Status and Prospects of Long-Baseline Neutrino Experiments

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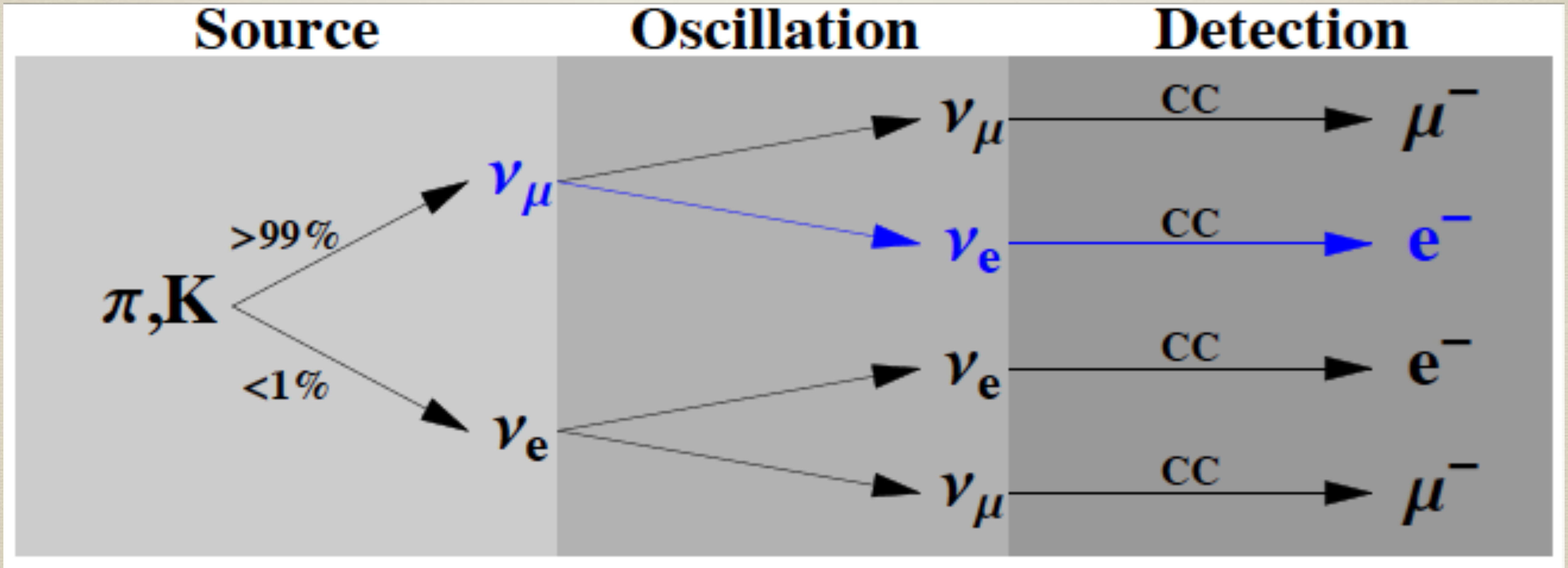
WHEPP XV, IISER BHOPAL

Plan of talk

- Current status of LBL experiments
- Forthcoming LBL experiments
- New physics at LBL experiments
- Breaking of degeneracies at future facilities

Status of LBL Expts

Accelerator Beams



Neutrino Oscillations

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

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

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

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

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

Resolves octant

Sanjib Agarwal's talk

where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \cos\theta_{13} \sin 2\theta_{21} \sin 2\theta_{23}$,

and $\hat{A} \equiv \pm(2\sqrt{2} G_F n_e E)/\Delta m^2_{31}$

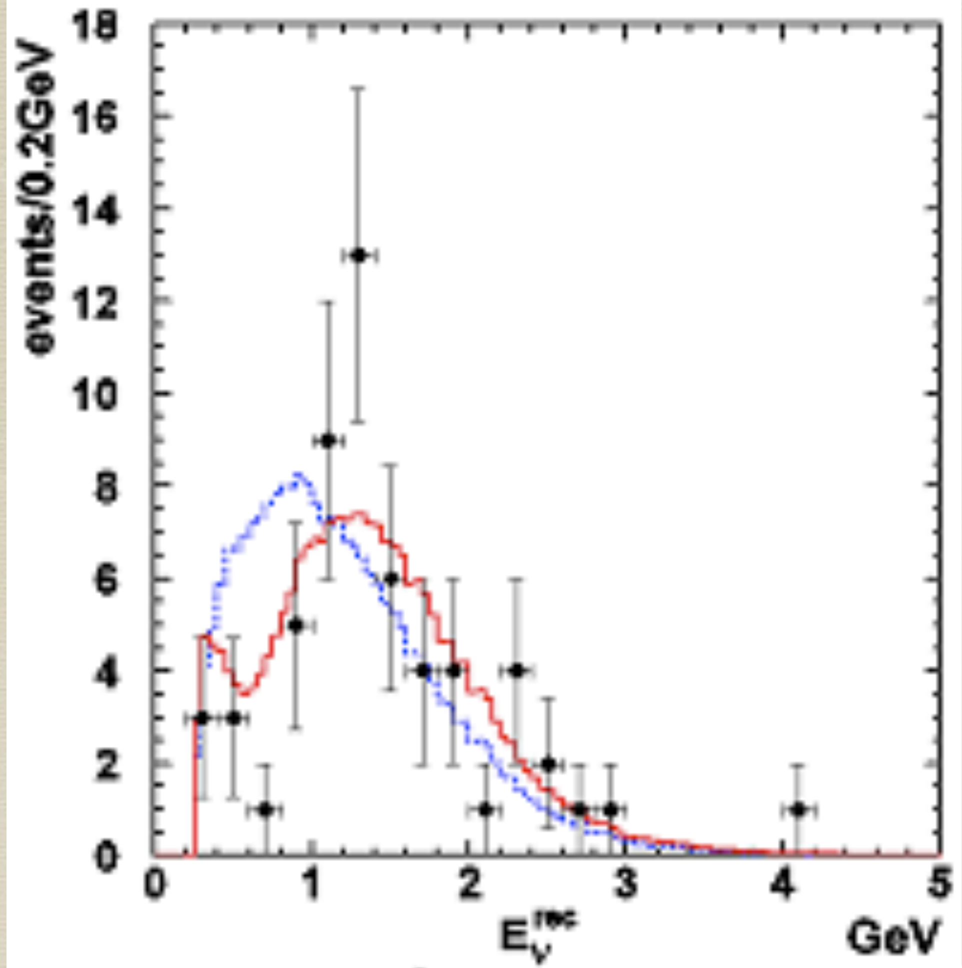
changes sign with sgn(Δm^2_{31})
key to resolve hierarchy!

changes sign with polarity
causes fake CP asymmetry!

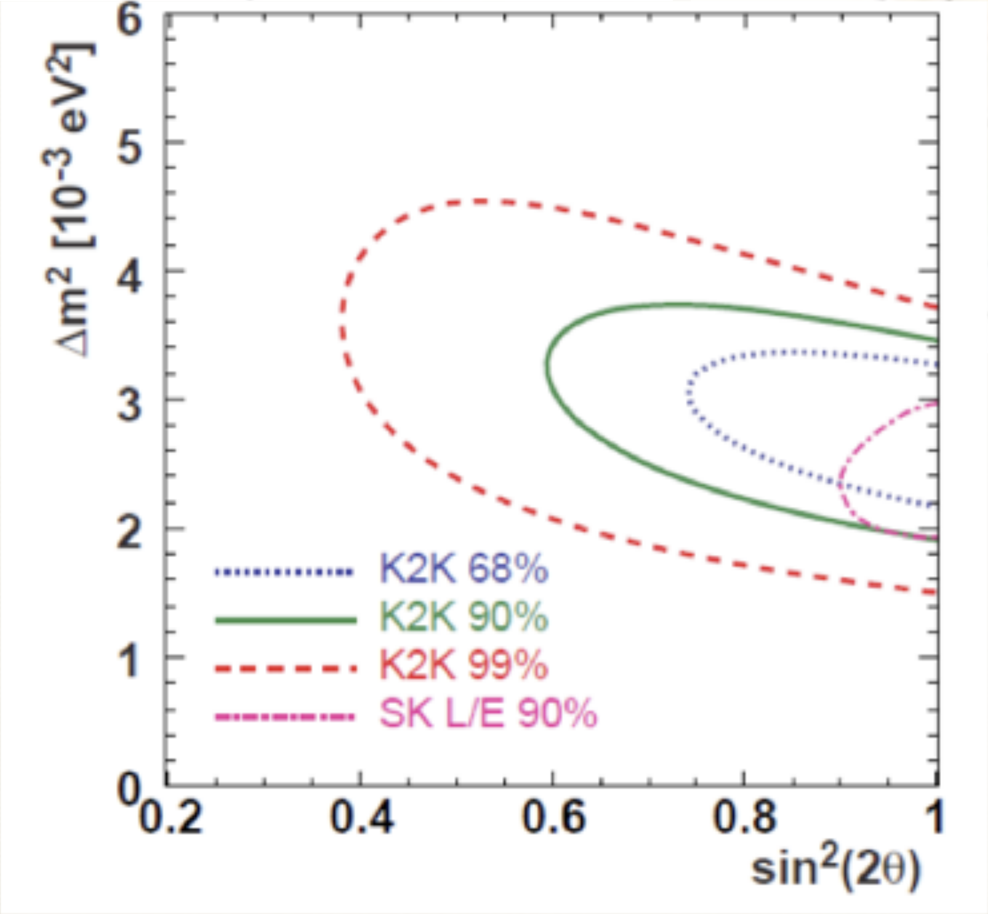
Cervera etal., hep-ph/0002108
Freund etal., hep-ph/0105071
See also, Agarwalla etal., arXiv:1302.6773 [hep-ph]

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

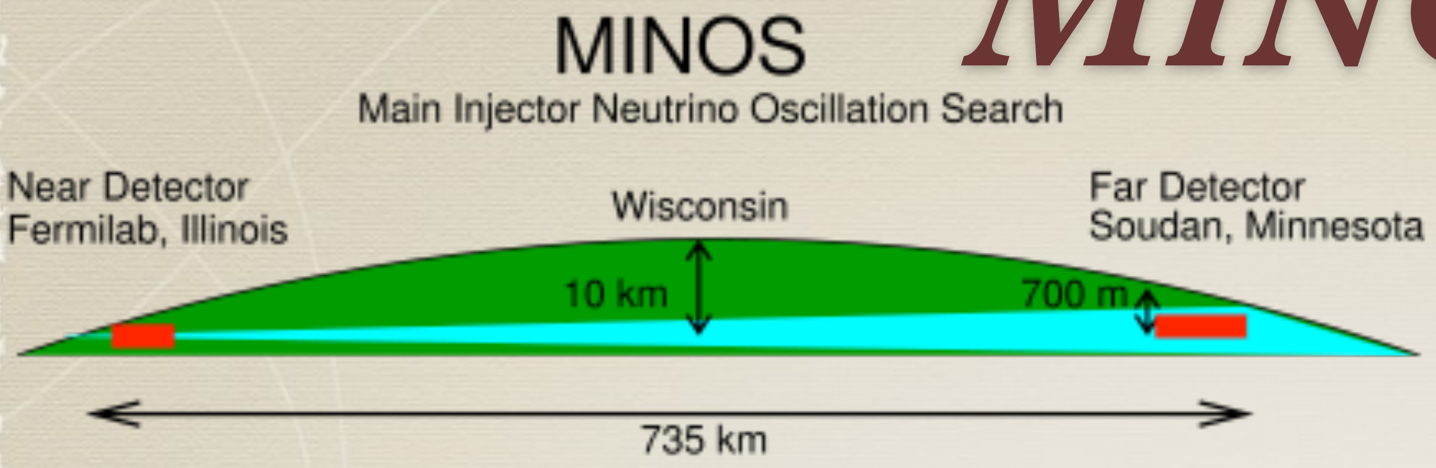
K2K

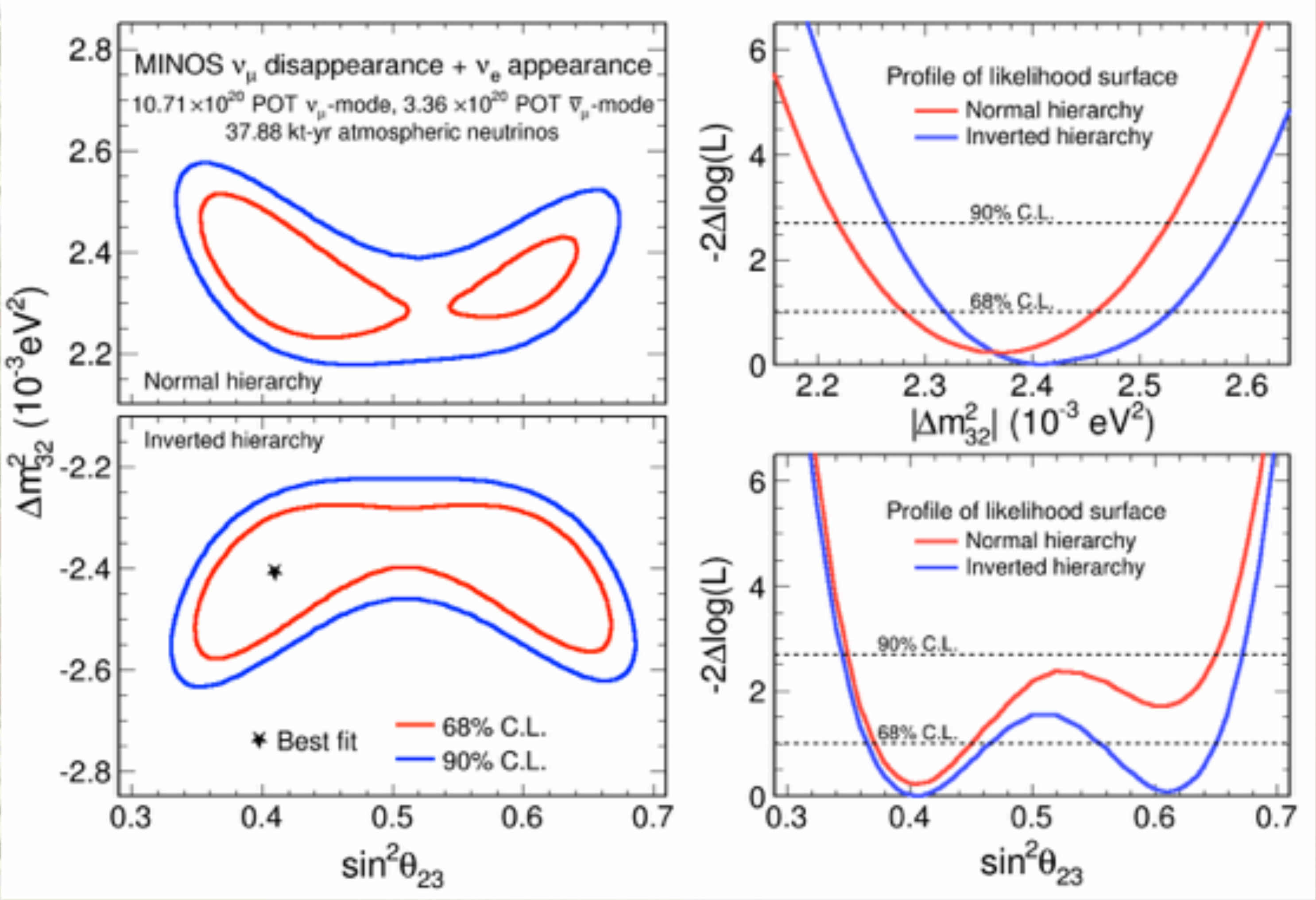

events/0.2GeV
18
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
E_ν^{rec}
GeV


Super Kamiokande
(Kamioka cho)
Ibaraki
Prefecture
Gifu
Prefecture
K E K
(Tsukuba City)
Proton
Synchrotron
Front
Detector

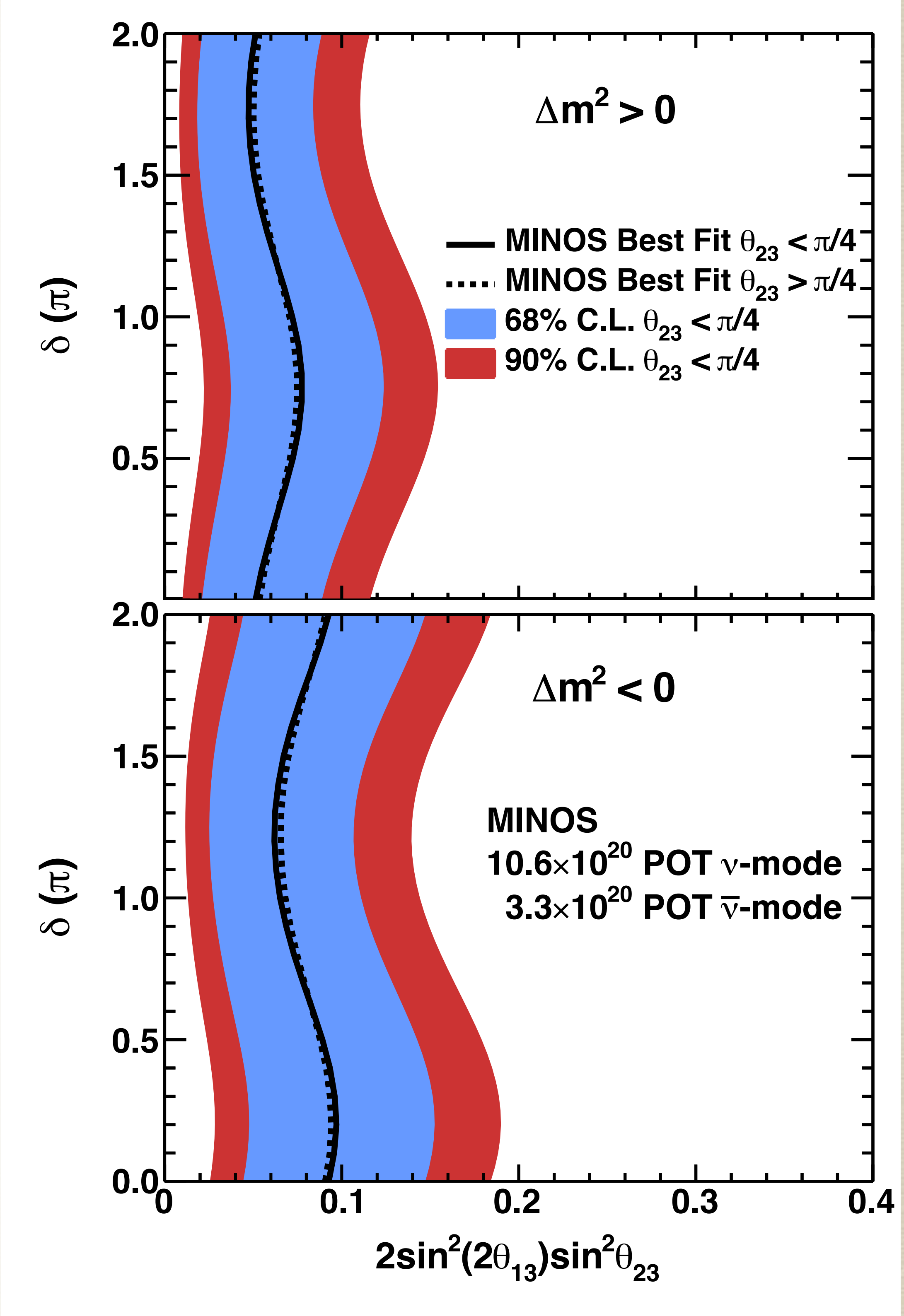

Δm^2 [10^{-3} eV^2]
6
5
4
3
2
1
0
0.2
0.4
0.6
0.8
1
$\sin^2(2\theta)$
K2K 68%
K2K 90%
K2K 99%
SK L/E 90%

MINOS



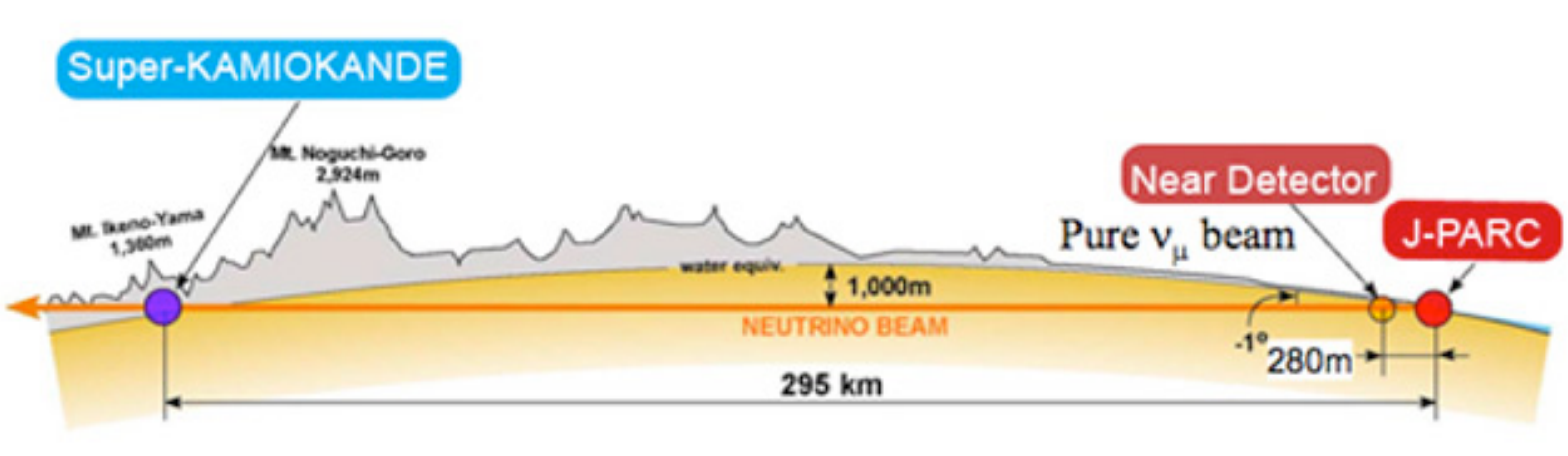


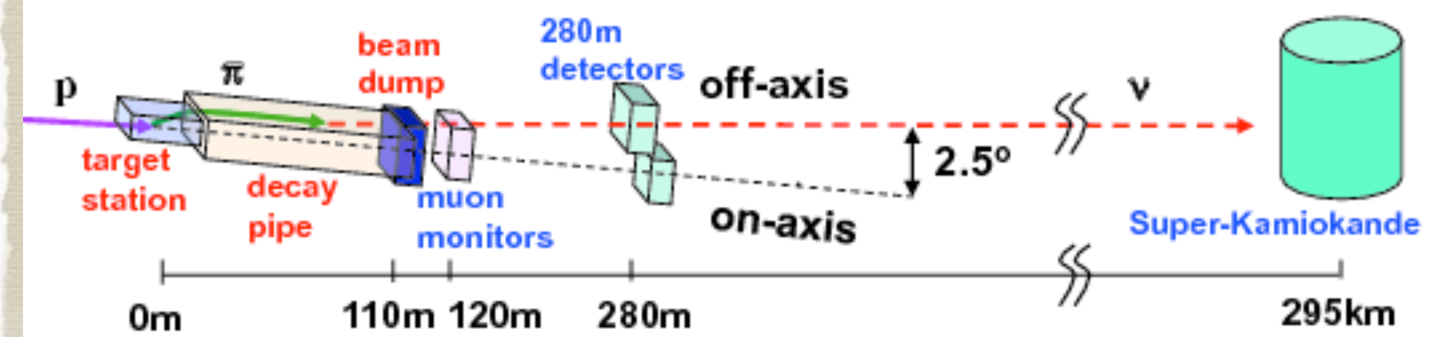
MINOS, PRL 112, 191801, 2014

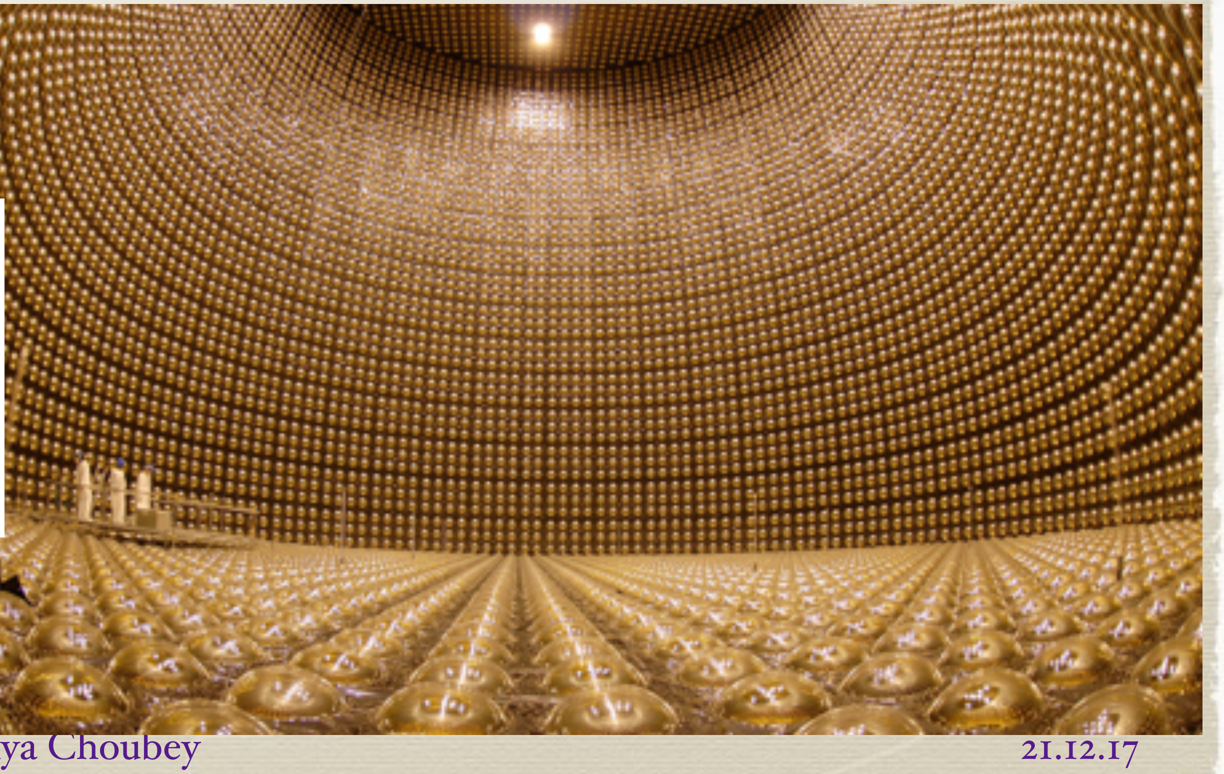


MINOS, PRL 110.171801, 2013

T2K

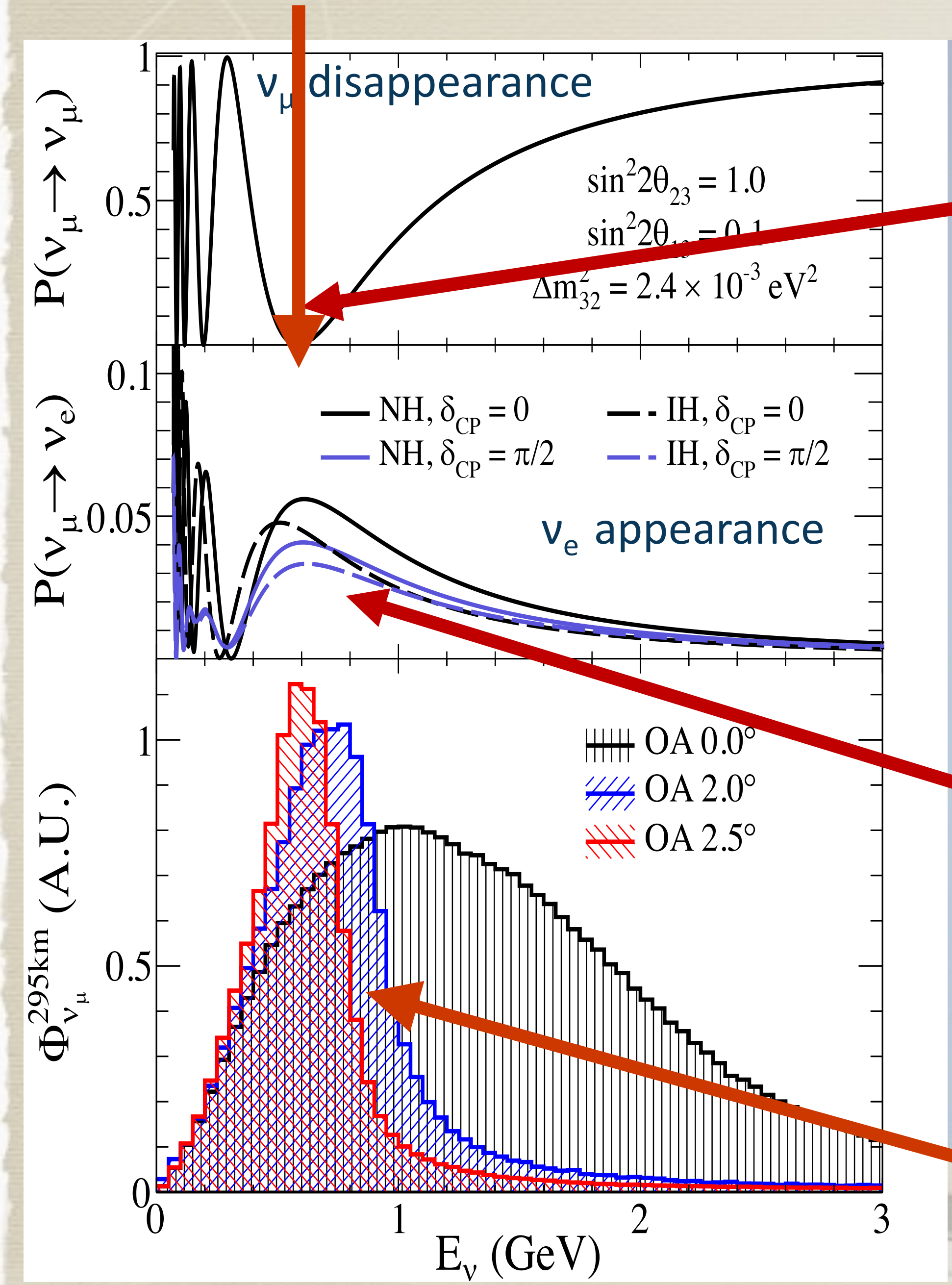

Super-KAMIOKANDE
Mt. Noguchi-Goro
2,924m
Mt. Ikeno-Yama
1,360m
Near Detector
Pure ν_μ beam
J-PARC
water equiv.
1,000m
NEUTRINO BEAM
-1°
280m
295 km


p
π
beam
dump
280m
detectors
off-axis
ν
target
station
decay
pipe
muon
monitors
2.5°
on-axis
Super-Kamiokande
0m
110m
120m
280m
295km



T2K

0.6 GeV



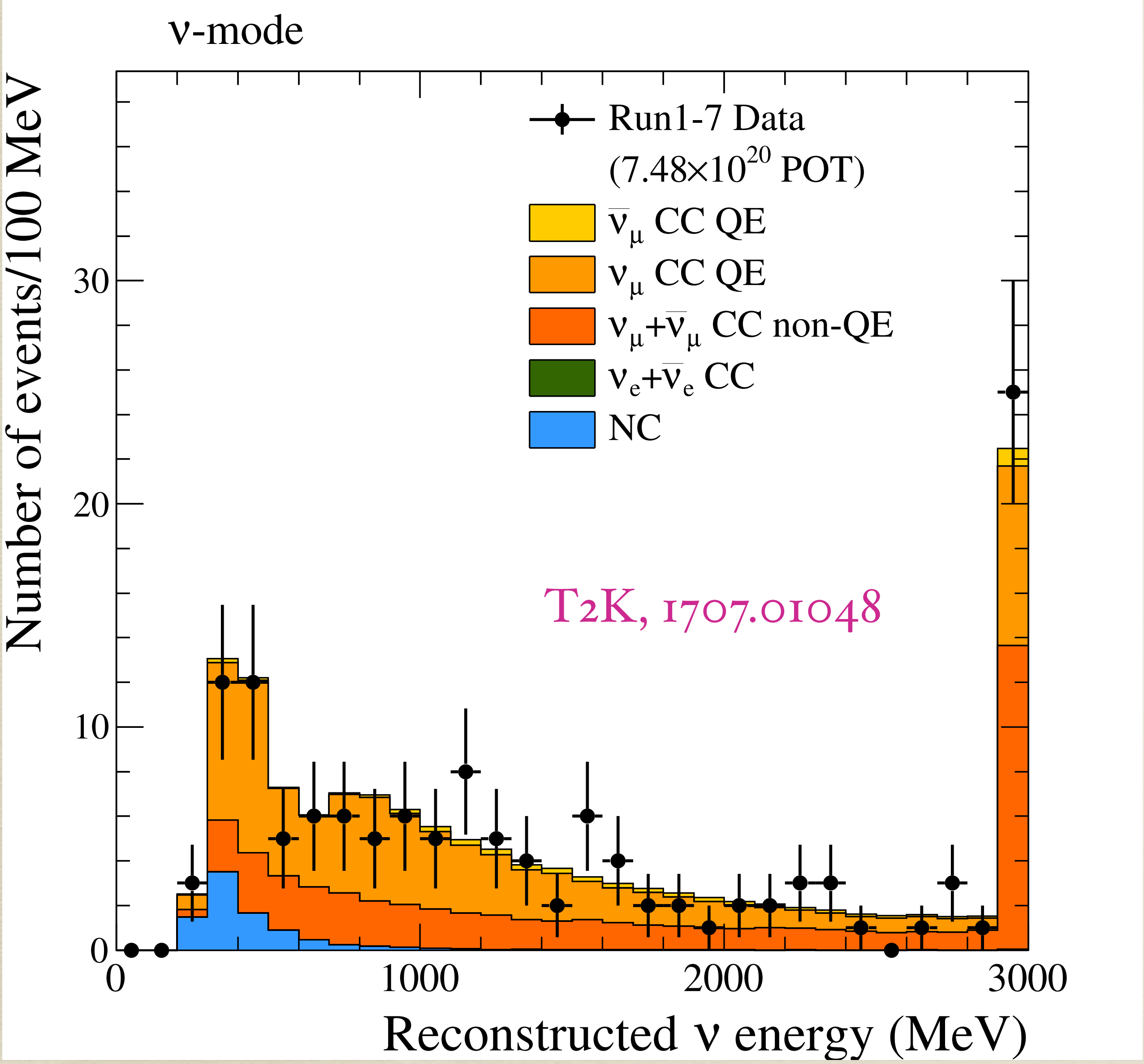
- Muon (anti)neutrino disappearance
  - Location of dip determined by Δm^2_{23} **Measures**
  - Depth of dip determined by $\sin^2(2\theta_{23})$ **Measures**
- Electron (anti)neutrino appearance
  - Leading term depends on $\sin^2(\theta_{23})$, $\sin^2(\theta_{13})$ and Δm^2_{23} **Measures**
  - Sub-leading dependance on δ_{CP}
    - $\delta_{CP} = \pi/2$: fewer neutrinos, more anti-neutrinos
    - $\delta_{CP} = -\pi/2$: more neutrinos, fewer anti-neutrinos **Measures**
  - Matter effects give dependence on mass hierarchy

(Not much)

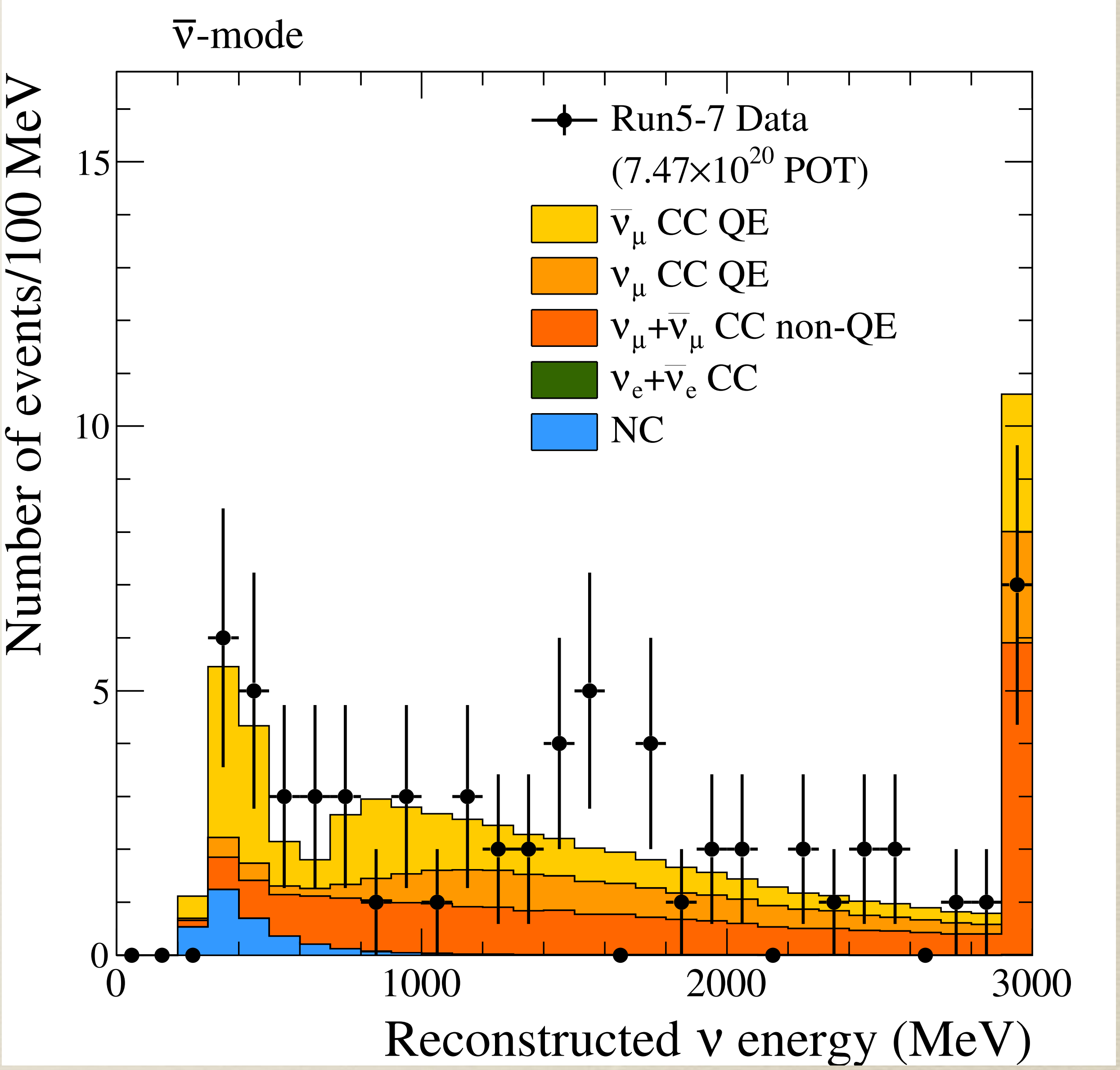
Off-axis beam used to reduce backgrounds
Peaked at 0.6 GeV

