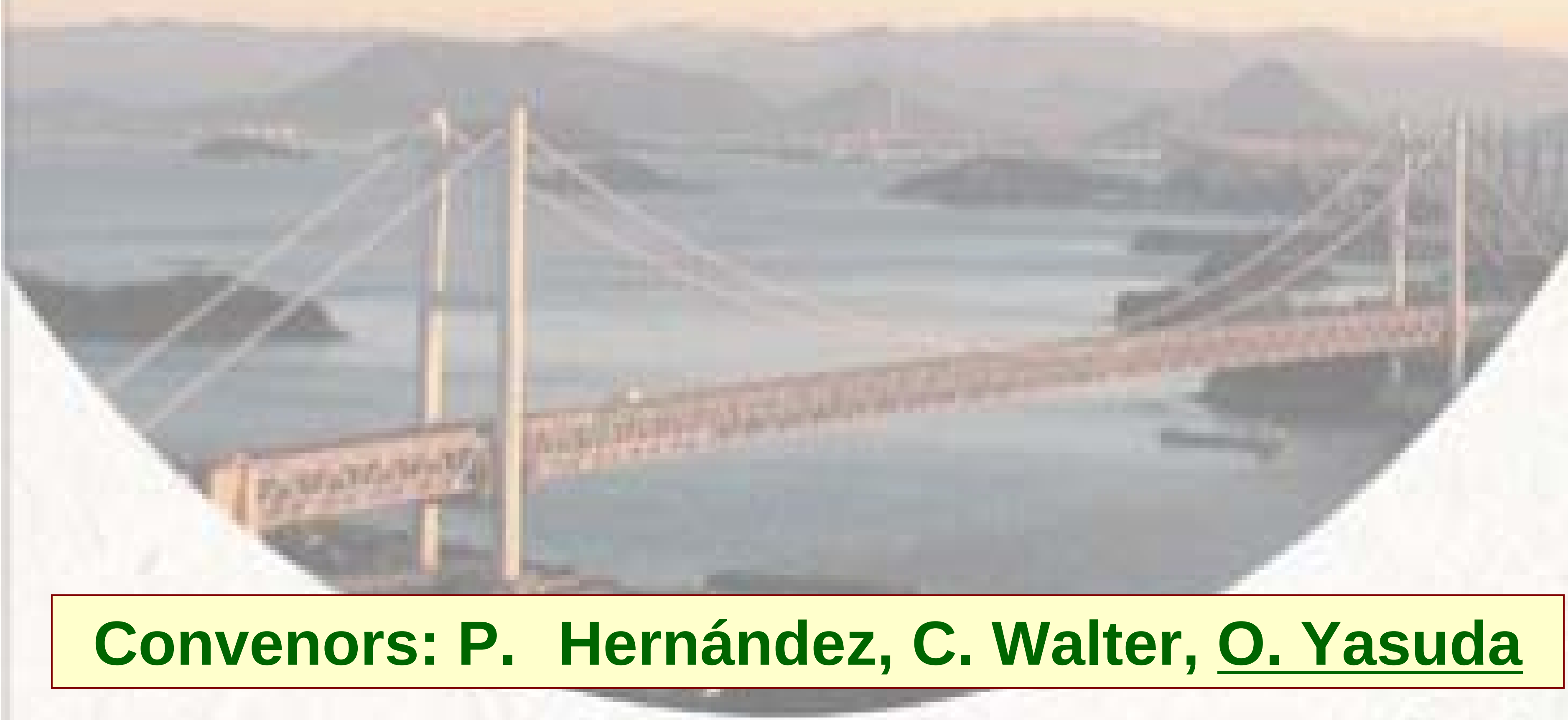
Summary of WG1 (Theoretical Part)



Convenors: P. Hernández, C. Walter, O. Yasuda

NuFact07, 11 August 2007 @Okayama Univ.

Department of Physics
Okayama University

Phenomenology with certain detectors

Terranova: ν hierarchy from CP-blind observables w/ high density mag. det.
Majumdar: Tri-bimaximal mixing

Theoretical discussions on ν masses

Farzan: CP violation: Zero, maximal or between the two extremes
Winter: extended quark-lepton complementarity

Sterile ν scenario

Schwetz-Mangold: Sterile ν oscillations after first MiniBooNE results
Karagiorgi: Sterile ν Oscillations and CP-Violation Implications for MiniBooNE

New physics/Non-Standard Interactions

Agarwalla: New Physics searches with Beta Beams
Ohlsson: Effects of NSI in MINOS
Sugiyama: More on NSI at MINOS
Ota: NSI in reactor and superbeam experiments

Unitarity

Xing: Leptonic unitarity triangle in matter
Kimura: CP Phase in ν_μ->ν_μ
Lopez-Pavon: CP-violation from non-unitary leptonic mixing

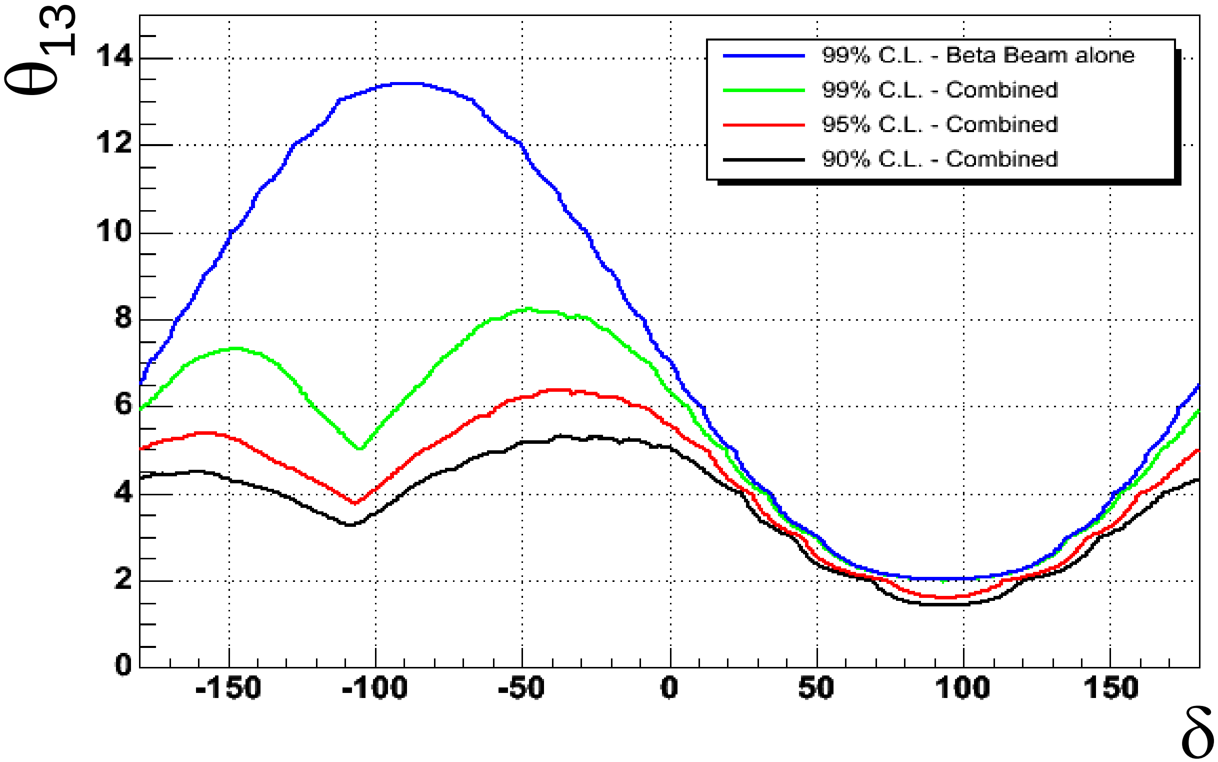
Terranova Combination of atmospheric + Beta Beam w/ charge ID by a magnetized iron detector

$$E_R = \pm \Delta m^2_{31} L_{magic} \ \cos 2\theta_{13}/4\pi$$

$$\Gamma_R = |\Delta m^2_{31}| L_{magic} \ \sin 2\theta_{13}/2\pi$$

resonance occurs only for ν (NH) or only for ν-bar (IH)

→ mass hierarchy can be determined at 90% CL for $\theta_{13} > 4°$ (normal hierarchy negative δ).



