भौतिक अनुसंधान प्रयोगशाला Physical Research Laboratory

Sterile Neutrinos

SERB INDIA

Srubabati Goswami

24April, **2023**

1995: LSND results

Candidate Events in a Search for $\bar{\nu}_\mu \to \bar{\nu}_e$ Oscillations

C. Athanassopoulos *et al.*
Phys. Rev. Lett. **75**, 2650 – Published 2 October 1995

Article | References | Citing Articles (446) | PDF | Export Citation

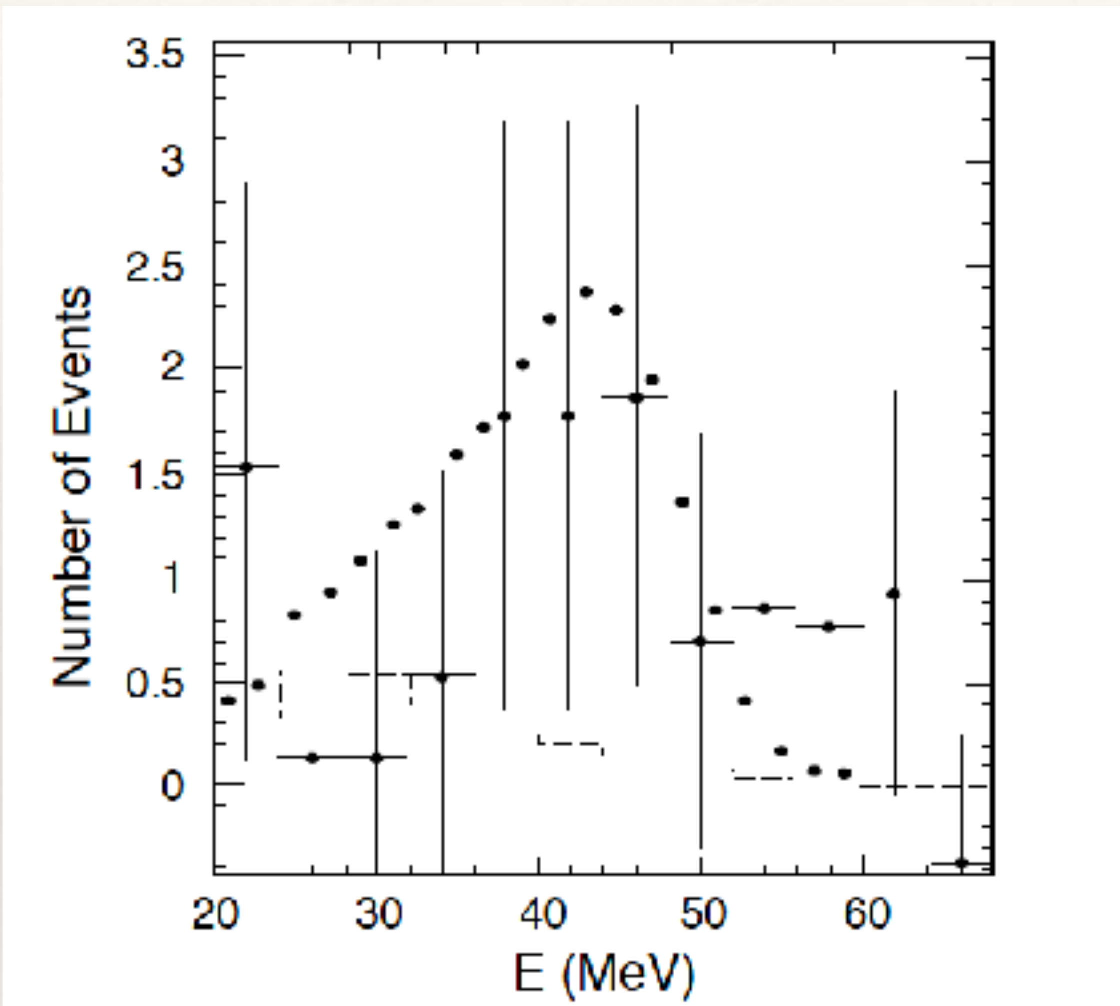
ABSTRACT

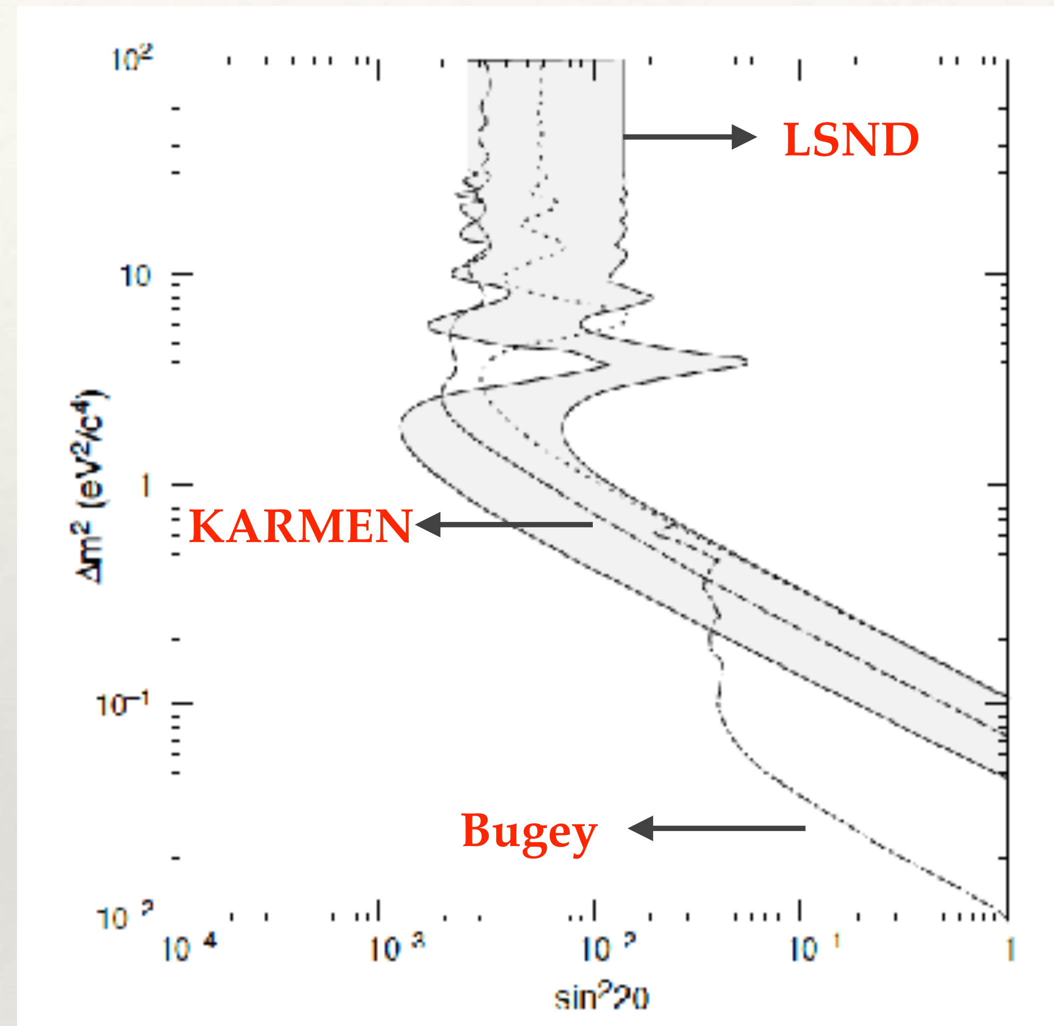
A search for $\bar{\nu}_e$'s in excess of the number expected from conventional sources has been made using the Liquid Scintillator Neutrino Detector, located 30 m behind the Los Alamos Meson Physics Facility beam stop. The $\bar{\nu}_e$ are detected via $\bar{\nu}_e p \to e^+ n$ with e^+ energy between 36 and $60\ \mathrm{MeV}$, followed by a γ ray from np $\to d\gamma$ ($2.2\ \mathrm{MeV}$). Using strict cuts to identify γ rays correlated with e^+ yields 9 events with only 2.1 ± 0.3 background expected. A likelihood fit to the entire e^+ sample results in a total excess of $16.4^{+9.7}_{-8.9} \pm 3.3$ events. If attributed to $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, this corresponds to an oscillation probability of ($0.34^{+0.20}_{-0.18} \pm 0.07$)%.

