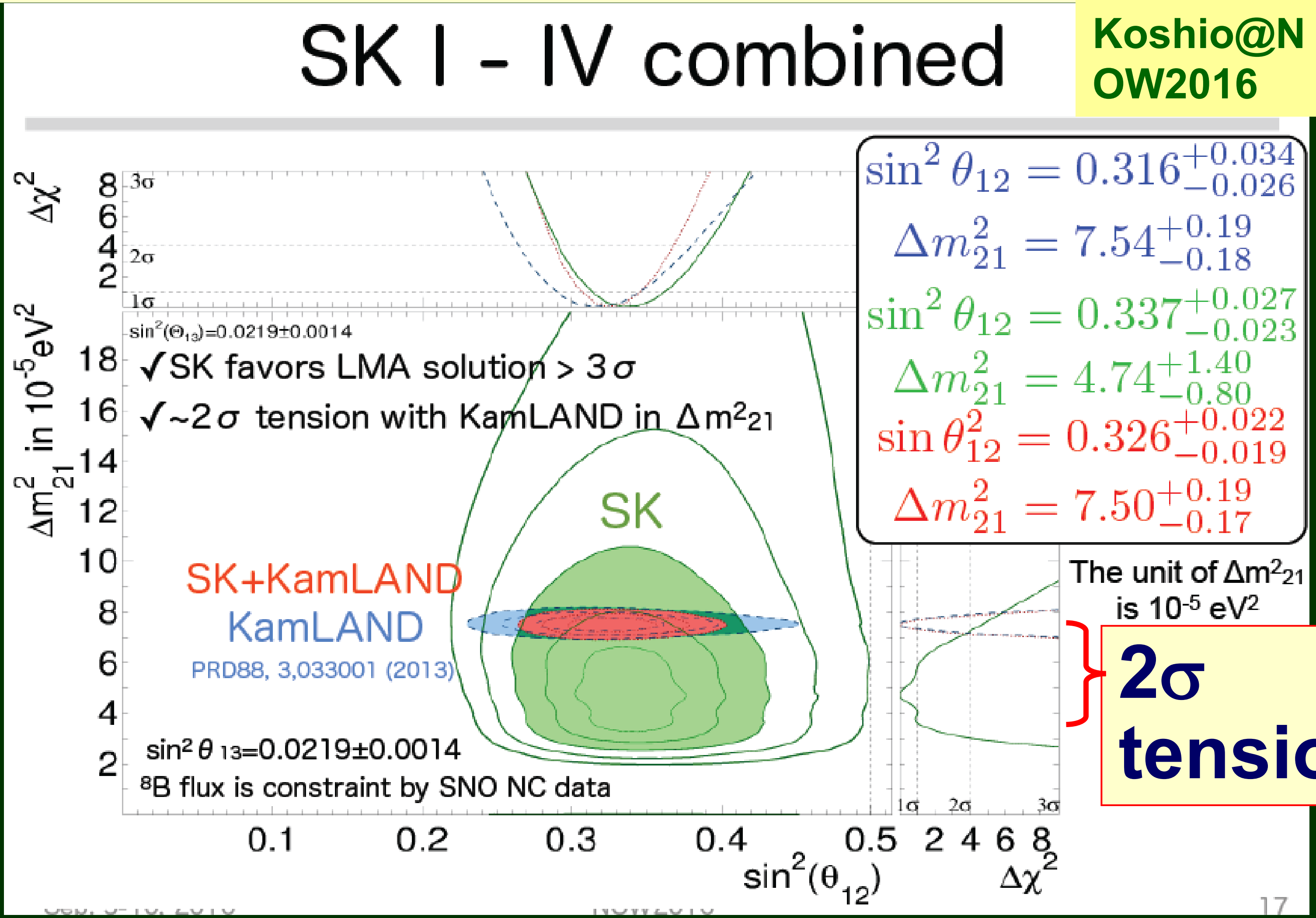
1. Introduction

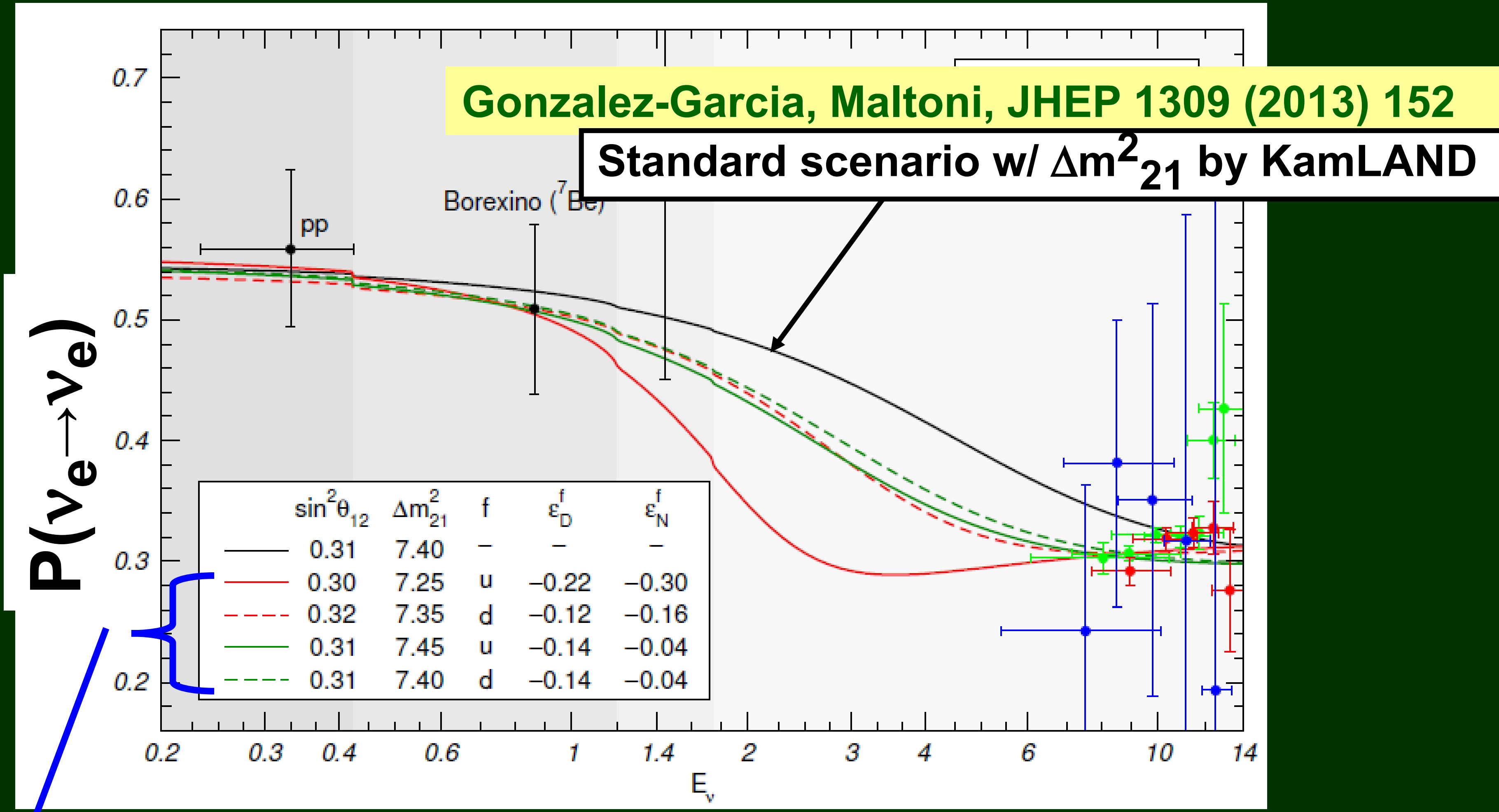
- **Tension between Δm^2_{21}(solar) & Δm^2_{21}(KamLAND)**



Koshio@NOW2016

2σ tension

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



NSI gives a better fit!

E_ν/MeV

●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

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

Only these parameters appear in low energy ν LBL experiments

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

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

Result1: $P(\nu_\mu \rightarrow \nu_e)$ & $P(\nu_\mu \rightarrow \nu_\mu)$ at low energy (<1GeV) involve only (δ, ε_D, ε_N , ε_I), ($\varepsilon_N := \varepsilon_{12}$, $\varepsilon_D \propto \varepsilon_{11} - \varepsilon_{22}$, $\varepsilon_I \propto \varepsilon_{11} + \varepsilon_{22}$) .

