Discussion on Light Sterile Neutrino

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Leptonic CP-violation: Important Open Question

Is CP violated in the neutrino sector, as in the quark sector?

Mixing can cause CPV in ν sector, provided $\delta_{CP} \neq 0°$ and $180°$

Need to measure the CP-odd asymmetries:

$$\Delta P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta;\, L) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta;\, L) \quad (\alpha \neq \beta)$$

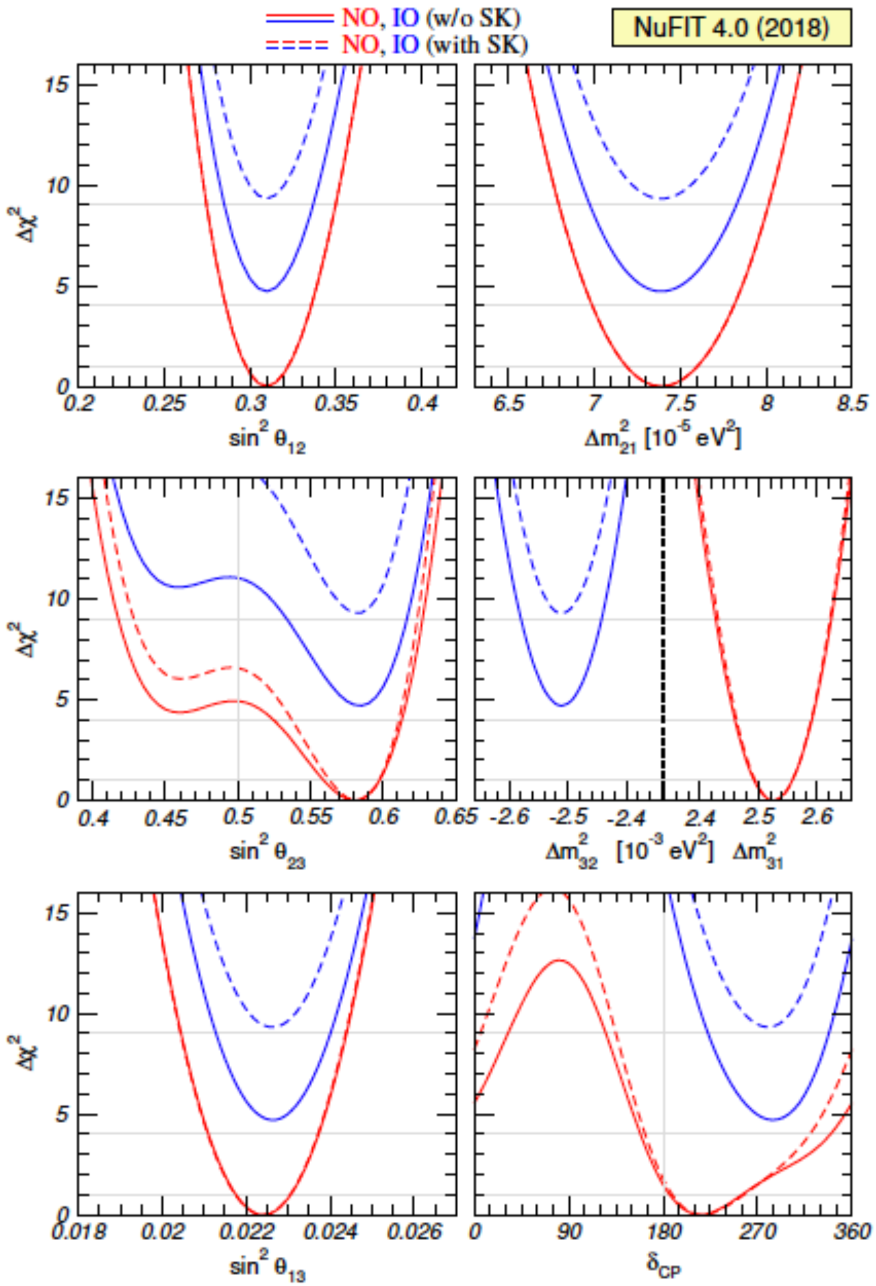
$$\Delta P_{e\mu} = \Delta P_{\mu\tau} = \Delta P_{\tau e} = 4J_{CP} \times \left[\sin\left(\frac{\Delta m^2_{21}}{2E}L\right) + \sin\left(\frac{\Delta m^2_{32}}{2E}L\right) + \sin\left(\frac{\Delta m^2_{13}}{2E}L\right)\right]$$

Jarlskog CP-odd Invariant → $J_{CP} = \frac{1}{8}\cos\theta_{13}\,\sin 2\theta_{13}\,\sin 2\theta_{23}\,\sin 2\theta_{12}\,\sin\delta_{CP}$

Three-flavor effects are key for CPV, need to observe interference

Conditions for observing CPV:
1) *Non-degenerate masses* ✔
2) *Mixing angles $\neq 0°$ and $90°$* ✔
3) *$\delta_{CP} \neq 0°$ and $180°$ (Hints)*

Present Status of Oscillation Parameters



Highlights!

with SK-atmospheric

Slight preference for higher octant

HO is preferred over LO by $\Delta\chi^2 = 6.0$ (~ 2.4σ)

NO is preferred over IO by $\Delta\chi^2 = 9.3$ (~ 3σ)

Best fit δ_{CP} = 215 degree

CP conservation allowed at $\Delta\chi^2 = 1.8$

Crucial information from T2K & NOvA

NuFIT Group, arXiv:1811.05487v1 [hep-ph]

Present Status of Oscillation Parameters

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK-atm	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.62 \to 36.27$
	$\sin^2\theta_{23}$	$0.582^{+0.015}_{-0.019}$	$0.428 \to 0.624$	$0.582^{+0.015}_{-0.018}$	$0.433 \to 0.623$
	$\theta_{23}/^\circ$	$49.7^{+0.9}_{-1.1}$	$40.9 \to 52.2$	$49.7^{+0.9}_{-1.0}$	$41.2 \to 52.1$
	$\sin^2\theta_{13}$	$0.02240^{+0.00065}_{-0.00066}$	$0.02044 \to 0.02437$	$0.02263^{+0.00065}_{-0.00066}$	$0.02067 \to 0.02461$
	$\theta_{13}/^\circ$	$8.61^{+0.12}_{-0.13}$	$8.22 \to 8.98$	$8.65^{+0.12}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{CP}/^\circ$	217^{+40}_{-28}	$135 \to 366$	280^{+25}_{-28}	$196 \to 351$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.525^{+0.033}_{-0.031}$	$+2.431 \to +2.622$	$-2.512^{+0.034}_{-0.031}$	$-2.606 \to -2.413$

Defining the 3σ relative precision of the parameter by $2(x^{up} - x^{low})/(x^{up} + x^{low})$, where x^{up} (x^{low}) is the upper (lower) bound on a parameter x at the 3σ level, we obtain the following 3σ relative precisions (marginalizing over ordering):

14% (θ_{12}) ,	8.9% (θ_{13}) ,	27 [24]% (θ_{23}) ,
16% (Δm^2_{21}) ,	7.8 [7.6]% ($\lvert\Delta m^2_{3\ell}\rvert$) ,	100 [92]% (δ_{CP}) ,

$$\Delta m^2_{3\ell} = \begin{cases} \Delta m^2_{31} > 0 & \text{for NO}, \\ \Delta m^2_{32} < 0 & \text{for IO}. \end{cases}$$

NuFIT Group, arXiv:1811.05487v1 [hep-ph]

Elements of the PMNS Matrix

NuFIT 4.0 (2018)

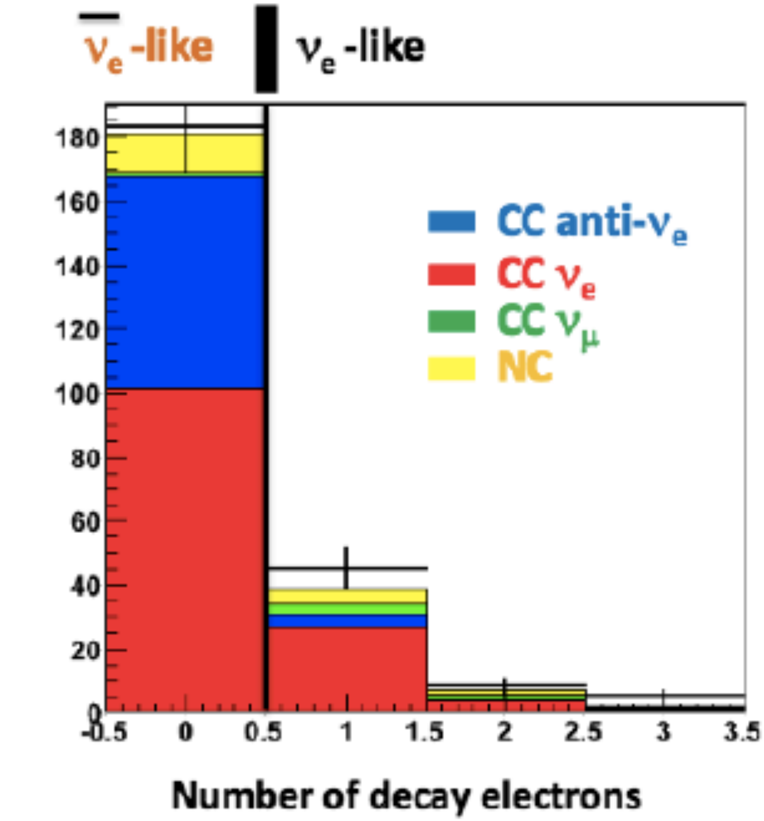
$$|U|_{3\sigma}^{\text{w SK atm}} = \begin{pmatrix} 0.797 \to 0.842 & 0.518 \to 0.585 & 0.143 \to 0.156 \\ 0.235 \to 0.484 & 0.458 \to 0.671 & 0.647 \to 0.781 \\ 0.304 \to 0.531 & 0.497 \to 0.699 & 0.607 \to 0.747 \end{pmatrix}$$

$$J_{\text{CP}}^{\text{best}} = -0.019, \qquad J_{\text{CP}}^{\text{quarks}} = (3.18 \pm 0.15) \times 10^{-5}$$

Very interesting developments in recent years

Great opportunity to establish CP-violation in lepton sector

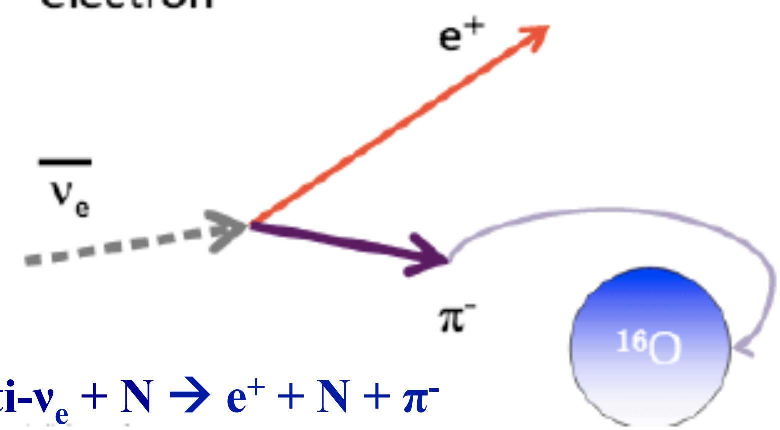
Sample selection: Multi-GeV Single Ring anti-ν_e and ν_e-like



(Multi-ring events are in general more complicated separation is done using a likelihood)

- Separate neutrinos from anti-neutrinos in the single-ring sample using the number of observed decay electrons

- The outgoing π^- from an anti-neutrino CC-1 π event can be absorbed on a ^{16}O nuclei before it decays. The lack of an outgoing muon means there is no possibility of a subsequent Michel (decay) electron



anti-ν_e + N $\rightarrow$ e^+ + N + π^-

ν_e + N $\rightarrow$ e^- + N + $\pi^{+,0}$

Light Sterile Neutrinos: Huge Interest in the Community

Light Sterile Neutrinos: A White Paper

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arXiv:1204.5379v1 [hep-ph] 18 Apr 2012

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According to INSPIRE: 669 Citations

Sterile neutrinos: singlets of $SU(2) \times U(1)$ gauge group, provide economical extension of the SM

Extensive study of sterile neutrinos at various energy scales

GUT: see-saw models of neutrino mass, leptogenesis

TeV: production at LHC and impact on EWPOs

keV: (warm) dark matter candidates

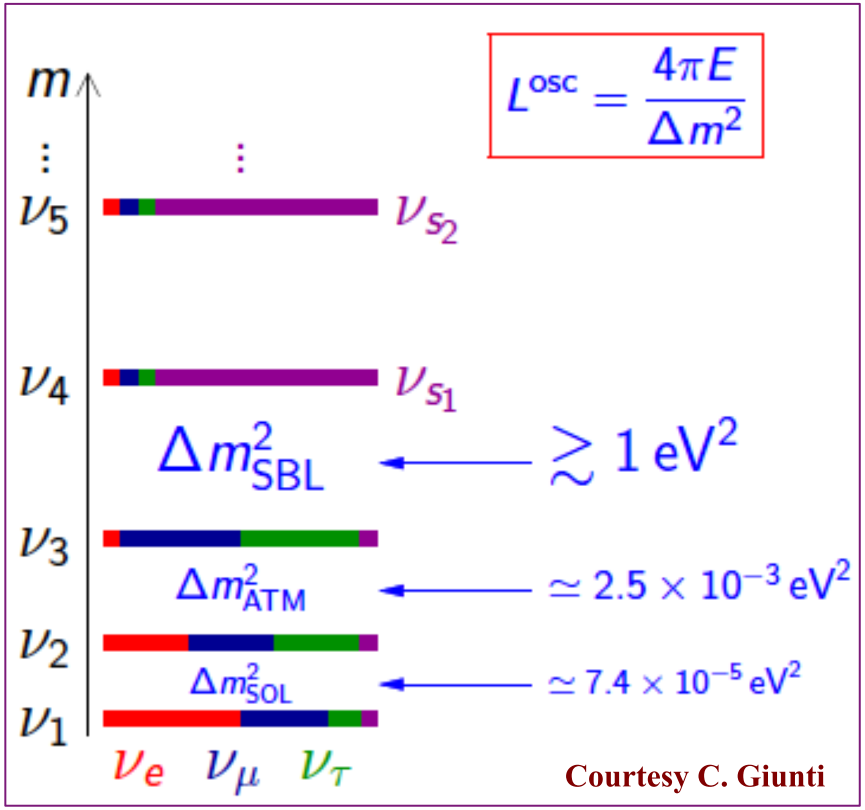
eV: SBL and LBL oscillation experiments

sub-eV: θ_{13} - reactors and solar neutrinos

SBL data hint towards a light eV-Scale Sterile Neutrino

Recent results from SBL experiments hint towards high $\Delta m^2 \approx 0.1 - 10$ eV^2 oscillation

Require additional neutrinos with masses at eV scale



- ν_s : Sterile States (no weak interactions)
- Can feel gravity
- Can affect oscillations through mixing
- Well postulated in see-saw models

Introduce ν_R in the SM: Dirac mass $m_D \overline{\nu_R} \nu_L$ + Majorana mass $m_M \overline{\nu_R^c} \nu_R$

6 massive Majorana neutrinos : $(\nu_{eL}, \nu_{\mu L}, \nu_{\tau L}) + (\nu_{eR}, \nu_{\mu R}, \nu_{\tau R})$

Light left-handed anti-ν_R = Light left-handed sterile neutrino : $\nu_R^c \rightarrow \nu_{sL}$

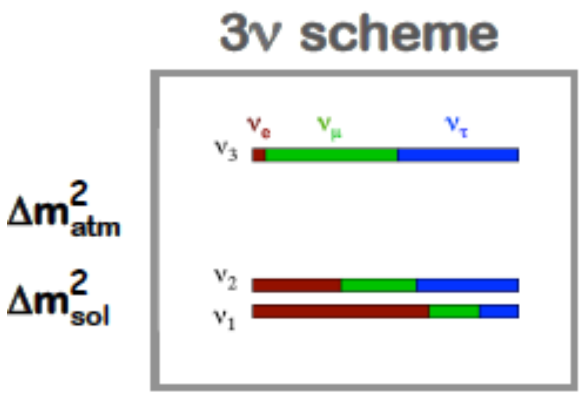
Where to look for eV-scale active-sterile oscillation?

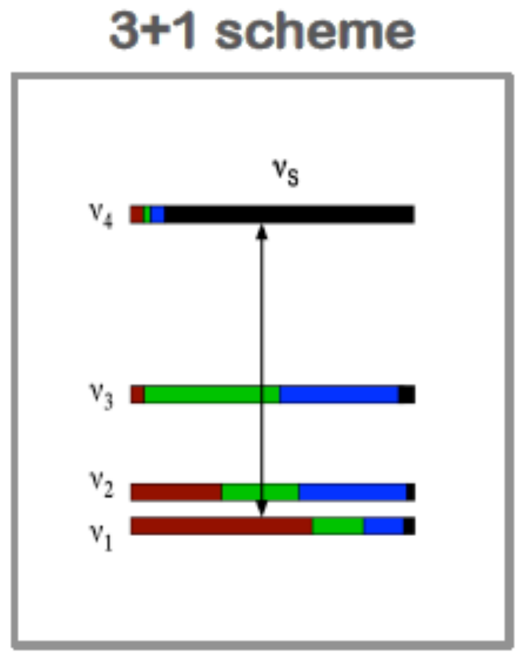
Short-baseline means : $L/E \sim 1$ (m/MeV or km/GeV)

It covers a wide range of experiments

- Radioactive $\nu_e/\bar{\nu}_e$ Source experiments
  ($L/E \sim 1$ m/1 MeV)
- Reactor $\bar{\nu}_e$ experiments
  ($L/E \sim 5$ m/5 MeV)
- Accelerator produced ν experiments
  ($L/E \sim 1$ km/1 GeV)
- Atmospheric Neutrinos in IceCube
  ($L/E \sim 1000$ km/1 TeV)

One Light eV-Scale Sterile Neutrino





$\Delta m^2_{41} \sim 1$ eV^2

Add one sterile ν with three active ones at the eV scale

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

Small perturbation of 3ν mixing

$$|U_{e4}|^2 << 1,\ |U_{\mu 4}|^2 << 1,\ |U_{\tau 4}|^2 << 1,\ |U_{s4}|^2 \approx 1$$

3+1 Short Baseline Oscillation

Appearance ($\alpha \neq \beta$)

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

Disappearance

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases

- Amplitude of ν_e disappearance:

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \simeq 4|U_{e4}|^2$$

- Amplitude of ν_μ disappearance:

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right) \simeq 4|U_{\mu 4}|^2$$

- Amplitude of $\nu_\mu \to \nu_e$ transitions:

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

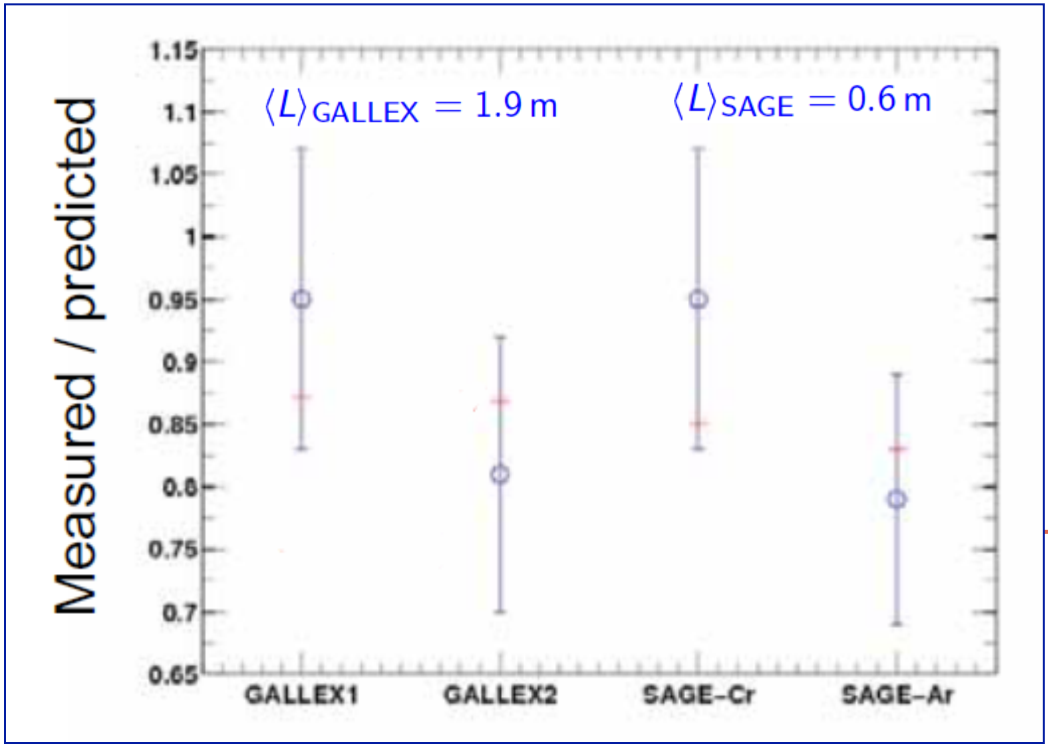
quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu 4}|^2$

$\Downarrow$

Appearance-Disappearance Tension

See reviews by C. Giunti

Gallium Neutrino Anomaly



Calibration measurements for the GALLEX & SAGE solar neutrino detectors using intense radioactive ν_e fluxes from ^{51}Cr & ^{37}Ar

^{51}Cr : 747 KeV (82%)
^{37}Ar: 811 KeV (90%)

Detection process:

$$\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$$

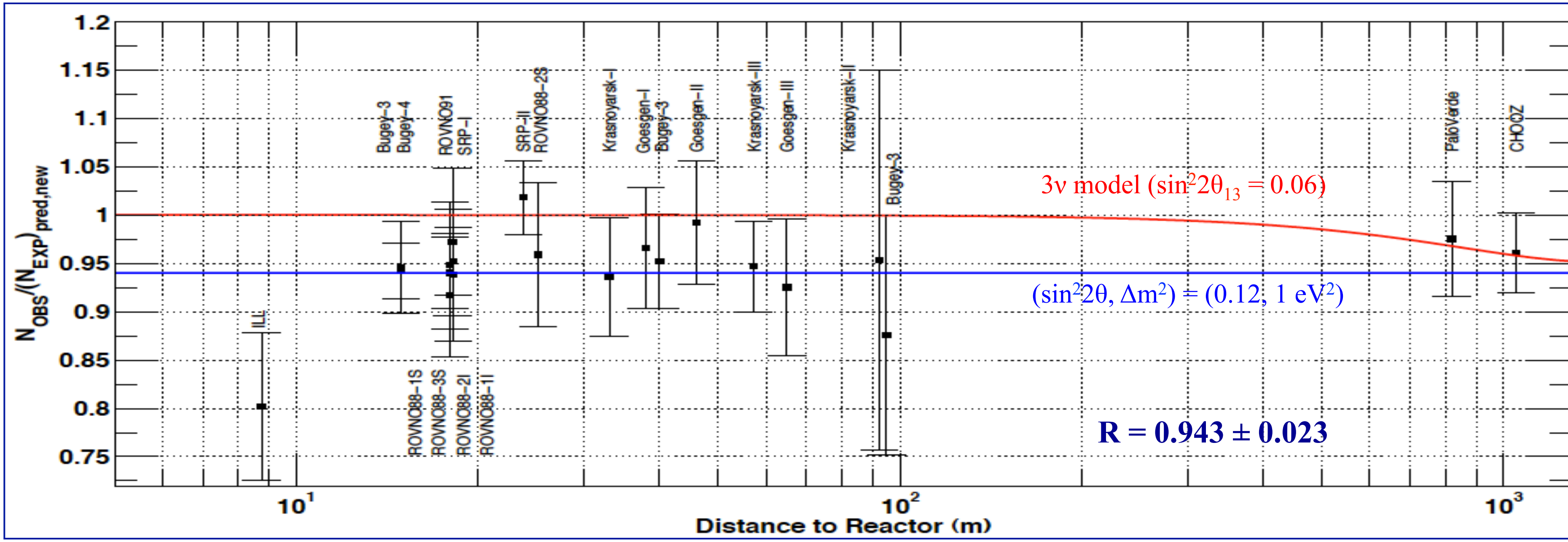
Measurements consistently lower than expectation

Suggests possible ν_e disappearance at 2.7σ due to active – sterile oscillation

Giunti and Laveder, arXiv:1006.3244

How well do we know the efficiencies of the radiochemical detection processes?

Reactor Anti-neutrino Anomaly



Mention et al., arXiv:1101.2755 [hep-ex]

Recent reanalysis of reactor fluxes shows ~ 3.5% upward shift in flux

Mueller et al., arXiv:1101.2663, confirmed by P. Huber, arXiv:1106.0687

Overall reduction in predicted flux compared to existing data can be interpreted as $\bar{\nu}_e$ disappearance with $\Delta m^2 \sim 1 eV^2$ and L = 10 – 100 m

Does source and detector size wash out oscillations?

Today's SBL Reactor Experiments

	Core Φ	Core H	P_{th}	^{235}U %	Baseline (m)
NEOS	3.1 m	3.8 m	2.8 GW	~ 4	23.7
DANSS	3.2 m	3.7 m	3.1 GW	~ 4	10.7 - 12.7

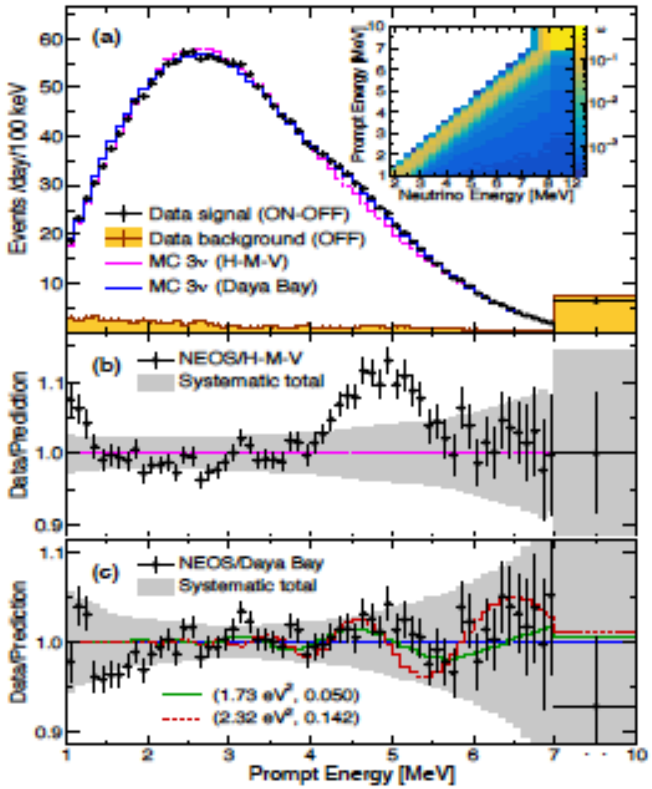
	Core Φ	Core H	P_{th}	^{235}U %	Baseline (m)
STEREO	40 cm	80 cm	58 MW	93	9-11
SOLID	50 cm	90 cm	50-80 MW	93	6-9
PROSPECT	44 cm	51 cm	85 MW	> 93	7-9

Core size and fuel composition impact on systematics & ν rates

	$\sigma/E\%$	average rate/day	n capture
DANSS	17	4101 ± 11	Gd
NEOS	5	~ 1976	Gd
STEREO	9	396 ± 4.7	Gd
PROSPECT	4.5	~ 750	Li
SOLID(preliminary)	14	~ 1750 ON &~ 1375 OFF	Li

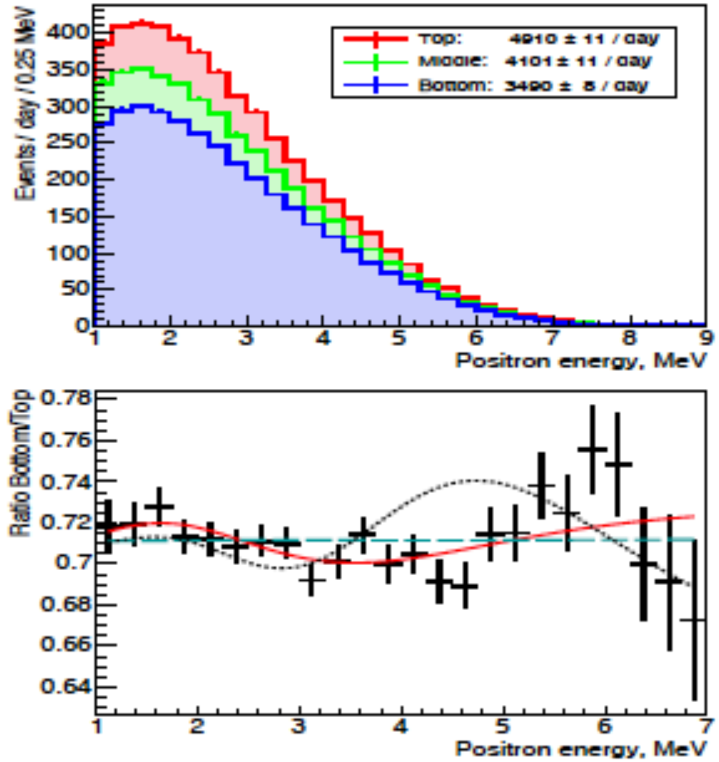
NEOS and DANSS

NEOS arXiv:1610:05134



$$\chi^2_{4\nu} - \chi^2_{3\nu} = -6.5$$

DANSS arXiv:1804:04046

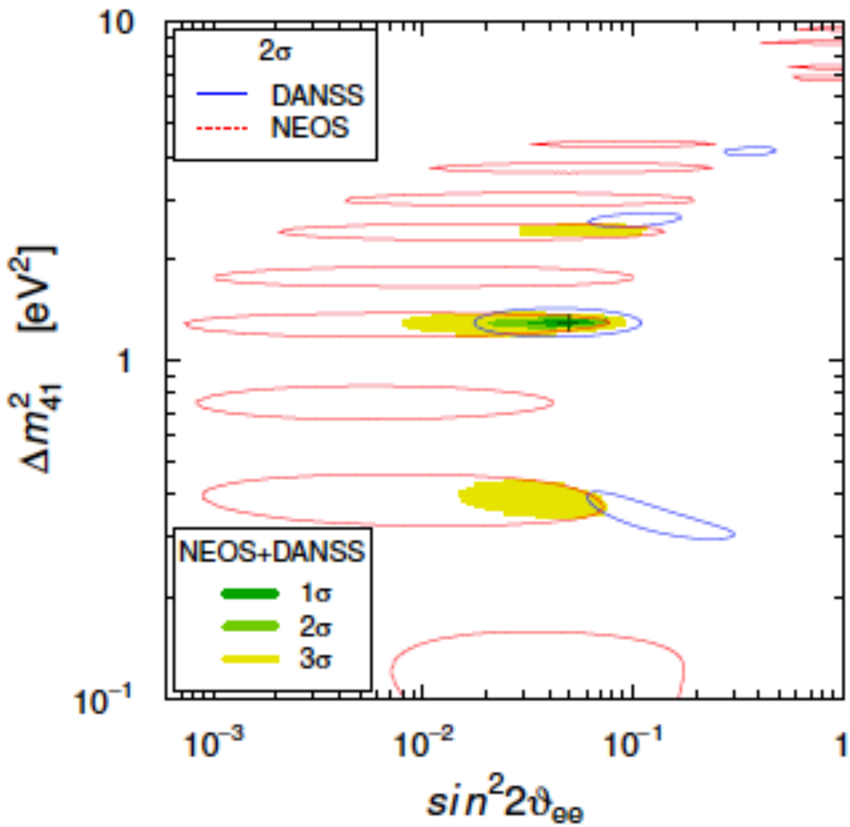


$$\chi^2_{4\nu} - \chi^2_{3\nu} = -13.1$$

Best fit points very similar: $(\sin^2 2\theta,\ \Delta m^2) \simeq (0.05,\ 1.4\mathrm{eV}^2)$

Model-Independent $\bar{\nu}_e$ SBL Oscillations

[Gariazzo, CG, Laveder, Li, PLB 782 (2018) 13, arXiv:1801.06467]



$\sim 3.7\sigma$

$\Delta m^2_{41} = 1.29 \pm 0.03$

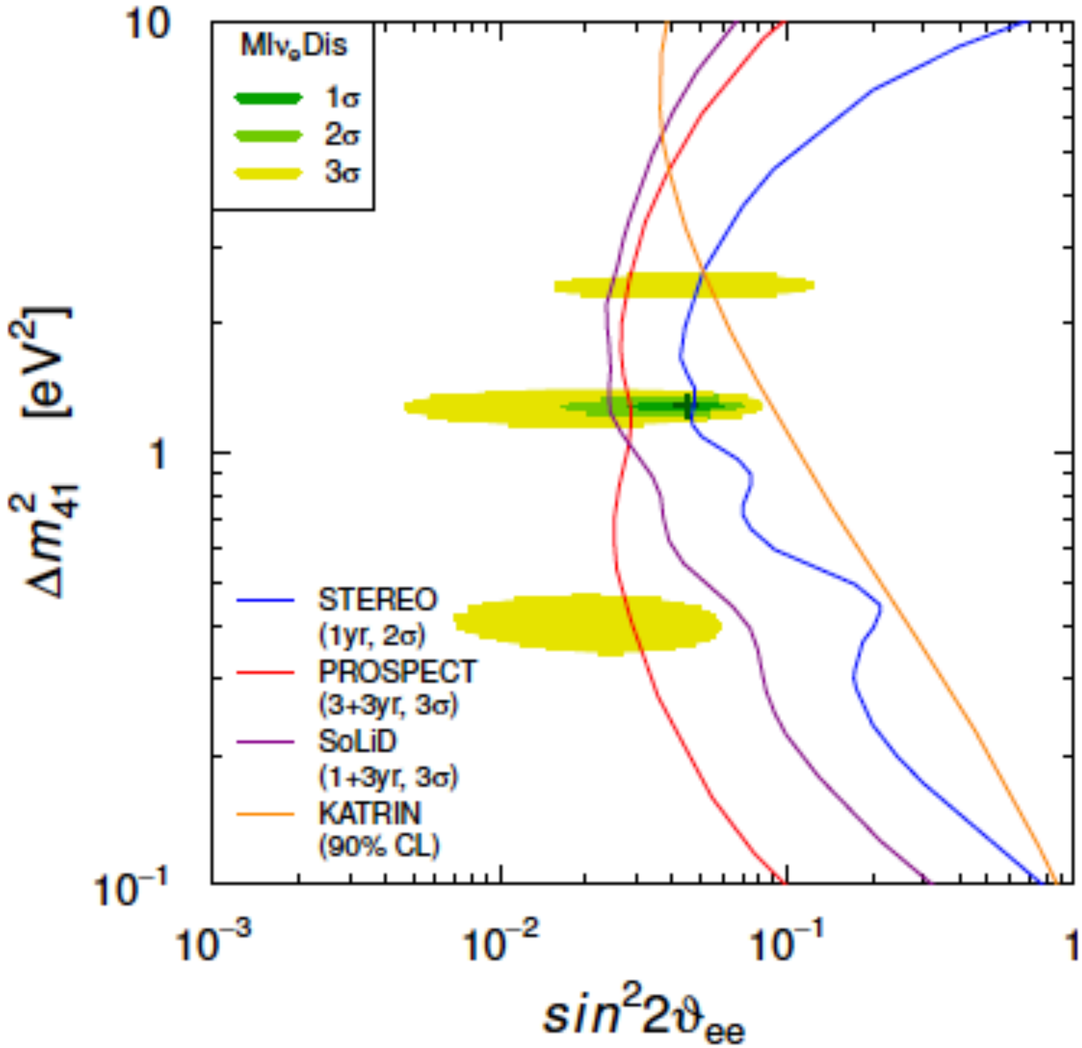
$\sin^2 2\vartheta_{ee} = 0.049 \pm 0.011$

$\sin^2 \vartheta_{14} = |U_{e4}|^2$

$\sin^2 \vartheta_{14} = 0.012 \pm 0.003$

$\sin^2 \vartheta_{13} = 0.022 \pm 0.001$

Global Analysis



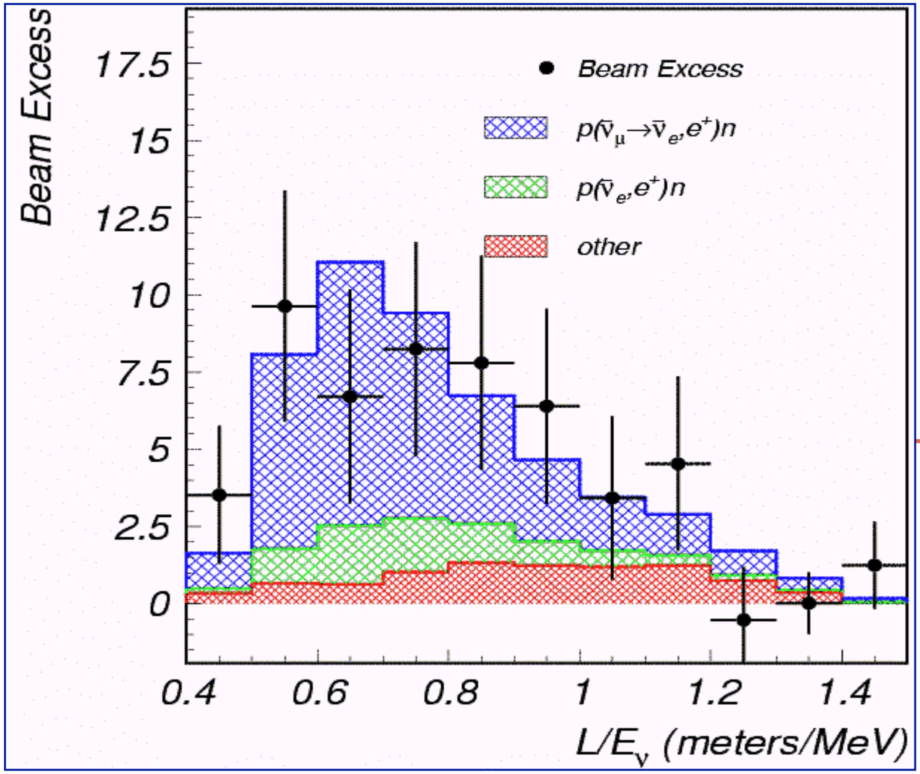
- NEOS and DANSS.
- Reactor rates with free ^{235}U and ^{239}Pu fluxes: r_{235} and r_{239}.
- Gallium data with free GALLEX and SAGE efficiencies: η_G and η_S.
- New reactor experiments: STEREO, Neutrino-4, SoLiD, PROSPECT
- Kinematic ν_4 mass measurement: KATRIN

