ニュートリノ振動研究の現状と展望

首都大理　安田修

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シンポジウム「宇宙と素粒子の残された謎の解明に向けた，次世代ニュートリノ観測・陽子崩壊実験」
＠日本物理学会年会

1. Introduction

2. 3 flavor ν oscillation

3. Scenarios beyond the standard 3 ν oscillation

4. Summary

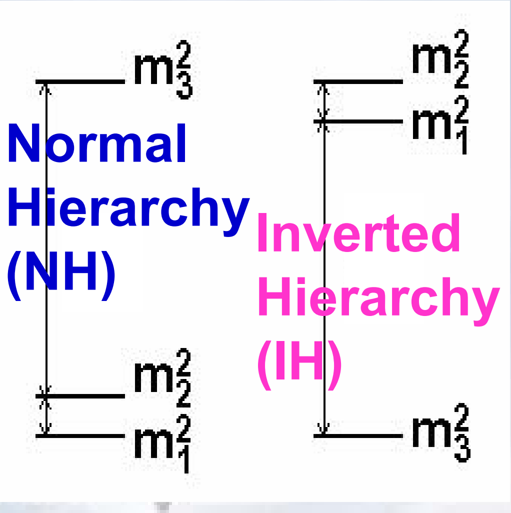
1. Introduction

Framework of 3 flavor ν oscillation

Mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Functions of mixing angles θ_{12}, θ_{23}, θ_{13}, and CP phase δ



All 3 mixing angles have been measured (2012):

ν_{solar}+KamLAND (reactor) → $\theta_{12} \simeq \frac{\pi}{6}, \Delta m_{21}^2 \simeq 8 \times 10^{-5}\,\mathrm{eV}^2$

ν_{atm}+K2K,MINOS(accelerators) → $\theta_{23} \simeq \frac{\pi}{4}, |\Delta m_{32}^2| \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2$

DCHOOZ+Daya Bay+Reno (reactors), T2K+MINOS, others → $\theta_{13} \simeq \pi / 20$

Motivation for precise measurement of oscillation parameters

From symmetry arguments, all kind of predictions have been made for oscillation parameters:

- **Quark-lepton complementarity**
  Minakata-Smirnov, PR D70 (2004) 073009

$$\theta_{12}+\theta_C= \pi/4$$

- **T' symmetry**
  Eby-Frampton, PR D86 (2012) 117304

$$\pi/4 - \theta_{23}= 2^{-1/2}\ \theta_{13}$$

- **Asymmetric TriBiMaximal Texture**
  Rahat-Ramond-Xu, PR D98 (2018) 055030

$$\delta_{CP} = \pm 1.32\pi$$

Quark mixing has been measured to the precision of O(0.01°):

CKM angles @1σ (PDG)

θ_{12} = 12.975 ± 0.026 deg

θ_{23} = 2.415 ± 0.044 deg

θ_{13} = 0.204 ± 0.010 deg

Lepton mixing which is measured to date

Lepton mixings @ 1σ

Capozzi, Lisi, Marrone, Palazzo, arXiv:1804.09678

$\theta_{12} = 33.46 + 0.87 - 0.88$ deg

$\theta_{23} = 47.9 + 1.1 - 4.0$ deg

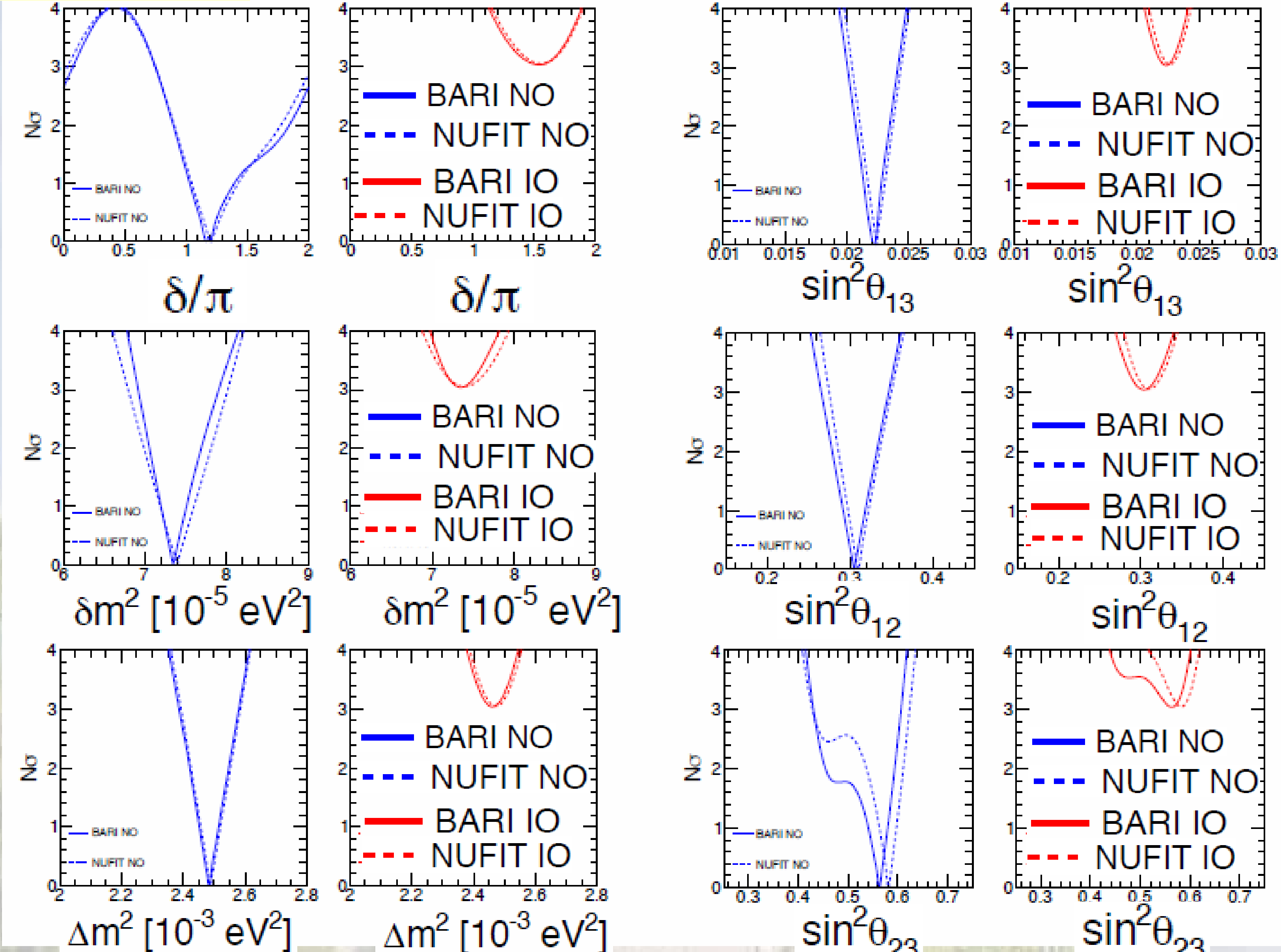
$\theta_{13} = 8.41 + 0.18 - 0.14$ deg

To test a hypothesis such as $\pi/4 - \theta_{23} = 2^{-1/2}\,\theta_{13}$, lepton mixing should be measured at least to order O(0.1°)

In particular, the precision of θ_{23} is a problem

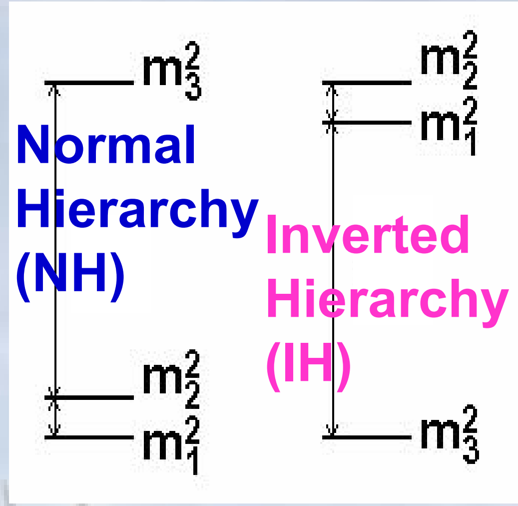
Status of 3ν fit

Lisi@Prospects of Neutrino Physics (IPMU, 2019/4)



NH(NO), δ~3π/2 is preferred over IH(IO), δ=0

Next task is to measure Mass Hierarchy (NH or IH), Octant (Higher Octant or Lower Octant) and δ (CP)



Experiments under construction / consideration

- **T2HK**(JP, JPARC-->HK) L=295km, E~0.6GeV
- DUNE (US, FNAL-->Homestake, SD) , L=1300km, E~2GeV
- **T2HKK**(JP, JPARC-->Korea) L=1100km, E~1GeV

$$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu + \overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$$

These experiments are expected to measure sign(Δm^2_{31}) , $\pi/4-\theta_{23}$ and δ

● Experiments under construction / consideration

T2HK

● **Extension of T2K (large #(events))**

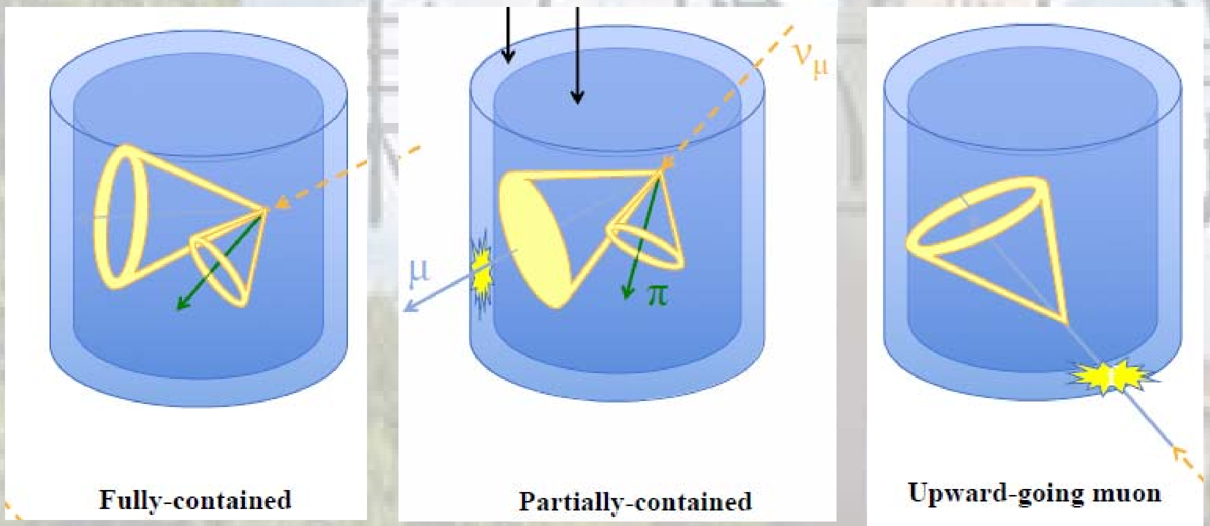
1.3MW ν beam ⇒ Hyperkamiokande

(3 times 2K) (10 times SK)

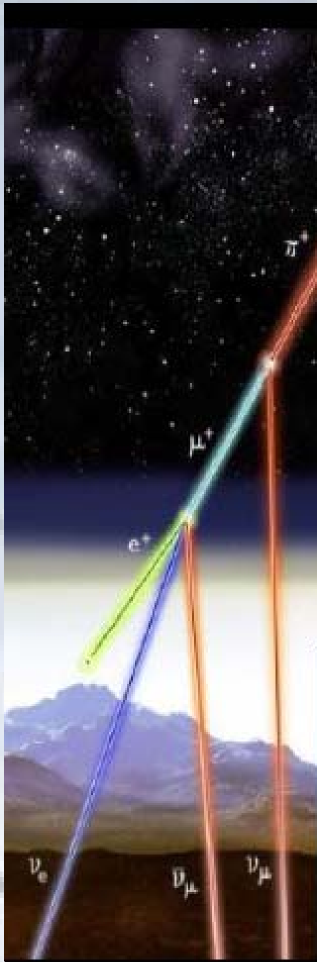
● **Measurement of CP phase δ**

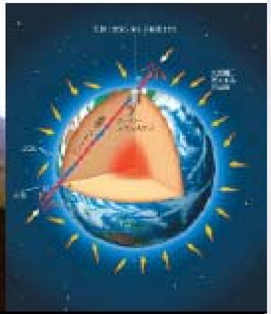
ν_{atm}@HK

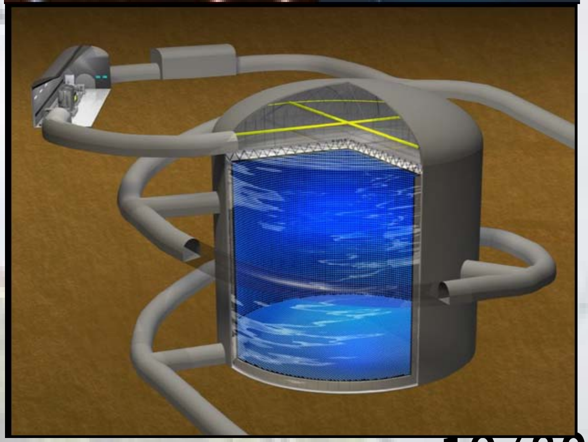
- 186 (×2) kton fiducial volume (2 × 8.3 × SK)
- Optically separated into
  - Inner Detector 40,000 (×2) PMTs (2×4×SK)
    - 40% Coverage (same as SK)
  - Outer Detector 12,000 (×2) PMTs (2×6×SK)
- ID Photosensors will be high QE
  - Single photon detection : 24% (2 × SK)



Fully-contained Partially-contained Upward-going muon







T2HKK (under consideration)