Majumdar

Tri-bimaximal mixing

$\sin^2\theta_{23} = 1/2$, $\sin^2\theta_{12} = 1/3$, $\sin^2\theta_{13} = 0$

Follows exactly from A_4 symmetry

$$U = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ \sqrt{1/6} & -\sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

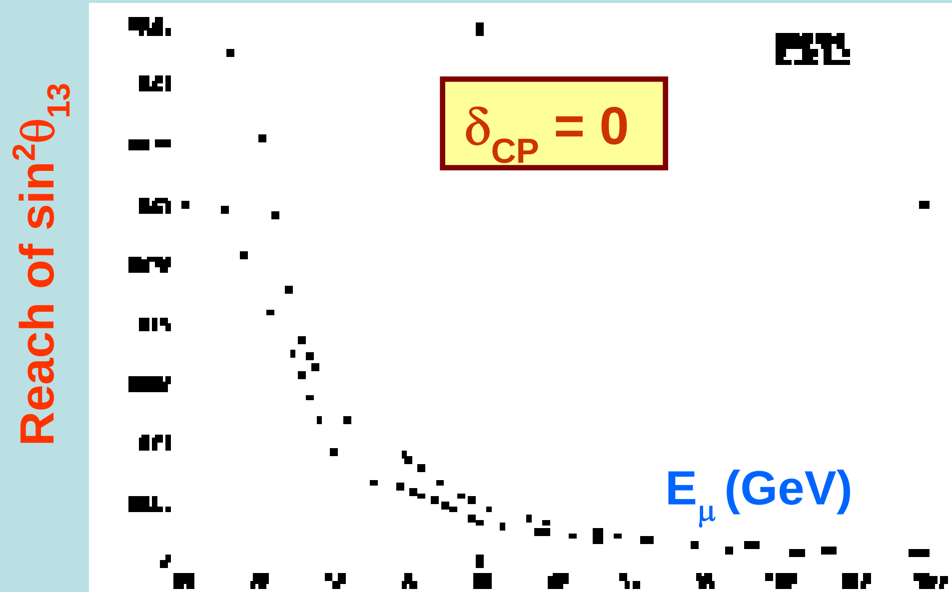
Some physics studies have been made for possible neutrino beams from Neutrino Factory with ICAL at INO as the End-detector.

Two baseline lengths are considered

Possible signals for deviation from tri-bimaximality are studied

$\sin^2\theta_{13}$ reach ~ 0.001 ($\theta_{13} < 2^0$) at INO is obtained for E_μ ~ 105 GeV.

The effect of CP-violation and of mass hierarchy on $\sin^2\theta_{13}$ reach is also studied.



Farzan

Principles/Symmetries to predict CP phases

- Zero Dirac phase
  – No CP-violation $\equiv$ zero Dirac as well as Majorana phases; Rephasing Invariants;
  – $\delta = 0$ but $\phi_1, \phi_2 \neq 0$: Conditions on m_ν;

- Maximal δ; $\mu - \tau$ reflection symmetry;

$$\nu_e \rightarrow \xi_1 \nu_e^c, \quad \nu_\mu \rightarrow \xi_2 \nu_\tau^c, \quad \nu_\tau \rightarrow \xi_3 \nu_\mu^c,$$

- Arbitrary δ between zero and maximal value: Generalized $\mu - \tau$ reflection symmetry.

$$\nu_\alpha \rightarrow \sum_\beta P_{\alpha\beta}(\alpha, \phi) \nu_\beta^c \qquad P(\alpha, \phi) = U_{23}(\alpha) \mathrm{Diag}[1, 1, e^{i\phi}] U_{23}^T(\alpha)$$

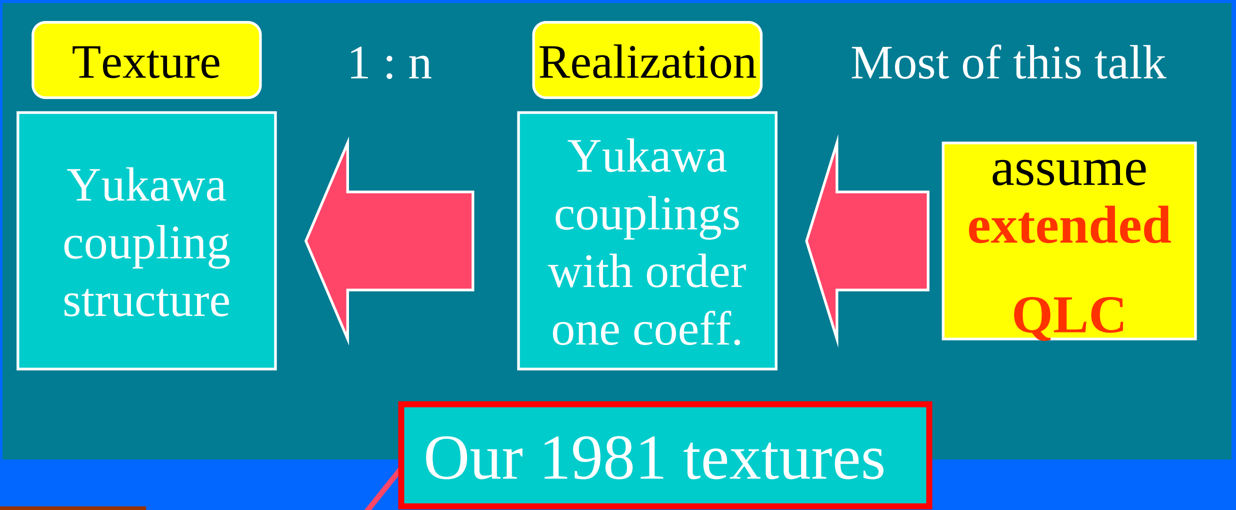
- Relations between the phases of the CKM and PMNS matrix