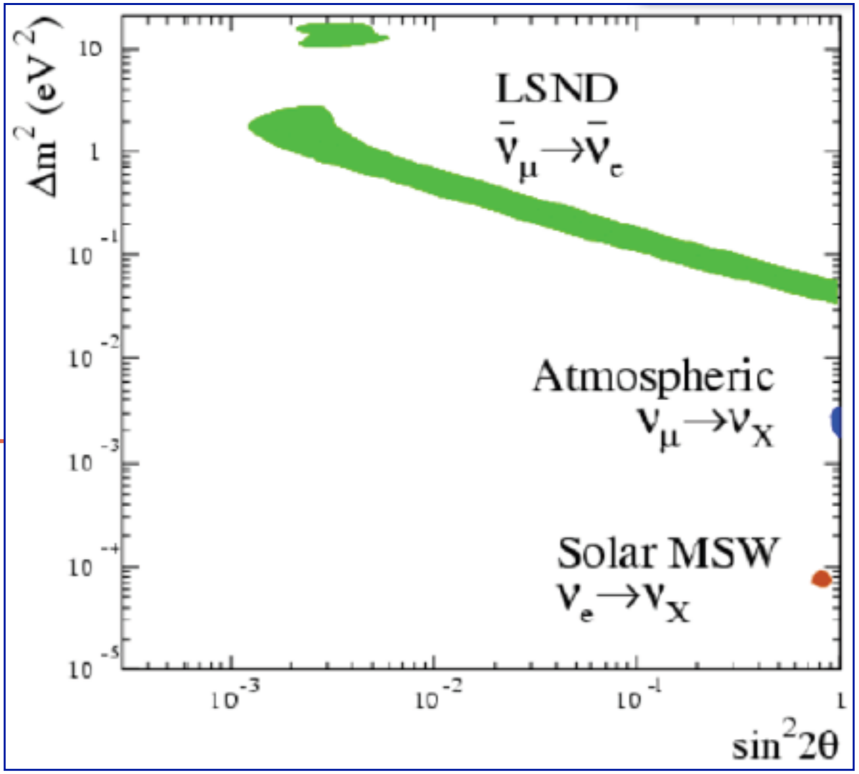
[See also Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]

Courtesy C. Giunti

LSND Result

$\mathrm{LSND: L = 30\ m,} < E_{\nu_{\bar{\mu}}} > = \mathrm{40\ MeV}$





Saw an excess of 87.9 ± 22.4 ± 6.0 events

$3.8\,\sigma$ excess of $\bar{\nu}_e$ events in a beam of $\bar{\nu}_\mu$

PRD 64, 112007 (2001)

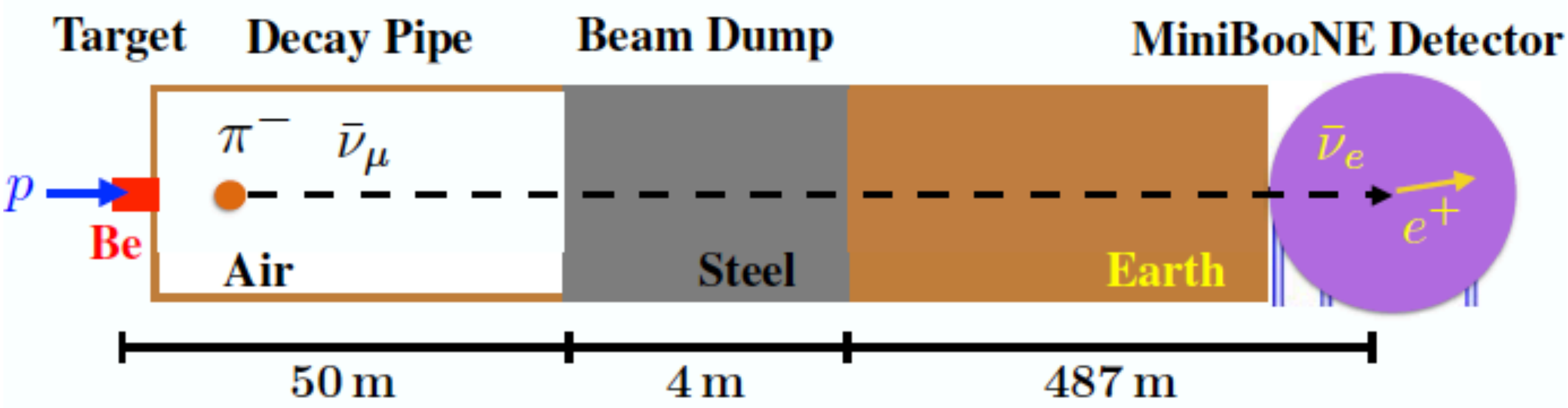
$P(\bar{\nu}_\mu \to \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\%$

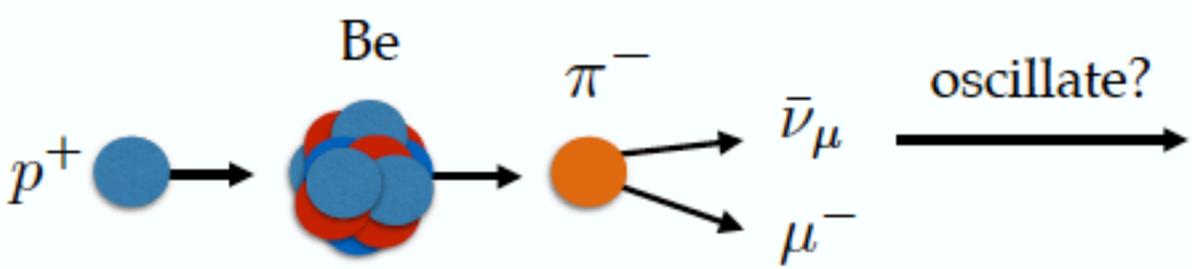
$\Delta m^2 \sim$0.1-10 eV^2, small mixing

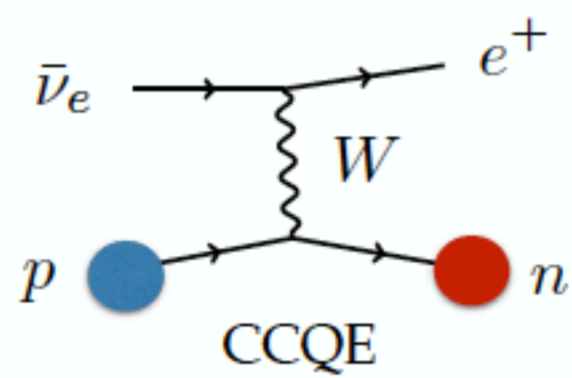
Large ($\sin^2 2\theta$, Δm^2) degeneracy

HARP @ CERN can test LSND $\bar{\nu}_e$ background estimate

MiniBooNE Experiment







10^{21} POT, $E_p = 9$ GeV

Energy and baseline chosen to test LSND

Comparable oscillation probabilities

MiniBooNE Collaboration 1805.12028

MiniBooNE Data Analysis

	neutrino mode	antineutrino mode
Luminosity	12.84×10^{20} POT	11.27×10^{20} POT
Reconstructed Neutrino Energy	$200 < E_\nu^{QE} < 1250$ MeV	
Excess events BG subtracted	381.2 ± 85.2	79.3 ± 28.6

Possibly Important Caveat

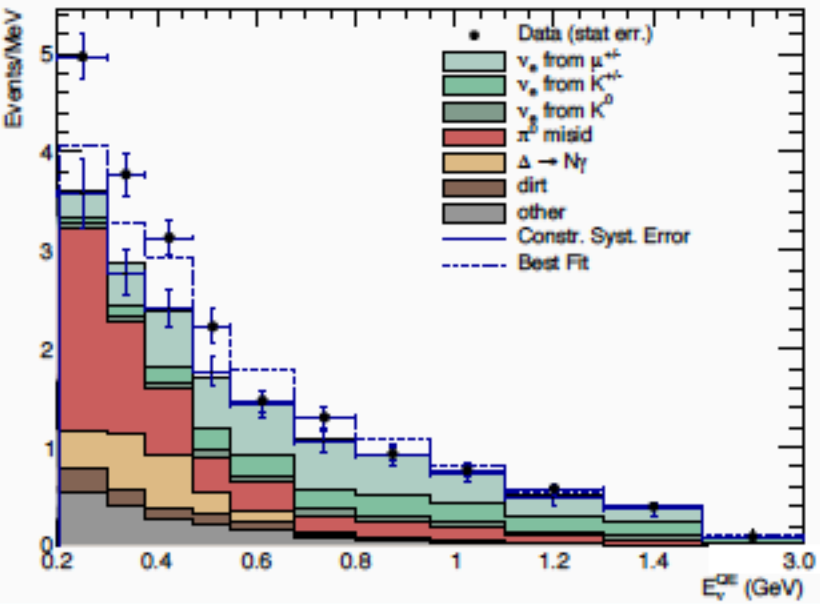
Mild tension ~ 2+ sigma between neutrino and antineutrino modes

Updated Neutrino Mode Analysis
MiniBooNE Collaboration1805.12028

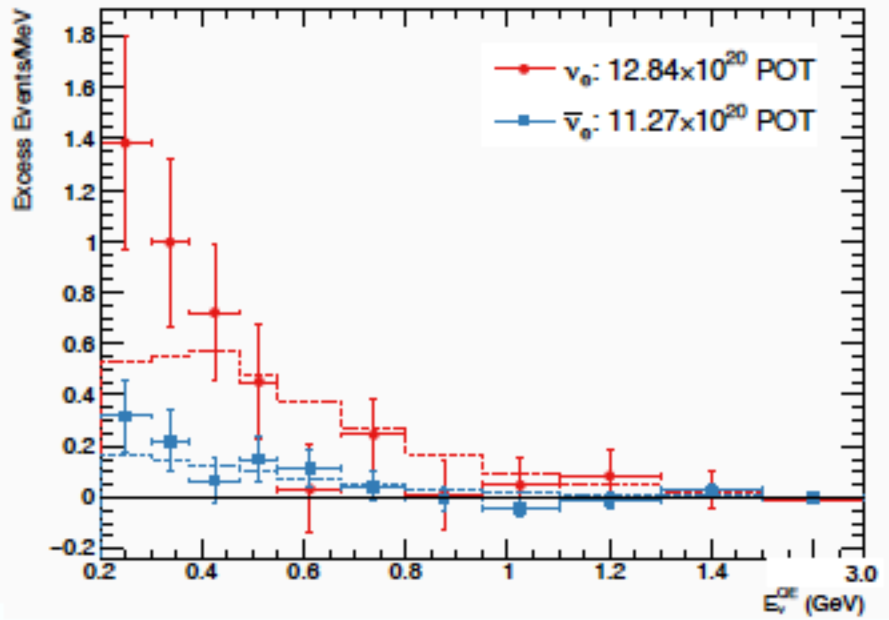
Complements earlier antineutrino
results collected 2002-2010

MiniBooNE Anomaly

Neutrino mode only



Both excesses, BG subtracted



$$E_\nu^{(\text{reconst.})} = \frac{2m_n E_e + m_p^2 - m_n^2 - m_e^2}{2(m_n - E_e + \cos\theta_e \sqrt{E_e^2 - m_e^2})}.$$

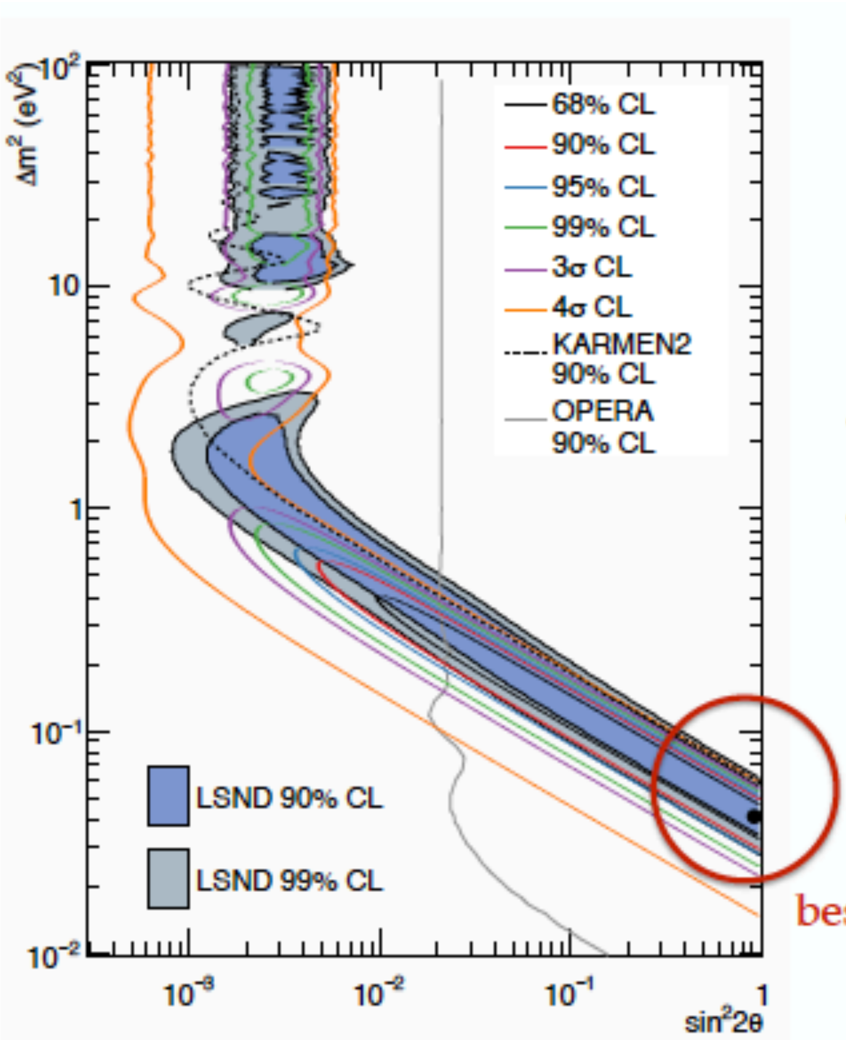
Measure charged lepton energy/angle

Observed ~ 400 events, PMNS predicts 0

Combined $\nu/\bar{\nu}$ modes : 4.8σ excess

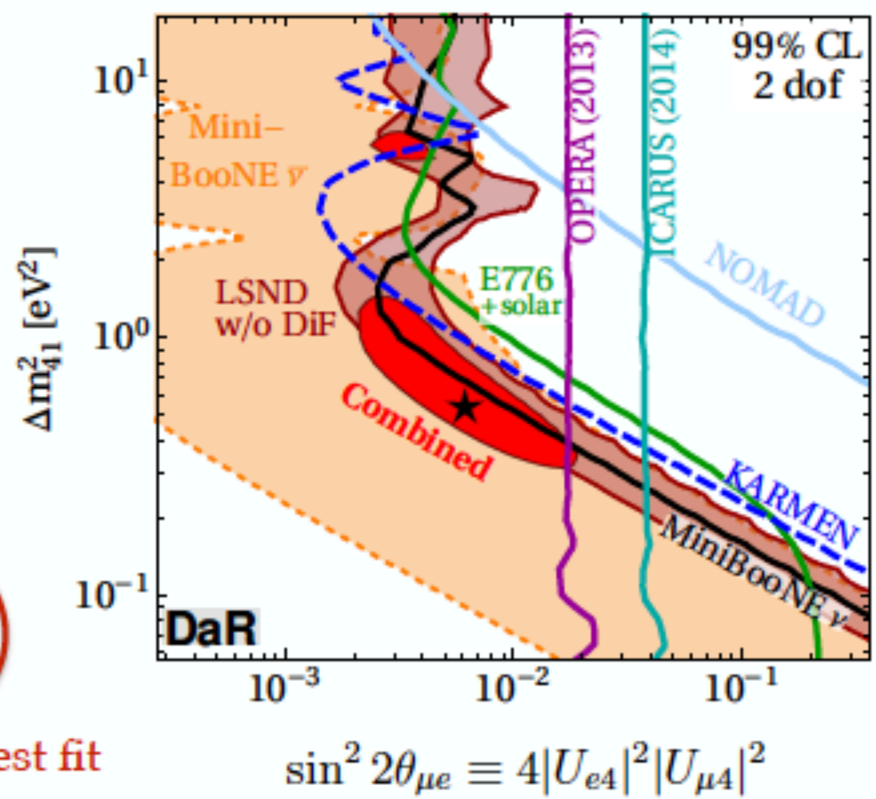
MiniBooNE Collaboration 1805.12028

Can eV-scale Sterile Neutrino explain LSND+ MiniBooNE Anomaly?



MiniBooNE Collaboration 1805.12028

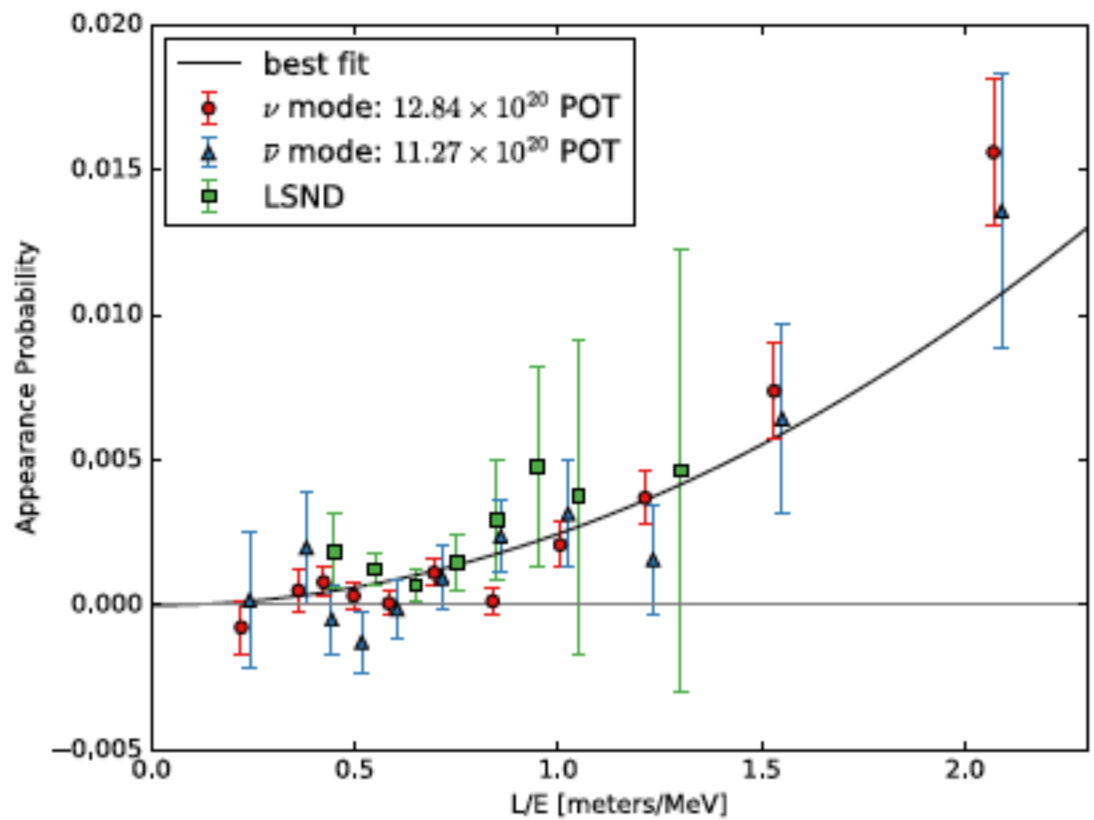
Best fits [appearance only]



Combined 6.1 sigma excess!

Dentler et. al. 1803.10661

Can eV-scale Sterile Neutrino explain LSND+ MiniBooNE Anomaly?

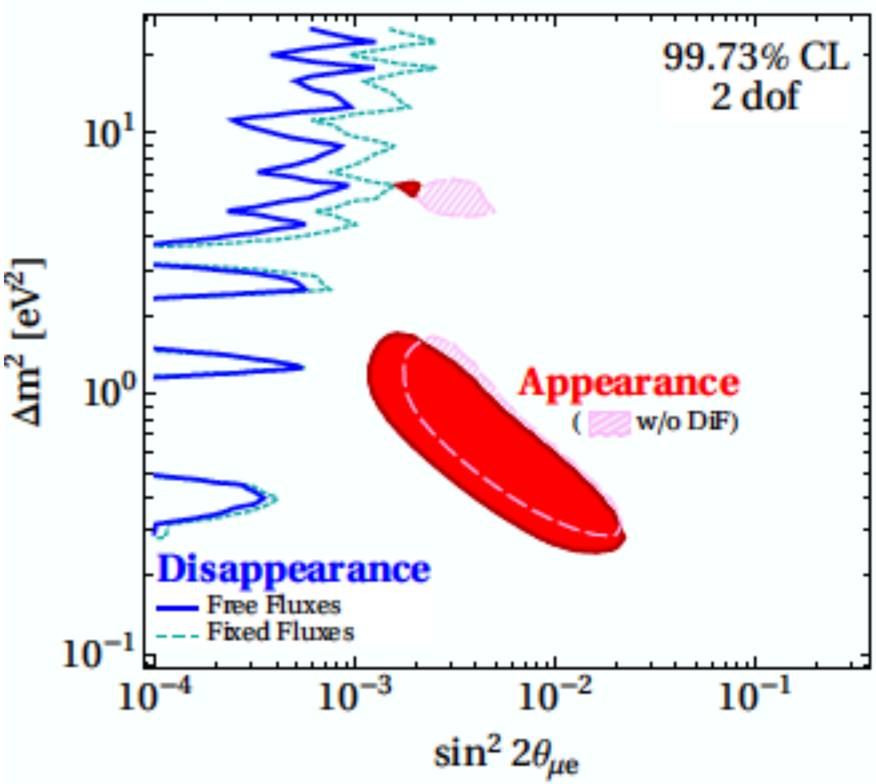


@ face value the scaling seems to support LSND / MB compatibility

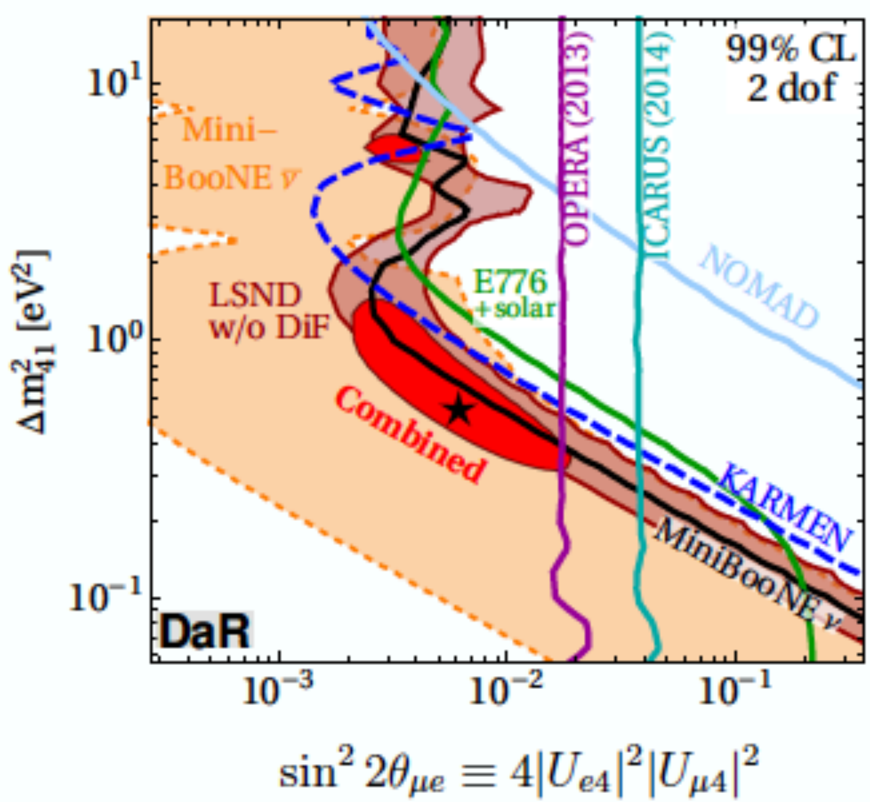
MiniBooNE Collaboration 1805.12028

Can eV-scale Sterile Neutrino explain LSND+ MiniBooNE Anomaly?

Including disappearance



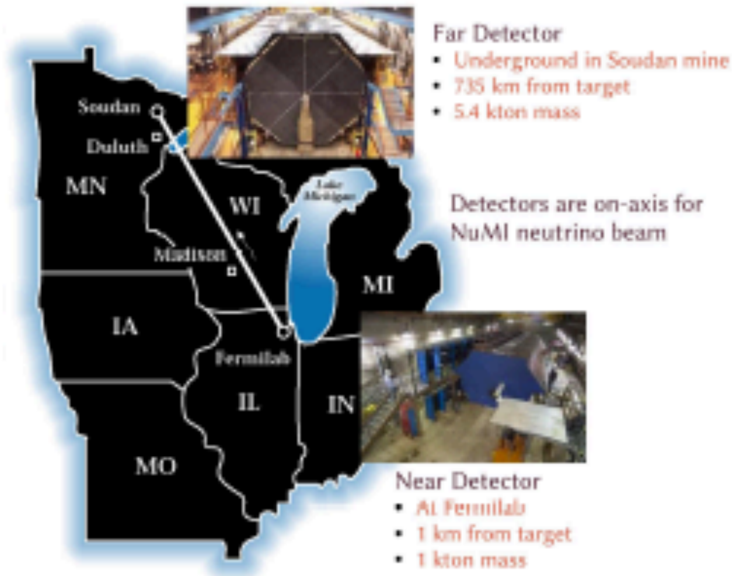
Best fits [appearance only]



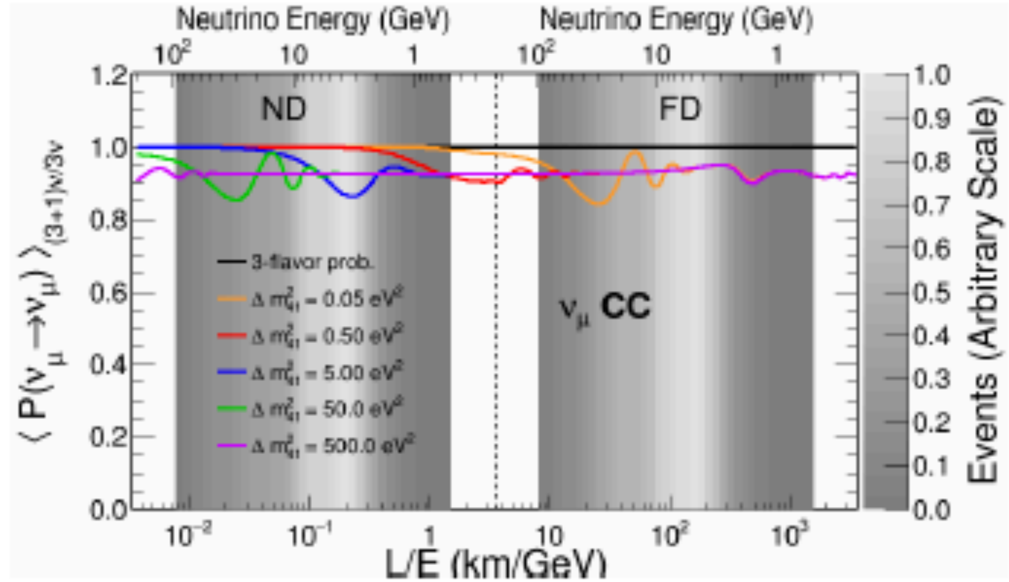
Significant tension with multiple null disappearance results

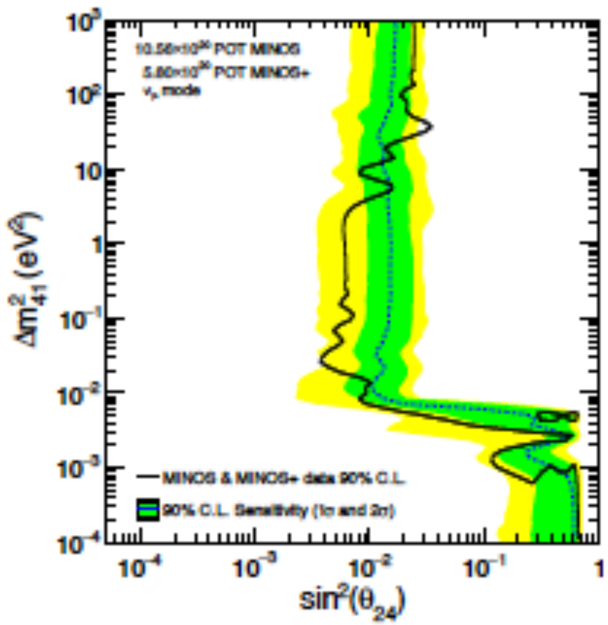
Dentler et. al. 1803.10661

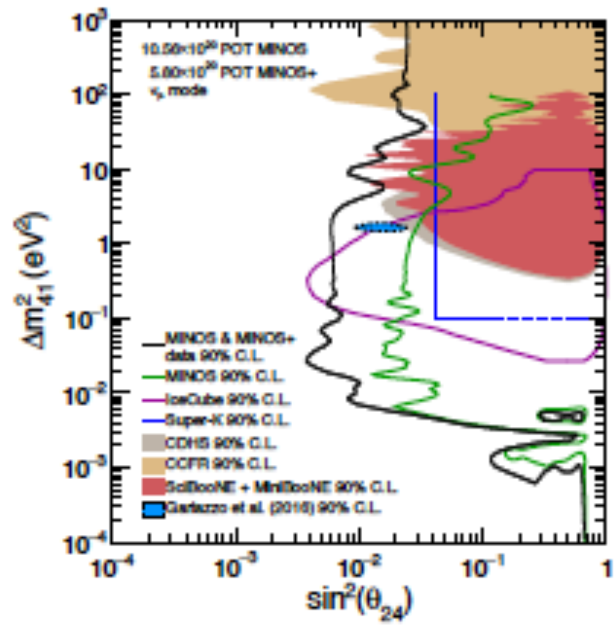
New Bounds from MINOS+



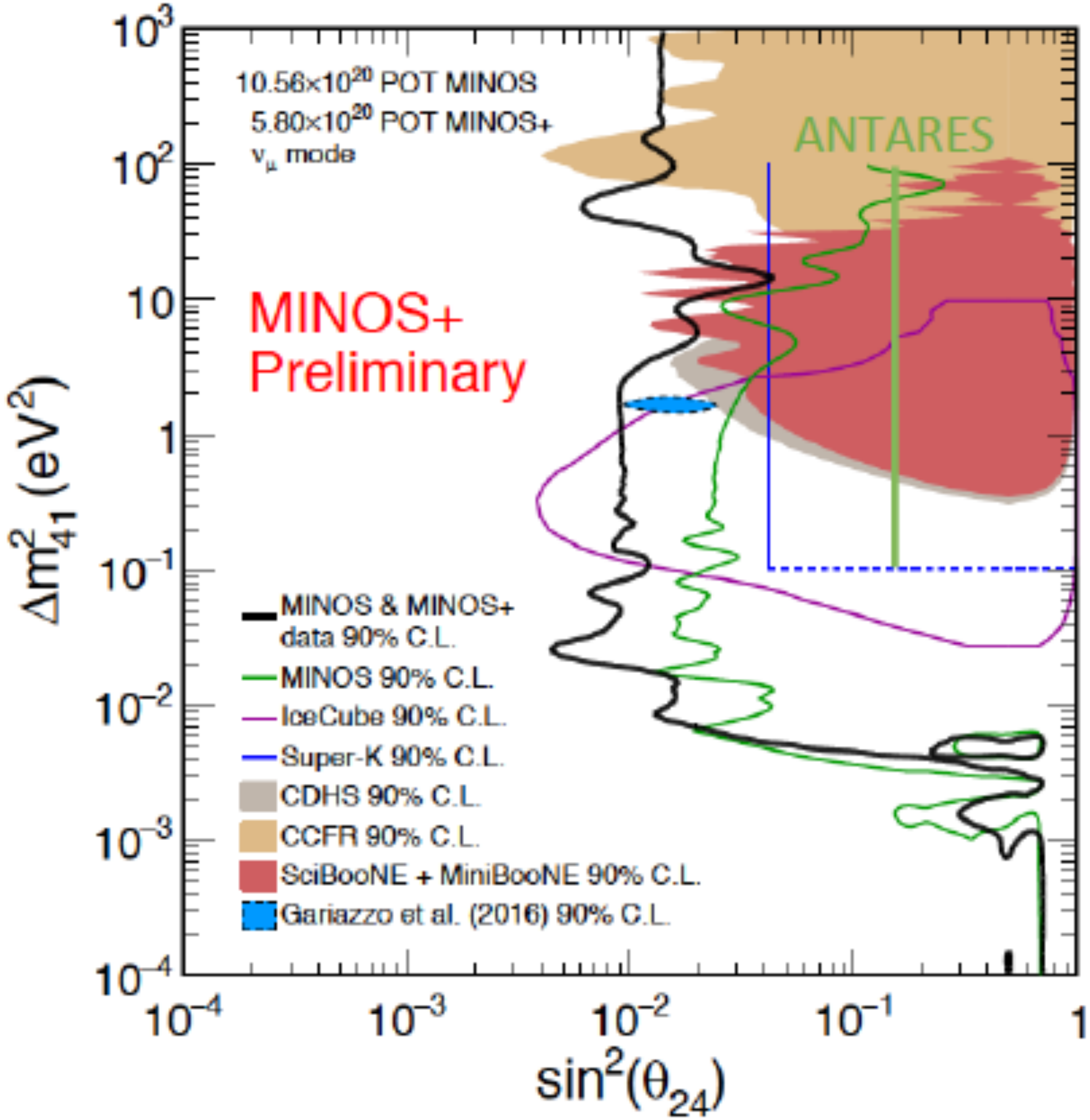
[arXiv:1710.06488]





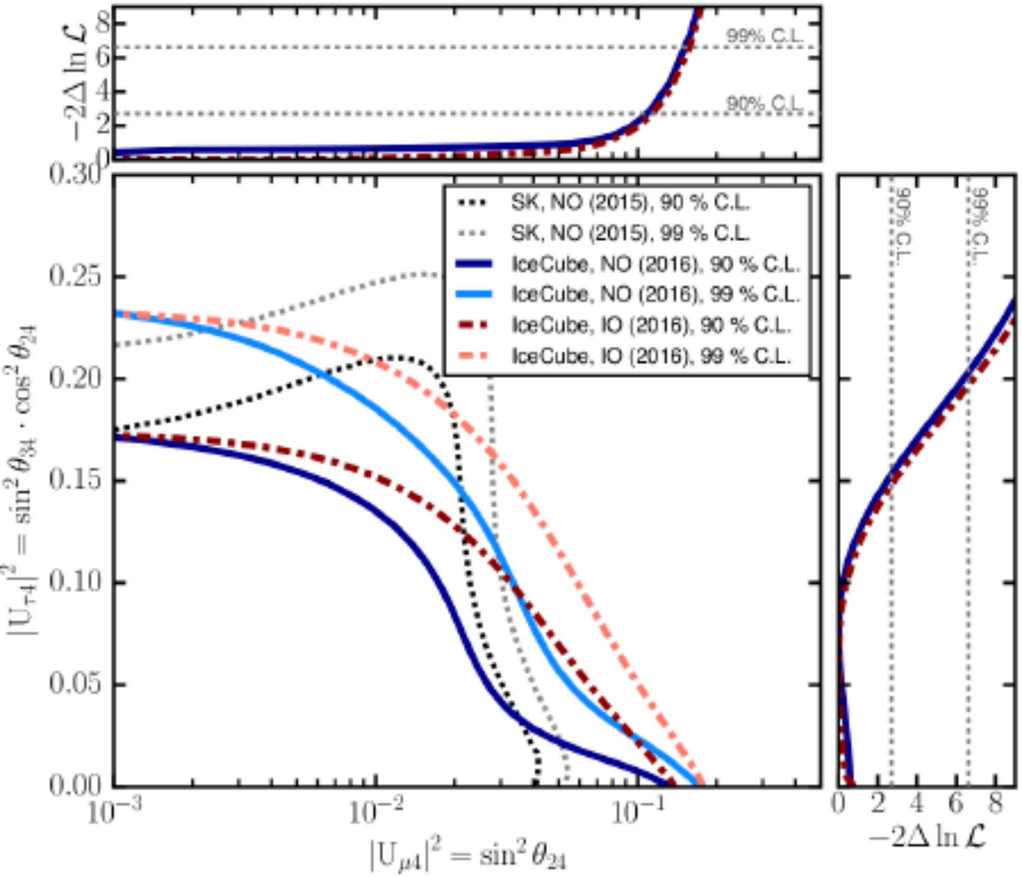


Let us Zoom the Muon Disappearance Results



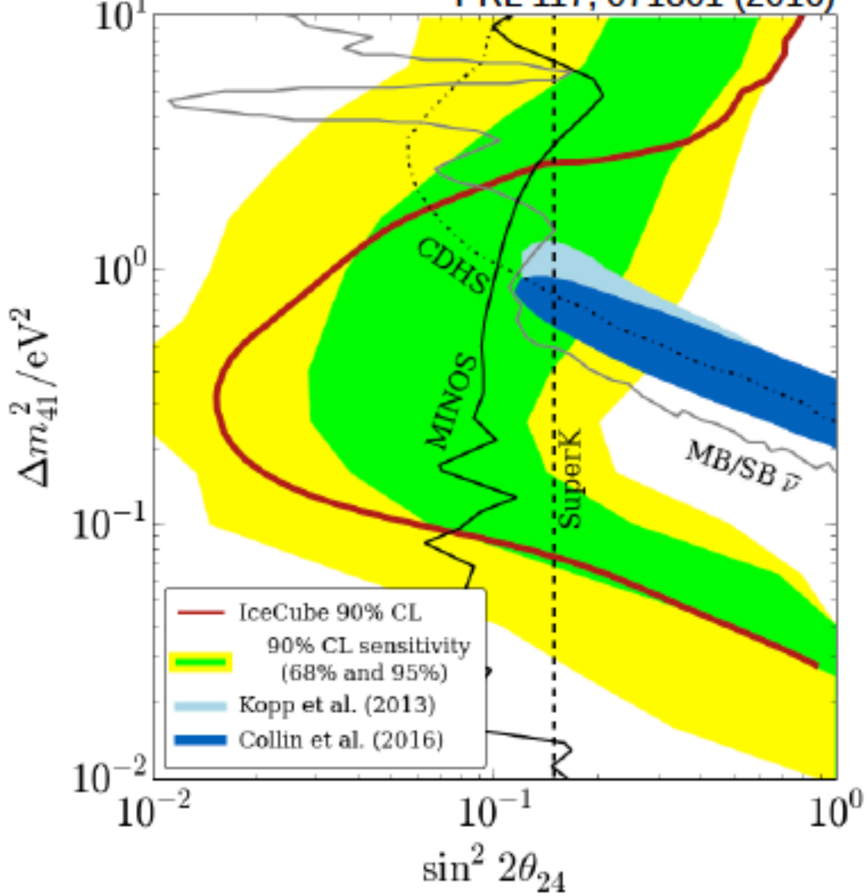
> Sterile neutrinos with DeepCore

PRD 95, 112002 (2017)