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

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:

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

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

$\varepsilon_N := \varepsilon_{12}$

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

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

Assumptions:

- $|U_{e3}| \sim |\epsilon_D| \sim |\epsilon_N| \sim |\epsilon_l| \sim O(0.1)$
- Experimental errors are ignored

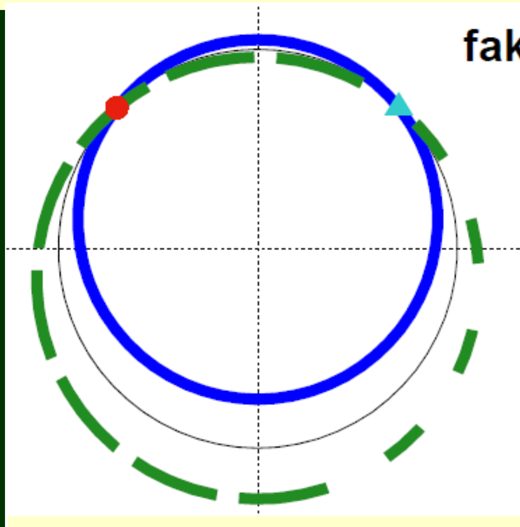
3.1 Disappearance & Appearance of T2HK

Oscillation probabilities at T2HK have little dependence on ϵ_D, ϵ_N, ϵ_l :

$P_{\mu e} \doteqdot P_{\mu e}(\theta_{23},\delta)$

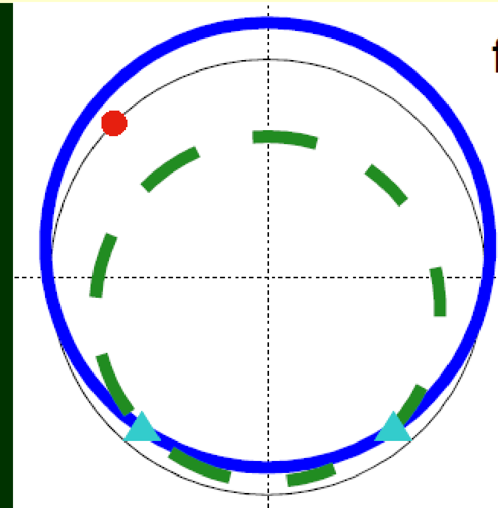
$P_{\mu\mu} \doteqdot P_{\mu\mu}(\theta_{23},\delta)$ for ν and $\bar{\nu}$

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



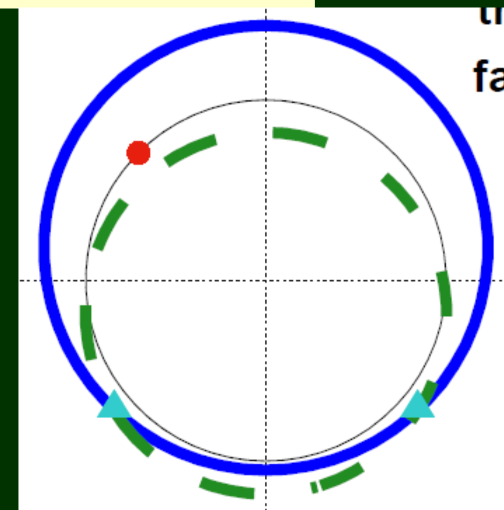
right octant

$(\theta_{23}^{\text{true}} > \pi/4)$



wrong octant

$(\theta_{23}^{\text{true}} > \pi/4)$



wrong octant

$(\theta_{23}^{\text{true}} < \pi/4)$

ν : $P(\nu_\mu \to \nu_e; \delta, \theta_{23}) = P(\nu_\mu \to \nu_e; \delta^{\text{true}}, \theta_{23}^{\text{true}})$