under certain conditions $\rightarrow$

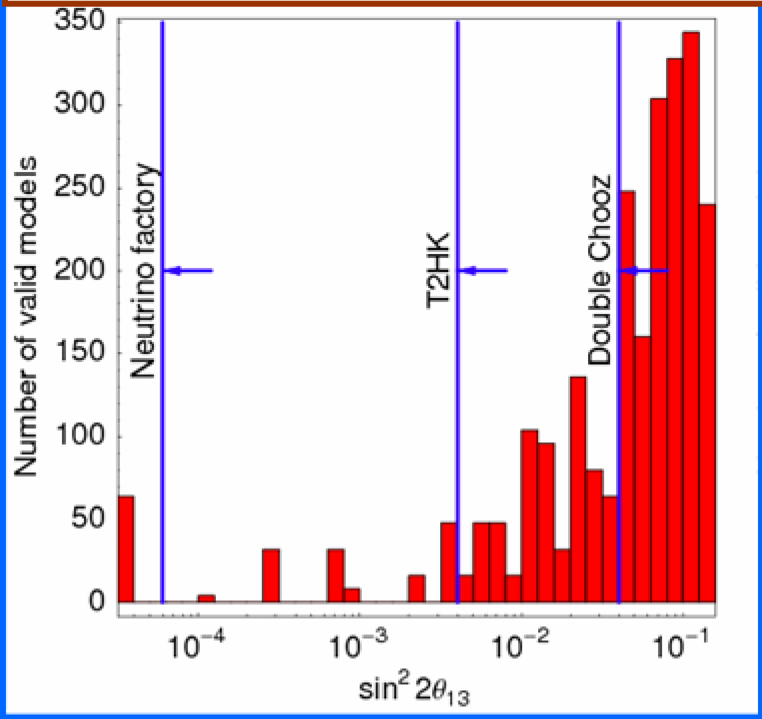
$$|\sin\theta_{13}| \simeq \frac{\sin\theta_C}{\sqrt{2}} \qquad \sin\delta \approx \frac{|V_{ub}|}{\sin\theta_C} \sin\delta_{CKM}$$

Winter

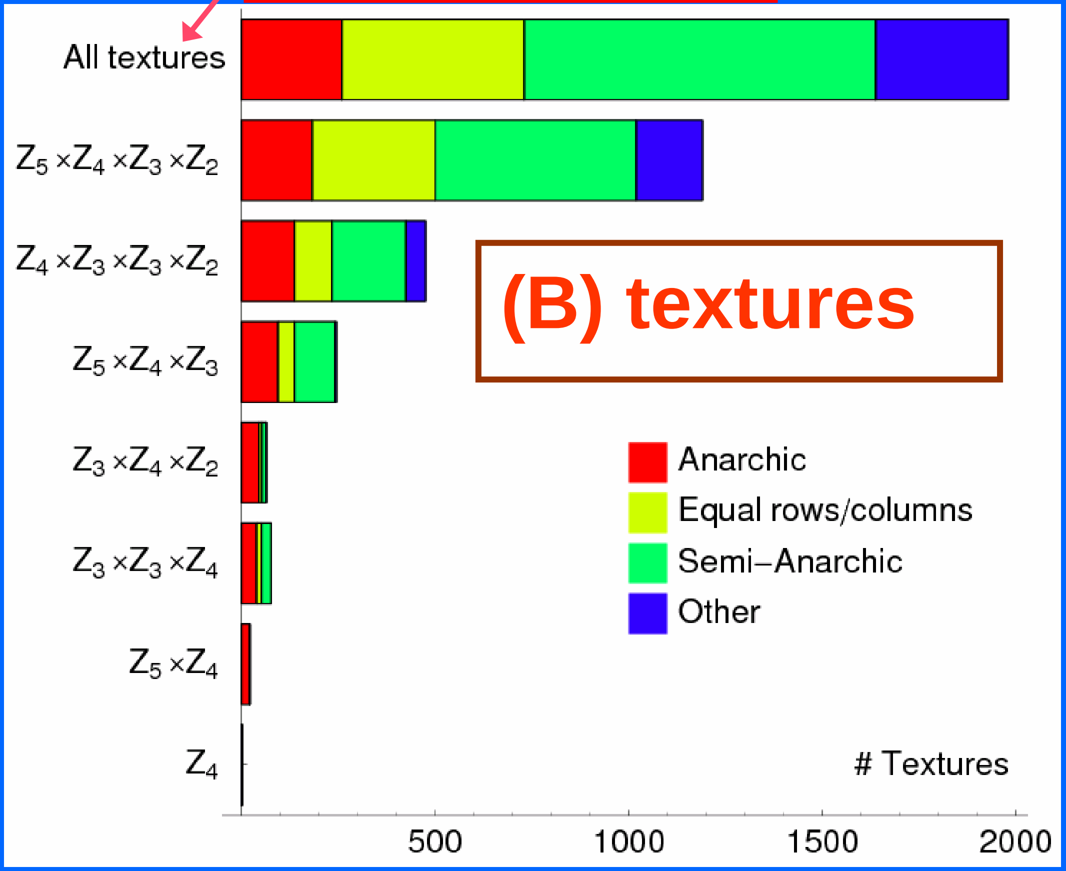
- Bottom-up approach:



(A) prediction for θ_{13}



(B) textures



Sterile neutrino scenario

$\Delta m^2_{\text{sol}} \sim 10^{-4}\text{eV}^2$ $\Delta m^2_{\text{atm}} \sim 10^{-3}\text{eV}^2$ $\Delta m^2_{\text{LSND}} \sim O(1)\text{eV}^2$

→ **at least one ν_s is required**

$\text{LSND}(\bar{\nu}_\mu \to \bar{\nu}_e)$: affirmative

$\text{MiniBOONE}(\nu_\mu \to \nu_e)$: negative

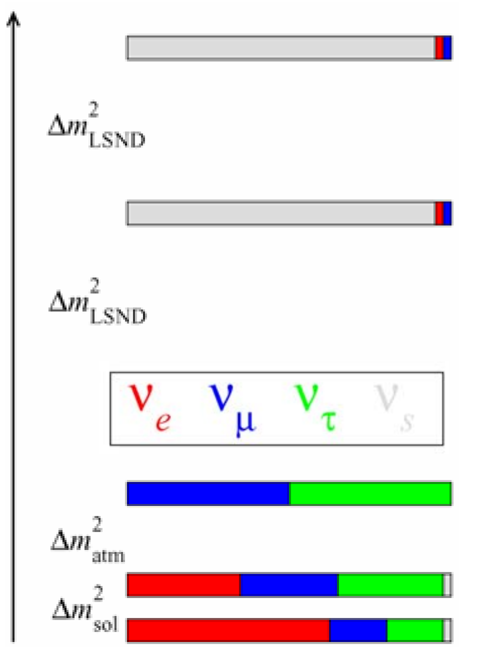
→ **difference between ν & anti-ν may offer a promising fit**

(3+2)-scheme w/ CP phase δ

$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} &= 4\,|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \phi_{41} \\
&+ 4\,|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2 \phi_{51} \\
&+ 8\,|U_{e4} U_{\mu 4} U_{e5} U_{\mu 5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \delta)
\end{aligned}
$$

with the definitions

$$\phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}, \qquad \delta \equiv \arg\left(U^*_{e4} U_{\mu 4} U_{e5} U^*_{\mu 5}\right).$$