Adapted from slide by P. Dunne, talk at NuFact 2017

T2K Disappearance Data

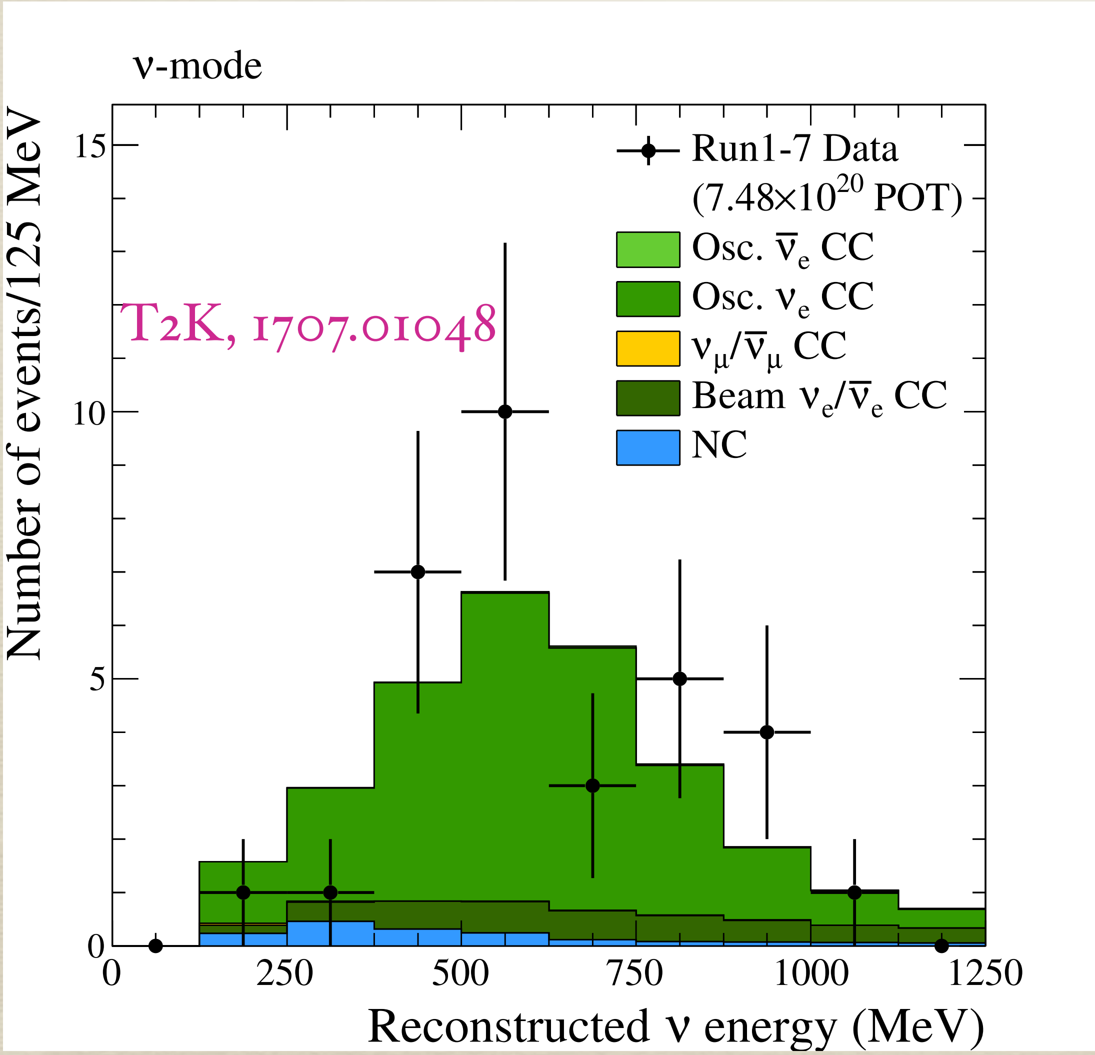


T2K, 1707.01048

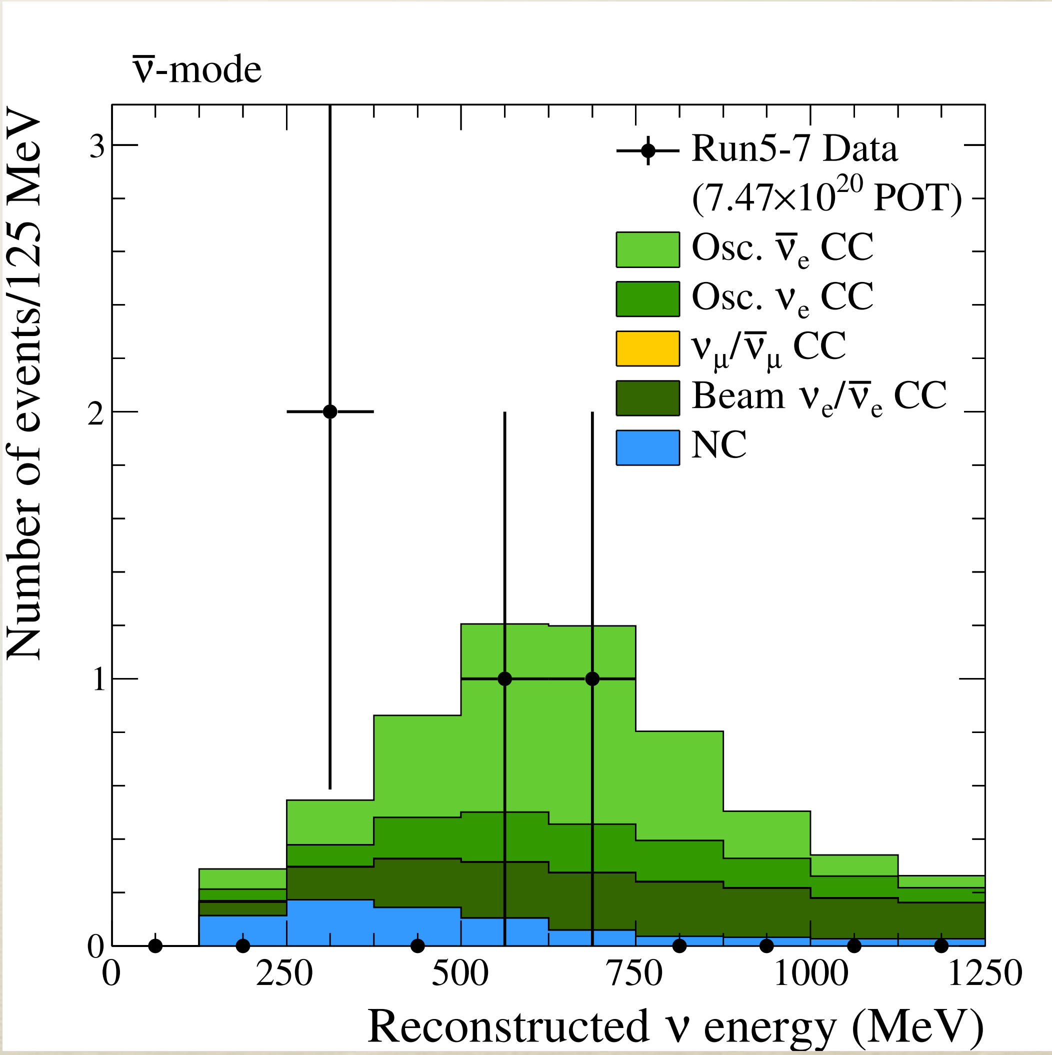


T2K Appearance Data

Sample	Predicted Rates				Observed Rates
	δ_{CP} = -π/2	δ_{CP} = 0	δ_{CP} = π/2	δ_{CP} = π	
CCQE 1-Ring e-like ν-mode	73.5	61.5	49.9	62.0	74
CC1π 1-Ring e-like ν-mode	6.92	6.01	4.87	5.78	15
CCQE 1-Ring e-like $\bar{\nu}$-mode	7.93	9.04	10.04	8.93	7

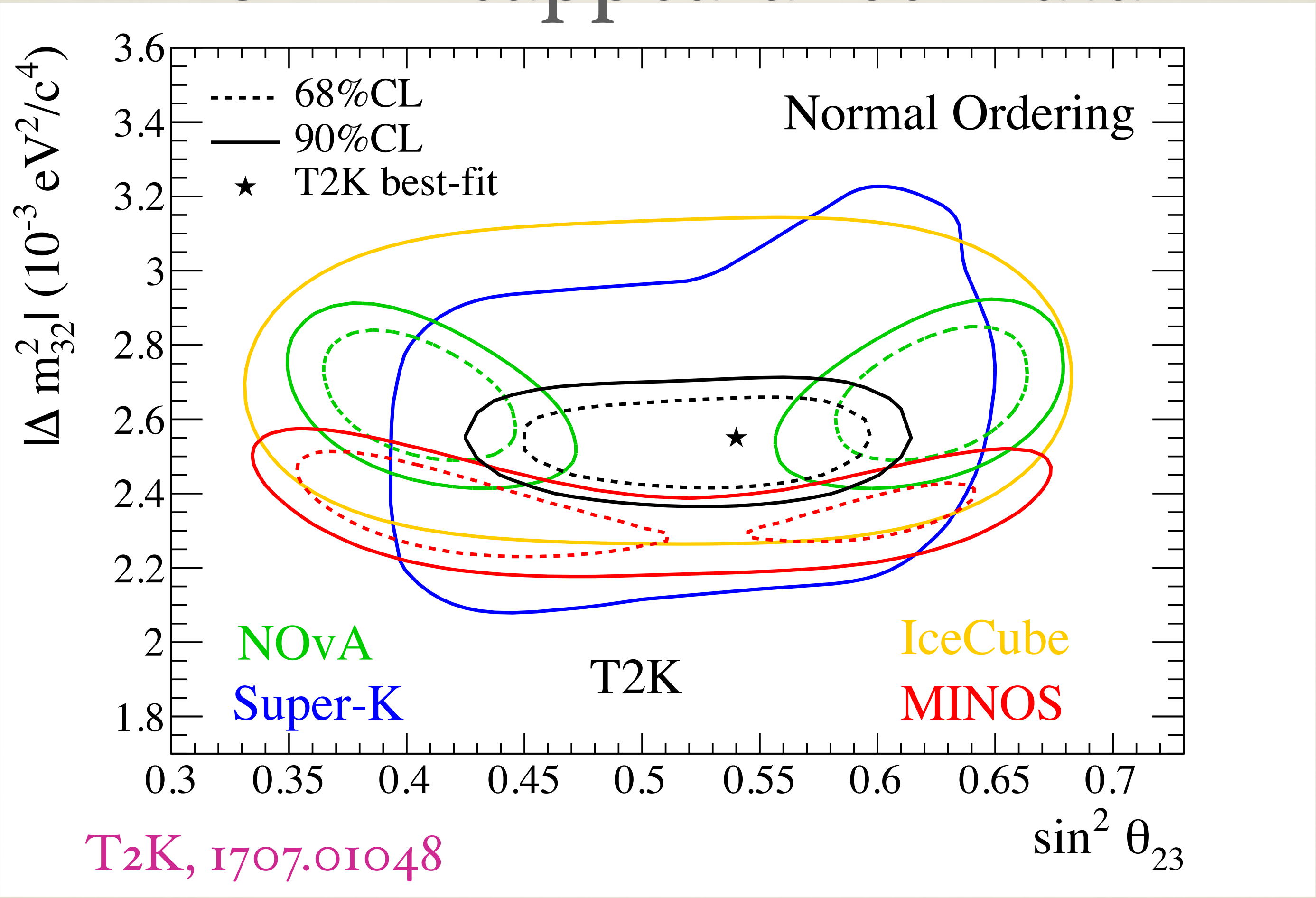


T2K, 1707.01048



Constraints on Oscillation Parameters

From Disappearance Data

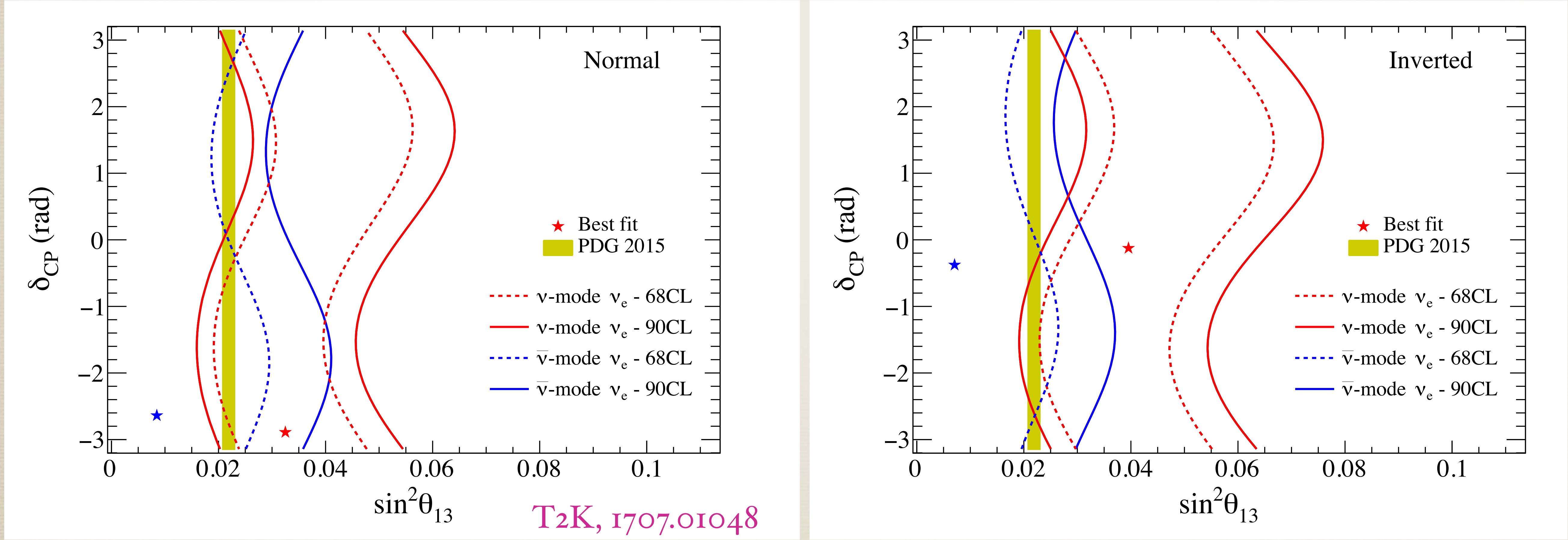


T2K, 1707.01048

FIG. 40. Allowed region at 90% confidence level for oscillation parameters $\sin^2\theta_{23}$ and Δm^2_{32} using T2K data with the reactor constraint $(\sin^2(2\theta_{13}) = 0.085 \pm 0.005)$. The normal mass ordering is assumed and the T2K results are compared with NOνA [86], MINOS [87], Super-K [88], and IceCube [89].

Constraints on Oscillation Parameters

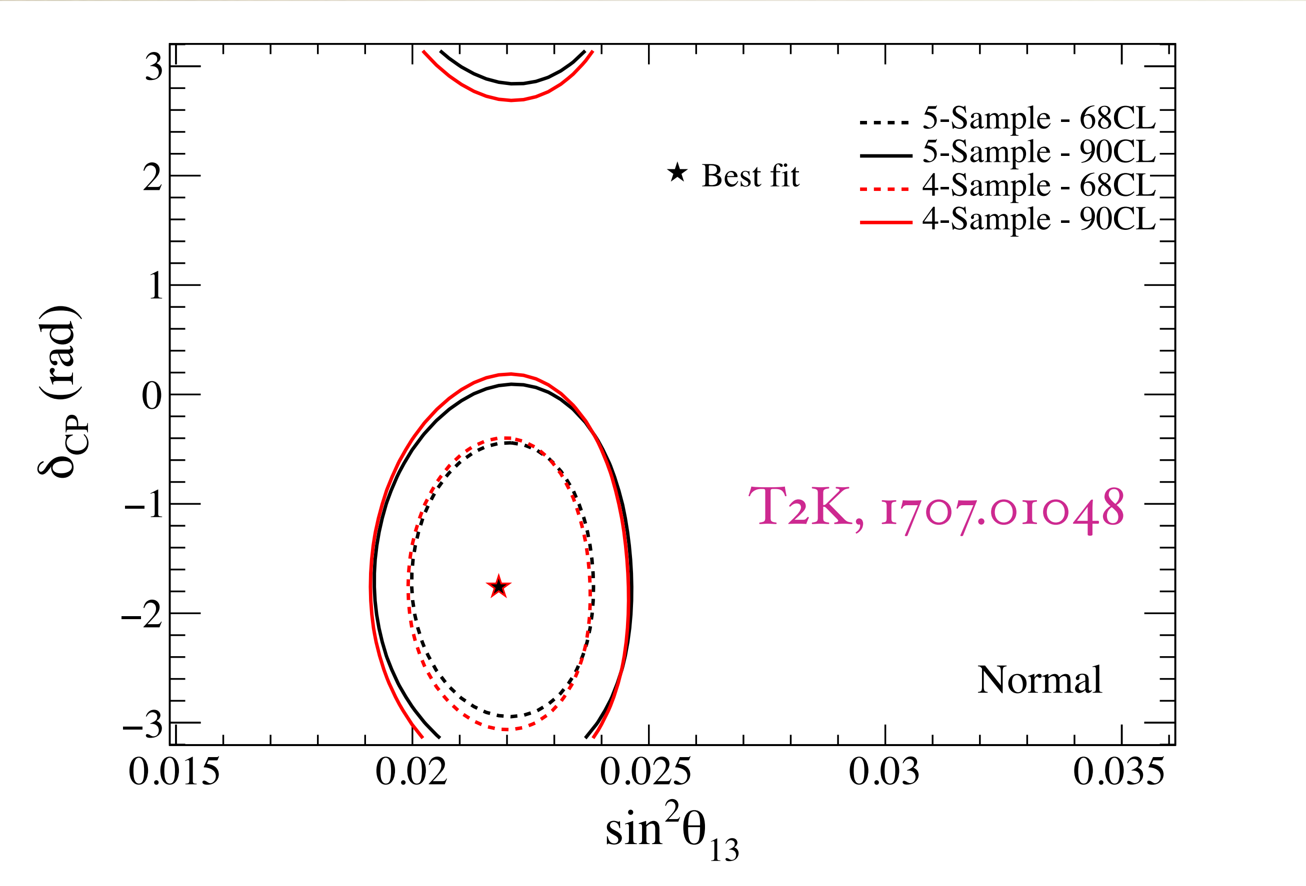
From Appearance Data



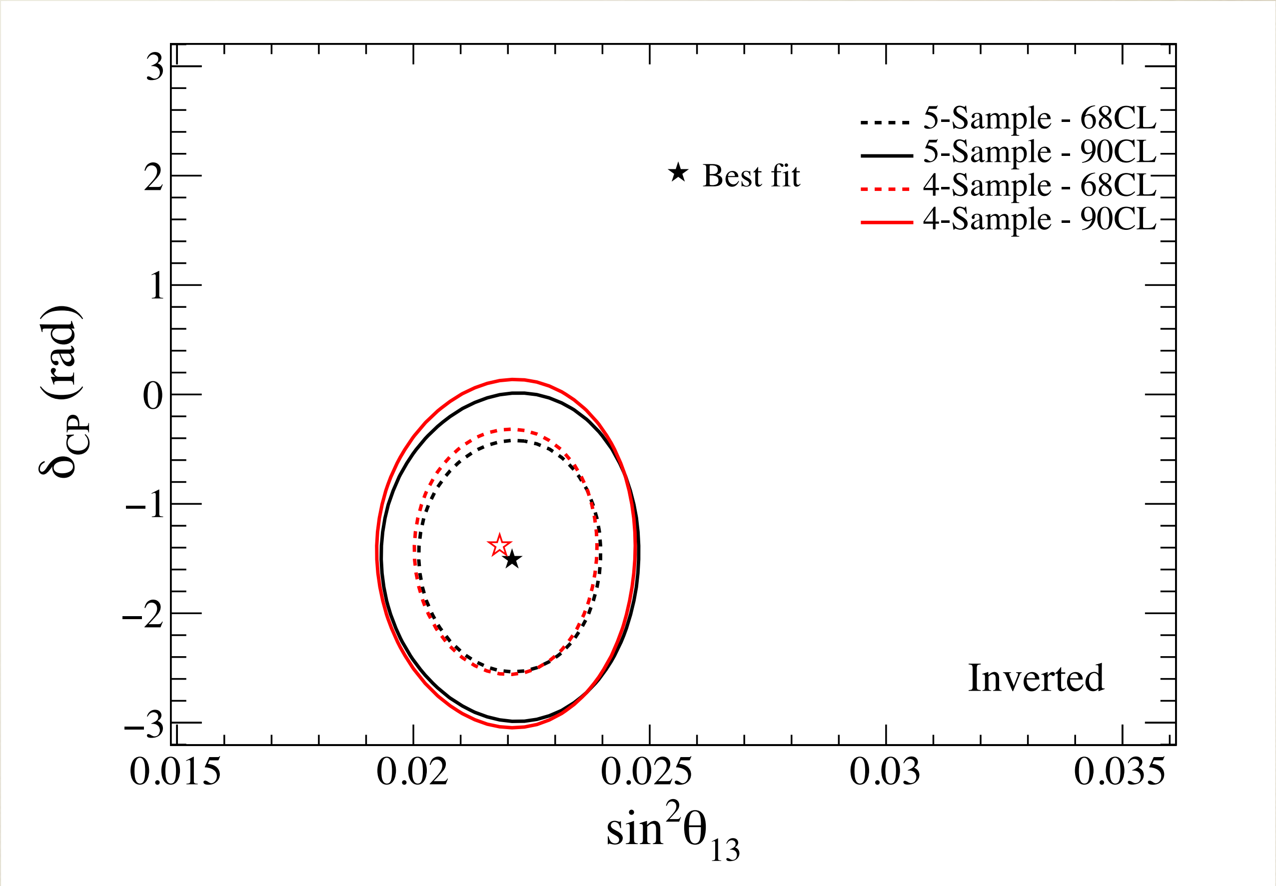
T2K, 1707.01048

Constraints on Oscillation Parameters

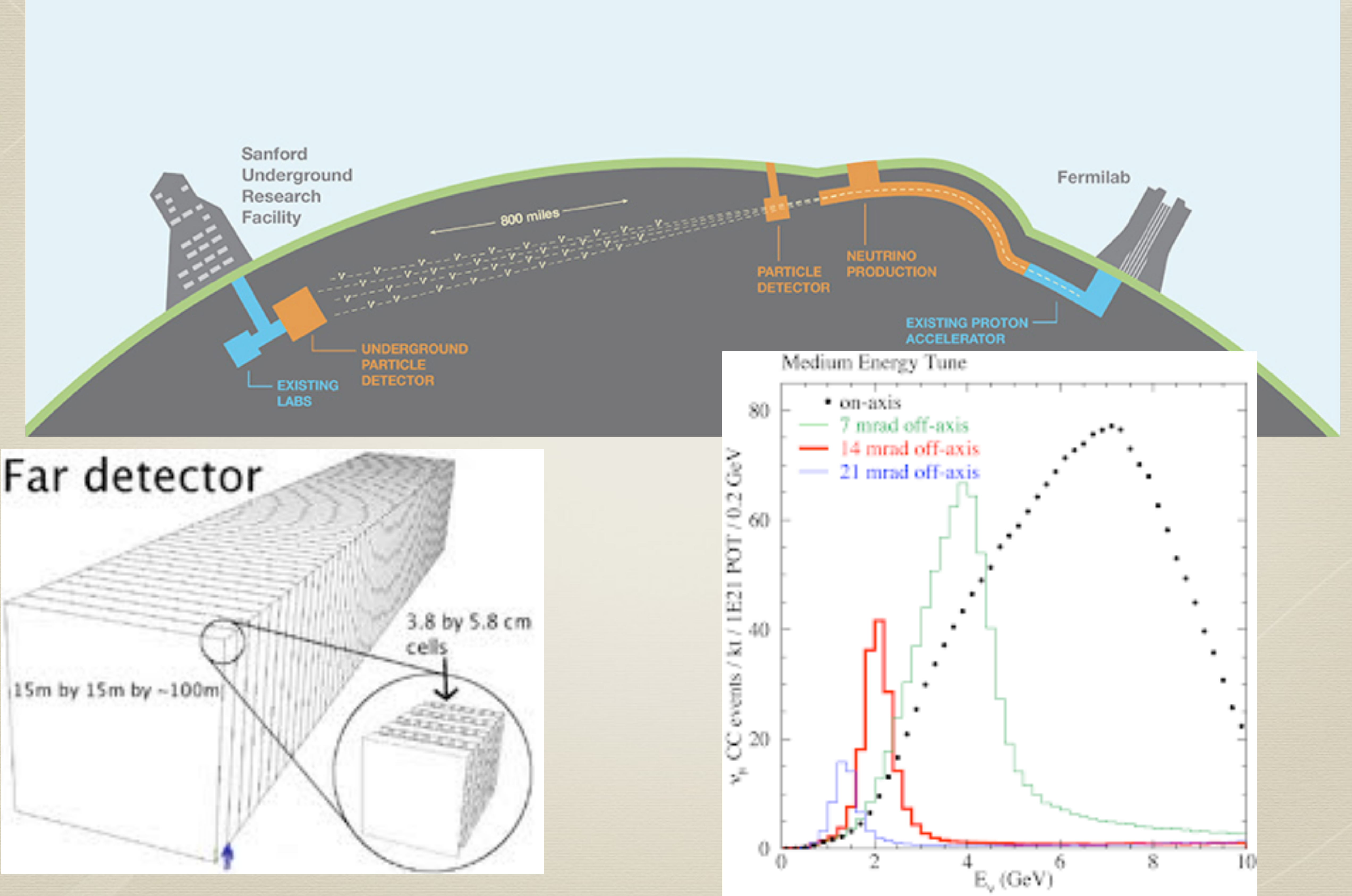
From T2K appearance Data and Daya Bay



T2K, 1707.01048

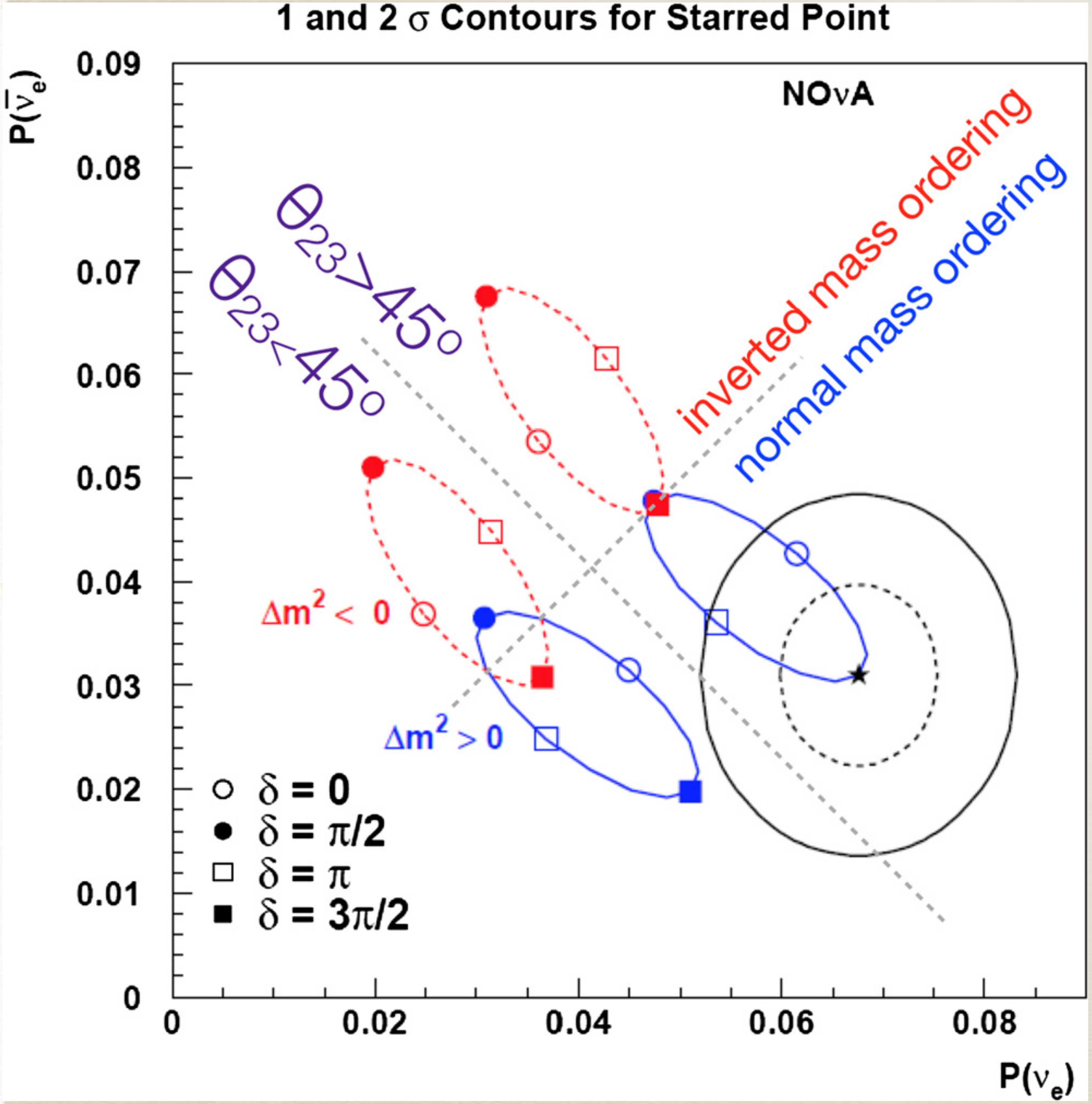


NOνA


Sanford Underground Research Facility
800 miles
Fermilab
PARTICLE DETECTOR
NEUTRINO PRODUCTION
EXISTING PROTON ACCELERATOR
UNDERGROUND PARTICLE DETECTOR
EXISTING LABS
Far detector
3.8 by 5.8 cm cells
15m by 15m by ~100m
Medium Energy Tune
on-axis
7 mrad off-axis
14 mrad off-axis
21 mrad off-axis
ν_μ CC events / kt / 1E21 POT / 0.2 GeV
E_ν (GeV)
0
20
40
60
80
0
2
4
6
8
10

What can NOνA do?

M.D. Messier / Nuclear Physics B 908 (2016) 151–160



From Disappearance Data

Can measure

Can measure

From Appearance Data

Can measure

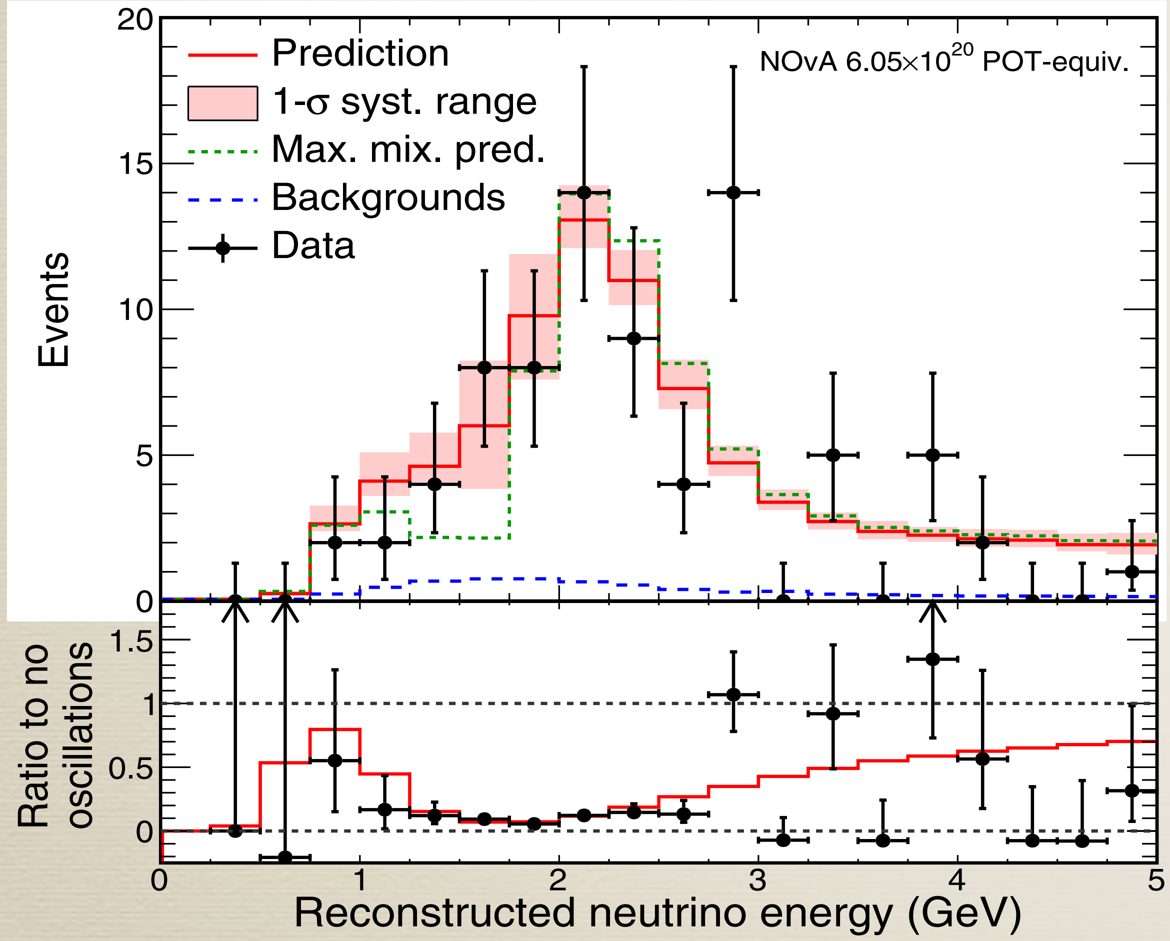
Can measure

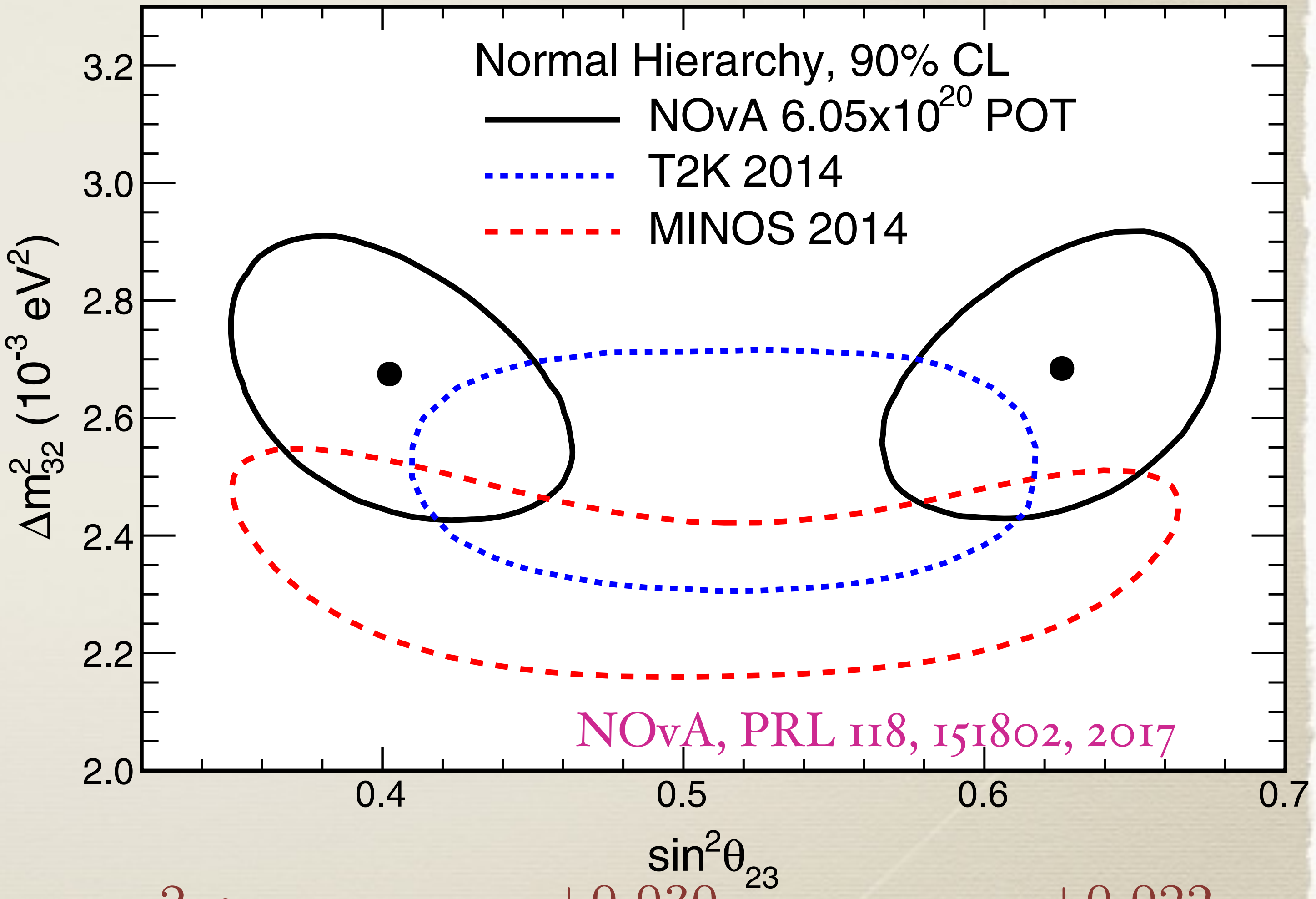
Can measure octant of

Can measure nu mass hierarchy

Constraints on Oscillation Parameters

From Disappearance Data





NOvA, PRL 118, 151802, 2017

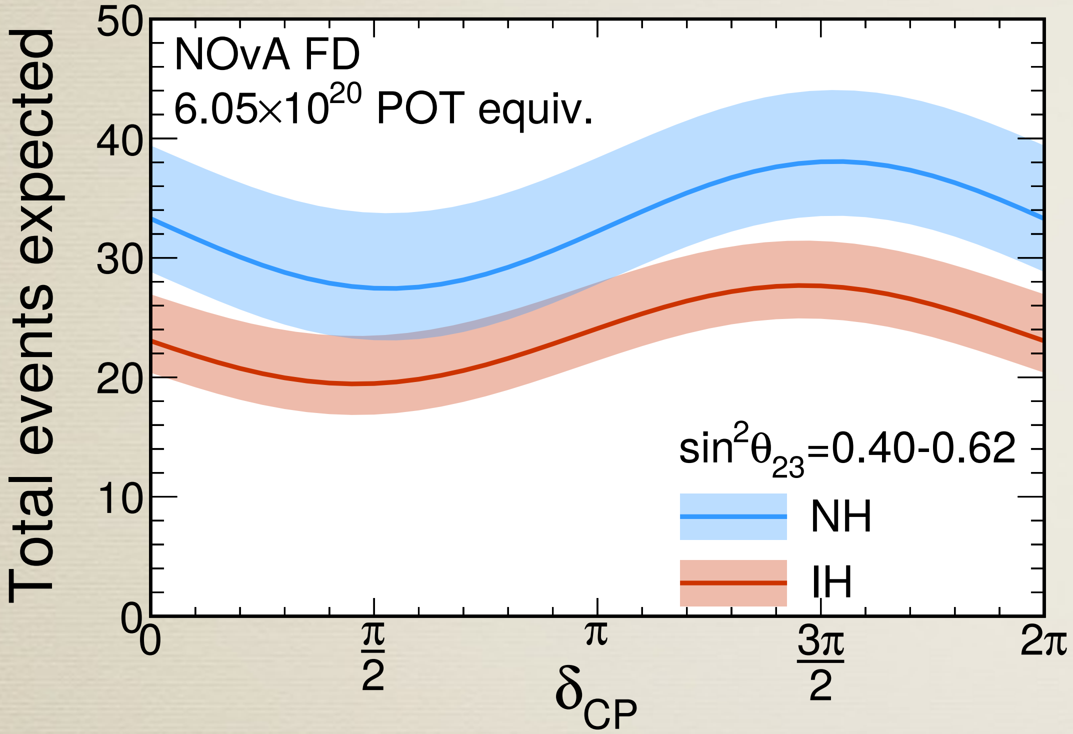
$$\Delta m^2_{32} = (2.67 \pm 0.11) \times 10^{-3} eV^2, \ \ \sin^2\theta_{23} = 0.404^{+0.030}_{-0.022} \text{ and } 0.624^{+0.022}_{0.030}$$

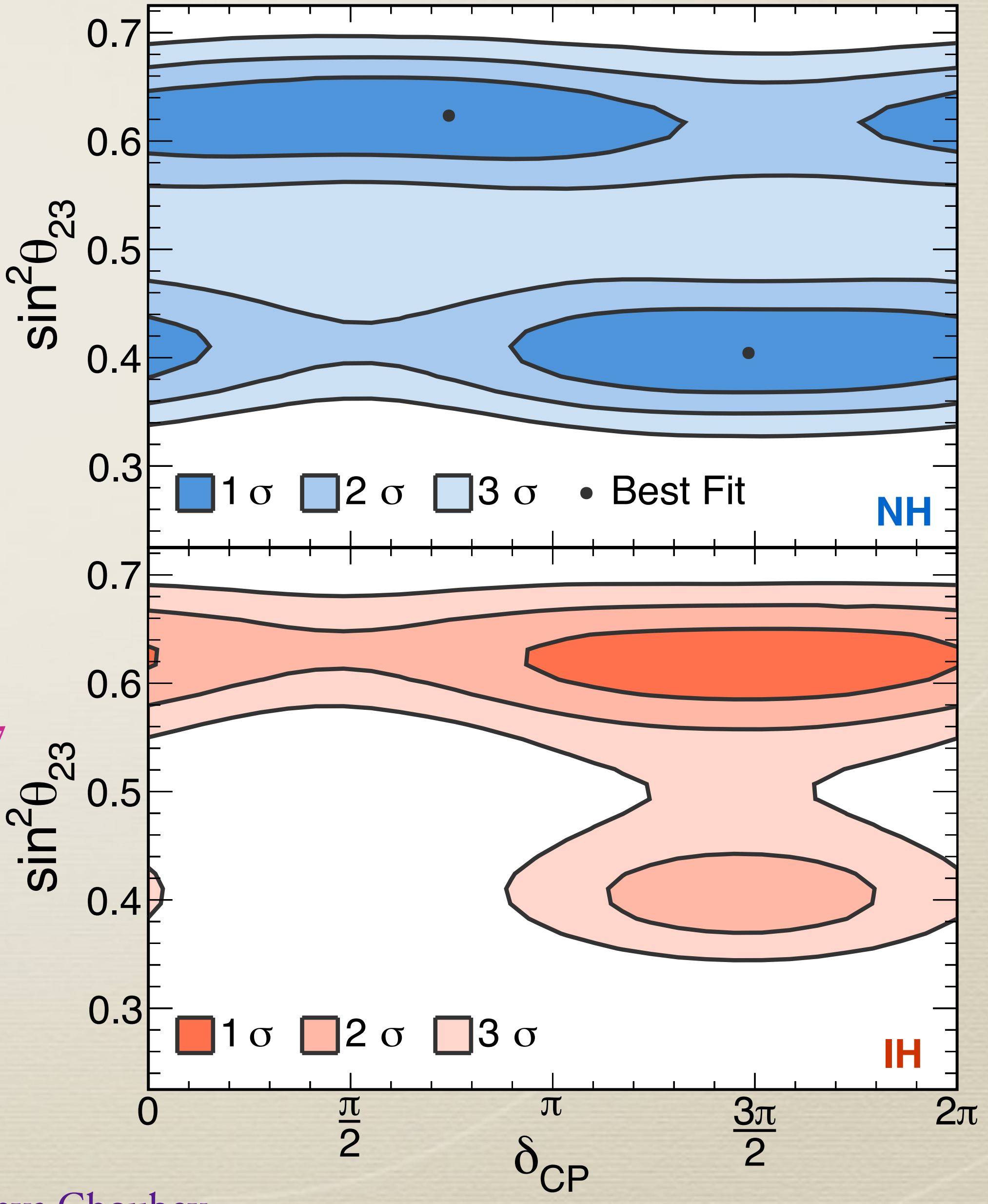
Maximal theta23 mixing is ruled out at 2.6 sigma