Extension of T2HK

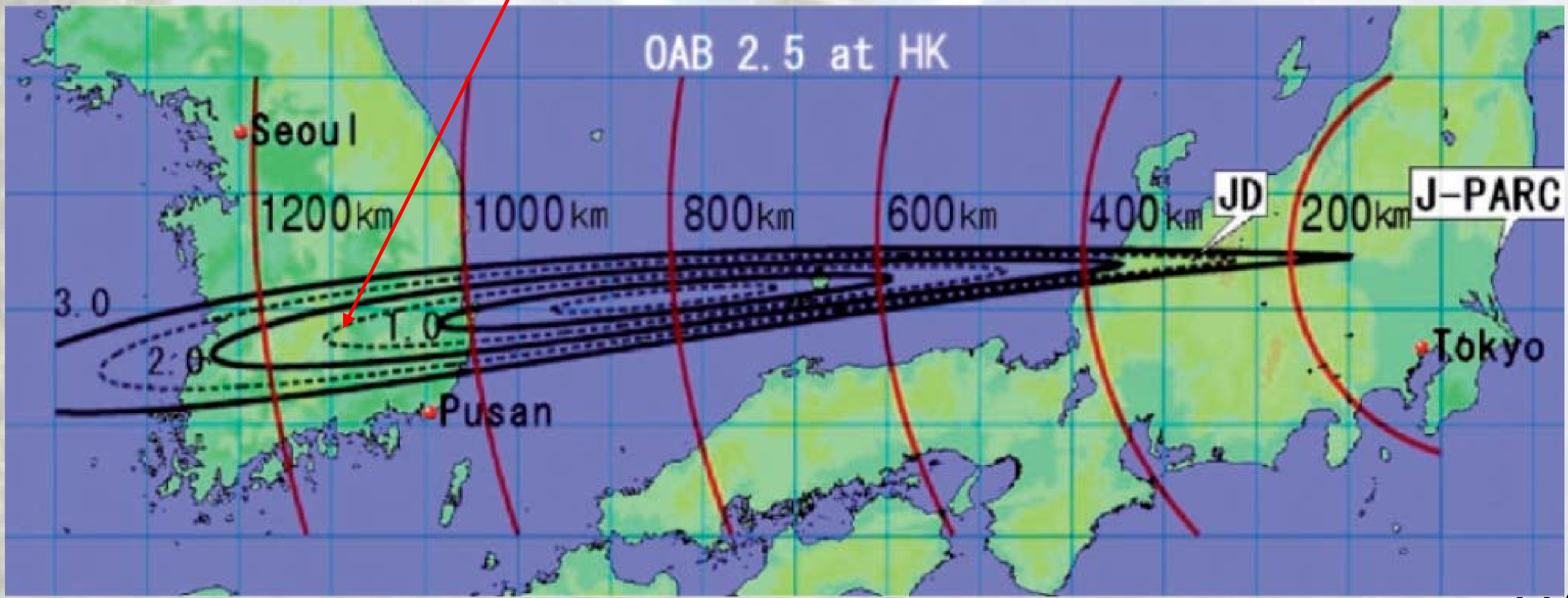
(L=295km, 187 kton fiducial volume)

+ (L=1100km, 187 kton fiducial volume)

ν:anti-ν = 1:3

Total exposure: 27 x 10^{21} POT

Off axis Angle = 1.5^{o} is the best (w/ max #(events))

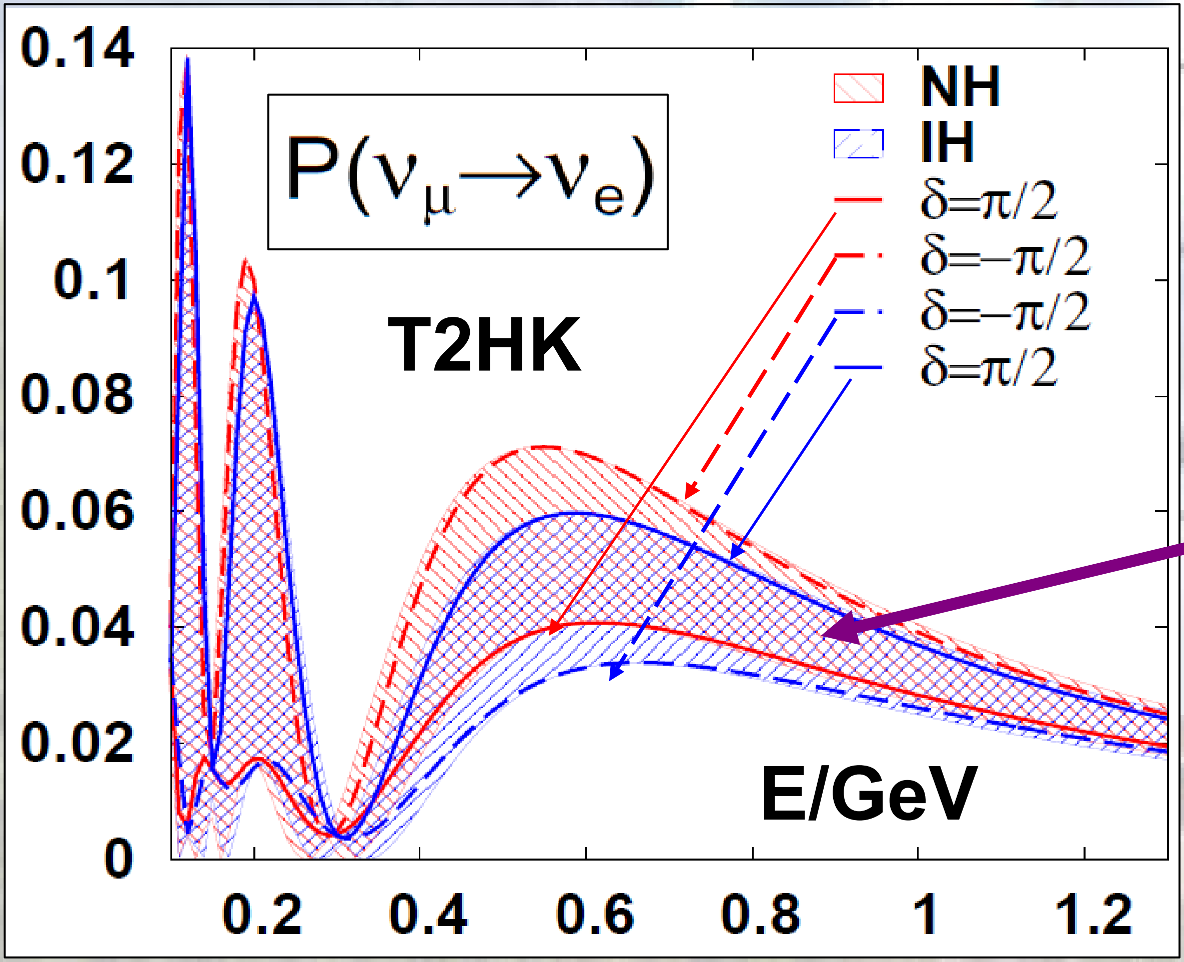


2. 3 flavor ν oscillation

Issue in measurement of δ at T2HK: Degeneracy in the appearance probabilities

hierarchy - δ

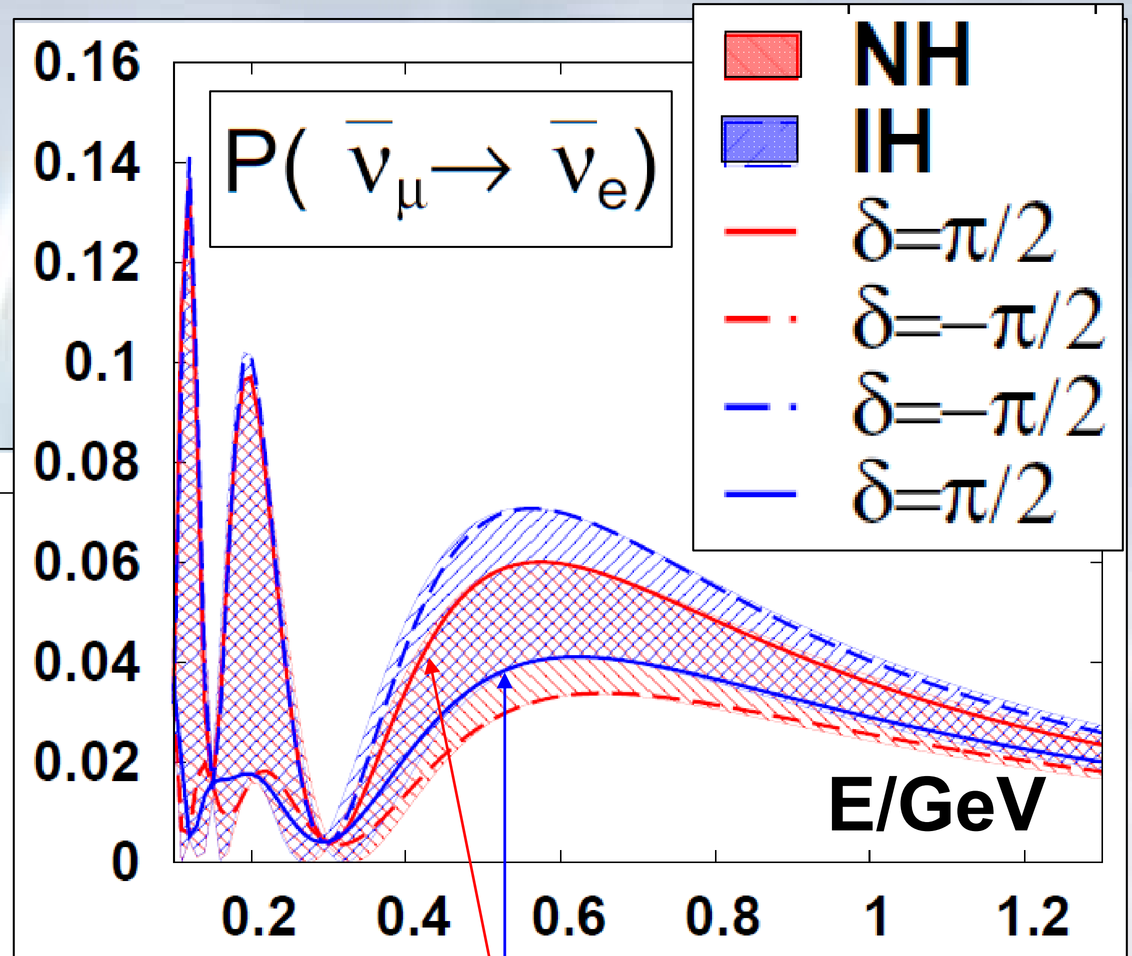
Prakash et al, PRD 86, 033012 ('12)

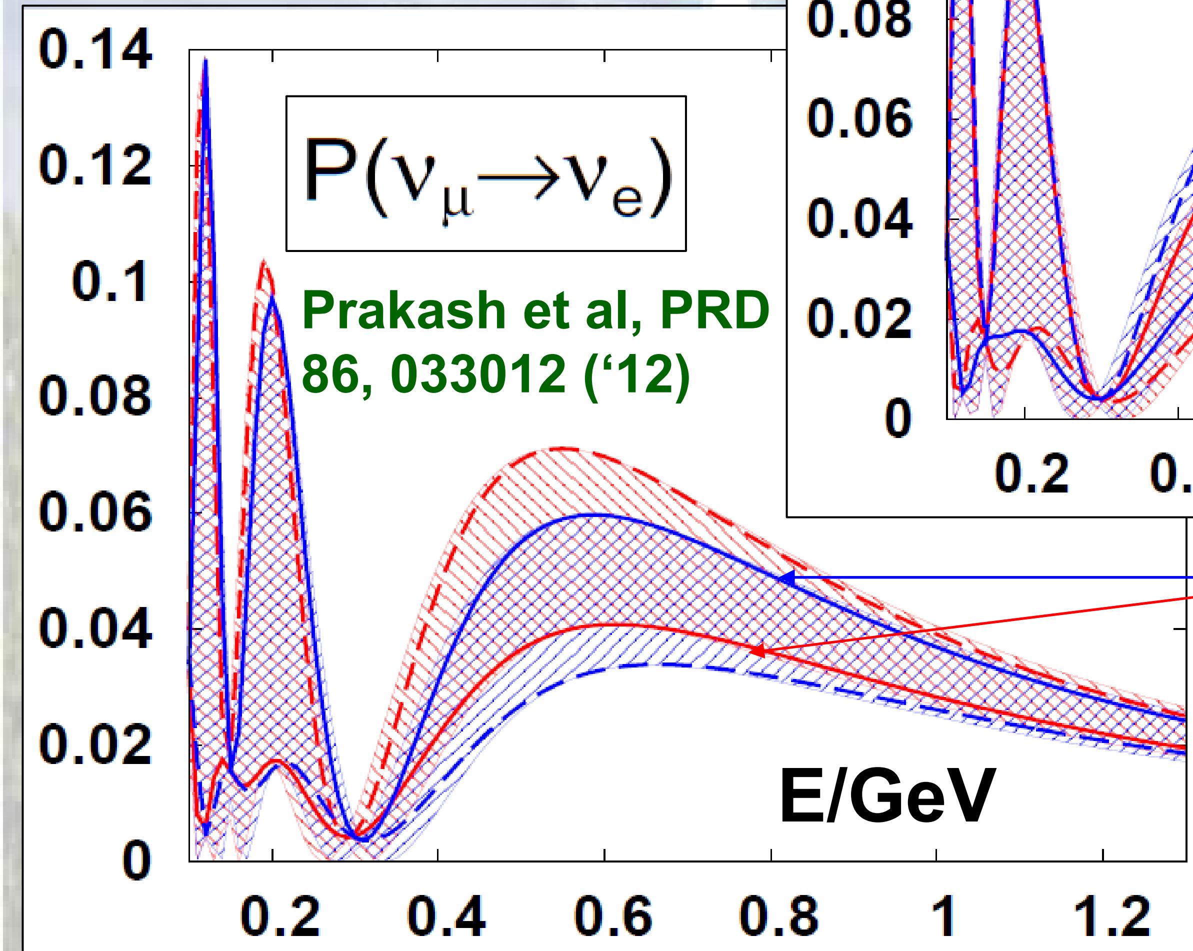


Due to uncertainty in δ, the appearance probabilities has finite width.
In the overlap region, δ has two possible values.

Hierarchy degeneracy @T2HK

NH-IH Separation is good (bad) for $\delta \sim -\pi/2$ $(+\pi/2)$





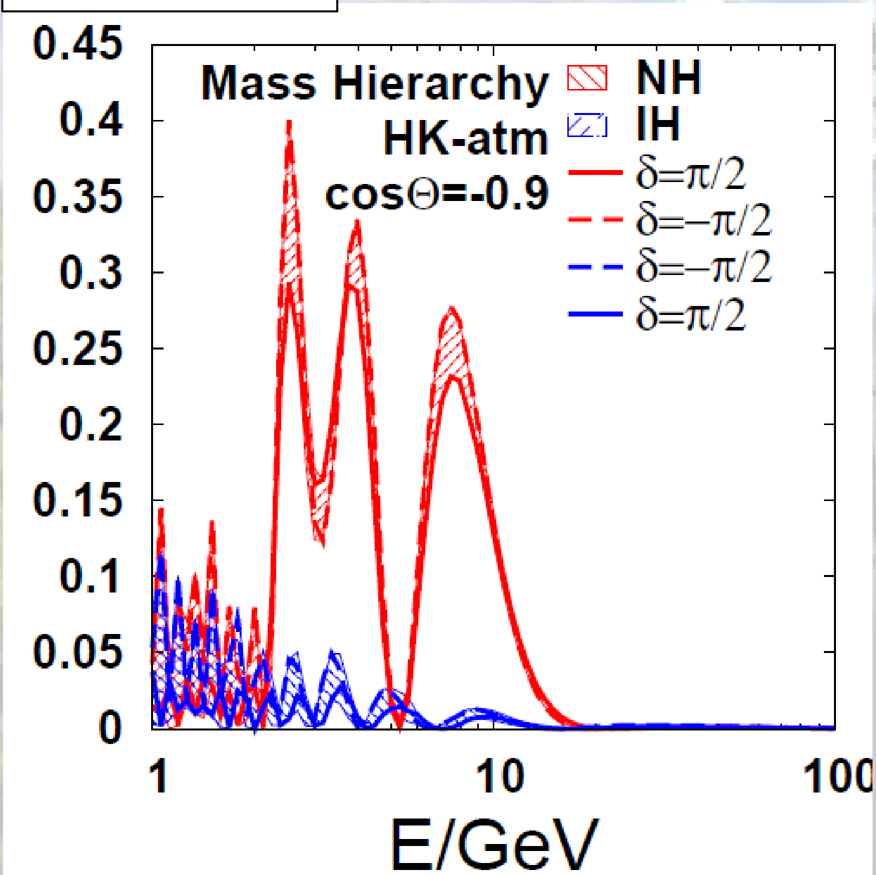
Prakash et al, PRD 86, 033012 ('12)