Received 19 April 1995

DOI: https://doi.org/10.1103/PhysRevLett.75.2650

1995: LSND results





$$\Delta m^2_{solar} \sim 10^{-5} eV^2$$
$$\Delta m^2_{atm} \sim 10^{-3} eV^2$$

Requires an additional neutrino

Sterile : no electroweak interaction

arXiv:hep-ph/9507212v1 3 Jul 1995

ACCELERATOR, REACTOR, SOLAR AND ATMOSPHERIC NEUTRINO OSCILLATION: BEYOND THREE GENERATIONS

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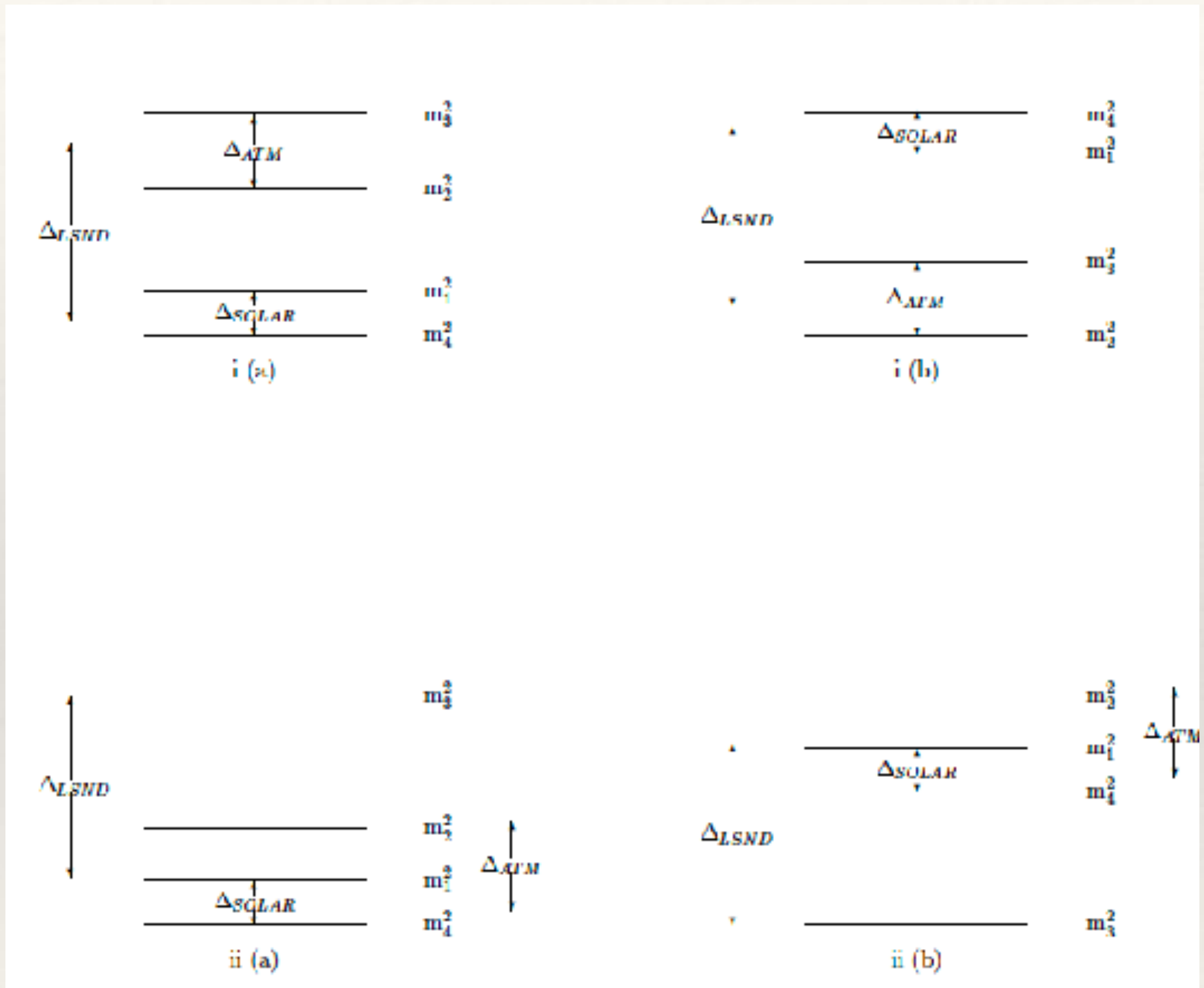
P.A.C.S. Nos.: 14.60.Pq, 14.60.Lm, 96.40.Tv, 96.60 Kx

We perform a phenomenological analysis of neutrino oscillation in a four generation framework introducing an additional sterile neutrino. In such a scenario, more than one pattern is possible that can accommodate three hieararchically different mass squared differences as required by the present experiments. We considered two different spectrums. Choosing the Δm^2s in the ranges suitable for the LSND, atmospheric and solar neutrino oscillation, limits on the mixing angles are derived, consistent with the most restrictive accelerator and reactor data as well as the atmospheric and solar neutrino results. The allowed mixing angles are found to be constrained very severely in both cases. For one mass pattern in the combined allowed zone the atmospheric anomaly can be explained by $\nu_e - \nu_\mu$ oscillation whereas for the other the $\nu_\mu - \nu_\tau$ channel is preferred. The accelerator experiments CHORUS and NOMAD have different sensitivities in these regions and they can distinguish between the two choices.