$\bar{\nu}$: $P(\bar{\nu}_\mu \to \bar{\nu}_e; \delta, \theta_{23}) = P(\bar{\nu}_\mu \to \bar{\nu}_e; \delta^{\text{true}}, \theta_{23}^{\text{true}})$

|z|

true

fake

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

3.2 Appearance of T2HKK

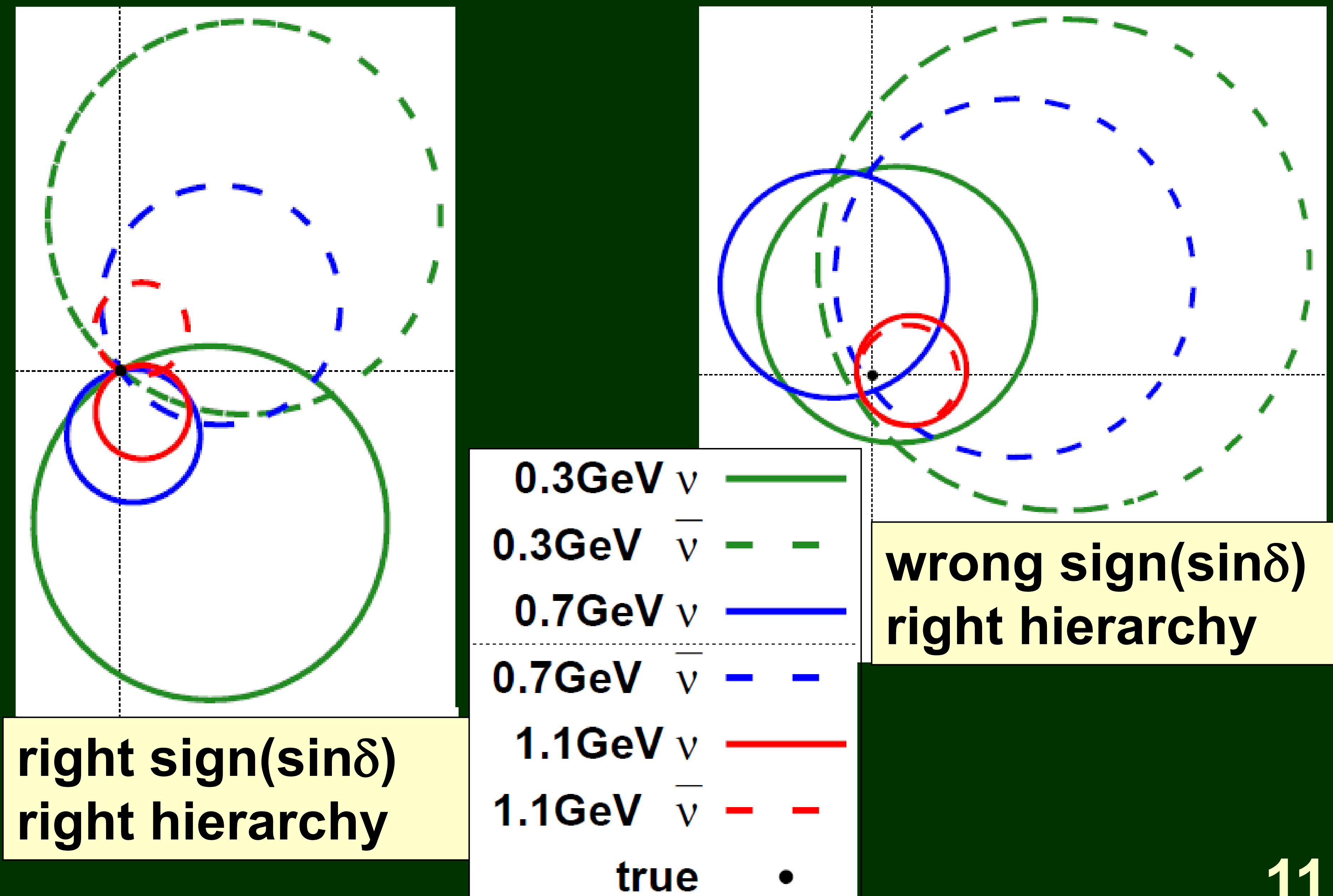
Appearance probability at T2HKK has little dependence on ε_D, ε_I :

