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Impact of sterile neutrinos on long baseline experiments

Niki Klop

Ludwig-Maximilians University Munich
Max Planck Institute for Physics Munich
Supervisor: Antonio Palazzo

Outline

- ν oscillations in the standard framework
- Motivations for a sterile neutrino
- What I am doing

Introduction

- In the Standard Model, neutrinos are massless
- Experiments have shown that neutrinos can change flavour
- Spectrum of 3 neutrino mass eigenstates
- Flavour states can be written as a superposition of mass eigenstates (and vice versa)

$$|\nu_\alpha\rangle = \sum_{i=1}^{N} U_{\alpha i}^{*} |\nu_i\rangle$$

$$|\nu_\alpha(t)\rangle = \sum_{k} U_{\alpha k}^{*} e^{-iE_k t} |\nu_k\rangle$$

Introduction

Transition probability

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E}\right)$$

Only dependent of Δm^2, not of the absolute mass.

The sensitivity to Δm^2 of an experiment is maximal for the values of Δm^2 such that

$$\frac{\Delta m^2_{kj} L}{2E} \sim 1$$

Introduction

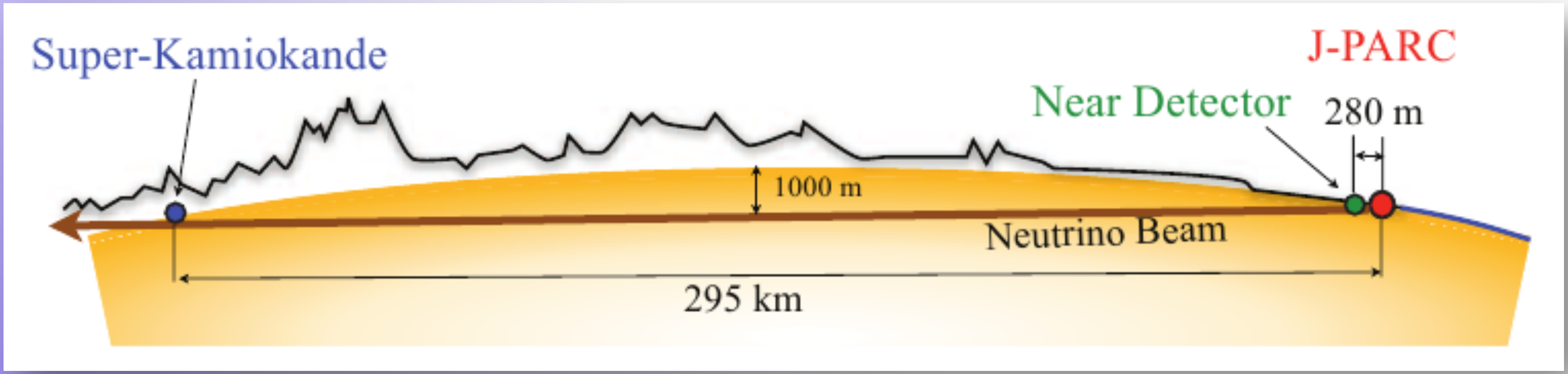
- The PMNS matrix

$$U = \begin{bmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta_{cp}} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{-i\delta_{cp}} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{-i\delta_{cp}} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{-i\delta_{cp}} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{-i\delta_{cp}} & c_{12}c_{23} \end{bmatrix}$$

$$c_{ij} = \cos\theta_{ij}, \quad s_{ij} = \sin\theta_{ij}$$

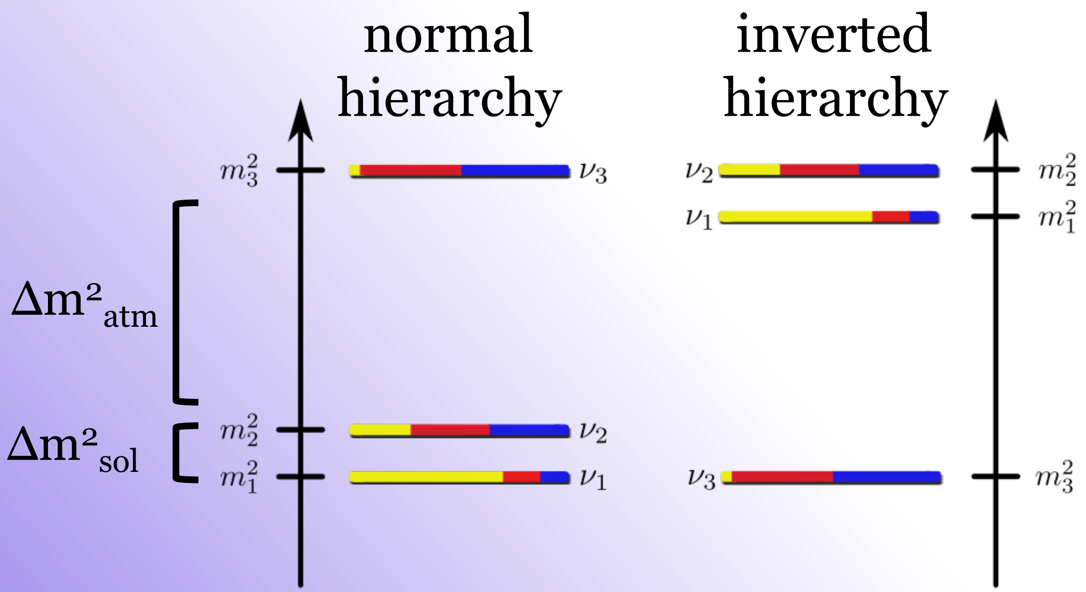
- Mixing angles are measured
  CP-violating phase still has to be determined
  → LBL experiments (T2K)