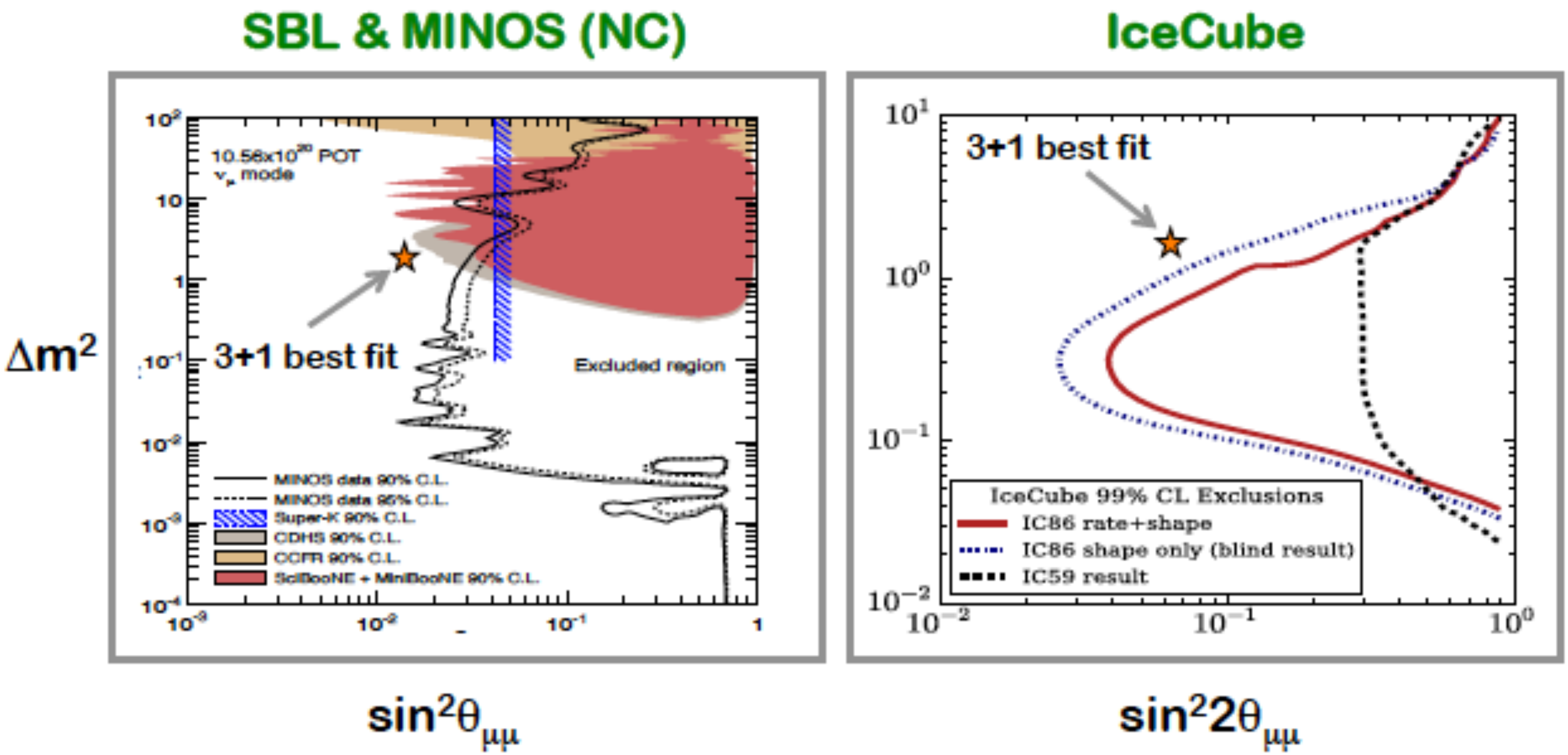
> TeV search for sterile neutrinos

PRL 117, 071801 (2016)



> Constraining limits on sterile neutrino mixing in muon and tau sectors

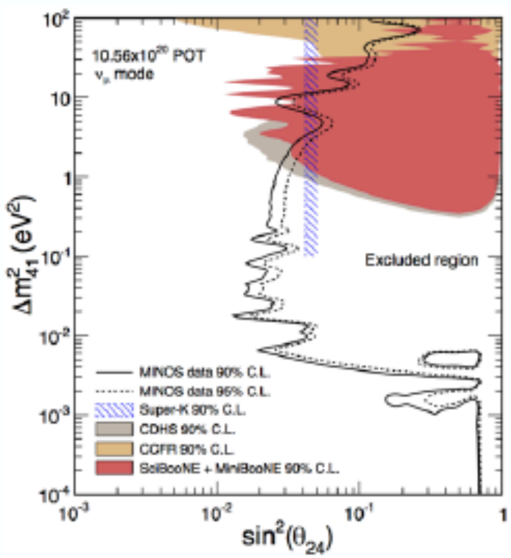
No Anomaly in Muon Neutrino Disappearance



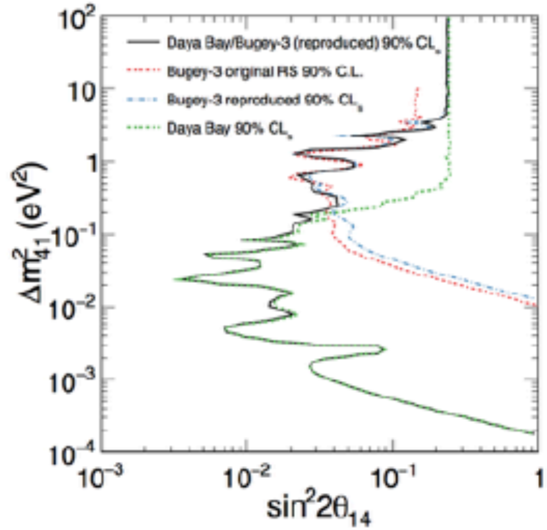
Joint Analysis of Daya Bay/Bugey-3/MINOS

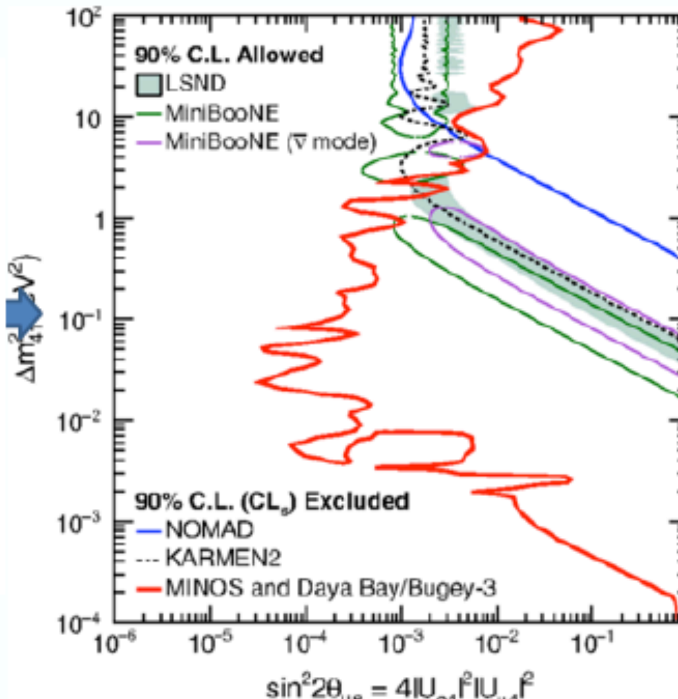
PRL 117, 151801 (2016)+MINOS+ results

MINOS/MINOS+ 2016



Daya Bay + Bugey-3





- The combined results can largely exclude the LSND and MiniBooNE region assuming 3+1 neutrino model

Combined : Phys. Rev. Lett. 117, 151801
MINOS : Phys. Rev. Lett. 117, 151803
Daya Bay : Phys. Rev. Lett. 117, 151802

What Cosmology can infer about Light Sterile Neutrino?

Sterile neutrinos require $\sin^2 2\theta_{\mu e} > 10^{-3}$, $m_4 < \text{few eV}$

Generic early universe thermalization

$$\Gamma > H \implies \sin^2 2\theta_{\mu e} G_F^2 T^5 > \sqrt{g_*}\frac{T^2}{m_{\rm Pl}} \implies n_4 \sim n_\nu$$

Excluded by BBN / CMB $N_{\rm eff} = 2.99 \pm 0.17$ Planck 1807.06209

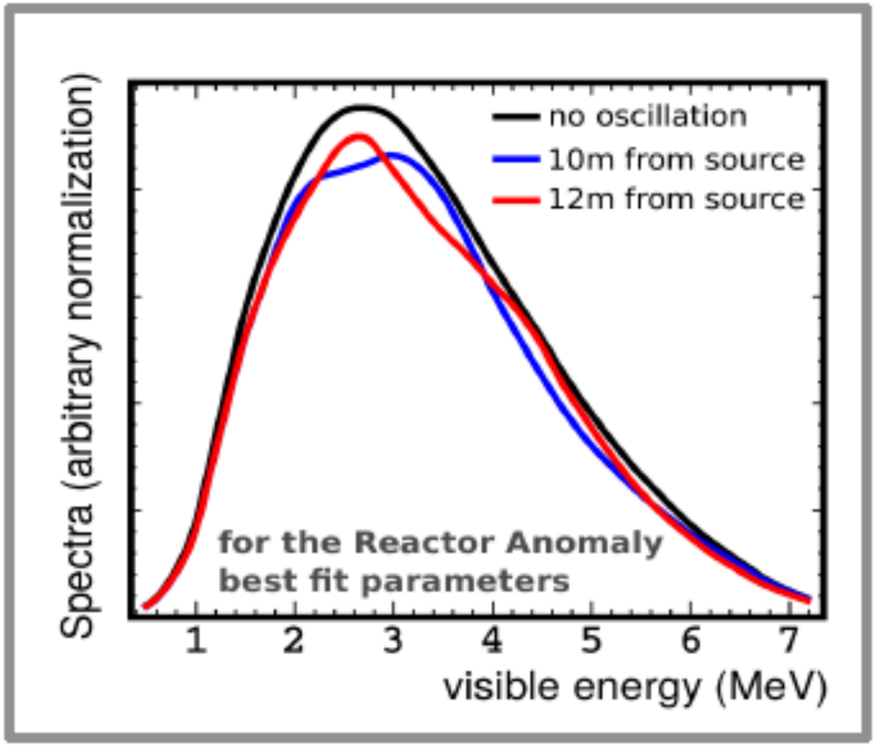
Unless max temperature satisfies $T_{\rm max} \lesssim 15\ \text{MeV} \left(\frac{10^{-3}}{\sin^2 2\theta_{\mu e}}\right)^{1/3}$

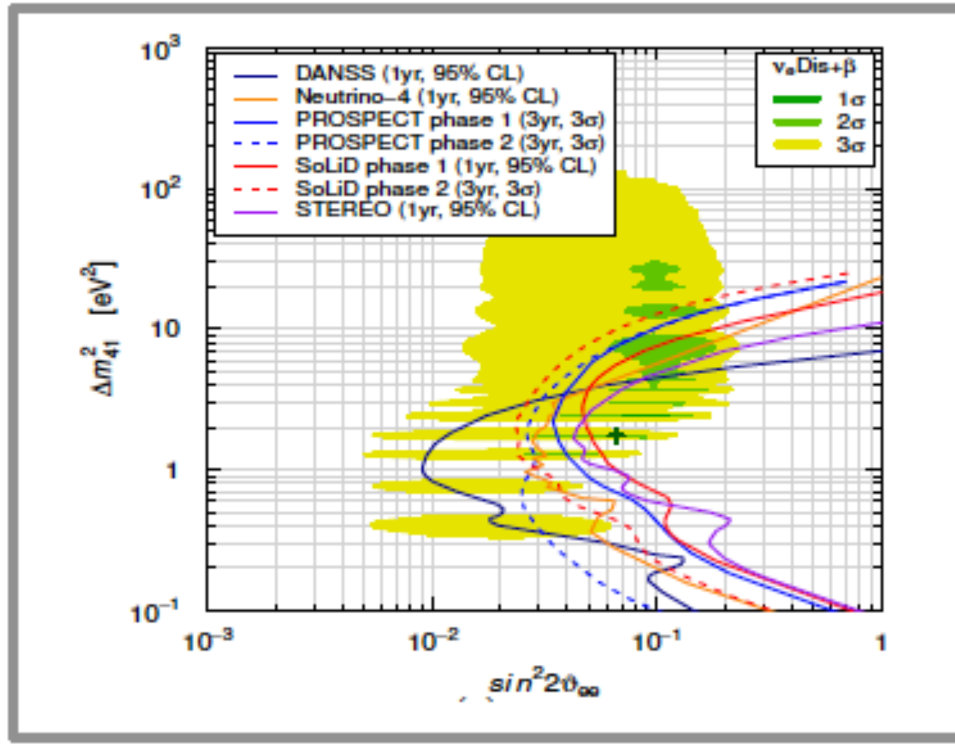
Interesting discussion in arXiv:1806.10629v1 by Chu, Dasgupta, Dentler, Kopp, Saviano

Need to see SBL Oscillation Pattern: Smoking Gun Signature

STEREO

Gariazzo et al., 1703.00860

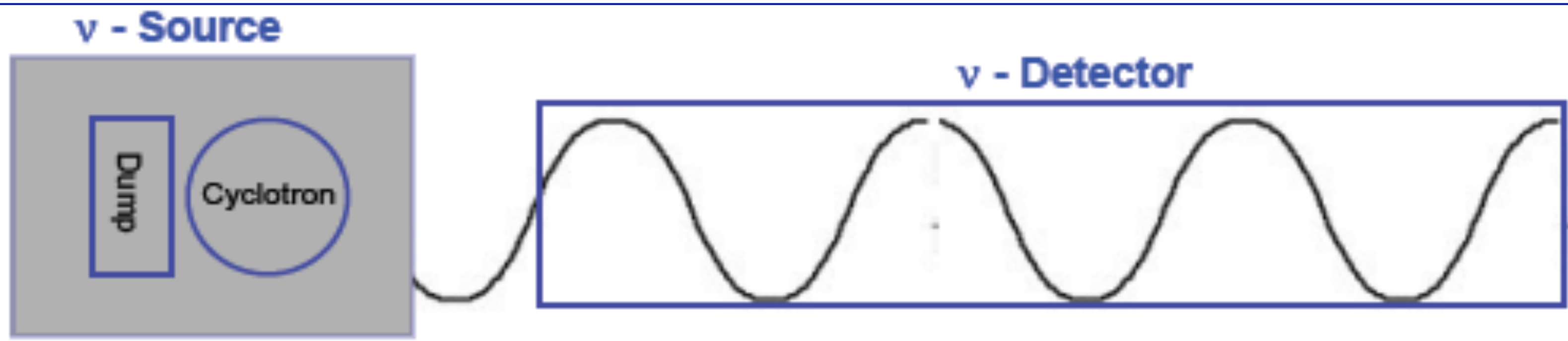




by observing the oscillation pattern

and we have already some hints…

Very Short Baseline Oscillation Experiment



$$1/L^2 \text{ flux rate modulated by } \mathrm{Prob}_{osc} = \sin^2 2\theta \cdot \sin^2\left(\Delta m^2 L/E\right)$$

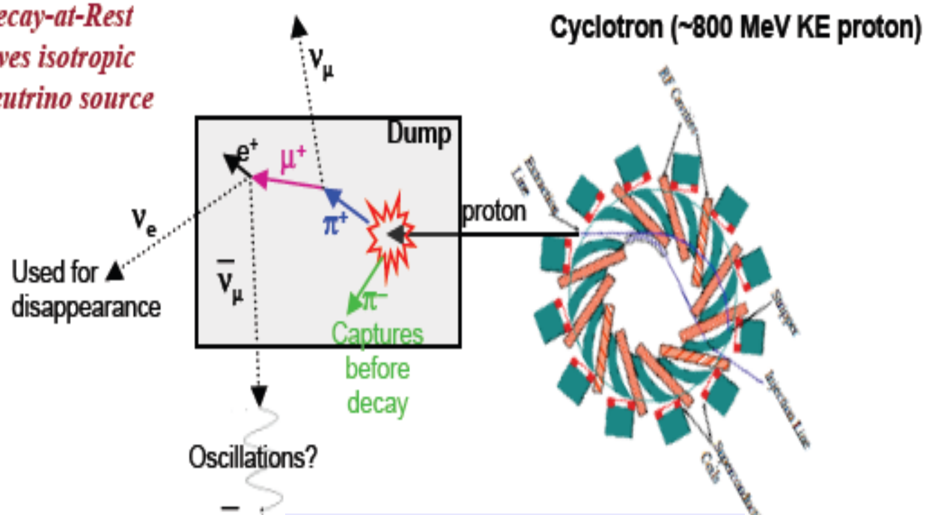
Neutrino Sources

- **Decay-at-rest beam from proton beam dump**
- **Small core reactor source**
- **Very high activity radioactive source**

- **Observe the L/E dependence of the event rates within a long ν detector**
- **Background distribution is either independent of L or goes like $1/L^2$**
- **Powerful verification of the short baseline oscillation/new physics**

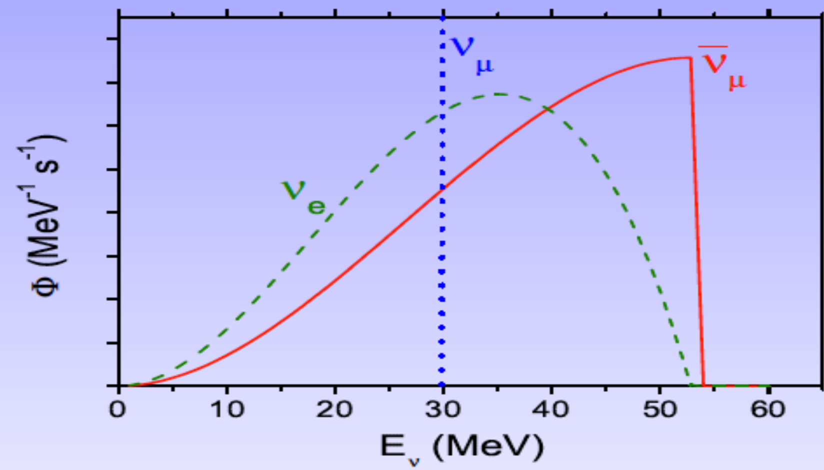
Decay-At-Rest (or Beam Dump) Neutrino Source

Decay-at-Rest gives isotropic neutrino source



Provides an equal, high-intensity, isotropic, DAR ν_μ, ν_e and $\bar{\nu}_\mu$ beam with tiny $\bar{\nu}_e$ contamination (4×10^{-4})

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

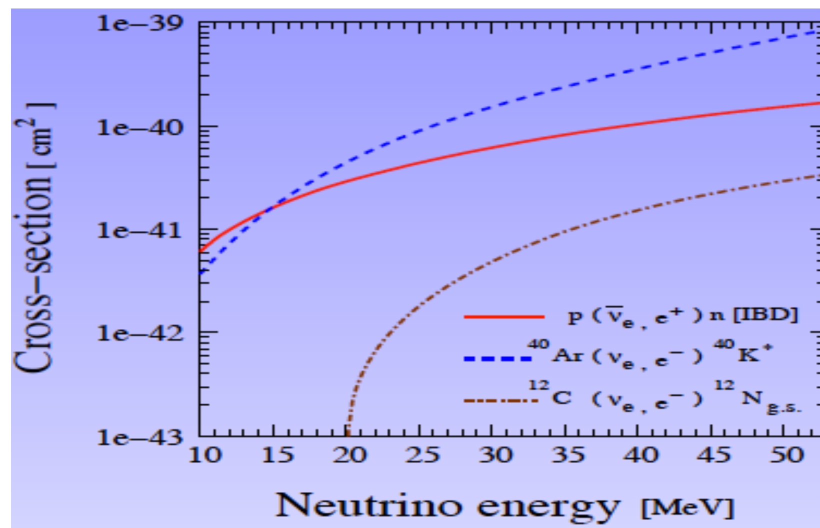


800 MeV protons from cyclotrons interact in a low-A target (C, H_2O) producing π^+ and, at a low level, π^-

$$p + X \rightarrow \pi^\pm + X'$$

Low-A target is embedded in a high-A, dense material where pions are brought to rest

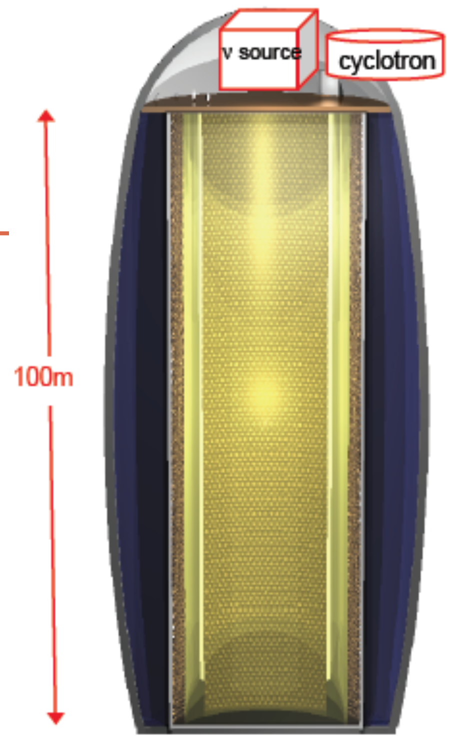
π^- & daughter μ^- captured before DIF, minimizing $\bar{\nu}_e$



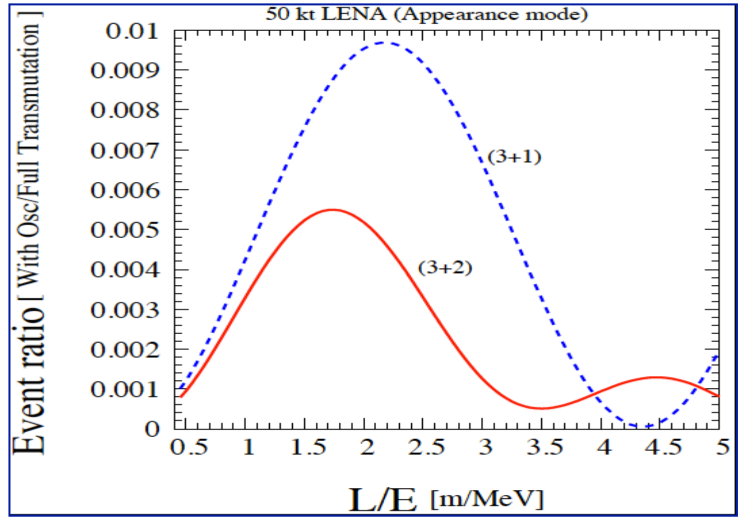
Agarwalla, Conrad and Shaevitz, arXiv: 1105.4984

Short Baseline Neutrino Oscillation Waves

- LENA Scintillation Detector
- 50 kt fiducial mass
- Source-to-detector face = 20 m
- Deep location (4000 mwe)
- Negligible cosmic muon background

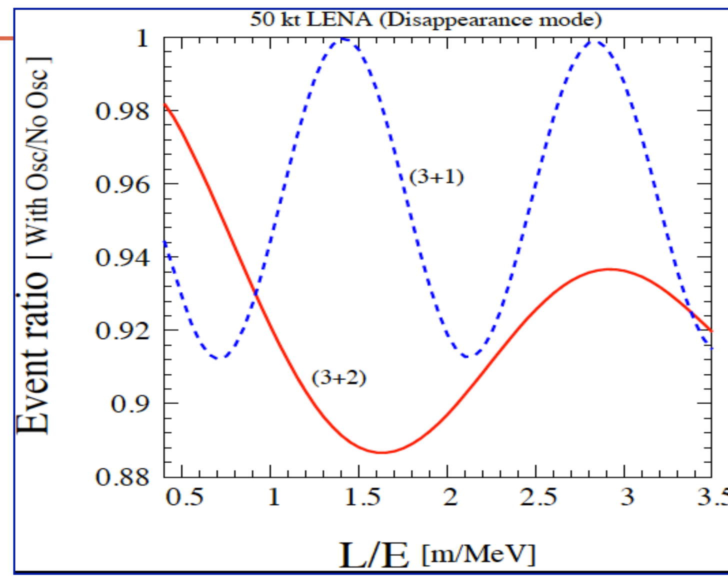


Similar study with NOνA, Gd doped Super-K, or JUNO



Distinguish between (3+1) & (3+2) models

Rate + Shape measurement



Several L/E bins cancel systematic uncertainties

Agarwalla and Huber, arXiv: 1007.3228
Agarwalla, Conrad and Shaevitz, arXiv: 1105.4984

An Intrinsic Limitation of SBL Setup

- In SBL expts, L/E ~ 1 (m/MeV) to probe ~ 1 eV^2 mass-squared difference
- Oscillations due to solar and atmospheric frequencies are almost negligible
- We essentially work in a two-flavor framework, governed by the new frequency Δm^2_{41}, and the new active-sterile mixing elements U_{e4}, $U_{\mu4}$, $U_{\tau4}$
- Cannot observe the interference between the sterile & atm/sol frequencies
- Cannot observe the presence of CP phases in SBL experiments
- Interference is the key in order to measure the new CP phases that are there due to the new sterile states, and LBL experiments can probe them

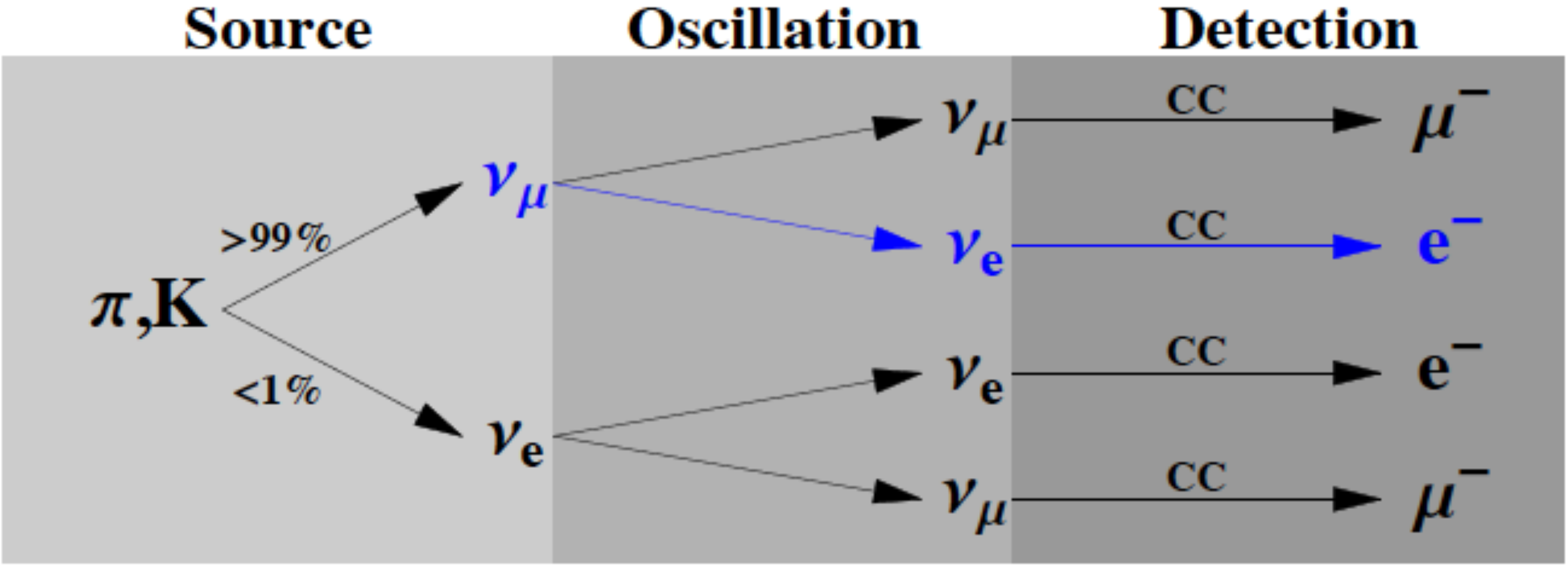
Accelerator Long-Baseline Neutrino Experiments

($\nu_\mu \rightarrow \nu_e$) and (anti-$\nu_\mu \rightarrow$ anti-ν_e)

T2K (Japan) & NOνA (USA) [running, off-axis]

DUNE (USA) [upcoming, on-axis]

T2HK (Japan) [upcoming, off-axis]



Traditional approach: Neutrino beam from pion decay

Impact of light eV-scale sterile neutrino in currently running and upcoming long-baseline neutrino oscillation experiments

Can sterile neutrinos generate new observable CP-violating effects at long-baseline experiments?

CPV and Averaged Oscillations

$$A^{\rm CP}_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

$$A^{\rm CP}_{\alpha\beta} = -16 J^{12}_{\alpha\beta} \sin\Delta_{21} \sin\Delta_{13} \sin\Delta_{32}$$

if $\Delta \equiv \Delta_{13} \simeq \Delta_{23} \gg 1$ → $\langle \sin^2\Delta \rangle = 1/2$

osc. averaged out by finite E resol.

It can be: $A^{\rm CP}_{\alpha\beta} \neq 0$ (if $\sin\delta = \emptyset$)

The bottom line is that if one of the three ν_i is ∞ far from the other two ones this does not erase CPV (relevant for the 4ν case)

Very New Topic: Lots of New Studies

Recent studies after θ_{13} discovery in the context of T2K, NOvA, and DUNE:

1) Imprints of CP violation induced by sterile neutrinos in T2K data
Klop, Palazzo (arXiv:1412.7524)

2) Sterile neutrino at the Deep Underground Neutrino Experiment
Berryman, de Gouvea, Kelly, Kobach (arXiv:1507.03986)

3) The impact of sterile neutrinos on CP measurements at long baselines
Gandhi, Kayser, Masud, Prakash (arXiv:1508.06275)

4) 3-flavor and 4-flavor implications of the latest T2K and NOvA electron (anti-)neutrino appearance results
Palazzo (arXiv:1509.03148)

5) Discovery potential of T2K and NOvA in the presence of a light sterile neutrino
Agarwalla, Chatterjee, Dasgupta, Palazzo (arXiv:1601.05995)

Recent studies after θ_{13} discovery in the context of T2K, NOvA, and DUNE:

6) Physics reach of DUNE with a light sterile neutrino
Agarwalla, Chatterjee, Palazzo (arXiv:1603.03759)

7) Constraints on sterile neutrino oscillations using DUNE near detector
Choubey, Pramanik (arXiv:1604.04731)

8) Octant of θ_{23} in danger with a light sterile neutrino
Agarwalla, Chatterjee, Palazzo (arXiv:1605.04299)

9) False signals of CP-Invariance violation at DUNE
de Gouvea, Kelly (arXiv:1605.09376)

10) Capabilities of long-baseline experiments in the presence of a sterile neutrino
Dutta, Gandhi, Kayser, Masud, Prakash (arXiv:1607.02152)

The list is not complete………

Mixing matrix in 3+1 Scheme

$$U = \tilde{R}_{34} R_{24} \tilde{R}_{14} \underbrace{R_{23} \tilde{R}_{13} R_{12}}_{3\nu}$$

$$R_{ij} = \begin{bmatrix} c_{ij} & s_{ij} \\ -s_{ij} & c_{ij} \end{bmatrix}$$

$$\tilde{R}_{ij} = \begin{bmatrix} c_{ij} & \tilde{s}_{ij} \\ -\tilde{s}^*_{ij} & c_{ij} \end{bmatrix}$$

$$s_{ij} = \sin\theta_{ij}$$
$$c_{ij} = \cos\theta_{ij}$$
$$\tilde{s}_{ij} = s_{ij} e^{-i\delta_{ij}}$$

3ν { 3 mixing angles, 1 Dirac phases, 2 Majorana phases }

3+1 { 6, 3, 3 }

3+N { 3+3N, 1+2N, 2+N }

We have more sources of CPV in the 3+1 flavor scheme

$\theta_{14} = \theta_{24} = \theta_{34} = 0$ ➔ 3-flavor case

Few words on Parameterization

- When mixing involving the 4th state is zero ($\theta_{14} = \theta_{24} = \theta_{34} = 0$), it returns the 3ν matrix in its common parameterization

- For small values of θ_{13}, and of the mixing angles involving the 4th state, one has $|U_{e3}|^2 \simeq s_{13}^2$, $|U_{e4}|^2 = s_{14}^2$, $|U_{\mu 4}|^2 \simeq s_{24}^2$ and $|U_{\tau 4}|^2 \simeq s_{34}^2$, with a clear physical interpretation of the new mixing angles

- The leftmost positioning of the matrix $\tilde{R}_{34}$ guarantees that the vacuum ν_μ to ν_e transition probability is independent of θ_{34} and of the related CP-phase δ_{34}

Three-flavor Oscillation Probability

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

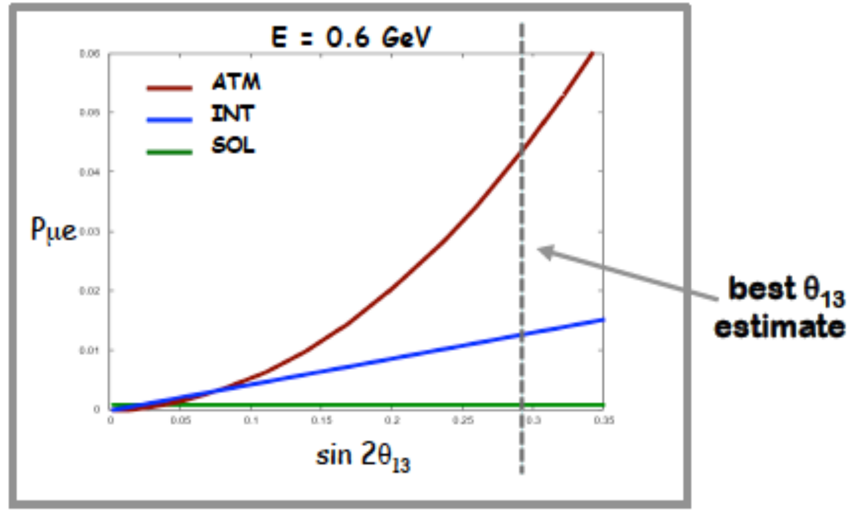
in vacuum:

$$P^{\rm ATM} = 4 s_{23}^2 s_{13}^2 \sin^2\Delta$$
$$P^{\rm SOL} = 4 c_{12}^2 c_{23}^2 s_{12}^2 (\alpha\Delta)^2$$
$$P^{\rm INT} = 8 s_{23} s_{13} c_{12} c_{23} s_{12} (\alpha\Delta) \sin\Delta \cos(\Delta + \delta_{CP})$$

$$\Delta = \frac{\Delta m_{31}^2 L}{4E}, \qquad \alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$$

$\Delta \sim \pi/2$

$\alpha \sim 0.03$

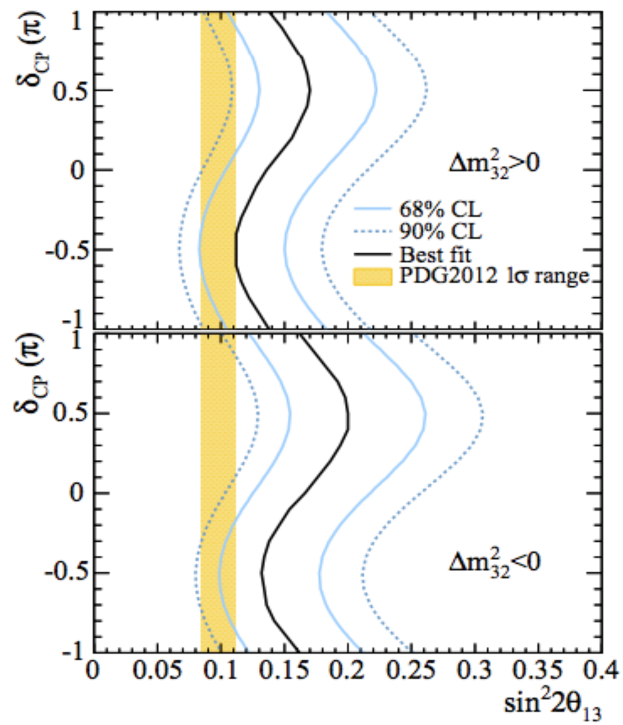


$P^{\rm ATM}$ leading → $\theta_{13} > 0$

$P^{\rm INT}$ sub-leading → dependency on δ

$P^{\rm SOL}$ negligible

Matter effects break NH-IH degeneracy



T2K + Reactors

A New Interference Term in the 3+1 Scheme

- $\Delta_{14} >> 1$: fast oscillations are averaged out

- But interference of Δ_{14} & Δ_{13} survives and is observable

$$P_{\mu e}^{4\nu} \simeq P^{\rm ATM} + P_{\rm I}^{\rm INT} + P_{\rm II}^{\rm INT}$$

$s_{13} \sim s_{14} \sim s_{24} \sim 0.15 \sim \varepsilon$

$\alpha = \delta m^2/\Delta m^2 \sim 0.03 \sim \varepsilon^2$

$$\begin{cases} P^{\rm ATM} \simeq 4 s_{23}^2 s_{13}^2 \sin^2\Delta & \sim \varepsilon^2 \\ P_{\rm I}^{\rm INT} \simeq 8 s_{13} s_{23} c_{23} s_{12} c_{12} (\alpha\Delta) \sin\Delta \cos(\Delta + \delta_{13}) & \sim \varepsilon^3 \\ P_{\rm II}^{\rm INT} \simeq 4 s_{14} s_{24} s_{13} s_{23} \sin\Delta \sin(\Delta + \delta_{13} - \delta_{14}) & \sim \varepsilon^3 \end{cases}$$

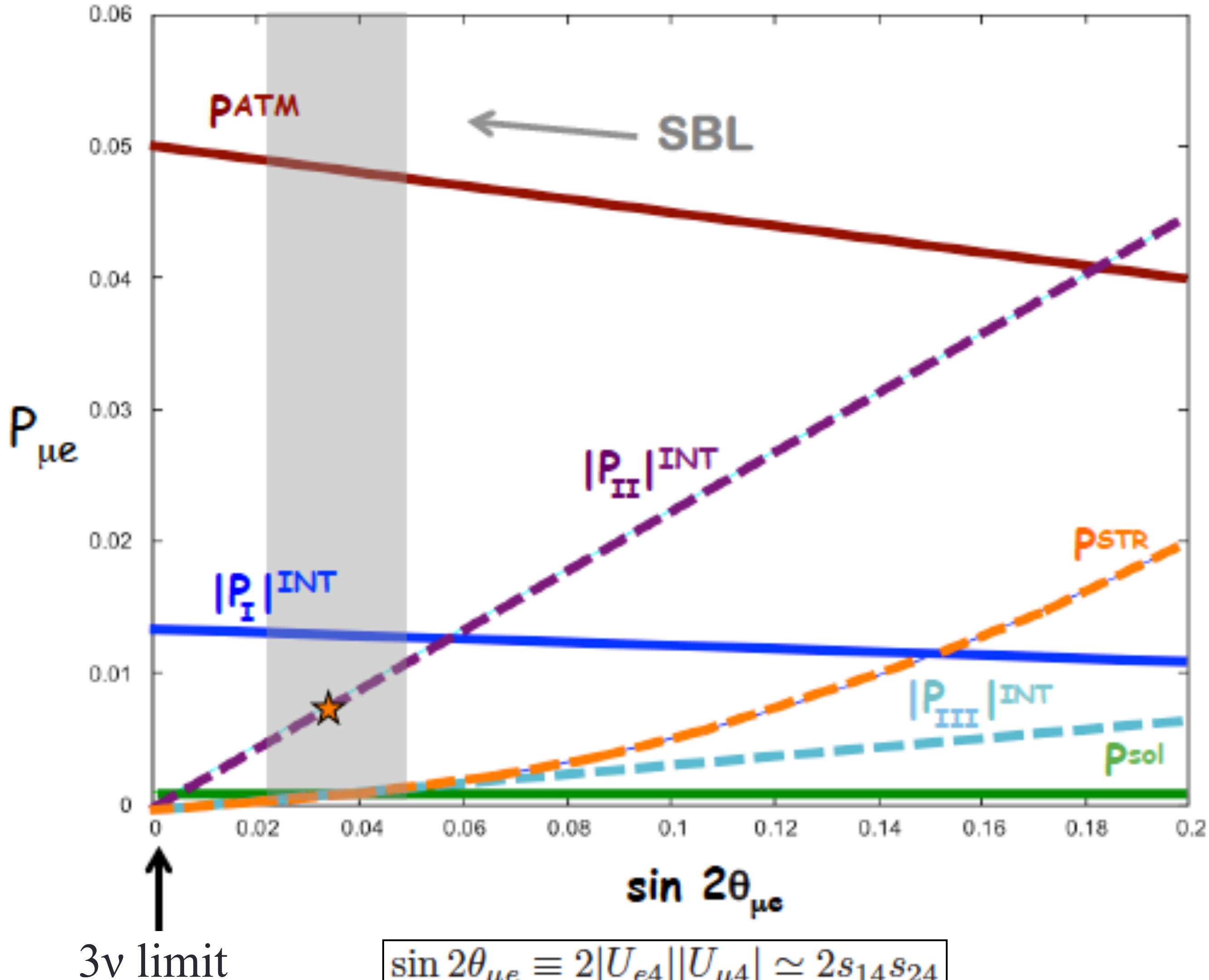
Sensitivity to the new CP-phase δ_{14}

Klop and Palazzo, arXiv:1412.7524v3 [hep-ph]