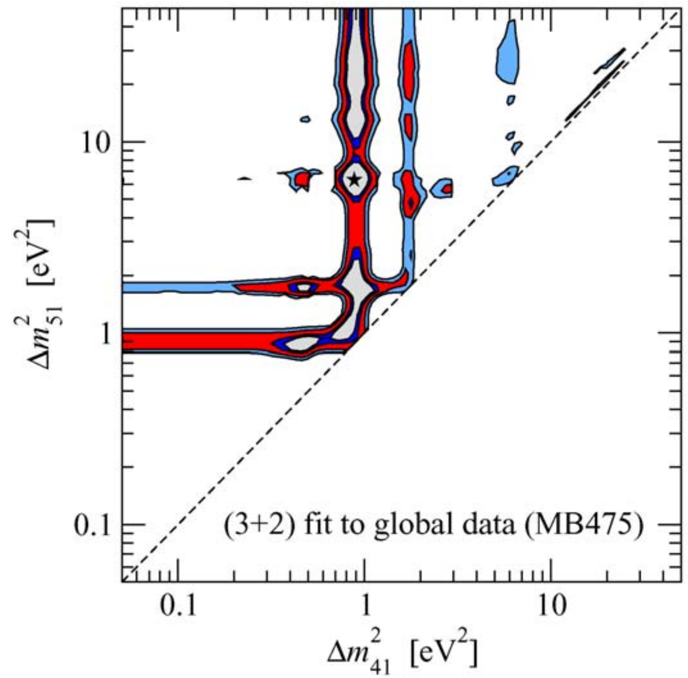


Schwetz-Mangold

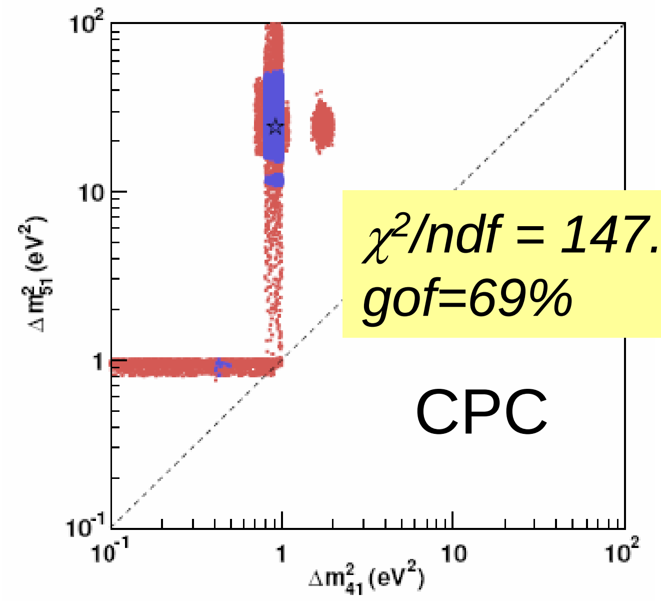
$$\Delta m^2_{41} = 0.89 \text{ eV}^2$$
$$\Delta m^2_{51} = 6.49 \text{ eV}^2$$

$$\chi^2_{\min} = 94.5/(107-7)$$

$\phi_{54}^{best} = 1.64\,\pi$

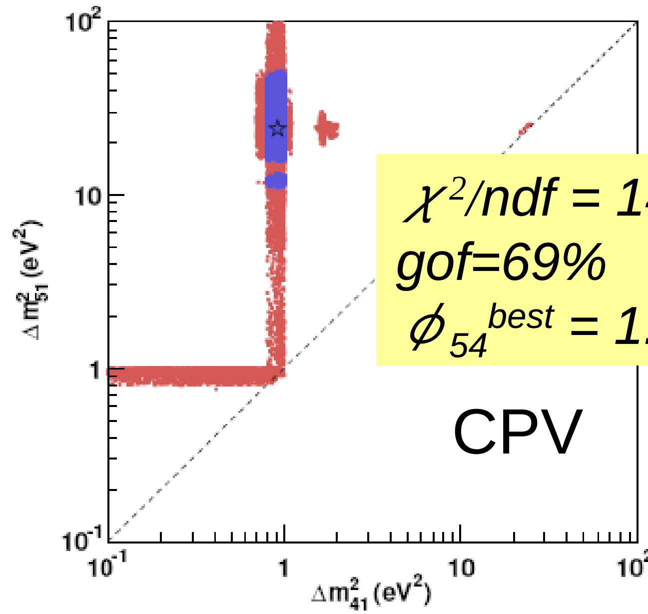


Karagiorgi



$\chi^2/ndf = 147.9/157$
gof=69%

CPC



$\chi^2/ndf = 146.7/156$
gof=69%
$\phi_{54}^{best} = 1.74\,\pi$

CPV

- (3+2) schemes
  - offer the possiblity of CP violation to reconcile LSND and MiniBooNE,
  - but there is tension between appearance and disappearance data ($3\sigma, 4\sigma$ for MB300)

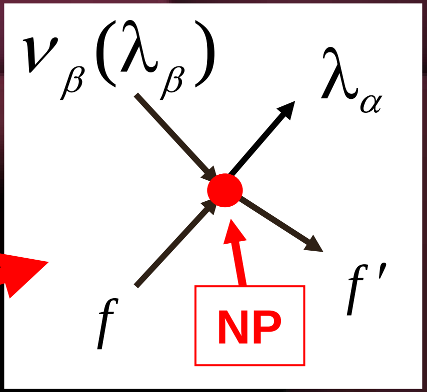
The two works basically agree, but some details (comparison between CPC & CPV, inclusion of low energy data, etc.) have to be worked out in future.

New Physics/Non-Standard Interaction

New Physics involving charged leptons

If either of the particles with flavor α and β in the NP interaction is charged lepton, then

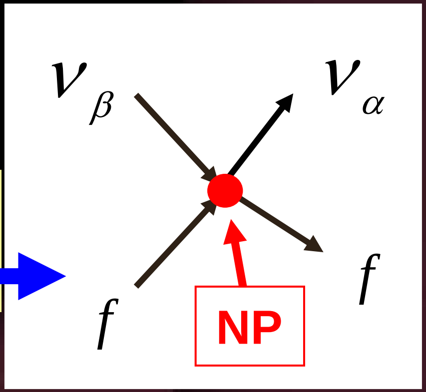
- **New Physics at source and detector:** Agarwalla, Ota , Lopez-Pavon



New Physics with neutral current

If the particles with flavor α and β in the NP interaction are both neutrinos, then