The T2K experiment



Introduction

The neutrino mass spectrum:



$\Delta m^2_{atm} = \Delta m^2_{23} = 2.4 \cdot 10^{-3}\ eV^2$

$\Delta m^2_{sol} = \Delta m^2_{12} = 7.6 \cdot 10^{-5}\ eV^2$

Motivation

Anomalies in short baseline (SBL) experiments:

experiments for which L/E ~ 1 km/GeV ($\Delta m^2 \sim 1$ eV^2)

ν_e appearance:

- LSND measured $\bar{\nu}_e$ appearance from $\bar{\nu}_\mu$ beam consistent with mixing with $\Delta m^2 \sim 1$ eV^2
- MiniBoone: rules out part of the LSND region

$$\frac{\Delta m^2_{kj} L}{2E}$$

$$P_{\nu_\mu \to \nu_e} = \underbrace{\sin^2 2\theta_{e\mu}}_{4|U_{e4}|^2|U_{\mu4}|^2} \sin^2 \frac{\Delta m^2 L}{4E}$$

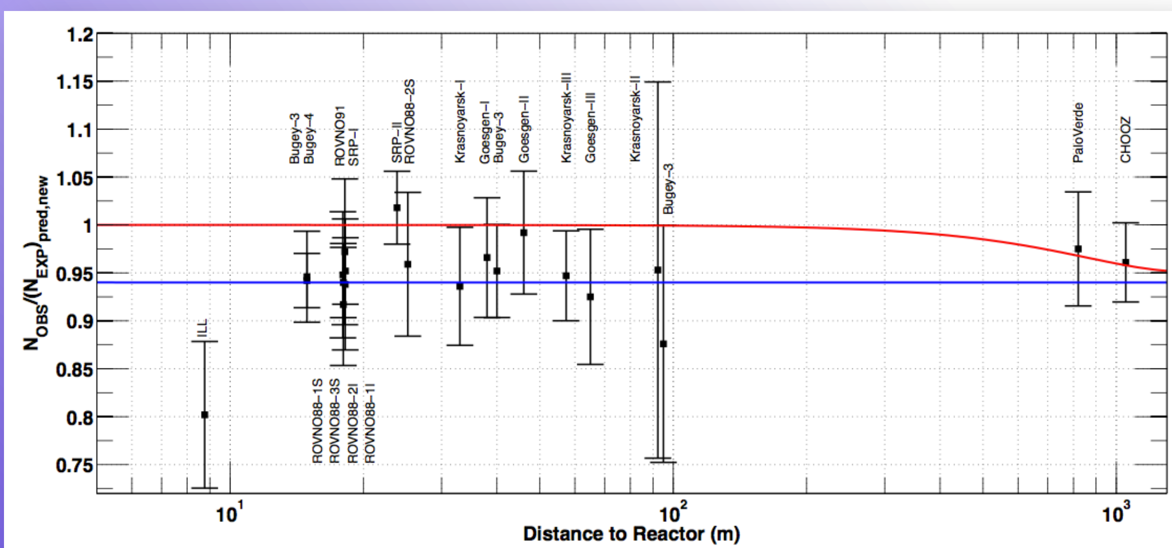
Motivation

ν_e disappearance   L/E ~ 1 m/MeV

- Reactor anomaly $P_{\nu_e \to \nu_e} < 1$