For $\delta \sim \pi/2$ degeneracy exists both in ν & $\bar{\nu}$

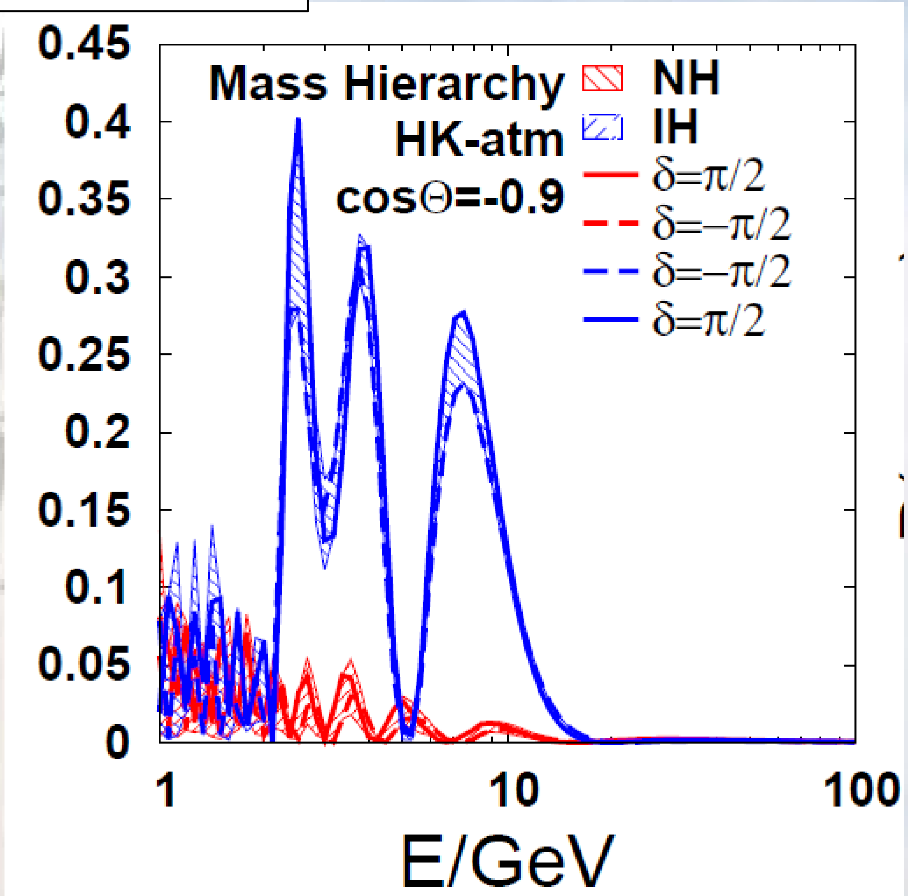
Hierarchy degeneracy ν_{atm}@HK

Hierarchy separation is excellent for cosΘ = -0.9 (L=11500km)

$P(\nu_\mu \rightarrow \nu_e)$

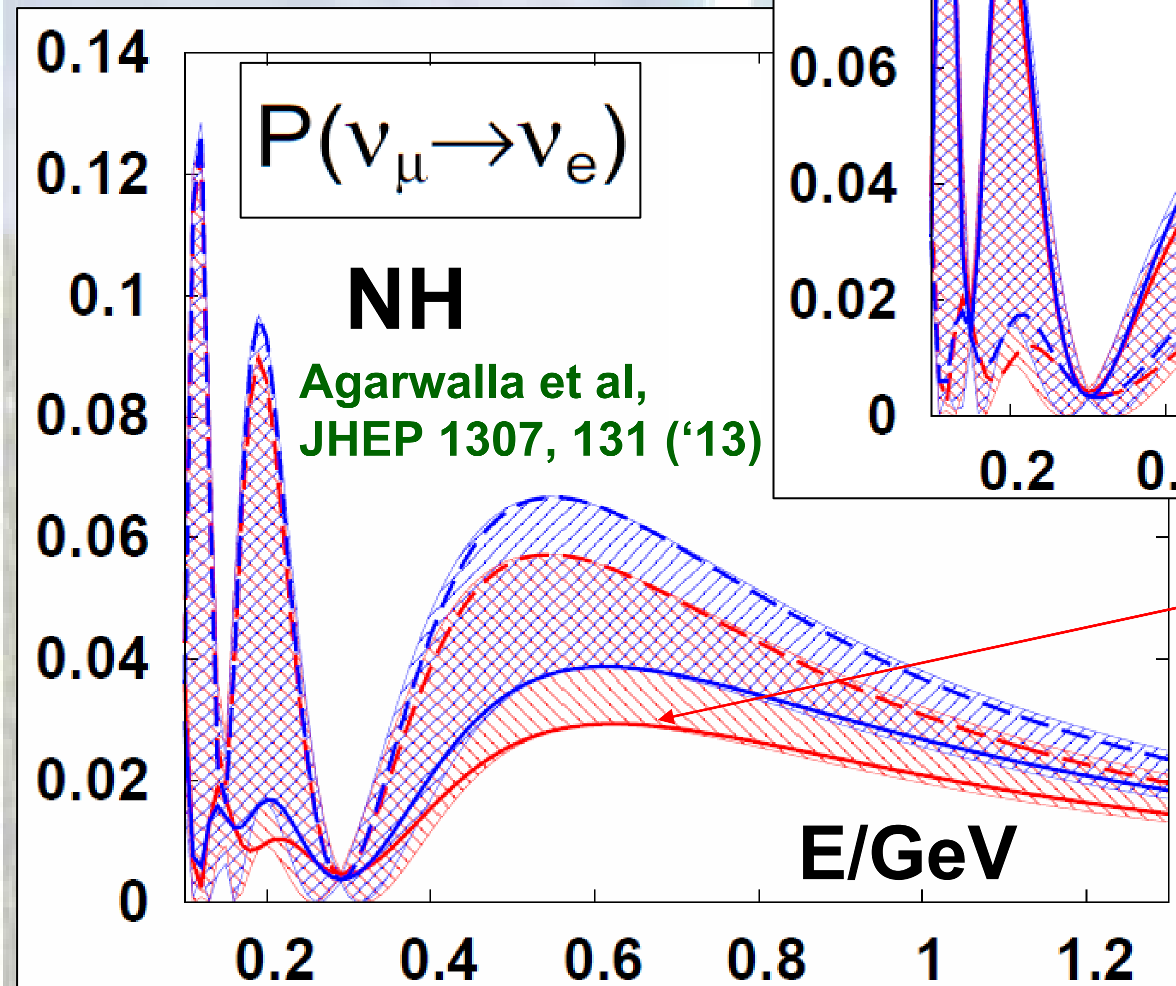


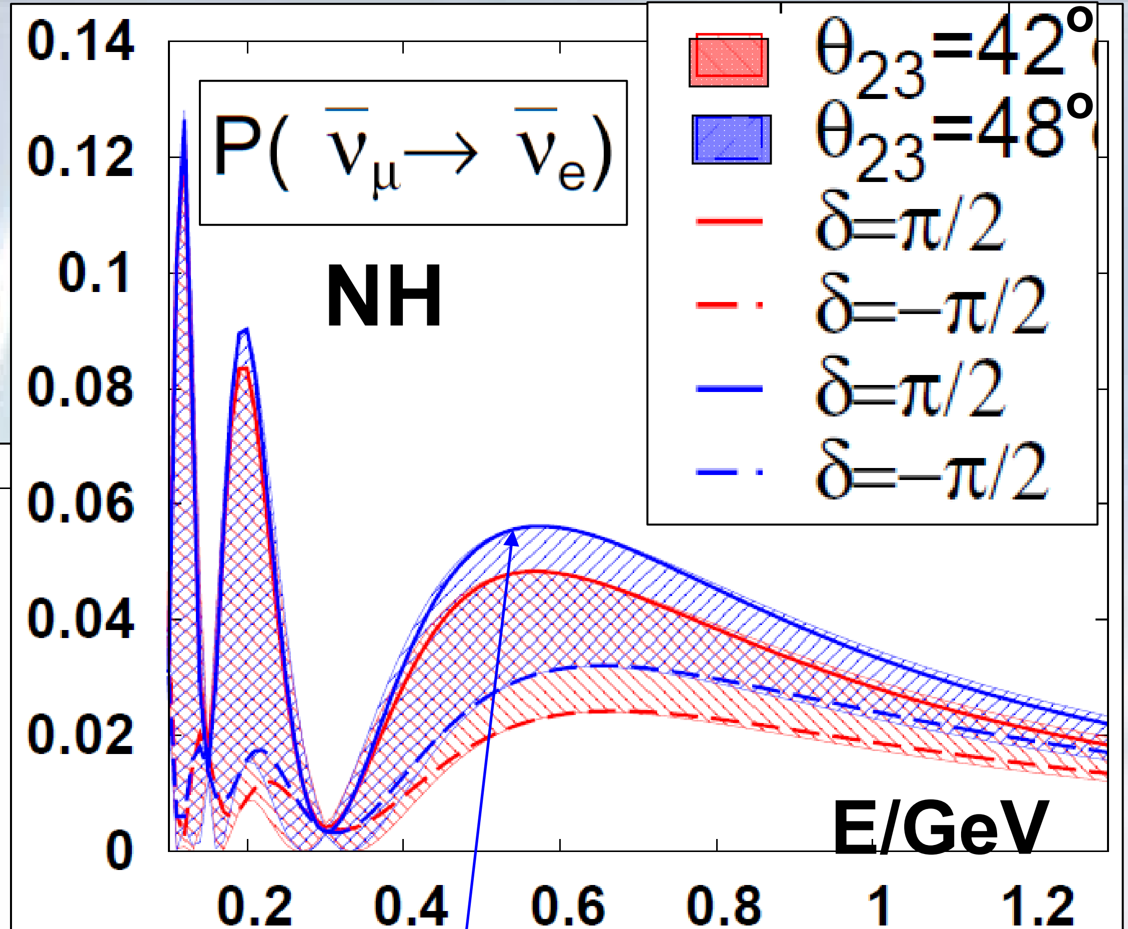
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$



Octant degeneracy @T2HK

HO-LO Separation is possible w/ ν & $\bar{\nu}$ for most of δ

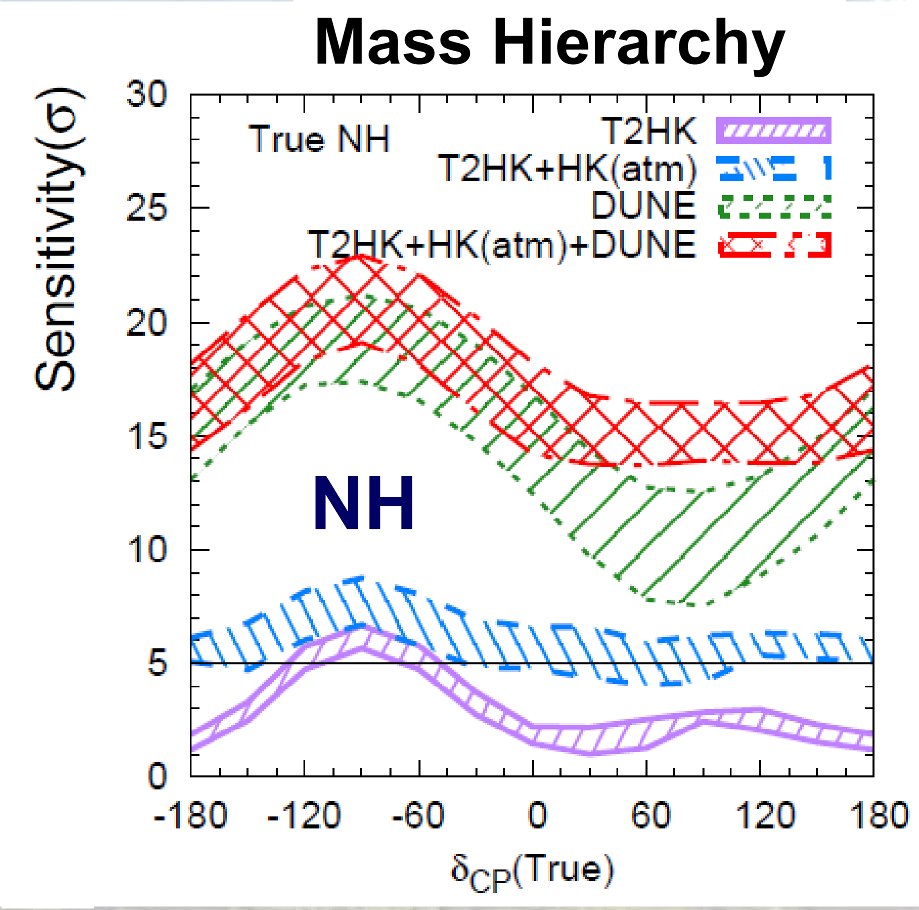


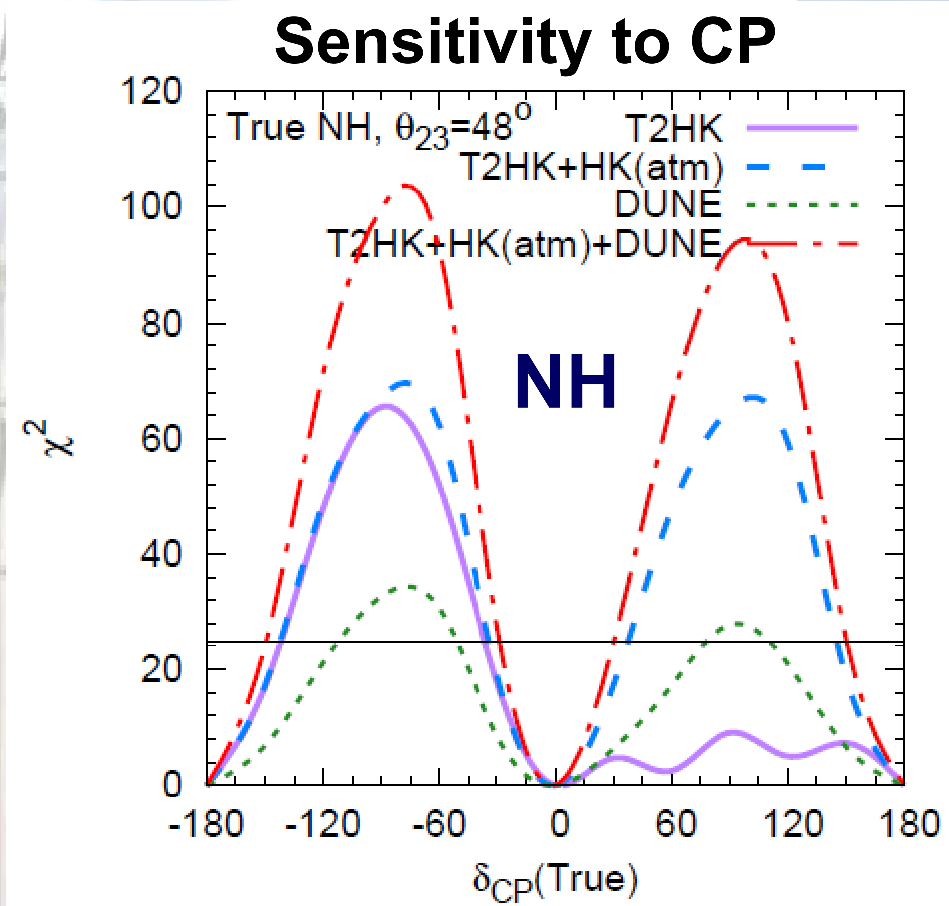


Unlike hierarchy degeneracy, $\delta=-\pi/2$ lies on the same side for ν & $\bar{\nu}$