- **New Physics in propagation (matter effect):** Ohlsson, Sugiyama, Ota

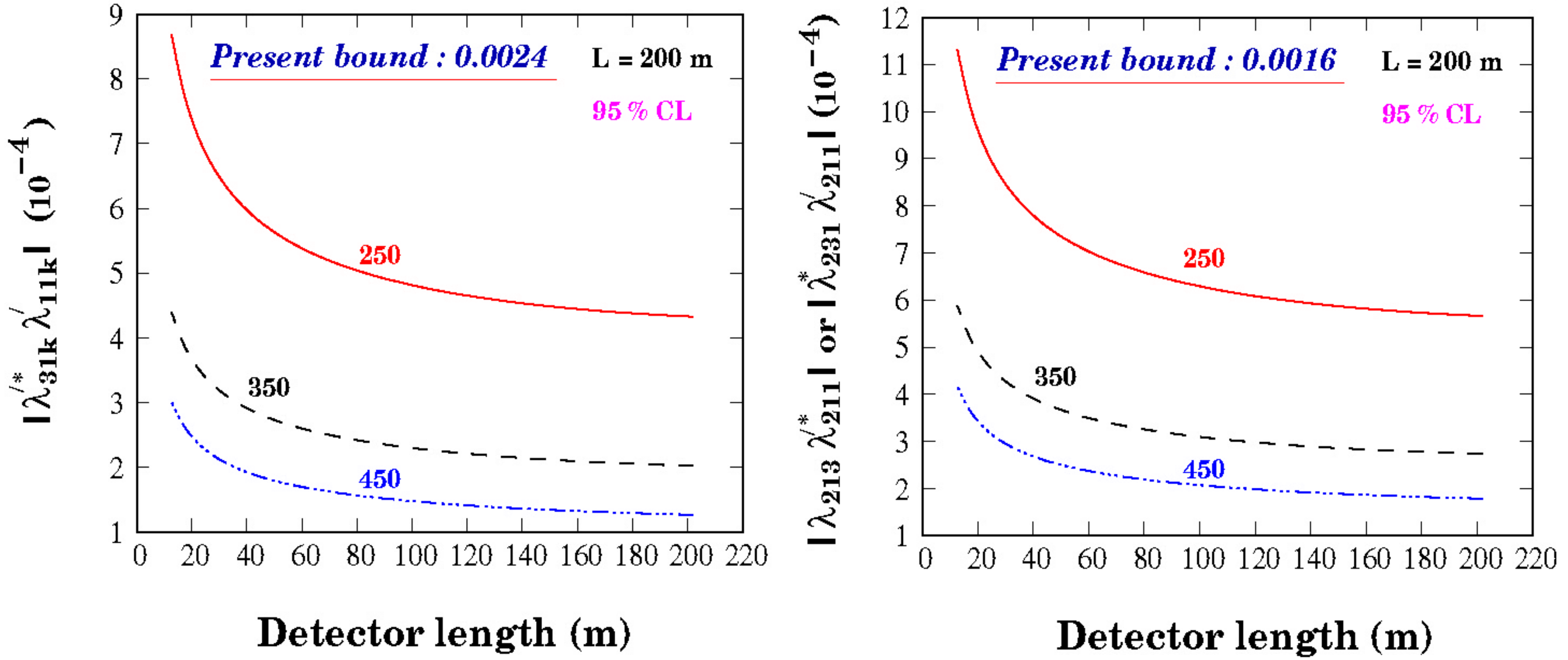


$$\begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \Rightarrow A\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\tau\mu} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\tau\mu} & \varepsilon_{\tau\tau} \end{pmatrix}$$

Agarwalla

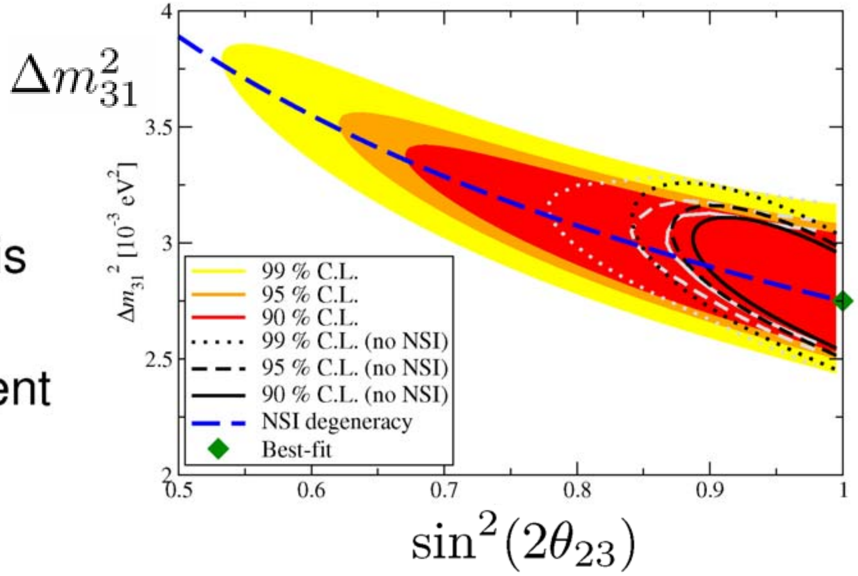
$$\mathcal{L}_{\lambda'} = \lambda'_{ijk}\left[\tilde{d}^j_L\,\bar{d}^k_R\nu^i_L + (\tilde{d}^k_R)^*(\bar{\nu}^i_L)^c d^j_L\right] + h.c.$$

- **We consider a β-beam experiment with CERN-INO baseline.** $R\!\!\!/$ interactions may obstruct a clean extraction of the mixing angle θ_{13} or determination of the **mass hierarchy** unless the bounds on the λ' couplings are tightened
- **one might see a clean signal of new physics and put tighter constraints on the λ' couplings**



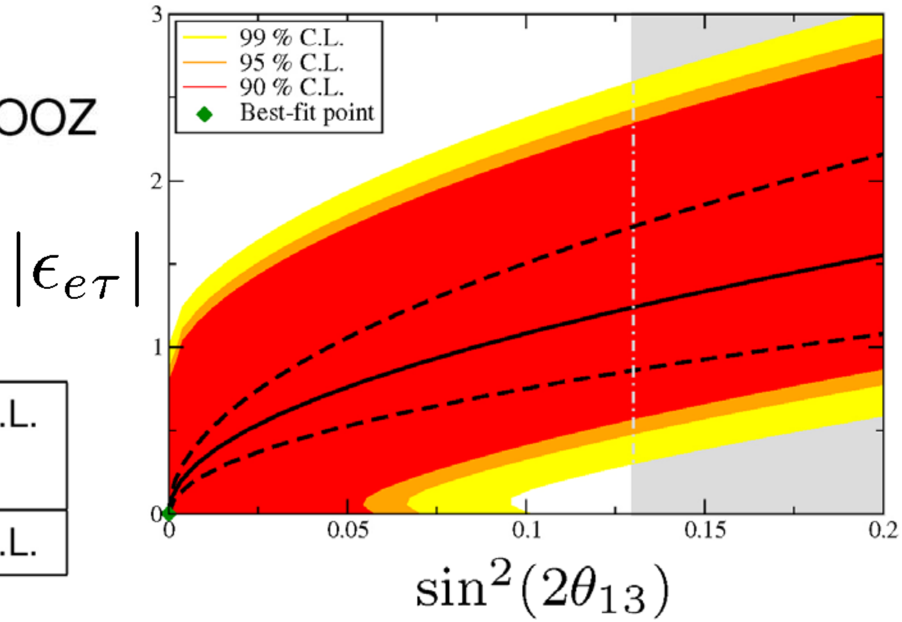
Ohlsson

$$A\begin{pmatrix} 1+\varepsilon_{ee} & 0 & \varepsilon_{e\tau} \\ 0 & 0 & 0 \\ \varepsilon^*_{e\tau} & 0 & \varepsilon_{\tau\tau} \end{pmatrix}$$



- Allowed region in the $\sin^2(2\theta_{23})$-Δm^2_{31} plane is extended to smaller values of $\sin^2(2\theta_{23})$ and larger values of Δm^2_{31} if NSI effects are present

- Possible bounds on the NSI parameter $\varepsilon_{e\tau}$ depending on the value of θ_{13}
- Better upper bound on $\sin^2(2\theta_{13})$ than CHOOZ only for small values of $|\varepsilon_{e\tau}|$