$$P_{\mu e} \doteqdot P_{\mu e}(\theta_{23},\delta,\varepsilon_N)$$

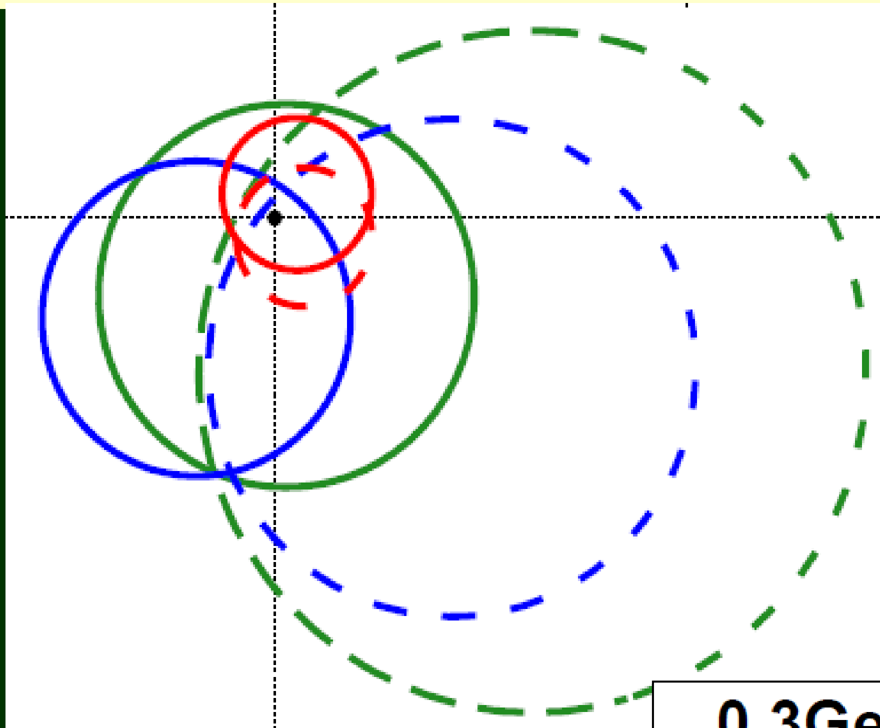
for ν and $\bar{\nu}$

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

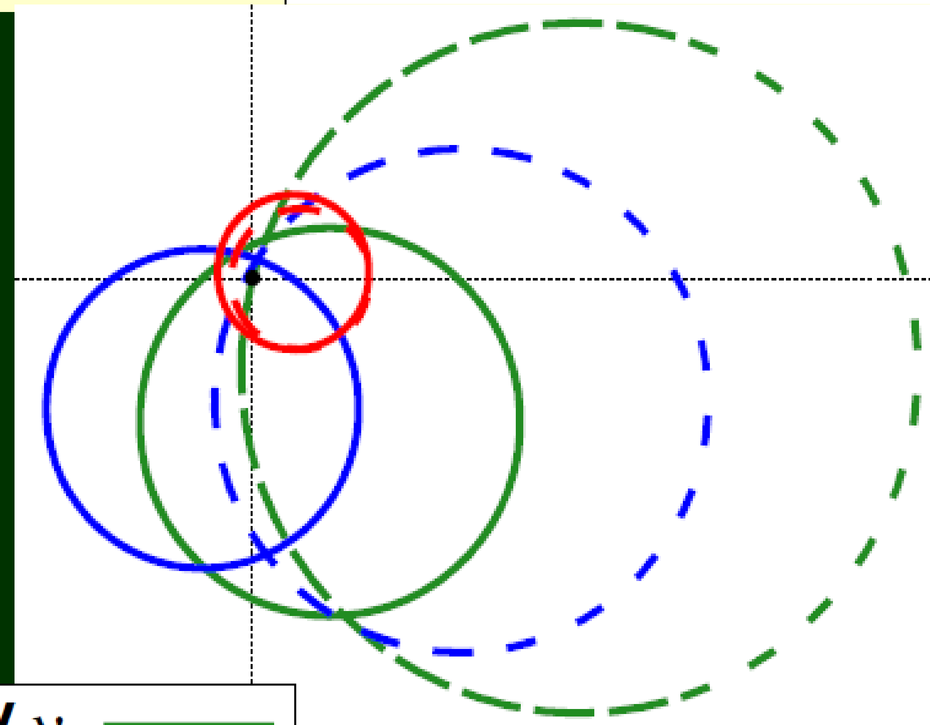
T2HKK with complex plane of $z \equiv (AL/2)U_{\tau 3}\epsilon_N$



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



right sign(sinδ)
wrong hierarchy



wrong sign(sinδ)
wrong hierarchy

3.3 Disappearance of T2HKK

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

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

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

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

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

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

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

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

4. Conclusions

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

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.