In vacuum, it is independent of θ_{34} and δ_{34}

Amplitude of the New Interference Term

Klop and Palazzo, arXiv:1412.7524v3 [hep-ph]



$$\sin 2\theta_{\mu e} \equiv 2|U_{e4}||U_{\mu 4}| \simeq 2s_{14}s_{24}$$

T2K

E = 0.6 GeV

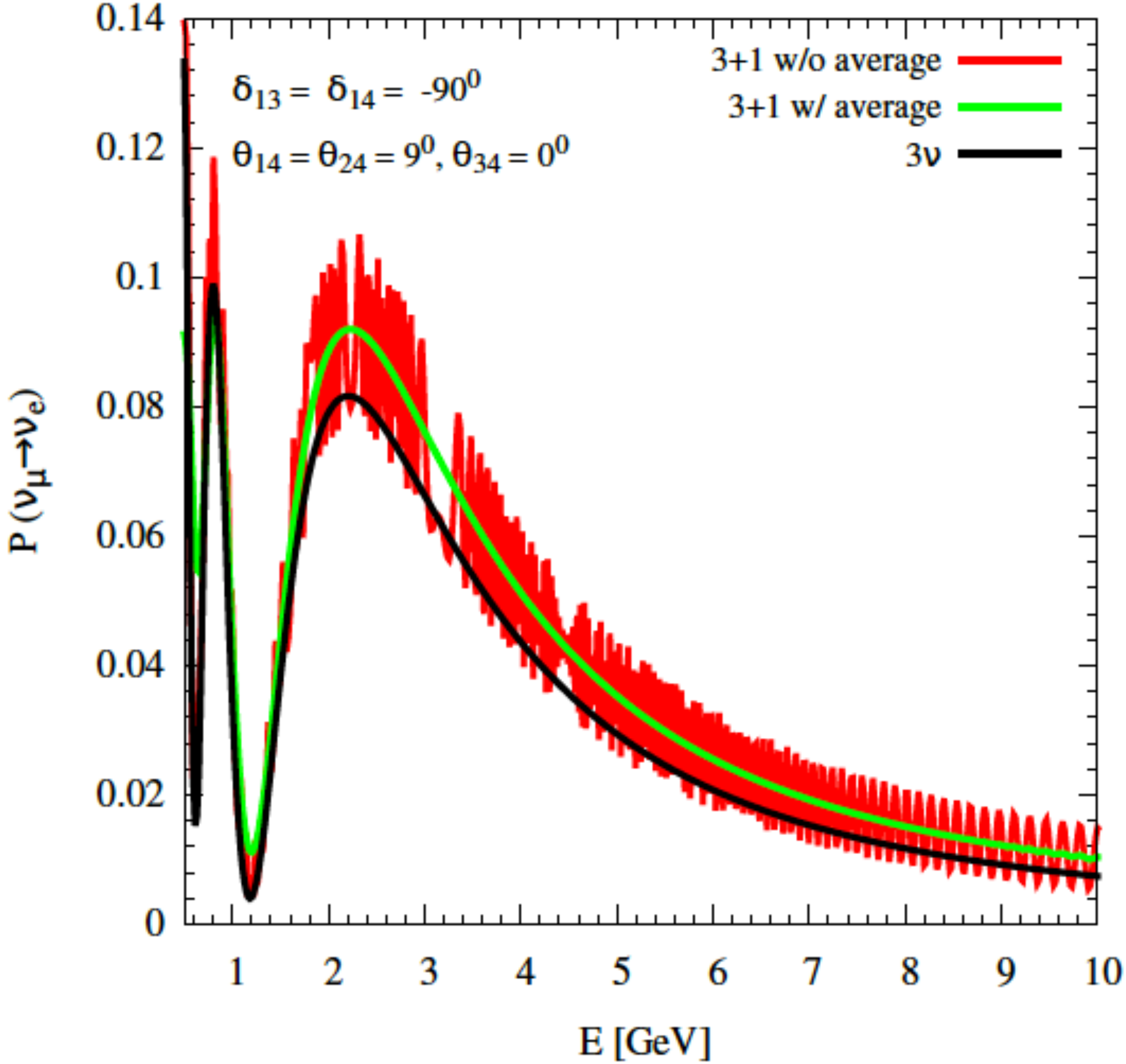
$\theta_{13} = 9^0$

Oscillation Parameters

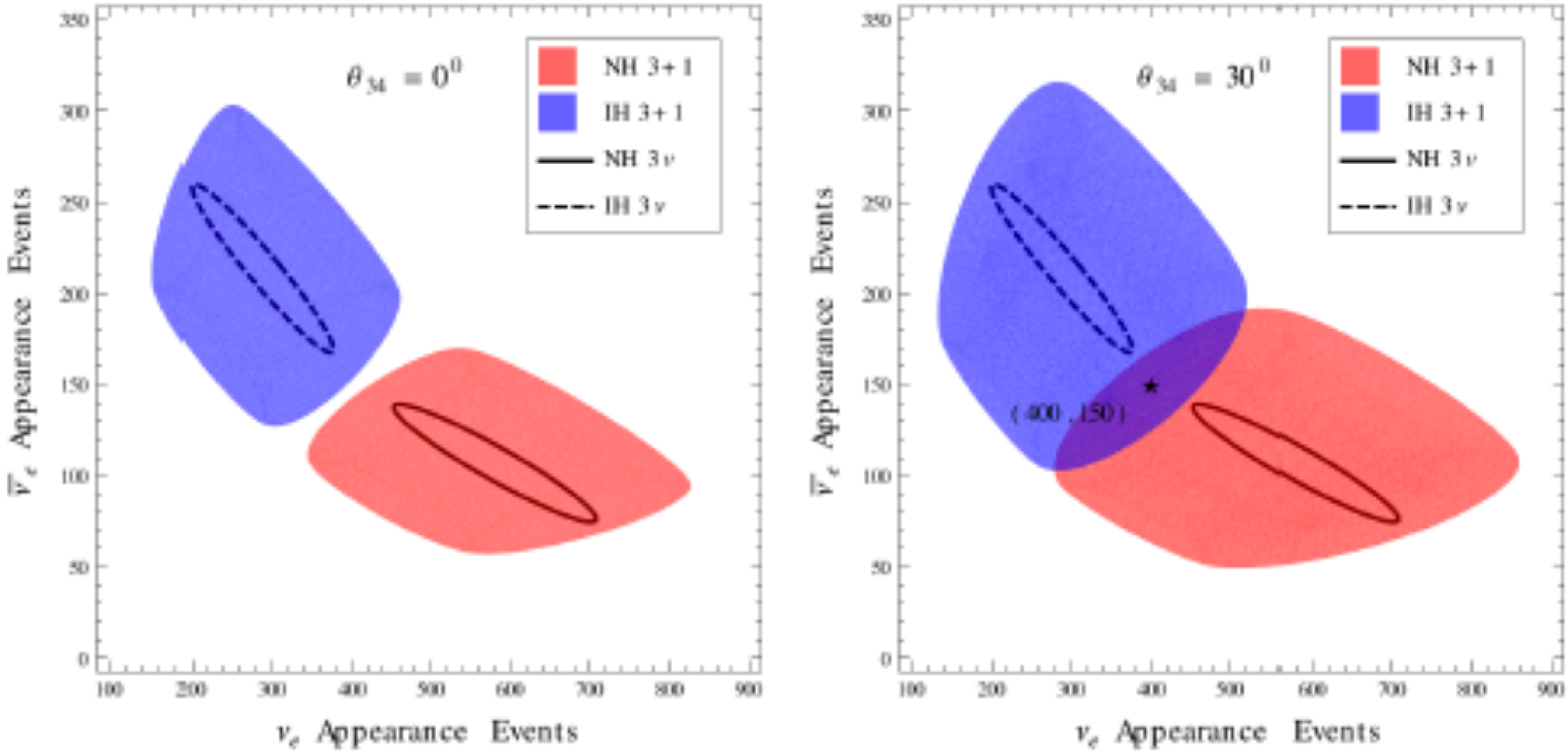
Parameter	True Value	Marginalization Range
$\sin^2\theta_{12}$	0.304	Not marginalized
$\sin^2 2\theta_{13}$	0.085	Not marginalized
$\sin^2\theta_{23}$	0.50	[0.34, 0.68]
$\sin^2\theta_{14}$	0.025	Not marginalized
$\sin^2\theta_{24}$	0.025	Not marginalized
$\sin^2\theta_{34}$	0, 0.025, 0.25	Not marginalized
$\delta_{13}/^\circ$	[- 180, 180]	[- 180, 180]
$\delta_{14}/^\circ$	[- 180, 180]	[- 180, 180]
$\delta_{34}/^\circ$	[- 180, 180]	[- 180, 180]
$\frac{\Delta m^2_{21}}{10^{-5}\,\mathrm{eV}^2}$	7.50	Not marginalized
$\frac{\Delta m^2_{31}}{10^{-3}\,\mathrm{eV}^2}$ (NH)	2.475	Not marginalized
$\frac{\Delta m^2_{31}}{10^{-3}\,\mathrm{eV}^2}$ (IH)	- 2.4	Not marginalized
$\frac{\Delta m^2_{41}}{\mathrm{eV}^2}$	1.0	Not marginalized

$$s_{13} \sim s_{14} \sim s_{24} \sim 0.15$$

DUNE Oscillation Probability

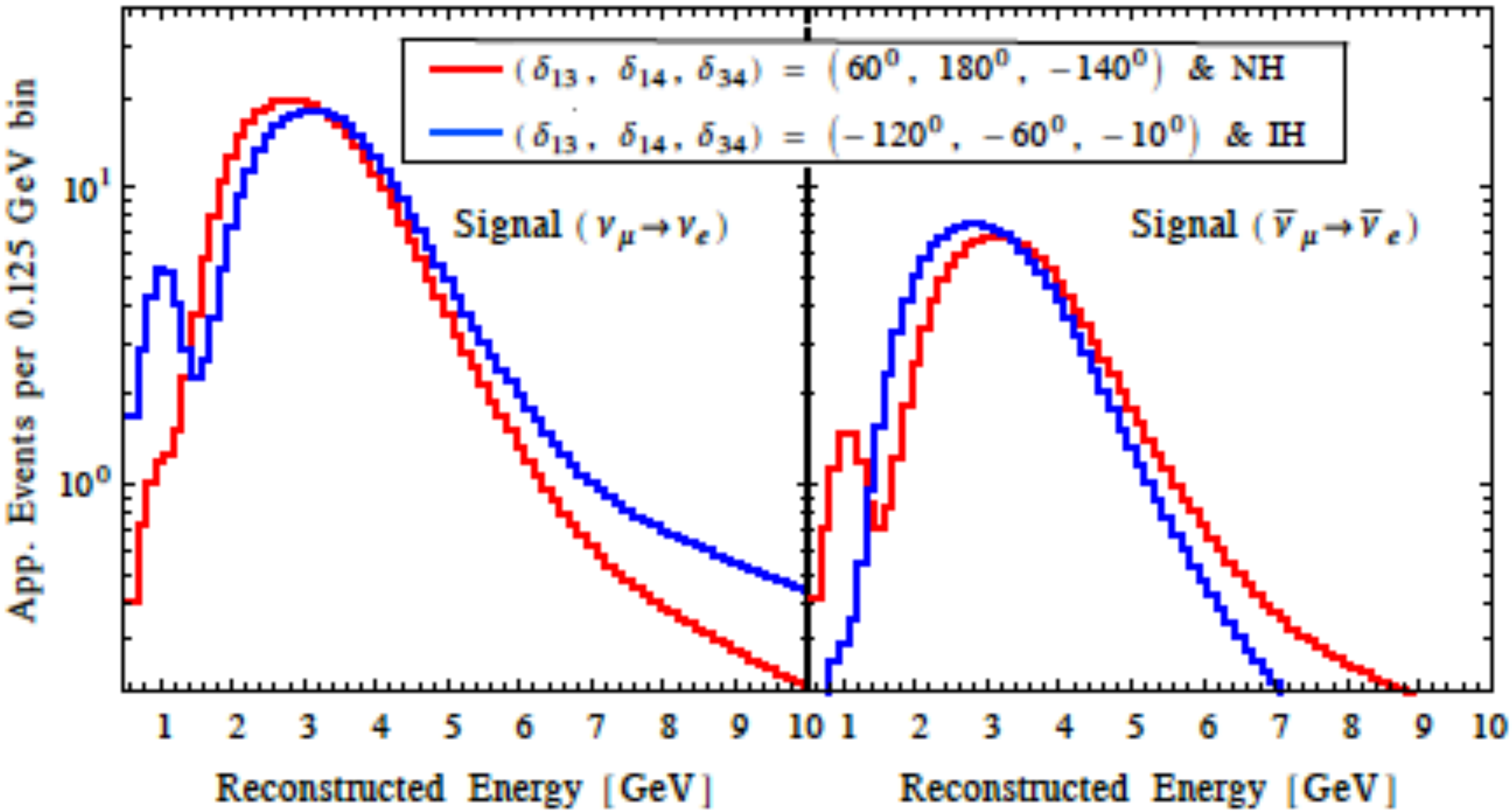


Bi-events Plot for DUNE



Agarwalla, Chatterjee, Palazzo (arXiv:1603.03759)

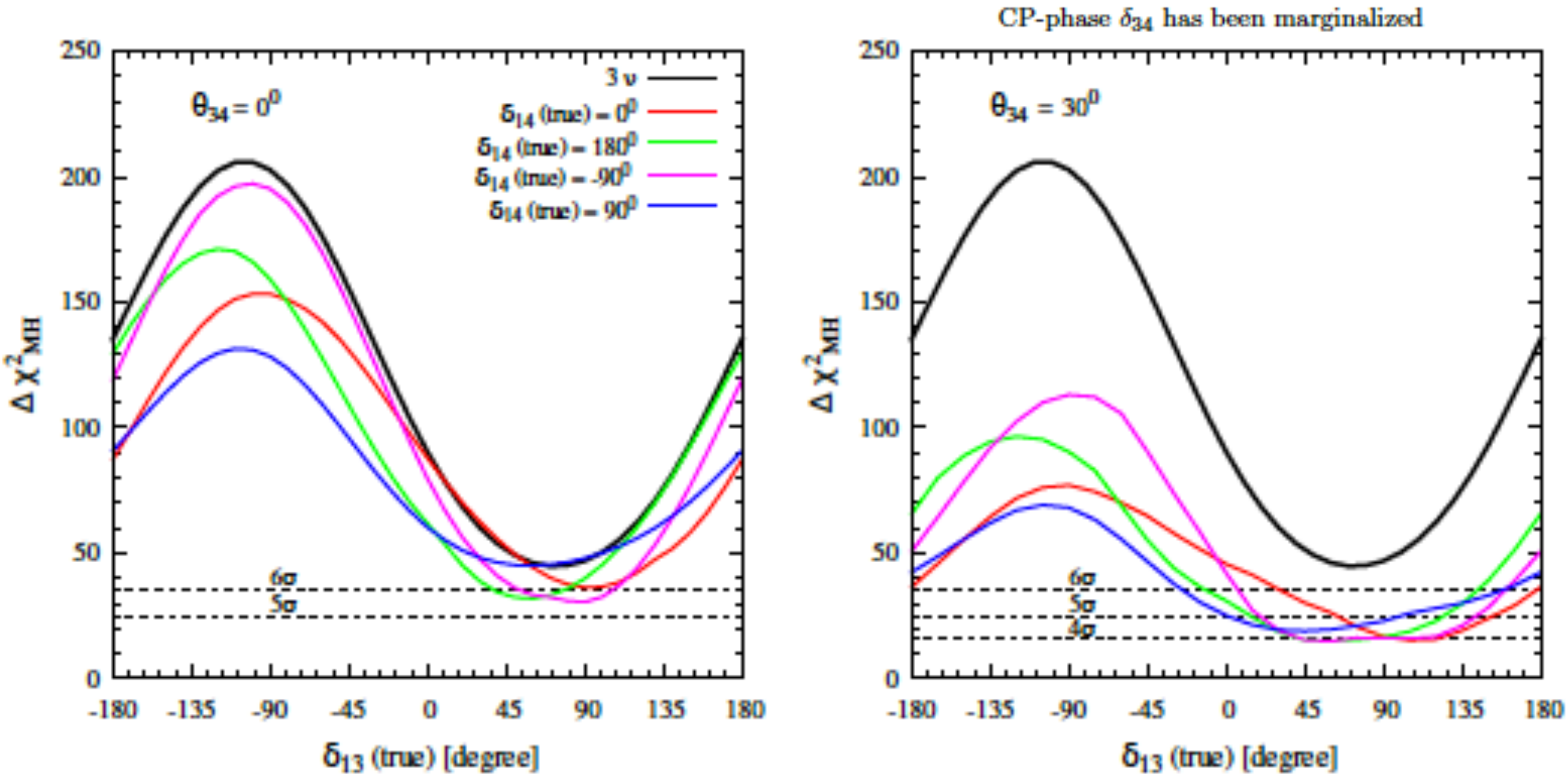
Spectral Study is Vital



Agarwalla, Chatterjee, Palazzo (arXiv:1603.03759)

Mass Hierarchy Discovery at DUNE

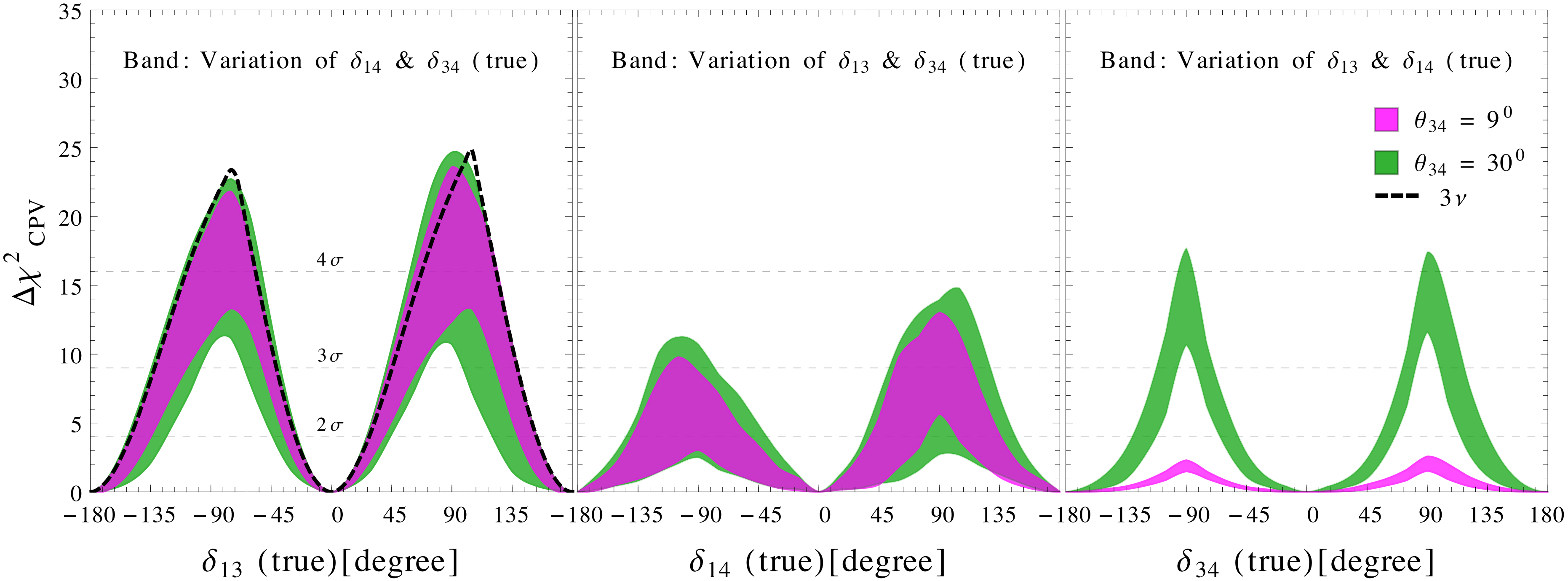
248 kt-MW-year of exposure (0.708 MW, 120 GeV proton energy, 35 kt, 10 years)



Agarwalla, Chatterjee, Palazzo (arXiv:1603.03759)

MH discovery still above 5σ if all the new mixing angles are close to θ_{13}
If θ_{34} = 30 degree, the sensitivity can decrease to 4σ

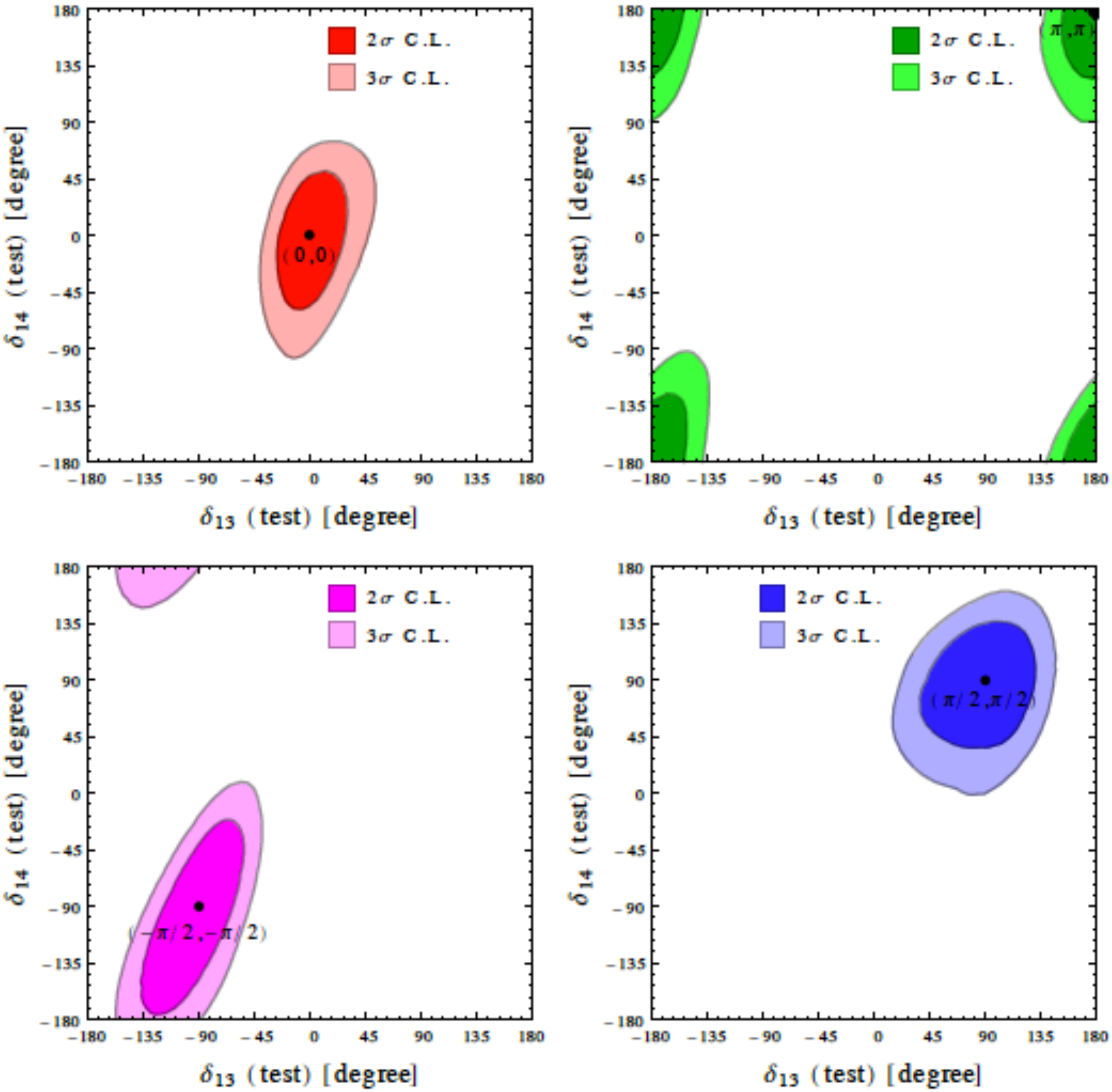
CP-violation Searches at DUNE



Agarwalla, Chatterjee, Palazzo (arXiv:1603.03759)

- Sensitivity to CPV induced by δ_{13} reduced in 3+1 scheme
- Potential sensitivity also to the new CP-phases δ_{14} e δ_{34}
- Clear hierarchy in the sensitivity: $\delta_{13}>\delta_{14}>\delta_{34}$ for $\theta_{14}=\theta_{24}=\theta_{34}=9^0$

Reconstruction of CP Phase at DUNE



Typical
1σ uncertainty
on $\delta_{13} \sim 20$ degree
and
on $\delta_{14} \sim 30$ degree
if θ_{34} is 0

Agarwalla, Chatterjee, Palazzo
(arXiv:1603.03759)

First Study on θ_{23} Octant with Light Sterile Neutrino

PRL **118,** 031804 (2017) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2017

Octant of θ_{23} in Danger with a Light Sterile Neutrino

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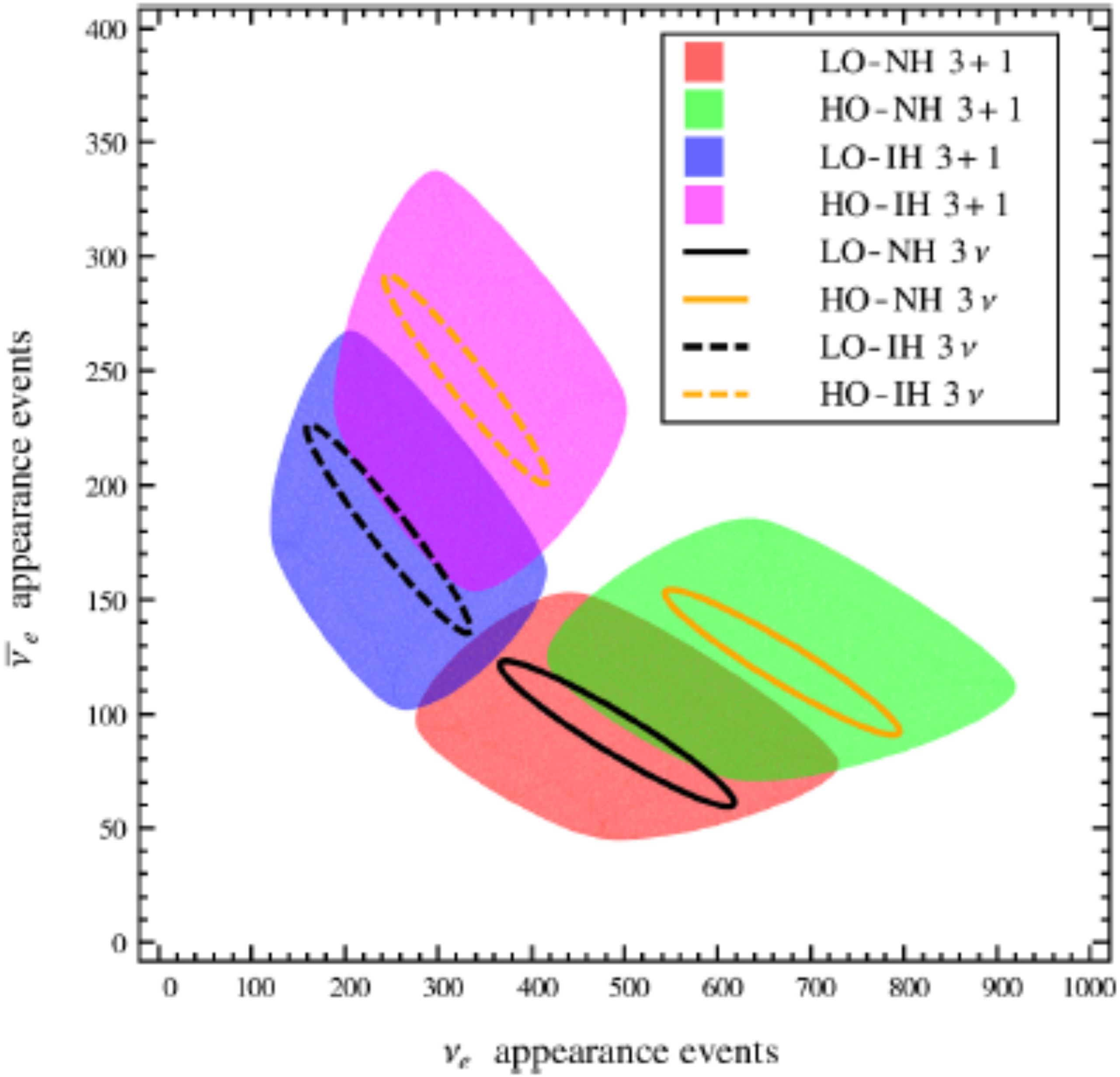
(Received 23 May 2016; revised manuscript received 5 December 2016; published 20 January 2017)

Bi-events Plot for DUNE



$\sin^2\theta_{23} = 0.42\ (0.58)$
LO (HO)

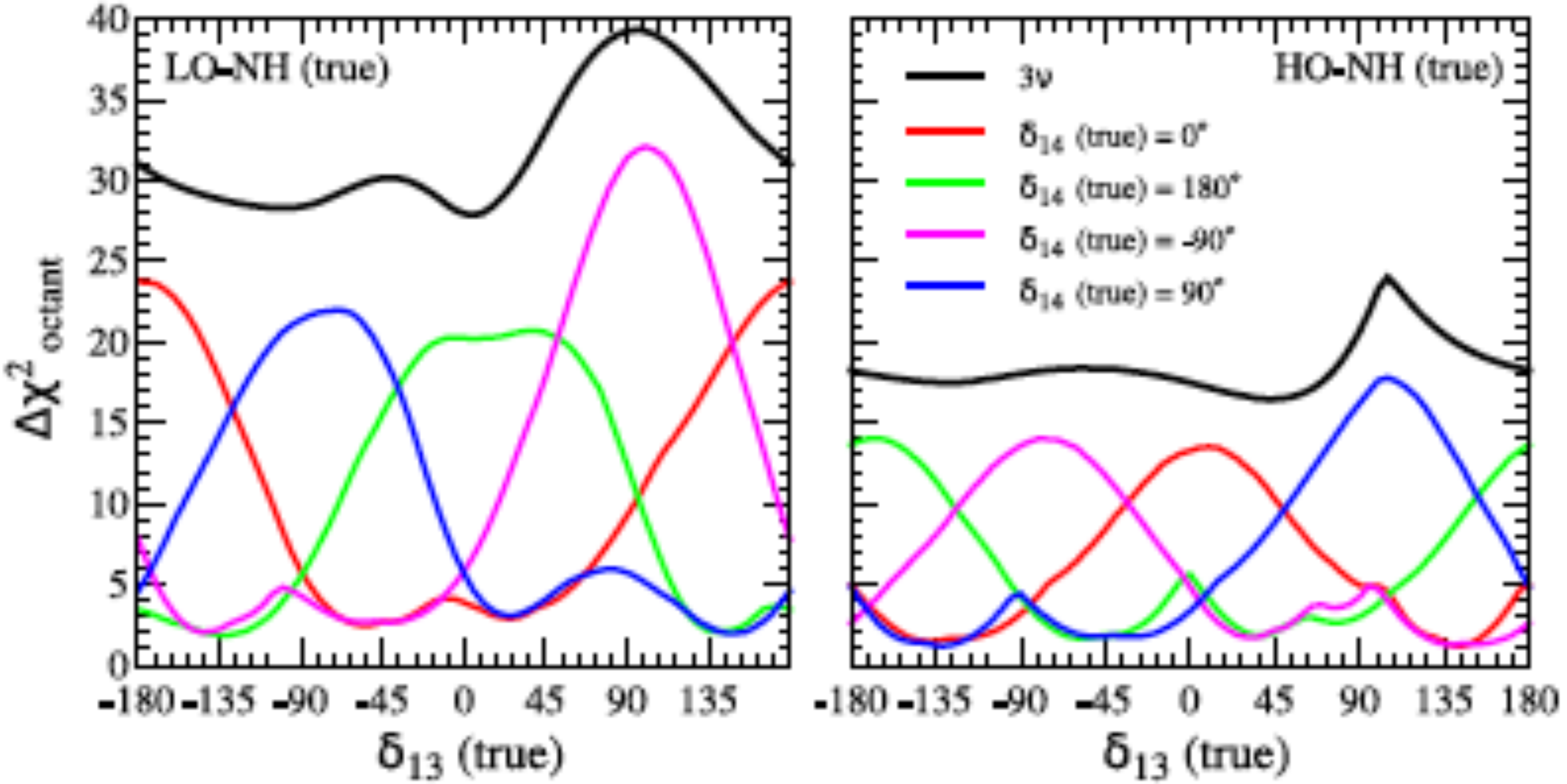
Three-flavor ellipses due to variation in δ_{13} in [-π to π]

Four-flavor blobs due to variation in δ_{13} and δ_{14} in [-π to π]

DUNE Exposure 248 kt.MW.yr

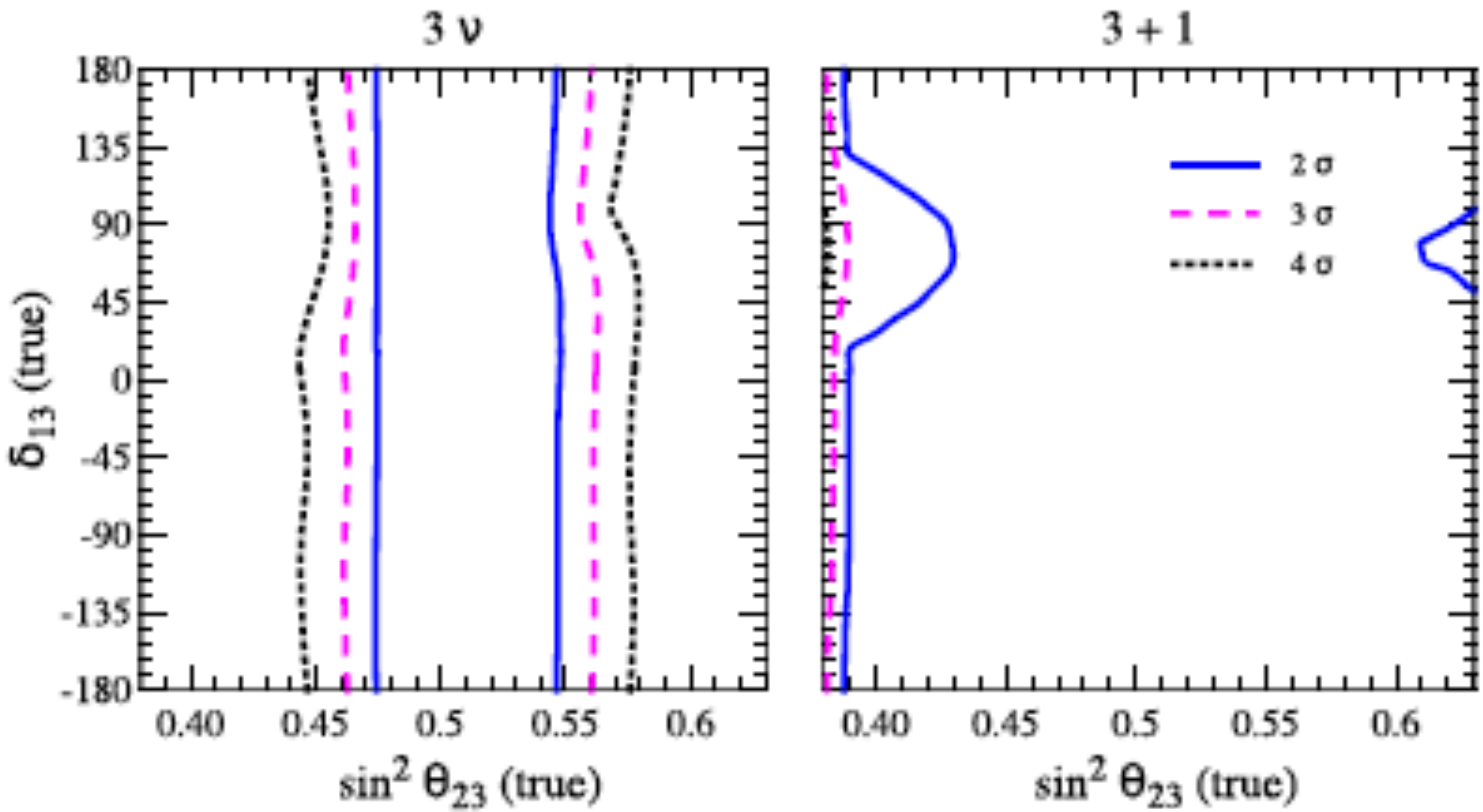
Octant Discovery at DUNE with a Light Sterile ν

DUNE Exposure, 248 kt.MW.yr



- Generate data with $\sin^2\theta_{23} = 0.42$ (0.58) for LO (HO)
- For 3ν case, we marginalize over θ_{23} and δ_{13} in the fit
- In 3+1 scheme, we fix $\theta_{14} = \theta_{24} = 9$ degrees and $\theta_{34} = 0$
- Marginalize over θ_{23}, $\delta_{13,}$ and δ_{14} in the fit

No Knowledge on Octant with a light Sterile ν

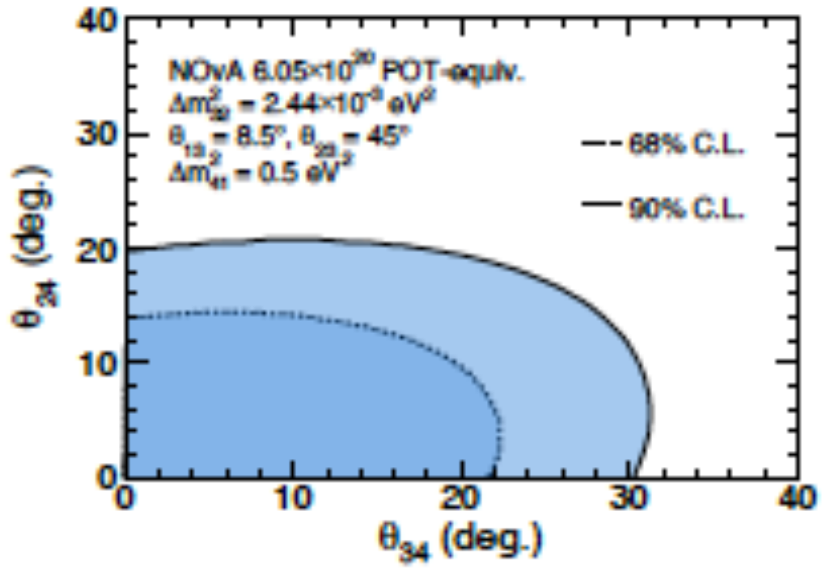


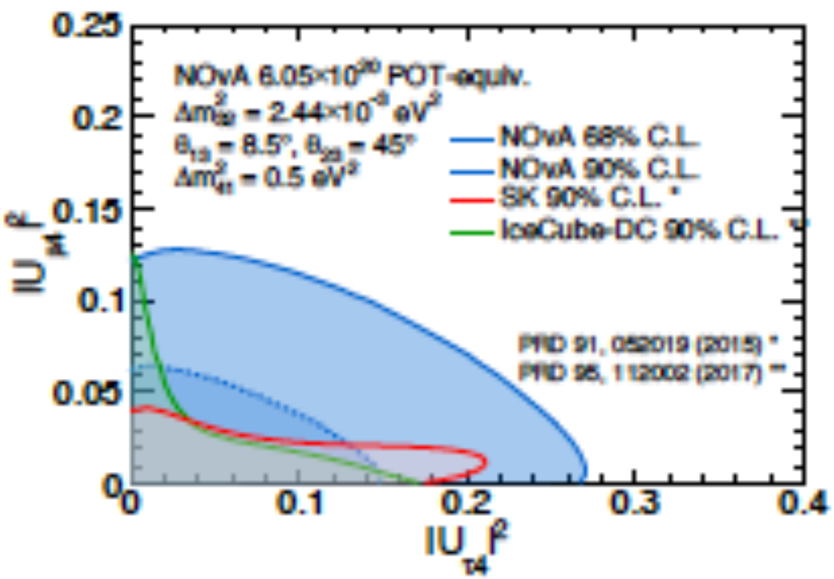
$$P_{II}^{INT} \simeq 4\, s_{13} s_{23} s_{14} s_{24} \sin\Delta \sin(\Delta + \delta_{13} - \delta_{14})$$

extra degree of freedom

In 3+1, the sensitivity to the octant of θ_{23} gets completely lost.