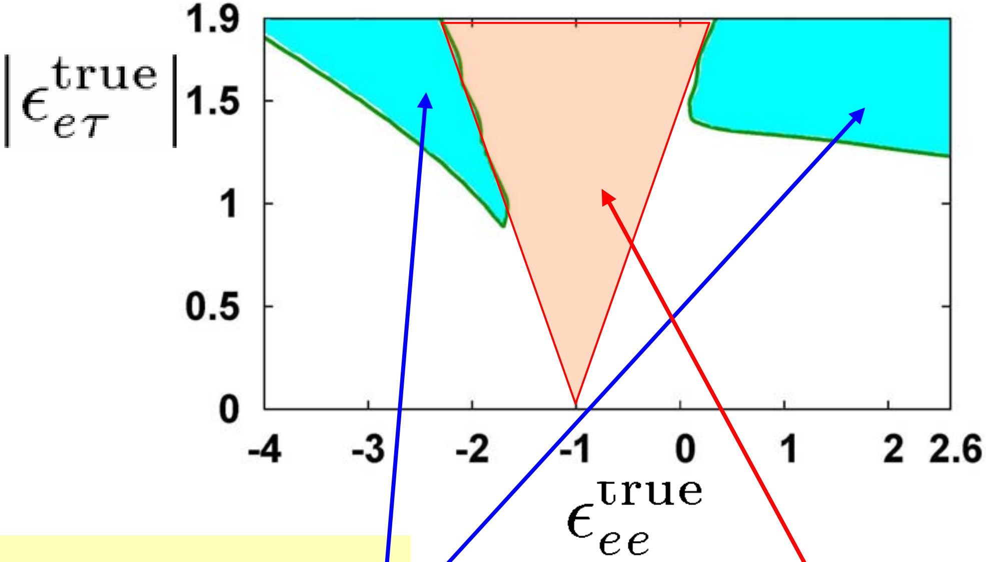


$\sin^2(2\theta_{13}) = 0.07$	$-2.16 < \varepsilon_{e\tau} < -1.31$ $-0.60 < \varepsilon_{e\tau} < 0.41$	90 % C.L.
$\sin^2(2\theta_{13}) = 0$	$-0.69 < \varepsilon_{e\tau} < 0.8$	90 % C.L.

Sugiyama

$$A\begin{pmatrix} 1+\varepsilon_{ee} & 0 & \varepsilon_{e\tau} \\ 0 & 0 & 0 \\ \varepsilon^*_{e\tau} & 0 & \varepsilon_{\tau\tau} \end{pmatrix}$$

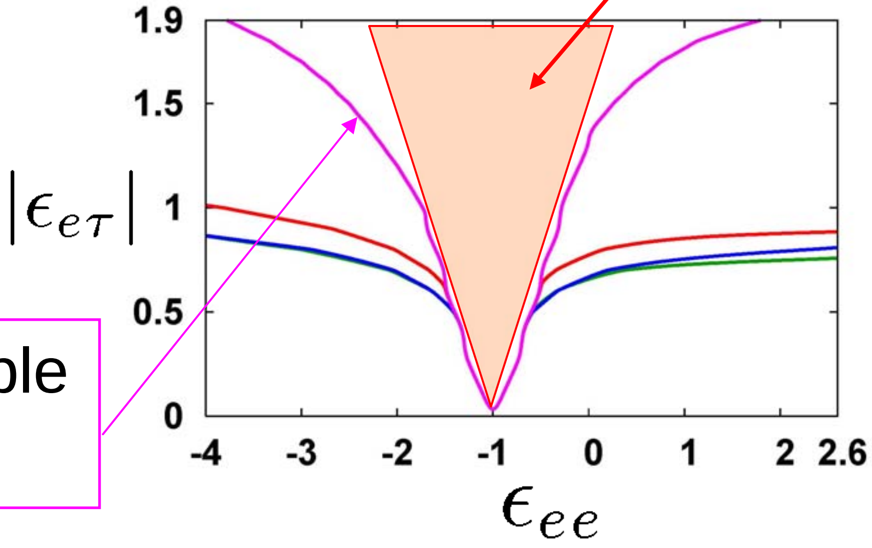
ν_e appearance in MINOS



- If MINOS finds ν_e appearance, and if true values exist within the light blue region, we **can exclude** $\varepsilon_{ee} = \varepsilon_{e\tau} = 0$

excluded by ν_{atm} & K2K

- If MINOS does not find ν_e appearance, constraints on ε does **not improve much**.