●Sensitivity of T2HK, ν_{atm}@HK & their combination

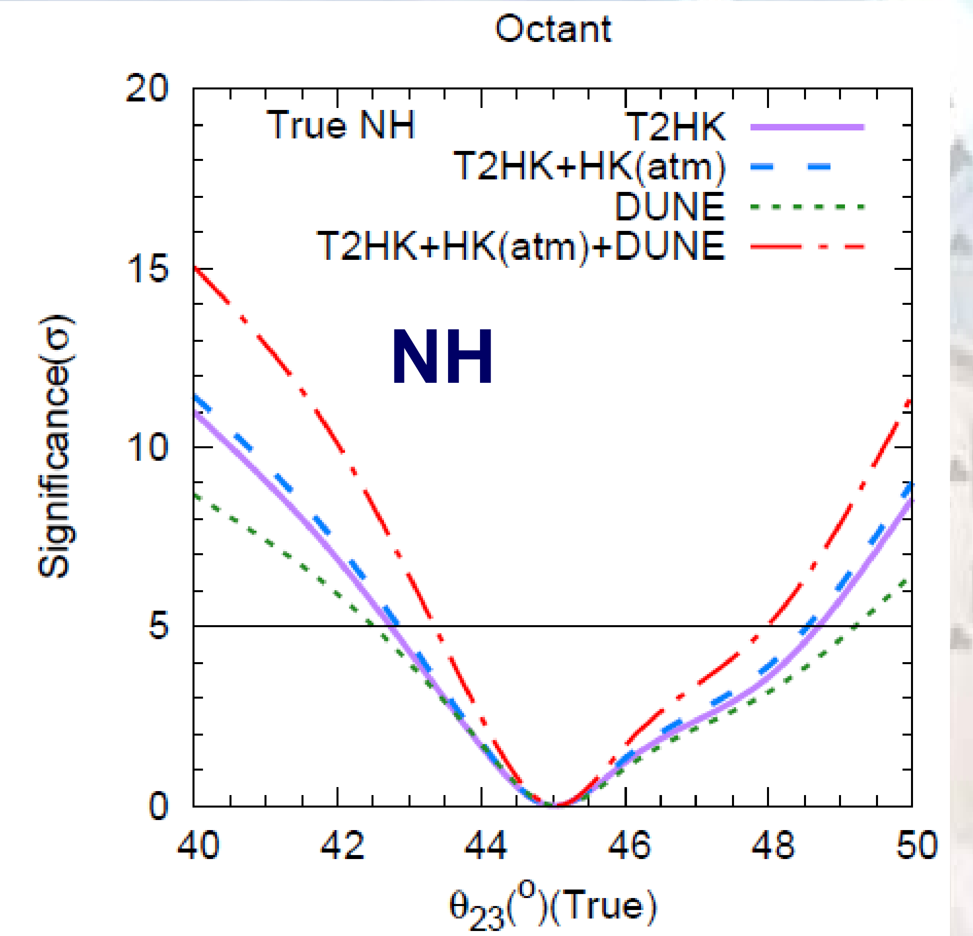
Fukasawa-Ghosh-OY, NPB918 ('17) 337

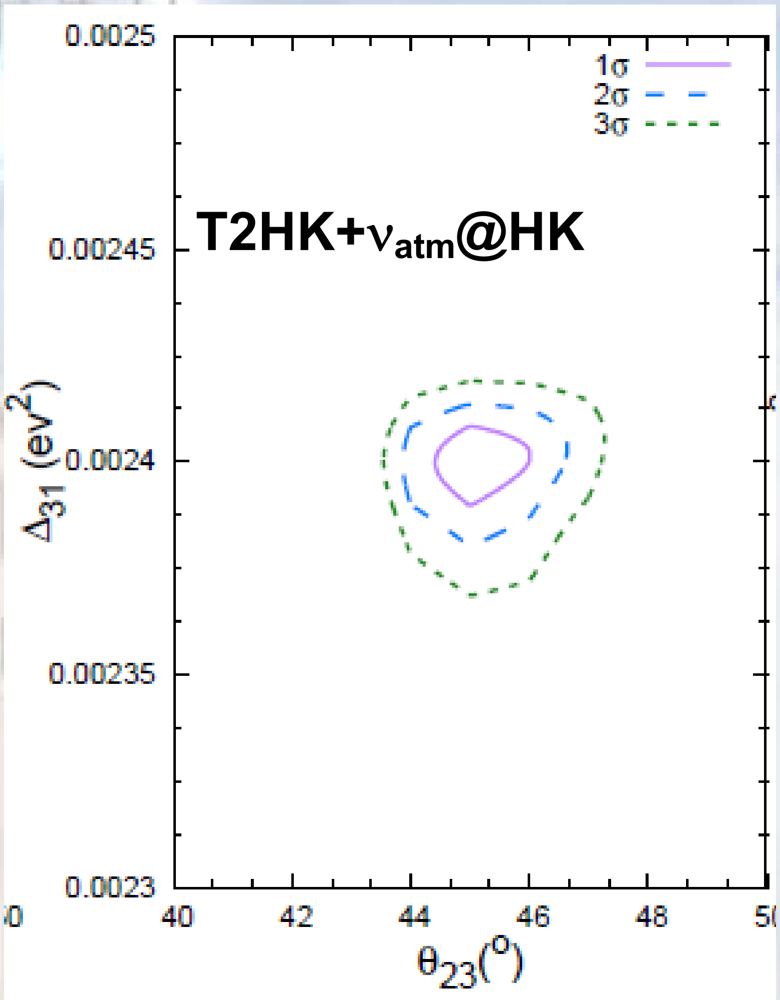




Sensitivity of T2HK, ν_{atm}@HK & their combination

Fukasawa, Ghosh, Yasuda, NPB918 ('17) 337





3. Scenarios beyond standard 3 ν oscillation

Motivation for research on New Physics

Just like at B factories, high precision measurements of ν oscillation in future experiments can be used to probe physics beyond SM by looking at deviation from SM+m_ν (beyond the PMNS paradigm).
→ Research on New Physics is important.

Test of the PMNS paradigm

Rather than looking for arbitrary possibilities of New Physics, here we discuss possible hints of the scenarios which have been discussed in the past.

List of popular NP in ν oscillation phenomenology

Scenario beyond SM+m_ν	Experimental indication ?	Phenomenological constraints on the magnitude of the effects
• Light sterile ν (ν_s)	Maybe	O(10%)
• Non Standard Interactions in propagation	Maybe	e-τ: O(100%) Others: O(1%)
Non Standard Interactions at production / detection	×	O(1%)
Unitarity violation due to heavy particles	×	O(0.1%)

In this talk, we will focus on these two because of potential experimental hints

In the past we have had some anomalies

- ν_{solar} - KamLAND: $\Delta m^2{}_{21}$ → NSI or ν_s

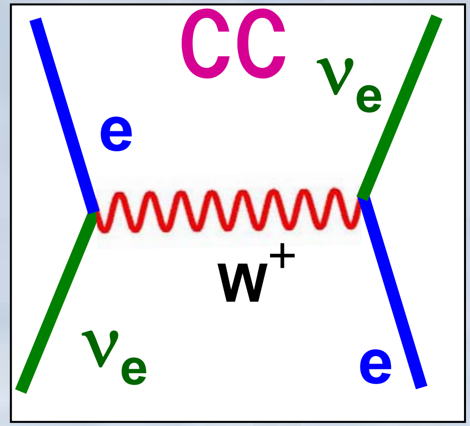
  $\Delta m^2 = O(10^{-5})\, eV^2$

- LSND-MiniBooNE anomaly, Reactor anomaly, Gallium anomaly → ν_s

  $\Delta m^2 = O(1)\, eV^2$

3.1. ν_s

3.1.1 Features of light sterile ν (ν_s)

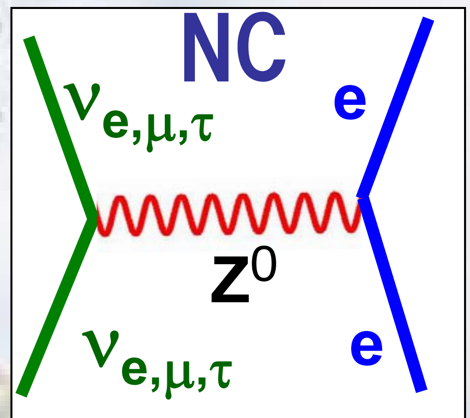


Interactions of active & sterile ν

$$A_e = \sqrt{2} G_F N_e$$

$$A_n = -(1/\sqrt{2}) G_F N_n$$

	ν_e	ν_μ, ν_τ	ν_s
CC	✓	×	×
NC	✓	✓	×
V	$A_e + A_n$	A_n	0



Matter effect in the presence of sterile ν

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \left[U\begin{pmatrix}E_1&0&0&0\\0&E_2&0&0\\0&0&E_3&0\\0&0&0&E_4\end{pmatrix}U^{-1}+\begin{pmatrix}A_e+A_n&0&0&0\\0&A_n&0&0\\0&0&A_n&0\\0&0&0&0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix}$$

$$U = R_{34}(\theta_{34},\delta_{34})R_{24}(\theta_{24},0)R_{14}(\theta_{14},\delta_{14})R_{23}(\theta_{23},0)R_{13}(\theta_{13},\delta_{13})R_{12}(\theta_{12},0)$$

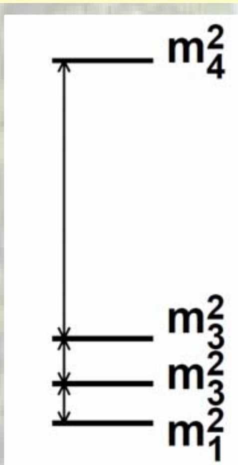
extra mixing angles ($R_{34}R_{24}R_{14}$) — **3ν mixing angles** ($R_{23}R_{13}R_{12}$)

The term which is proportional to identity can be ignored

$$U \equiv \begin{pmatrix}U_{e1}&U_{e2}&U_{e3}&U_{e4}\\U_{\mu1}&U_{\mu2}&U_{\mu3}&U_{\mu4}\\U_{\tau1}&U_{\tau2}&U_{\tau3}&U_{\tau4}\\U_{s1}&U_{s2}&U_{s3}&U_{s4}\end{pmatrix}$$

$$A_e \equiv \sqrt{2}G_F N_e,$$

$$A_n \equiv -\frac{G_F N_n}{\sqrt{2}}$$



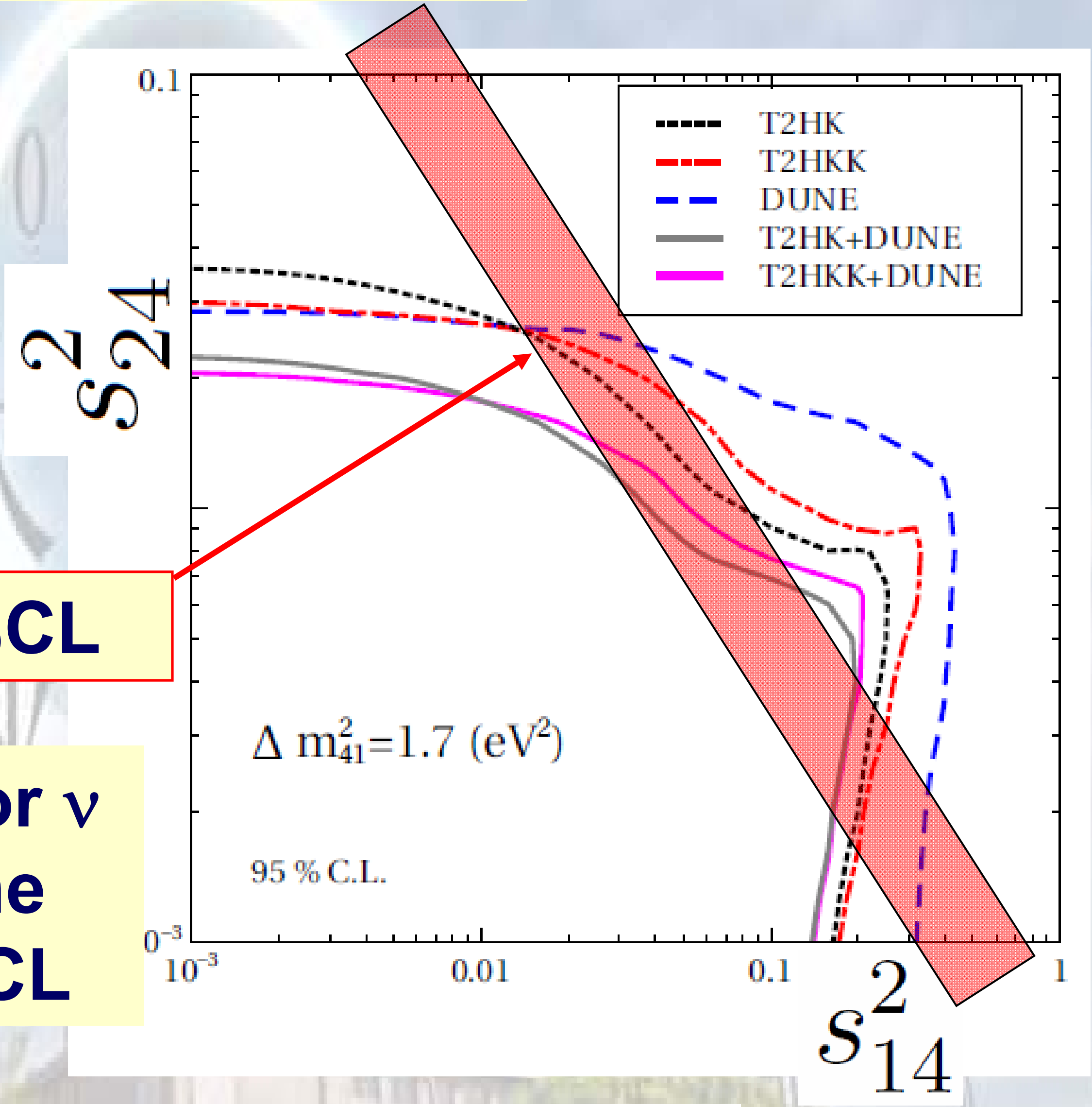
$$= \left[U\begin{pmatrix}0&0&0&0\\0&\Delta E_{21}&0&0\\0&0&\Delta E_{31}&0\\0&0&0&\Delta E_{41}\end{pmatrix}U^{-1}+\begin{pmatrix}A_e&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&-A_n\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix}$$