$$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2 L}{4E}$$

$$4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \sim 4|U_{e4}|^2$$

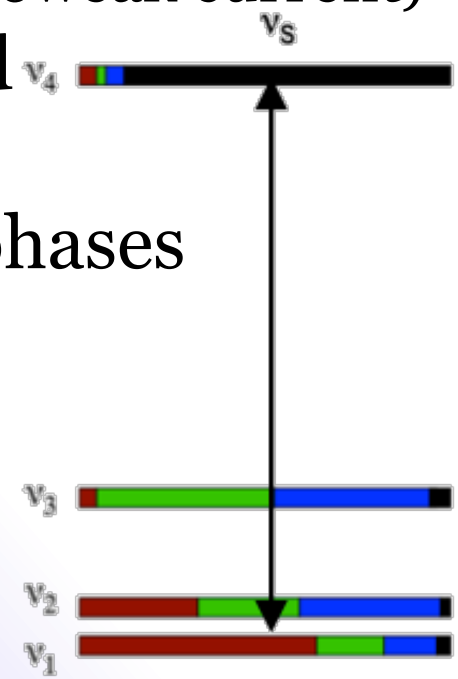


Mention et al.
arXiv:1101:2755

Motivation

→ Introduction of a 4th neutrino with $\Delta m^2 \sim 1\ eV^2$

- 4th neutrino should be *sterile*
  (must not couple to the standard electroweak current)
- Success of 3ν should be preserved
- 4x4 mixing matrix
- 6 mixing angles, 3 CP-violating phases



What I am doing

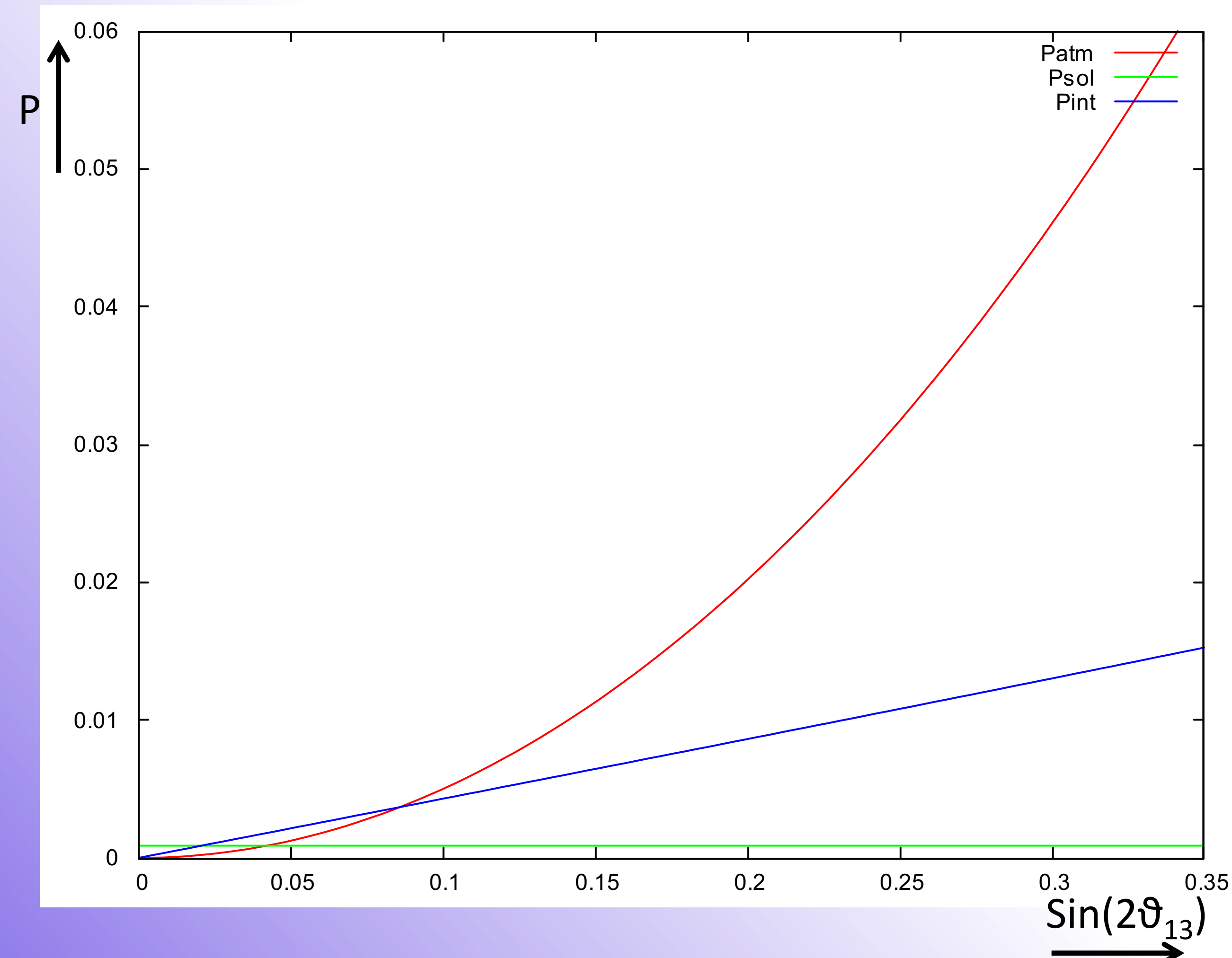
- If sterile neutrinos indeed exist, this will have both positive and negative effects on the efficiency of the LBL experiments
- Simulation of 3+1 neutrino oscillation in a LBL experiment (T2K)

- Goal: put LBL-experiments in a wider perspective.