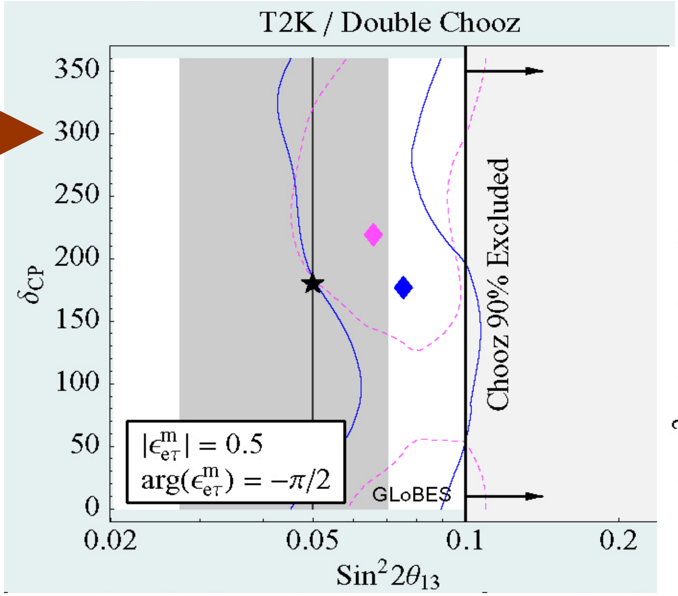


excluded above the purple line for $\delta+\arg[\varepsilon_{e\tau}]=-\pi/2$

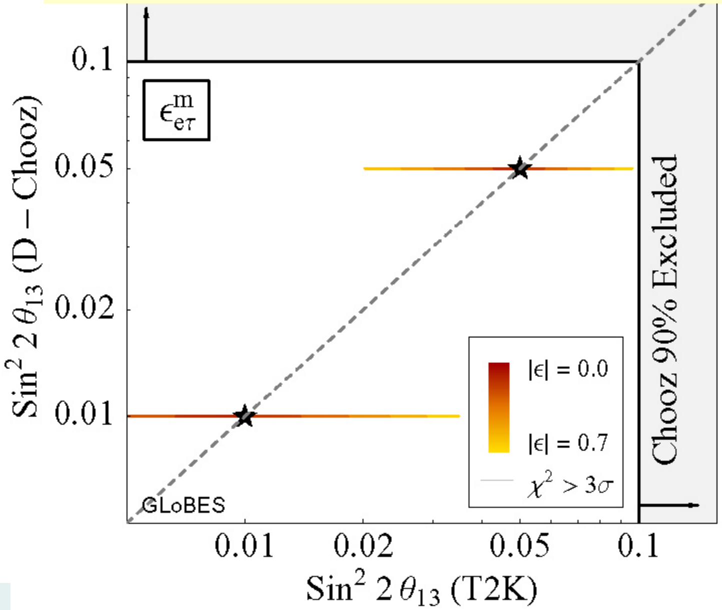
Ota

Mismatch

Best fit points for reactor & T2K don't agree

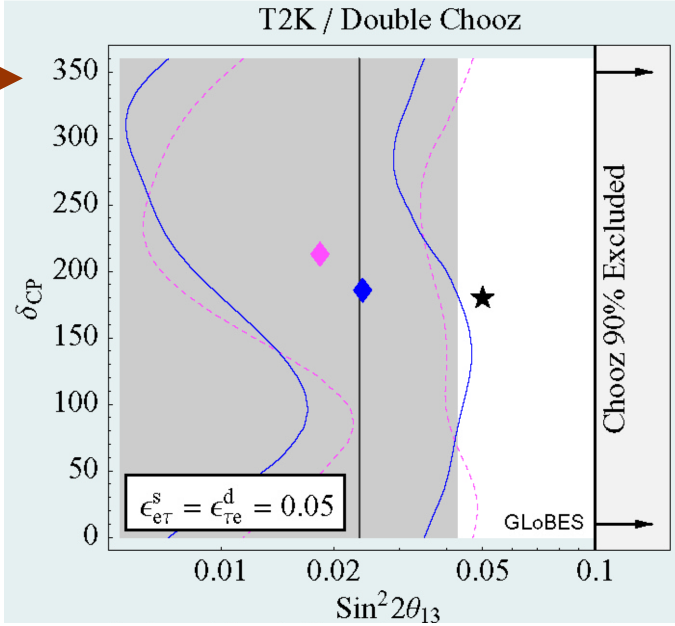


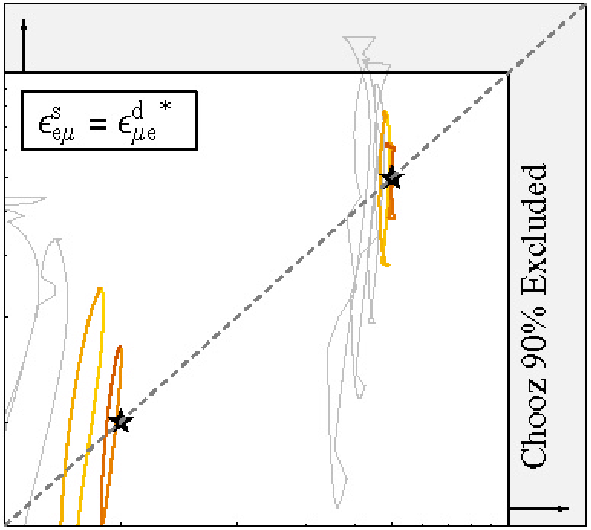
$|\varepsilon^m|$=0-0.7, arg[ε]=0-2π



Offset

Best fit points for two agree but miss the true point

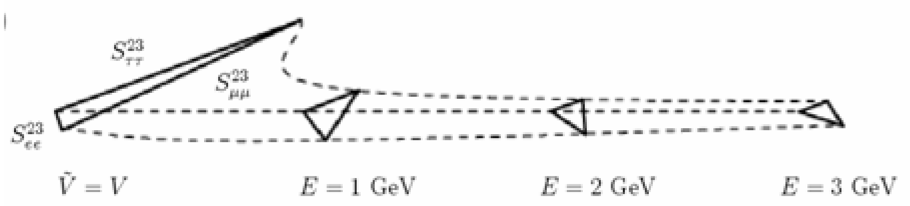




$|\varepsilon^{s,d}|$=0-0.1, arg[ε]=0-2π

Discovery reach : depends on arg[ε]

Xing



◆ **Testing the unitarity of lepton flavor mixing is an important task in the era of precision measurements. A way to explore new physics.**

$$\tilde{V}_{\mu 1}\tilde{V}^*_{\tau 1} = \frac{(\hat{\Delta}_{21} + A)\Delta_{31}}{\tilde{\Delta}_{21}\tilde{\Delta}_{31}} V_{\mu 1}V^*_{\tau 1} + \frac{(\hat{\Delta}_{11} + A)\Delta_{32}}{\tilde{\Delta}_{21}\tilde{\Delta}_{31}} V_{\mu 2}V^*_{\tau 2}$$

$$\tilde{V}_{\mu 2}\tilde{V}^*_{\tau 2} = \frac{(\hat{\Delta}_{32} + A)\Delta_{21}}{\tilde{\Delta}_{32}\tilde{\Delta}_{21}} V_{\mu 2}V^*_{\tau 2} + \frac{(\hat{\Delta}_{22} + A)\Delta_{31}}{\tilde{\Delta}_{32}\tilde{\Delta}_{21}} V_{\mu 3}V^*_{\tau 3}$$

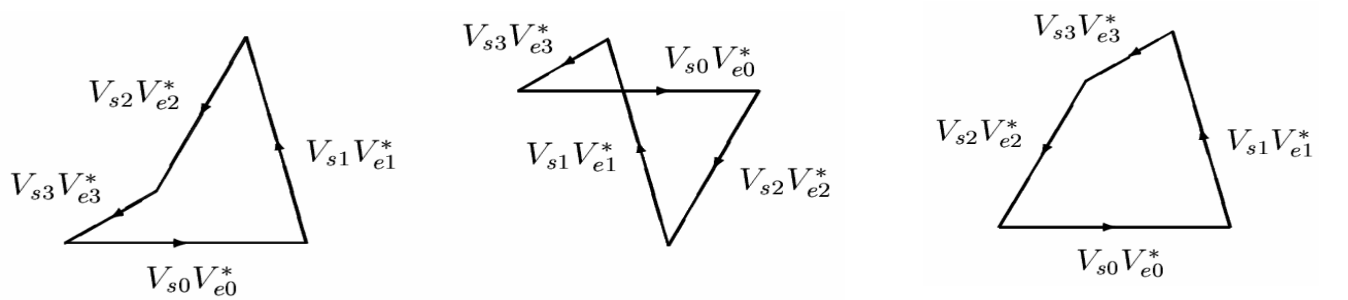
$$\tilde{V}_{\mu 3}\tilde{V}^*_{\tau 3} = \frac{(\hat{\Delta}_{13} + A)\Delta_{23}}{\tilde{\Delta}_{13}\tilde{\Delta}_{23}} V_{\mu 3}V^*_{\tau 3} + \frac{(\hat{\Delta}_{33} + A)\Delta_{21}}{\tilde{\Delta}_{13}\tilde{\Delta}_{23}} V_{\mu 1}V^*_{\tau 1}$$

◆ **In realistic seesaw models, the 3×3 MNS matrix is non-unitary.**

Natural seesaw: unitarity violation ~< 10^{-24}

Unnatural seesaw: unitarity violation ~< 10^{-2}

◆ **The existence of sterile neutrinos would violate the unitarity of the 3×3 MNS matrix (at a detectable level?)**



Kimura

Independent determination of δ from $\nu_\mu \to \nu_\mu$ → Test of unitarity

General feature on CP dependence

$$P_{\mu e} = A_{\mu e}\cos\delta + B_{\mu e}\sin\delta + C_{\mu e}$$
$$P_{\mu\mu} = A_{\mu\mu}\cos\delta + C_{\mu\mu}$$