ν_s has matter effect different from others

3.1.2 Accelerator ν (T2HK, T2HKK)

Choubey-Dutta-Pramanik, Eur.Phys.J. C78 ('18) 339

$\Delta m^2_{41}=1.7\ (\mathrm{eV}^2)$



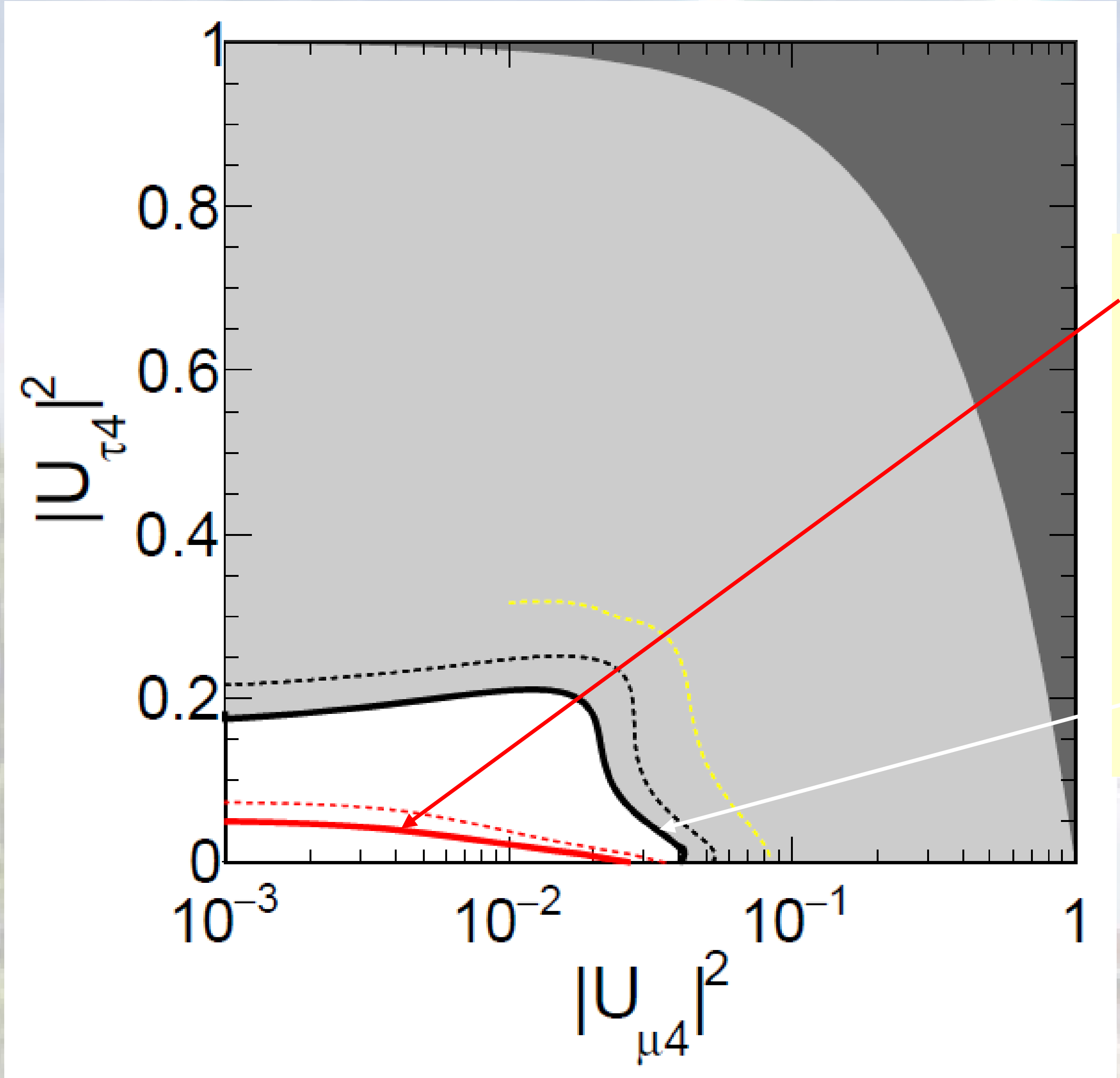
LSND region @ 90%CL

Combined accelerator ν can cover some of the LSND region @ 90%CL

$$P(\nu_\mu \to \nu_e) = 4\mathrm{Re}\left[U_{e3}U^*_{\mu 3}(U^*_{e3}U_{\mu 3} + U^*_{e4}U_{\mu 4})\right]\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \cdots$$

3.1.3 HK ν_{atm}

HK, arXiv:1805.04163v2



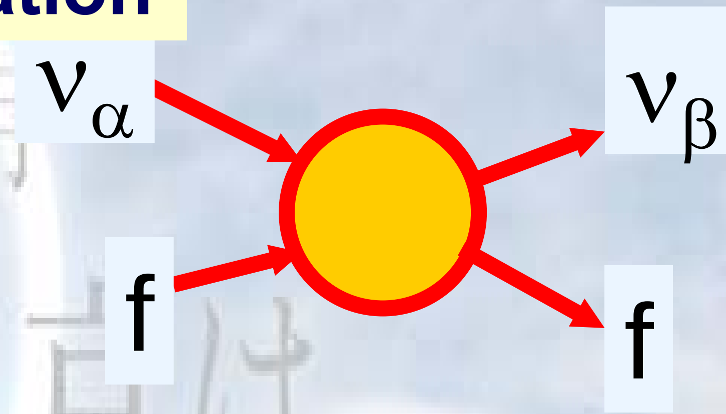
HK Sensitivity to θ_{34} (θ_{24}) is (is not much) improved compared to SK:
90% CL (solid)
99% CL (dashed)

3.2 NSI in propagation

3.2.1 Features of NSI in propagation

Phenomenological New Physics considered in this talk: 4-fermi Non Standard Interactions:

$$\mathcal{L}_{eff} = G_{NP}^{\alpha\beta}\,\bar{\nu}_\alpha \gamma^\mu \nu_\beta\,\bar{f}\gamma_\mu f'$$



neutral current non-standard interaction

Modification of matter effect

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U\,\mathrm{diag}\left(E_1, E_2, E_3\right)U^{-1} + A\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

NP

$A \equiv \sqrt{2}G_F N_e$ $N_e \equiv$ electron density

● NSI for solar ν: $\varepsilon_{\alpha\beta}$ vs (ε_D, ε_N)

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152

In solar ν analysis, Δm_{31}^2 -> infinity, H -> $H^{\rm eff}$, the problem is reduced to the 2 flavor case:

$$H^{\rm eff} = \frac{\Delta m_{21}^2}{4E}\begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix} + \begin{pmatrix} c_{13}^2 A & 0 \\ 0 & 0 \end{pmatrix} + A \sum_{f=e,u,d} \frac{N_f}{N_e} \begin{pmatrix} -\epsilon_D^f & \epsilon_N^f \\ \epsilon_N^{f*} & \epsilon_D^f \end{pmatrix}$$

(ε^f_D, ε^f_N) are related by $\varepsilon^f_{\alpha\beta}$:

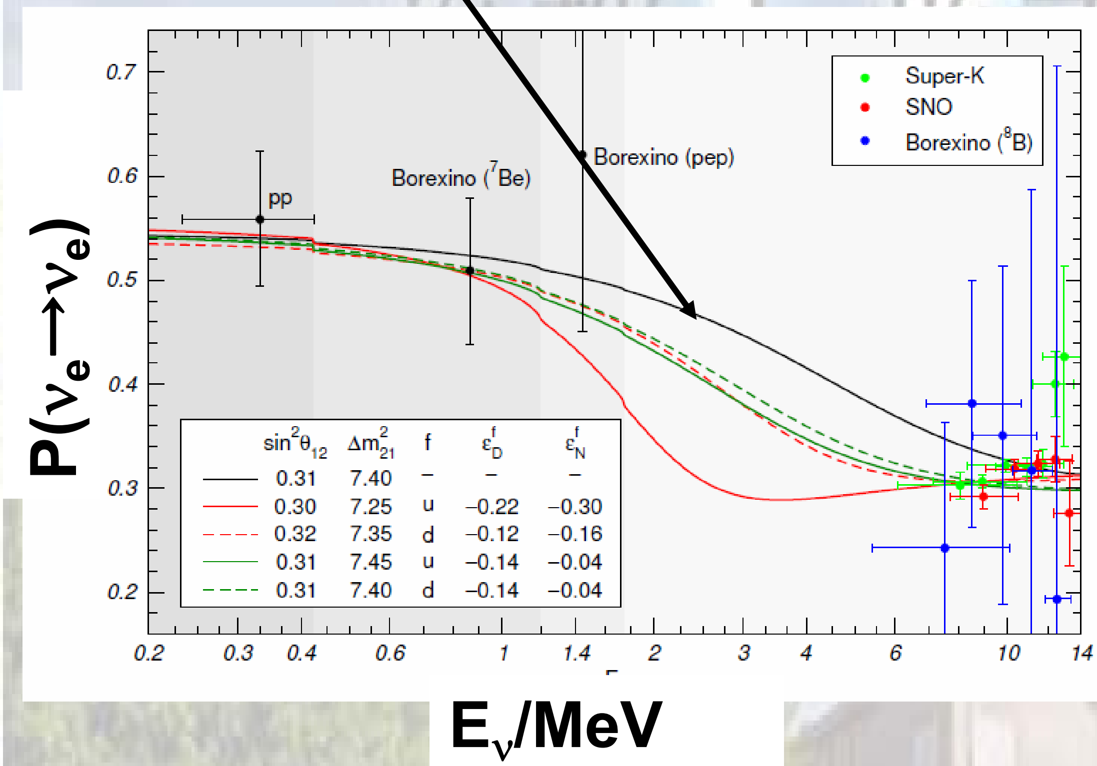
$$\begin{aligned} \epsilon_D^f &= c_{13}s_{13}\mathrm{Re}\left[e^{i\delta_{\rm CP}}\left(s_{23}\epsilon_{e\mu}^f + c_{23}\epsilon_{e\tau}^f\right)\right] - \left(1+s_{13}^2\right)c_{23}s_{23}\mathrm{Re}\left[\epsilon_{\mu\tau}^f\right] \\ &\quad -\frac{c_{13}^2}{2}\left(\epsilon_{ee}^f - \epsilon_{\mu\mu}^f\right) + \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right) \\ \epsilon_N^f &= c_{13}\left(c_{23}\epsilon_{e\mu}^f - s_{23}\epsilon_{e\tau}^f\right) + s_{13}e^{-i\delta_{\rm CP}}\left[s_{23}^2\epsilon_{\mu\tau}^f - c_{23}^2\epsilon_{\mu\tau}^{f*} + c_{23}s_{23}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right)\right] \end{aligned}$$

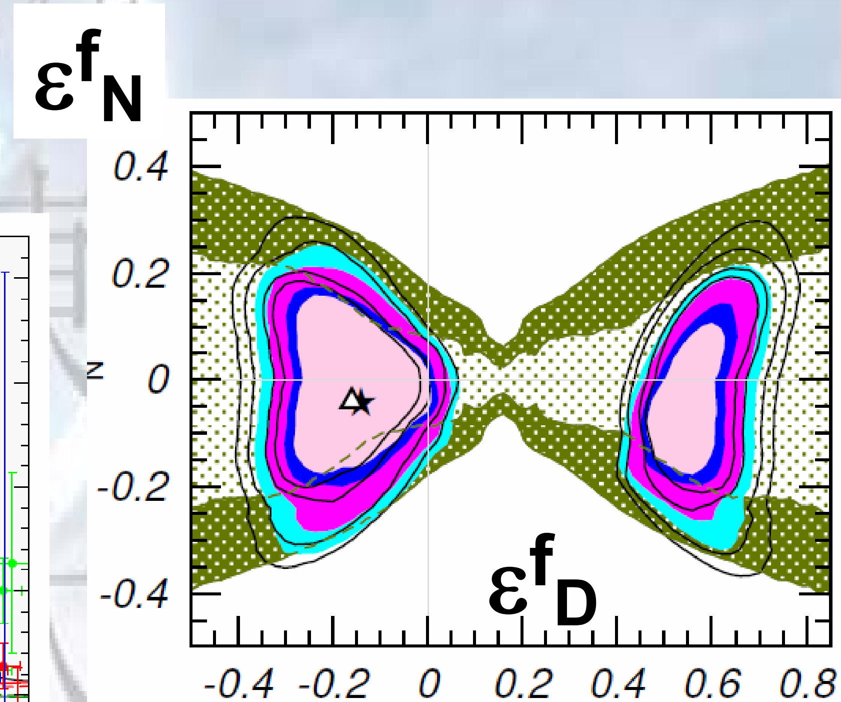
f = e, u or d

Tension between solar ν & KamLAND data comes from little observation of upturn by SK & SNO

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152

Standard scenario w/ Δm^2_{21} by KamLAND





Best fit value of global fit

$$(\epsilon^u_D, \epsilon^u_N) = (-0.140, -0.030)$$

$$(\epsilon^d_D, \epsilon^d_N) = (-0.145, -0.036)$$

In solar ν analysis, (ε_D, ε_N) was used:

$$U = R_{23}(\theta_{23},0)R_{13}(\theta_{13},\delta_{13})R_{12}(\theta_{12},0)$$