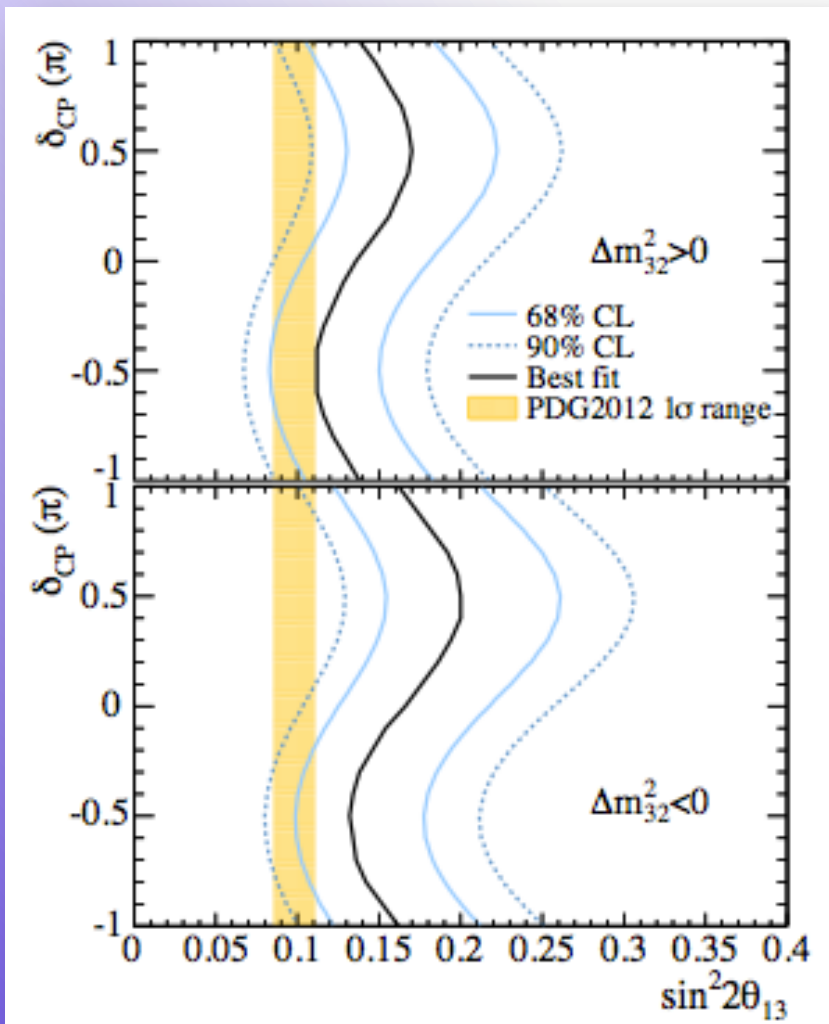
  → 3+1 case

3ν probability

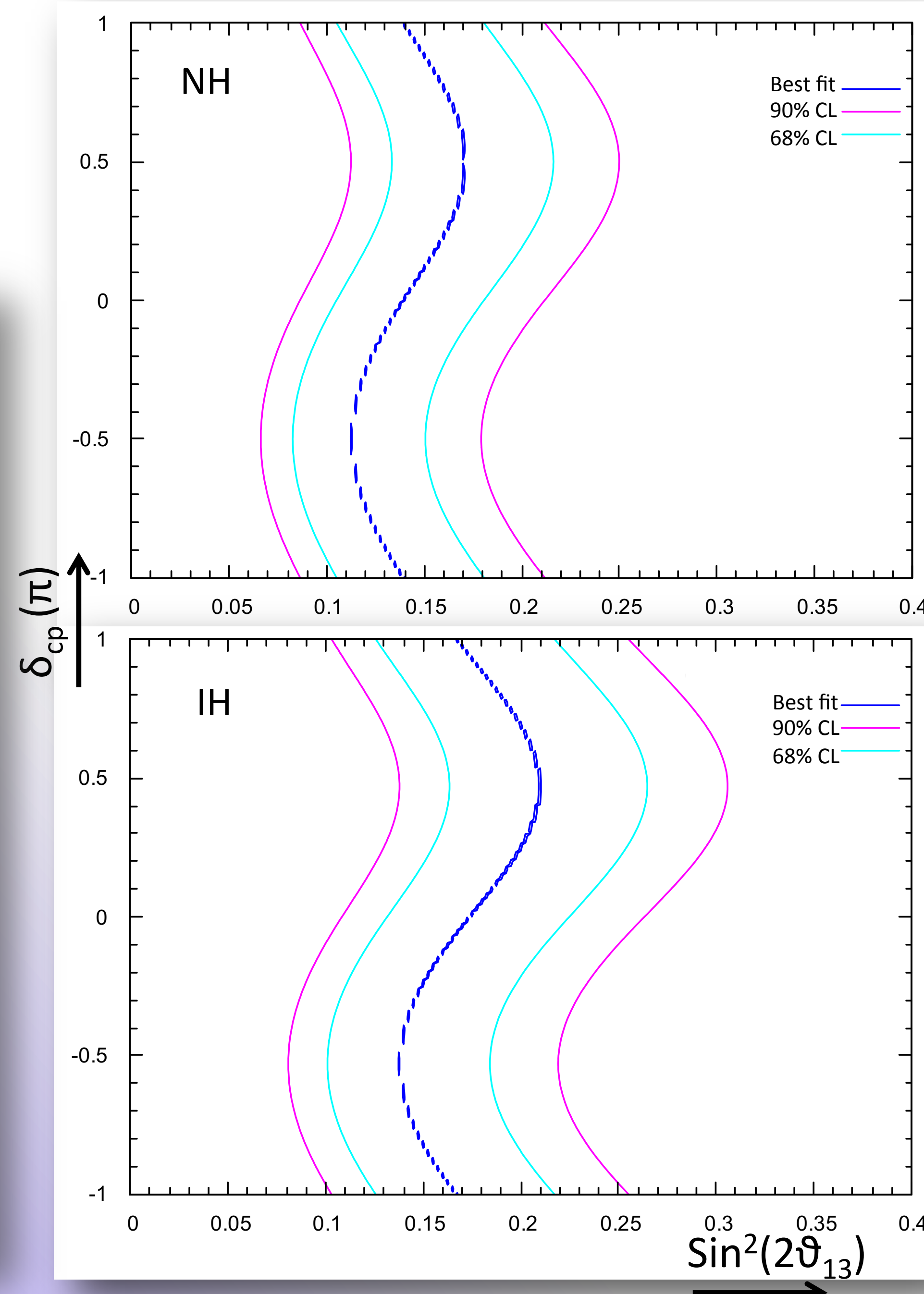
$$P^{3\nu}_{\nu_\mu \to \nu_e} = P^{\mathrm{ATM}} + P^{\mathrm{SOL}} + P^{\mathrm{INT}}$$



3ν (matter)