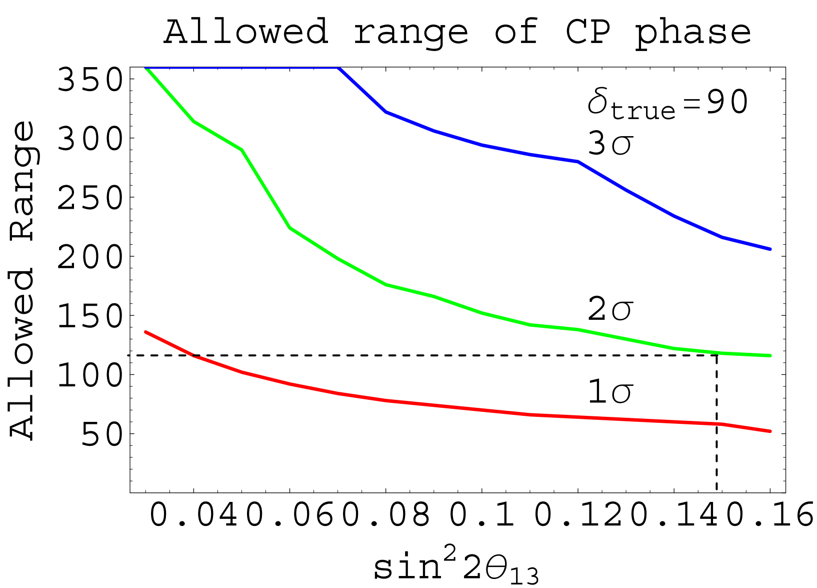
Magnitude of each coefficient

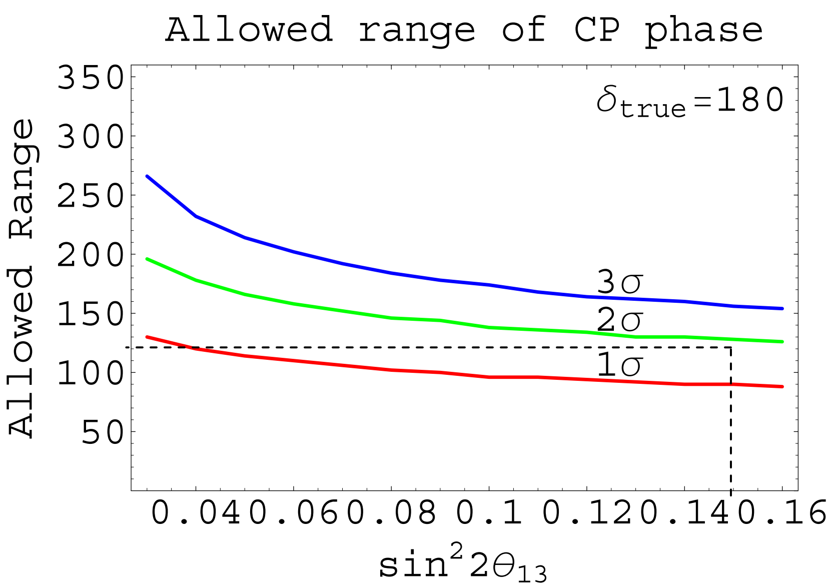
$$A_{\mu\mu} = -A_{\mu e} = O(\alpha s_{13})$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$$

3 flavor unitarity is assumed

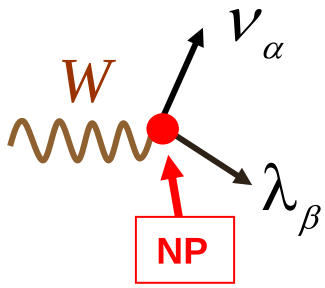
4MW JPARC beam, 500kt WC Detector,
E=0.4-10 GeV and L=295km, 5000km,
10 years run





Lopez-Pavon

Unitarity of the leptonic mixing matrix



minimal non-unitary model

$U \rightarrow N$ (non-unitary)

$NN^\dagger - 1$: deviation from unitarity

mostly from rare decays

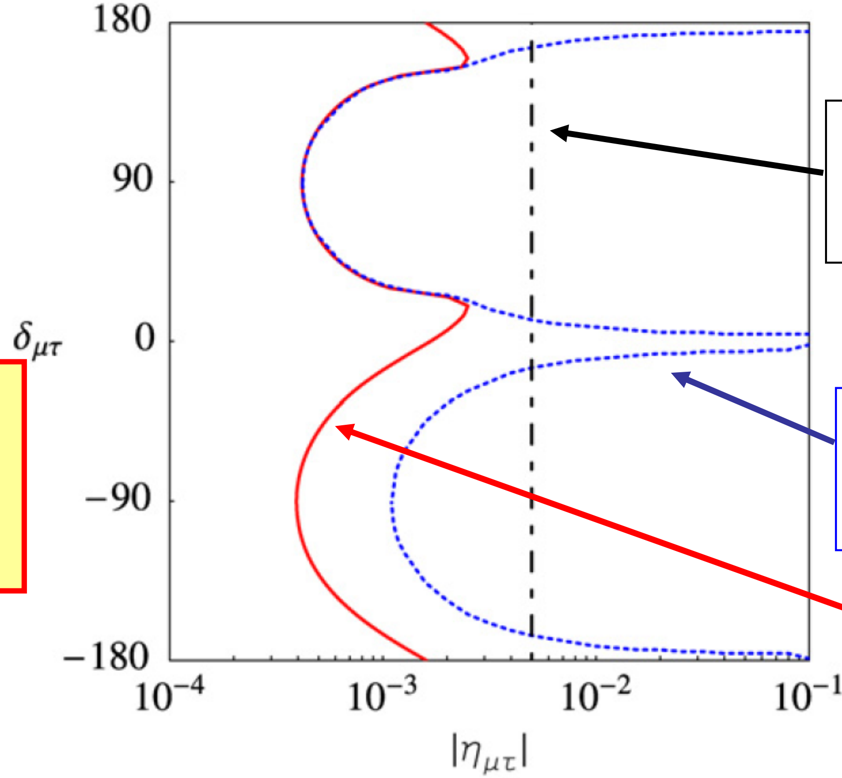
$$|NN^\dagger| \approx \begin{pmatrix} 0.994 \pm 0.005 & < 7.1\cdot 10^{-5} & < 1.6\cdot 10^{-2} \\ < 7.1\cdot 10^{-5} & 0.995 \pm 0.005 & < 1.0\cdot 10^{-2} \\ < 1.6\cdot 10^{-2} & < 1.0\cdot 10^{-2} & 0.995 \pm 0.005 \end{pmatrix}$$

90% C.L.

Phase of N

$\nu_\mu \leftrightarrow \nu_\tau$

For non-trivial $\delta_{\mu\tau}$, one order of magnitude improvement for $|\eta_{\mu\tau}|$



Present bound from $\tau \rightarrow \mu\gamma$

Sensitivity to $\delta_{\mu\tau}$

Sensitivity to $|\eta_{\mu\tau}|$

Future problems toward nufact08

After the ISS report is finished, there are still a lot of problems ahead of us:

- Predictions of various schemes on deviation from SM+massive ν
- Quantitative discussions on determination of small quantities such as θ_{13}, $\pi/4-\theta_{23}$, and parameters of new physics and/or non-unitarity (correlations of errors, degeneracies, dependence on the beam energy and the baseline, etc.)
- Test of leptonic unitarity
- Other strong physics case for future LBL
- Many more .....