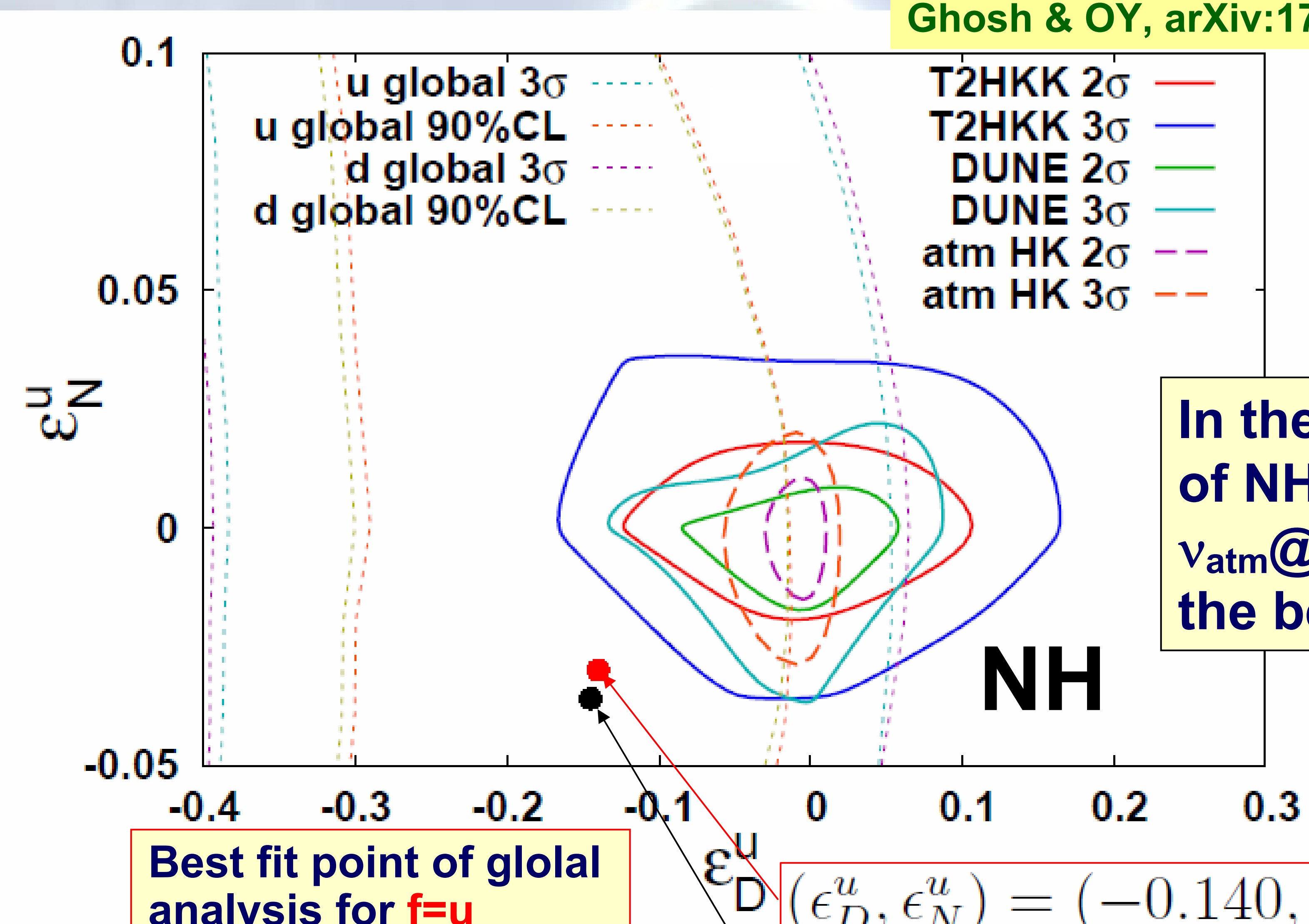
$$(\epsilon'_{\alpha\beta}) \equiv R_{13}^{-1}(\theta_{13},\delta_{13})\, R_{23}^{-1}(\theta_{23},0)\ (\epsilon_{\alpha\beta})\ R_{23}(\theta_{23},0)\, R_{13}(\theta_{13},\delta_{13})$$

$$\equiv \begin{pmatrix} \epsilon'_{11} & \epsilon'_{12} & \epsilon'_{13} \\ \epsilon'_{21} & \epsilon'_{22} & \epsilon'_{23} \\ \epsilon'_{31} & \epsilon'_{32} & \epsilon'_{33} \end{pmatrix} = \begin{pmatrix} \frac{\epsilon'_{11}+\epsilon'_{22}}{2} - \epsilon_D & \epsilon_N & \epsilon'_{13} \\ \epsilon_N^* & \frac{\epsilon'_{11}+\epsilon'_{22}}{2} + \epsilon_D & \epsilon'_{23} \\ \epsilon'_{31} & \epsilon'_{32} & \epsilon'_{33} \end{pmatrix}$$

-> Also for analysis of ν_{atm} & LBL, (ε_D, ε_N) will be used instead of $\varepsilon_{\alpha\beta}$.

3.2.2 Comparison of sensitivity T2HKK, DUNE, ν_{atm}@HK

Ghosh & OY, arXiv:1709.08264



In the case of NH, ν_{atm}@HK is the best

Best fit point of glolal analysis for f=u

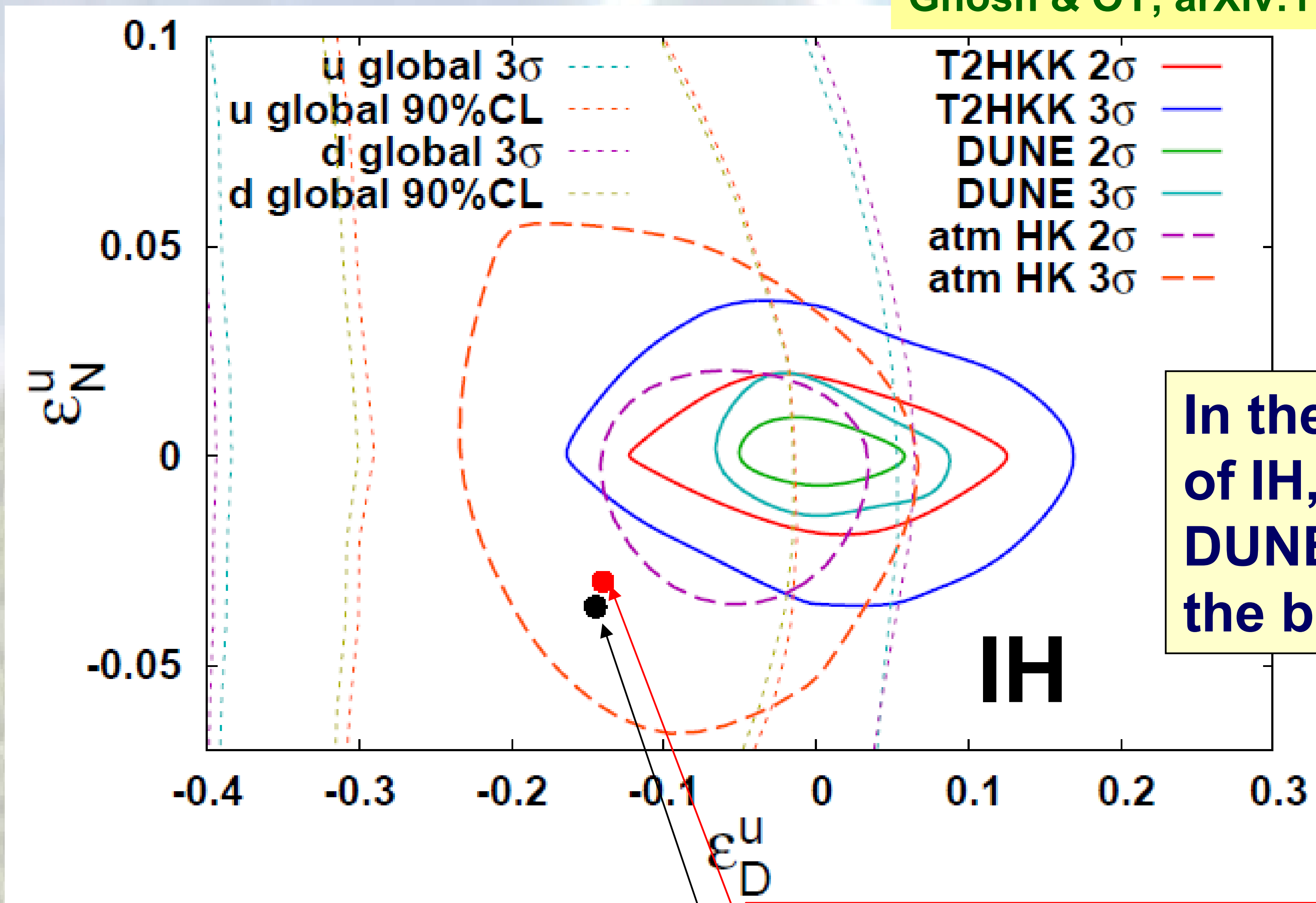
$$(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)$$

Best fit point of glolal analysis for f=d

$$(\epsilon_D^d, \epsilon_N^d) = (-0.145, -0.036)$$

Comparison of sensitivity T2HKK, DUNE, ν_{atm}@HK

Ghosh & OY, arXiv:1709.08264



$$(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)$$

$$(\epsilon_D^d, \epsilon_N^d) = (-0.145, -0.036)$$

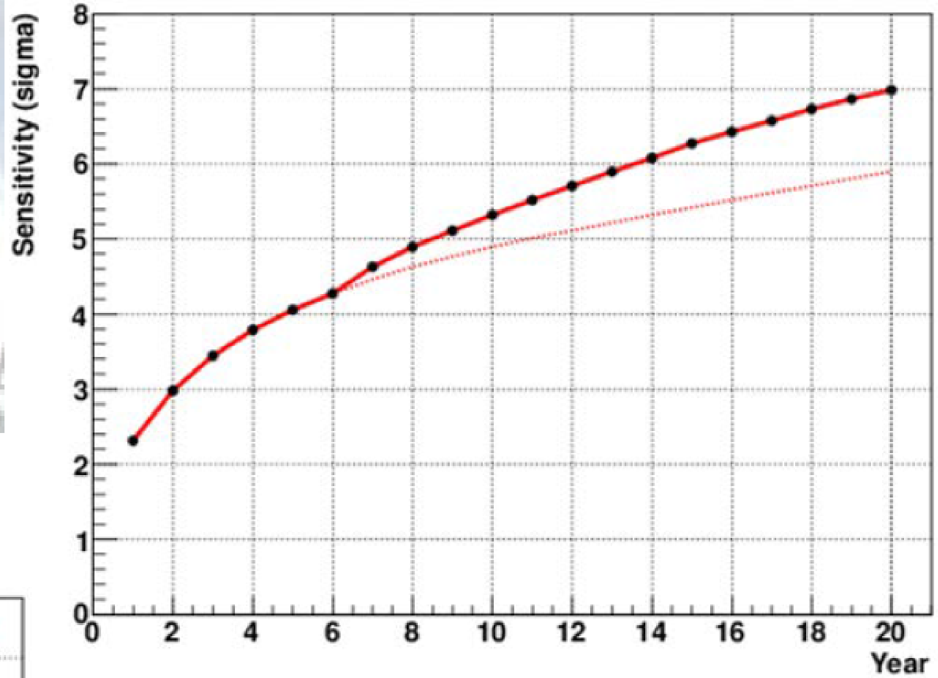
In the case of IH, DUNE is the best

Sensitivity ν_{solar}@HK

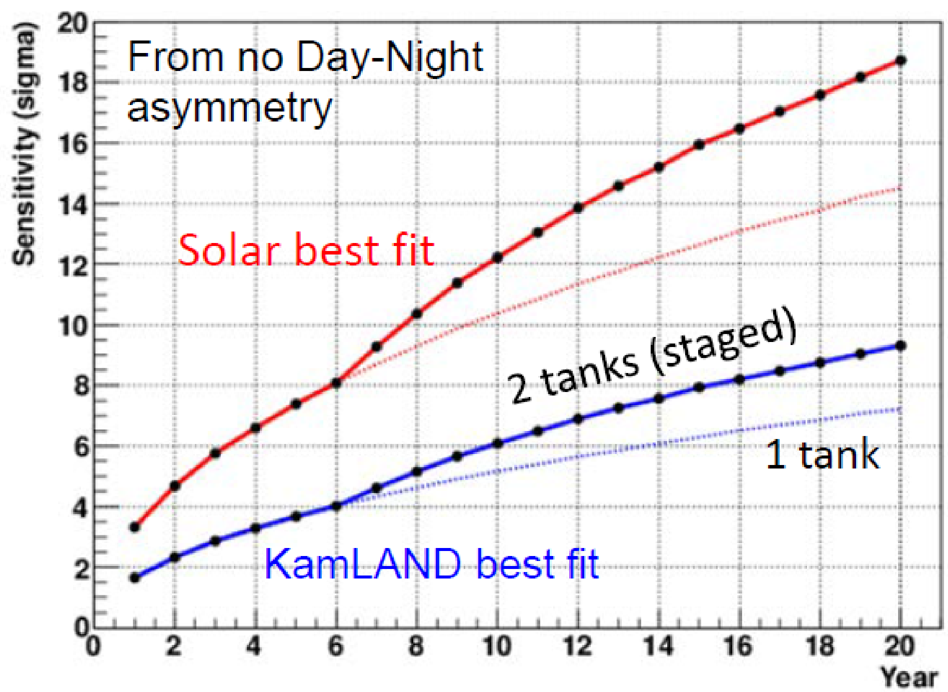
Kajita @ NOW2016

ν_{solar}@HK will tell us whether deviation form the PMNS paradigm exists

Spectrum upturn discovery sensitivity



Day-night asymmetry sensitivity



4. Summary

- In the standard 3 flavor ν scenario, the 3 mixing angles have been roughly determined, and we have some indication for $\Delta m^2_{31}>0$, $\theta_{23} > \pi/4$, $\delta\neq 0$.

- T2HK & ν_{atm}@HK will determine Mass Hierarchy and Octant (unless $|\pi/4-\theta_{23}|$ is small) and δ.

- T2HK, ν_{atm}@HK , ν_{solar}@HK , T2HKK are expected to constrain the two scenarios, which may be suggested by experiments, beyond the standard 3 flavor ν scenario: ν_s & NSI in propagation.

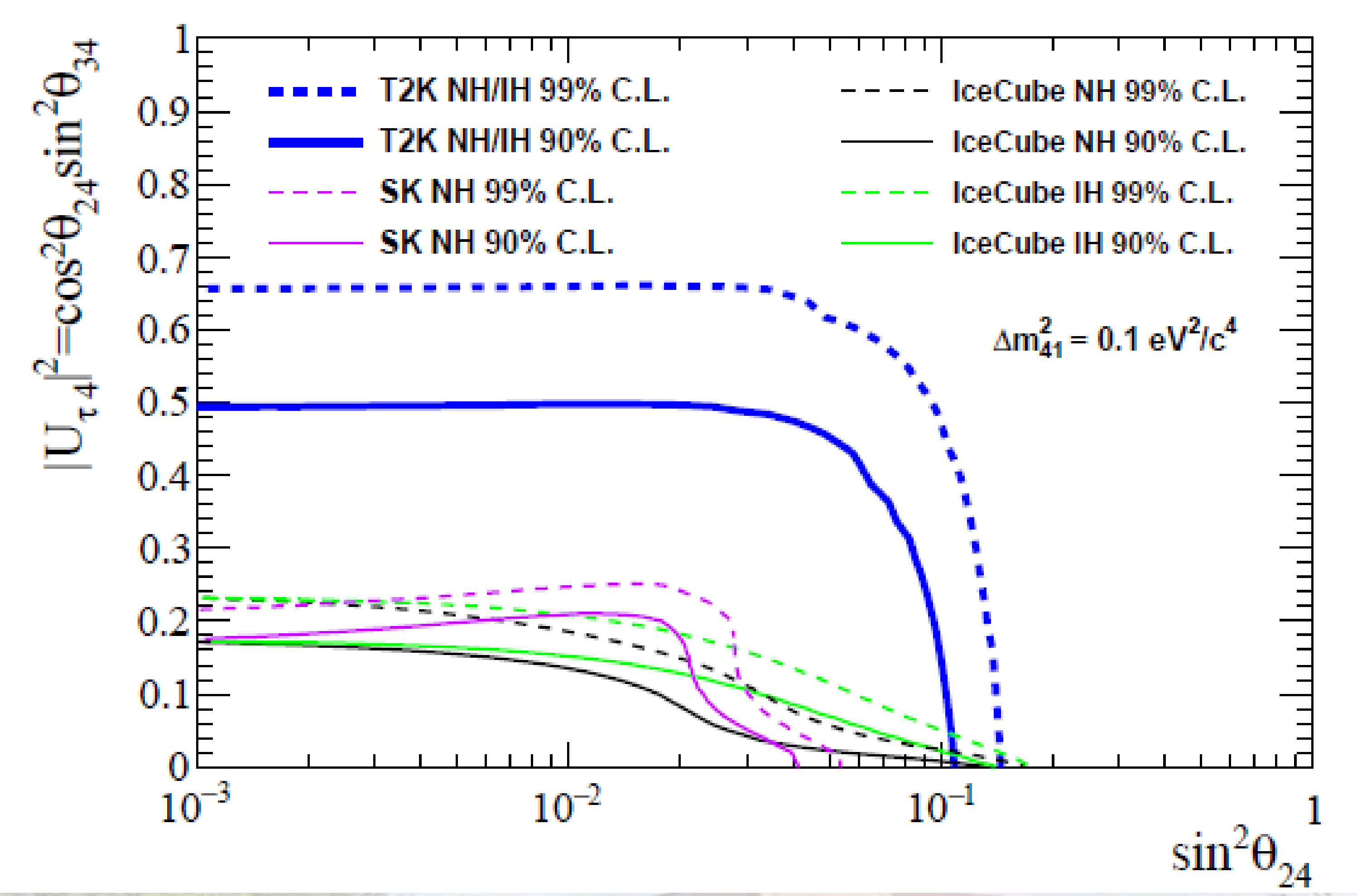
Backup slides

Parametrization of the 4x4 matrix

$$U = R_{34}(\theta_{34},\,0)\;R_{24}(\theta_{24},\,\delta_3)\;R_{23}(\theta_{23},\,0)\;R_{14}(\theta_{14},\,\delta_1)\;R_{13}(\theta_{13},\,\delta_2)\;R_{12}(\theta_{12},\,0)$$

$$\begin{cases} U_{e1} &= c_{12}c_{13}c_{14} \\ U_{e2} &= c_{13}c_{14}s_{12} \\ U_{e3} &= c_{14}s_{13}e^{-i\delta_2} \\ U_{e4} &= s_{14}e^{-i\delta_1} \\ U_{\mu 4} &= c_{14}s_{24}e^{-i\delta_3} \\ U_{\tau 4} &= c_{14}c_{24}s_{34} \\ U_{s4} &= c_{14}c_{24}c_{34} \end{cases}$$