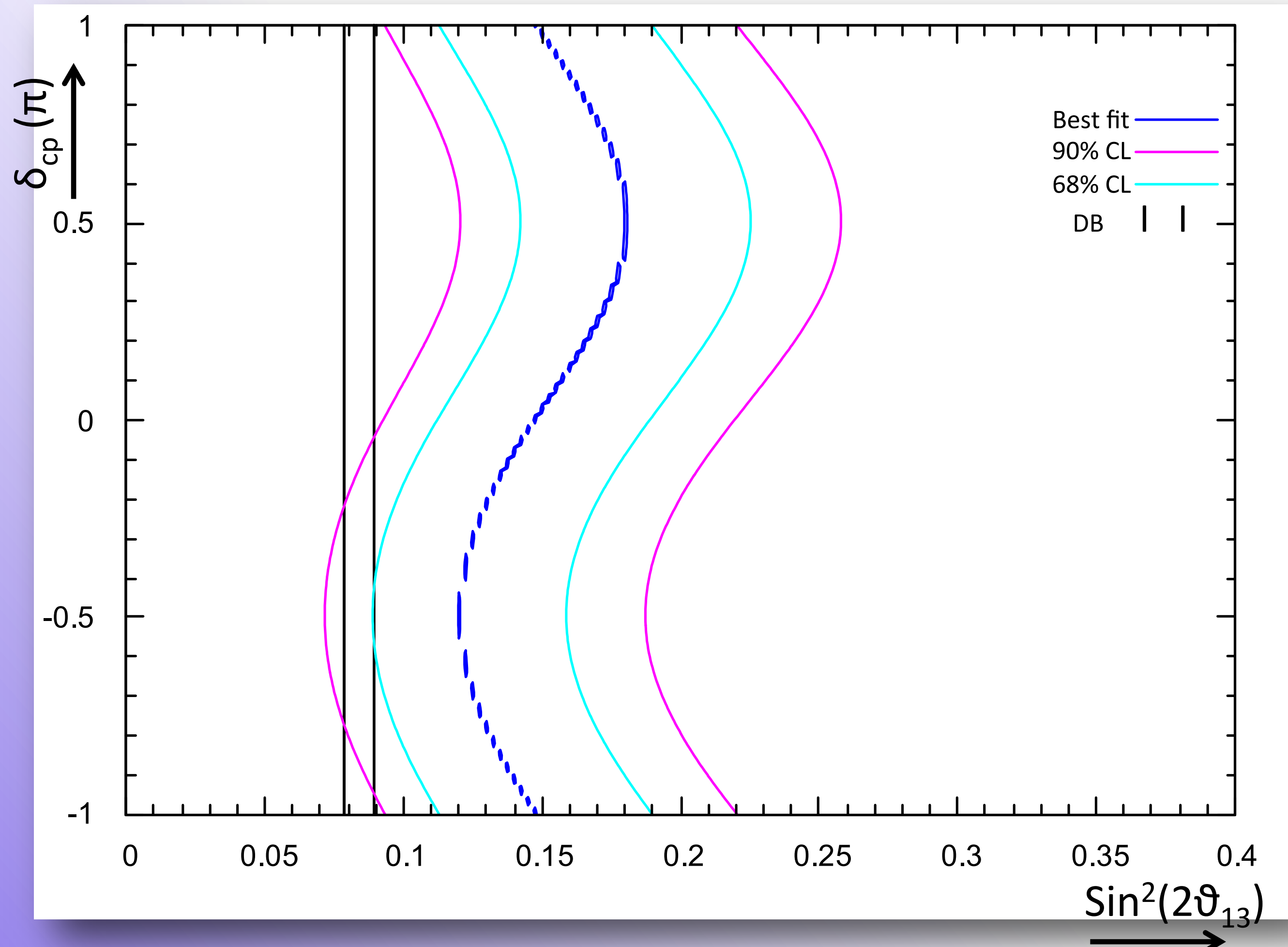


δ_{CP} (π)
$\Delta m^2_{32}>0$
68% CL
90% CL
Best fit
PDG2012 1σ range
$\Delta m^2_{32}<0$
$\sin^2 2\theta_{13}$