Constraints on Oscillation Parameters

From Appearance + Disappearance Data

33 candidate ν_e events with 8.2 ± 0.8 (syst) expected backgrounds





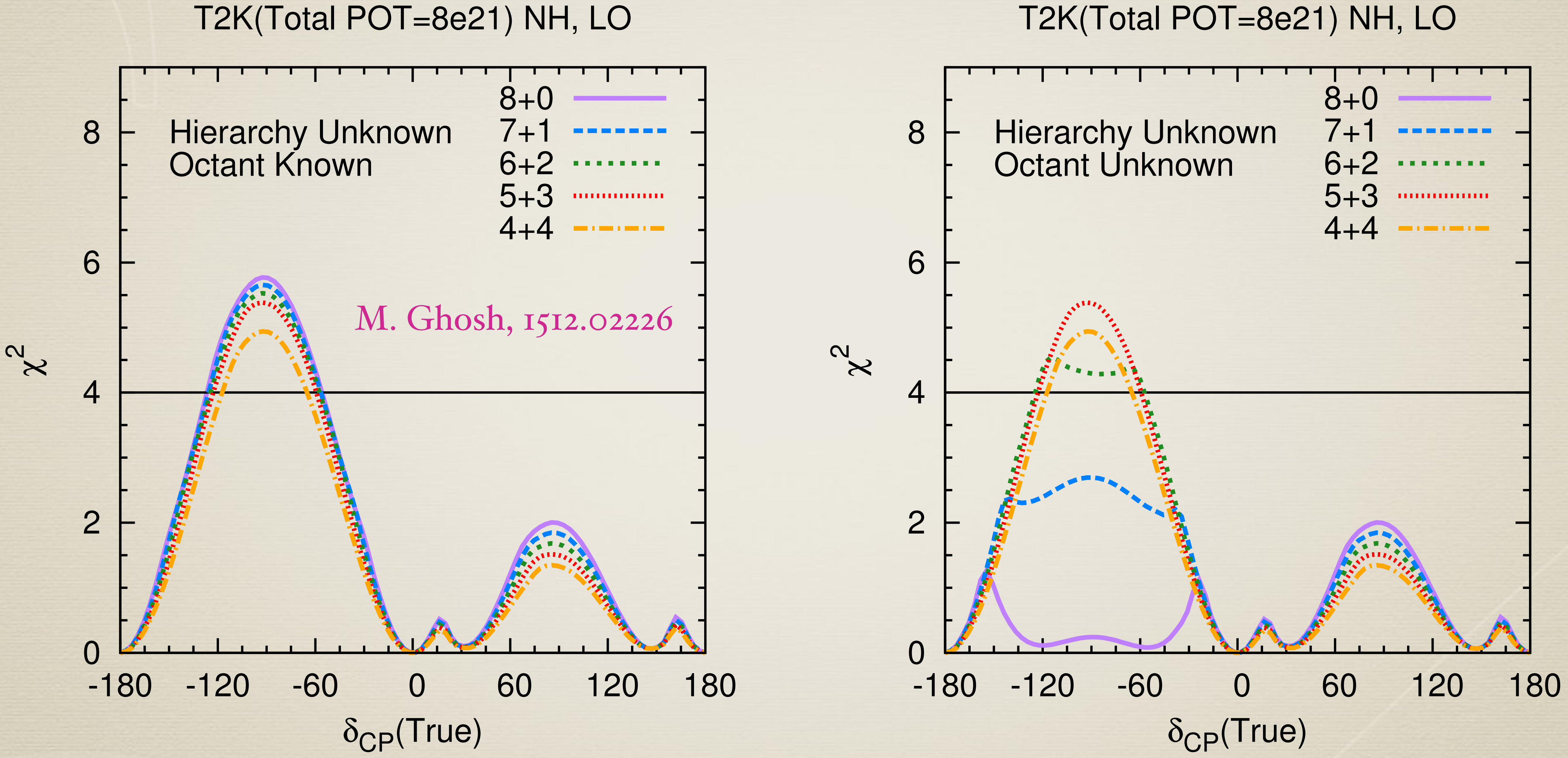
NOvA, PRL 118, 231801, 2017

Gaussian prior on theta13

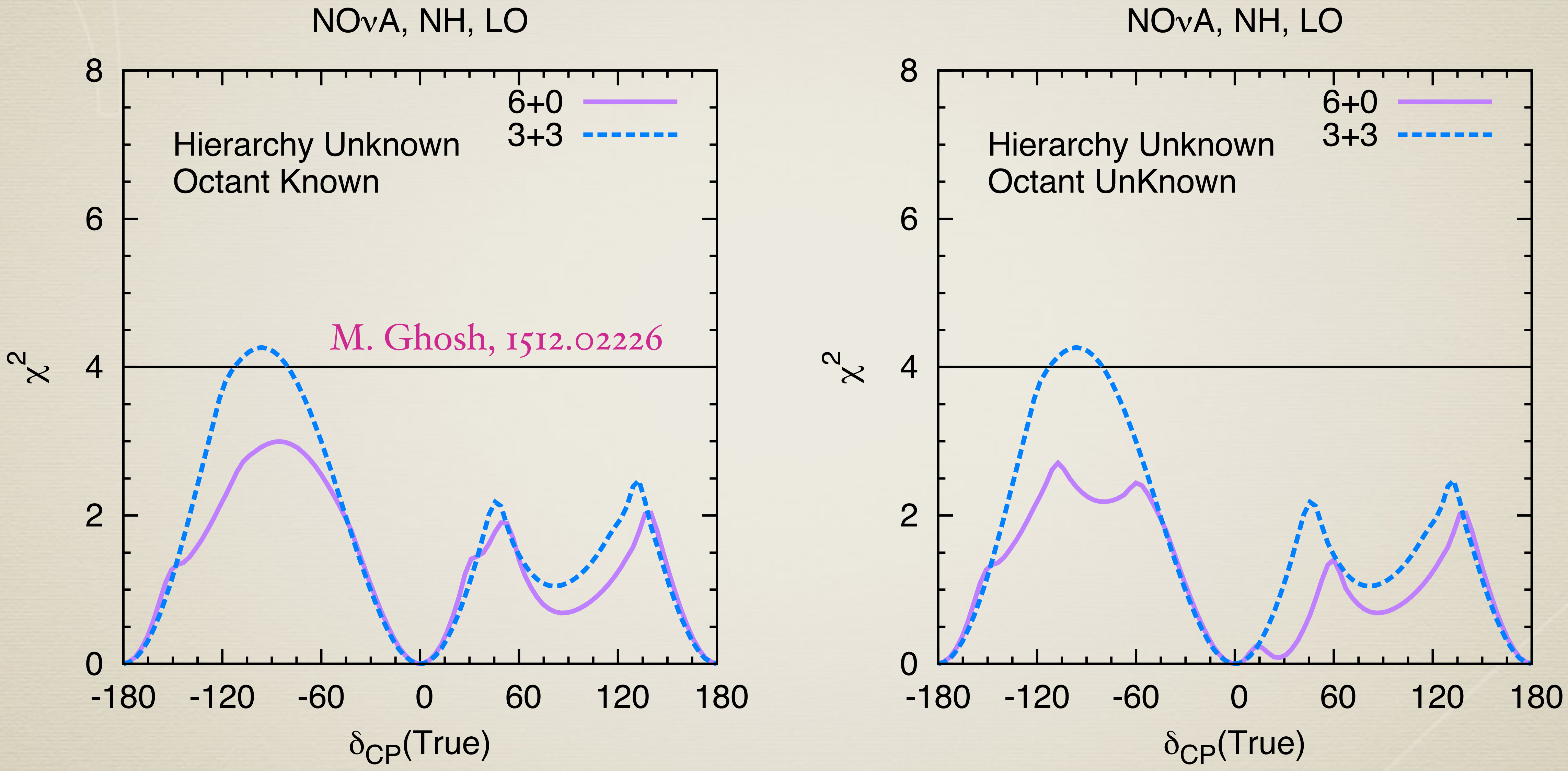
$$\sin^2 2\theta_{13} = 0.085 \pm 0.005$$

Inverted hiearchy with theta23 in lower octant disfavoured at 93% C.L.

What more from T2K and NOvA?

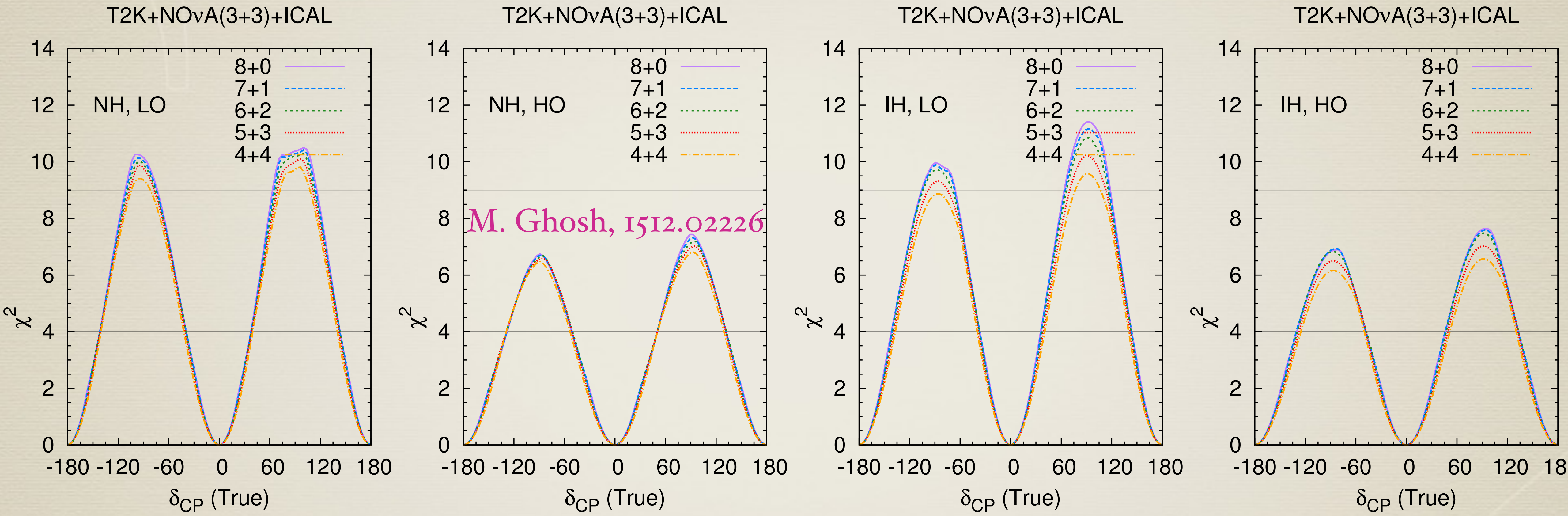


What more from T2K and NOνA?



The anti-nu run helps here since the flux does not peak at the osc max

What more from T2K and NOνA?



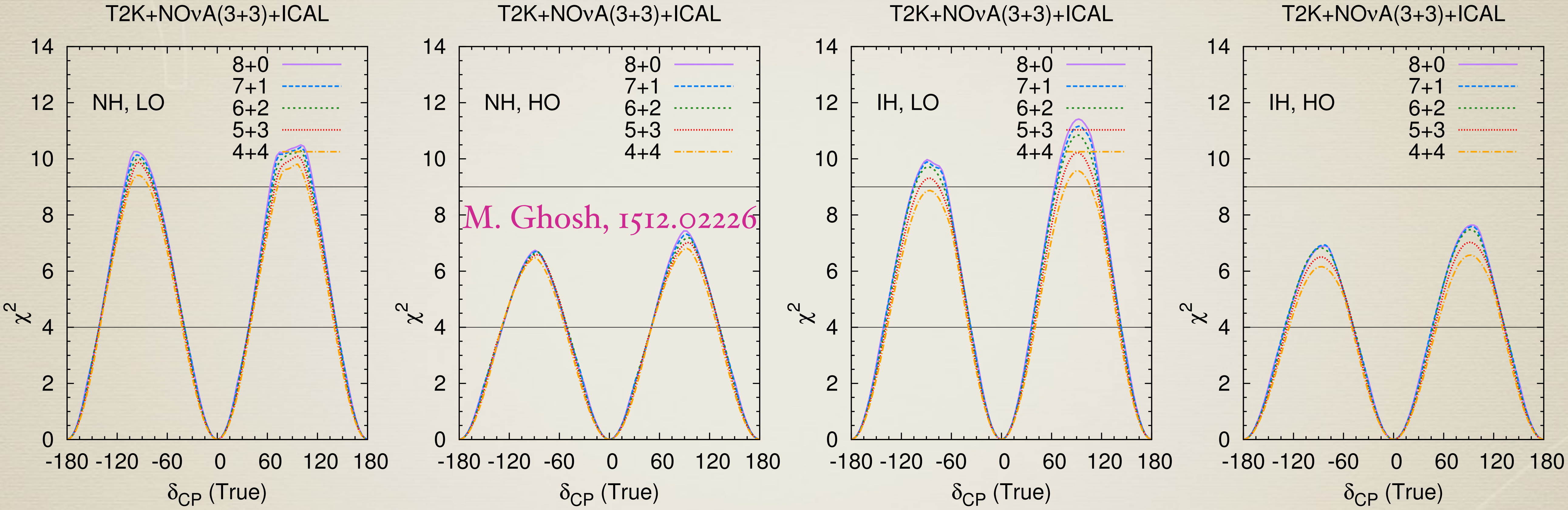
M. Ghosh, 1512.02226

Running T2K dominantly in nu mode appears best, tho the diff is not much

About 3 sigma CPV sensitivity can be expected for NH-LO as well as IH-LO

For NH-HO as well as IH-HO CPV sensitivity is less

What more from T2K and NOνA?



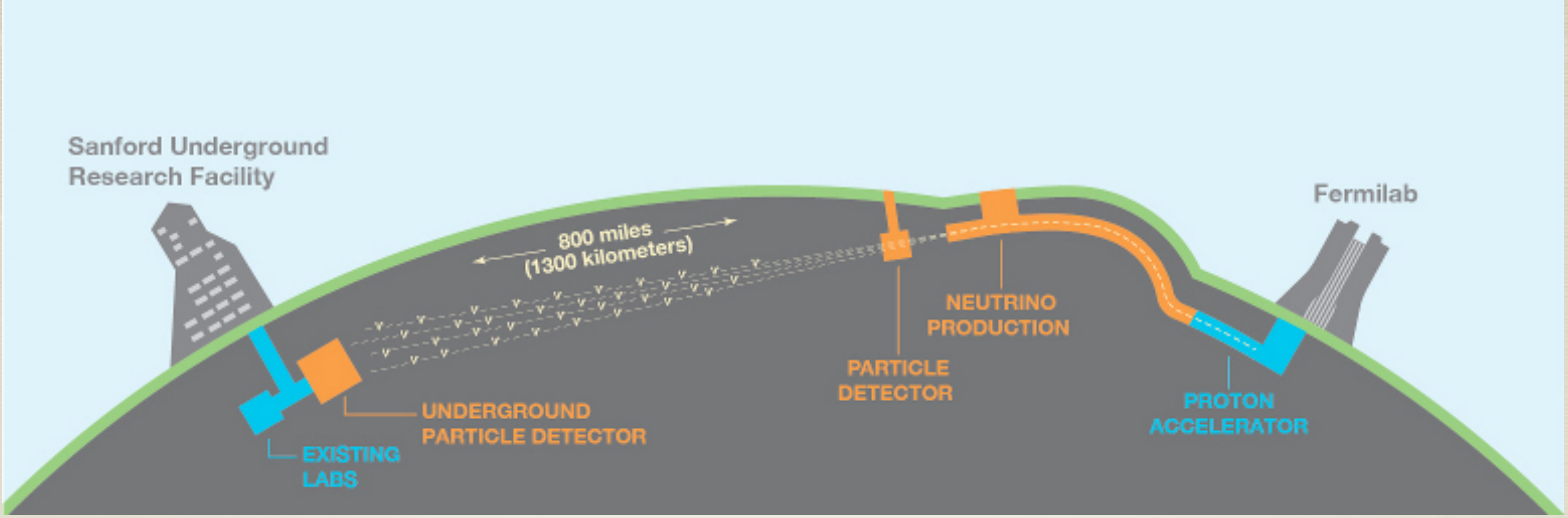
M. Ghosh, 1512.02226

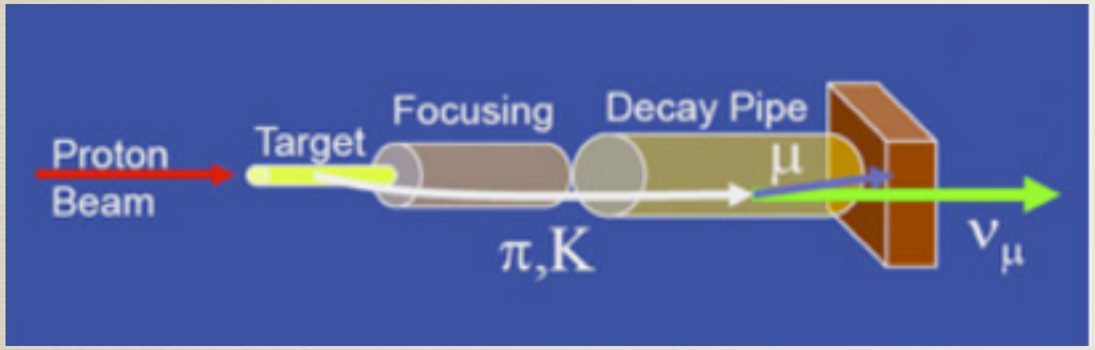
Potential of T2K and NOvA has been studied by a large number of authors

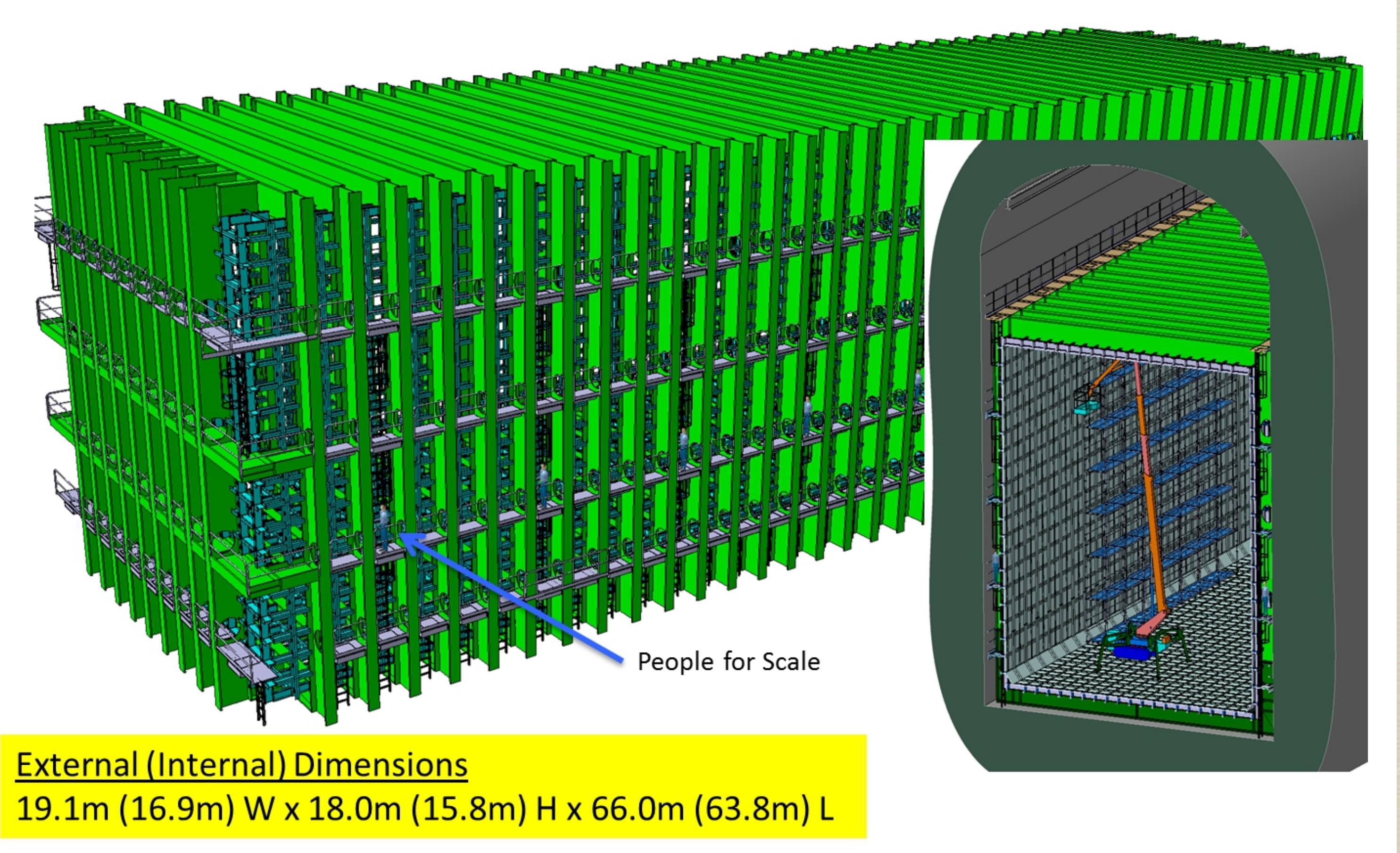
Apologies for not being able to cite all papers here for lack of space

Next-Gen LBL Expts

DUNE

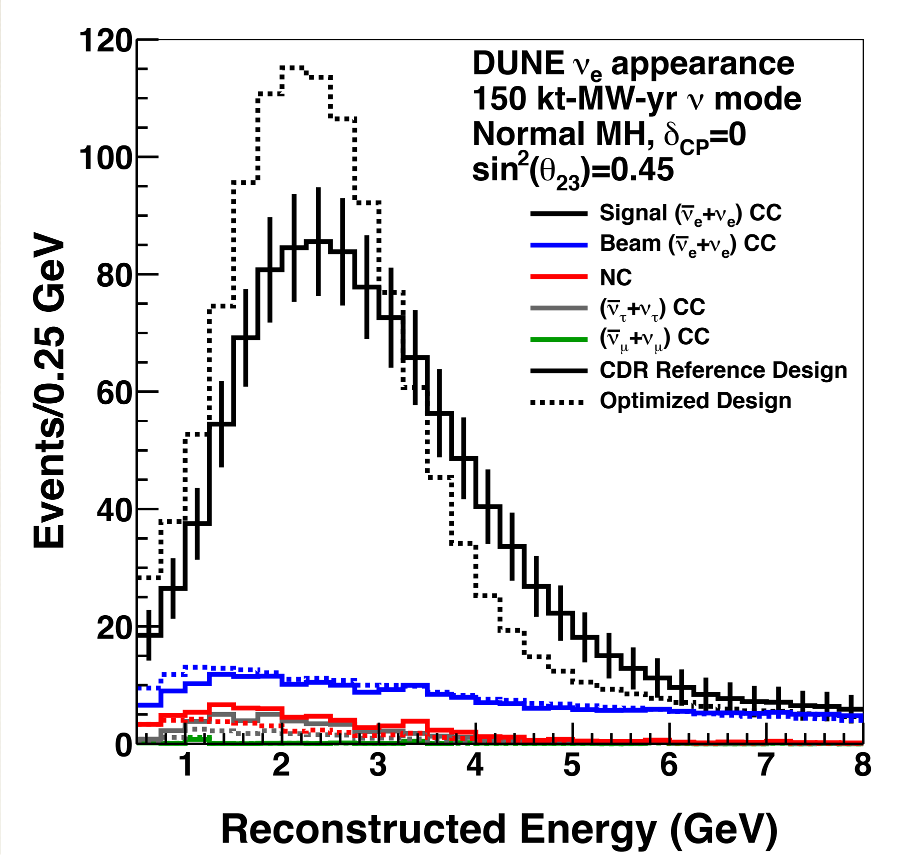


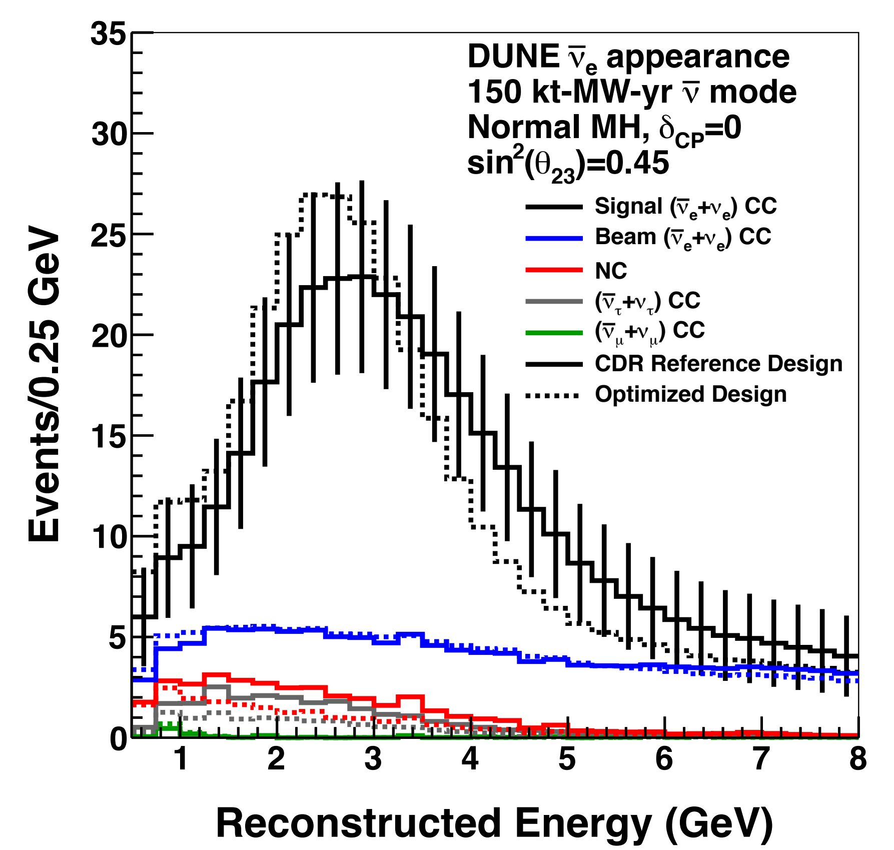


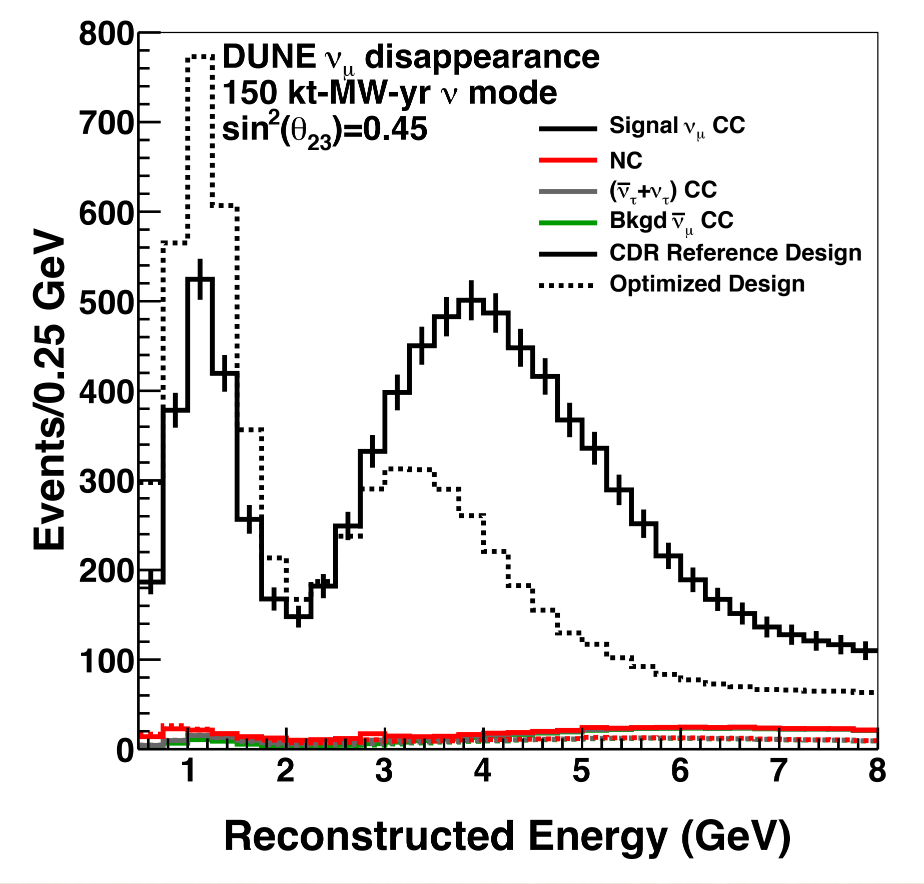


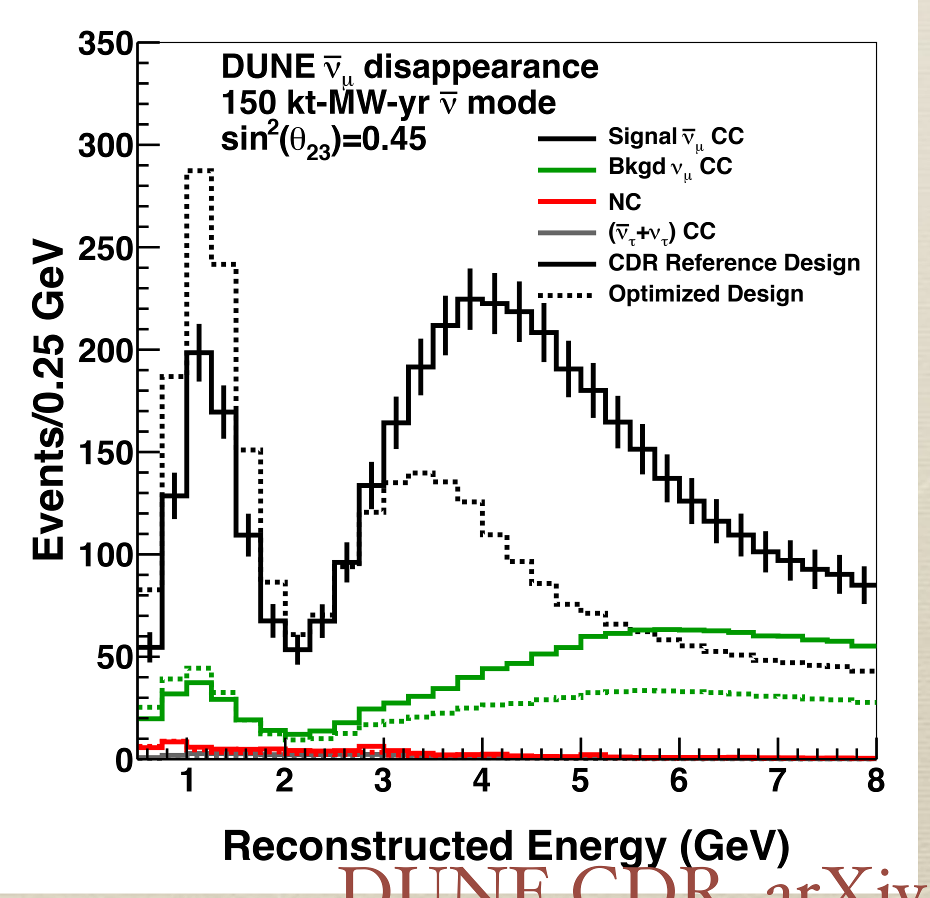
External (Internal) Dimensions
19.1m (16.9m) W x 18.0m (15.8m) H x 66.0m (63.8m) L

DUNE events



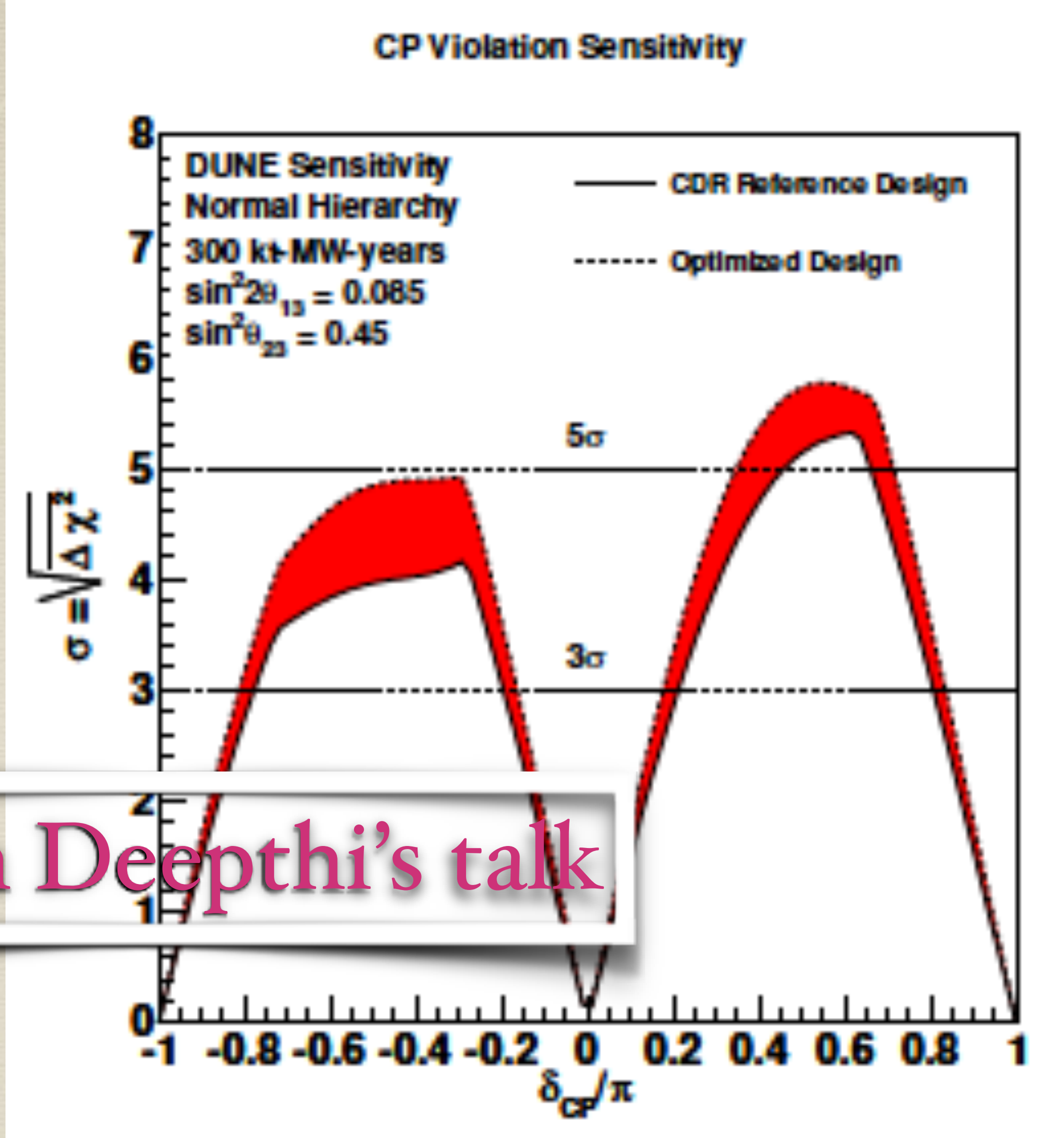




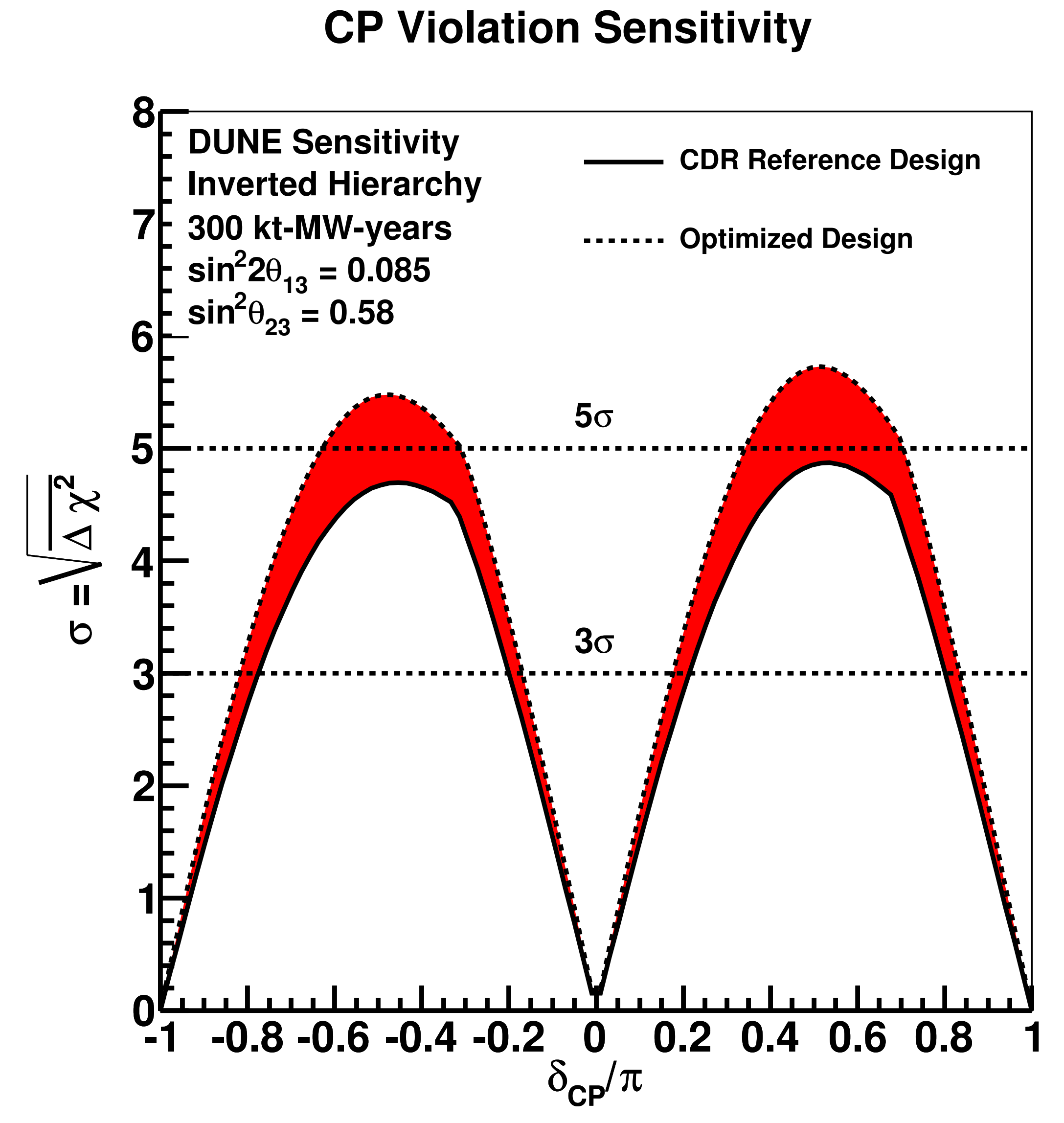


DUNE CDR, arXiv:1512.06148

CPV Sensitivity of DUNE



More in Deepthi's talk

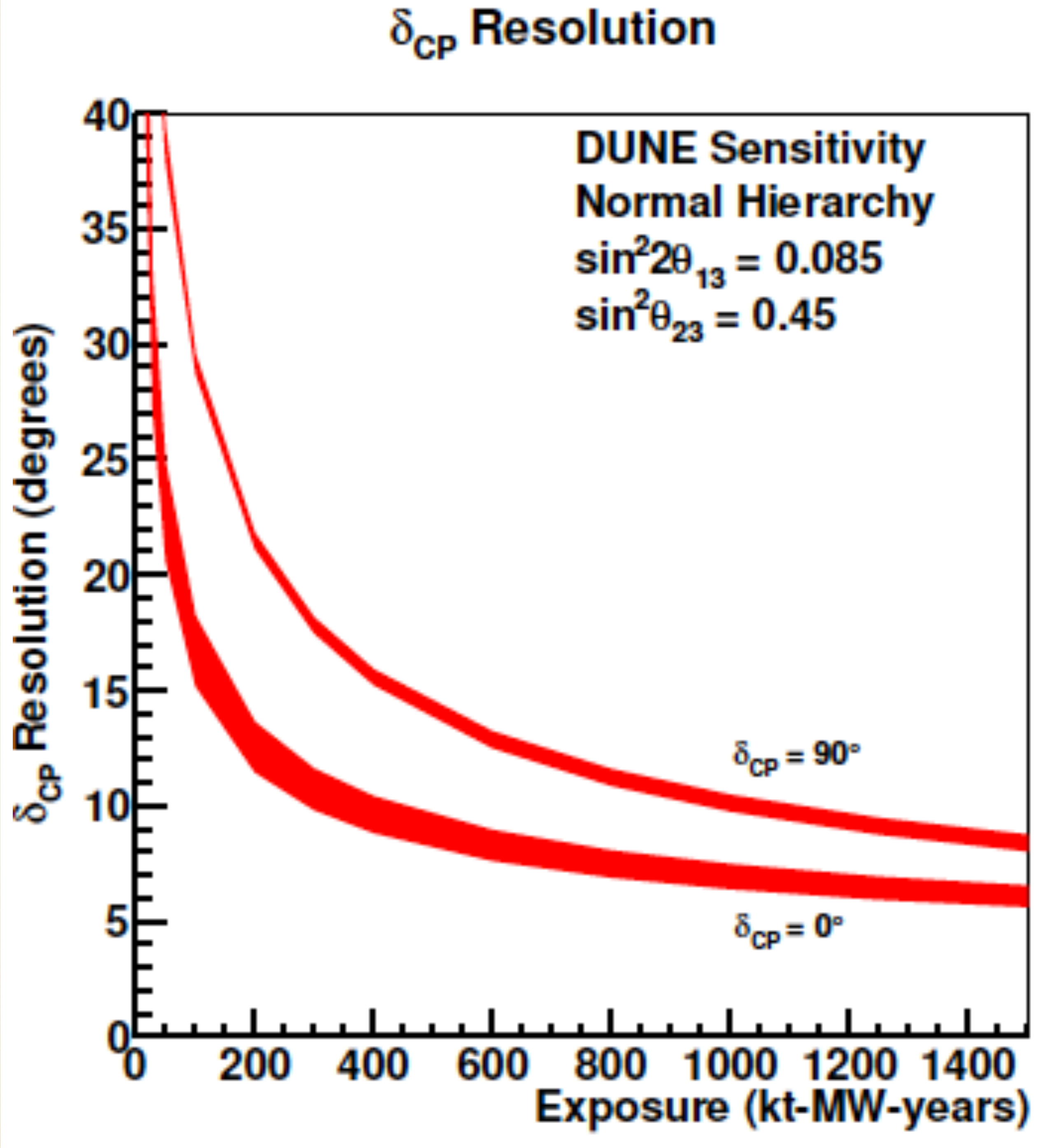


$$\begin{aligned}\Delta\chi^2_{CPV} &= Min[\Delta\chi^2_{CP}(\delta^{test}_{\rm CP}=0), \Delta\chi^2_{CP}(\delta^{test}_{\rm CP}=\pi)], \text{ where} \\ \Delta\chi^2_{CP} &= \chi^2_{\delta^{test}_{\rm CP}} - \chi^2_{\delta^{true}_{\rm CP}}.\end{aligned}$$