NC Searches in NOvA





$$|U_{\mu 4}|^2 = \cos^2\theta_{14}\sin^2\theta_{24}$$
$$|U_{\tau 4}|^2 = \cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34},$$

	θ_{24}	θ_{34}	$\lvert U_{\mu 4}\rvert^2$	$\lvert U_{\tau 4}\rvert^2$
NOvA	20.8°	31.2°	0.126	0.268
MINOS	7.3°	26.6°	0.016	0.20
SuperK	11.7°	25.1°	0.041	0.18
IceCube	4.1°	-	0.005	-
IceCube-DeepCore	19.4°	22.8°	0.11	0.15

NOvA NC Searches:
arXiv:1706.04592v2

NuMI beam at Fermilab, we observe 95 neutral-current candidates at the Far Detector compared with 83.5 ± 9.7(stat.) ± 9.4(syst.) events predicted assuming mixing only occurs between active neutrino species. No evidence for $\nu_\mu \rightarrow \nu_s$ transitions is found. Interpreting these results within a

NC Searches in DUNE

FERMILAB-PUB-17-271-T

arXiv:1707.05348v1 [hep-ph] 17 Jul 2017

DUNE sensitivities to the mixing between sterile and tau neutrinos

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(Dated: July 17, 2017)

Light sterile neutrinos can be probed in a number of ways, including electroweak decays, cosmology and neutrino oscillation experiments. At long-baseline experiments, the neutral-current data is directly sensitive to the presence of light sterile neutrinos: once the active neutrinos have oscillated into a sterile state, a depletion in the neutral-current data sample is expected since they do not interact with the Z boson. This channel offers a direct avenue to probe the mixing between a sterile neutrino and the tau neutrino, which remains largely unconstrained by current data. In this work, we study the potential of the DUNE experiment to constrain the mixing angle which parametrizes this mixing, θ_{34}, through the observation of neutral-current events at the far detector. We find that DUNE will be able to improve significantly over current constraints thanks to its large statistics and excellent discrimination between neutral- and charged-current events.

arXiv:1708.01816v2 [hep-ph] 17 Dec 2017

PREPARED FOR SUBMISSION TO JHEP FERMILAB-PUB-17-276-T

What measurements of neutrino neutral current events can reveal

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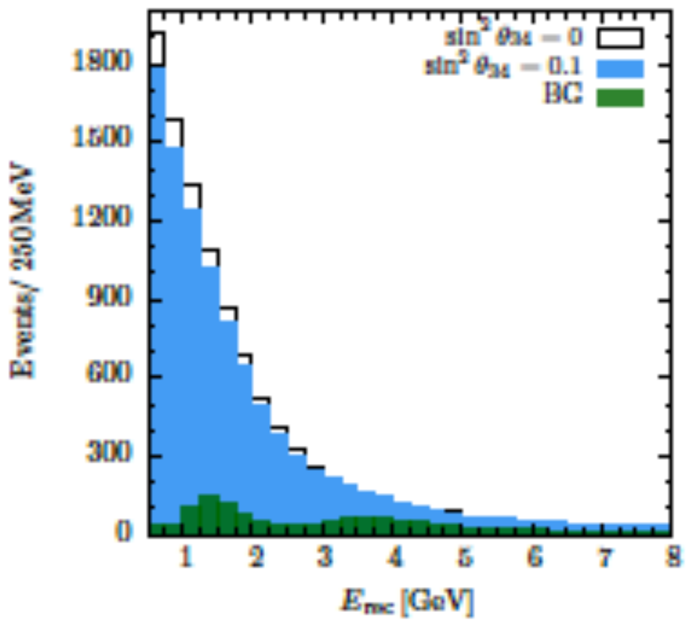
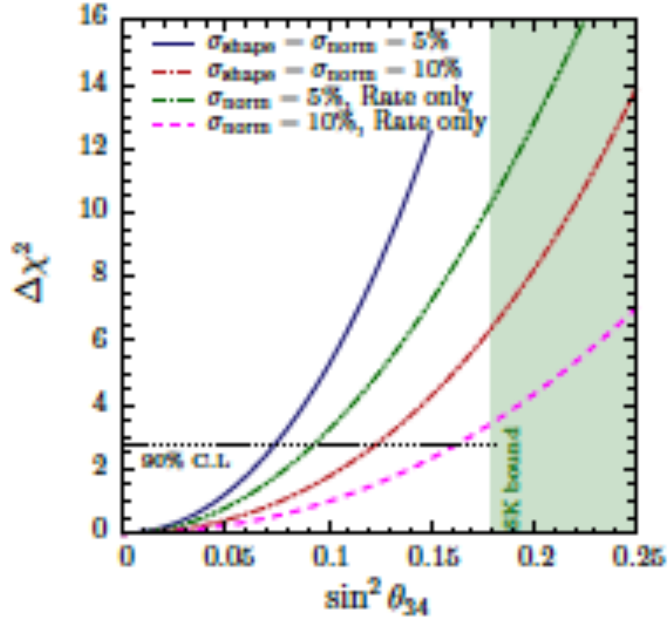
ABSTRACT: We show that neutral current (NC) measurements at neutrino detectors can play a valuable role in the search for new physics. Such measurements have certain intrinsic features and advantages that can fruitfully be combined with the usual well-studied charged lepton detection channels in order to probe the presence of new interactions or new light states. In addition to the fact that NC events are immune to uncertainties in standard model neutrino mixing and mass parameters, they can have small matter effects and superior rates since all three flavours participate. We also show, as a general feature, that NC measurements provide access to different combinations of CP phases and mixing parameters compared to CC measurements at both long and short baseline experiments. Using the Deep Underground Neutrino Experiment (DUNE) as an illustrative setting, we demonstrate the capability of NC measurements to break degeneracies arising in CC measurements, allowing us, in principle, to distinguish between new physics that violates three flavour unitarity and that which does not. Finally, we show that NC measurements can enable us to restrict new physics parameters that are not easily constrained by CC measurements.

NC Searches in DUNE



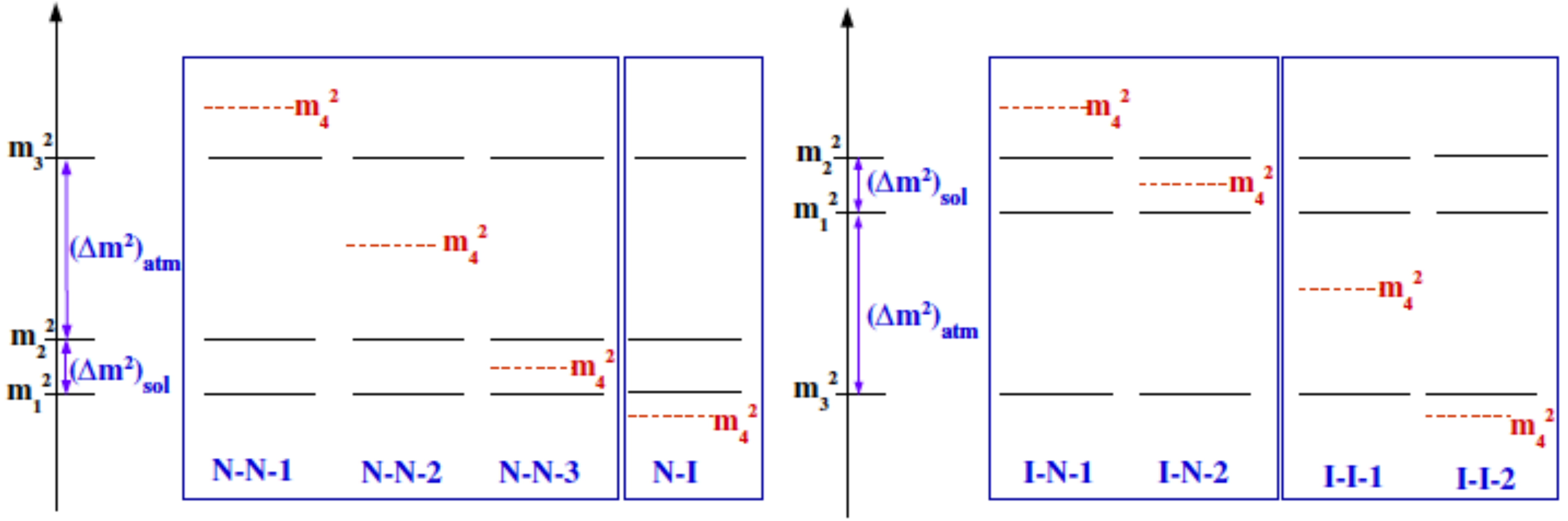


$$N_{NC} = N_{NC}^{e} + N_{NC}^{\mu} + N_{NC}^{\tau} = \phi_{\nu_\mu}\,\sigma_{\nu}^{NC}\left\{P(\nu_\mu \to \nu_e) + P(\nu_\mu \to \nu_\mu) + P(\nu_\mu \to \nu_\tau)\right\}$$
$$= \phi_{\nu_\mu}\,\sigma_{\nu}^{NC}\left\{1 - P(\nu_\mu \to \nu_s)\right\}\,,$$

$$\Delta_{21} \ll \Delta_{31}, \Delta_{41} \qquad \Delta_{ij} \equiv \Delta m_{ij}^2 L/4E.$$

$$P_{\mu s} \equiv P(\nu_\mu \to \nu_s) = 4|U_{\mu 4}|^2|U_{s4}|^2 \sin^2\Delta_{41} + 4|U_{\mu 3}|^2|U_{s3}|^2\sin^2\Delta_{31}$$
$$+\,8\,\mathrm{Re}\left[U_{\mu 4}^* U_{s4} U_{\mu 3} U_{s3}^*\right]\cos\Delta_{43}\sin\Delta_{41}\sin\Delta_{31}$$
$$+\,8\,\mathrm{Im}\left[U_{\mu 4}^* U_{s4} U_{\mu 3} U_{s3}^*\right]\sin\Delta_{43}\sin\Delta_{41}\sin\Delta_{31},$$

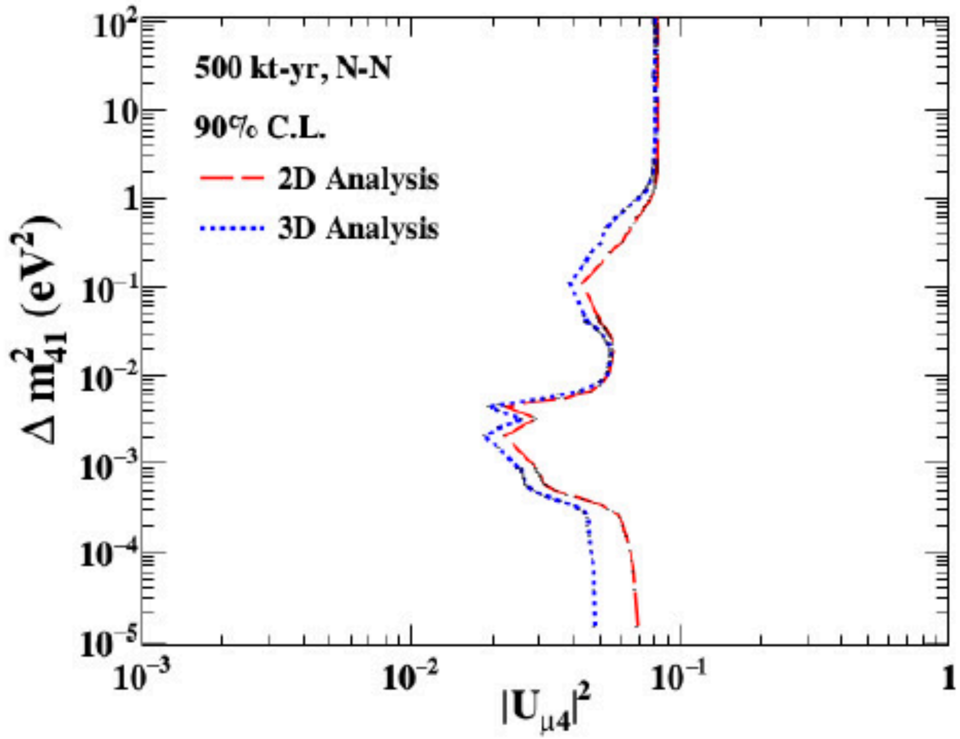
Mass Ordering in 4ν Scheme



Ordering scheme	N-N			N-I	I-N		I-I	
Sign of Δm^2_{31}	+			+	-		-	
Sign of Δm^2_{41}	+			-	+		-	
Sign of Δm^2_{42}	+	+	-	-	+	-	-	-
Sign of Δm^2_{43}	+	-	-	-	+	+	+	-
Configuration	N-N-1	N-N-2	N-N-3	N-I	I-N-1	I-N-2	I-I-1	I-I-2

Thakore, Devi, Agarwalla, Dighe, arXiv:1804.09613 [hep-ph]

Sterile Neutrino Sensitivity with ICAL at INO

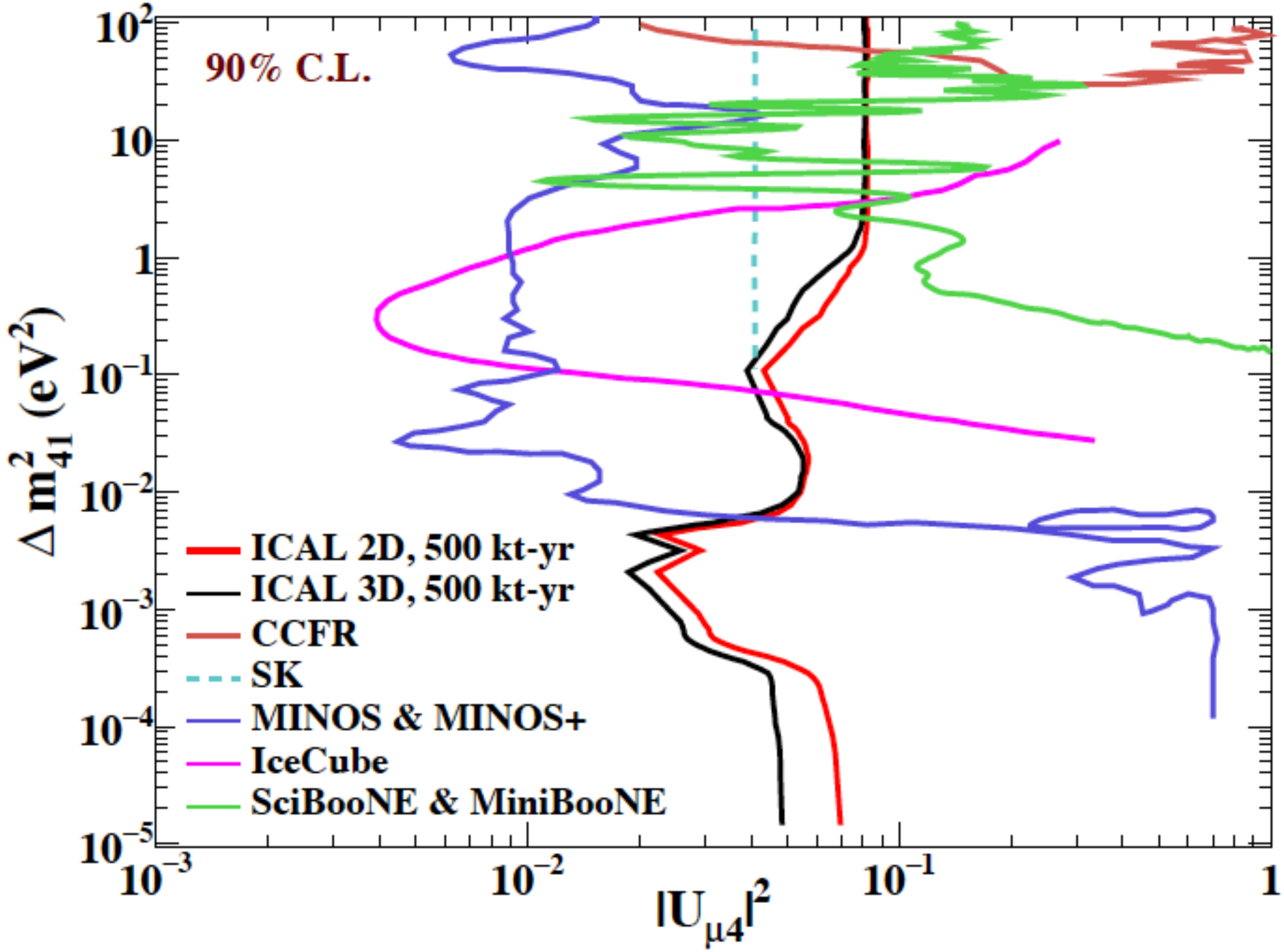


- For higher Δm^2, information is mainly in the number of events, so information about E'_h not so useful
- For lower Δm^2, oscillation information in the energy and angular spectra, so E'_h crucial

$$V_{es} = \sqrt{2} G_F (N_e - N_n/2) \quad \text{between } \nu_e \text{ and } \nu_s ,$$
$$V_{\mu s} = V_{\tau s} = -\sqrt{2} G_F N_n/2 \quad \text{between } \nu_{\mu/\tau} \text{ and } \nu_s ,$$

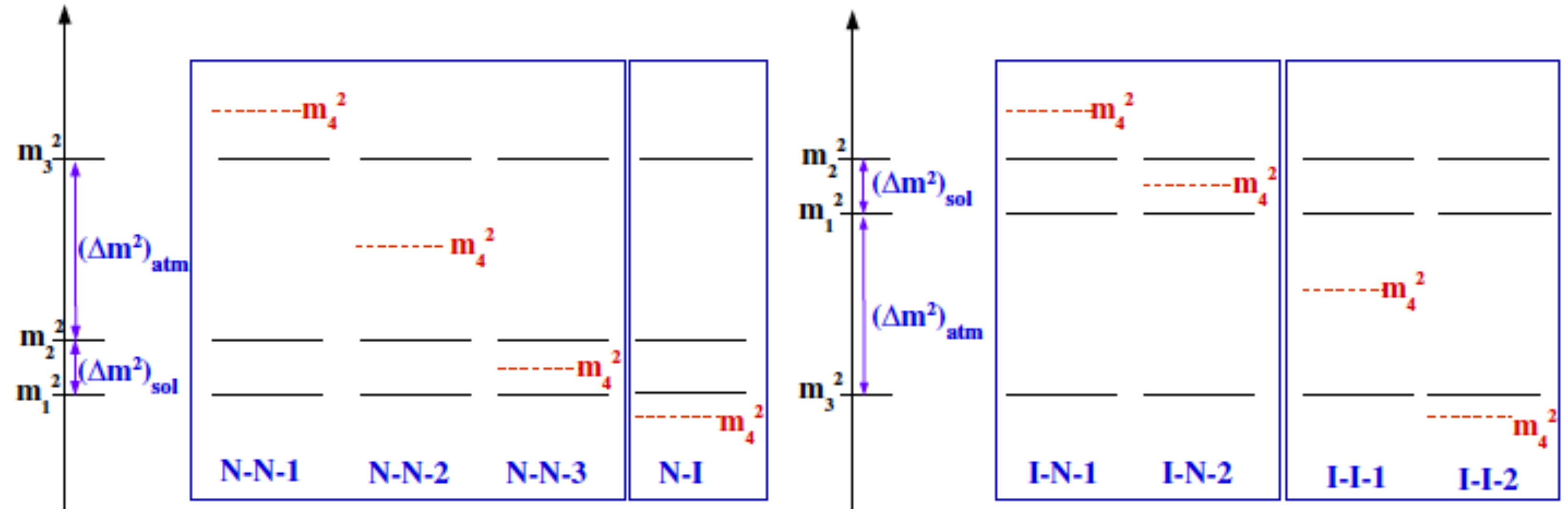
Thakore, Devi, Agarwalla, Dighe, arXiv:1804.09613 [hep-ph]

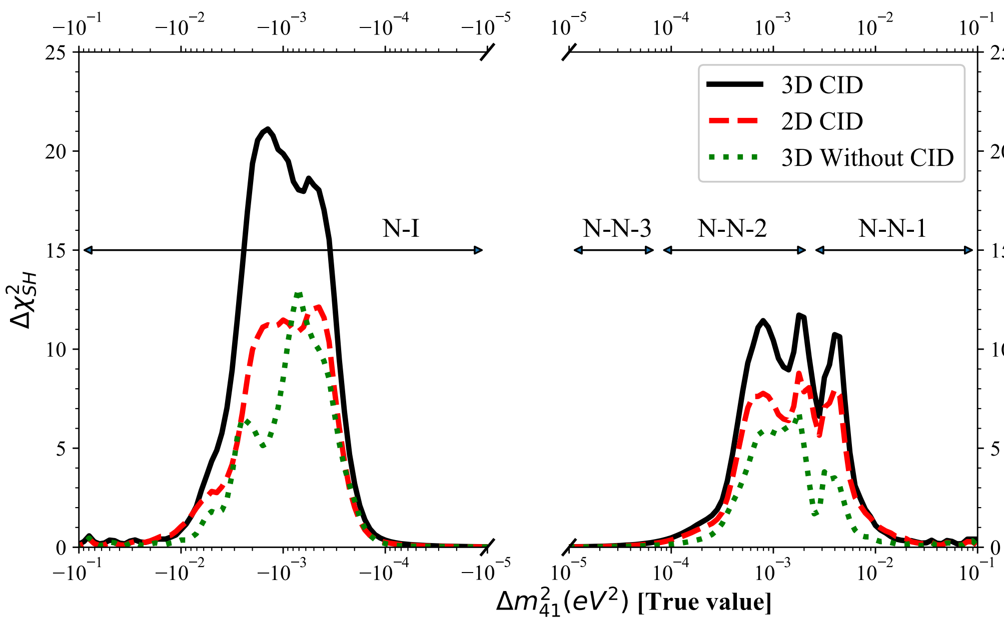
Sterile Neutrino Sensitivity with ICAL at INO



Thakore, Devi, Agarwalla, Dighe, arXiv:1804.09613 [hep-ph]

Mass Ordering of Sterile Neutrino





Addition of E'_h information improves sterile MH sensitivity by $\sim$ 40% for $\Delta m^2_{41} \sim (0.5 - 5) \times 10^{-3}$ eV^2

Thakore, Devi, Agarwalla, Dighe, arXiv:1804.09613 [hep-ph]

Concluding Remarks

Light sterile neutrinos were interesting, are still interesting, and will remain interesting in near future as well………

Discovery of a light sterile neutrino would prove that there is new physics beyond the SM at low-energies, which is completely orthogonal to new physics searches at high energies at the LHC……

Let us continue our effort to look for them at any mass scale and at any energies……

Thank you

Three Flavor Effects in $\nu_\mu \rightarrow \nu_e$ oscillation probability

The appearance probability $(\nu_\mu \rightarrow \nu_e)$ in matter, upto second order in the small parameters $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ (0.03) and $\sin 2\theta_{13}$ (0.3),

$$P_{\mu e} \simeq \underbrace{\sin^2 2\theta_{13}}_{0.09} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$ → θ_{13} Driven

$$- \underbrace{\alpha \sin 2\theta_{13}}_{0.009} \xi \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$ → CP odd

$$+ \alpha \sin 2\theta_{13} \xi \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$ → CP even

$$+ \underbrace{\alpha^2}_{0.0009} \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2};$$ → Solar Term

Resolves octant ($\sin^2\theta_{23}$)

where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \cos\theta_{13} \sin 2\theta_{21} \sin 2\theta_{23}$,
and $\hat{A} \equiv \pm(2\sqrt{2} G_F n_e E)/\Delta m^2_{31}$

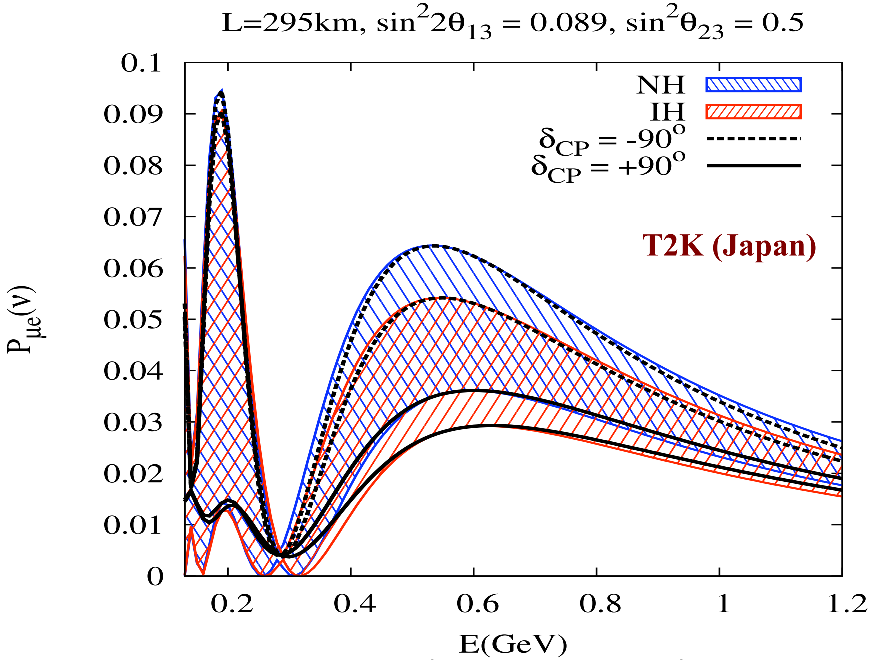
changes sign with sgn(Δm^2_{31}) key to resolve hierarchy!

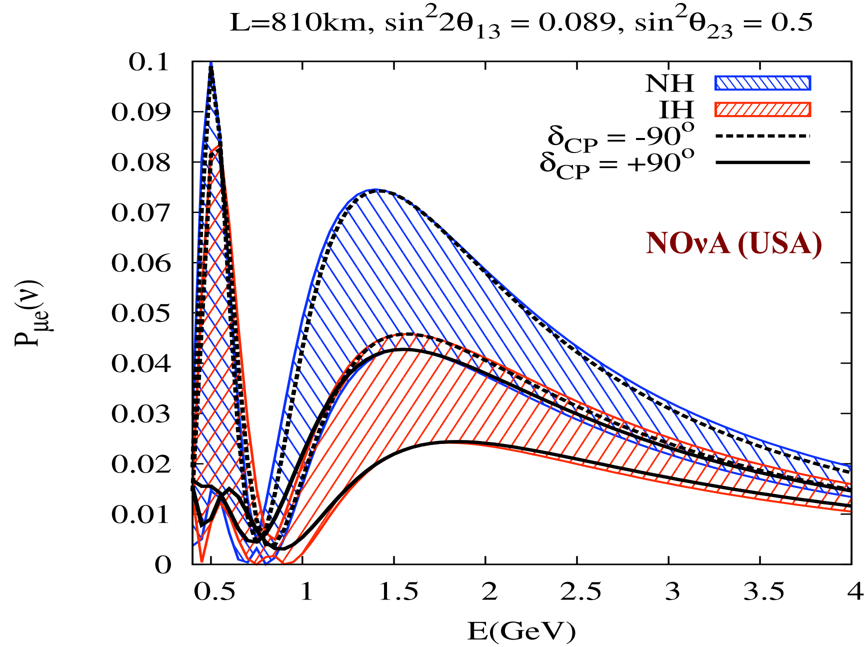
changes sign with polarity causes fake CP asymmetry!

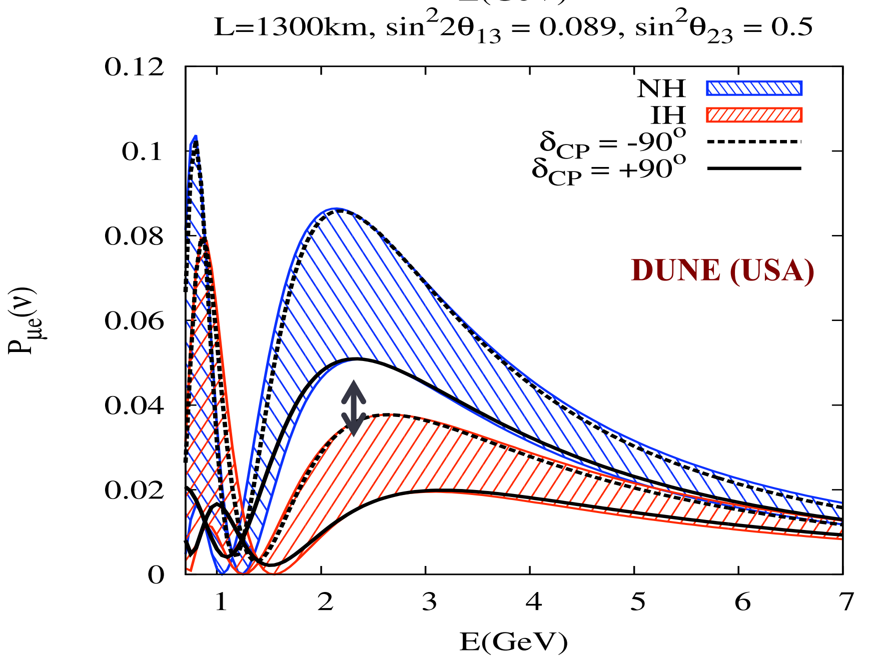
Cervera etal., hep-ph/0002108
Freund etal., hep-ph/0105071
See also, Agarwalla etal., arXiv:1302.6773 [hep-ph]

This channel suffers from: (Hierarchy – δ_{CP}) & (Octant – δ_{CP}) degeneracy! How can we break them?

Hierarchy – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel







For ν: Max: NH, -90° and Min: IH, 90°

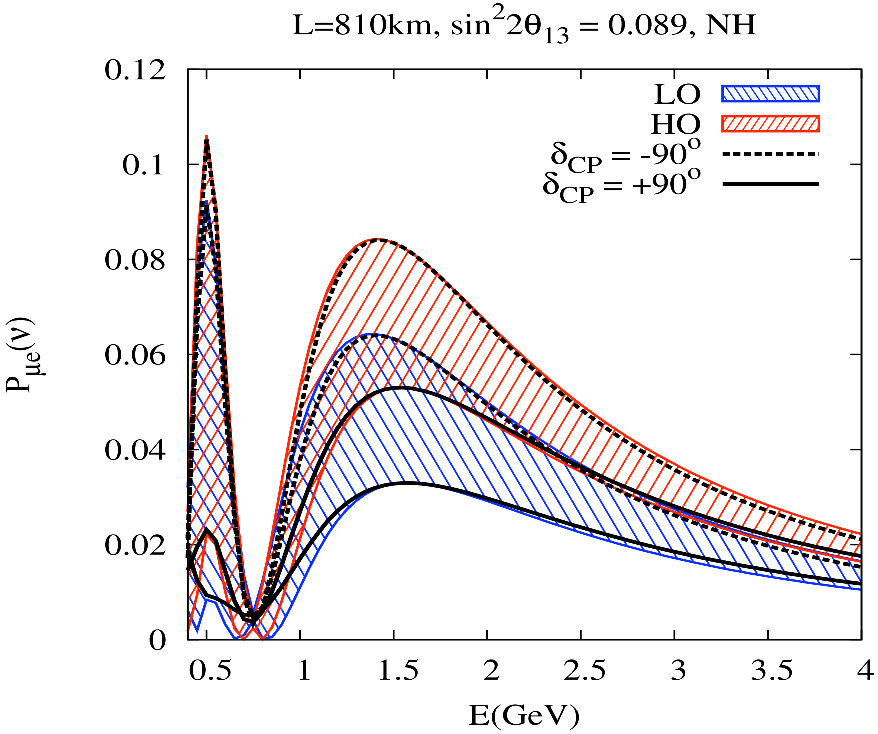
Favorable combinations
NH, LHP (-180° to 0°) and IH, UHP (0° to 180°)

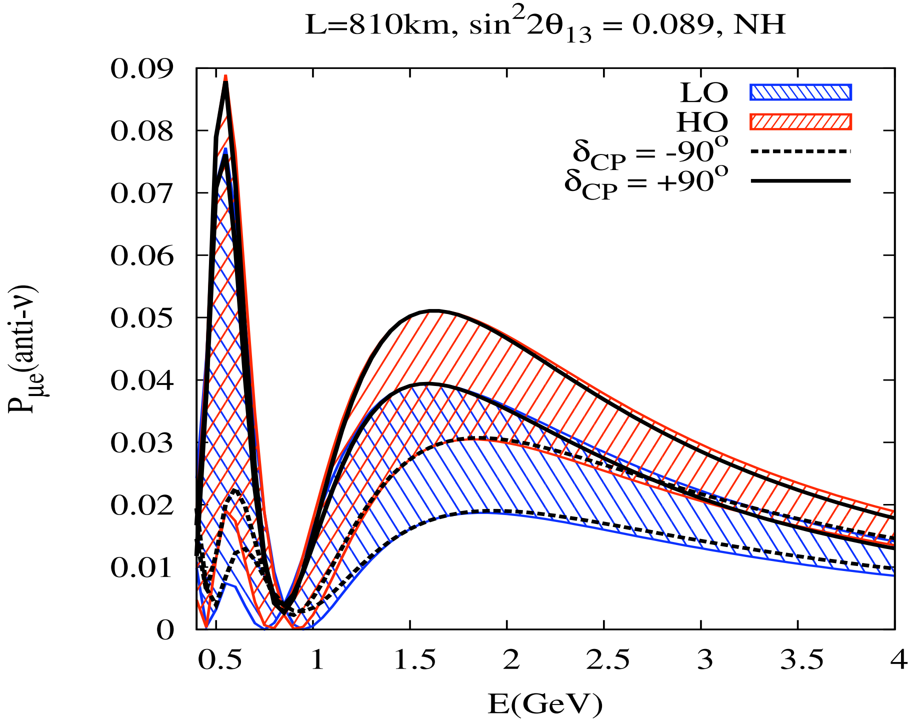
Degeneracy pattern different between T2K & NOνA

DUNE: Large Earth matter effects
Clear separation between NH and IH

Agarwalla, arXiv:1401.4705 [hep-ph]

Octant – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel





For neutrino:
Maximum: HO, -90°
Minimum: LO, 90°

LO: $\sin^2\theta_{23} = 0.41$
HO: $\sin^2\theta_{23} = 0.59$

For anti-neutrino:
Maximum: HO, 90°
Minimum: LO, -90°

Unfavorable CP values for neutrino are favorable for anti-neutrino & vice-versa

Agarwalla, Prakash, Sankar, arXiv: 1301.2574

Analytical Treatment

$$P_{\mu e}^{4\nu} \simeq P_0 + P_1 + P_2,$$

which in vacuum take the form

$$P_0 \simeq 4 s_{23}^2 s_{13}^2 \sin^2\Delta,$$

$$P_1 \simeq 8 s_{13} s_{12} c_{12} s_{23} c_{23} (\alpha\Delta) \sin\Delta \cos(\Delta \pm \delta_{13}),$$

$$P_2 \simeq 4 s_{14} s_{24} s_{13} s_{23} \sin\Delta \sin(\Delta \pm \delta_{13} \mp \delta_{14}),$$

the three small mixing angles have the similar size $s_{13} \sim s_{14} \sim s_{24} \simeq 0.15$, and therefore they can all be assumed to be of the same order ϵ, while the ratio $\alpha \simeq \pm 0.03$ is of the order ϵ^2. This implies that

$$P_0 \sim \epsilon^2, \qquad P_1 \sim \epsilon^3, \qquad P_2 \sim \epsilon^3.$$

Analytical Treatment

$$\theta_{23} = \frac{\pi}{4} \pm \eta,$$

$\sin^2\theta_{23}$ must lie in the range $\sim[0.4, 0.6]$. This implies that η is confined to relatively small values ($\eta \lesssim 0.1$) and can be considered of the same order of magnitude (ϵ) as s_{13}, s_{14}, and s_{24}. Therefore, it is legitimate to use the expansion

$$s_{23}^2 = \frac{1}{2}(1 \pm \sin 2\eta) \simeq \frac{1}{2} \pm \eta.$$

An experiment can be sensitive to the octant if, despite the freedom introduced by the unknown CP phases, there is still a difference between the probabilities in the two octants, i.e.,

$$\Delta P \equiv P_{\mu e}^{\rm HO}(\delta_{13}^{\rm HO}, \delta_{14}^{\rm HO}) - P_{\mu e}^{\rm LO}(\delta_{13}^{\rm LO}, \delta_{14}^{\rm LO}) \neq 0.$$

$$\Delta P = \Delta P_0 + \Delta P_1 + \Delta P_2.$$

Analytical Treatment

$$\Delta P_0 \simeq 8\eta s_{13}^2 \sin^2 \Delta.$$

$$\Delta P_1 = A[\cos(\Delta \pm \phi^{\rm HO}) - \cos(\Delta \pm \phi^{\rm LO})],$$

$$\Delta P_2 = B[\sin(\Delta \pm \psi^{\rm HO}) - \sin(\Delta \pm \psi^{\rm LO})],$$

$$A = 4s_{13}s_{12}c_{12}(\alpha\Delta)\sin\Delta, \qquad \phi = \delta_{13},$$

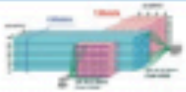
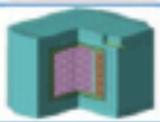
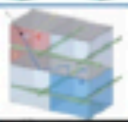
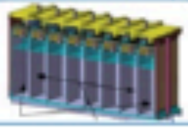
$$B = 2\sqrt{2}s_{14}s_{24}s_{13}\sin\Delta, \qquad \psi = \delta_{13} - \delta_{14},$$

benchmark value $\sin^2\theta_{23} = 0.42$ (0.58) for LO (HO), i.e., $\eta = 0.08$, at the first oscillation maximum ($\Delta = \pi/2$), we have

$$\Delta P_0 \simeq 0.014, \qquad |A| \simeq 0.013, \qquad |B| \simeq 0.010.$$

experiment can be sensitive to the octant only if the positive-definite difference ΔP_0 cannot be completely compensated for by a negative contribution coming from the sum of ΔP_1 and ΔP_2.