NH
Best fit
90% CL
68% CL
IH
Best fit
90% CL
68% CL
δ_{cp} (π)
$\mathrm{Sin}^2(2\vartheta_{13})$

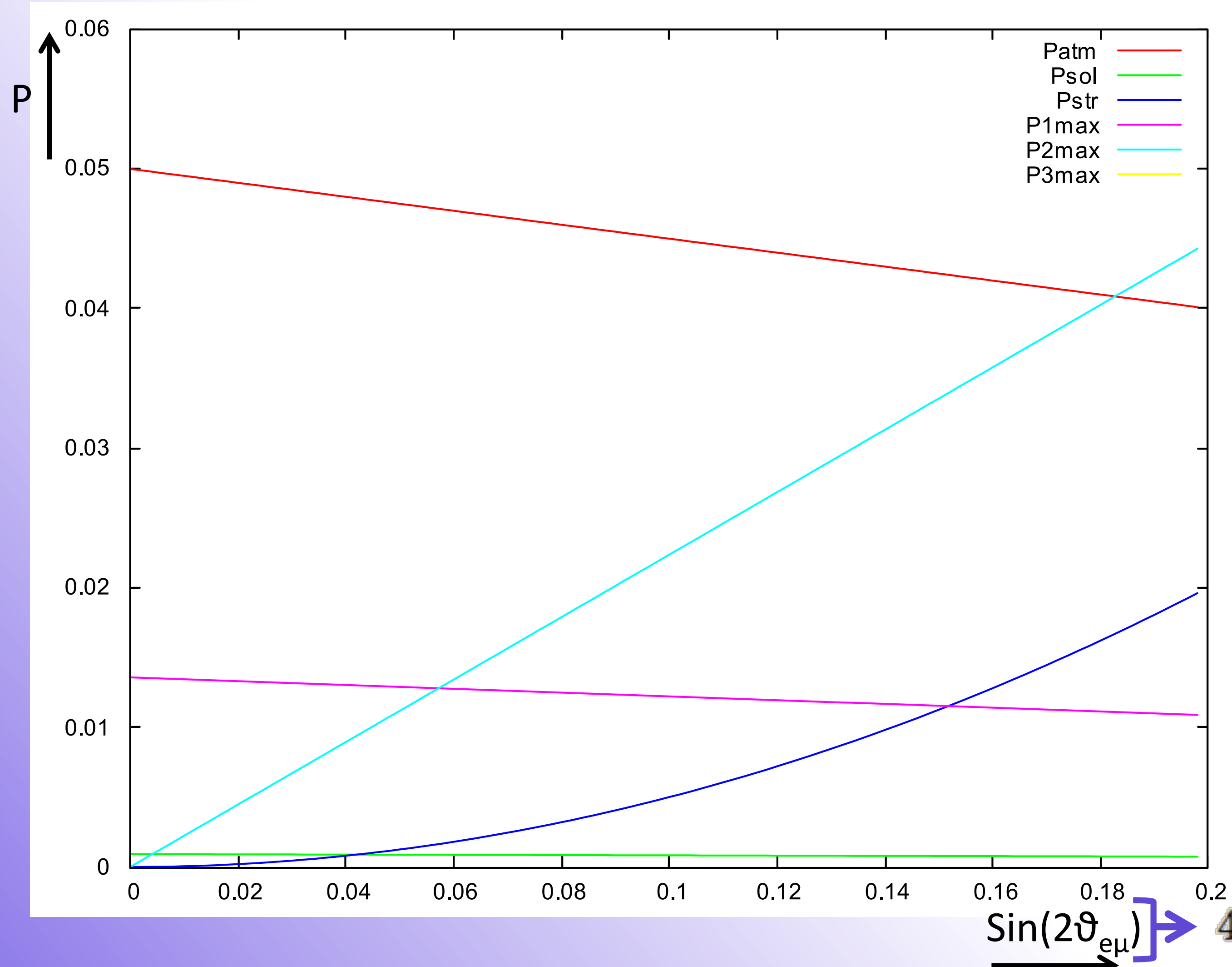
3ν (vacuum)