Significance	CDR Reference Design	Optimized Design
3σ for 75% of $\delta_{\rm CP}$ values	1320 kt · MW · year	850 kt · MW · year
5σ for 50% of $\delta_{\rm CP}$ values	810 kt · MW · year	550 kt · MW · year

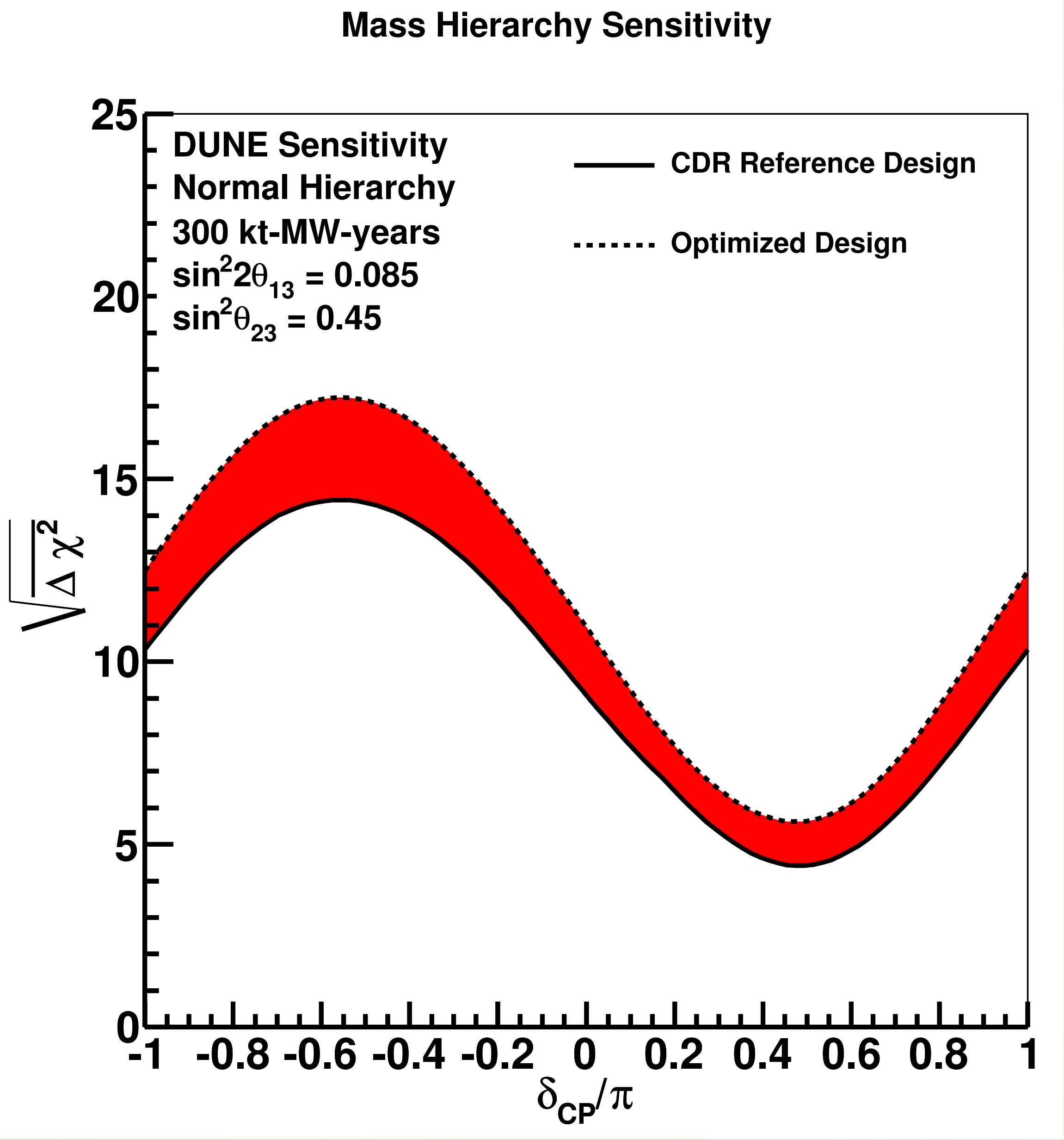
DUNE CDR, arXiv:1512.06148

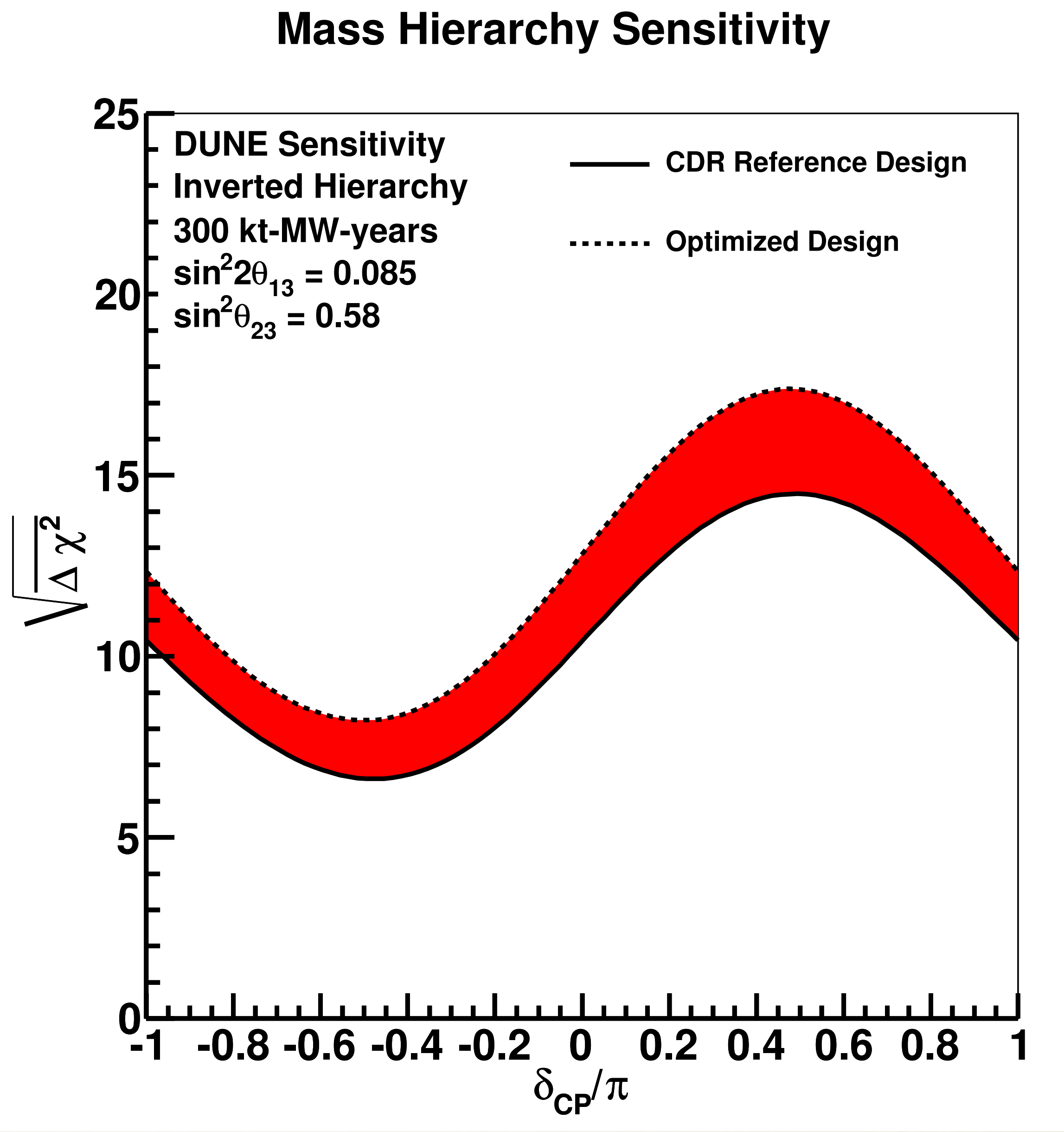
CP Precision



DUNE CDR, arXiv:1512.06148

DUNE MH Sensitivity

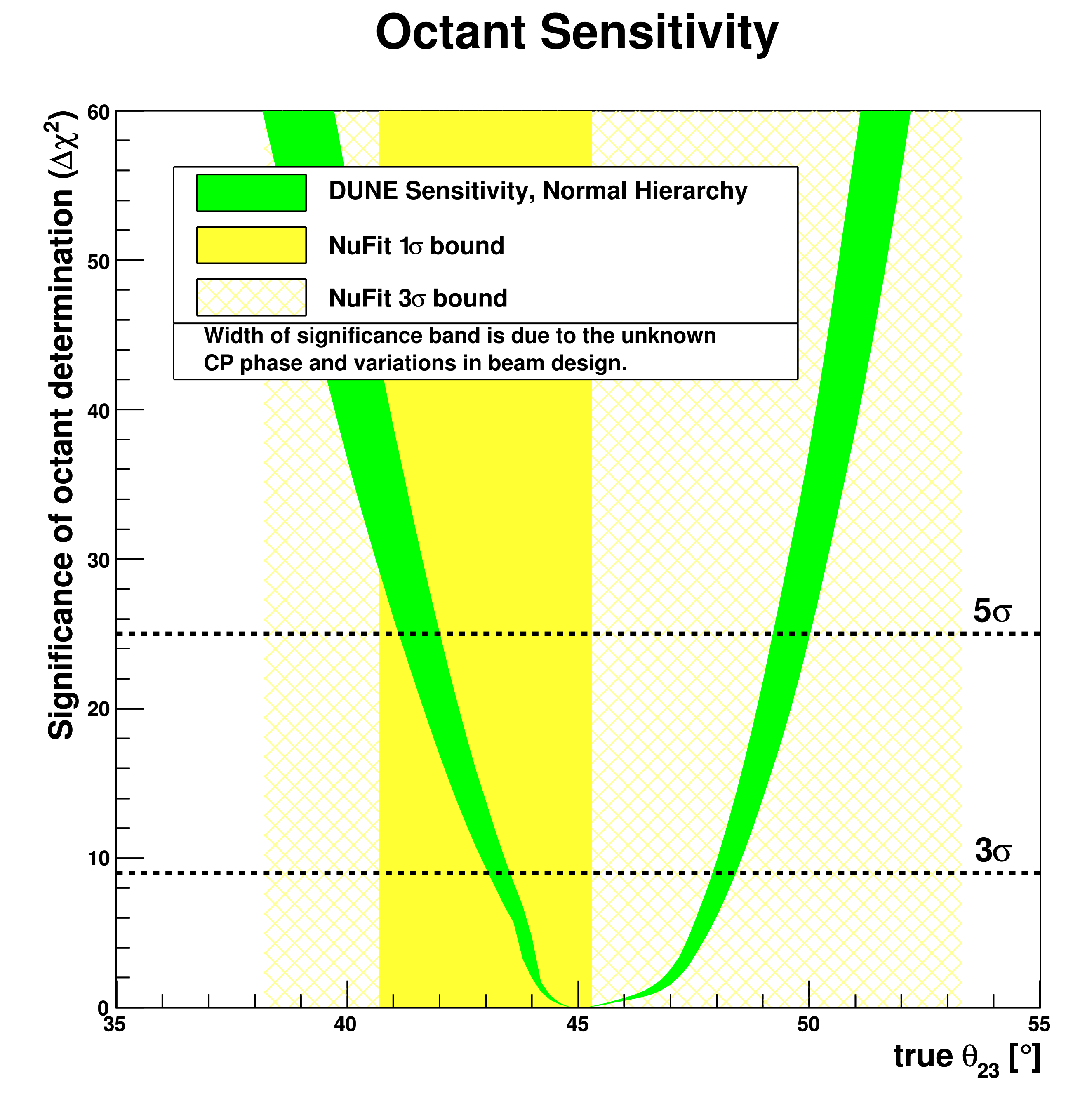




$$\begin{aligned} \Delta\chi^2_{MH} &= \chi^2_{IH} - \chi^2_{NH} \text{ (true normal hierarchy)}, \\ \Delta\chi^2_{MH} &= \chi^2_{NH} - \chi^2_{IH} \text{ (true inverted hierarchy)}, \end{aligned}$$

DUNE CDR, arXiv:1512.06148

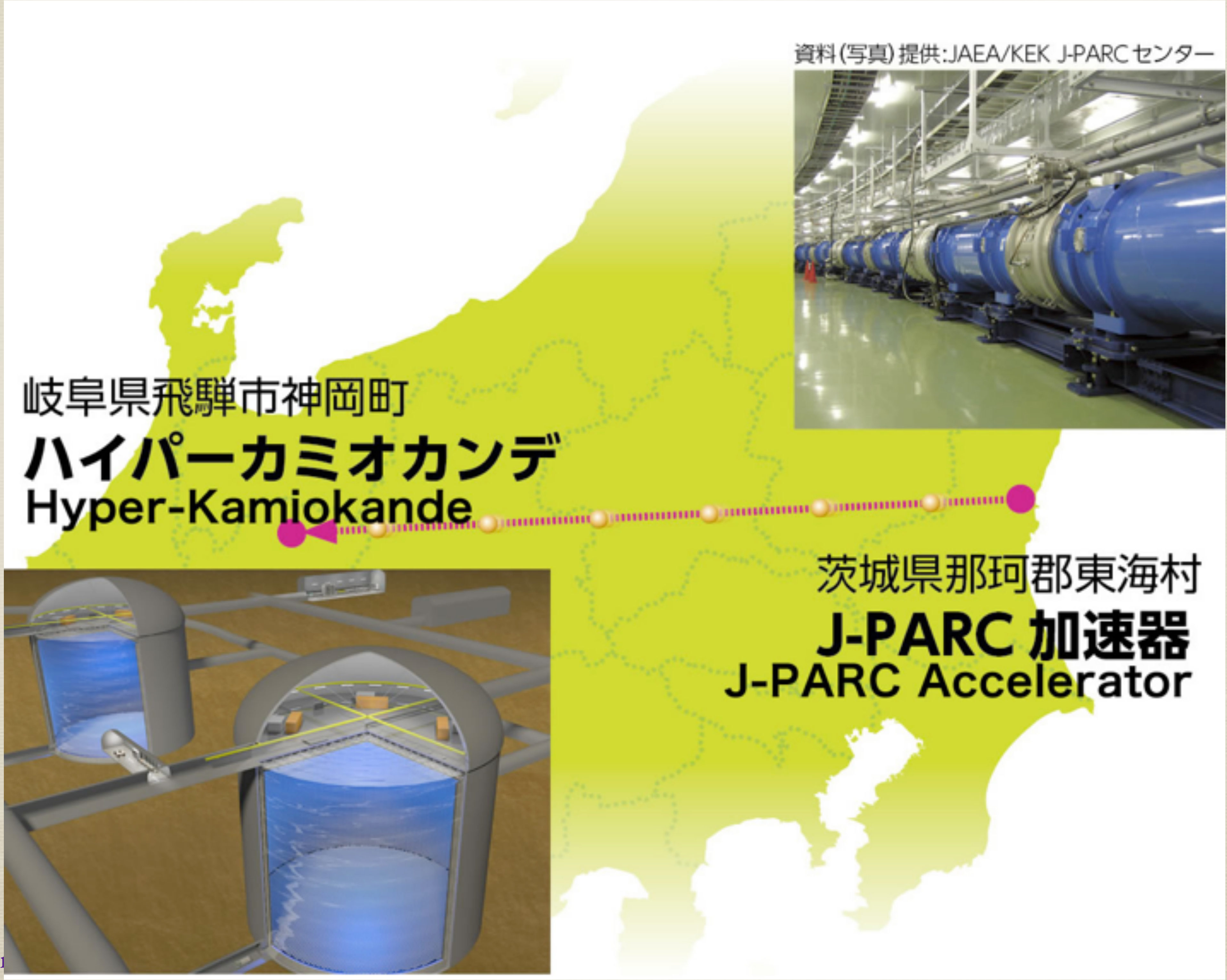
DUNE Octant Sensitivity



DUNE CDR, arXiv:1512.06148

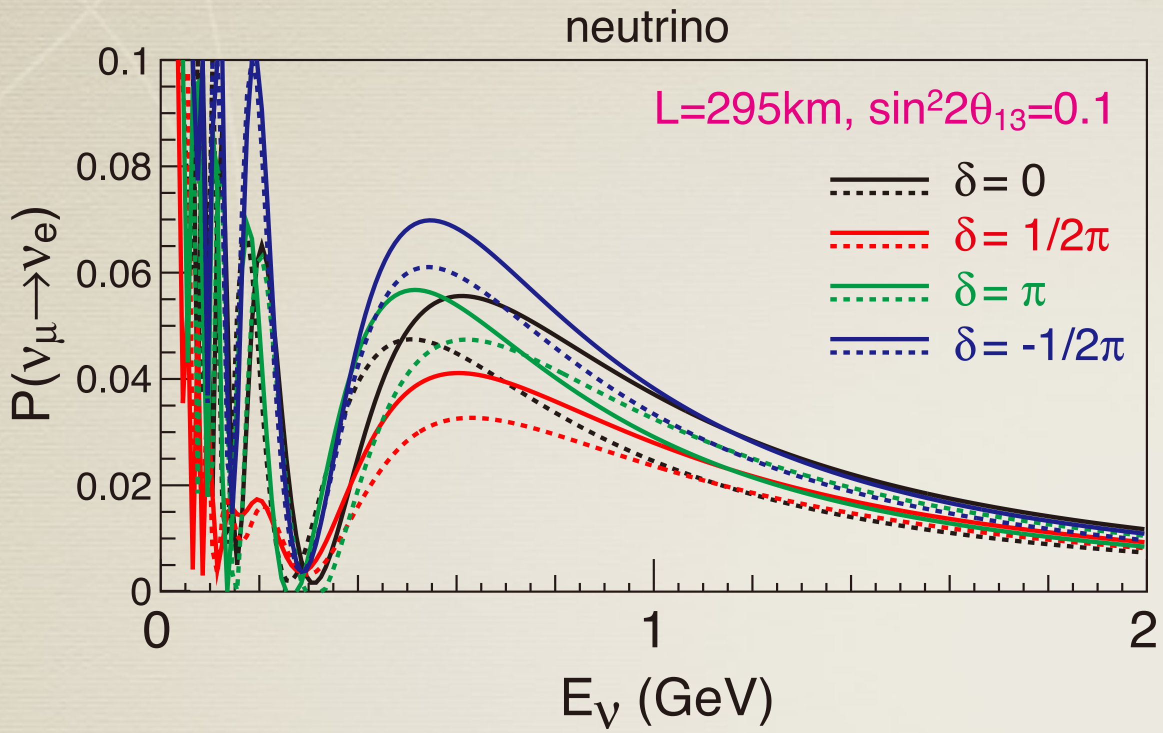
Exposure needed to have 3sig CPV for 75% CP values taken

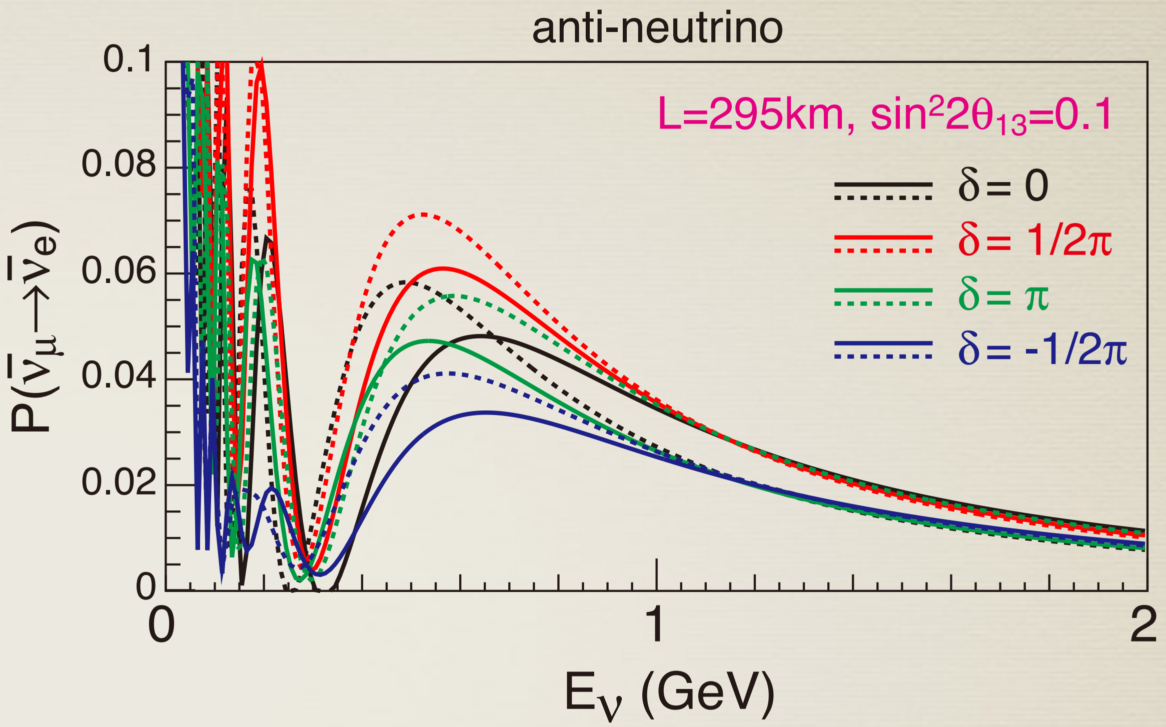
T2HK


資料(写真)提供:JAEA/KEK J-PARCセンター
岐阜県飛騨市神岡町
ハイパーカミオカンデ
Hyper-Kamiokande
茨城県那珂郡東海村
J-PARC 加速器
J-PARC Accelerator

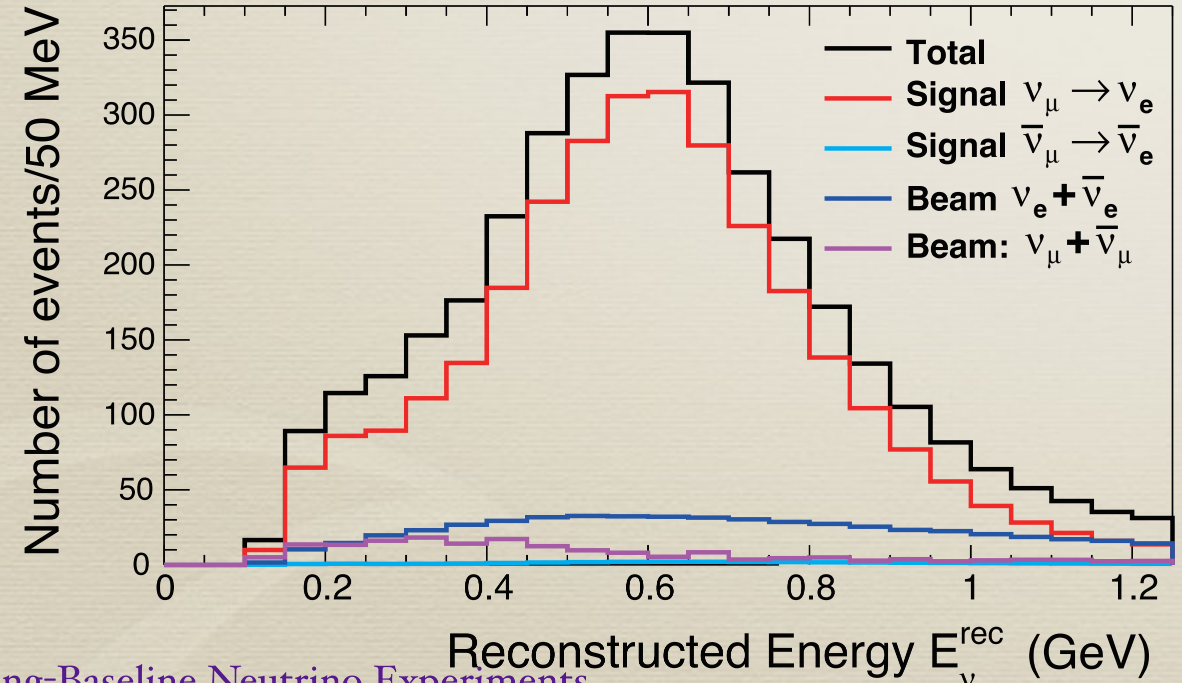
HK LOI, arXiv:1412.4673

T2HK

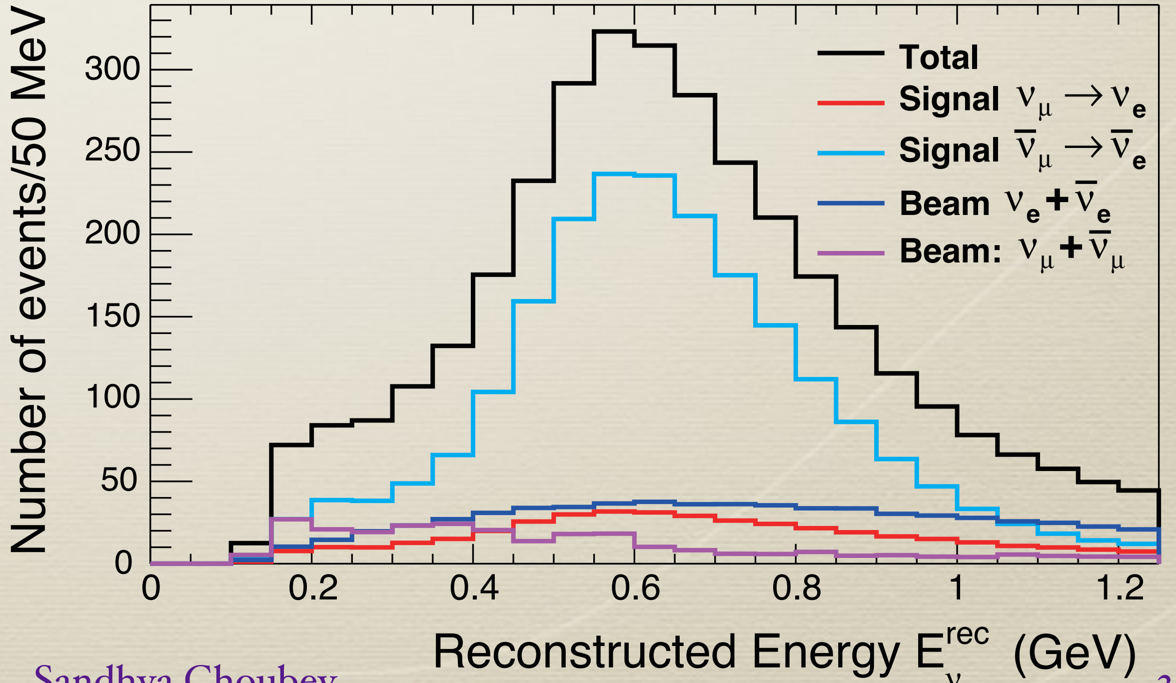




Appearance ν mode

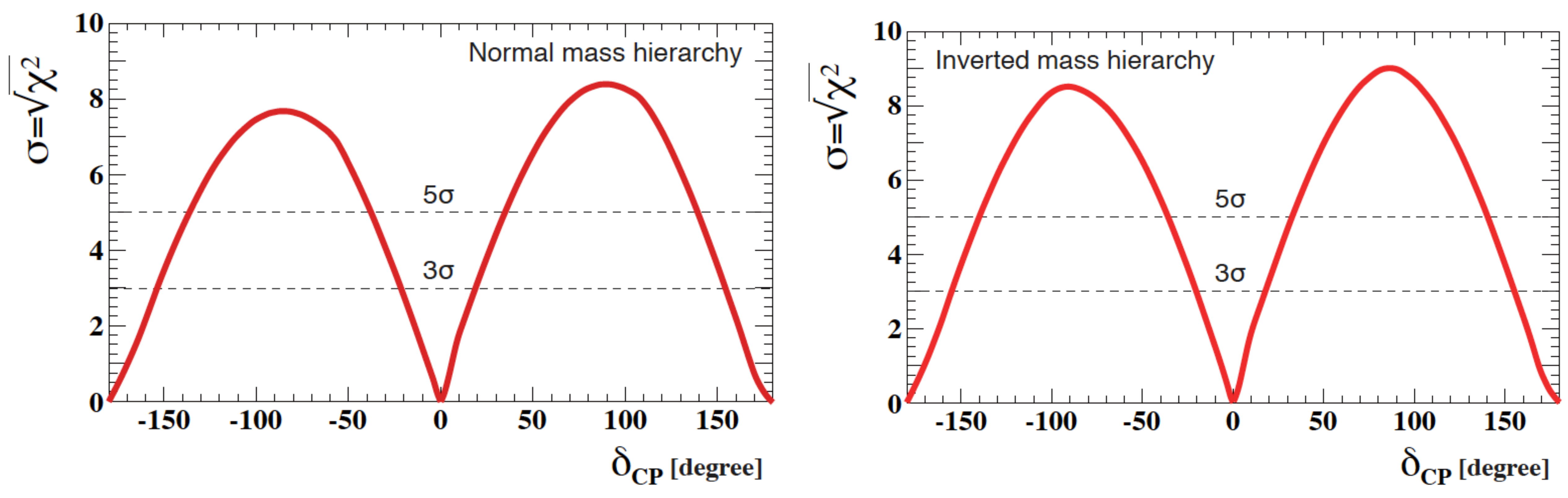


Appearance ν̄ mode



HK LOI, arXiv:1412.4673

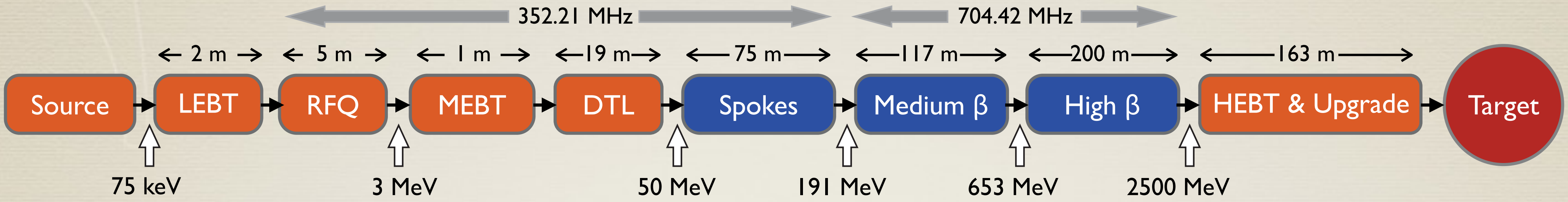
CPV Sensitivity of T2HK



- Off-axis narrow beam from Tokai to HK at 295 km
- Fudicial mass of HK is 560 kton
- 5 years at 1.5 MW, nu:antinu is 1:3
- 74% CP coverage at 3 sigma, 58% CP coverage at 5 sigma
- CP precision < 19° fo 5 sigma
- Marginalisation over hierarchy not done

More in Deepthi's talk

Prospects at ESSnuSB



352.21 MHz

704.42 MHz

← 2 m →

← 5 m →

← 1 m →

←19 m→

←75 m→

←117 m→

←200 m→

←163 m→

Source → LEBT → RFQ → MEBT → DTL → Spokes → Medium β → High β → HEBT & Upgrade → Target

75 keV

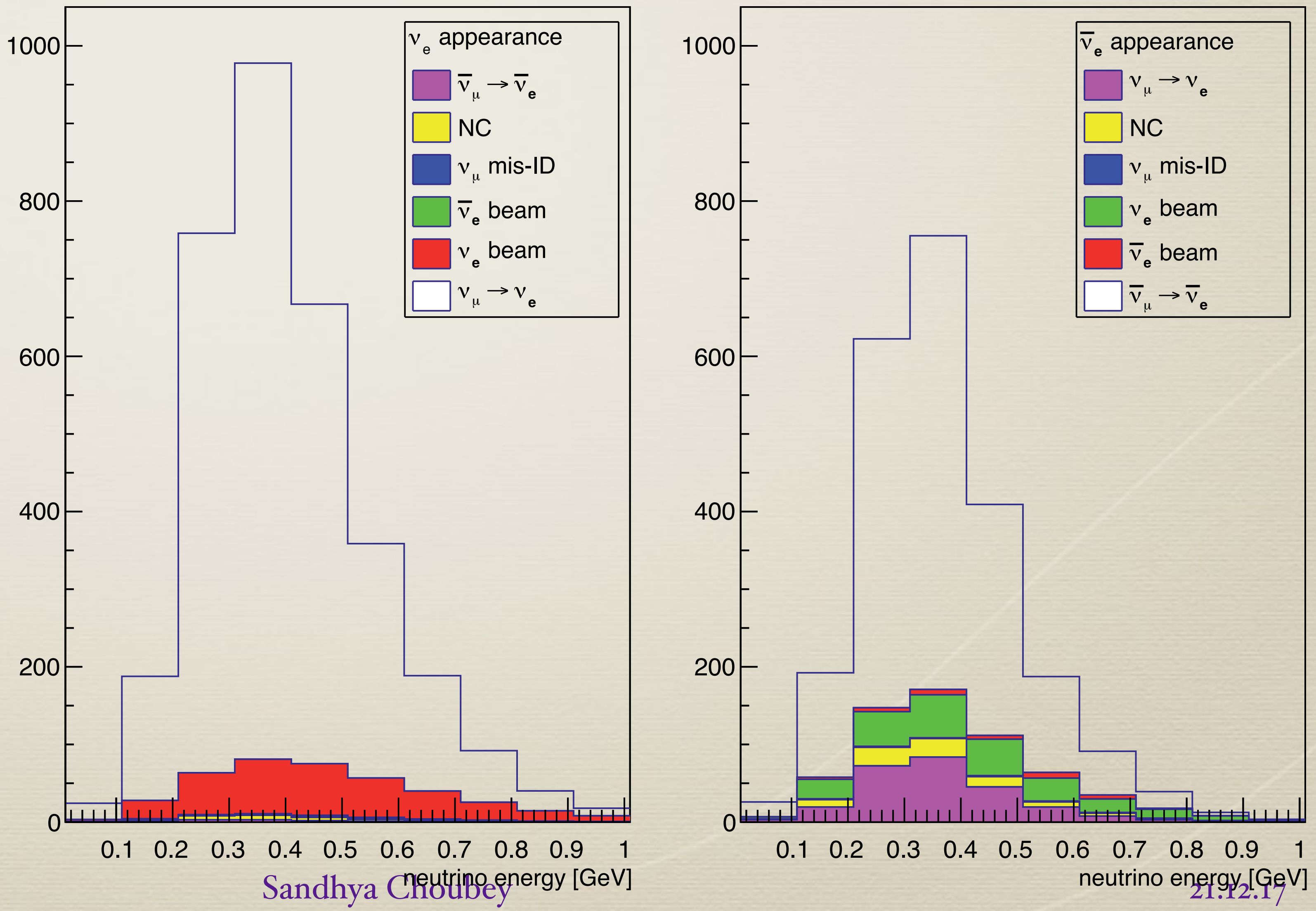
3 MeV

50 MeV

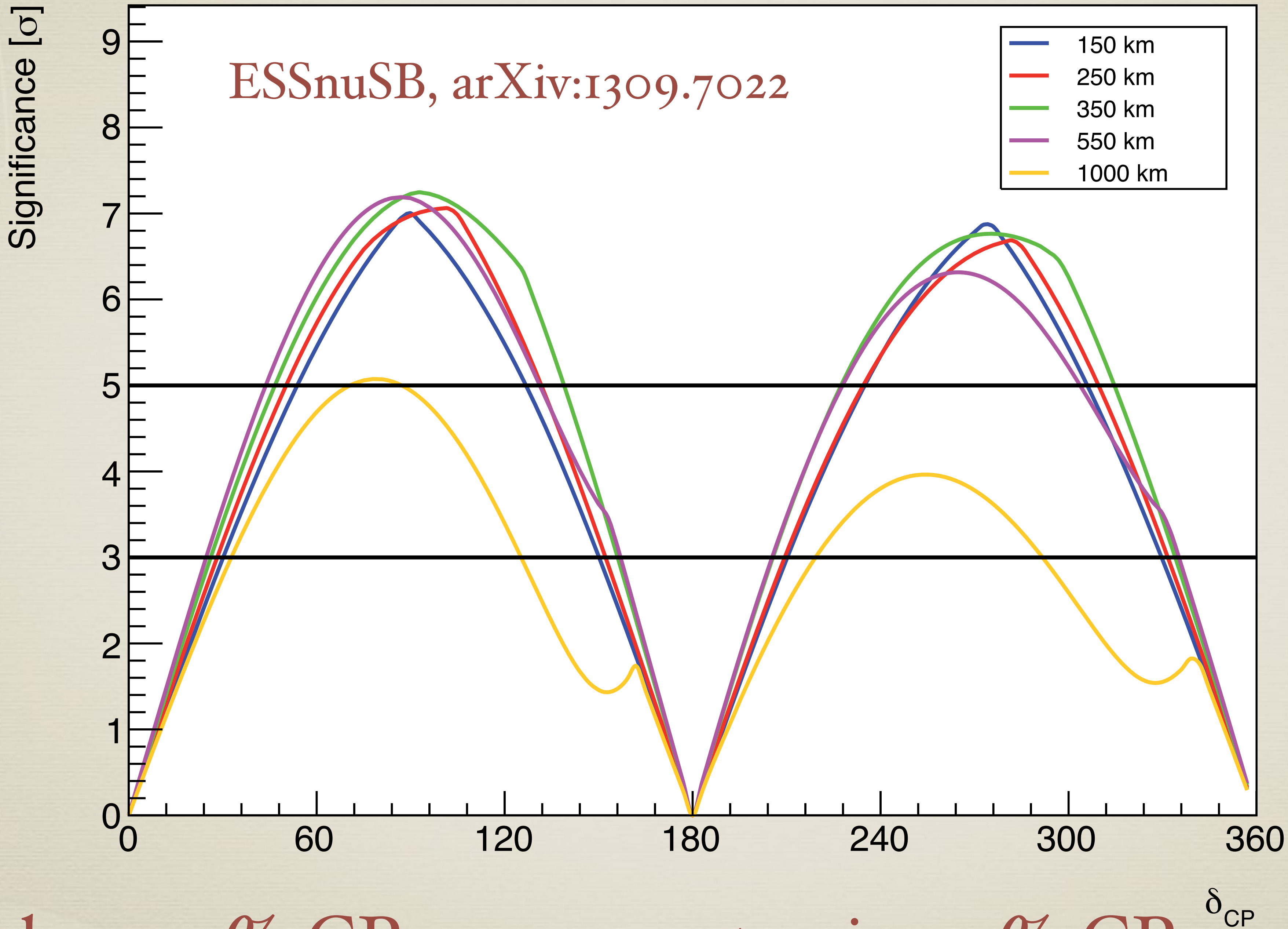
191 MeV

653 MeV

2500 MeV

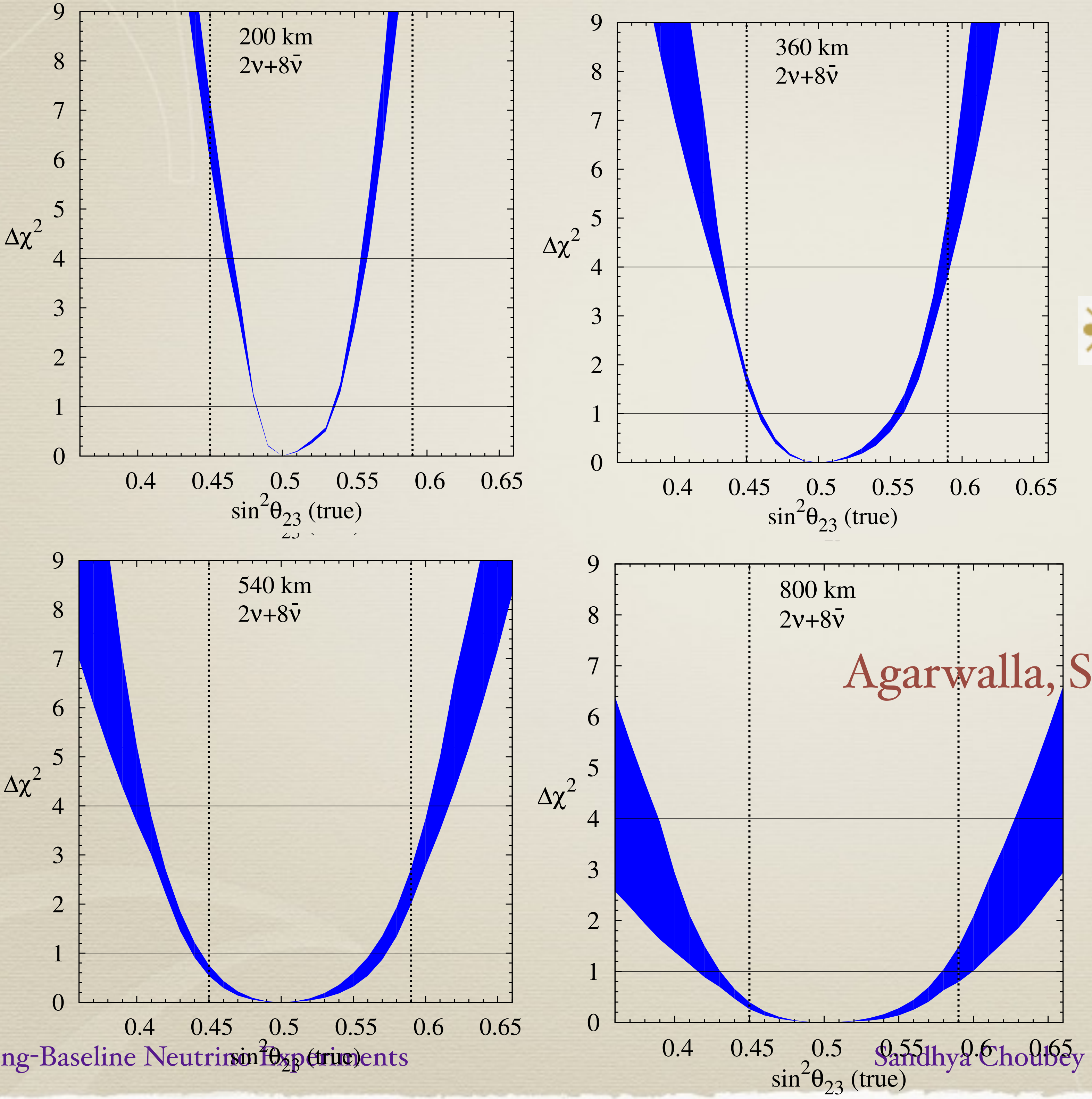


CPV at ESSnuSB



- L=540 km, 70% CP coverage at 3 sig, 45% CP coverage at 5 sig
- L=200 km, 60% CP coverage at 3 sig, 32% CP coverage at 5 sig