SBL Reactor Experiments

Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

N. Bowden, AAP 2016

Hint from MiniBooNE: $\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$

p beam: Booster in FNAL, 8 GeV
ν beam: π Decay-in-flight

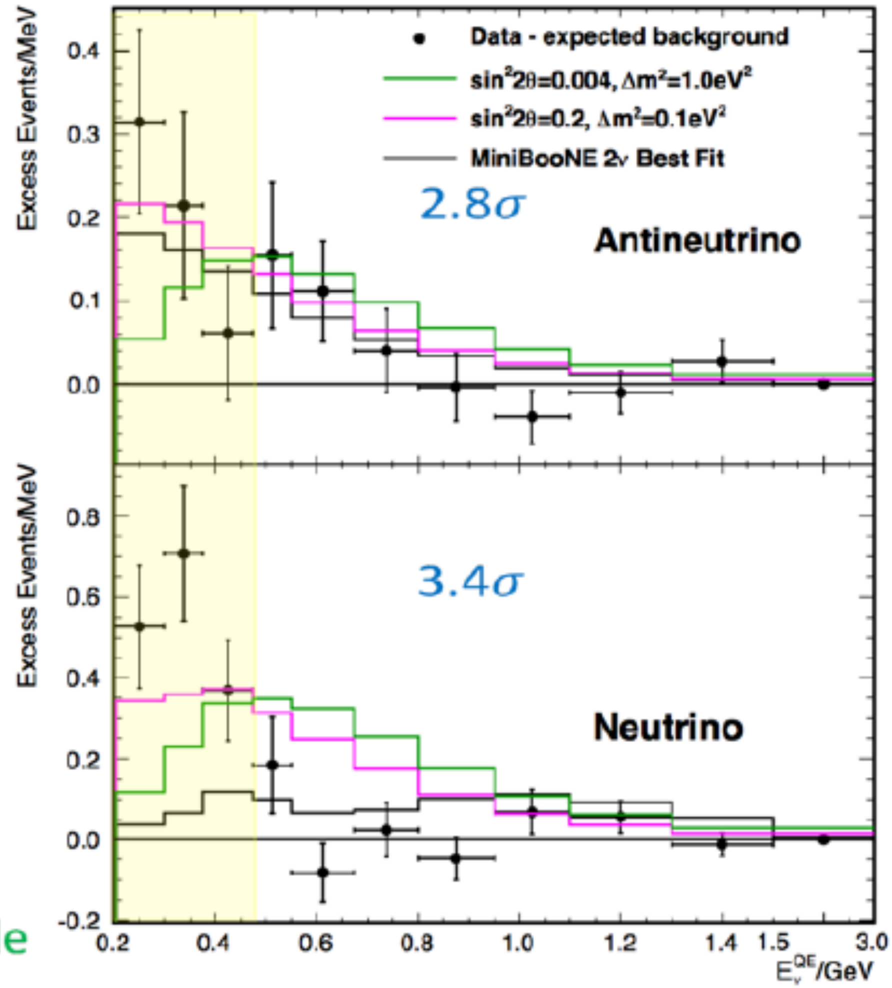
$$\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

Oscillation modes: $\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$
Detection mode: $\nu_e + n \to e^- + p$
$\bar{\nu}_e + p \to e^+ + n$
Baseline: 500 m
Peak Energy: 600 / 400 MeV
L/E : ~ 1 m / MeV

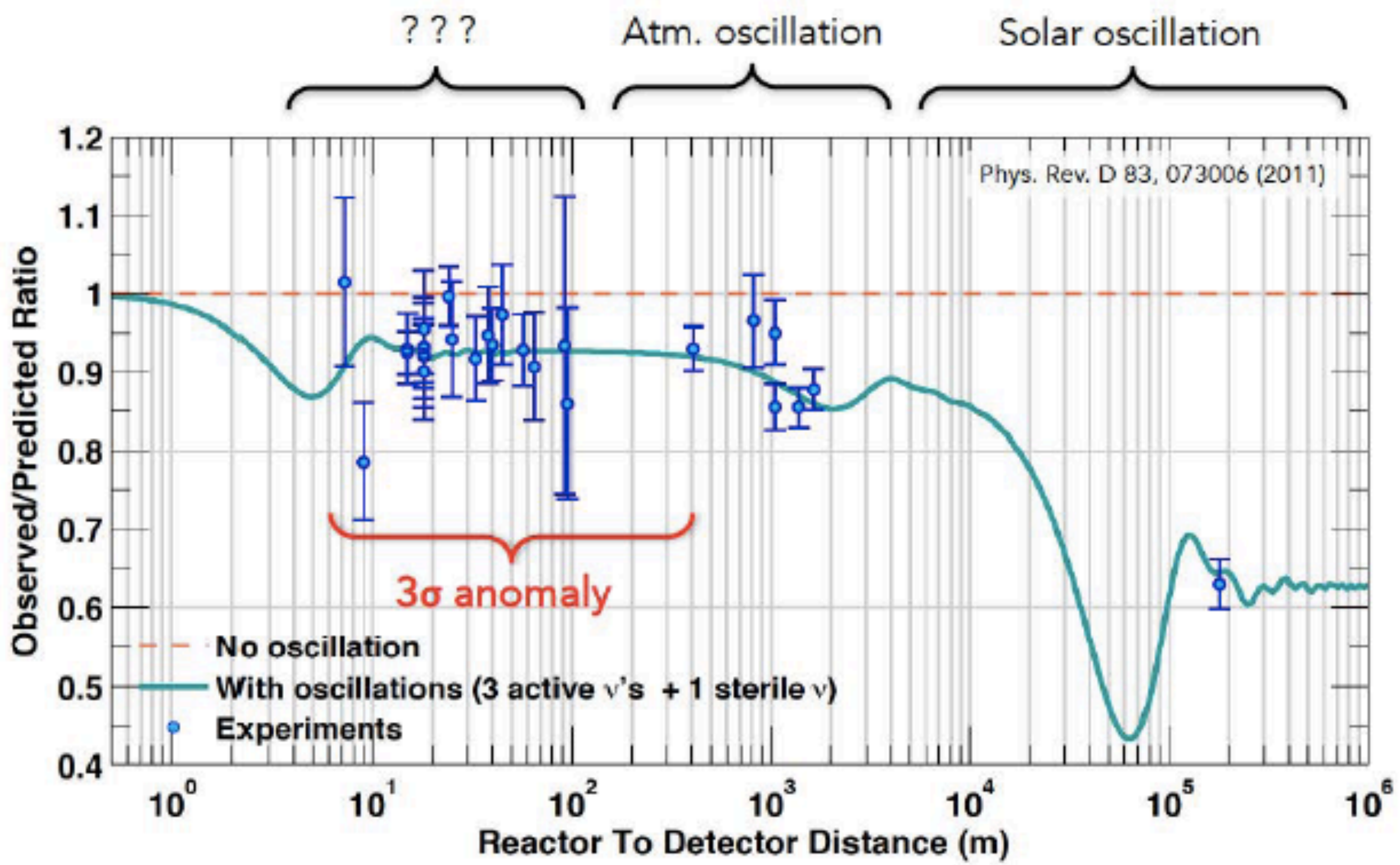
Event excess:
ν mode - 162.0 $\pm$ 47.8 (3.4σ)
$\bar{\nu}$ mode - 78.4 $\pm$ 28.5 (2.8σ)

Above 475 MeV, no event excess for ν mode

Phys. Rev. Lett.110, 161801 (2013)

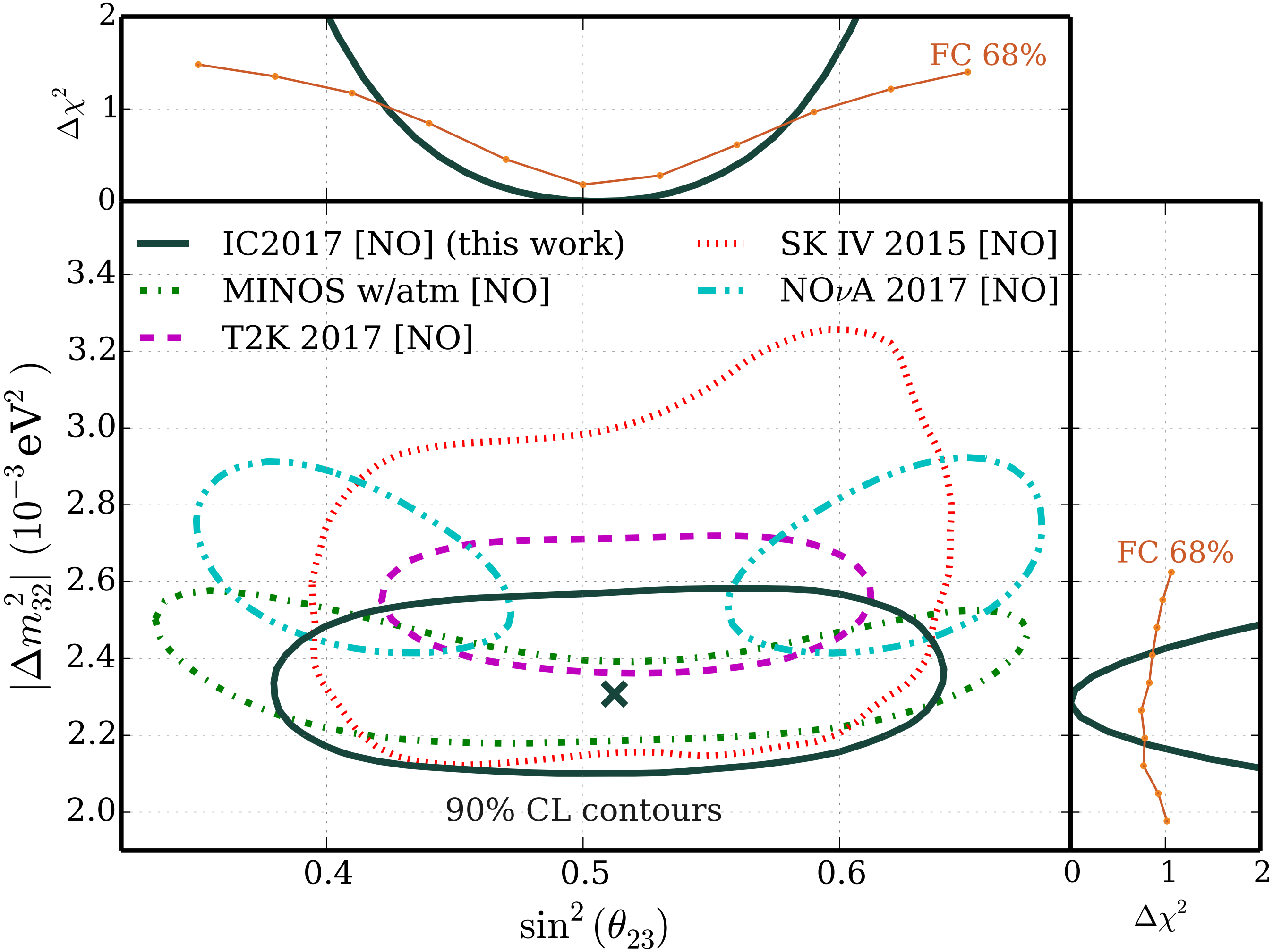


The reactor anomaly



G. Mention, M. Fechner, Th. Lasserre, Th. A. Mueller, D.Lhuillier, M. Cribier, and A. Letourneau, Phys. Rev. D 83, 073006 (2011)

Comparison among Different Experiments



Three years of data from DeepCore in the energy range 5.6 to 56 GeV

MINOS (arXiv:1304.6335)

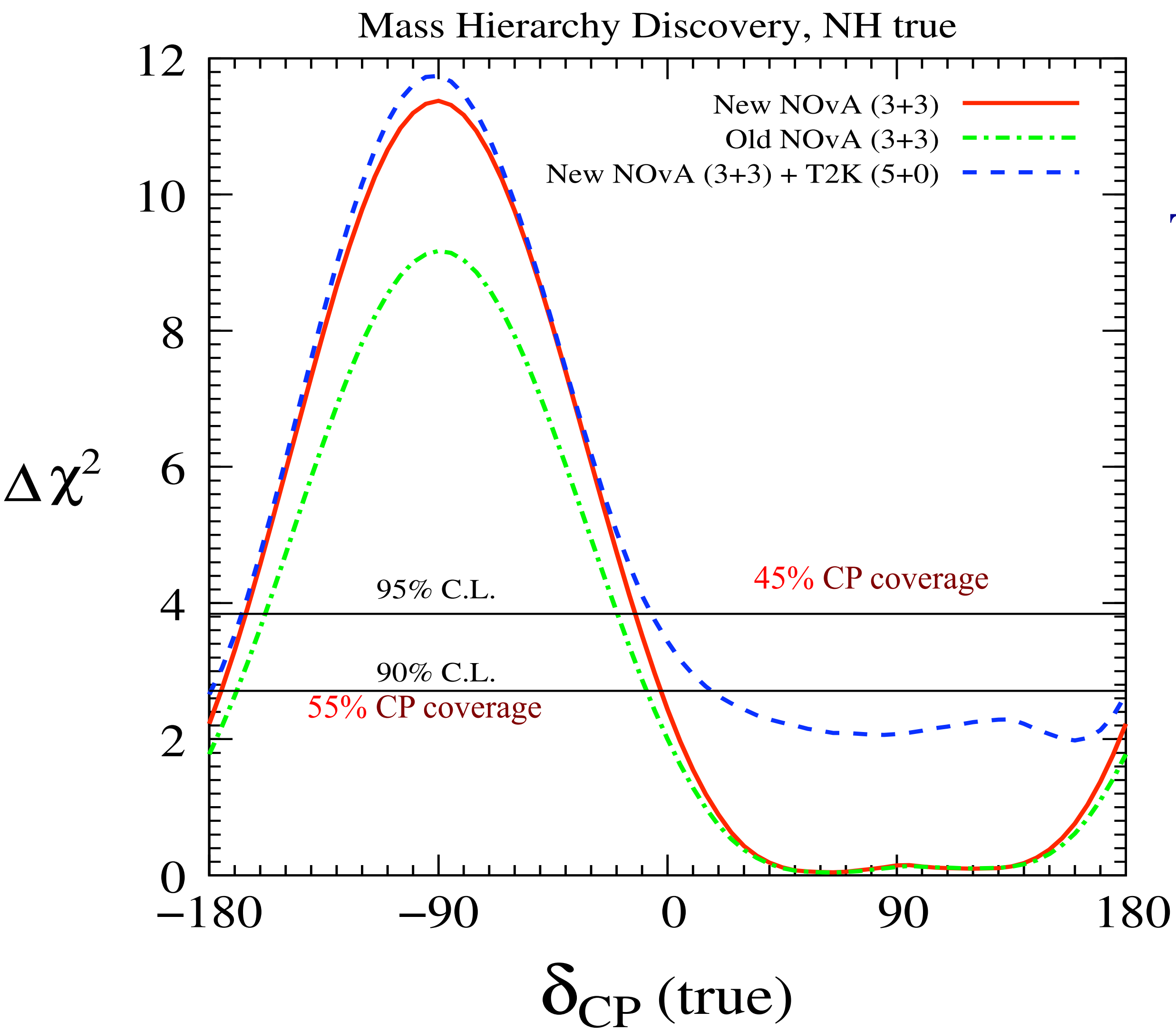
T2K (arXiv:1701.00432)

NOvA (arXiv:1701.05891)

Super-K (arXiv:1412.5234)

IceCube Collaboration, Aartsen etal, arXiv:1707.07081v1 [hep-ph]

Mass Hierarchy Discovery with T2K and NOvA



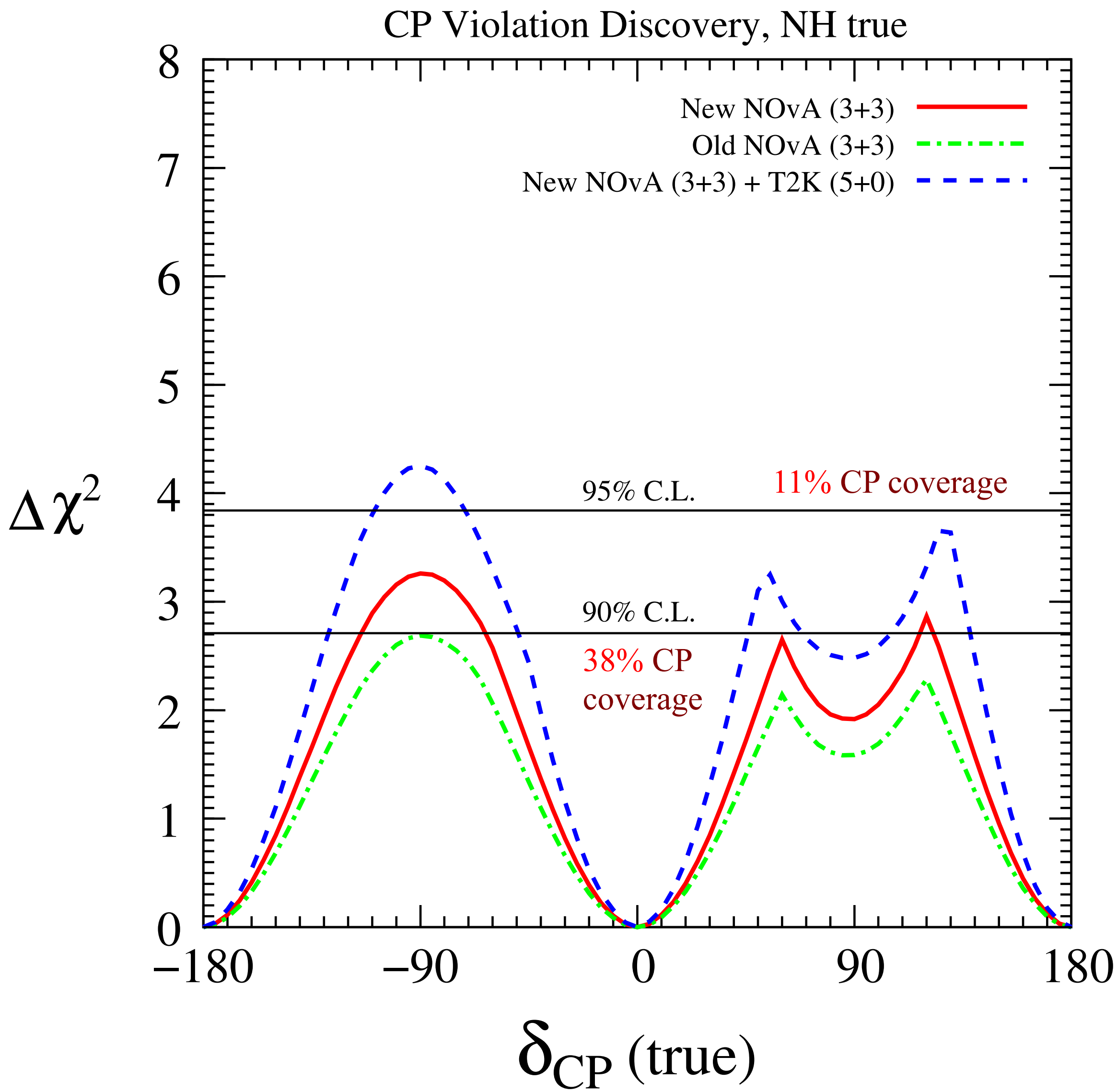
T2K: Total p.o.t.: 7.8×10^{21}

NOvA: Total p.o.t.: 3.6×10^{21}

Adding data from T2K and NOvA is useful to kill the intrinsic degeneracies

Agarwalla, Prakash, Raut, Sankar, arXiv: 1208.3644 [hep-ph]

CP-Violation Discovery with T2K and NOvA



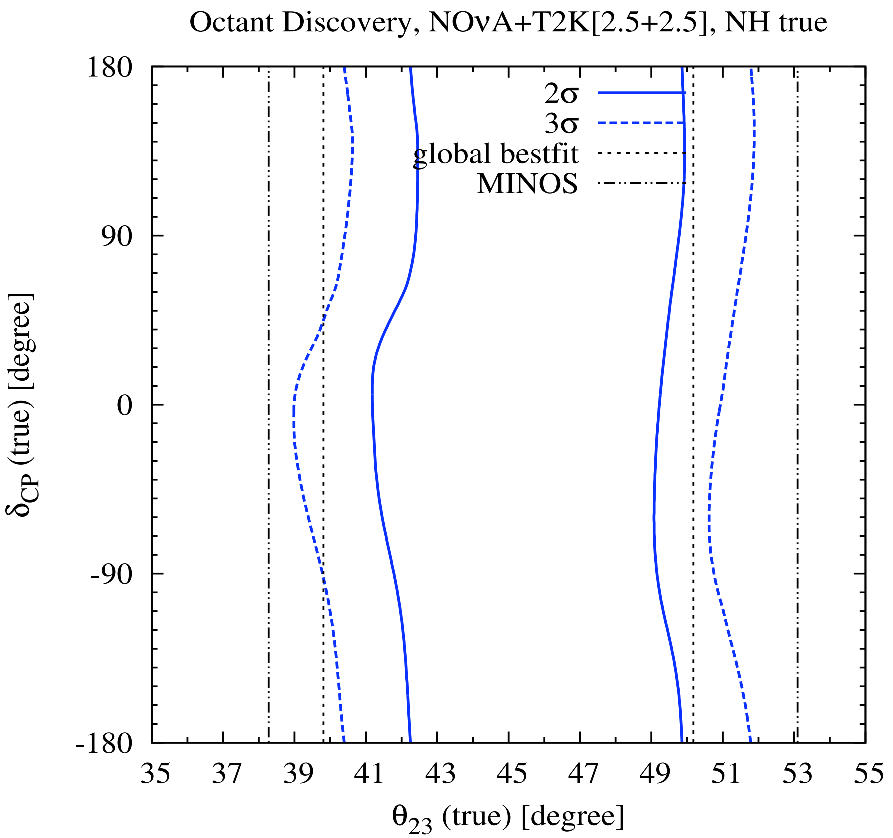
CP asymmetry $\propto 1/\sin 2\theta_{13}$

Large θ_{13} increases statistics but reduces asymmetry

Systematics are important

Agarwalla, Prakash, Raut, Sankar, arXiv: 1208.3644 [hep-ph]

Resolving Octant of θ_{23} with T2K and NOνA



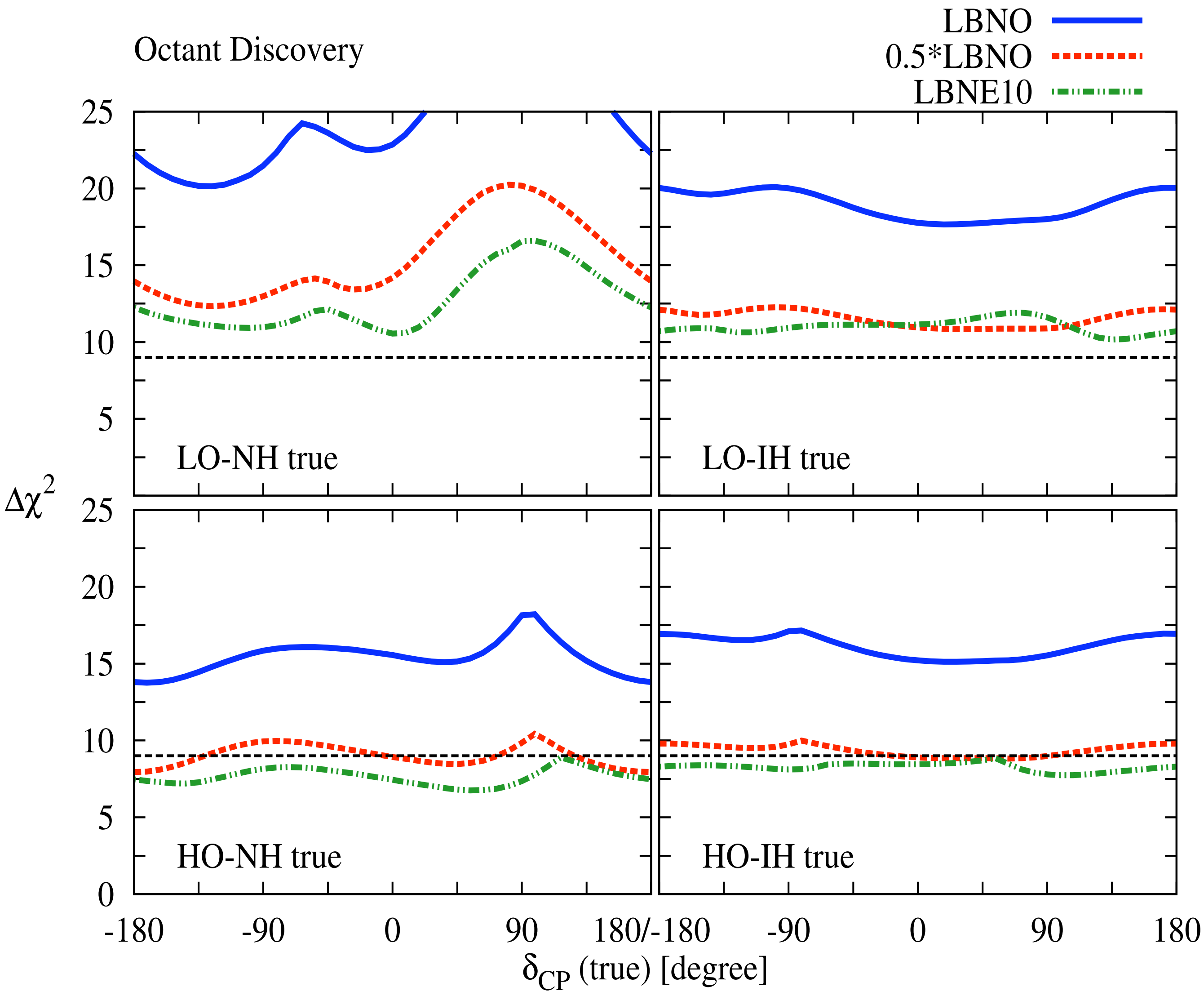
Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]

If $\theta_{23} < 41°$ or $\theta_{23} > 50°$, we can resolve the octant issue at 2σ irrespective of δ_{CP}

If $\theta_{23} < 39°$ or $\theta_{23} > 52°$, we can resolve the octant issue at 3σ irrespective of δ_{CP}

Important message: T2K must run in anti-neutrino mode in future

Octant Discovery with LBNE and LBNO



Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]

For octant: in their first phases, 4σ discovery for LBNO and 3σ for LBNE10

Present Understanding of the 2-3 Mixing Angle

Information on θ_{23} comes from: a) atmospheric neutrinos and b) accelerator neutrinos

In two-flavor scenario: $$P_{\mu\mu} = 1 - \sin^2 2\theta_{\rm eff} \sin^2\left(\frac{\Delta m^2_{\rm eff} L}{4E}\right)$$

For accelerator neutrinos: relate effective 2-flavor parameters with 3-flavor parameters:

$$\Delta m^2_{\rm eff} = \Delta m^2_{31} - \Delta m^2_{21}(\cos^2\theta_{12} - \cos\delta_{\rm CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23})$$

$$\sin^2 2\theta_{\rm eff} = 4\cos^2\theta_{13}\sin^2\theta_{23}\left(1 - \cos^2\theta_{13}\sin^2\theta_{23}\right)$$ where $$\frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2} = \tan^2\theta_{23}$$

Nunokawa etal, hep-ph/0503283; A. de Gouvea etal, hep-ph/0503079

Combining bean and atmospheric data in MINOS, we have:

MINOS Collaboration: arXiv:1304.6335v2 [hep-ex]

$$\sin^2 2\theta_{\rm eff} = 0.95^{+0.035}_{-0.036}\ (10.71\times 10^{21}\ \text{p.o.t})$$

$$\sin^2 2\bar{\theta}_{\rm eff} = 0.97^{+0.03}_{-0.08}\ (3.36\times 10^{21}\ \text{p.o.t})$$

Atmospheric data, dominated by Super-Kamiokande, still prefers maximal value of $\sin^2 2\theta_{\rm eff} = 1$ (≥ 0.94 (90% C.L.))

Talk by Y. Itow in Neutrino 2012 conference, Kyoto, Japan

Bounds on θ_{23} from the global fits

	Forero etal	Fogli etal	Gonzalez-Garcia etal
$\sin^2\theta_{23}$ (NH)	$0.427^{+0.034}_{-0.027} \oplus 0.613^{+0.022}_{-0.040}$	$0.386^{+0.024}_{-0.021}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$
3σ range	$0.36 \to 0.68$	$0.331 \to 0.637$	$0.34 \to 0.67$
$\sin^2\theta_{23}$ (IH)	$0.600^{+0.026}_{-0.031}$	$0.392^{+0.039}_{-0.022}$	**Relative 1σ precision of 11%**
3σ range	$0.37 \to 0.67$	$0.335 \to 0.663$	

All the three global fits indicate for non-maximal 2-3 mixing!

In ν_μ survival probability, the dominant term is mainly sensitive to $\sin^2 2\theta_{23}$!

If $\sin^2 2\theta_{23}$ differs from 1 (as indicated by recent data), we get two solutions for θ_{23}:

one in lower octant (LO: θ_{23} < 45 degree), other in higher octant (HO: θ_{23} > 45 degree)

In other words, if ($0.5 - \sin^2\theta_{23}$) is +ve (-ve) then θ_{23} belongs to LO (HO)

This is known as the octant ambiguity of θ_{23} !

Fogli and Lisi, hep-ph/9604415

ν_μ to ν_e oscillation data can break this degeneracy!

The preferred value would depend on the choice of the neutrino mass hierarchy!

Octant – δ_{CP} degeneracy in $\nu_\mu \to \nu_e$ oscillation channel

$$P_{\mu e} = \beta_1 \sin^2\theta_{23} + \beta_2 \cos(\hat{\Delta} + \delta_{\rm CP}) + \beta_3 \cos^2\theta_{23}$$ (upto second order in $\alpha = \Delta_{21}/\Delta_{31}$ and $\sin 2\theta_{13}$)

$$\beta_1 = \sin^2 2\theta_{13} \frac{\sin^2\hat{\Delta}(1-\hat{A})}{(1-\hat{A})^2}, \quad \beta_3 = \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{13} \frac{\sin^2\hat{\Delta}\hat{A}}{\hat{A}^2}$$

$$\beta_2 = \alpha \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \frac{\sin\hat{\Delta}\hat{A}}{\hat{A}} \frac{\sin\hat{\Delta}(1-\hat{A})}{1-\hat{A}}$$

$$A({\rm eV}^2) = 0.76 \times 10^{-4} \rho\ ({\rm g/cc}) E({\rm GeV}) \qquad \hat{\Delta} = \Delta_{31} L/4E,\ \hat{A} = A/\Delta_{31}$$

Cervera etal, hep-ph/0002108; Freund etal, hep-ph/0105071

We demand that: $P_{\mu e}({\rm LO}, \delta_{\rm CP}^{\rm LO}) = P_{\mu e}({\rm HO}, \delta_{\rm CP}^{\rm HO})$

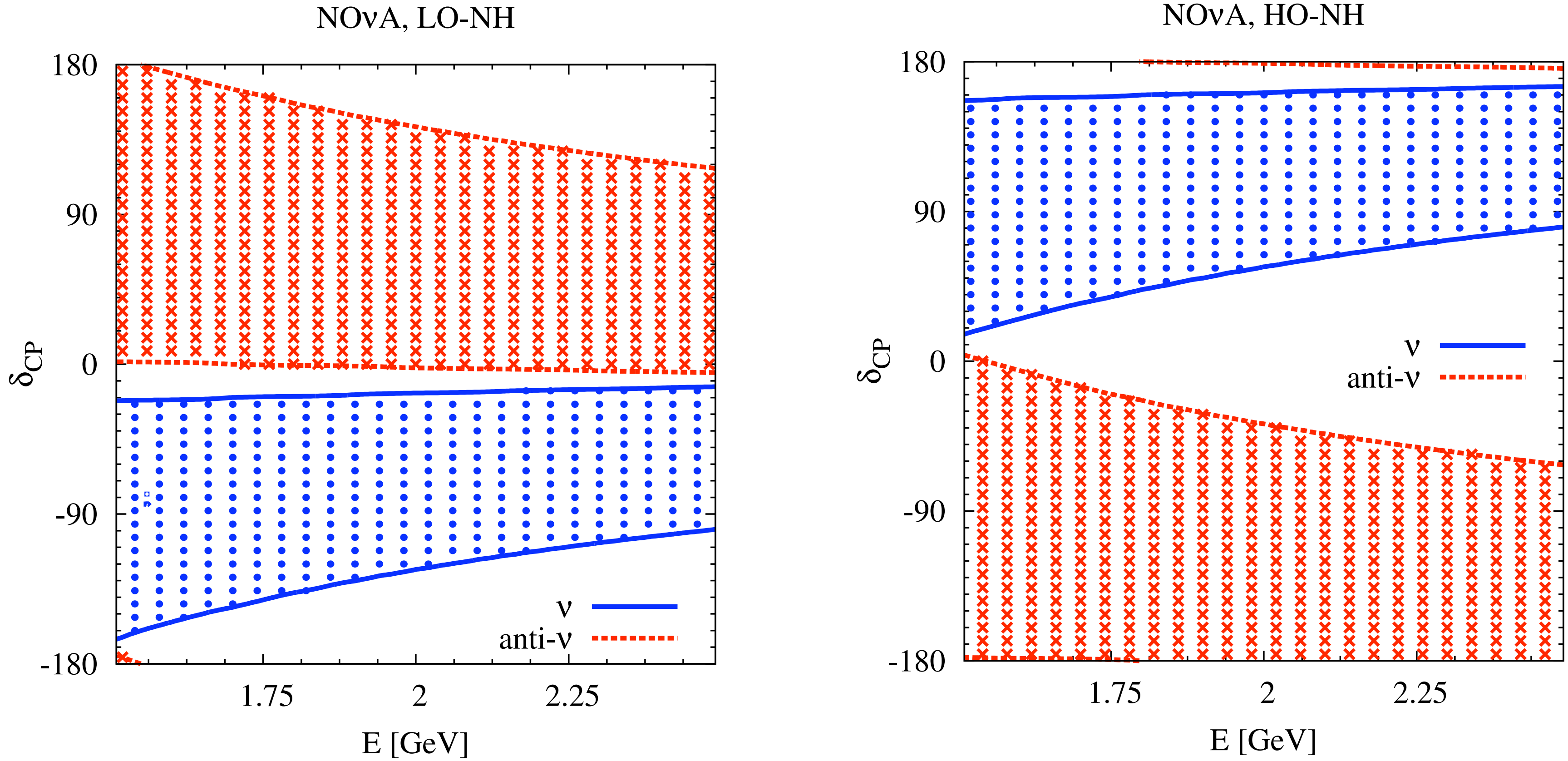
Above condition gives us: $\cos(\hat{\Delta} + \delta_{\rm CP}^{\rm LO}) - \cos(\hat{\Delta} + \delta_{\rm CP}^{\rm HO}) = \frac{\beta_1 - \beta_3}{\beta_2}(\sin^2\theta_{23}^{\rm HO} - \sin^2\theta_{23}^{\rm LO})$

For L=810 km & E=2 GeV, we get for NH and neutrino: $\cos(\hat{\Delta} + \delta_{\rm CP}^{\rm LO}) - \cos(\hat{\Delta} + \delta_{\rm CP}^{\rm HO}) = 1.7$

$P_{\mu e}({\rm LO}, -116^\circ \le \delta_{\rm CP} \le -26^\circ)$ is degenerate with $P_{\mu e}({\rm HO}, 64^\circ \le \delta_{\rm CP} \le 161^\circ)$

Agarwalla, Prakash, Uma Sankar, arXiv:1301.2574

Octant – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel



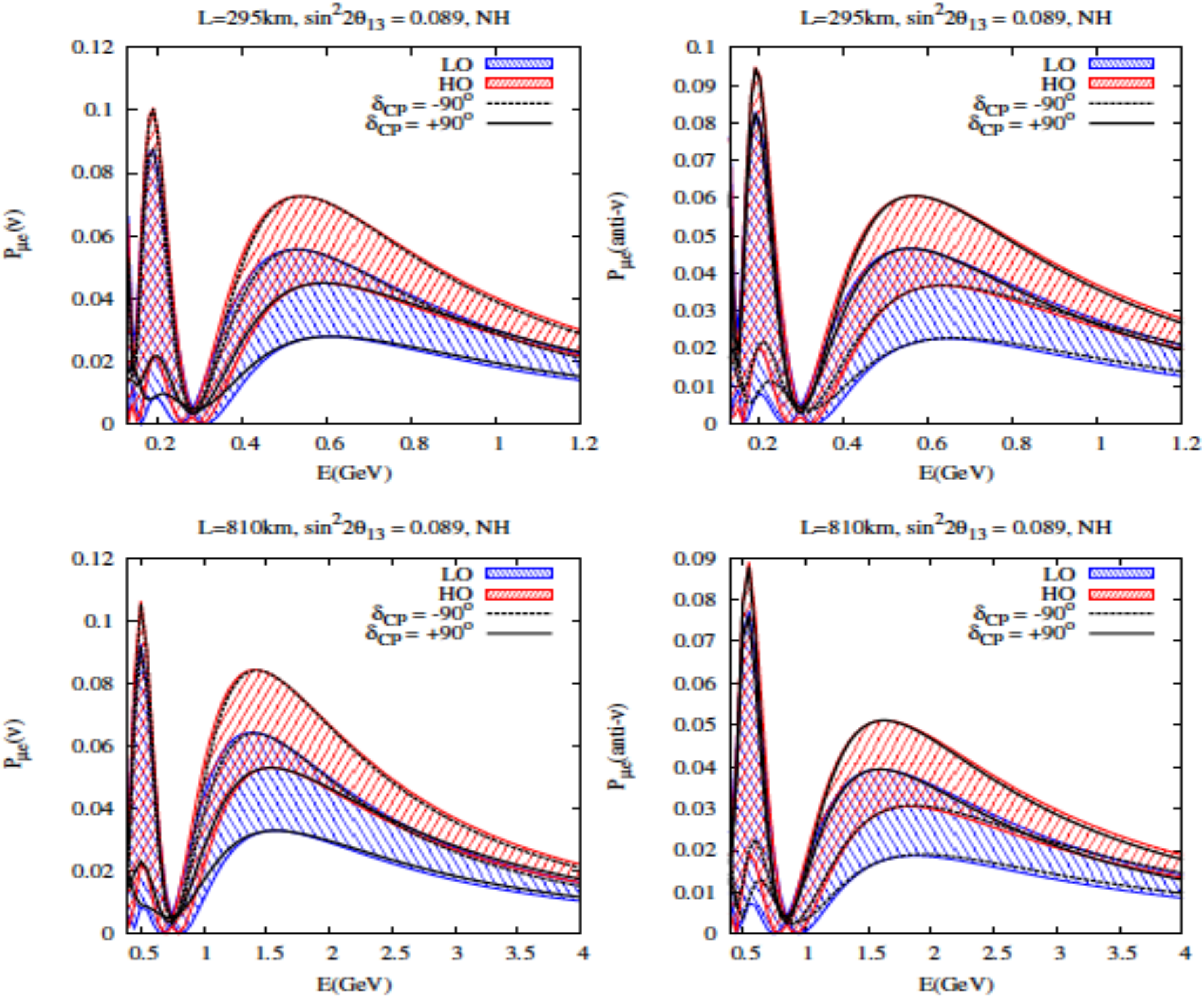
Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]

Octant – δ_{CP} degeneracy in $P_{\mu e}$ as a function of neutrino energy

At 2 GeV, $P_{\mu e}(\text{LO}, -116^\circ \le \delta_{\text{CP}} \le -26^\circ)$ is degenerate with $P_{\mu e}(\text{HO}, 64^\circ \le \delta_{\text{CP}} \le 161^\circ)$

As an example, $P_{\mu e}(\text{LO}, \delta_{\text{CP}} = -90^\circ)$ is degenerate with $P_{\mu e}(\text{HO}, \delta_{\text{CP}} \approx 66^\circ)$

Octant – δ_{CP} degeneracy in T2K and NOνA



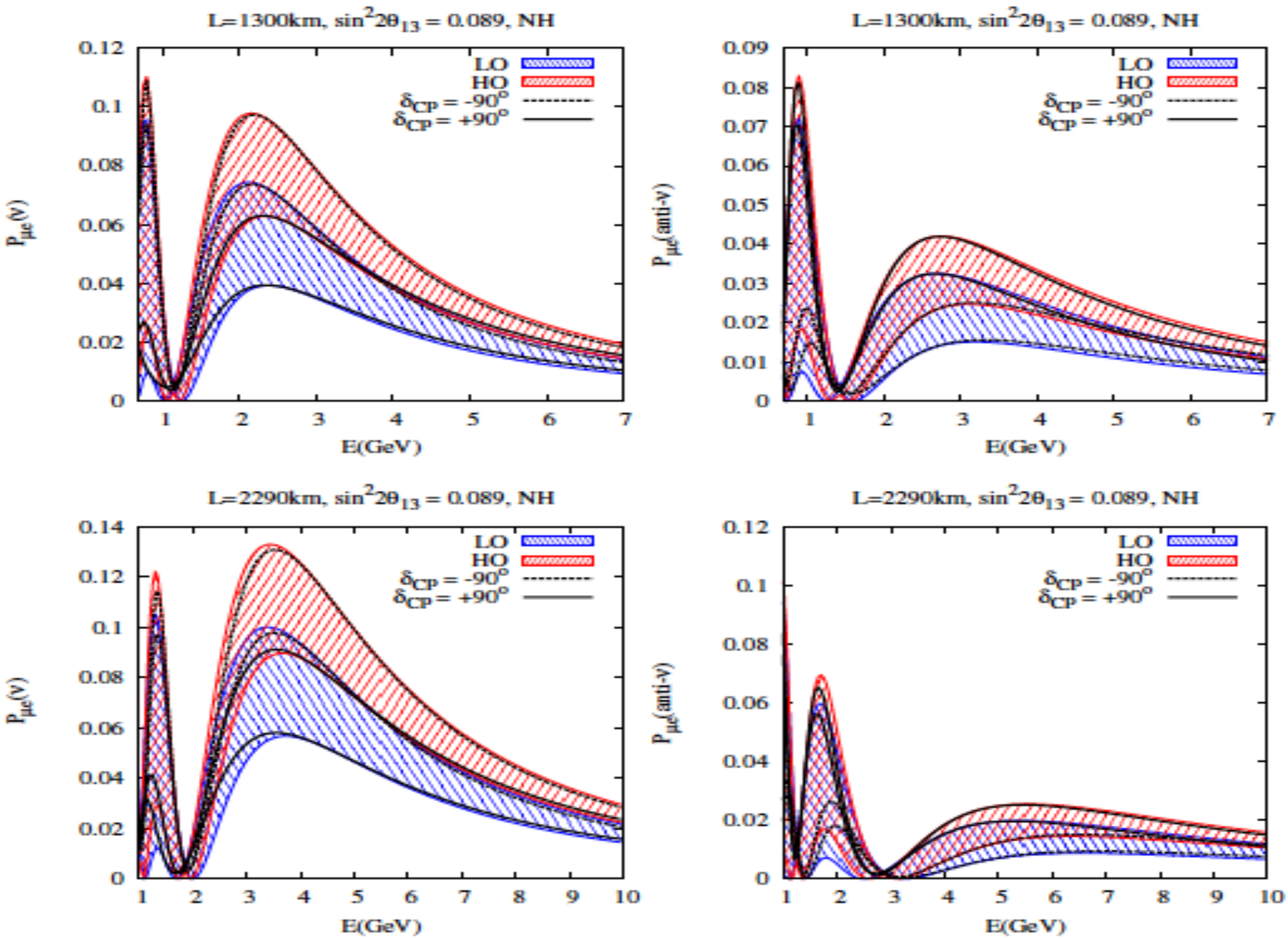
For neutrino: favorable combinations:
Max: HO, -90°
Min: LO, 90°

For anti-neutrino: favorable combinations:
Max: HO, 90°
Min: LO, -90°

Unfavorable CP values for neutrino are favorable for anti-neutrino and vice-versa!