Present bounds on θ_{24} & θ_{34}



T2K, PRD99 ('19) 071103

Constraints on $\varepsilon_{\alpha\beta}$ for expts on Earth

Davidson et al., JHEP 0303:011,2003; Berezhiani, Rossi, PLB535 ('02) 207; Barranco et al., PRD73 ('06) 113001; Barranco et al., arXiv:0711.0698

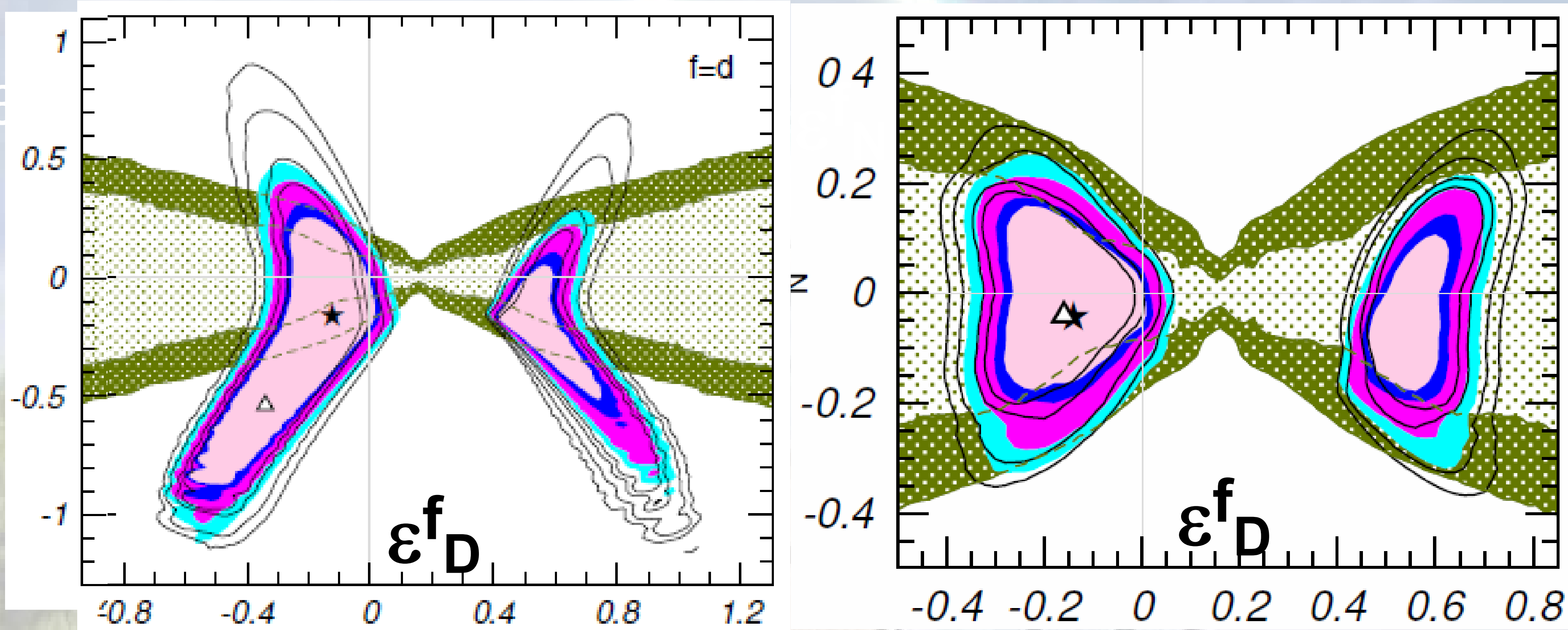
Biggio et al., JHEP 0908, 090 (2009) w/o 1-loop arguments

Constraints are weak

$$\begin{pmatrix} |\epsilon_{ee}| \lesssim 4 \times 10^{0} & |\epsilon_{e\mu}| \lesssim 3 \times 10^{-1} & |\epsilon_{e\tau}| \lesssim 3 \times 10^{0} \\ & |\epsilon_{\mu\mu}| \lesssim 7 \times 10^{-2} & |\epsilon_{\mu\tau}| \lesssim 3 \times 10^{-1} \\ & & |\epsilon_{\tau\tau}| \lesssim 2 \times 10^{1} \end{pmatrix}$$

Tension between solar ν & KamLAND can be solved by NSI

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152



Best fit value of solar-KL

$$(\epsilon^u_D, \epsilon^u_N) = (-0.22, -0.30)$$

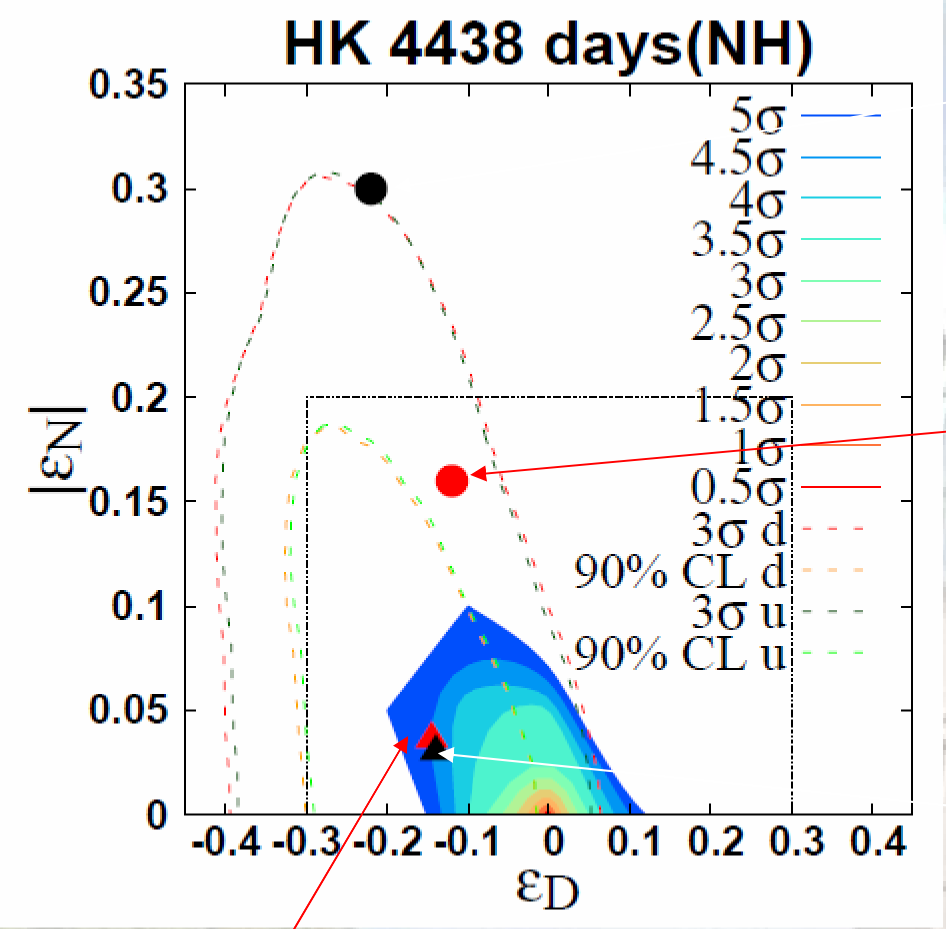
$$(\epsilon^d_D, \epsilon^d_N) = (-0.12, -0.16)$$

Best fit value of global fit

$$(\epsilon^u_D, \epsilon^u_N) = (-0.140, -0.030)$$

$$(\epsilon^d_D, \epsilon^d_N) = (-0.145, -0.036)$$

Sensitivity of HK: (1) Complex $|\varepsilon_N|$ for NH



$(\epsilon_D^u, \epsilon_N^u) = (-0.22, -0.30)$

Best fit point of solar & KamLAND for f=u: significance:38σ

$(\epsilon_D^d, \epsilon_N^d) = (-0.12, -0.16)$

Best fit point of solar & KamLAND for f=d: significance:11σ

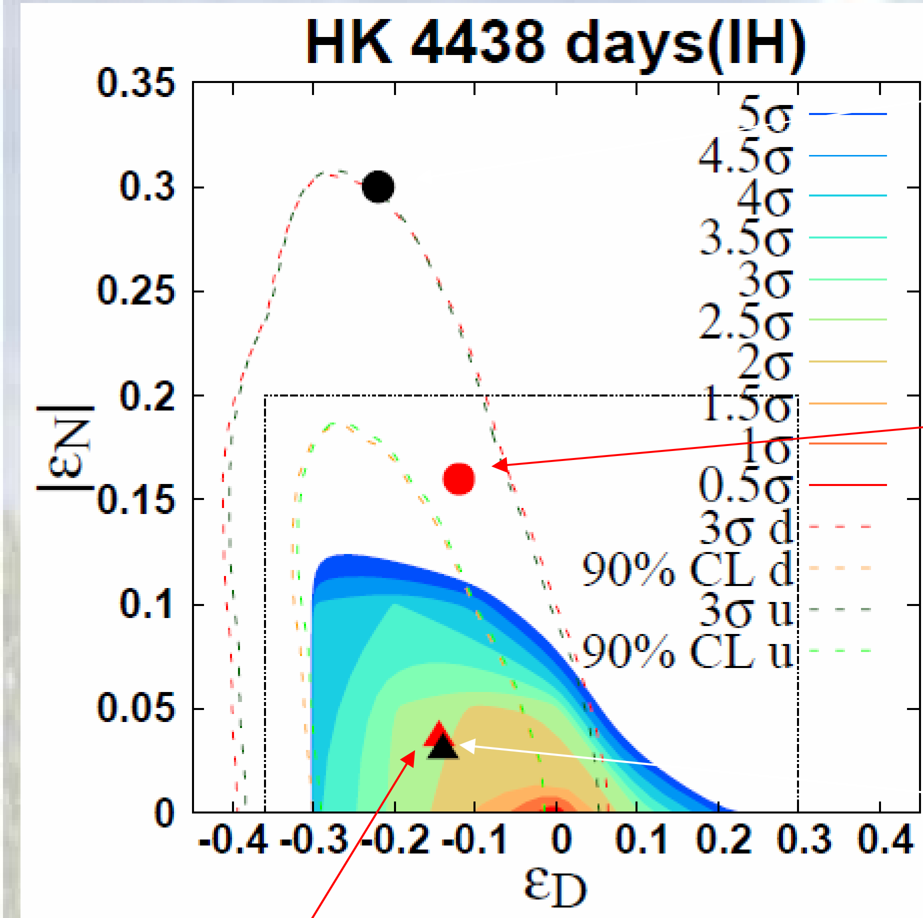
$(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)$

Best fit point of glolal analysis for f=u: significance:5σ

$(\epsilon_D^d, \epsilon_N^d) = (-0.145, -0.036)$

Best fit point of glolal analysis for f=d: significance:5σ

Sensitivity of HK: (1) Complex $|\varepsilon_N|$ for IH



$(\epsilon_D^u, \epsilon_N^u) = (-0.22, -0.30)$

Best fit point of solar & KamLAND for f=u: significance:35σ

$(\epsilon_D^d, \epsilon_N^d) = (-0.12, -0.16)$

Best fit point of solar & KamLAND for f=d: significance:8σ

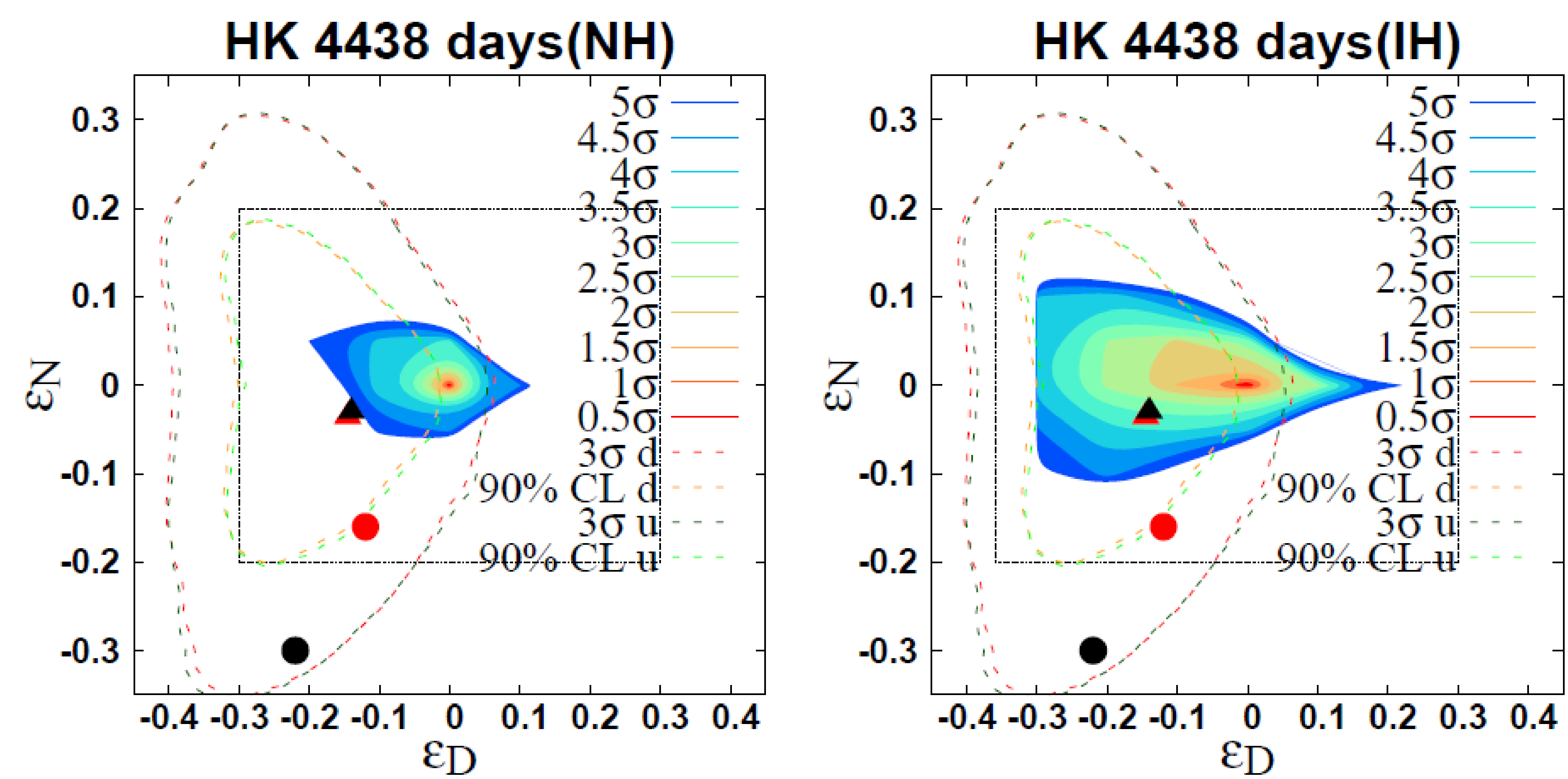
$(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)$