Octant at ESSnuSB



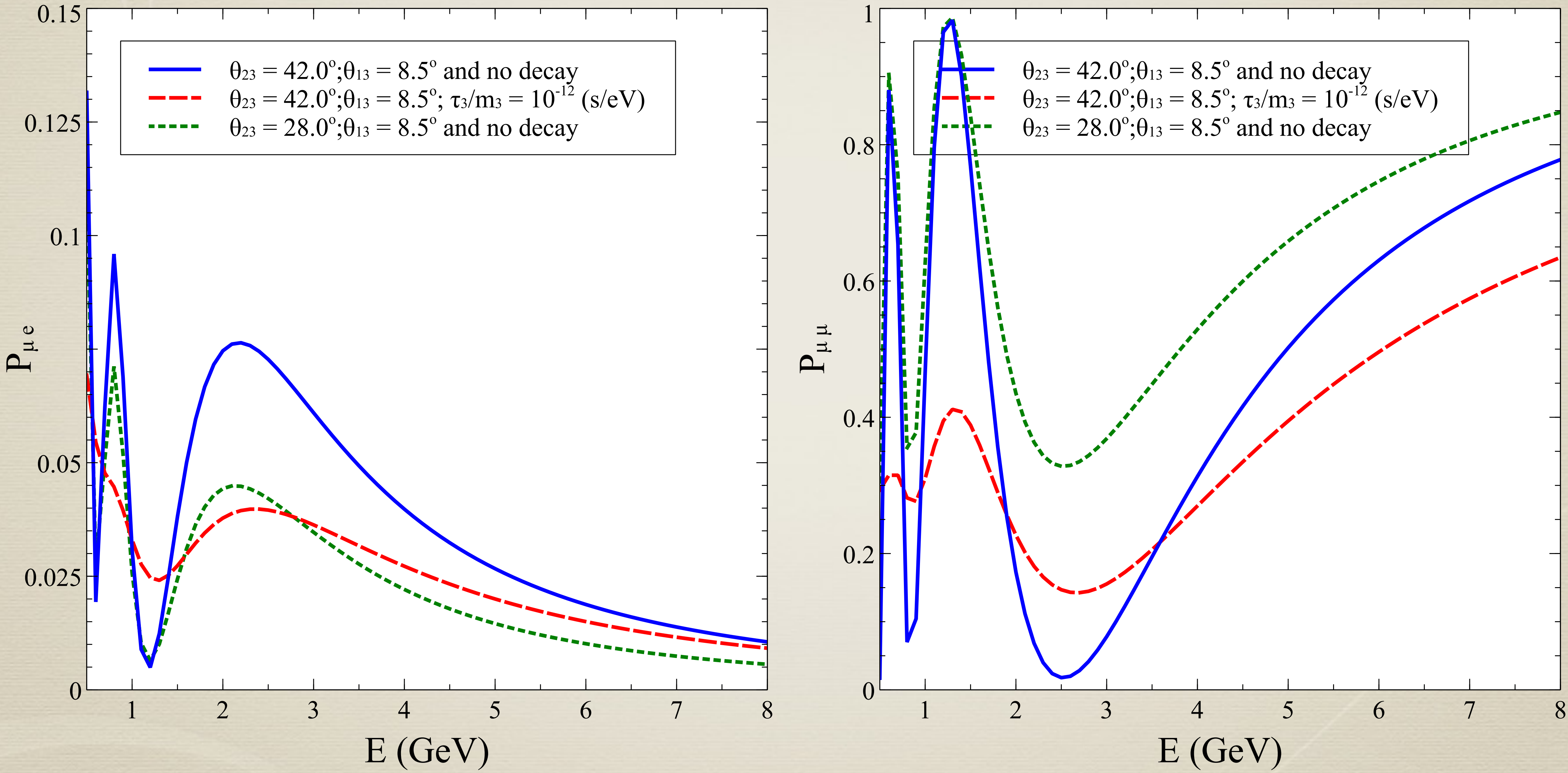
- Best sensitivity for 200 km baseline

Agarwalla, S.C., Prakash, arXiv:1406.2219

New Physics at LBL

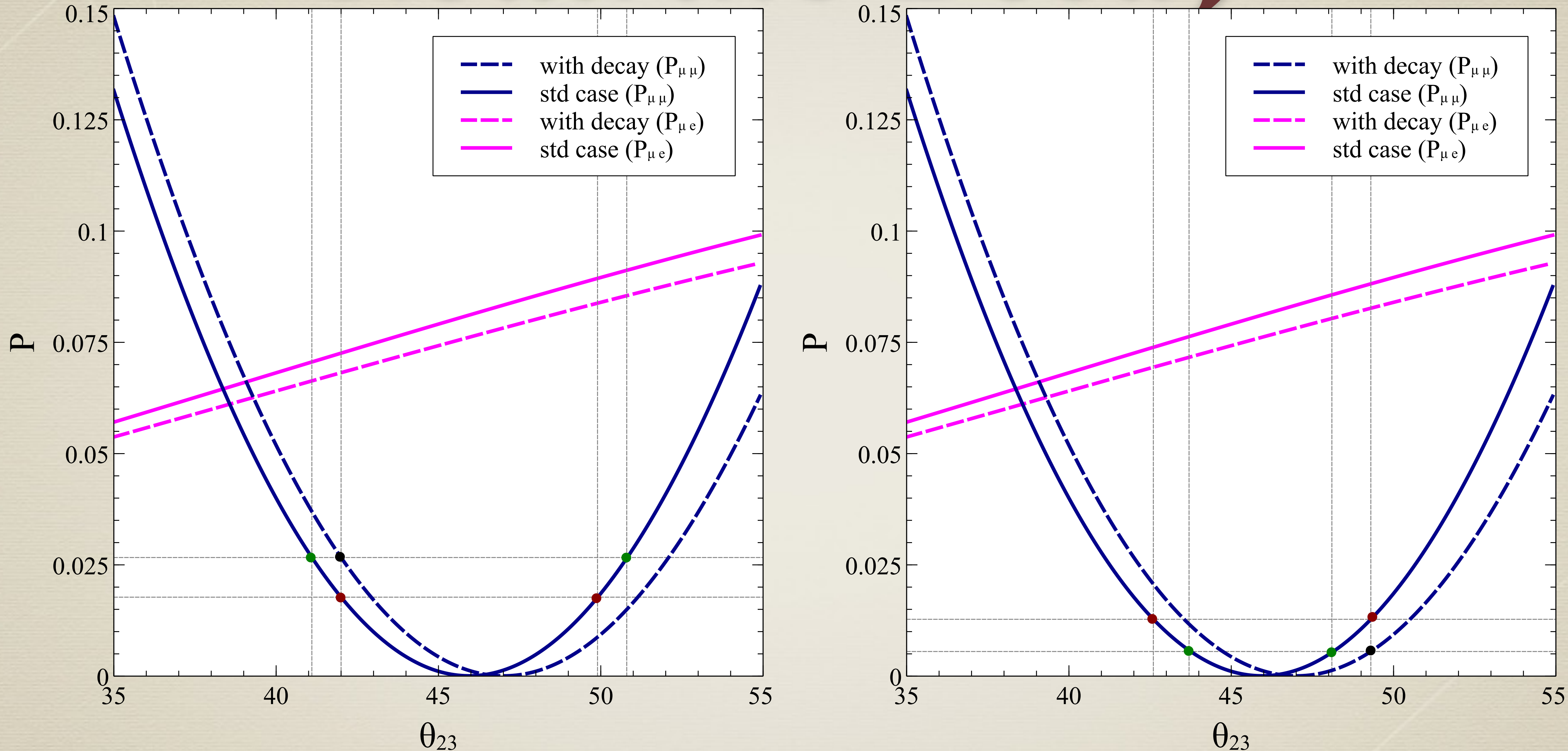
Neutrino Decay

Impact of Invisible Neutrino Decay



Choubey,Goswami,Pramanik,1705.05820

Impact of Invisible Neutrino Decay



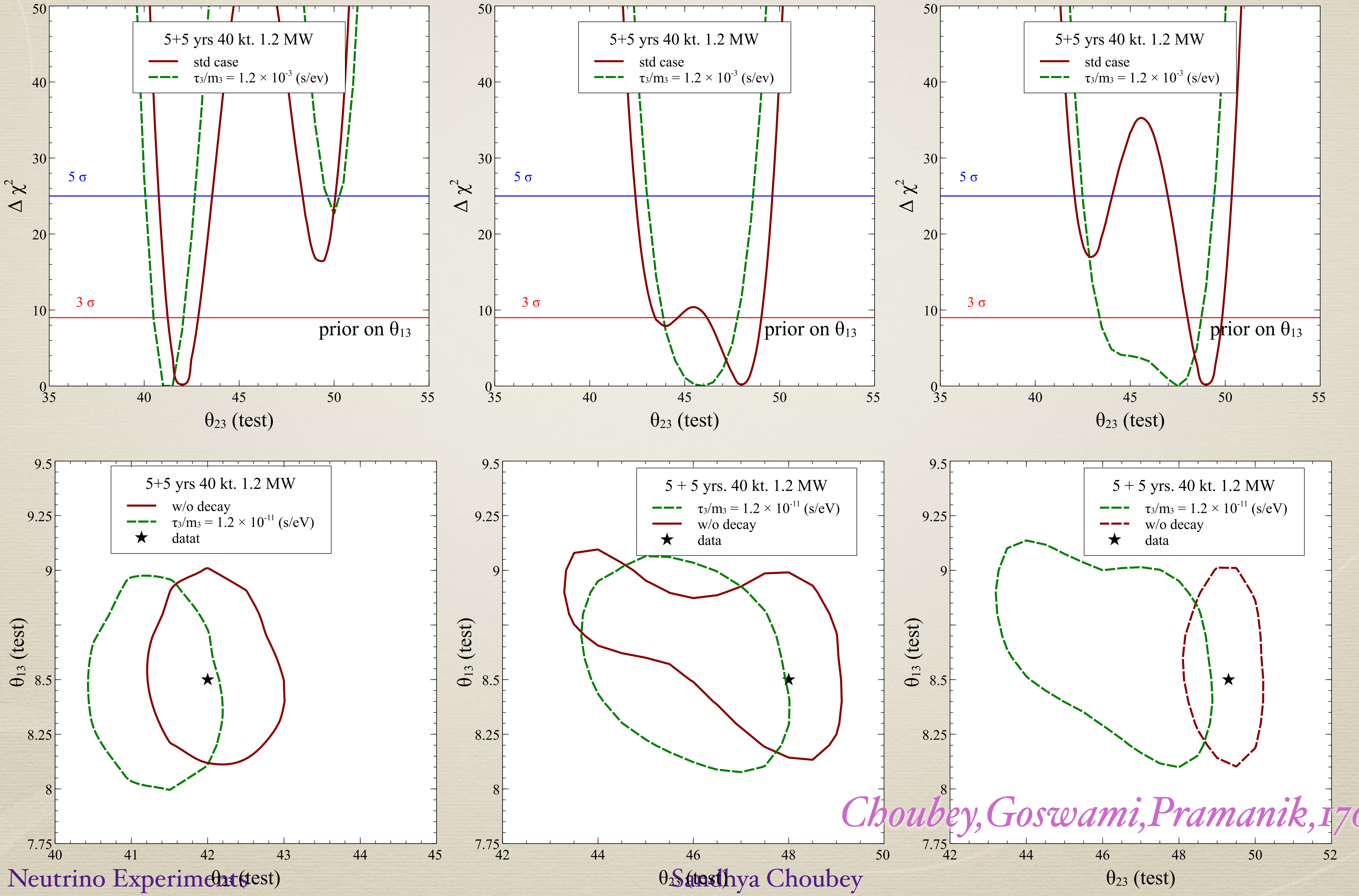
$$\sin\theta_{23}^{LO} = \frac{\sin\theta_{\mu\mu}^{LO}}{\cos\theta_{13}} \quad ; \quad \sin\theta_{23}^{HO} = \frac{\sin\theta_{\mu\mu}^{HO}}{\cos\theta_{13}}$$

$$\theta_{\mu\mu}^{LO} = 90^\circ - \theta_{\mu\mu}^{HO} ,$$

$$P_{\mu\mu}^{2G} = \left[\cos^2\theta_{23} + \sin^2\theta_{23} e^{-\frac{m_3 L}{\tau_3 E}}\right]^2 - \sin^2 2\theta_{23} e^{-\frac{m_3 L}{2\tau_3 E}} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

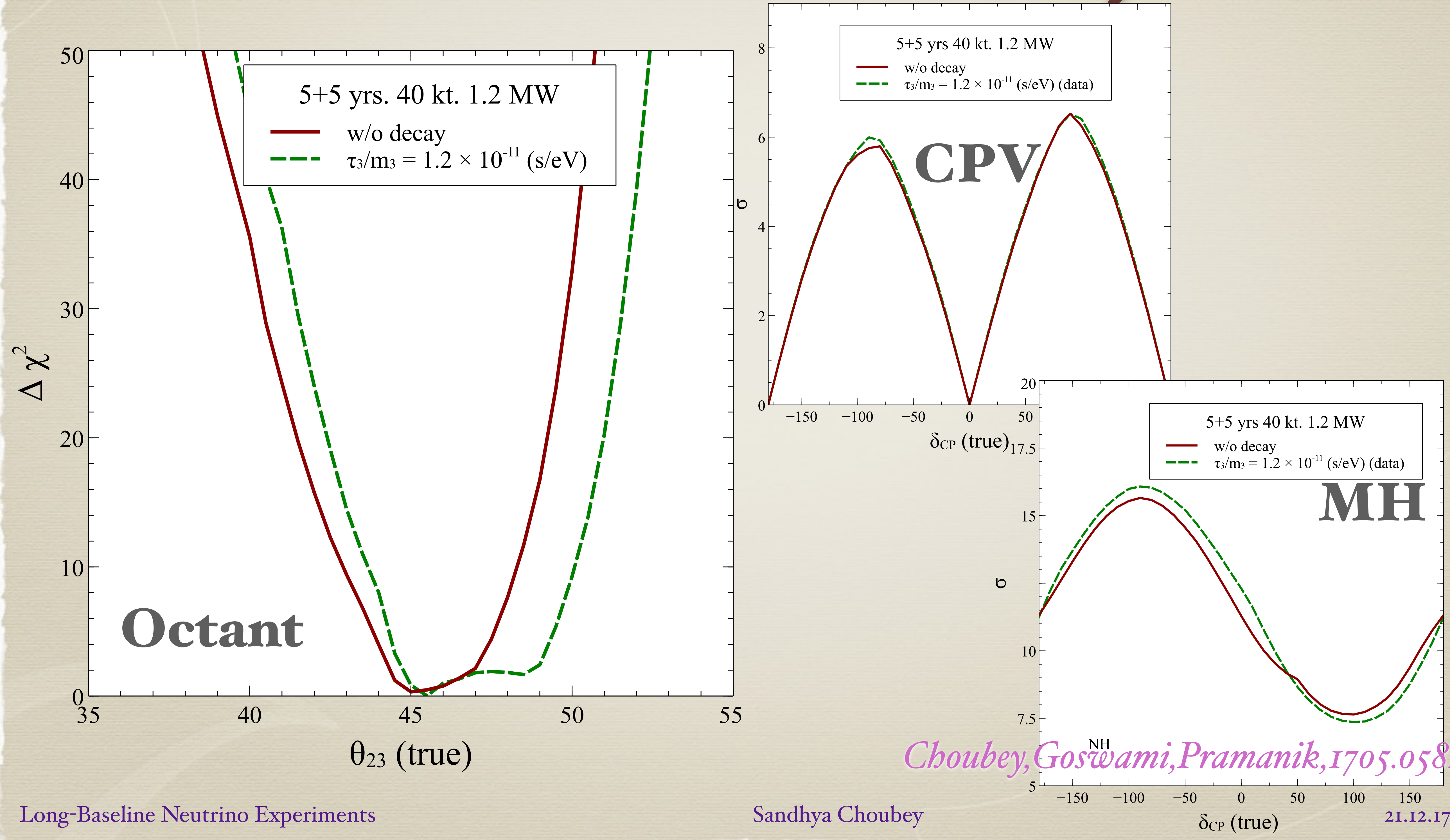
Choubey,Goswami,Pramanik,1705.05820

Impact of Invisible Neutrino Decay



Choubey,Goswami,Pramanik,1705.05820

Impact of Invisible Neutrino Decay



Choubey,Goswami,Pramanik,1705.05820

NSI

If there exist effective operators of the form

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{ff'C} \left(\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta\right)\left(\overline{f}\gamma_\mu P_C f'\right)$$

then they will modify neutrino evolution inside matter

$$\hat{H} = \frac{1}{2E}\left[U{\rm diag}(m_1^2, m_2^2, m_3^2)U^\dagger + {\rm diag}(A,0,0) + A\varepsilon^m\right]$$

These epsilon parameters are called matter NSIs

The corresponding epsilon parameters in an effective charged current operator are called source/detector NSIs

Impact of Matter NSI

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \frac{1}{2E}\left\{U^\dagger\begin{bmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{bmatrix}U + A\begin{bmatrix}1+\varepsilon^m_{ee} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau}\\ \varepsilon^m_{\mu e} & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau}\\ \varepsilon^m_{\tau e} & \varepsilon^m_{\tau\mu} & \varepsilon^m_{\tau\tau}\end{bmatrix}\right\}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix}$$

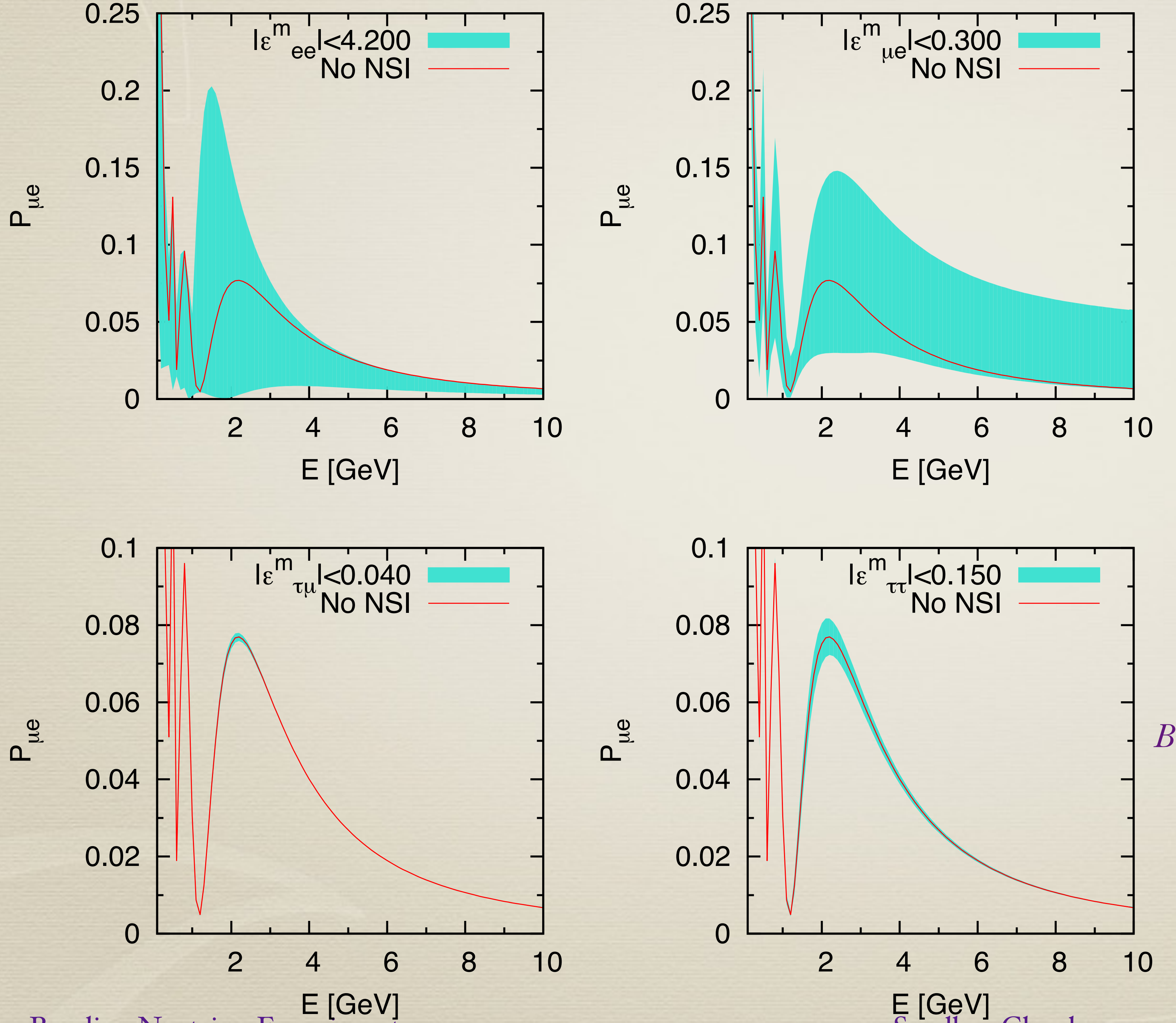
$$|\varepsilon^m_{\alpha\beta}| < \begin{bmatrix}4.2 & 0.3 & 3.0\\ 0.3 & - & 0.04\\ 3.0 & 0.04 & 0.15\end{bmatrix}$$

Biggio, blennow,Fernandez-Martinez, 0907.0097
see also Ohlsson (2013) and references therein

$$\varepsilon^m_{\alpha\beta} = \varepsilon^m_{\beta\alpha}{}^*$$

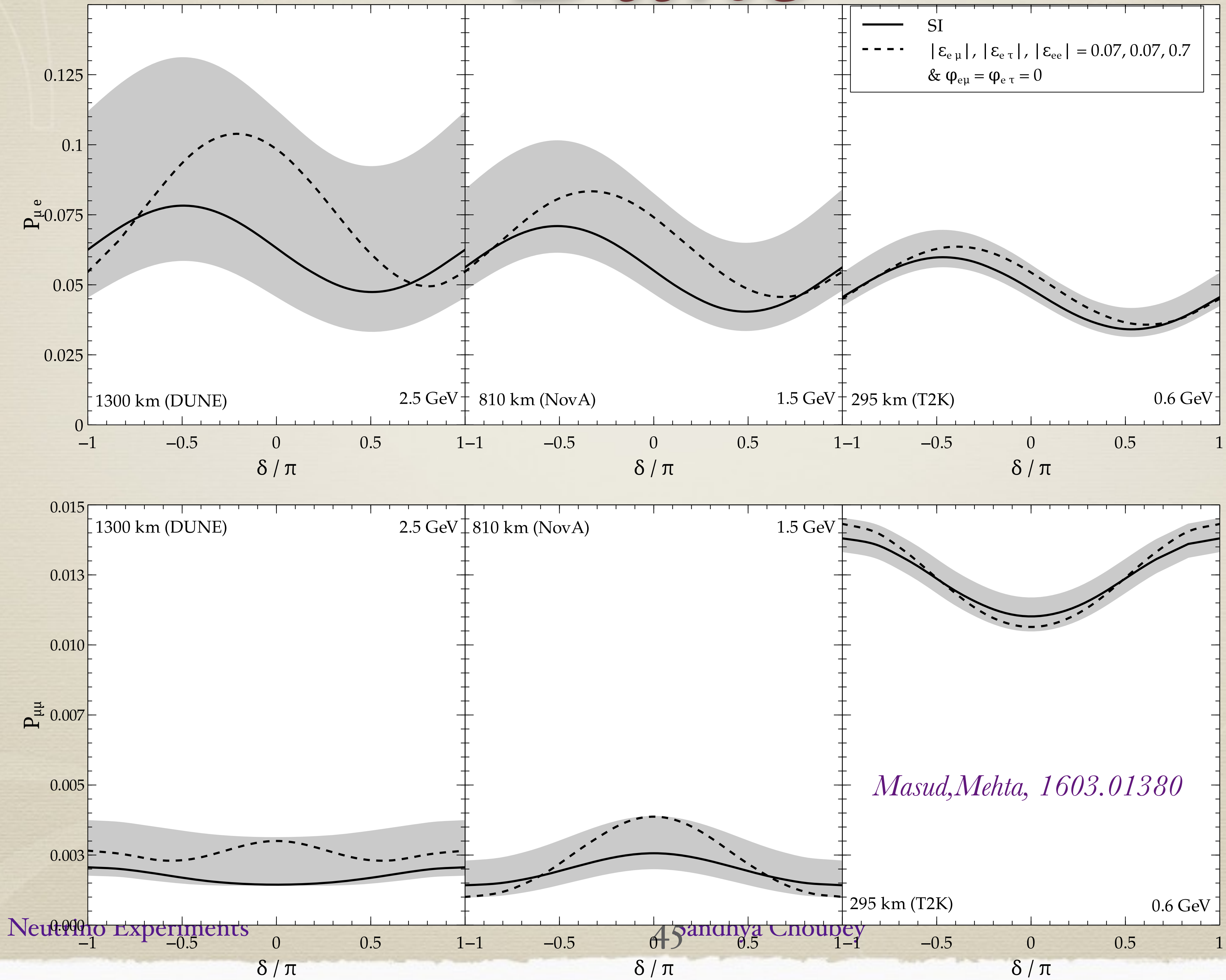
nine real parameters in the matter NSI matrix
six amplitudes and three phases

Impact of Matter NSI on Dune



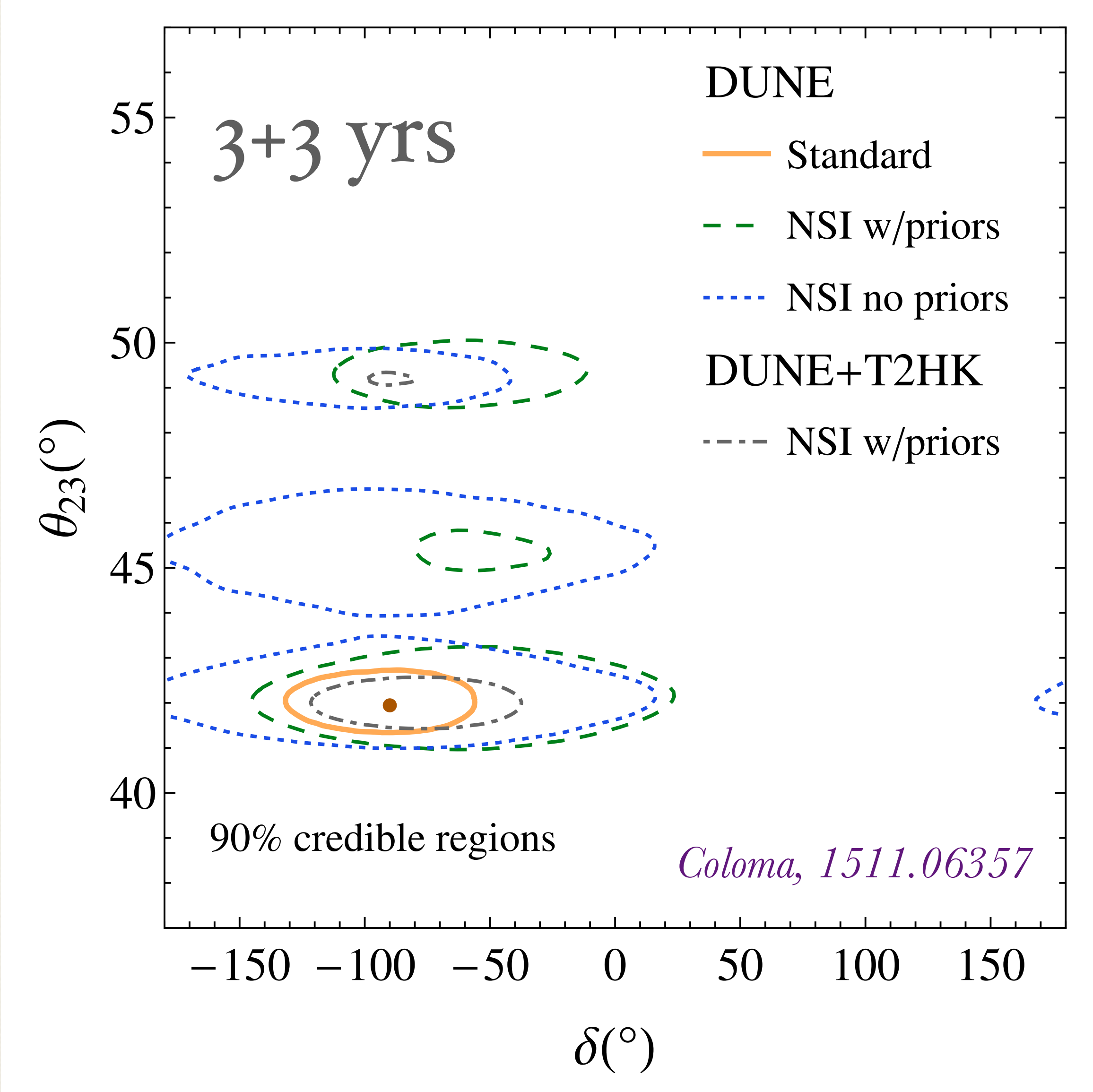
Blennow, S.C. Ohlsson, Pramanik, Raut, 1606.08851

Impact of Matter NSI on Dune



Masud,Mehta, 1603.01380

Impact of Matter NSI on Dune



Coloma, 1511.06357

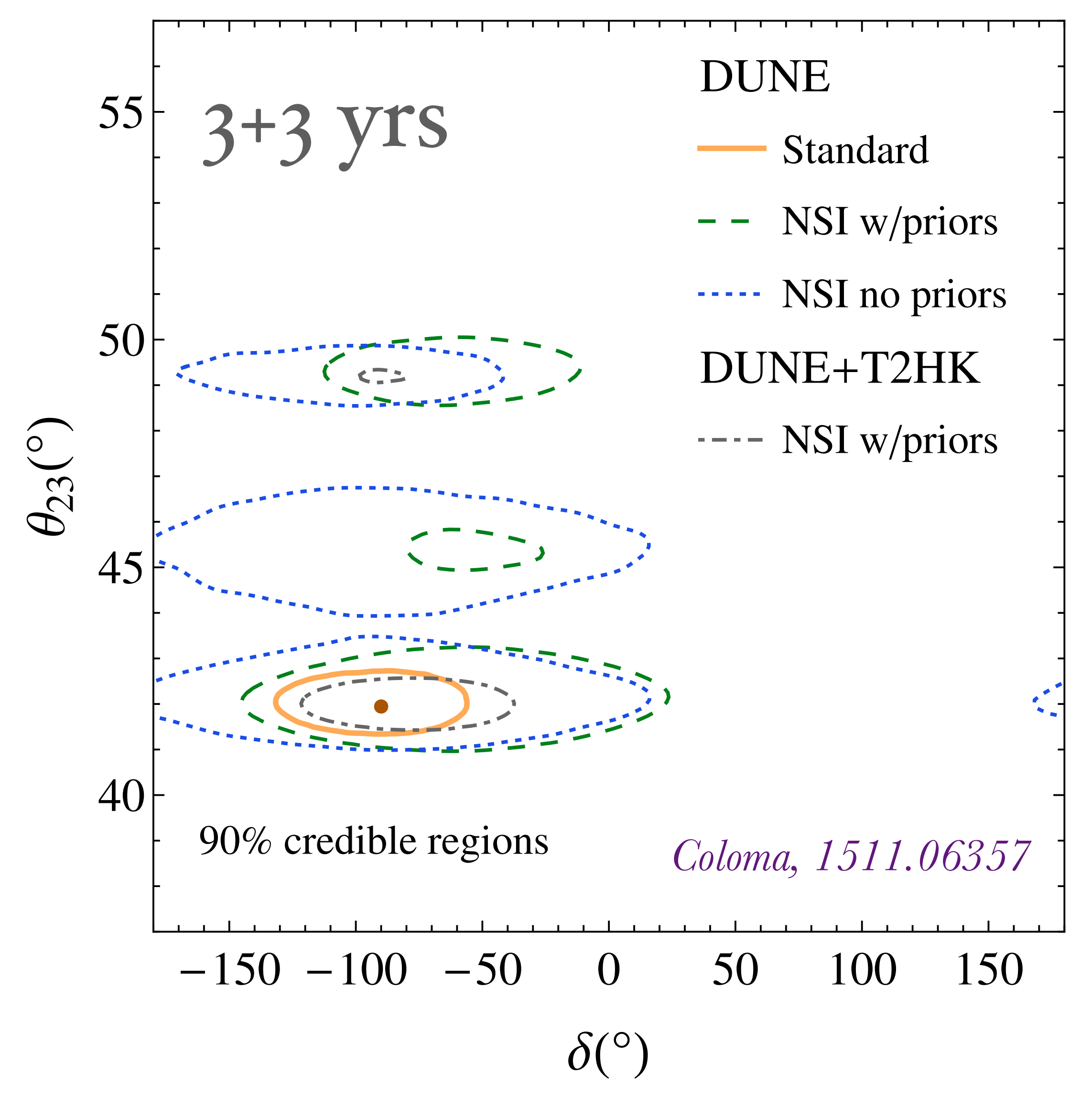
- *Scan of the entire matter NSI space performed with priors*

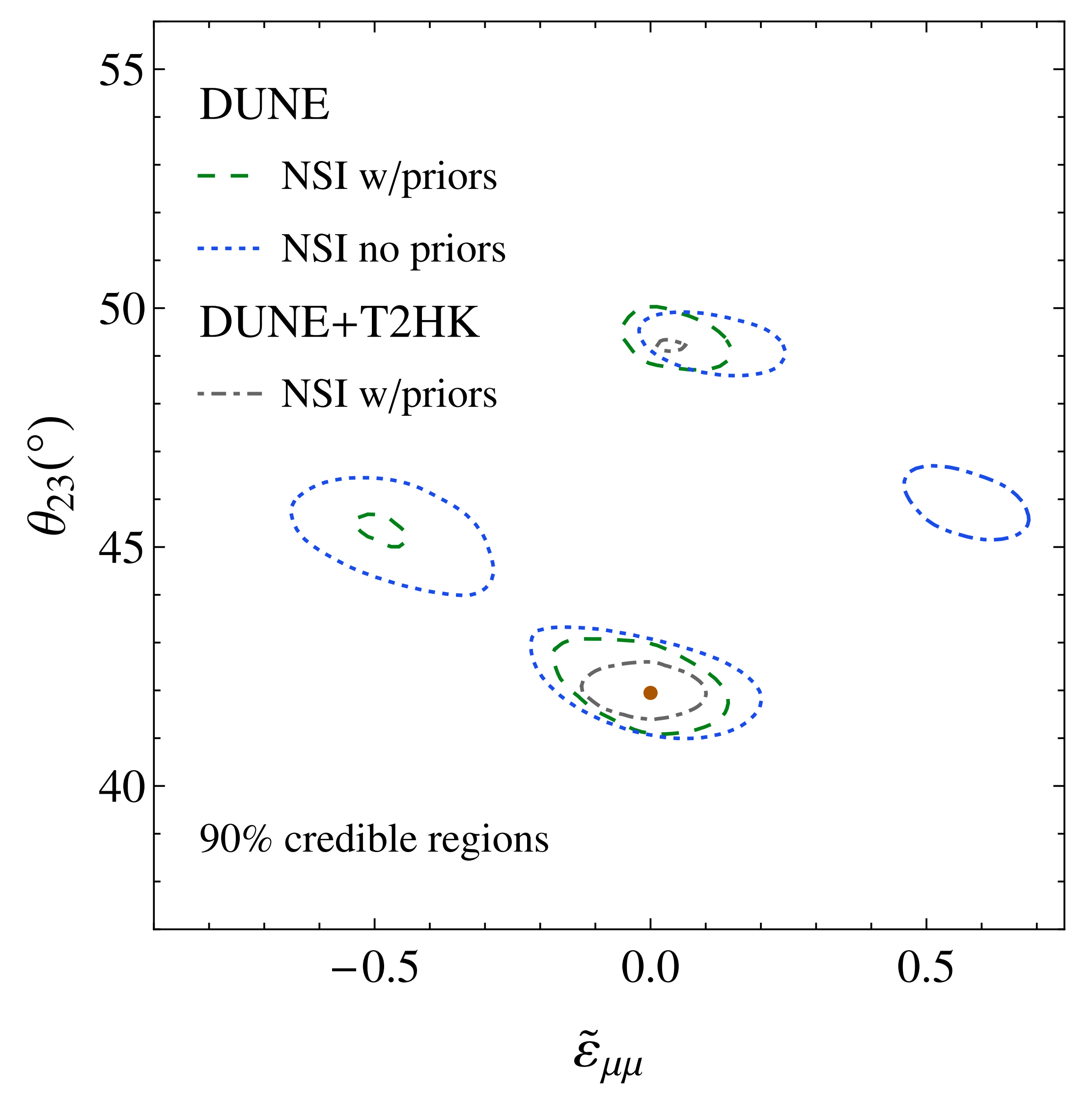
Rathin Adhikari's talk

See also,
Masud,Chatterjee,Mehta, 1510.08261
De Gouvea,Kelly, 1511.05562
Masud,Mehta, 1603.01380
Masud,Mehta1606.05662
Blennow, S.C. Ohlsson, Pramanik, Raut, 1606.08851
Agarwalla,Chakraborty,Palazzo,1607.01745
Bakhti,Khan, 1607.00065
Rout,Masud,Mehta, 1702.02163
Masud,Bishai,Mehta,1704.08650