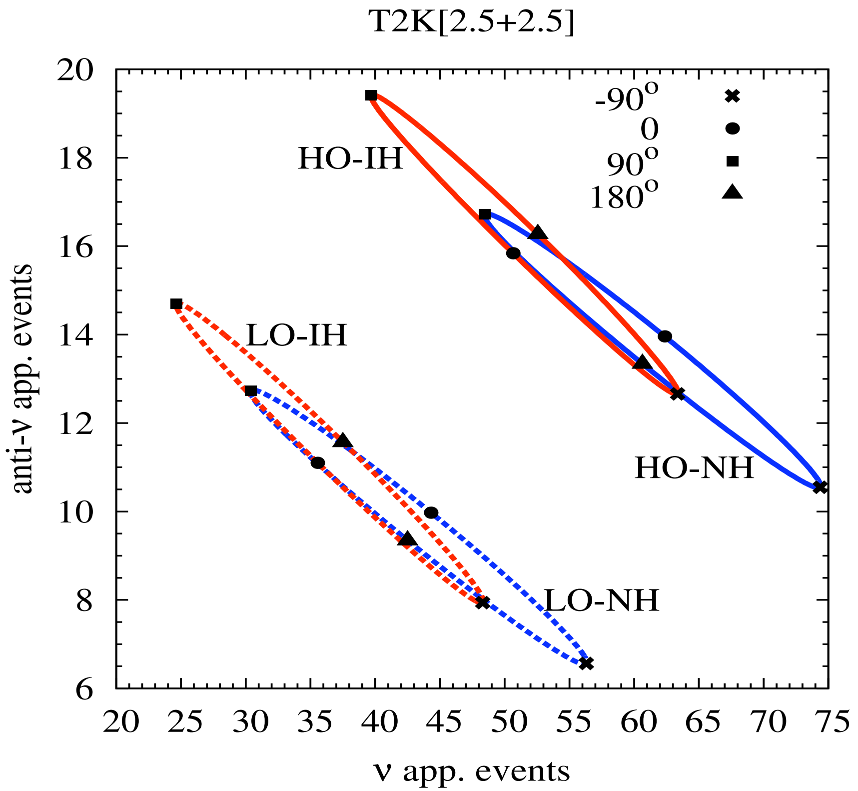
Agarwalla, Prakash, Uma Sankar, arXiv:1301.2574

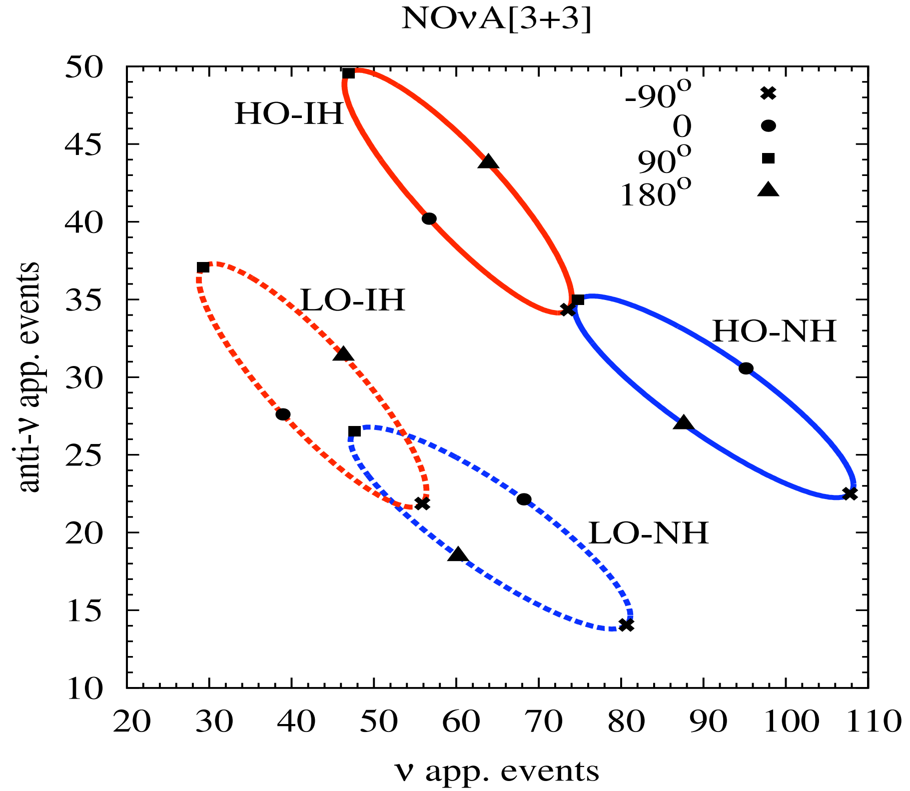
Octant – δ_{CP} degeneracy in LBNE and LBNO



Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]

Bi-Event Plots for T2K and NOvA





Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]; see also the talk by T. Nakadaira in this workshop

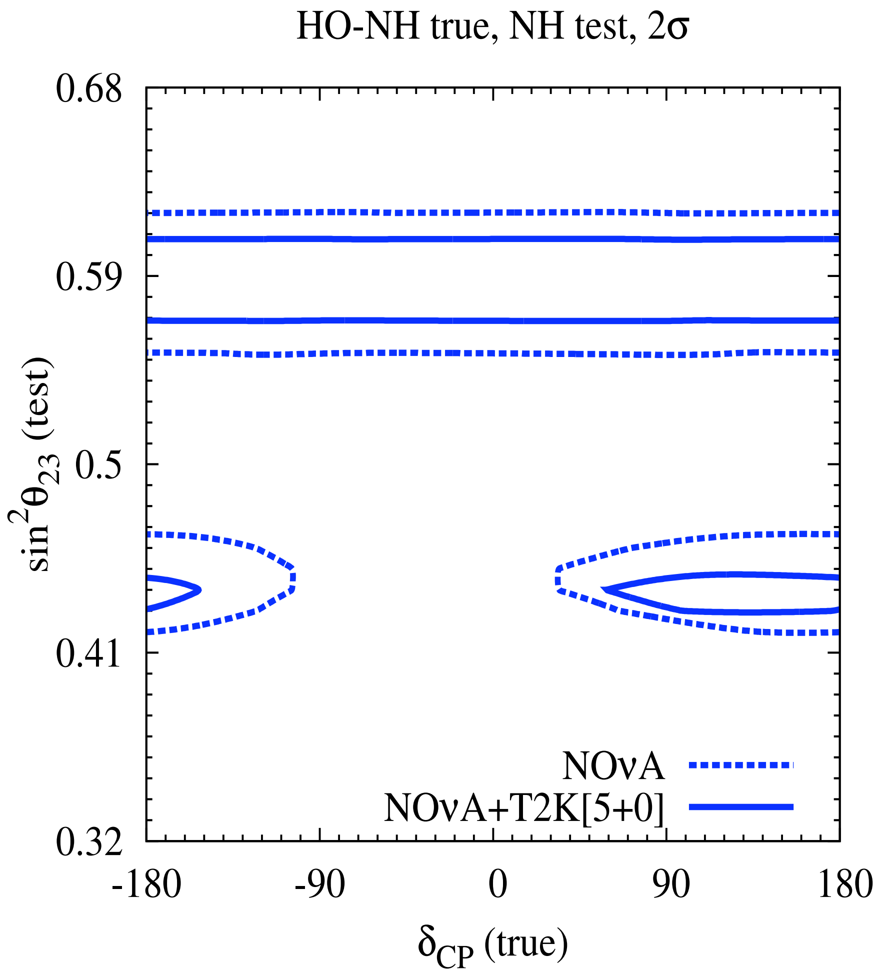
neutrino vs. anti-neutrino events for various octant-hierarchy combinations, ellipses due to varying δ_{CP}!

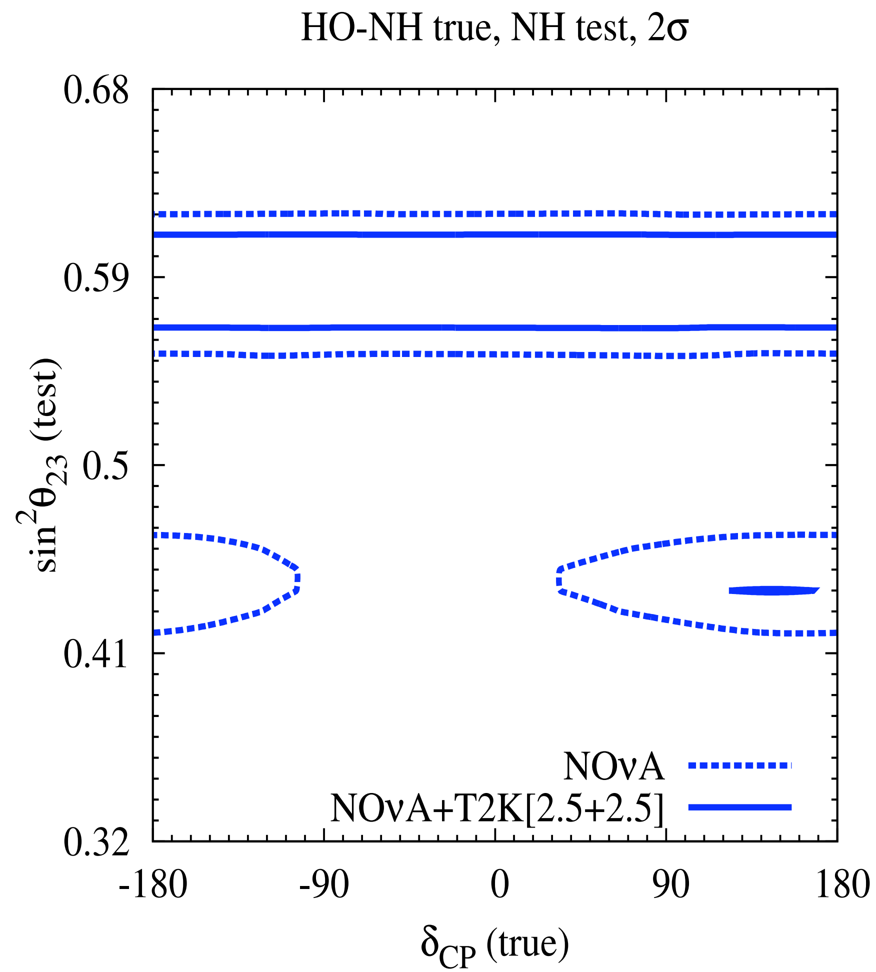
If δ_{CP} = -90° (90°), the asymmetry between ν and anti-ν events is largest for NH (IH)

For NOνA & T2K, the ellipses for the two hierarchies overlap whereas the ellipses of LO are well separated from those of HO, the same is true for T2K as well!

Octant discovery: balanced neutrino & anti-neutrino runs needed in each experiment!

Allowed regions in test $\sin^2\theta_{23}$ - true δ_{CP} plane

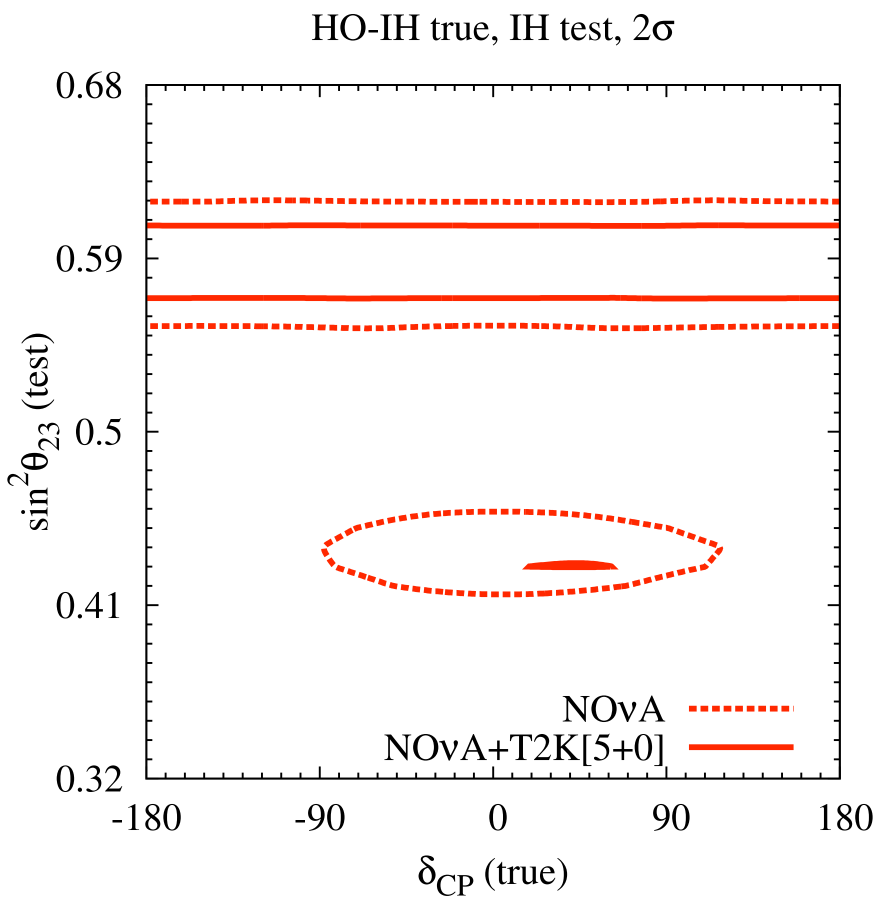


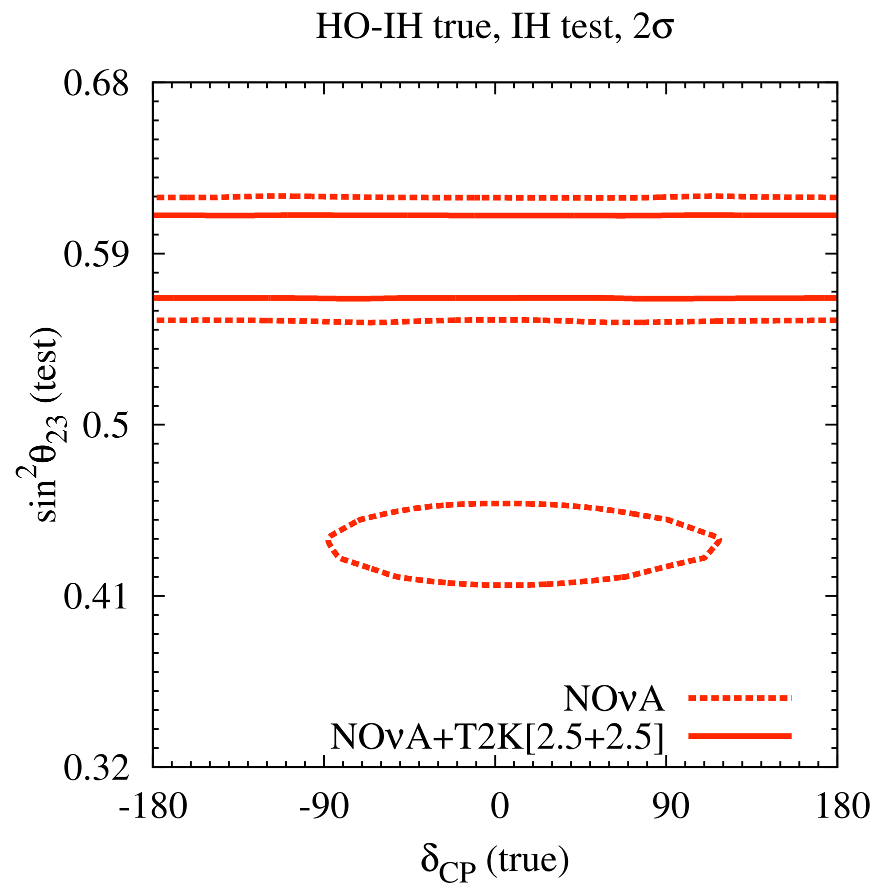


Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]

Balanced neutrino & anti-neutrino runs from T2K are mandatory if HO turns out to be the right octant!

Allowed regions in test $\sin^2\theta_{23}$ - true δ_{CP} plane

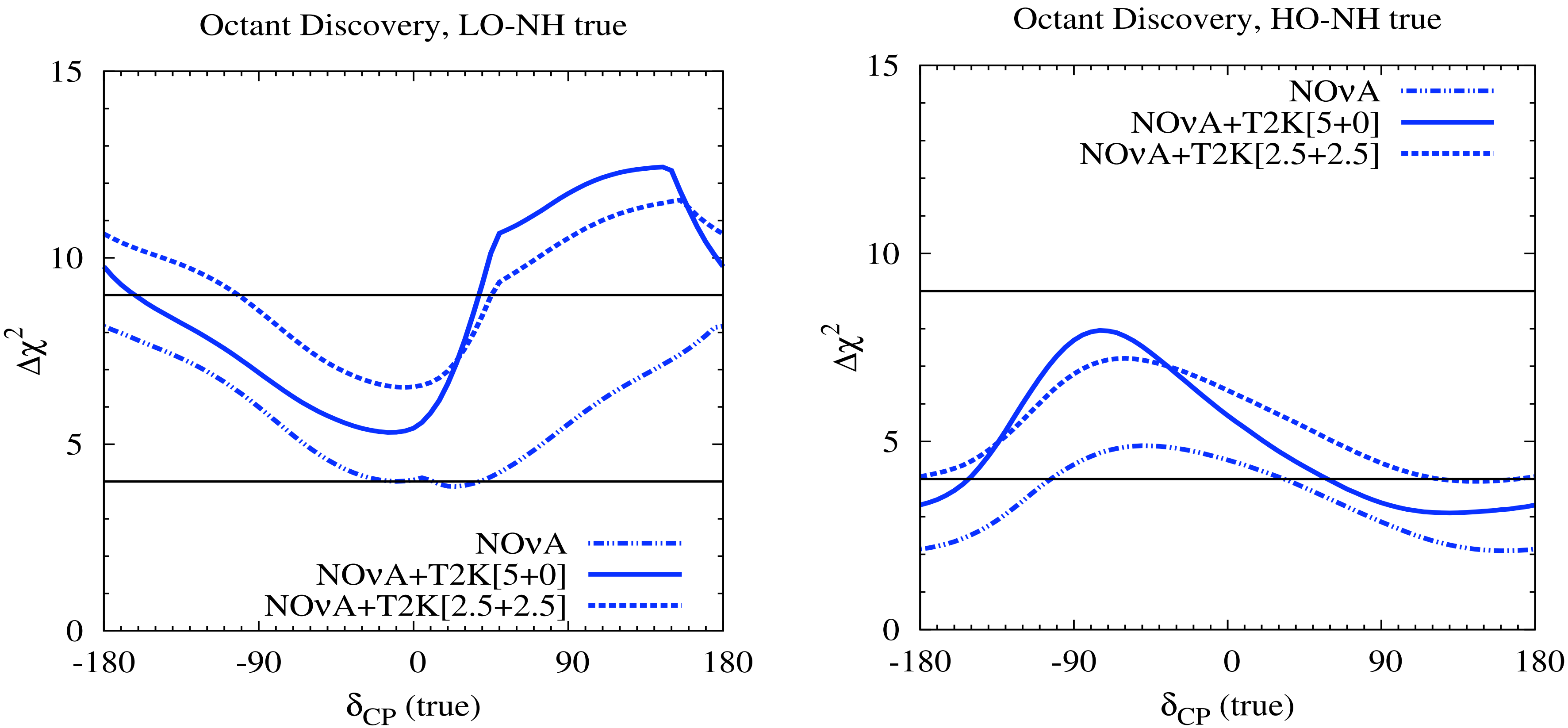




Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]

Balanced neutrino & anti-neutrino runs from T2K are mandatory if HO turns out to be the right octant!

Resolving Octant of θ_{23} with T2K and NOvA

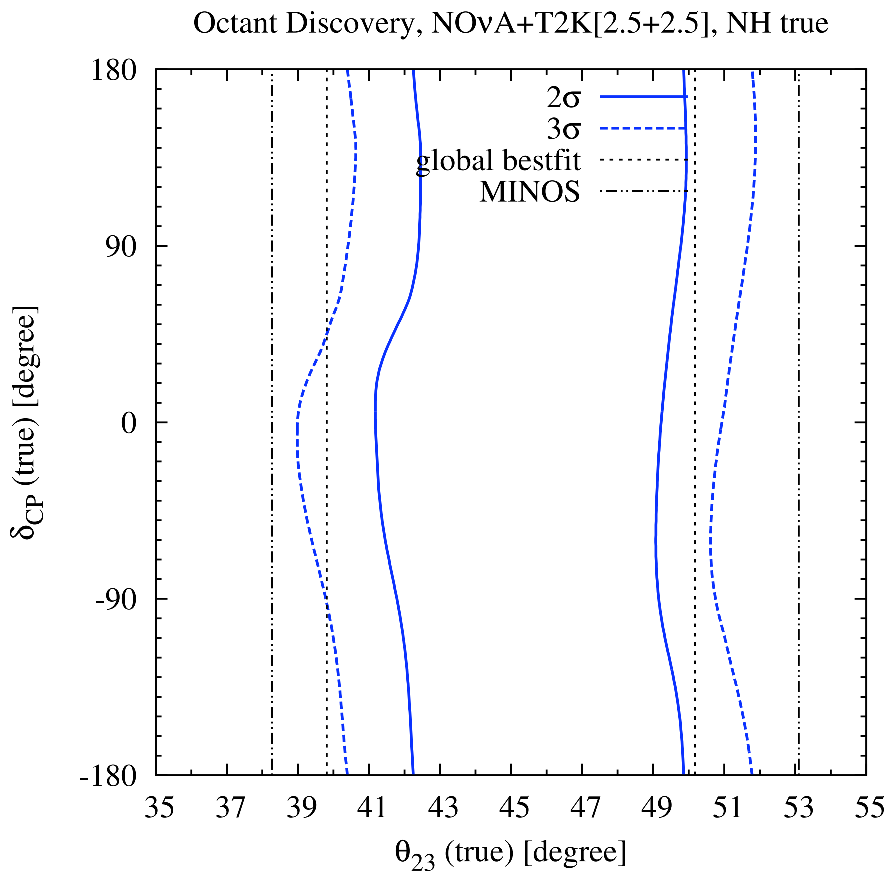


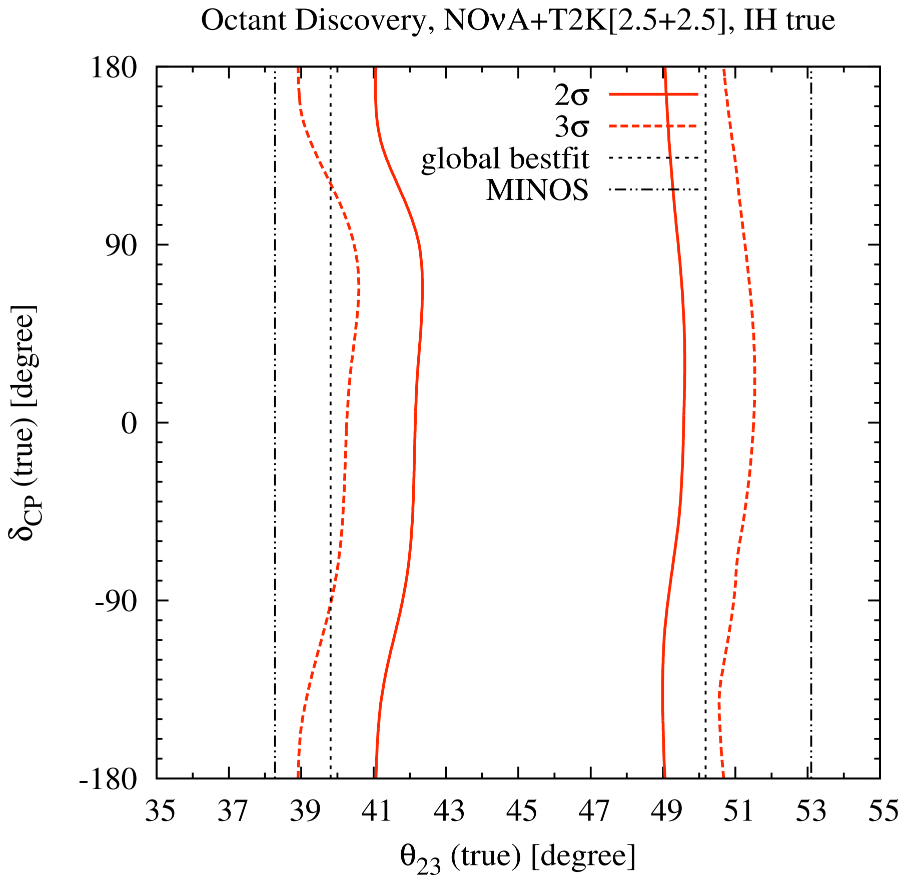
Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]

A 2σ resolution of the octant, for all combinations of neutrino parameters, becomes possible if we add the balanced neutrino and anti-neutrino runs from T2K (2.5 years ν + 2.5 years anti-ν) and NOνA (3 years ν + 3 years of anti-ν)

Important message: T2K must run in anti-neutrino mode in future!

Octant discovery in θ_{23} (true) – δ_{CP} (true) plane with T2K & NOvA





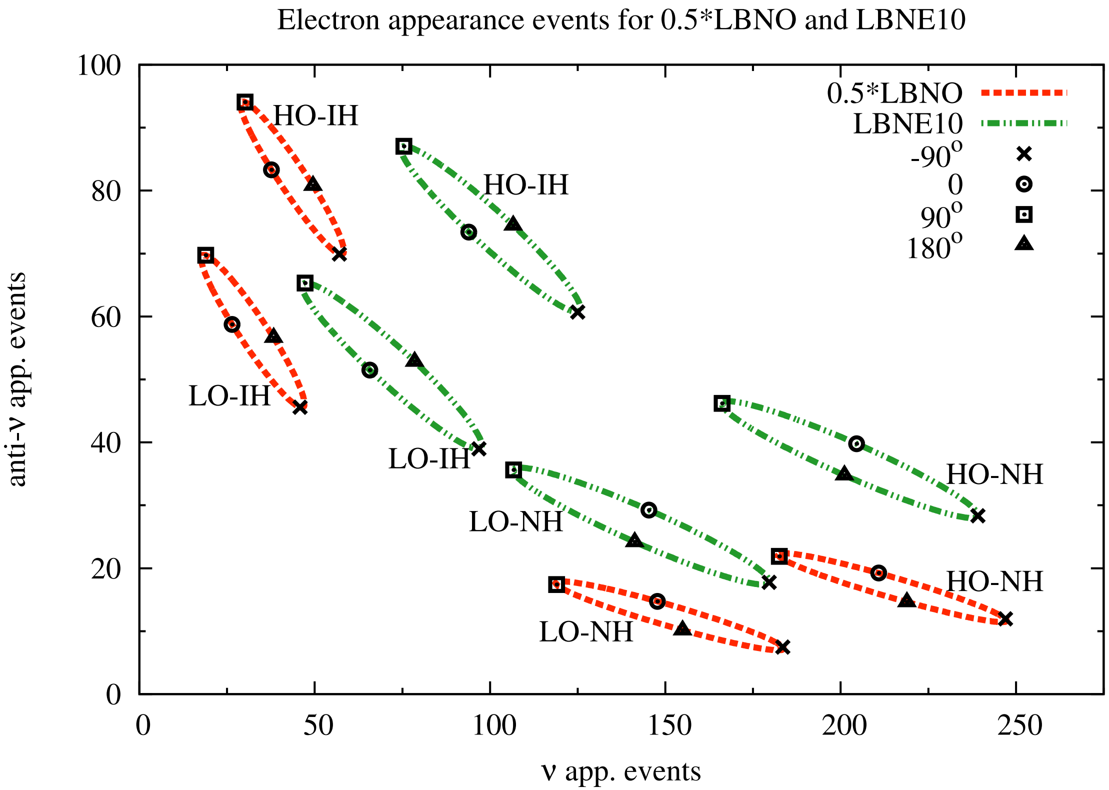
Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]

With Normal Hierarchy

If $\theta_{23} < 41°$ or $\theta_{23} > 50°$, we can resolve the octant issue at 2σ irrespective δ_{CP}

If $\theta_{23} < 39°$ or $\theta_{23} > 52°$, we can resolve the octant issue at 3σ irrespective δ_{CP}

Future Superbeam Expts with LAr Detector: LBNE & LBNO



LBNO: CERN-Pyhasalmi (2290 km)
750 kW beam power, 20 kt LArTPC

0.5*LBNO: reduce detector size to 10 kt

For octant, balanced ν & anti-ν data must!

LBNE10: FNAL-Homestake (1300 km)
708 kW beam power, 10 kt LArTPC

For LBNE10, in case of LO, hierarchy discovery is very limited!

Octant determination in LBNE10 is similar to 0.5*LBNO!

Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]

Wide Band Beam ➔ Higher statistics ➔ cover several L/E values ➔ kill clone solutions

LAr Detector ➔ Excellent Detection efficiency at 1st & 2nd Osc. maxima, good background rejection!

High L ➔ High E ➔ High cross-section ➔ Less uncertainties in cross-section at high E

Few Remarks

Recent measurement of a moderately large value of θ_{13} signifies an important breakthrough in establishing the standard three flavor oscillation picture of neutrinos!

It has opened up exciting possibilities for current & future oscillation experiments!

T2K and NOνA are now poised to probe the impact of full 3 flavor effects to discover octant of θ_{23} (a first step towards CP violation discovery)!

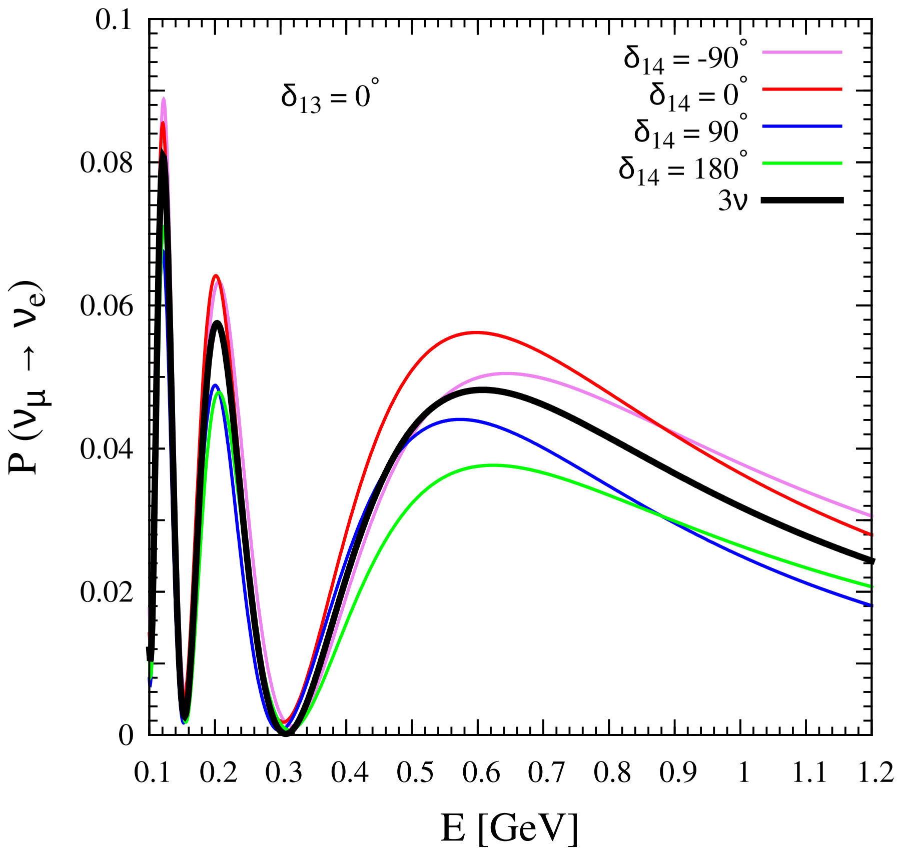
Balanced ν and anti-ν runs from T2K & NOνA can establish the correct octant at 2σ for any combination of hierarchy and CP phase if $\sin^2\theta_{23} \leq 0.43$ or ≥ 0.58

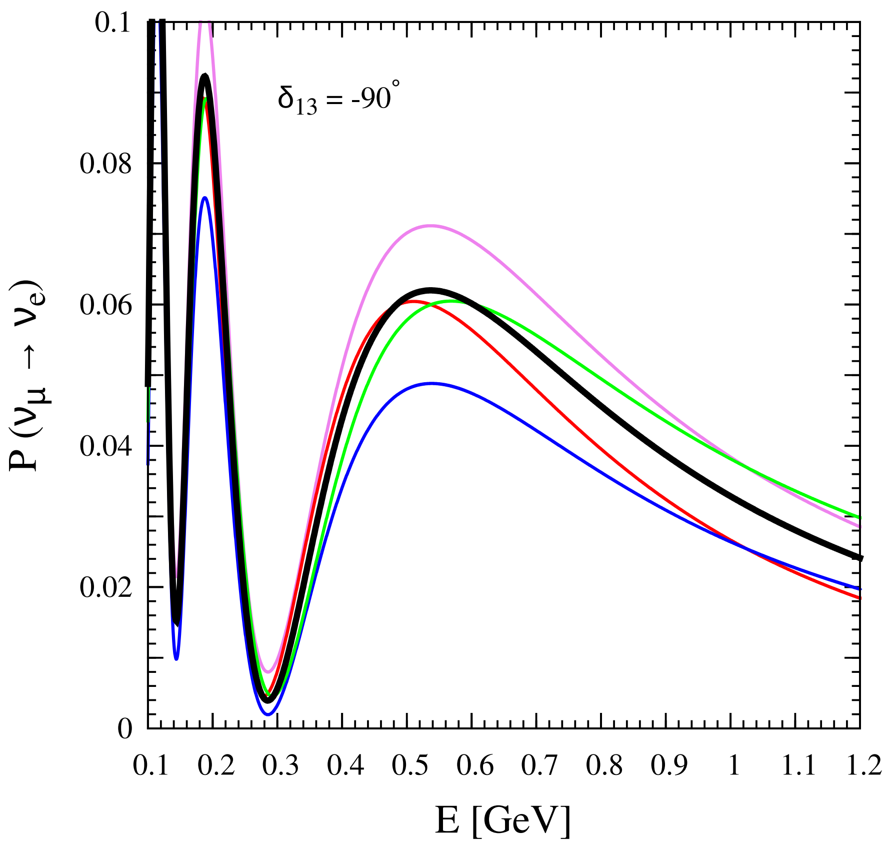
In its first phase, LBNE10 can resolve the octant ambiguity of θ_{23} around 3σ C.L.

In its first phase, LBNO can decide the correct octant of θ_{23} around 4σ C.L.

Large value of θ_{13} allows us to explore Octant with atmospheric neutrinos!
ICAL@INO experiment, IceCube Deepcore, PINGU will play a vital role!