1
0.5
0
-0.5
-1
δ_{cp} (π)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
$Sin^2(2\vartheta_{13})$
Best fit
90% CL
68% CL
DB

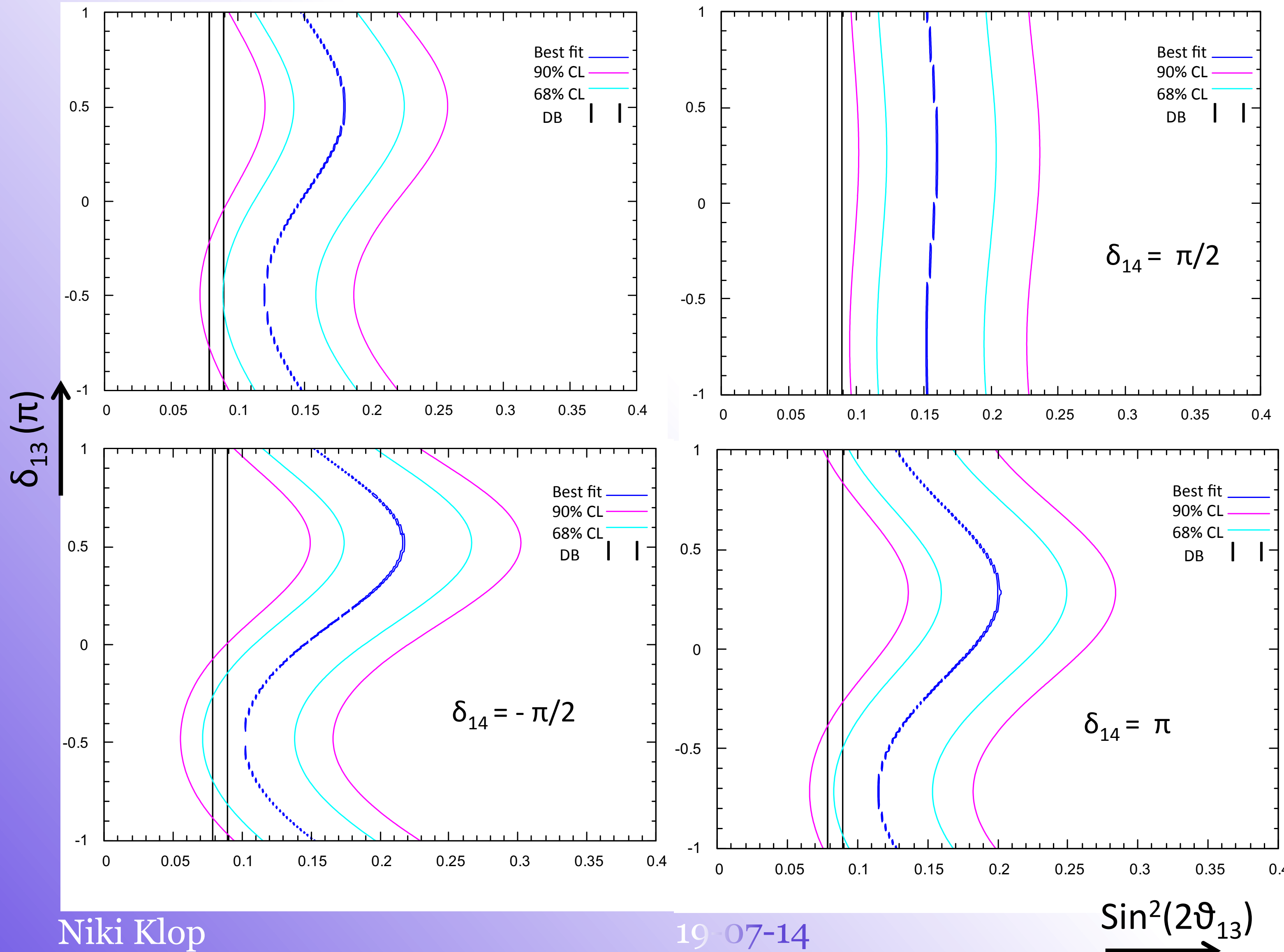
4ν probability

$$P^{4\nu}_{\nu_\mu \to \nu_e} = P^{\rm ATM} + P^{\rm SOL} + P^{\rm STR} + P^{\rm INT}_{\rm I} + P^{\rm INT}_{\rm II} + P^{\rm INT}_{\rm III}$$



$4|U_{e4}|^2|U_{\mu 4}|^2$

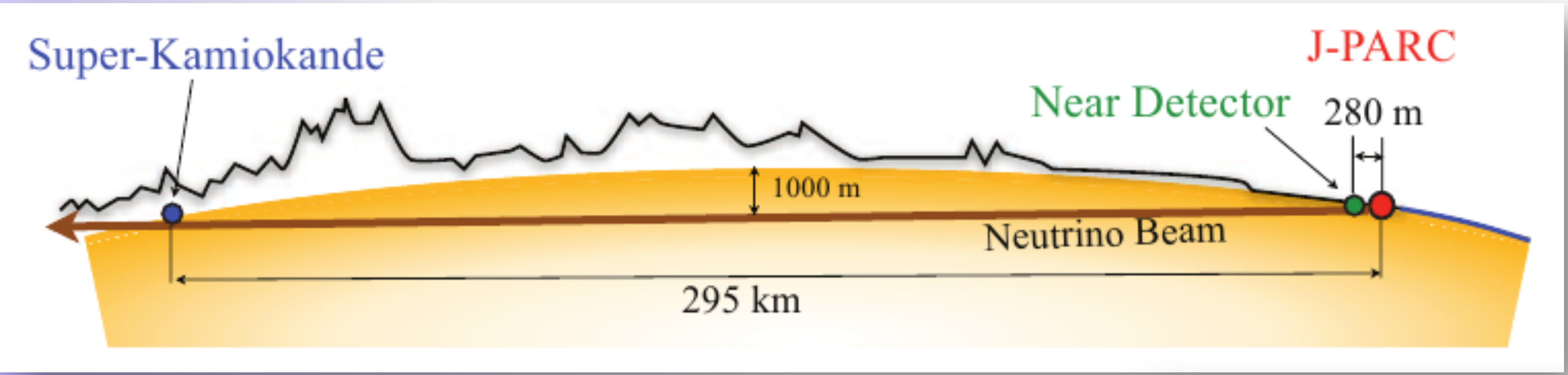
4ν "results" (vacuum)



Summary

- The standard 3 ν framework may be not complete
- Intriguing indications in the favour of light sterile neutrinos ~ 1 eV
- Large experimental activity on sterile ν
- Large theoretical activity on sterile ν
- I focus on impact of these sterile neutrinos in LBL experiments

The T2K experiment



$$P_{\mu e}^{\rm LBL} \simeq P_{\rm ATM.}^{3\nu\rm SM} + P_{\odot}^{3\nu\rm SM} + 2\sqrt{P_{\odot}^{3\nu\rm SM} P_{\rm ATM.}^{3\nu\rm SM}} \cos(\Delta_{32} - \delta_3)$$

$$P_{atm}^{3\nu} \cong 4|U_{e3}|^2|U_{\mu 3}|^2 \sin^2 \Delta_{31}$$

$$P_{sol}^{3\nu} \cong 4|U_{e2}|^2|U_{\mu 2}|^2 \sin^2 \Delta_{21}$$

$$P^{int} \cong 8|U_{e3}||U_{\mu 3}||U_{e2}||U_{\mu 2}| \sin \Delta_{31} \sin \Delta_{21} \cos(\Delta 32 - \delta)$$