- *Reduced sensitivity in delta*
- *New degenerate solutions in theta23*

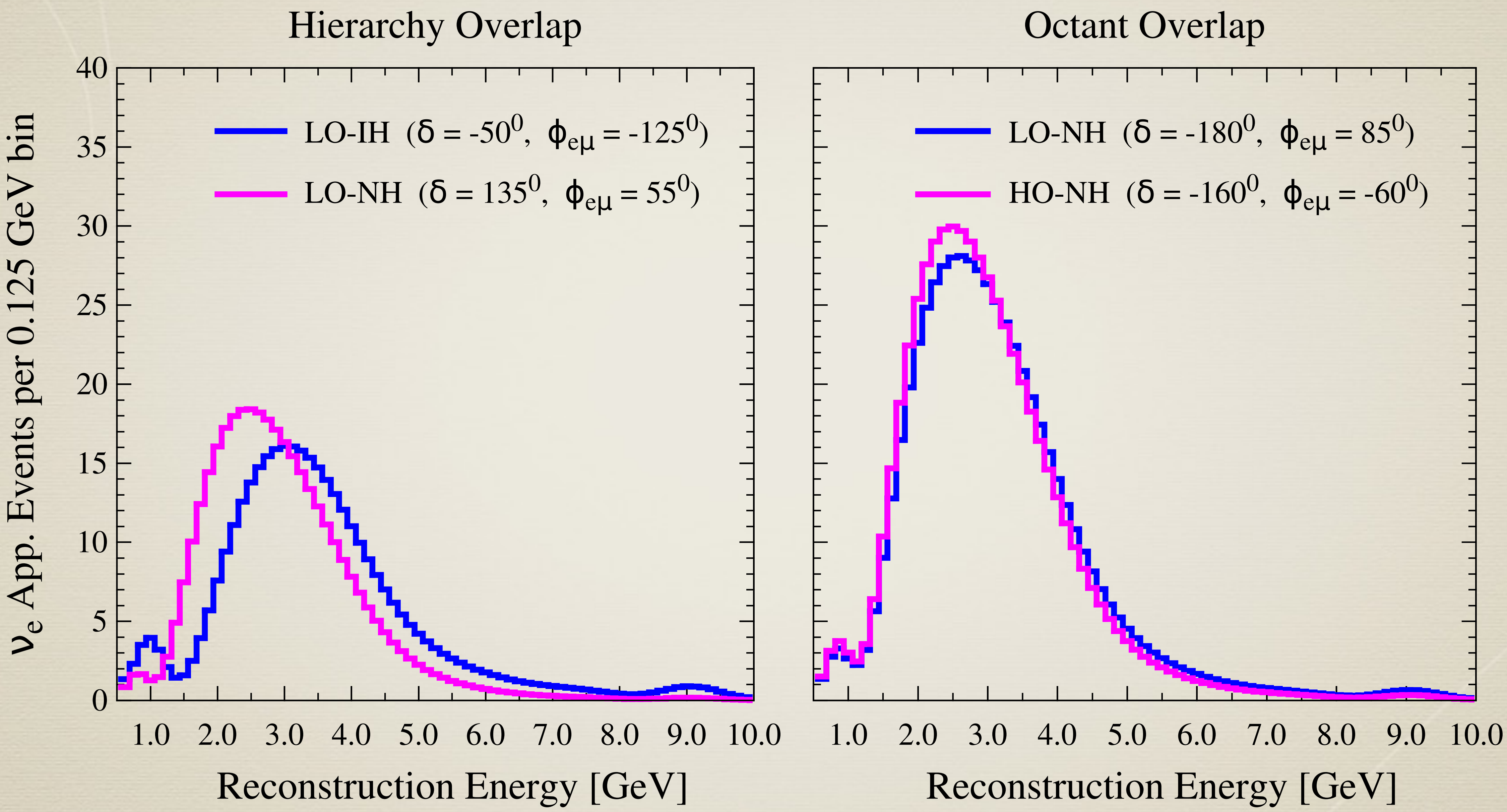
Impact of Matter NSI on CP Phase at Dune





- *Reduced sensitivity in delta*
- *New degenerate solutions in theta23*

Impact of Matter NSI on Hierarchy and theta23 octant



Agarwalla,Chakraborty,Palazzo,1607.01745

- *Other degeneracies e.g. between delta and* ϵ_{ee} *and* $\epsilon_{\tau e}$

Impact of Source and Detector NSI

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \varepsilon^s_{\alpha\gamma}|\nu_\gamma\rangle$$

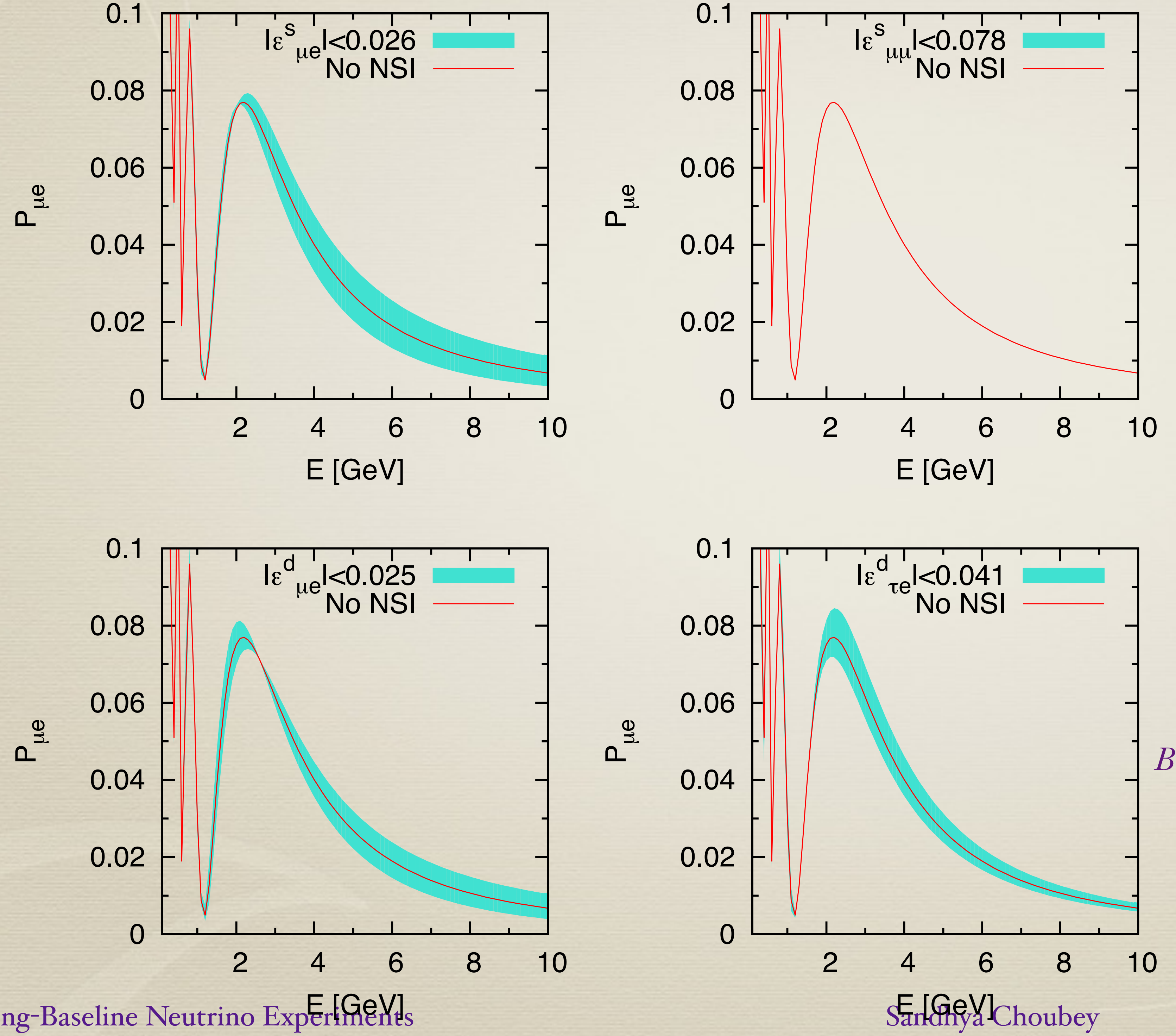
$$\langle\nu_\beta^d| = \langle\nu_\beta| + \sum_{\gamma=e,\mu,\tau} \varepsilon^d_{\gamma\beta}\langle\nu_\gamma|$$

The matrices ε^s and ε^d that represent the source and the detector NSIs, repectively, are in general complex matrices with 18 real parameters each. These are the nine amplitudes $|\varepsilon^{s/d}_{\alpha\beta}|$ and nine phases $\varphi^{s/d}_{\alpha\beta}$.

$$|\varepsilon^{s/d}_{\alpha\beta}| < \begin{bmatrix} 0.041 & 0.025 & 0.041 \\ 0.026 & 0.078 & 0.013 \\ 0.12 & 0.018 & 0.13 \end{bmatrix}$$

Biggio, blennow,Fernandez-Martinez, 0907.0097

Impact of Source and Detector NSI



Blennow, S.C. Ohlsson, Pramanik, Raut, 1606.08851

Correlation between S/D and Matter NSI

$$P_{\mu e} \supset -4\varepsilon^d_{\tau e}\tilde{s}_{13}s^2_{23}c_{23}\cos\delta\left[\sin^2\frac{AL}{4E}-\sin^2\frac{\Delta m^2_{31}L}{4E}-\sin^2\frac{(\Delta m^2_{31}-A)L}{4E}\right]$$
$$-2\varepsilon^d_{\tau e}\tilde{s}_{13}s^2_{23}c_{23}\sin\delta\left[\sin\frac{AL}{2E}-\sin\frac{\Delta m^2_{31}L}{2E}+\sin\frac{(\Delta m^2_{31}-A)L}{2E}\right]$$
$$+4\varepsilon^m_{\tau e}\tilde{s}_{13}s^2_{23}c_{23}\cos\delta\left[\sin^2\frac{AL}{4E}-\sin^2\frac{\Delta m^2_{31}L}{4E}+\sin^2\frac{(\Delta m^2_{31}-A)L}{4E}\right]$$
$$+2\varepsilon^m_{\tau e}\tilde{s}_{13}s^2_{23}c_{23}\sin\delta\left[\sin\frac{AL}{2E}-\sin\frac{\Delta m^2_{31}L}{2E}+\sin\frac{(\Delta m^2_{31}-A)L}{2E}\right]$$
$$+8\varepsilon^m_{\tau e}\tilde{s}_{13}s^2_{23}c_{23}\cos\delta\frac{A}{\Delta m^2_{31}-A}\sin^2\frac{(\Delta m^2_{31}-A)L}{4E},$$

Kopp, Lindner, Ota, Sato, 0708.0152

$$\varepsilon^m_{\tau e}-\varepsilon^d_{\tau e}$$

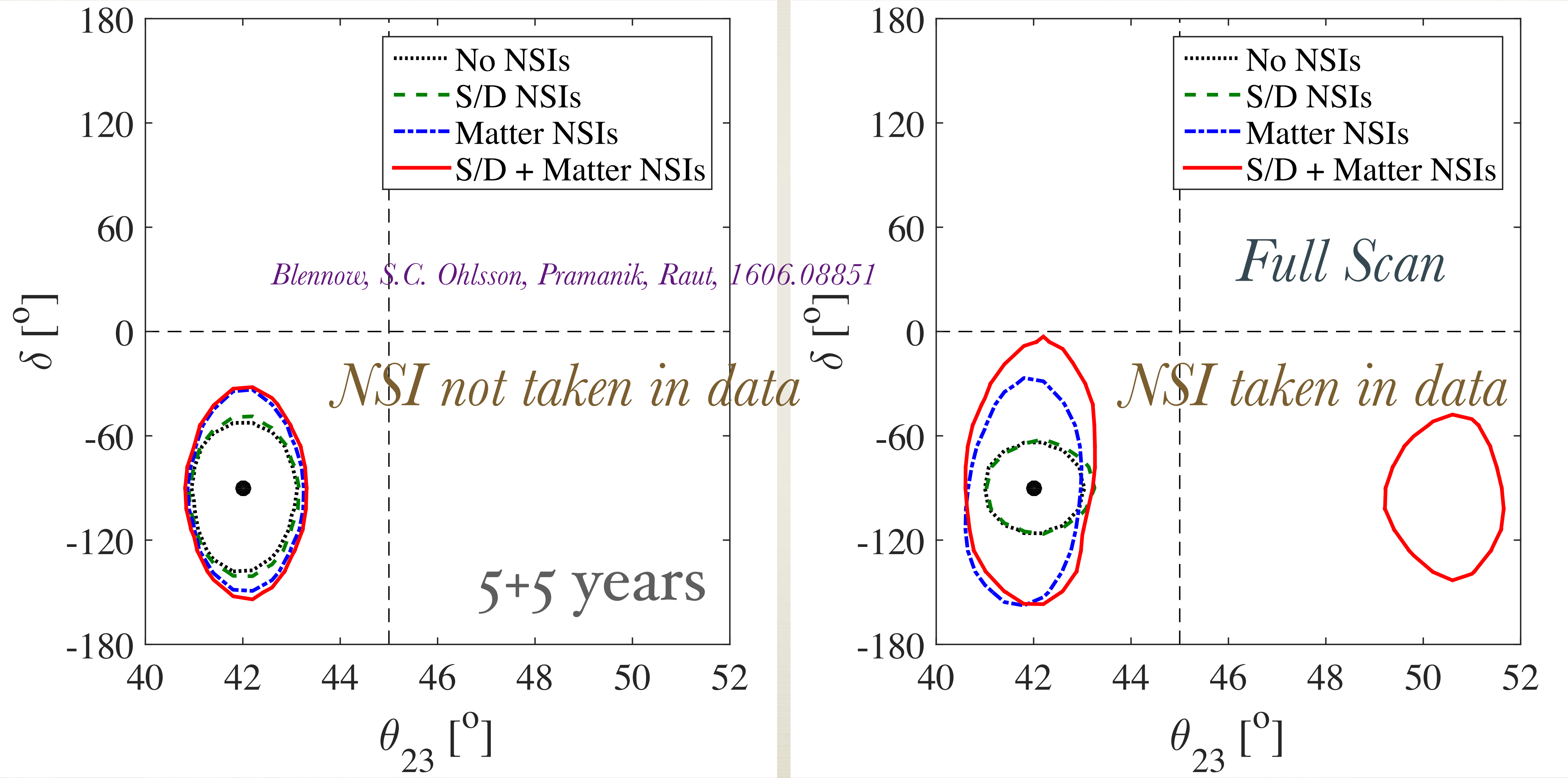
$$P_{\mu e} \supset -4\varepsilon^d_{\tau e}\tilde{s}_{13}s^2_{23}c_{23}\cos\delta\left[\sin^2\frac{AL}{4E}-\sin^2\frac{\Delta m^2_{31}L}{4E}-\sin^2\frac{(\Delta m^2_{31}-A)L}{4E}\right]$$
$$-2\varepsilon^d_{\tau e}\tilde{s}_{13}s^2_{23}c_{23}\sin\delta\left[\sin\frac{AL}{2E}-\sin\frac{\Delta m^2_{31}L}{2E}+\sin\frac{(\Delta m^2_{31}-A)L}{2E}\right]$$
$$-4\varepsilon^m_{\mu e}\tilde{s}_{13}s_{23}c^2_{23}\cos\delta\left[\sin^2\frac{AL}{4E}-\sin^2\frac{\Delta m^2_{31}L}{4E}+\sin^2\frac{(\Delta m^2_{31}-A)L}{4E}\right]$$
$$-2\varepsilon^m_{\mu e}\tilde{s}_{13}s_{23}c^2_{23}\sin\delta\left[\sin\frac{AL}{2E}-\sin\frac{\Delta m^2_{31}L}{2E}+\sin\frac{(\Delta m^2_{31}-A)L}{2E}\right]$$
$$+8\varepsilon^m_{\mu e}\tilde{s}_{13}s^3_{23}\cos\delta\frac{A}{\Delta m^2_{31}-A}\sin^2\frac{(\Delta m^2_{31}-A)L}{4E}.$$

Kopp, Lindner, Ota, Sato, 0708.0152

$$\varepsilon^m_{\mu e}+\varepsilon^d_{\tau e}$$

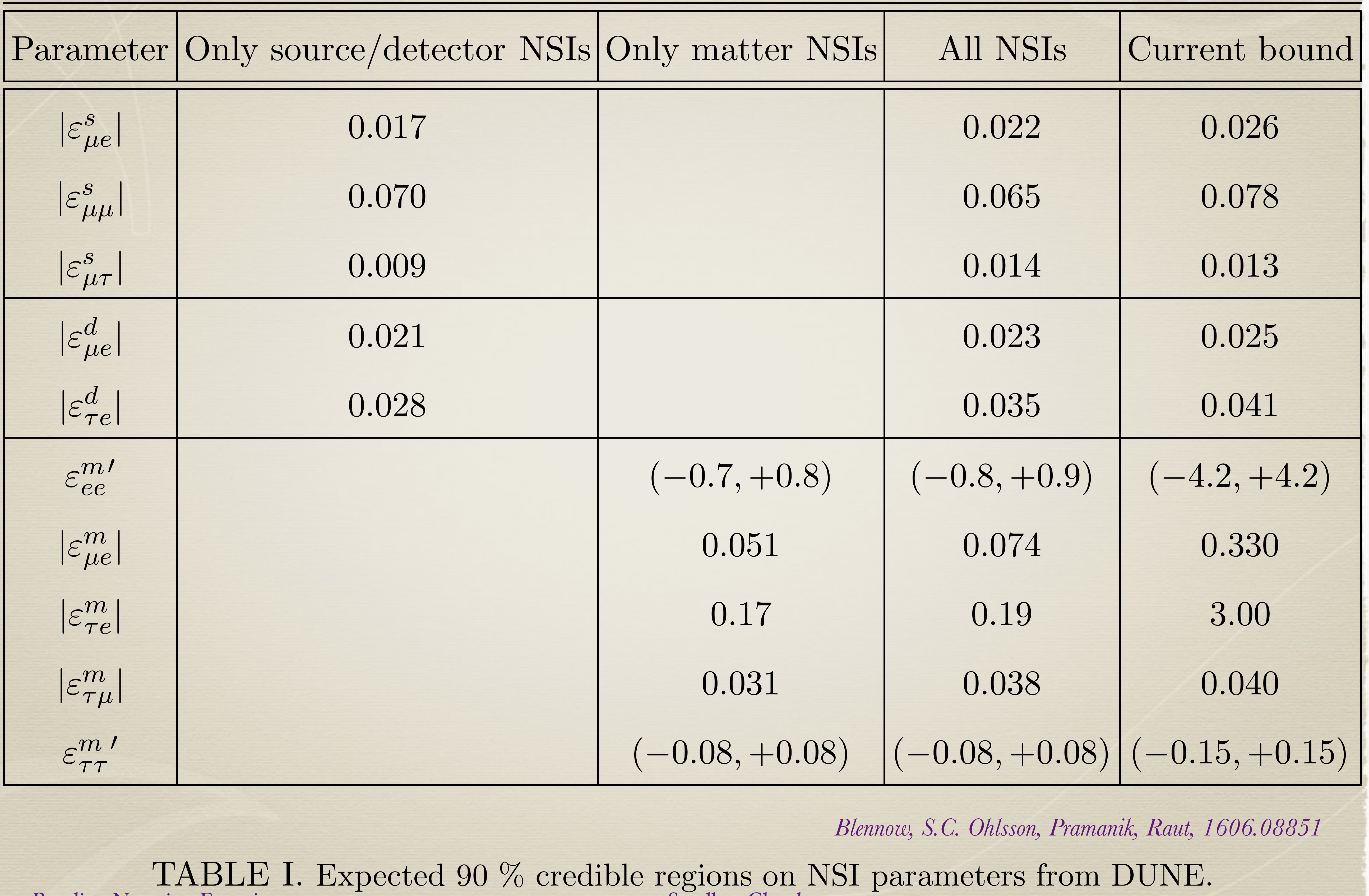
- *Very strange to believe that matter NSI exist and S/D NSI do not*
- *One should perform a* **combined analysis** *of both S/D and matter*

Combined Analysis of all NSI at DUNE



- *Correlations between matter and S/D NSIs lead to a new degenerate solution in theta23*

Constraining NSI at DUNE



Parameter	Only source/detector NSIs	Only matter NSIs	All NSIs	Current bound
$\|\varepsilon^s_{\mu e}\|$	0.017		0.022	0.026
$\|\varepsilon^s_{\mu\mu}\|$	0.070		0.065	0.078
$\|\varepsilon^s_{\mu\tau}\|$	0.009		0.014	0.013
$\|\varepsilon^d_{\mu e}\|$	0.021		0.023	0.025
$\|\varepsilon^d_{\tau e}\|$	0.028		0.035	0.041
$\varepsilon^{m\,\prime}_{ee}$		$(-0.7, +0.8)$	$(-0.8, +0.9)$	$(-4.2, +4.2)$
$\|\varepsilon^m_{\mu e}\|$		0.051	0.074	0.330
$\|\varepsilon^m_{\tau e}\|$		0.17	0.19	3.00
$\|\varepsilon^m_{\tau\mu}\|$		0.031	0.038	0.040
$\varepsilon^{m\,\prime}_{\tau\tau}$		$(-0.08, +0.08)$	$(-0.08, +0.08)$	$(-0.15, +0.15)$

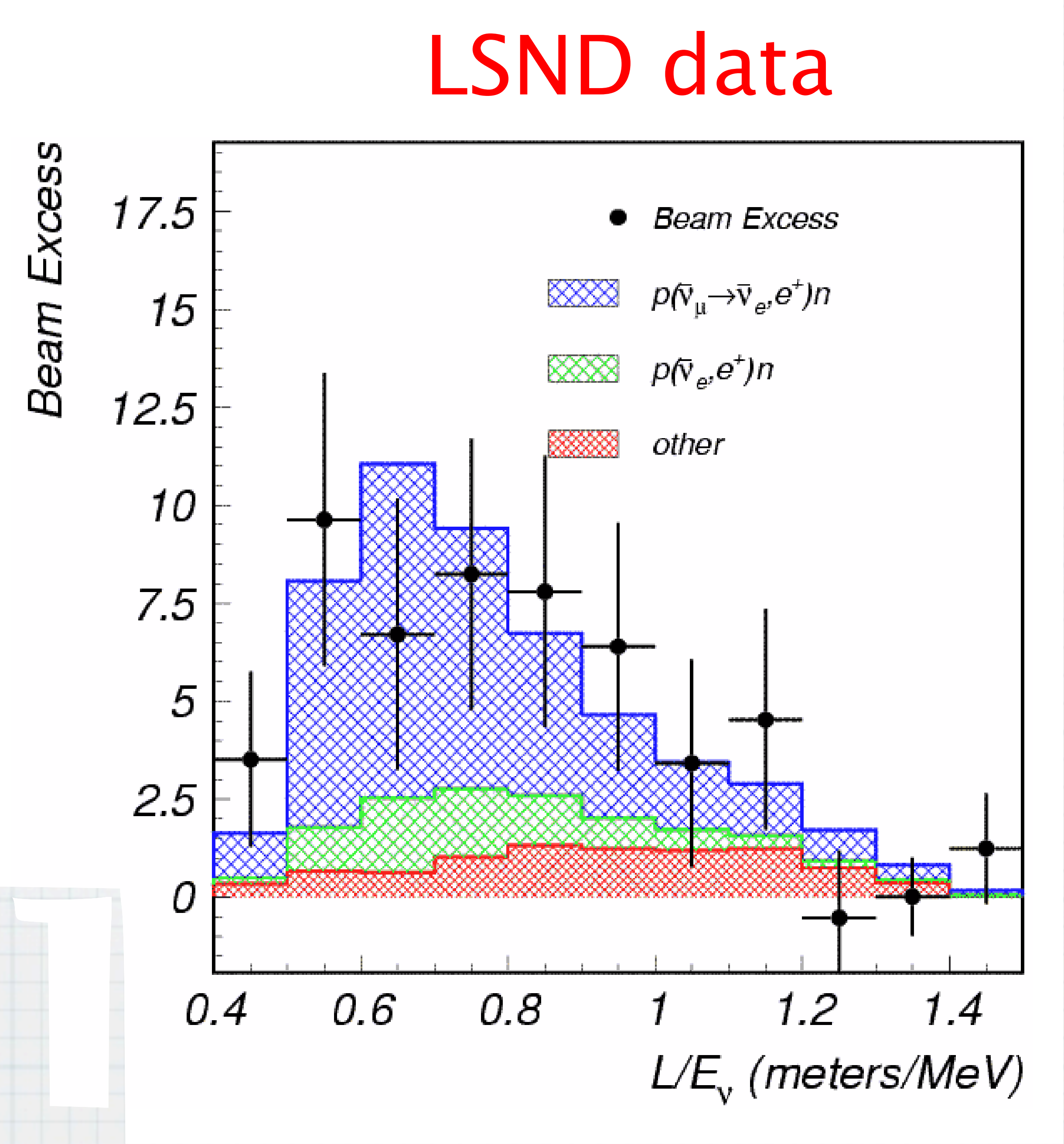
Blennow, S.C. Ohlsson, Pramanik, Raut, 1606.08851

TABLE I. Expected 90 % credible regions on NSI parameters from DUNE.

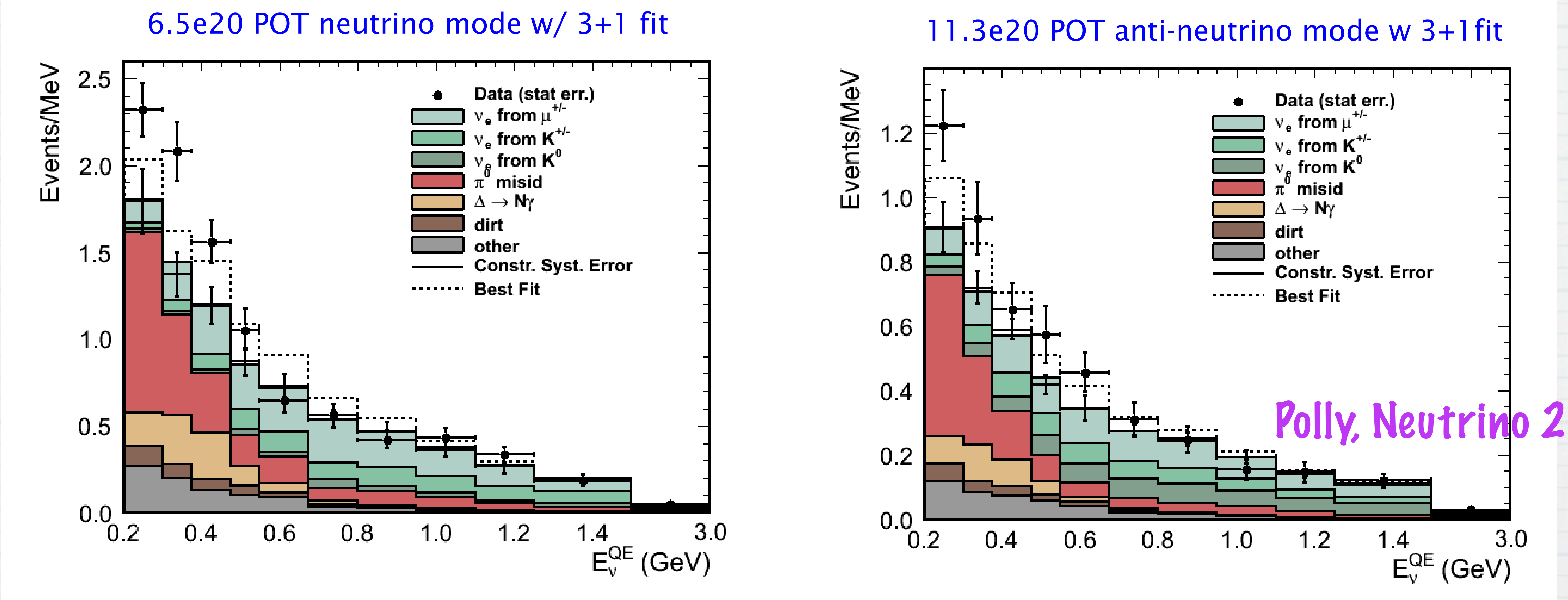
Sterile Neutrinos

LSND

- 3.8σ excess in antineutrinos at L/E ≈ 0.4-1.2 m/MeV
- requires presence of sterile neutrino states with $\Delta m^2 = 1\ eV^2$



MiniBooNE



6.5e20 POT neutrino mode w/ 3+1 fit

11.3e20 POT anti-neutrino mode w 3+1fit

Polly, Neutrino 2012

- Neutrino and anti-neutrino data now consistent
- Together they see a 3.8σ excess....LSND??

Sterile nu Oscillations

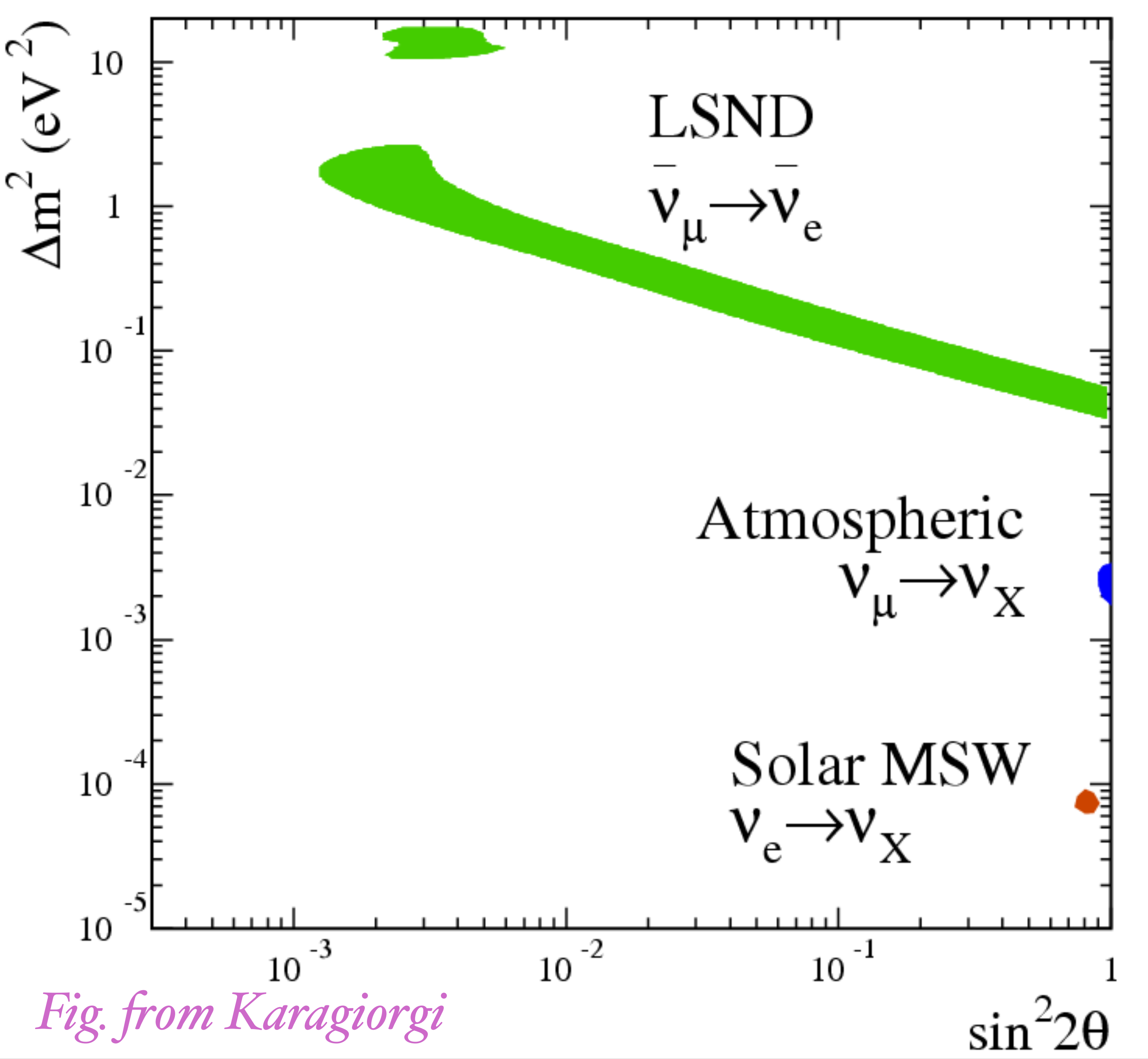


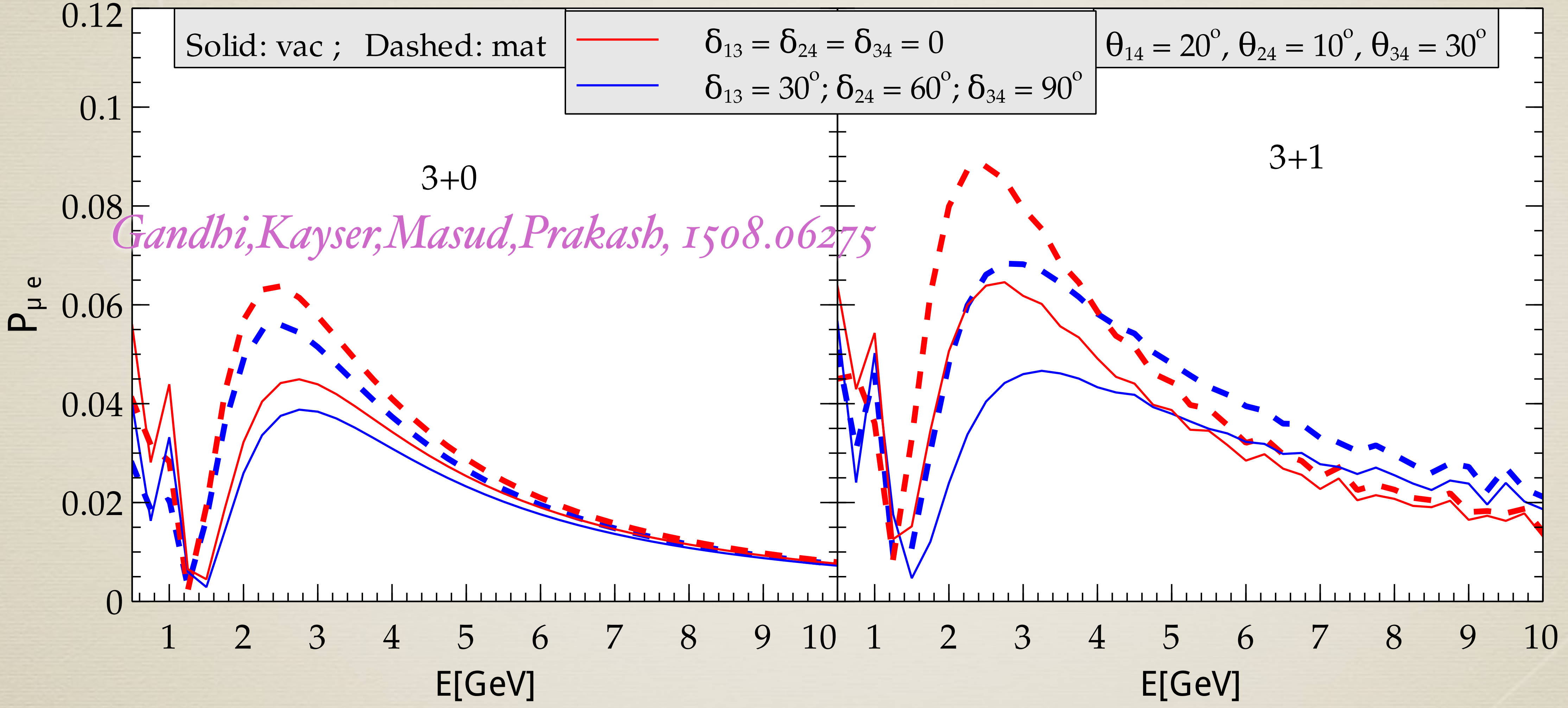
Fig. from Karagiorgi

An additional 4th neutrino is needed

The neutrino mass spectrum allowed are

3+1	*S. Goswami (1995)*
3+2	*Karagiorgi et al (2006)*
1+3+1	*Choubey,Haries,Ross(2006)*

Impact of Sterile Neutrinos on Dune

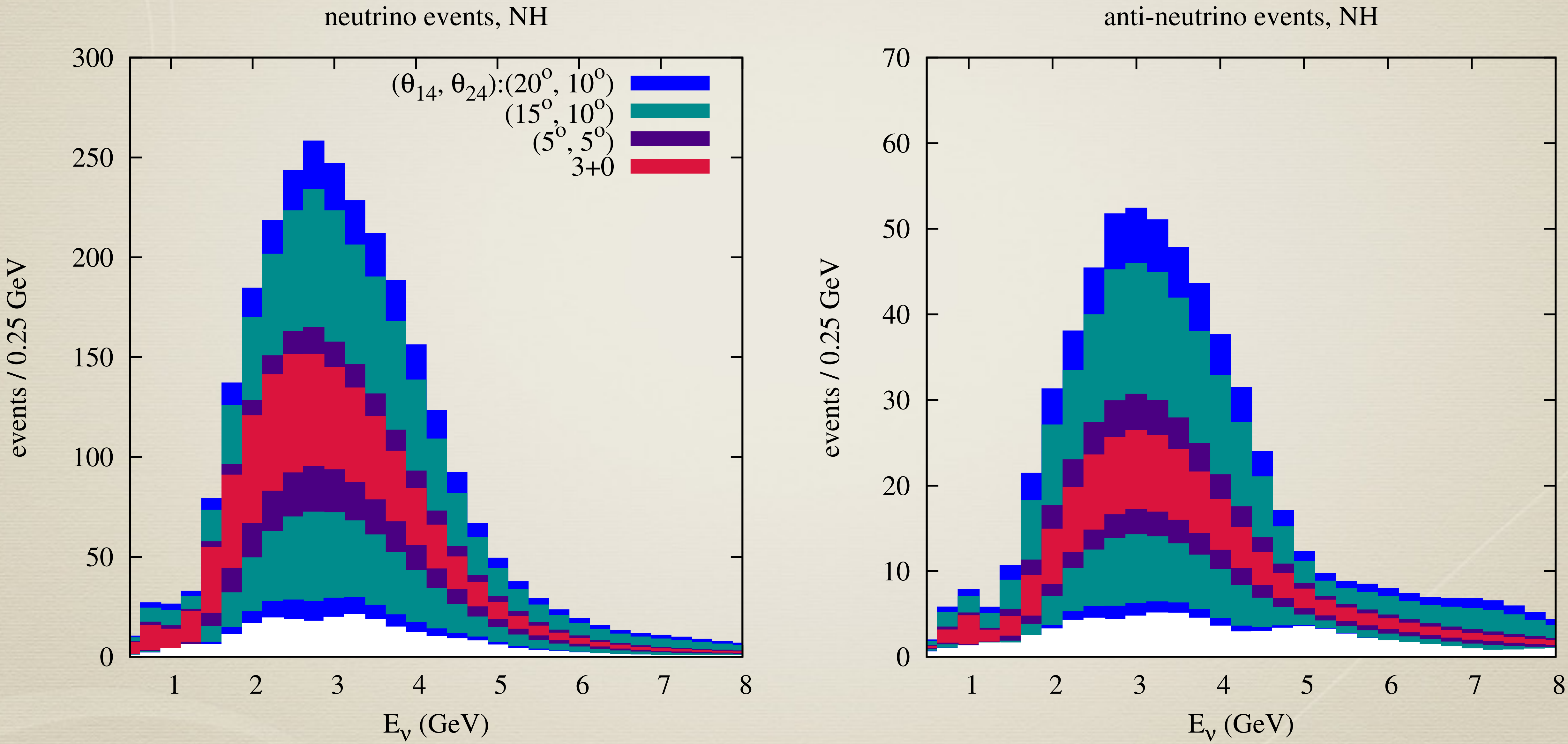


Gandhi,Kayser,Masud,Prakash, 1508.06275

S.C., Dutta, Pramanik, 1704.07269
S.C., Dutta, Pramanik, 1711.07464
Coloma,Forero,Parke, 1707.05348
Gandhi,Kayser,Prakash,Roy,1708.01816