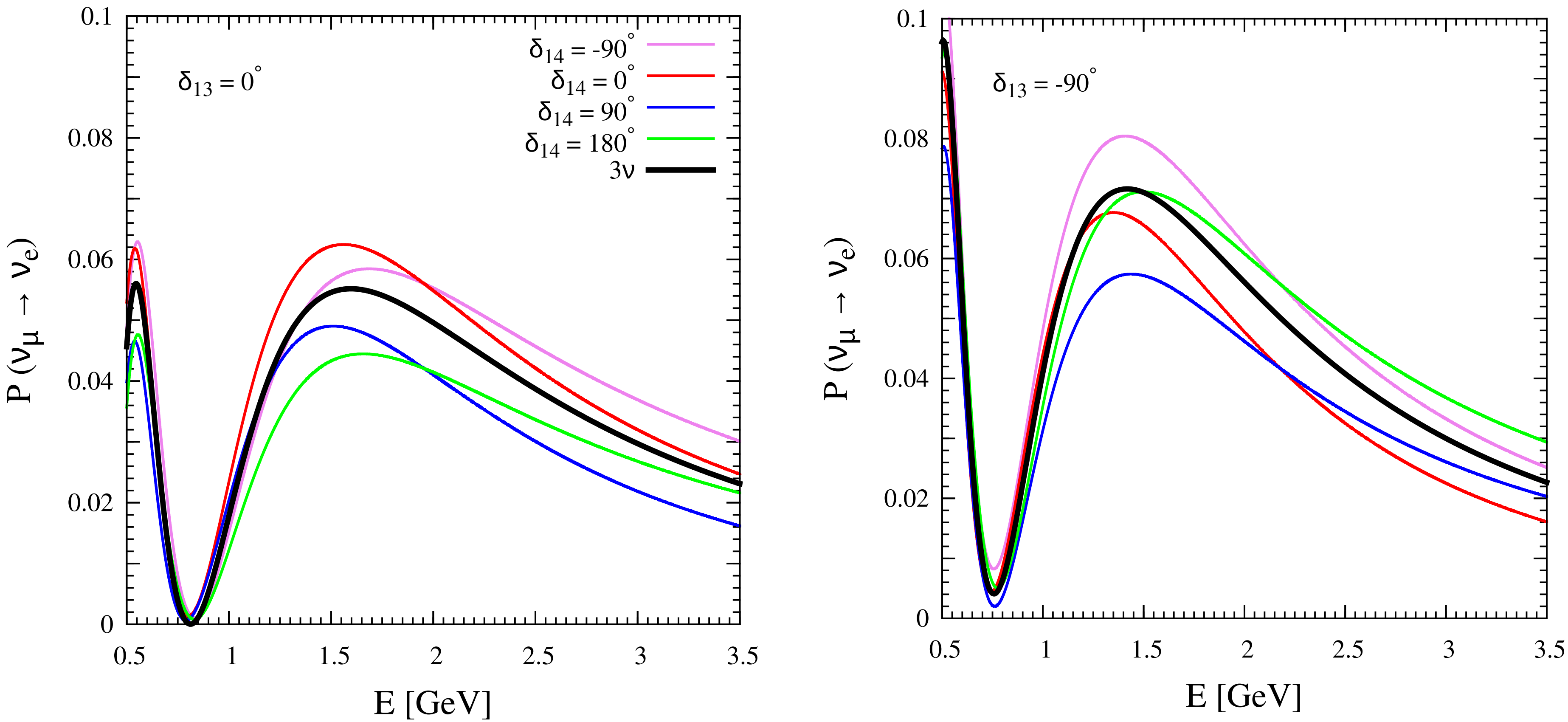
Oscillation Probability in T2K





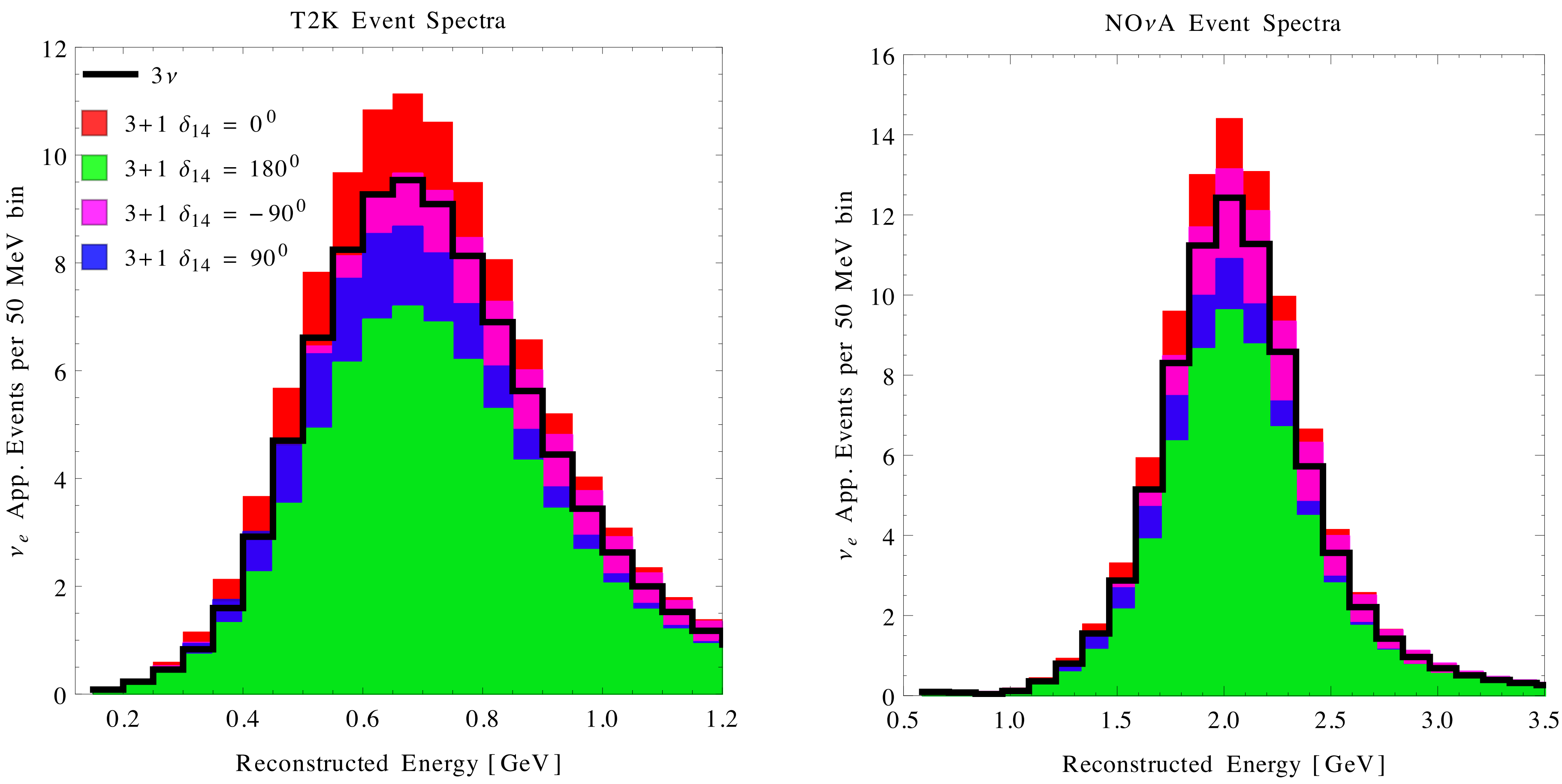
Agarwalla, Chatterjee, Dasgupta, Palazzo (arXiv:1601.05995)

Oscillation Probability in NOvA



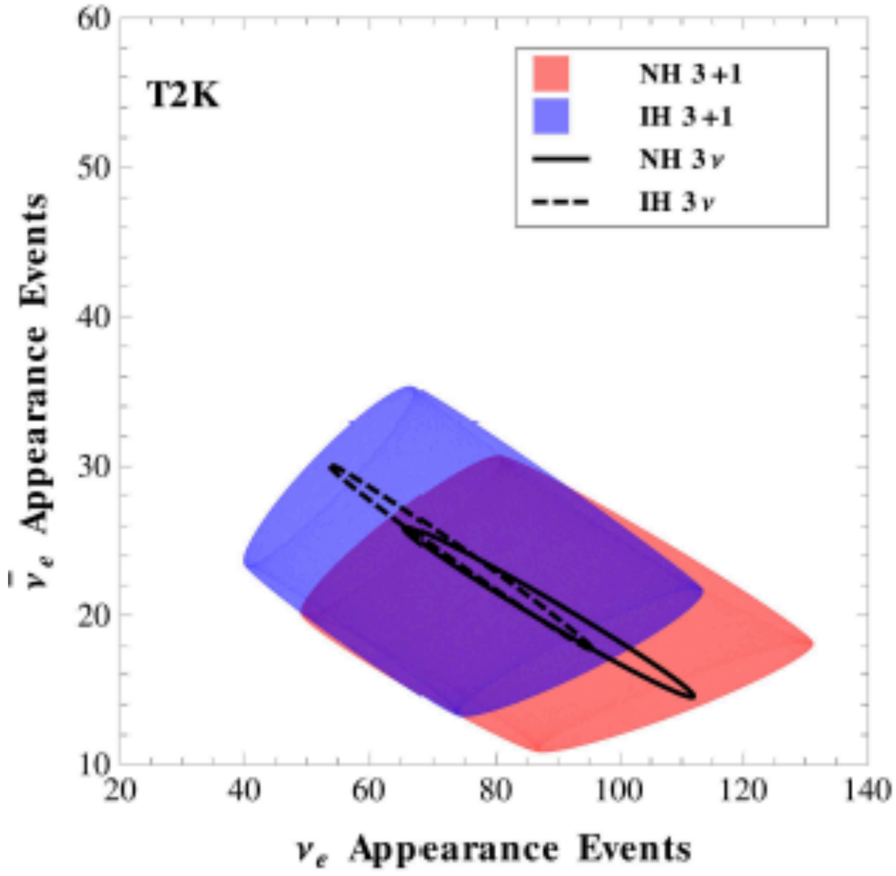
Agarwalla, Chatterjee, Dasgupta, Palazzo (arXiv:1601.05995)

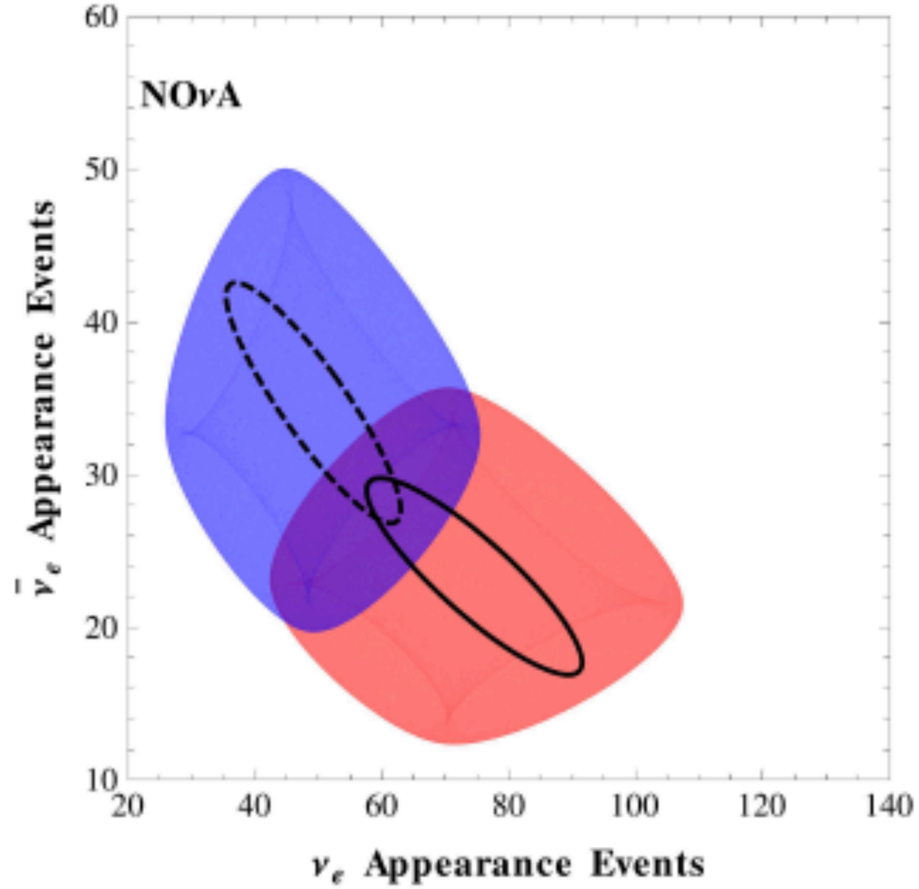
T2K and NOνA Event Spectra



Agarwalla, Chatterjee, Dasgupta, Palazzo (arXiv:1601.05995)

T2K and NOνA Bi-events Plot





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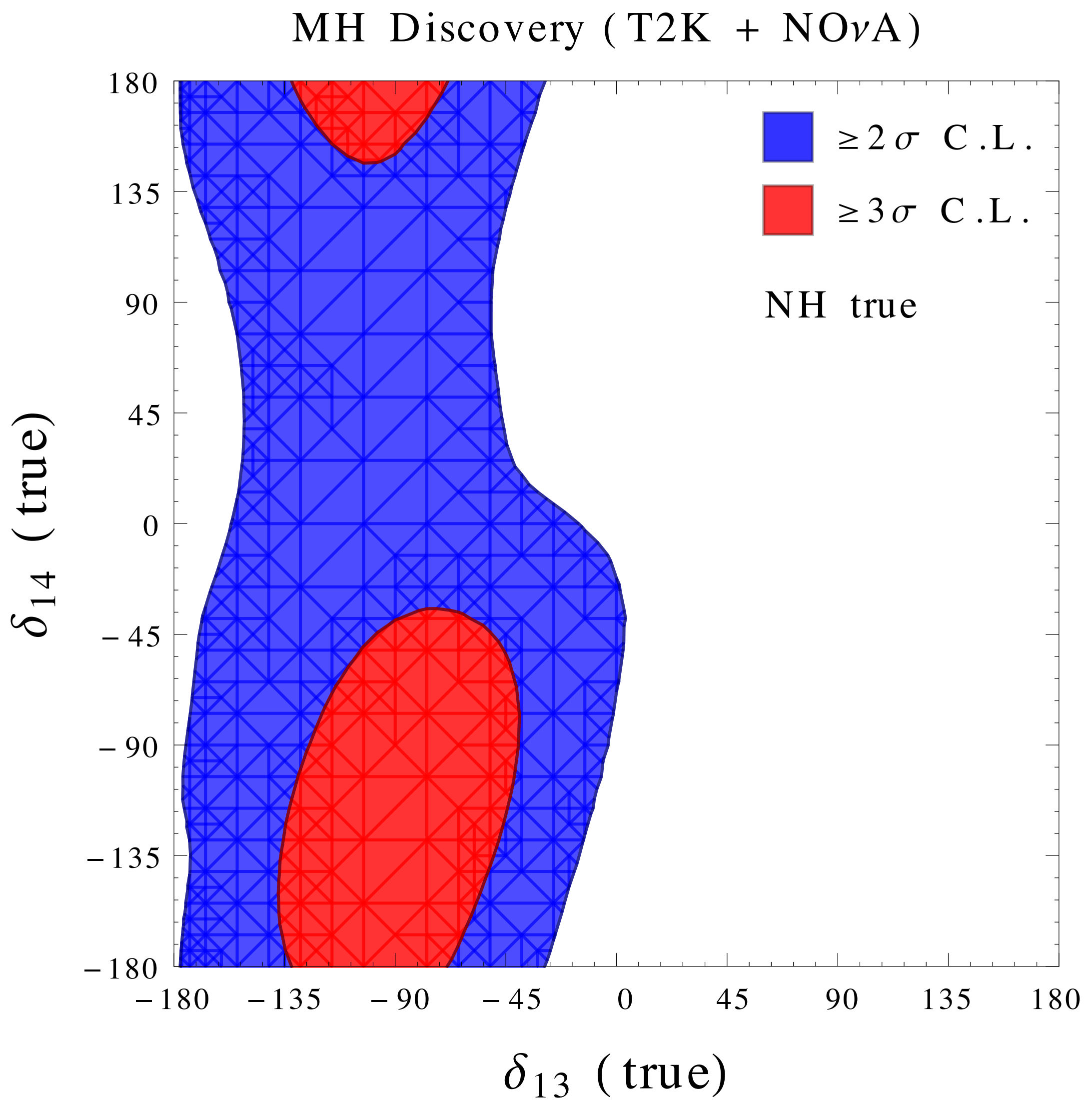
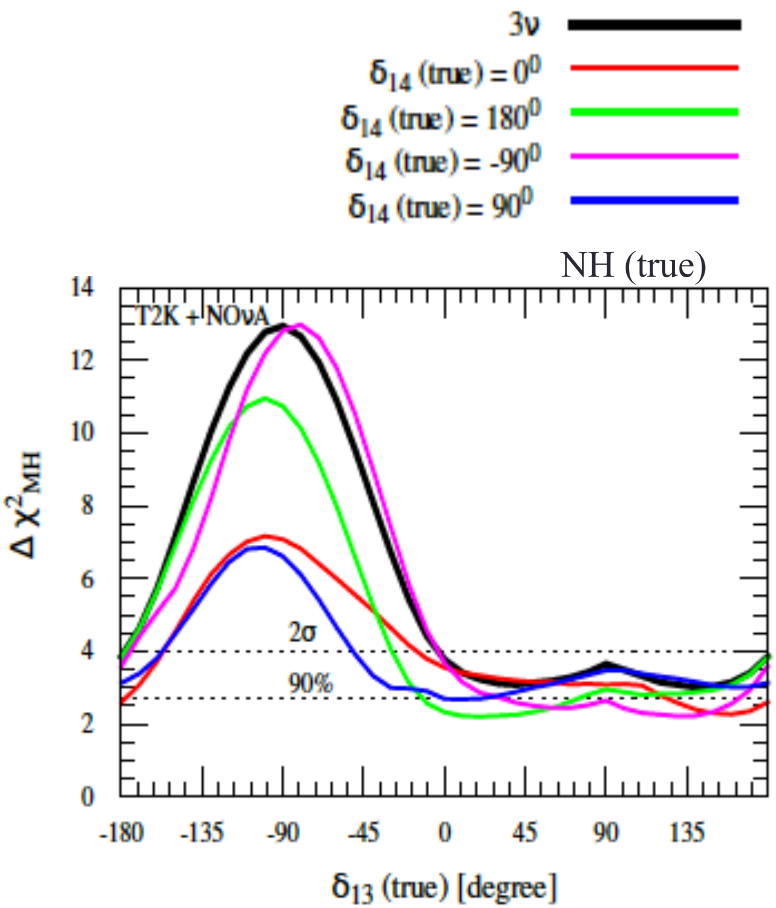
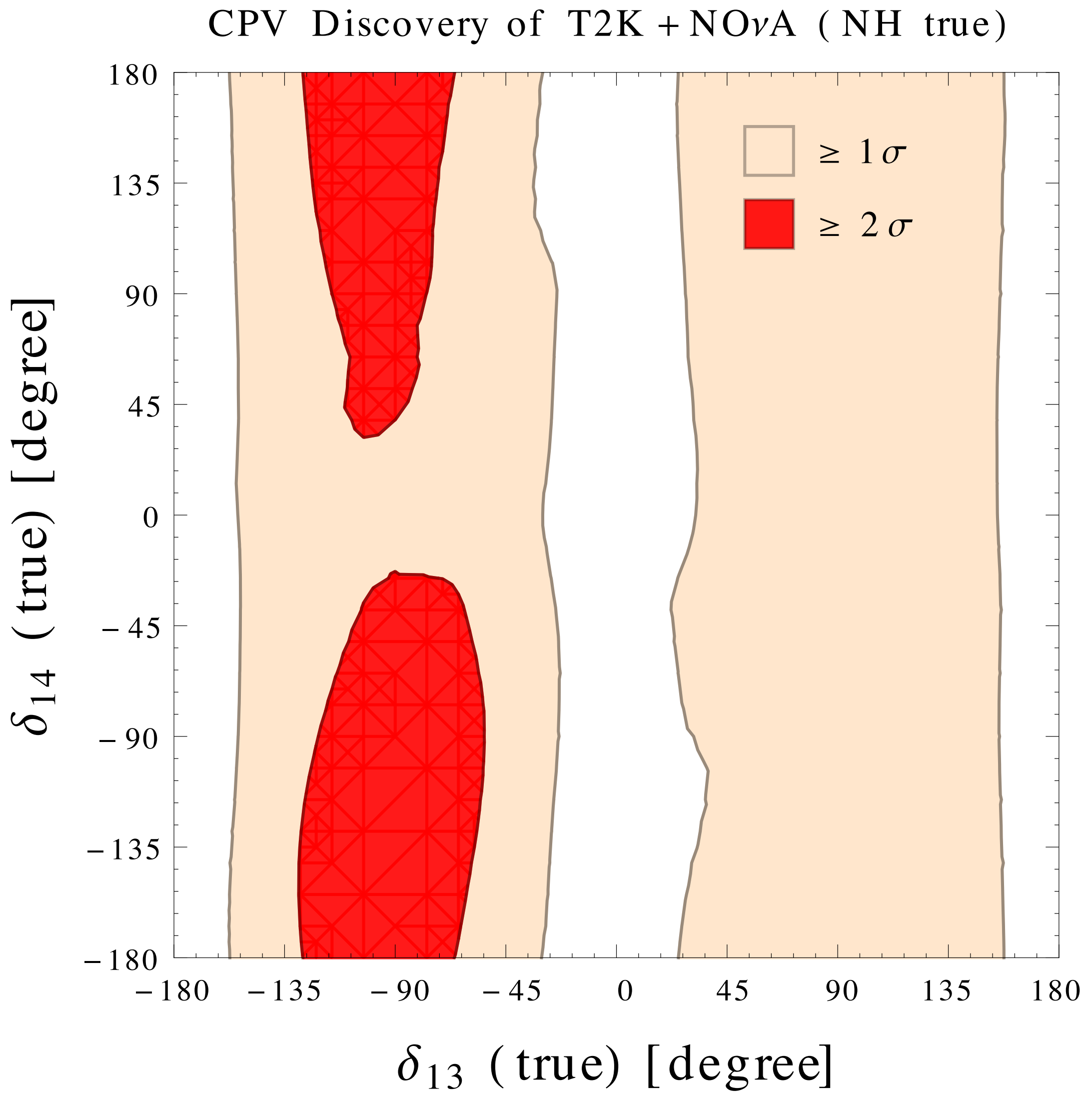
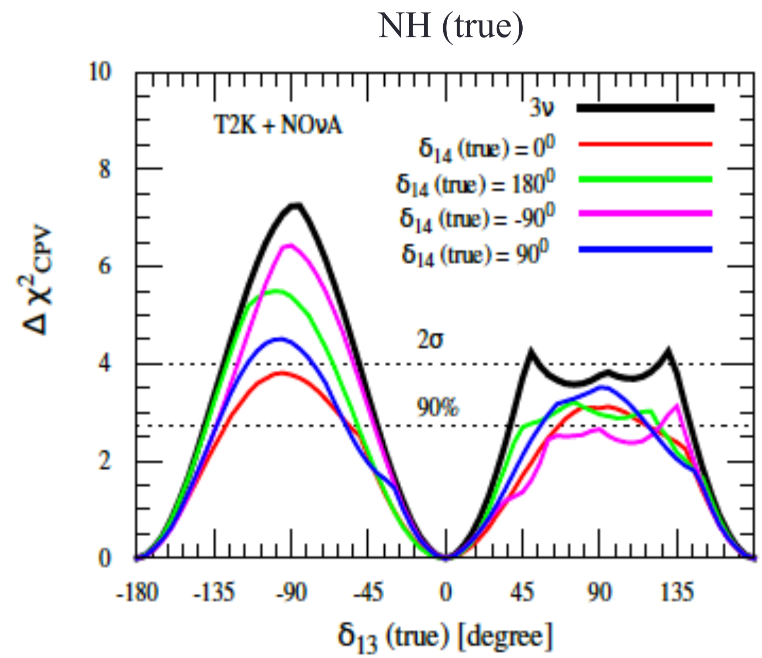




Agarwalla, Chatterjee, Dasgupta, Palazzo (arXiv:1601.05995)

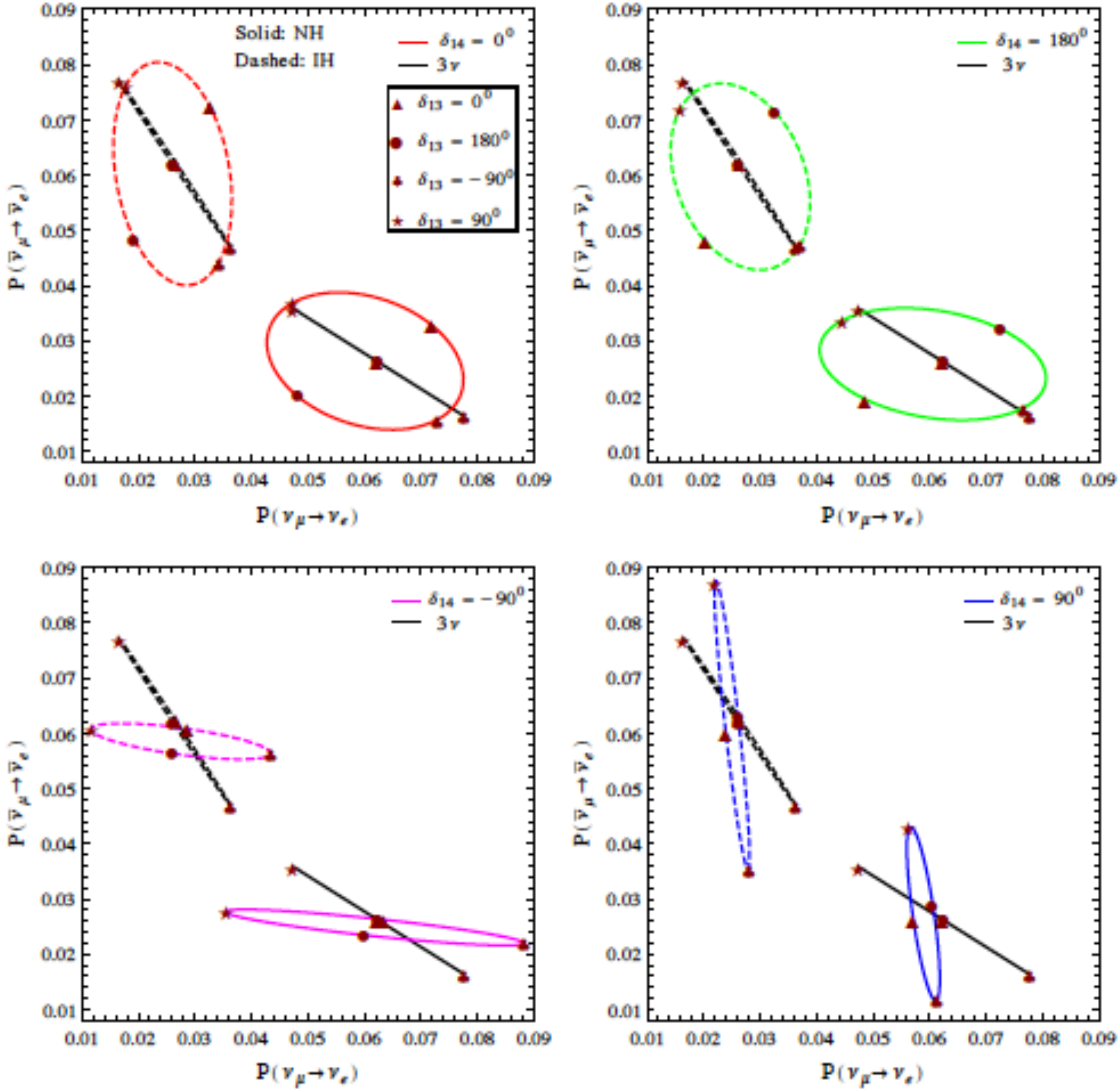
CPV Discovery (T2K+NOνA)





Agarwalla, Chatterjee, Dasgupta, Palazzo (arXiv:1601.05995)

Bi-Probability in DUNE

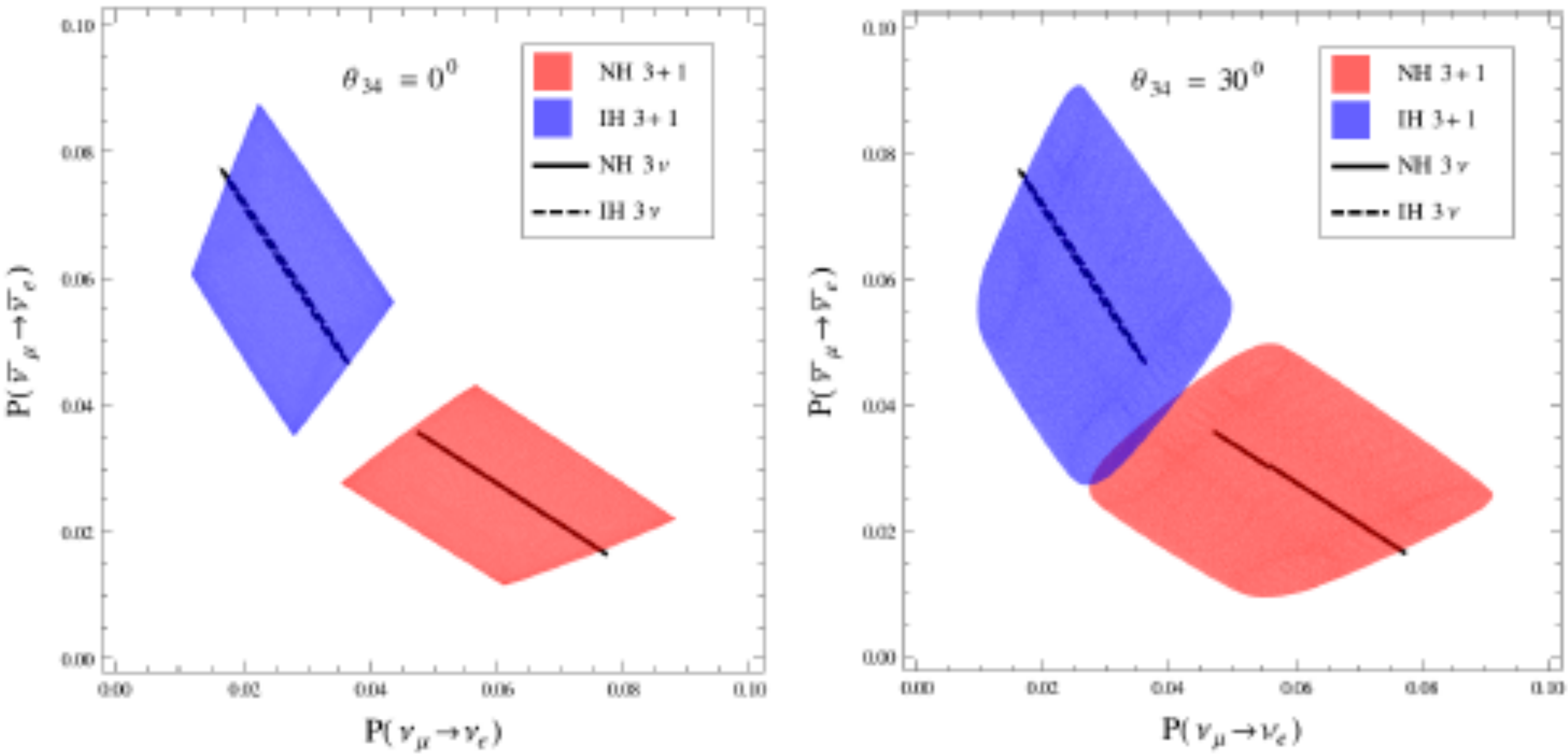


$E = 2.54\,\text{GeV}$

$\theta_{34} = 0$

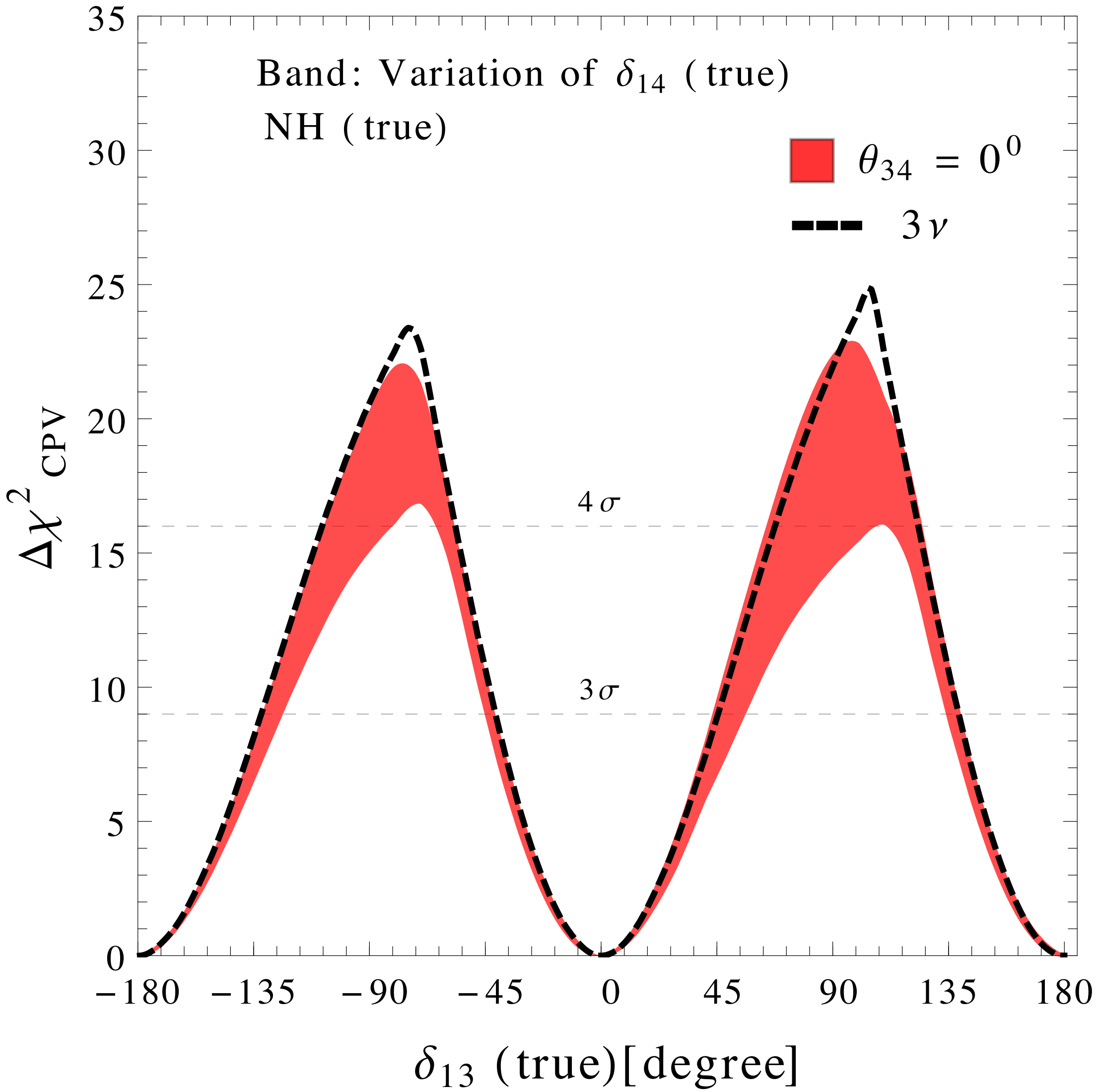
Agarwalla, Chatterjee, Palazzo
(arXiv:1603.03759)

Bi-Probability in DUNE



Agarwalla, Chatterjee, Palazzo
(arXiv:1603.03759)

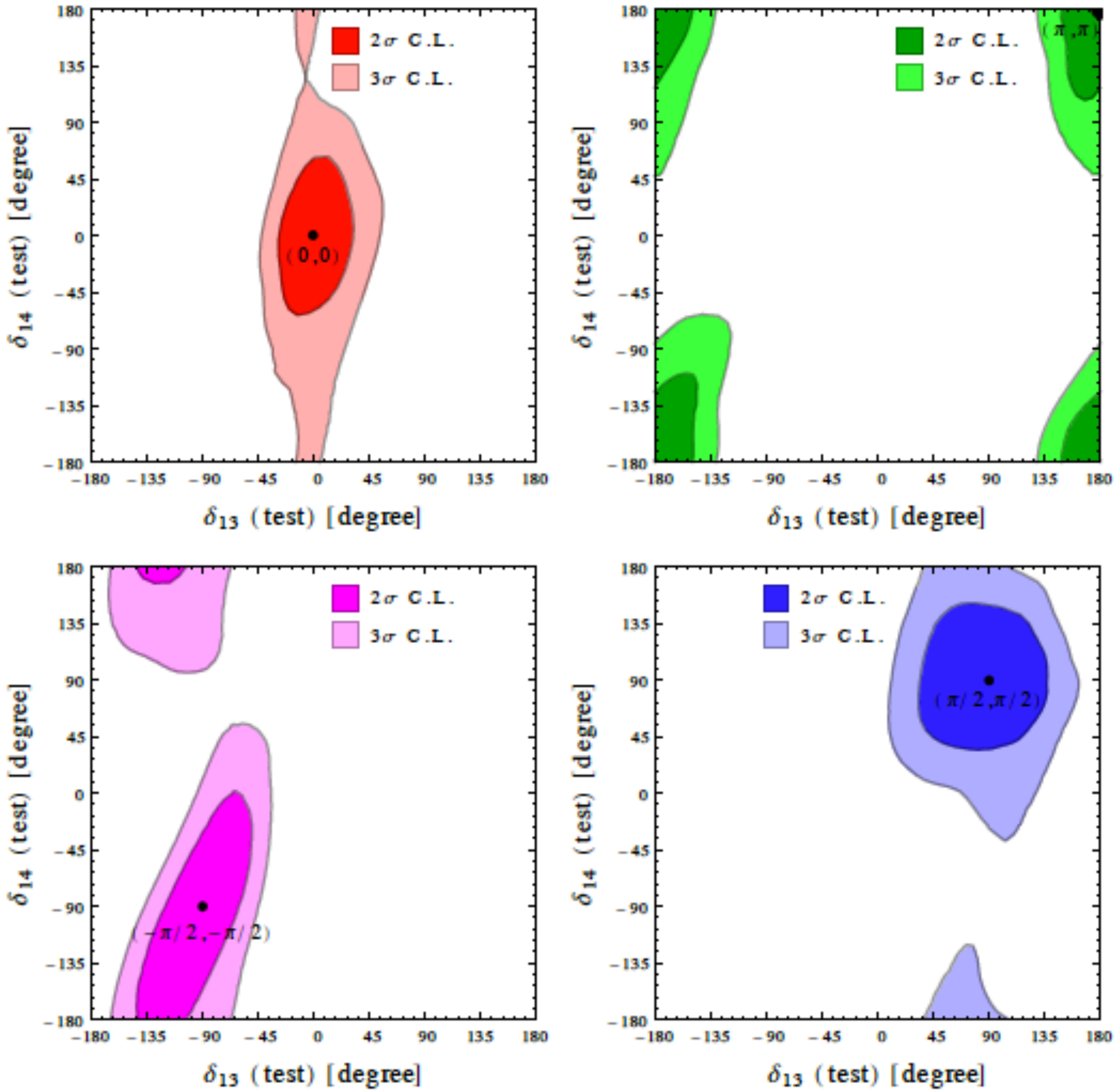
CP-violation Searches at DUNE



Maximal sensitivity decreases from 5σ to 4σ if all the new angles are close to θ_{13}

Agarwalla, Chatterjee, Palazzo (arXiv:1603.03759)

Reconstruction of CP Phase at DUNE



The error on δ_{14} is large if θ_{34} is 30 degree

Agarwalla, Chatterjee, Palazzo
(arXiv:1603.03759)