Best fit point of glolal analysis for f=u: significance:1.4σ

$(\epsilon_D^d, \epsilon_N^d) = (-0.145, -0.036)$

Best fit point of glolal analysis for f=d: significance:1.5σ

Sensitivity of HK: (2) Real $|\varepsilon_N|$

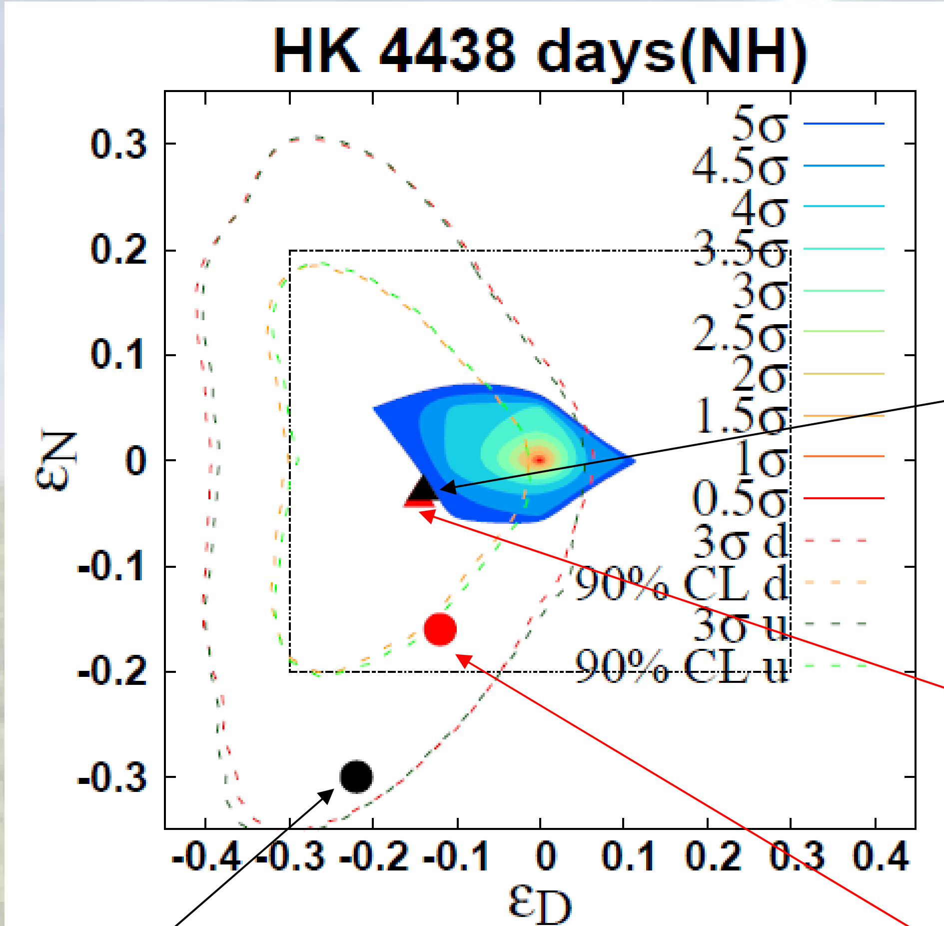


Allowed regions and significance are similar to the case for complex ε_N

HK ν_{atm}

(NH, Real ε_N)

Fukasawa-OY, NPB914 ('17) 99



HK ν_{atm} has sensitivity to some region of the ν_{solar} anomaly

$$(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)$$

Best fit point of glolal analysis for f=u: significance:5σ

$$(\epsilon_D^d, \epsilon_N^d) = (-0.145, -0.036)$$

Best fit point of glolal analysis for f=d: significance:5σ

$$(\epsilon_D^d, \epsilon_N^d) = (-0.12, -0.16)$$

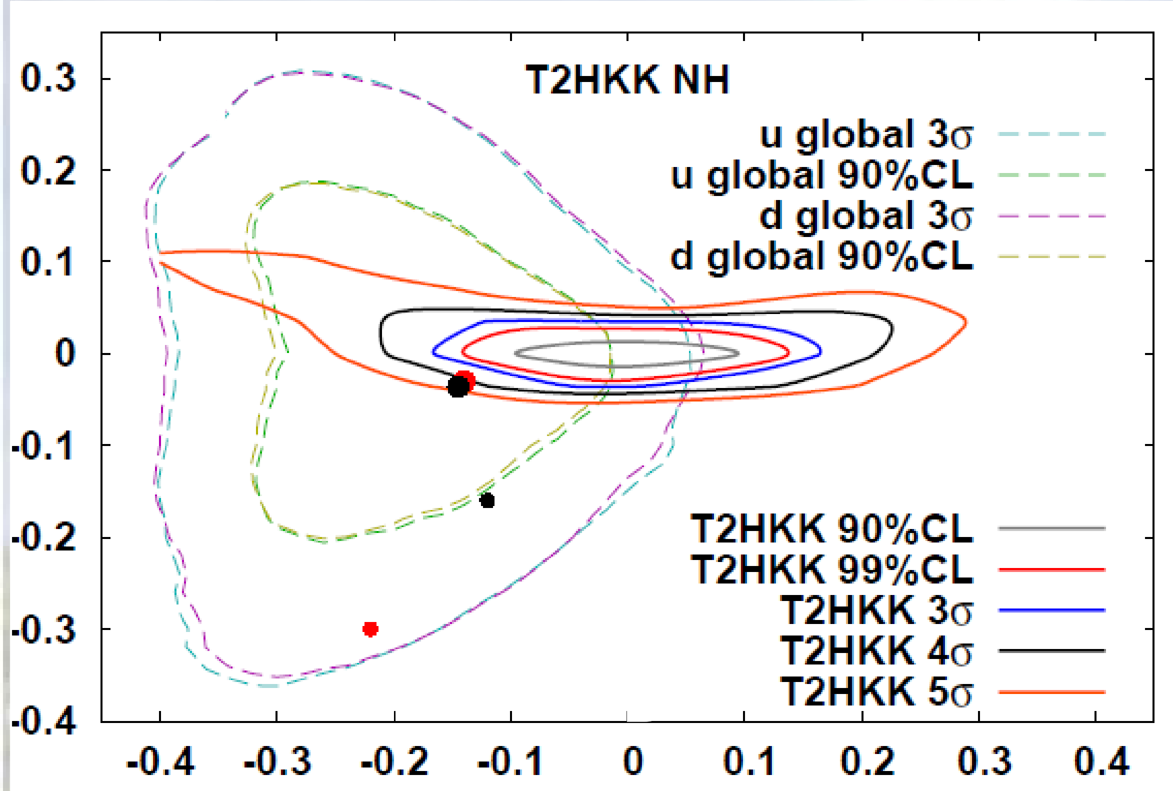
Best fit point of solar & KamLAND for f=d: significance:11σ

$$(\epsilon_D^u, \epsilon_N^u) = (-0.22, -0.30)$$

Best fit point of solar & KamLAND for f=u: significance:38s

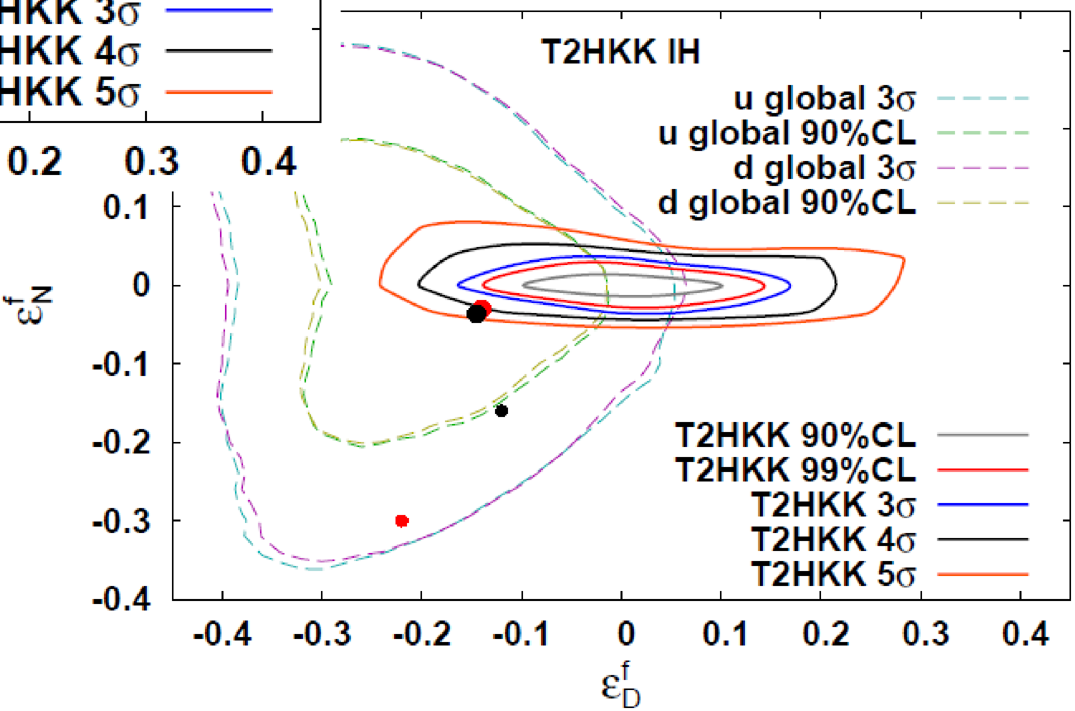
Accelerator ν (T2HKK)

Ghosh & OY, arXiv:1709.08264

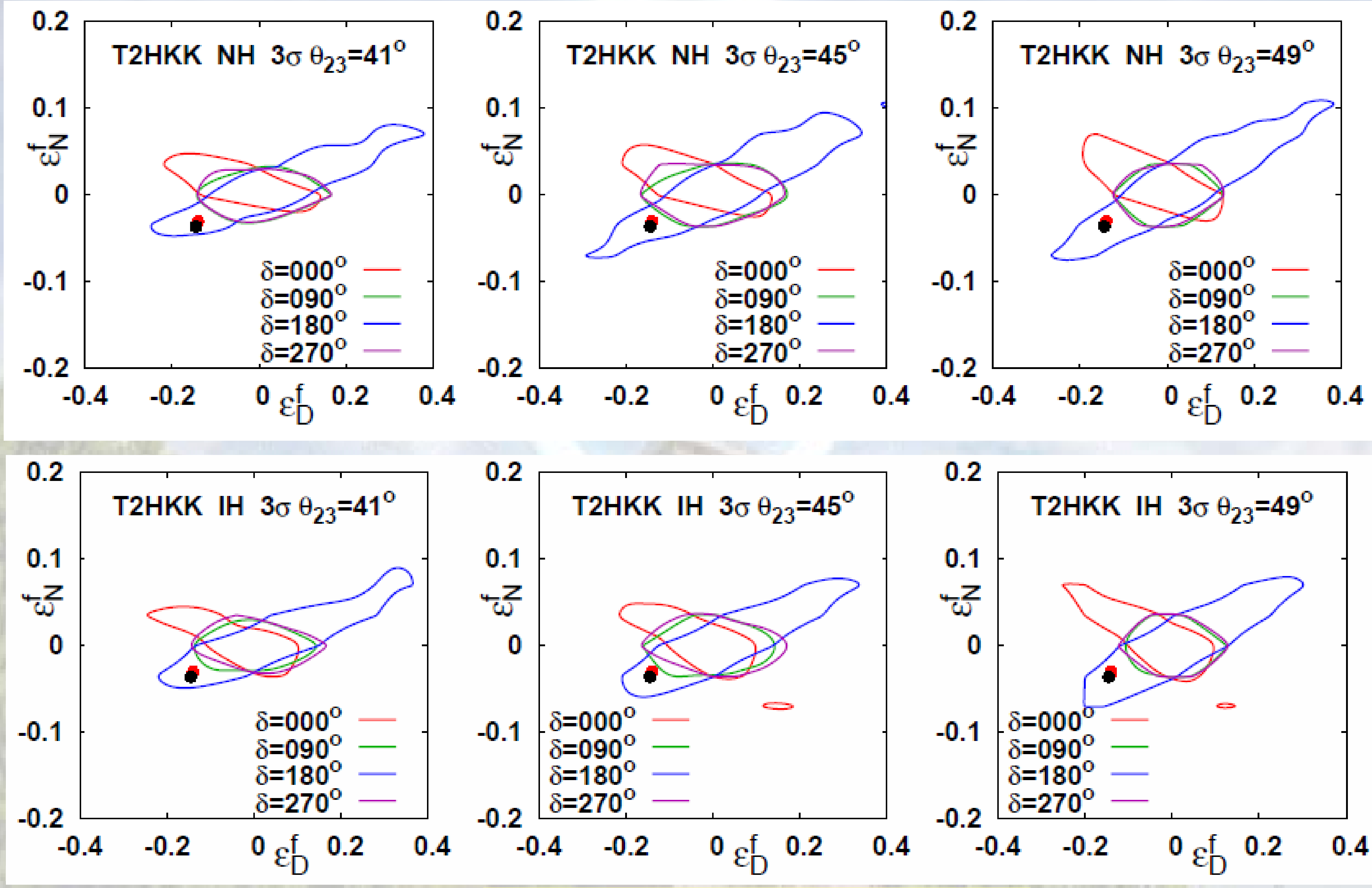


Excluded region by LBL is outside of the curve

δ(true) = -90°



Dependence of T2HKK on θ_{23}(true) & δ(true)



Ghosh & OY, arXiv:1709.08264