Klop,Palazzo,1412.7524
Berryman,de Gouvea,Kelly,Kobach,1507.03986
Agarwalla,Chakraborty,Palazzo,1603.03759
Agarwalla,Chakraborty,Palazzo,1605.04299
Dutta,Gandhi,Kayser,Masud,Prakash,1607.02152

Impact of Sterile Neutrinos on Dune

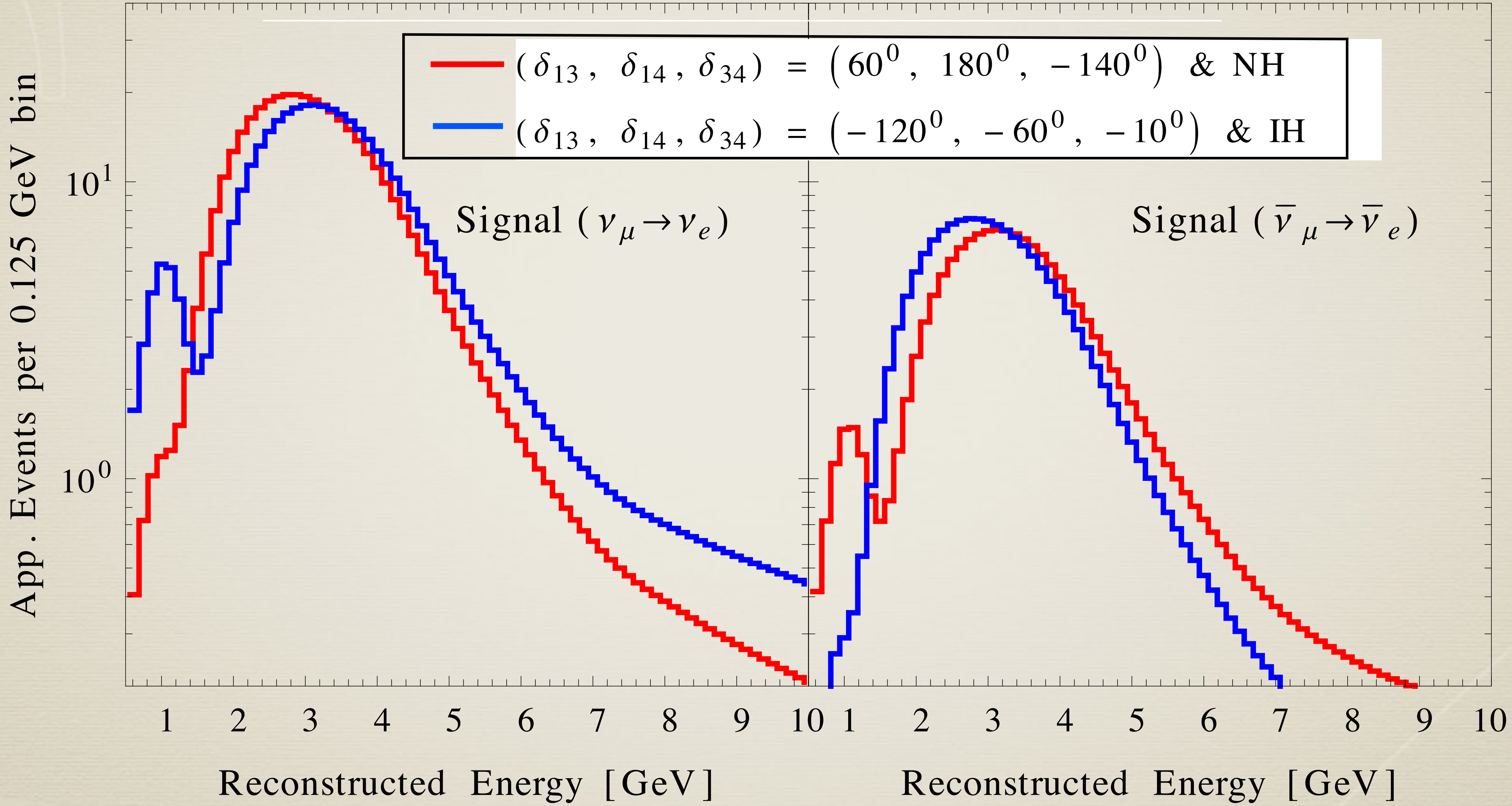


neutrino events, NH

anti-neutrino events, NH

Gandhi,Kayser,Masud,Prakash, 1508.06275

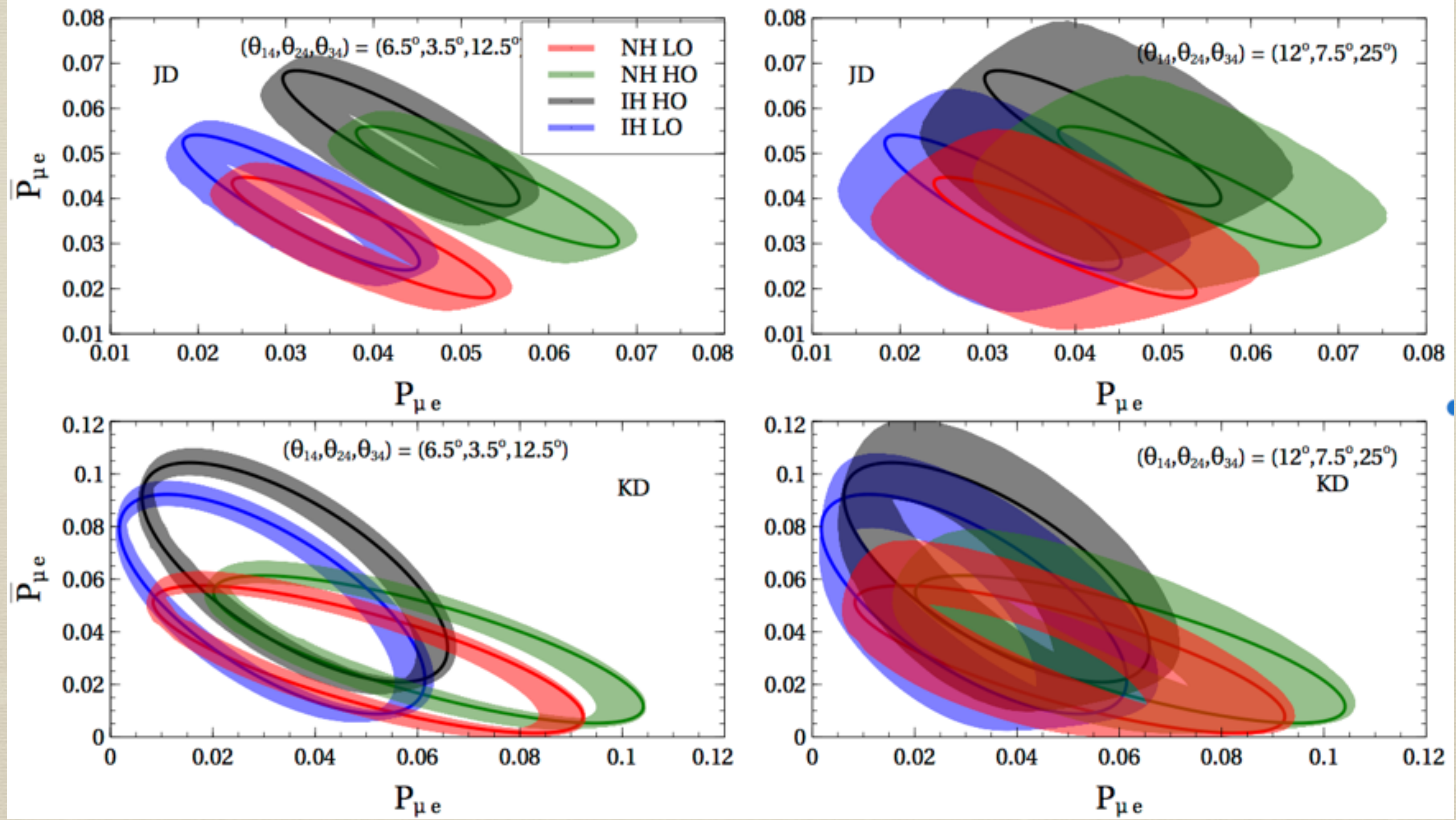
Impact of Sterile Neutrinos on Dune



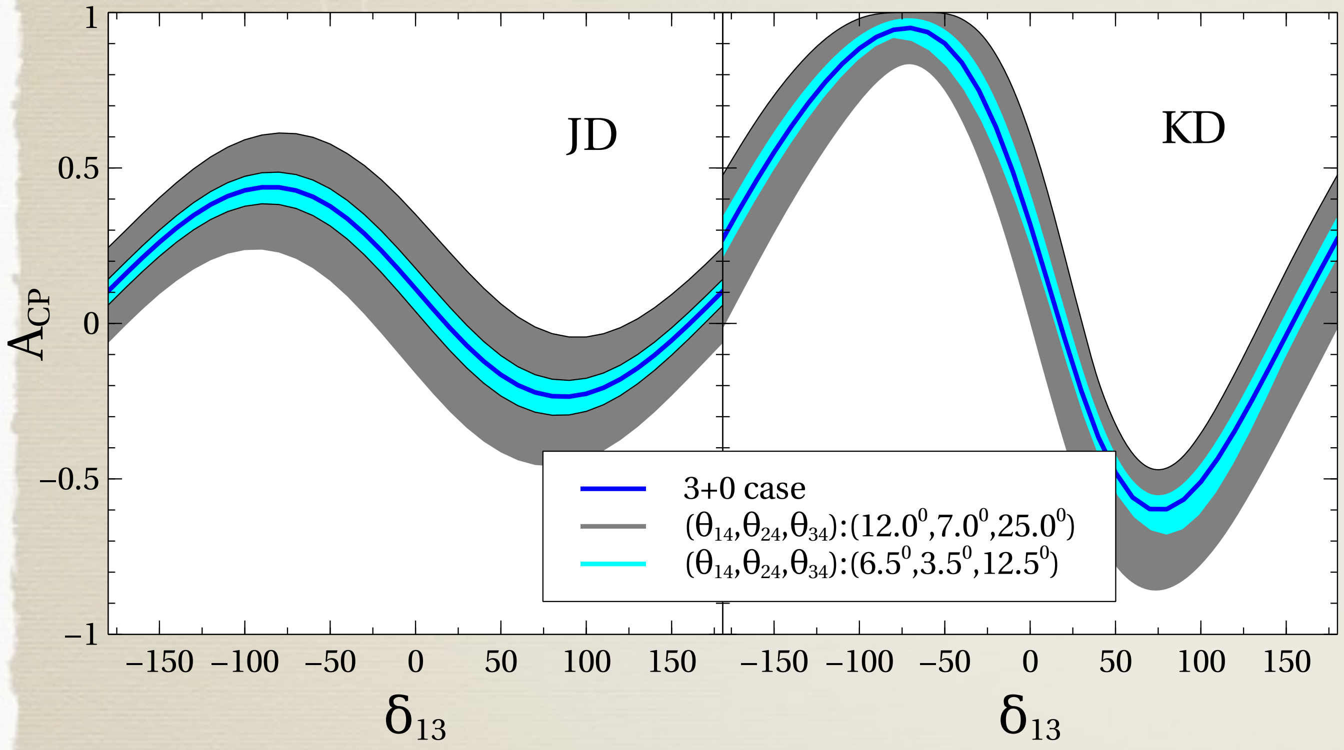
Agarwalla,Chakraborty,Palazzo,1603.03759

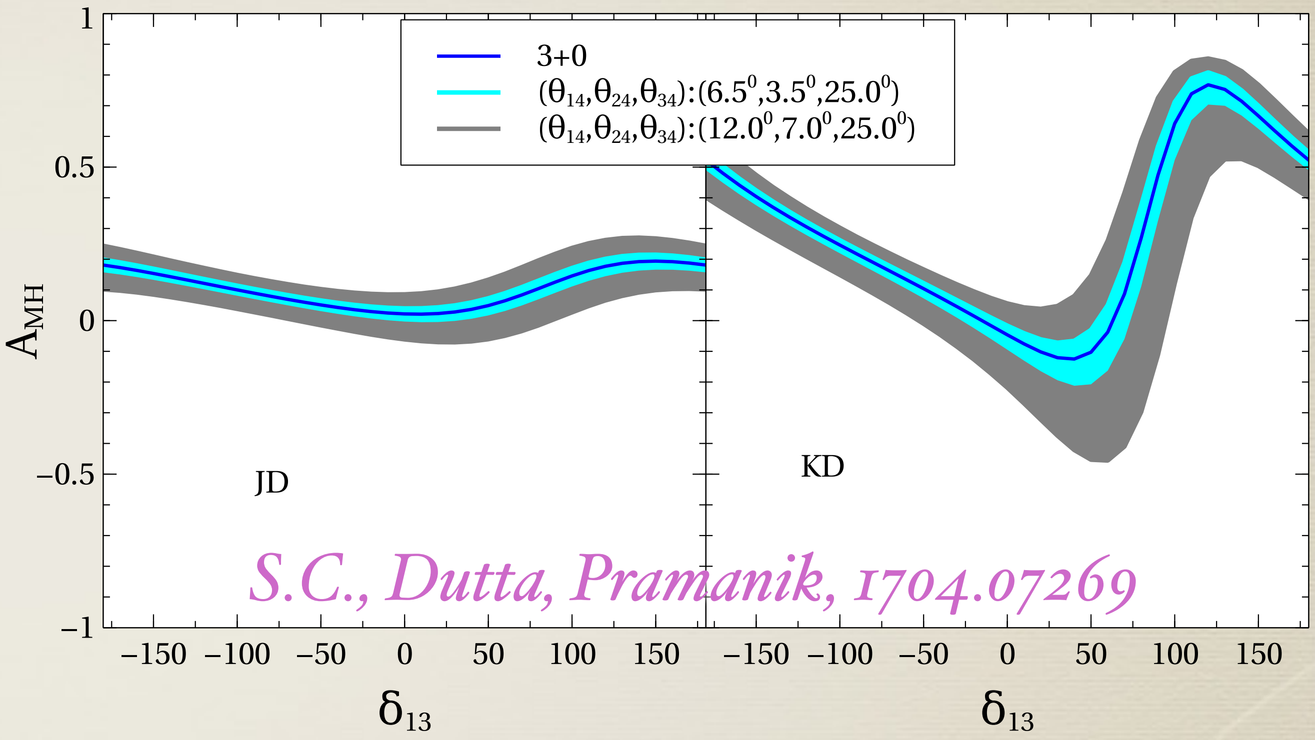
Impact of Sterile Neutrinos on T2HK/T2HKK

S.C., Dutta, Pramanik, 1704.07269



Impact of Sterile Neutrinos on T2HK/T2HKK

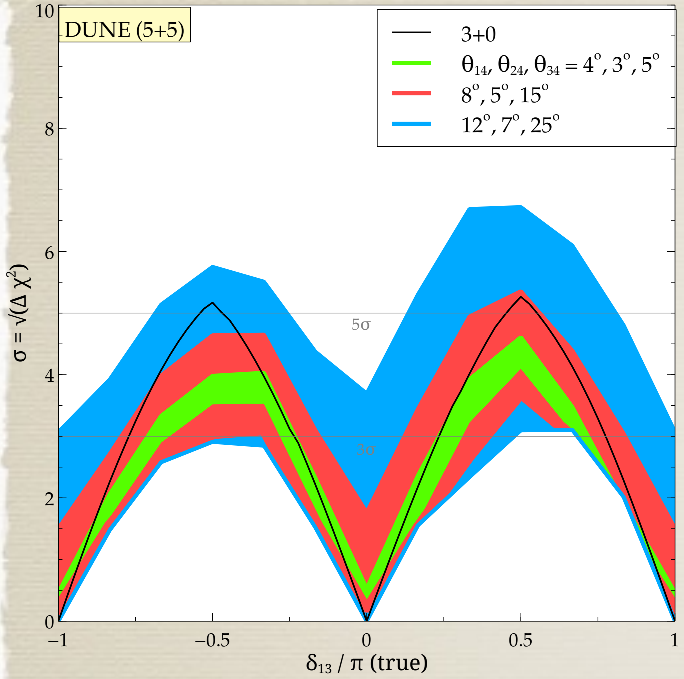




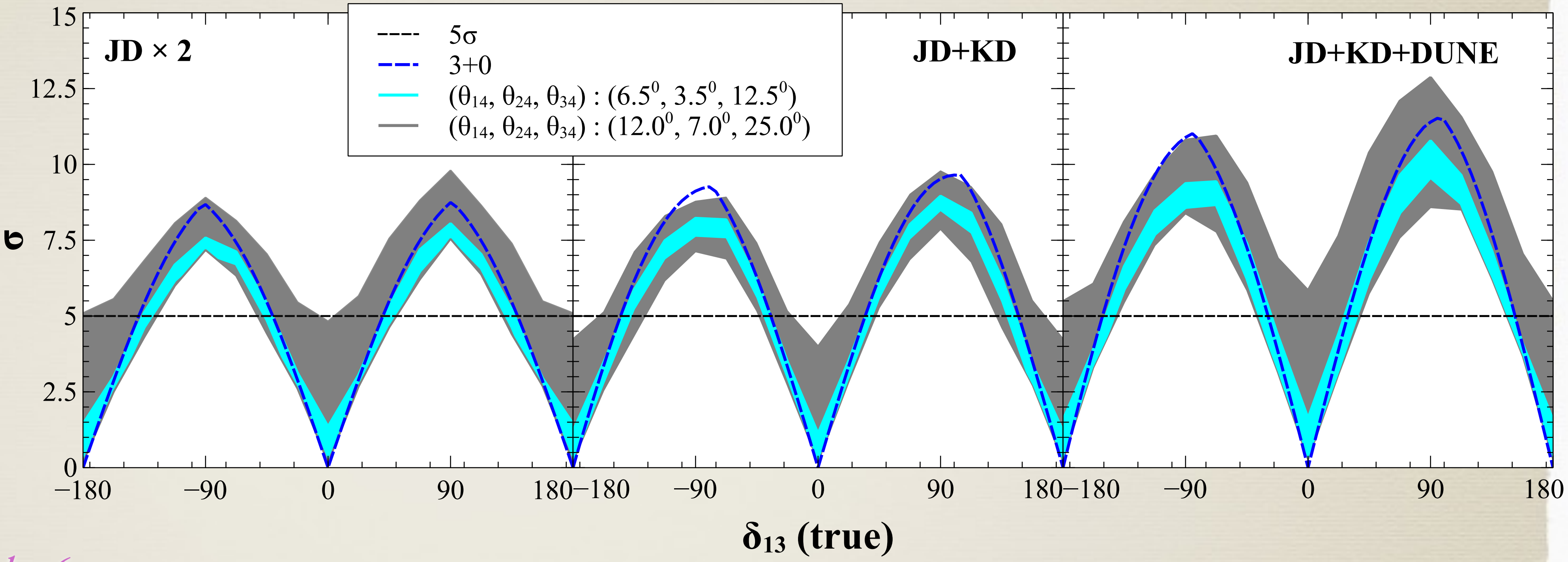
S.C., Dutta, Pramanik, 1704.07269

$$A_{CP} = \frac{P_{\mu e} - \bar{P}_{\mu e}}{P_{\mu e} + \bar{P}_{\mu e}} \qquad A_{MH} = \frac{P^{NH}_{\mu e} - P^{IH}_{\mu e}}{P^{NH}_{\mu e} + P^{IH}_{\mu e}}$$

Impact of Sterile Neutrinos on CPV at T2HK and DUNE

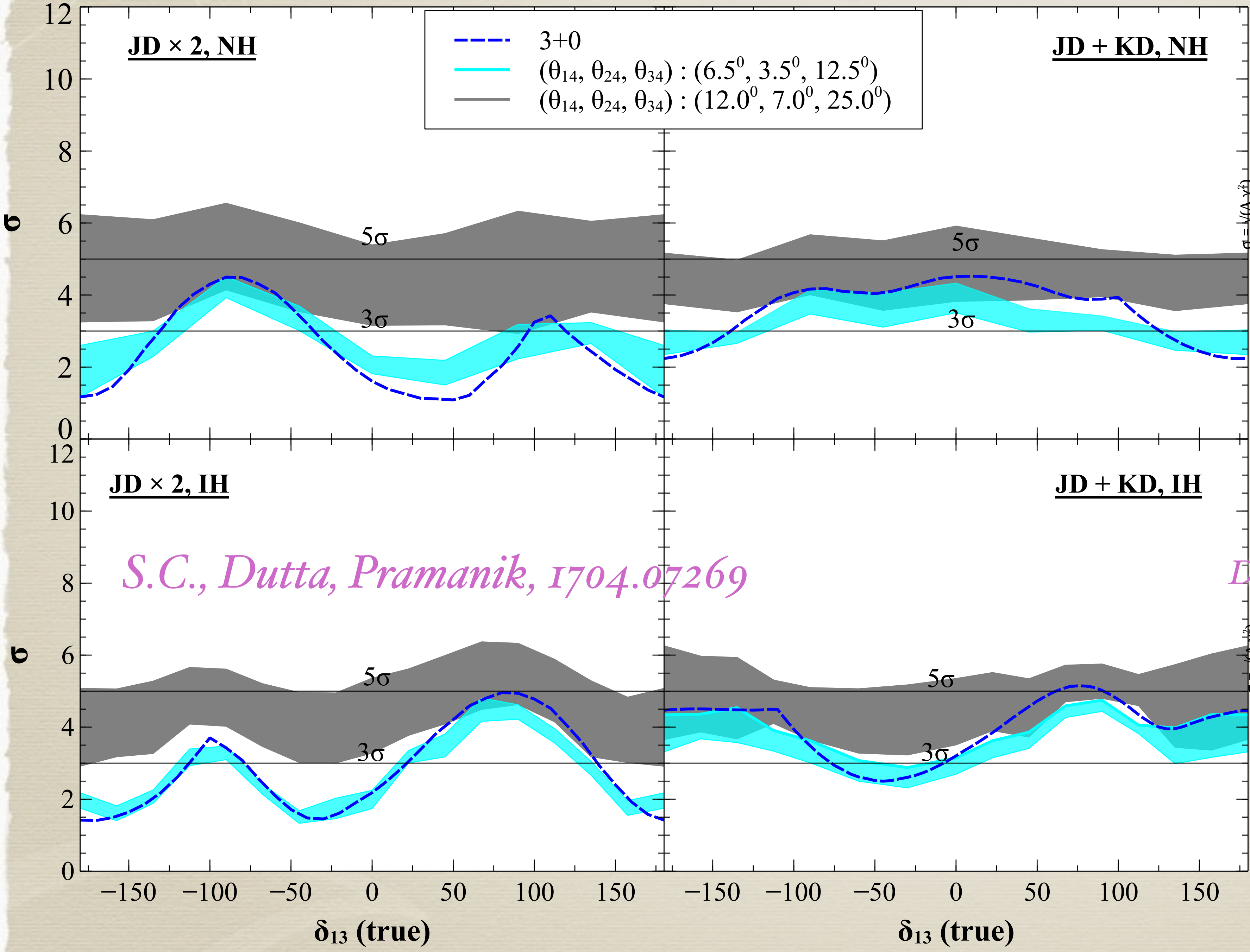


Dutta,Gandhi,Kayser,Masud,Prakash, 1607.02152

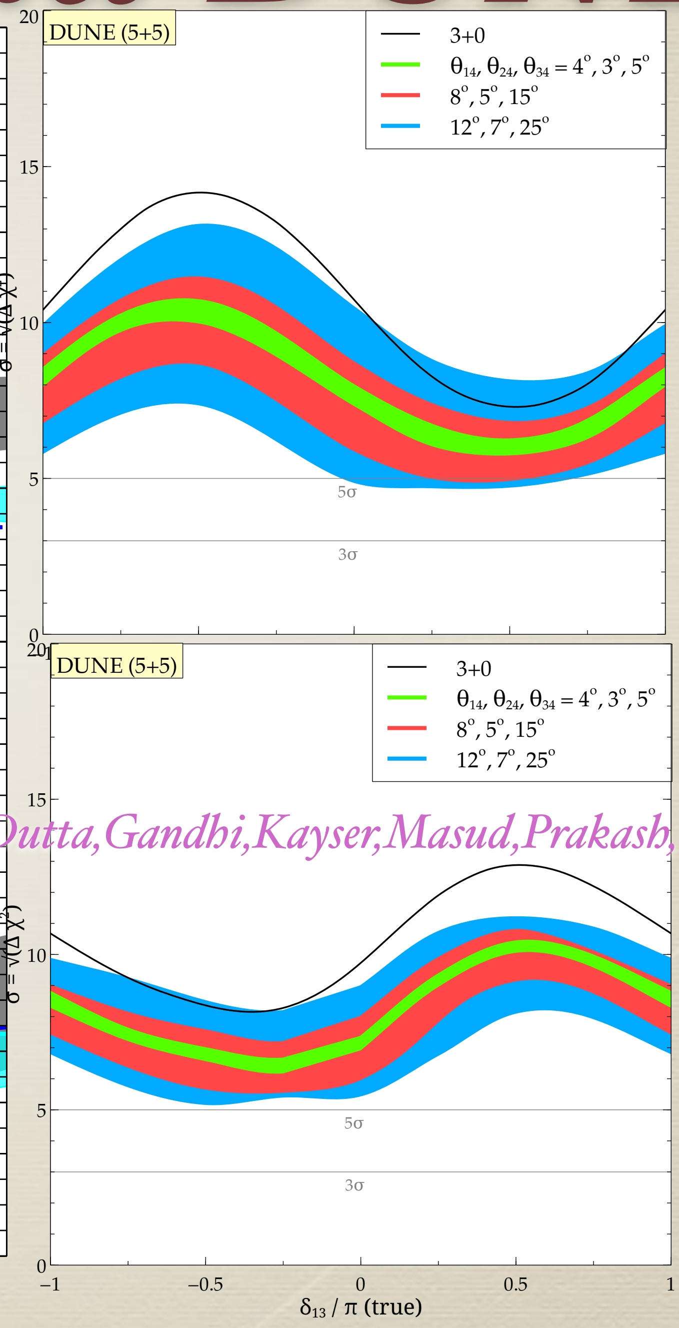


S.C., Dutta, Pramanik, 1704.07269

Impact of Sterile Neutrinos on MH at T2HK and DUNE

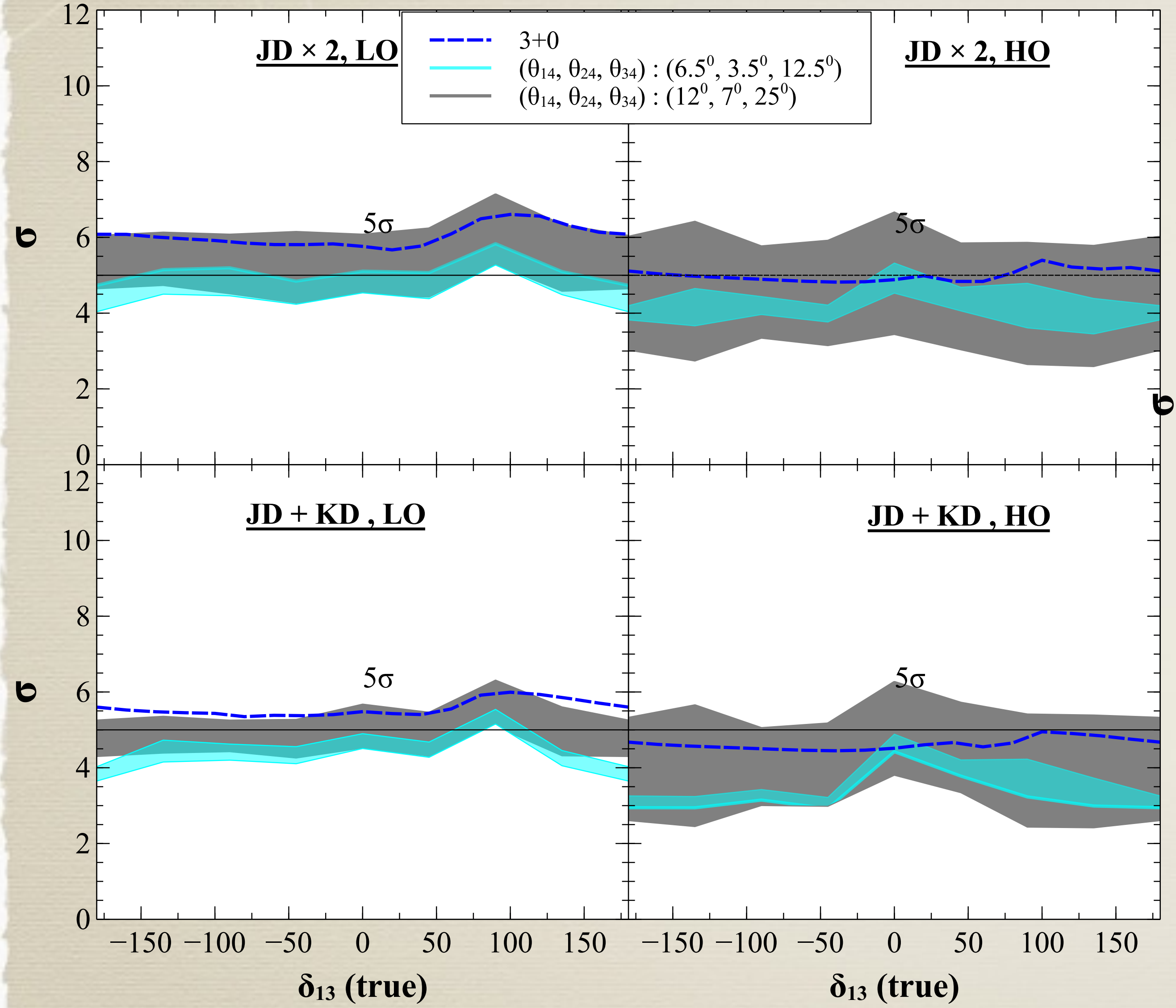


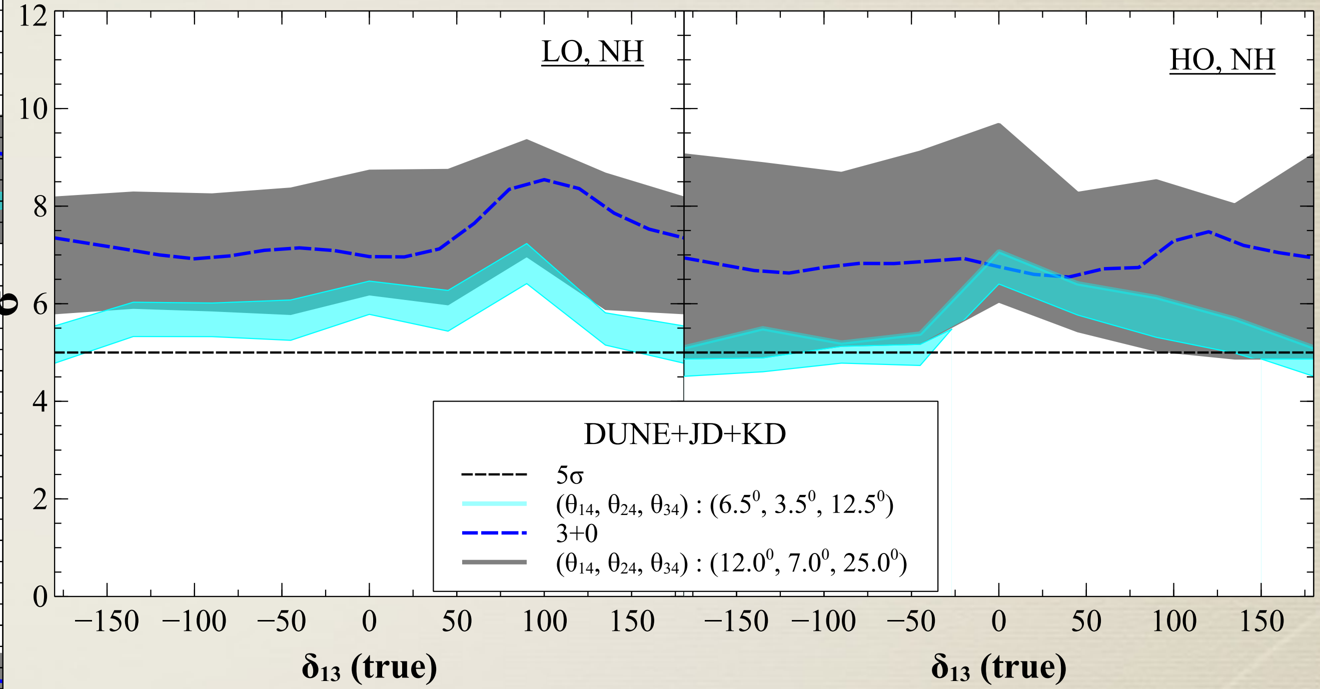
S.C., Dutta, Pramanik, 1704.07269



Dutta,Gandhi,Kayser,Masud,Prakash, 1607.02152

Impact of Sterile Neutrinos on octant at T2HK and DUNE

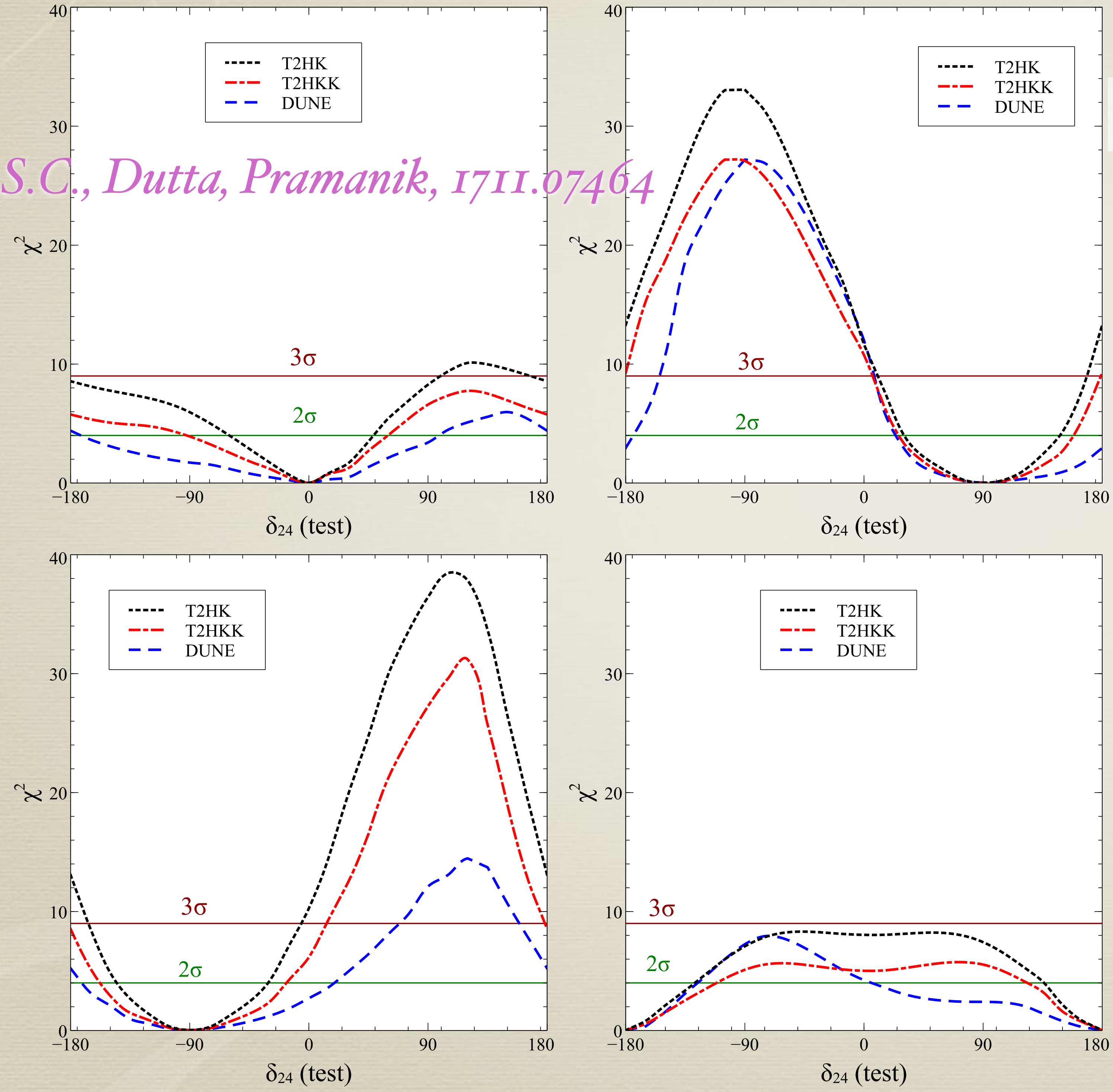




More in Sabya Sachi's talk

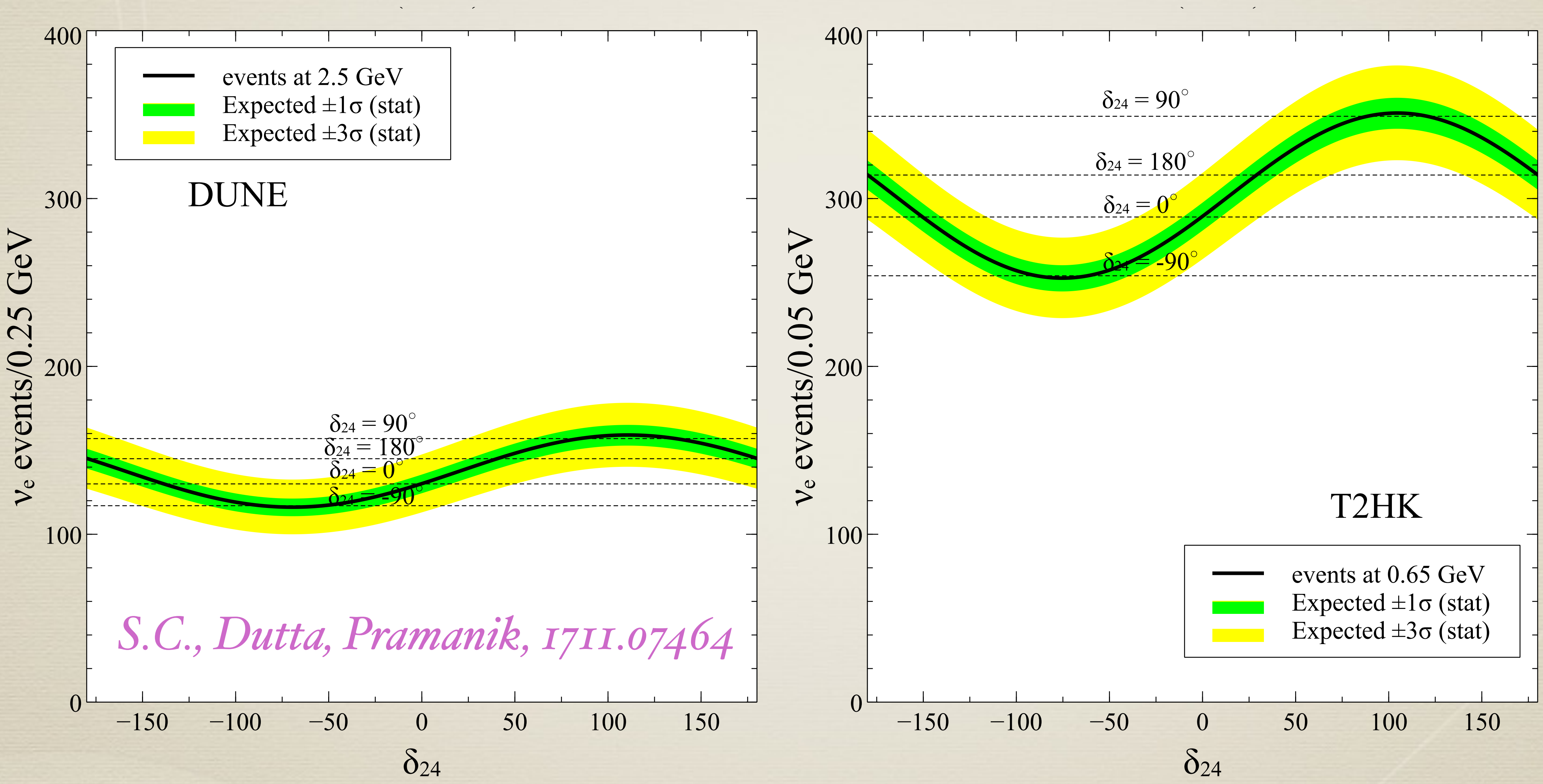
S.C., Dutta, Pramanik, 1704.07269

Measuring Sterile CP Phase at LBL Experiments



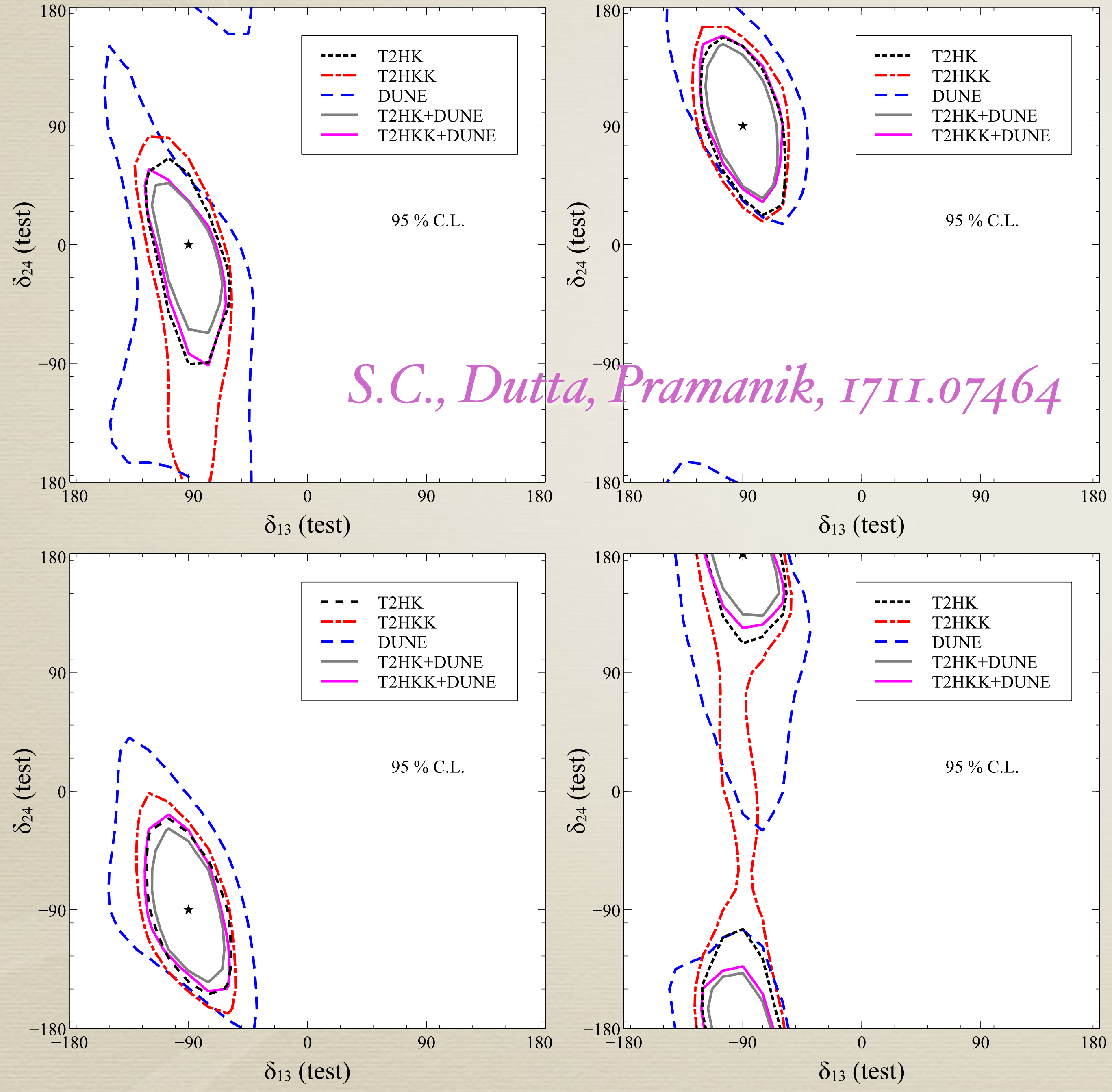
S.C., Dutta, Pramanik, 1711.07464

Measuring Sterile CP Phase at LBL Experiments



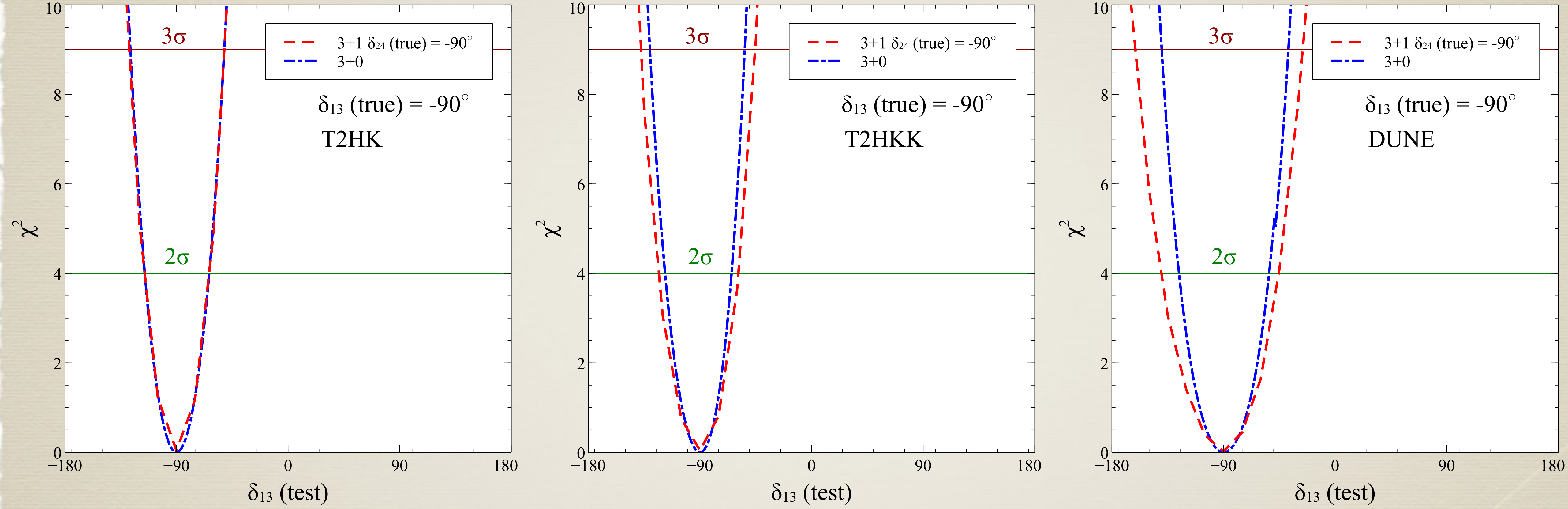
S.C., Dutta, Pramanik, 1711.07464

Measuring Sterile CP Phase at LBL Experiments



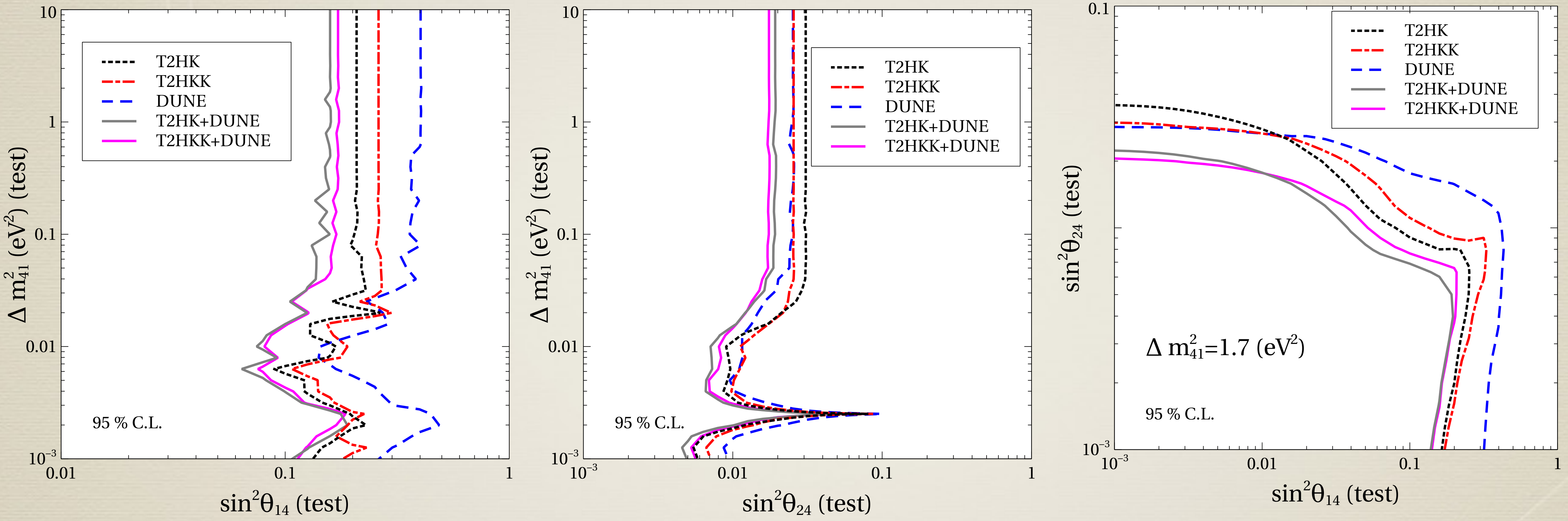
S.C., Dutta, Pramanik, 1711.07464

Impact of delta_24 on delta_13 measurement



S.C., Dutta, Pramanik, 1711.07464

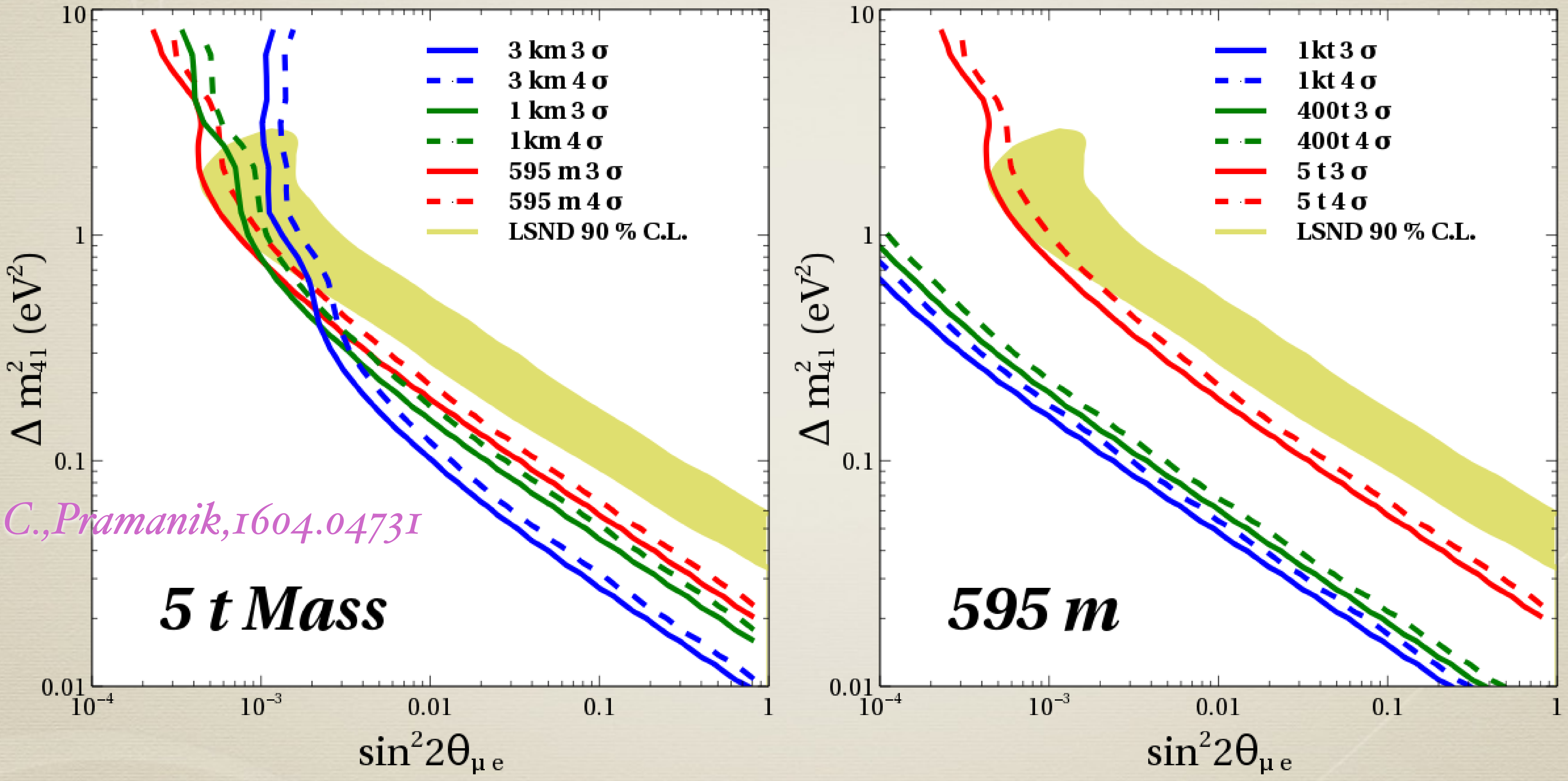
Probing Sterile Neutrinos at LBL Far Detectors



S.C., Dutta, Pramanik, 1711.07464

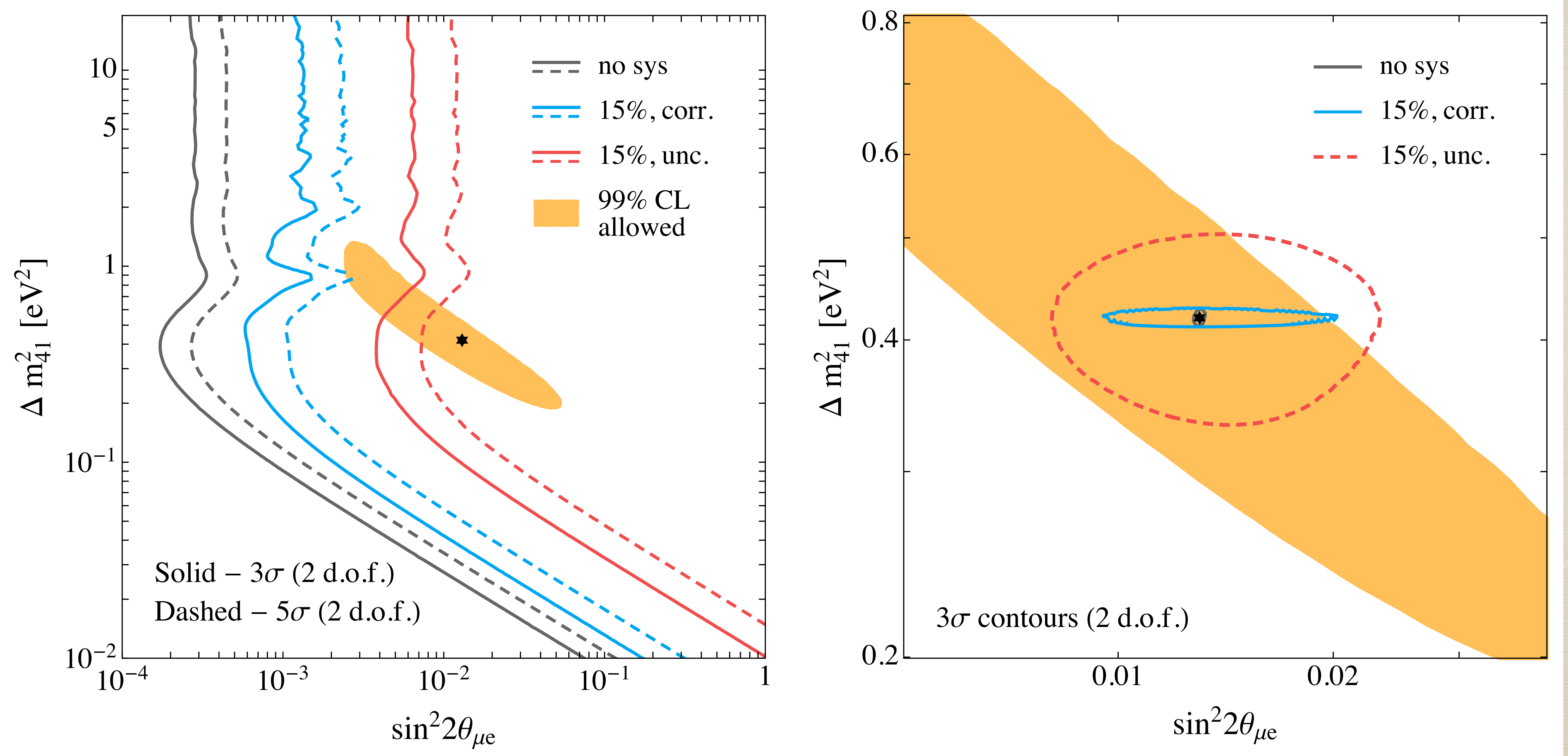
- MINOS+ is putting strong constraints on theta24

Probing Sterile Nus at LBL Near Detectors (DUNE)



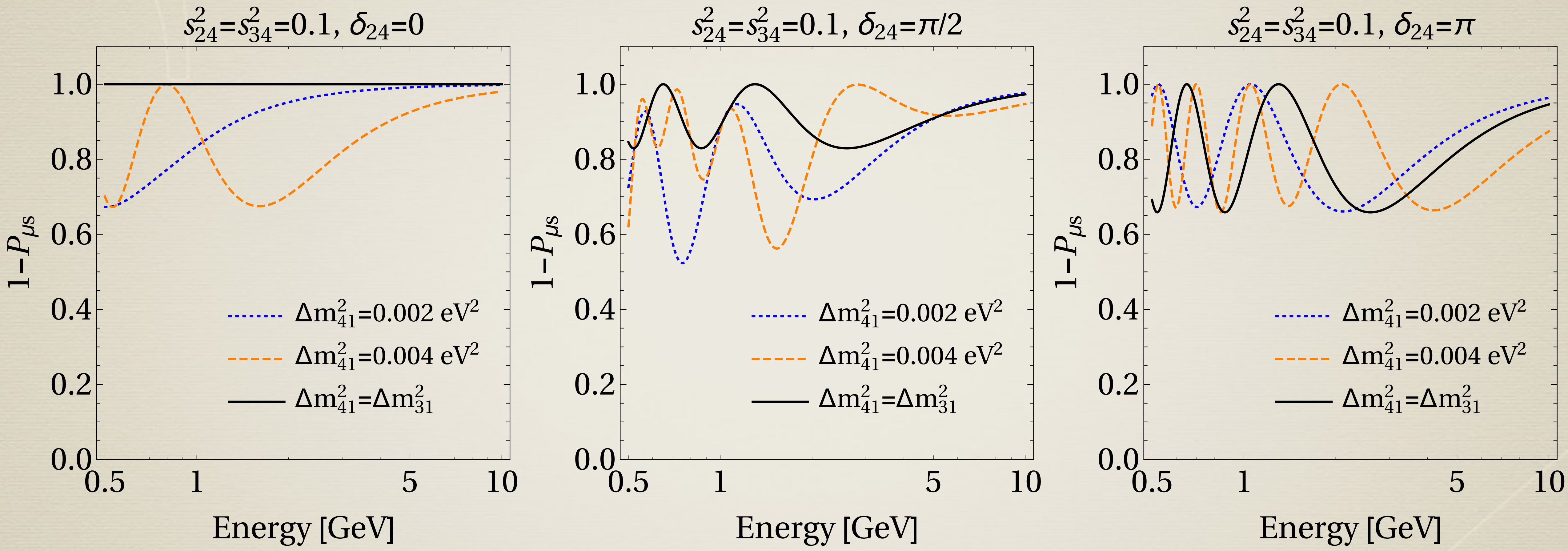
S.C.,Pramanik,1604.04731

Probing Sterile Nus at LBL Near Detectors(ESSnuSB)



Blennow,Coloma,Fernandez-Martinez,1407.1317

NC Events to Probe Sterile Neutrino Mixing



Suprabh Prakash's talk

Coloma,Forero,Parke, 1707.05348

Gandhi,Kayser,Prakash,Roy,1708.01816

- Best constraint on theta34 from NOvA NC

Other New Physics

Long Range Force

- Suppose our model has L_e-L_μ/τ gauge symmetry
- For corresponding light $Z_{e\mu/\tau}$, we can have long range force
- Neutrinos on earth can then be fine tuned to feel the pot due to matter in the Sun

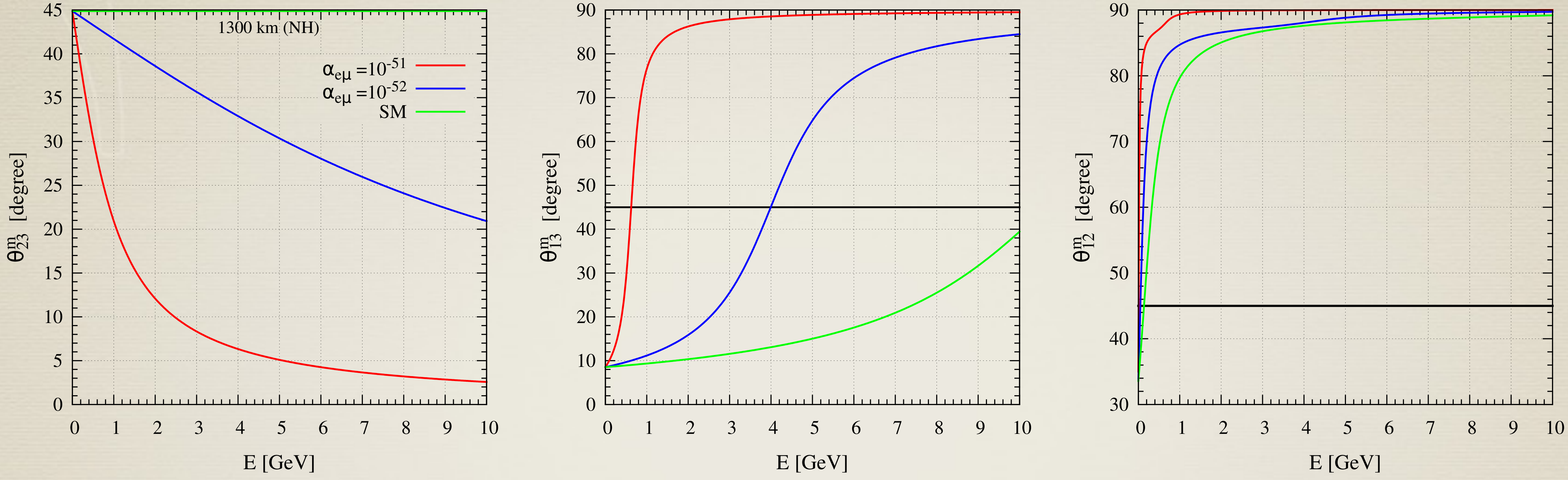
$$V_{e\mu/e\tau}(R_{SE}) = \alpha_{e\mu/e\tau}\frac{N_e}{R_{SE}} \approx 1.3 \times 10^{-11}\text{eV}\left(\frac{\alpha_{e\mu/e\tau}}{10^{-50}}\right)$$

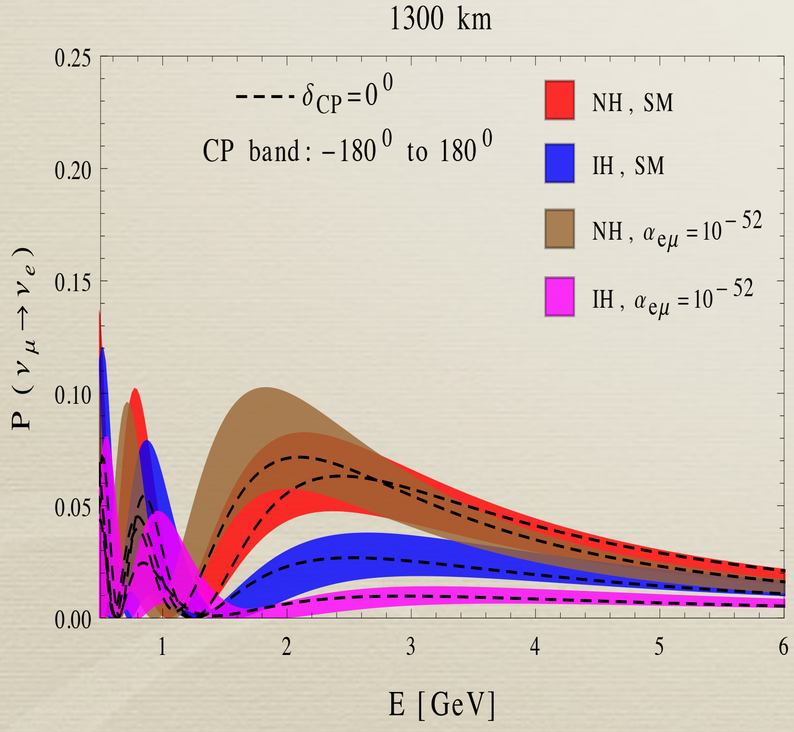
- bound from solar+KL $\alpha_{e\mu} < 3.4 \times 10^{-53}$ and $\alpha_{e\tau} < 2.5 \times 10^{-53}$ at 3σ C.L.

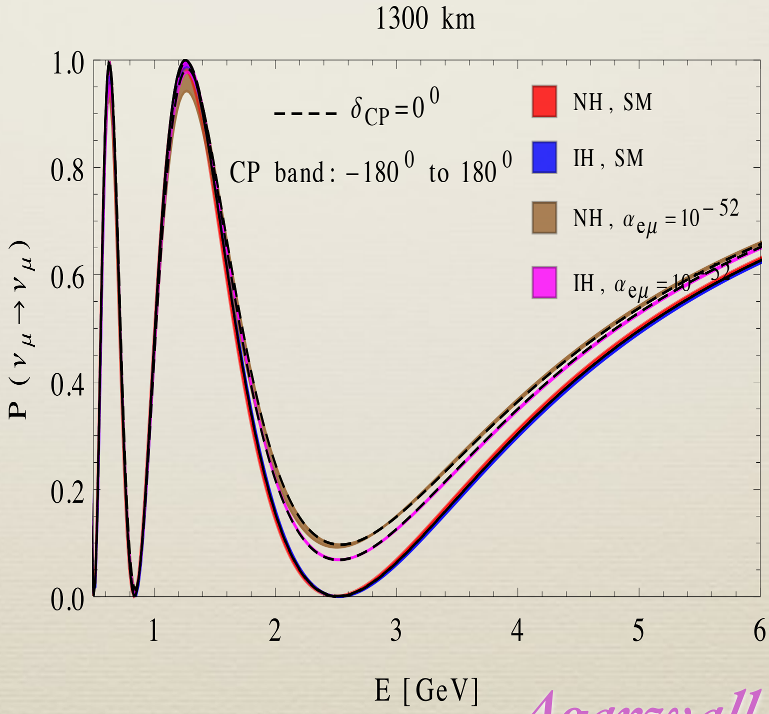
Joshipura,Mohanty, 0310210
Gonzalez-Garcia,de Hollanda,Masso, 0609094
Bandyopadhyay,Dighe,Joshipura, 0610263
Gonzalez-Garcia,de Hollanda,Zukanovich-Funchal, 0803.1180
Samanta, 1001,5344

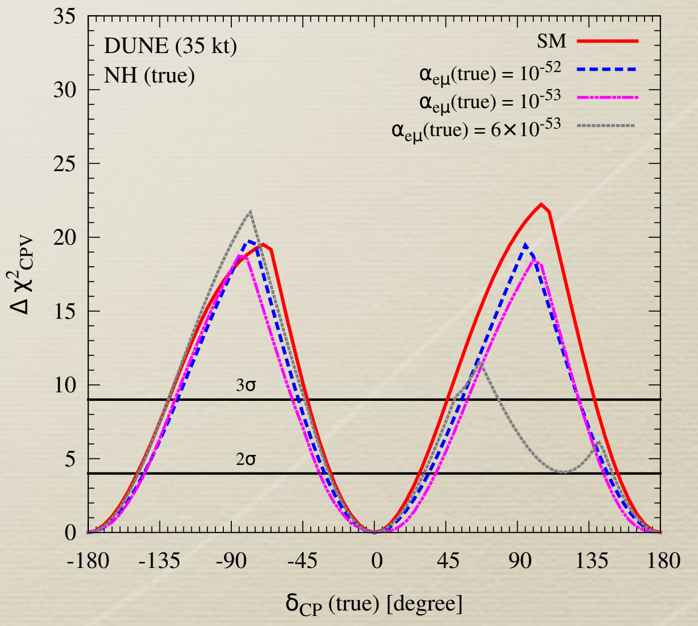
Amina Khatun's talk

Long Range Force



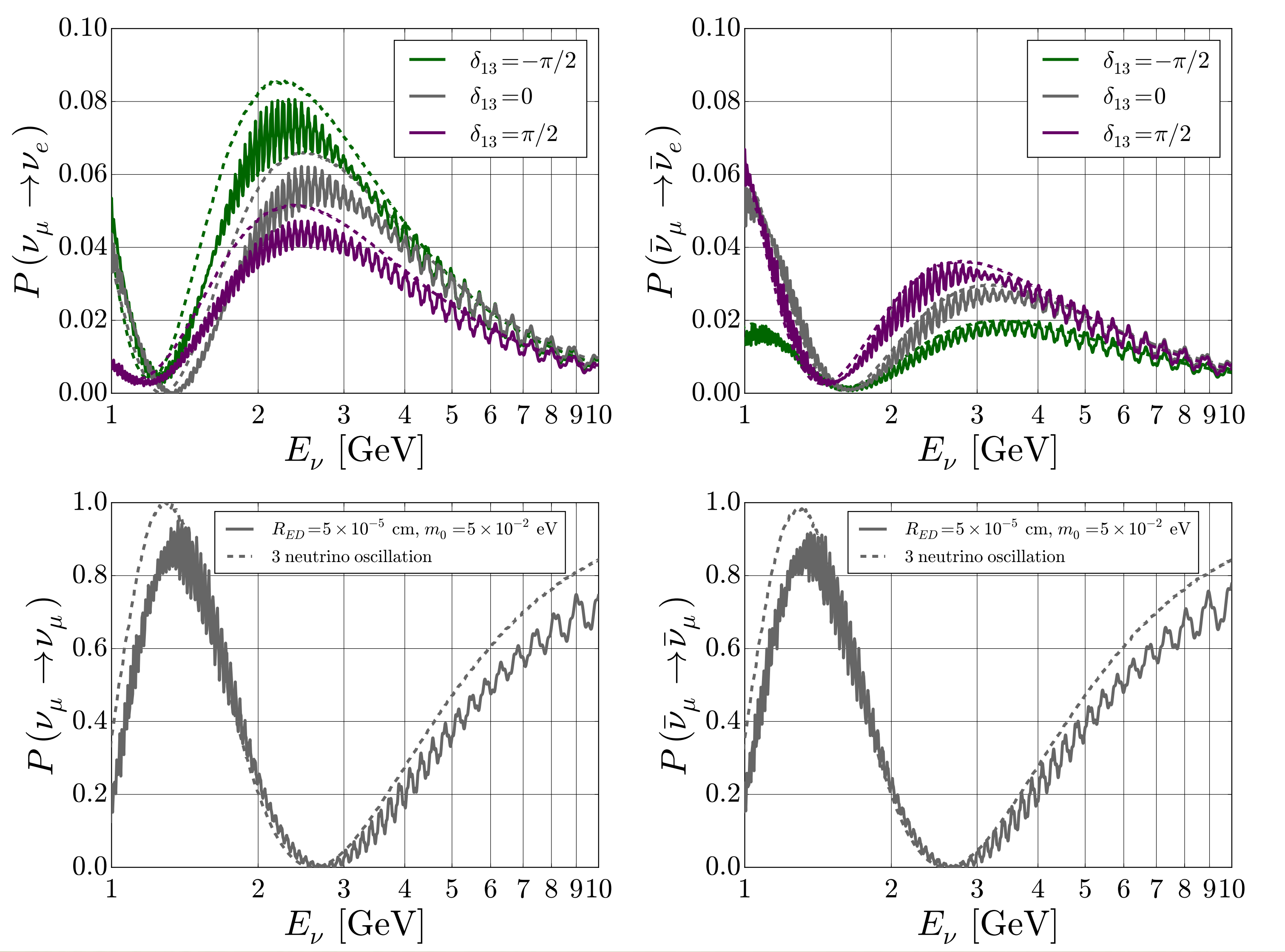






Agarwalla, Dagupta,Chatterjee, 1509.03517

Large Extra Dimensions



Berryman,de Gouvea, Kelly,Peres,Tabrisi,1603.00018

- They also looked at how to distinguish LED and 3+1

Impact of Non-Unitarity

$$N = N^{NP} U$$

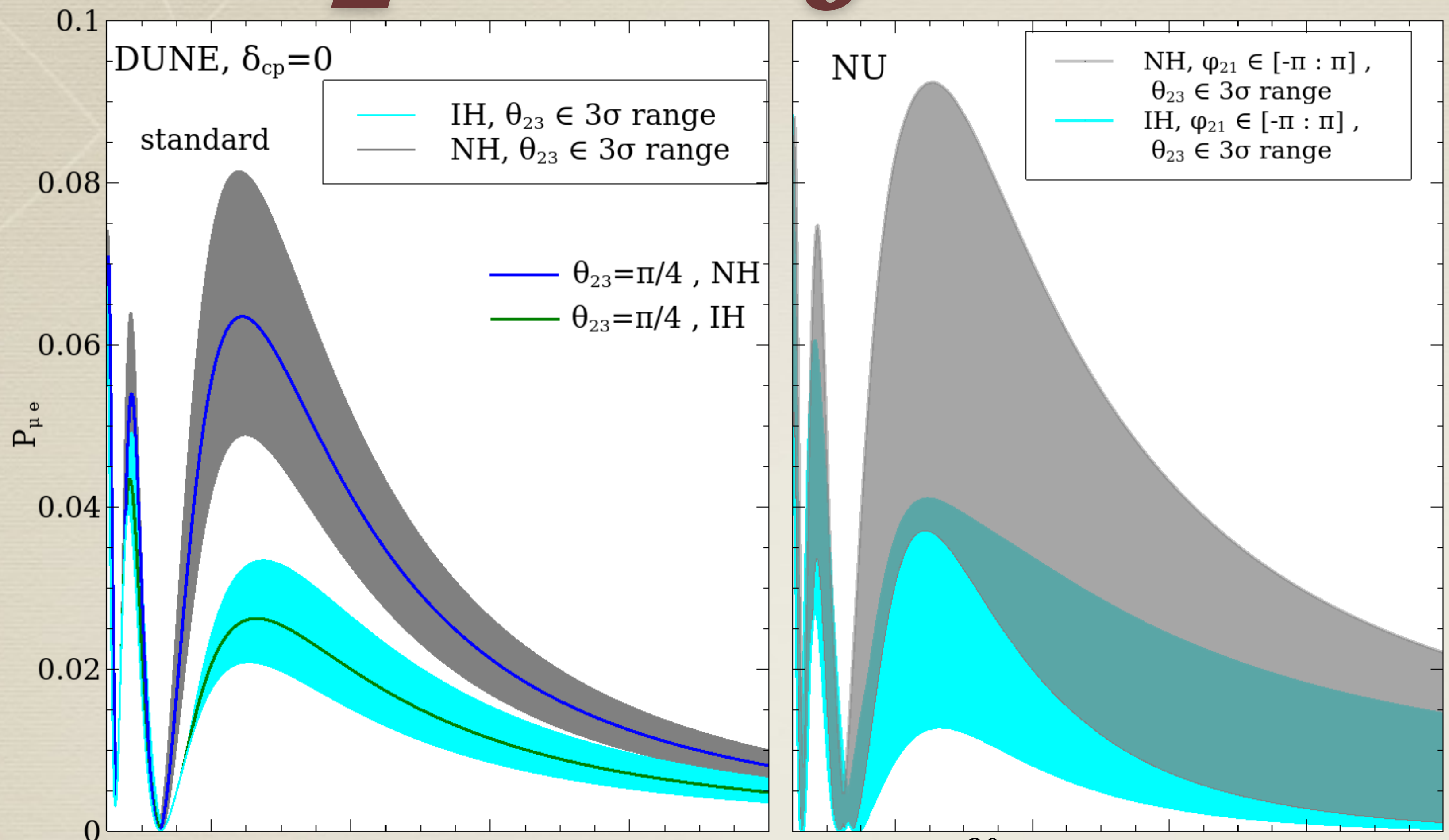
$$N^{NP} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix}$$

$$P_{\mu e} = (\alpha_{11}\alpha_{22})^2 P_{\mu e}^{3\times 3} + \alpha_{11}^2 \alpha_{22} |\alpha_{21}| P_{\mu e}^I + \alpha_{11}^2 |\alpha_{21}|^2$$

$$P_{\mu e}^I = -2[\sin(2\theta_{13})\ \sin\theta_{23}\ \sin(\frac{\triangle m_{31}^2 L}{4E_\nu})\ \sin(\frac{\triangle m_{31}^2 L}{4E_\nu} + \phi_{21} - I_{123})]$$
$$-\cos\theta_{13}\ \cos\theta_{23}\ \sin(2\theta_{12})\ \sin(\frac{\triangle m_{21}^2 L}{2E_\nu})\sin(\phi_{21})$$

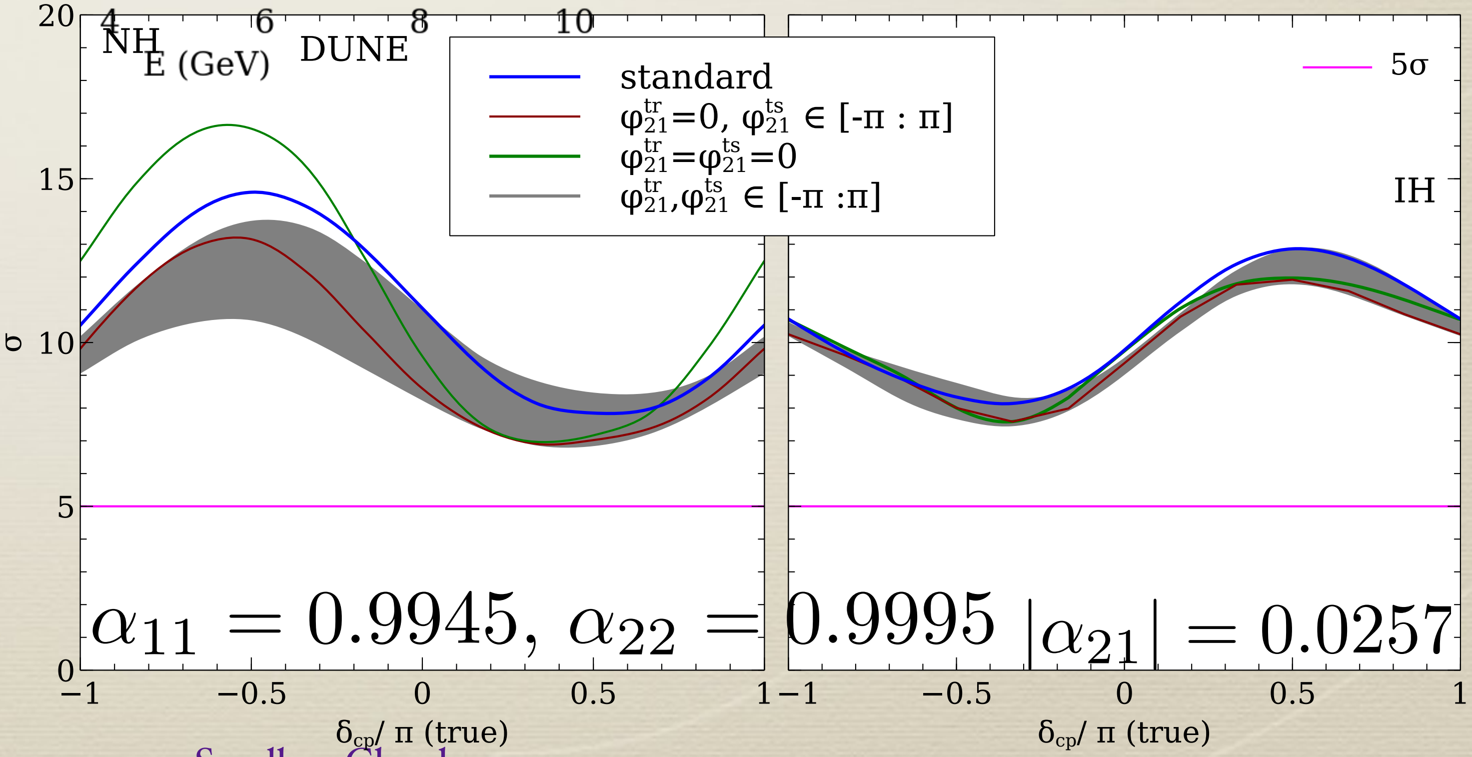
$\alpha_{11}^2 \geq 0.989$, $\alpha_{22}^2 \geq 0.999$ and $|\alpha_{21}|^2 \leq 0.0007$ at 90% C.L.

Impact of Non-Unitarity



Dutta,Ghoshal,Roy, 1607.07094
Dutta, Ghoshal, 16007.02500

Non-unitarity vs Sterile, Blennow,Coloma, Fernandez-Martinez,Hernandez-Garcia, Lopez-Pavon, 1705.01840



More New Physics

CPT Violation

Lorentz Invariance Violation

Quantum Decoherence

Has been discussed a lot here

VEP

Problems for discussions

- More new physics at LBL
- How to break the SM vs New Physics at LBL
- Using LBL experiments to study new physics
- Combining experiments to look for synergies