June 28, 1995

Analysis in 2+2 and 3+1 picture



S. Goswami, hep-ph/9507212

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SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY (REPOSITORY FOR LECTURE NOTES FROM THE SCANNED HISTORICAL ARCHIVE) | (smr 858)

Starts 12 Jun 1995
Ends 27 Jul 1995
Central European Time

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Update of the solar neutrino oscillation analysis with the 766 Ty KamLAND spectrum #5

Abhijit Bandyopadhyay (Saha Inst.), Sandhya Choubey (INFN, Trieste and SISSA, Trieste), Srubabati Goswami (Harish-Chandra Res. Inst.), S.T. Petcov (SISSA, Trieste and INFN, Trieste and Sofiya, Inst. Nucl. Res.), D.P. Roy (ICTP, Trieste and Tata Inst.) (Jun, 2004)

Published in: *Phys.Lett.B* 608 (2005) 115-129 • e-Print: hep-ph/0406328 [hep-ph]

pdf DOI cite claim reference search 157 citations

Constraints on neutrino oscillation parameters from the SNO salt phase data #6

Abhijit Bandyopadhyay (Saha Inst.), Sandhya Choubey (INFN, Trieste and SISSA, Trieste), Srubabati Goswami (Harish-Chandra Res. Inst. and ICTP, Trieste), S.T. Petcov (SISSA, Trieste and INFN, Trieste and Sofiya, Inst. Nucl. Res.), D.P. Roy (Tata Inst.) (Sep, 2003)

Published in: *Phys.Lett.B* 583 (2004) 134-148 • e-Print: hep-ph/0309174 [hep-ph]

pdf DOI cite claim reference search 118 citations

On the measurement of solar neutrino oscillation parameters with KamLAND #7

Abhijit Bandyopadhyay (Saha Inst.), Sandhya Choubey (INFN, Trieste and SISSA, Trieste), Srubabati Goswami (Harish-Chandra Res. Inst.), S.T. Petcov (SISSA, Trieste and INFN, Trieste and Sofiya, Inst. Nucl. Res.) (Sep, 2003)

Published in: *Phys.Lett.B* 581 (2004) 62-74 • e-Print: hep-ph/0309236 [hep-ph]

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published (?) 6

Author

- [x] Srubabati Goswami 7
- [x] Serguey T. Petcov 7
- [ ] Sandhya Choubey 6
- [ ] Abhijit Bandyopadhyay 6
- [ ] Durga Prasad Roy 3
- [ ] Shamayita Ray 1
- [ ] Werner Rodejohann 1

Subject

- [ ] Phenomenology-HEP 7

arXiv Category

- [ ] hep-ph 7

Large |U(e3)| and Tri-bimaximal Mixing

#1

Srubabati Goswami (Ahmedabad, Phys. Res. Lab), Serguey T. Petcov (SISSA, Trieste and INFN, Trieste and Tokyo U., IPMU), Shamayita Ray (Tata Inst.), Werner Rodejohann (Heidelberg, Max Planck Inst.) (Jul, 2009)

Published in: *Phys.Rev.D* 80 (2009) 053013 • e-Print: 0907.2869 [hep-ph]

pdf DOI cite claim reference search 61 citations

Neutrino Oscillation Parameters After High Statistics KamLAND Results

#2

Abhijit Bandyopadhyay (Harish-Chandra Res. Inst.), Sandhya Choubey (Harish-Chandra Res. Inst.), Srubabati Goswami (Harish-Chandra Res. Inst.), S.T. Petcov (SISSA, Trieste and INFN, Trieste), D.P. Roy (Valencia U., IFIC and Tata Inst.) (Apr, 2008)

e-Print: 0804.4857 [hep-ph]

pdf cite claim reference search 58 citations

Solar Model Parameters and Direct Measurements of Solar Neutrino Fluxes

#3

Abhijit Bandyopadhyay (Tata Inst.), Sandhya Choubey (Harish-Chandra Res. Inst. and Oxford U., Theor. Phys.), Srubabati Goswami (Harish-Chandra Res. Inst. and Munich, Tech. U.), S.T. Petcov (SISSA, Trieste) (Aug, 2006)

Published in: *Phys.Rev.D* 75 (2007) 093007 • e-Print: hep-ph/0608323 [hep-ph]

pdf DOI cite claim reference search 11 citations

High precision measurements of theta(solar) in solar and reactor neutrino experiments

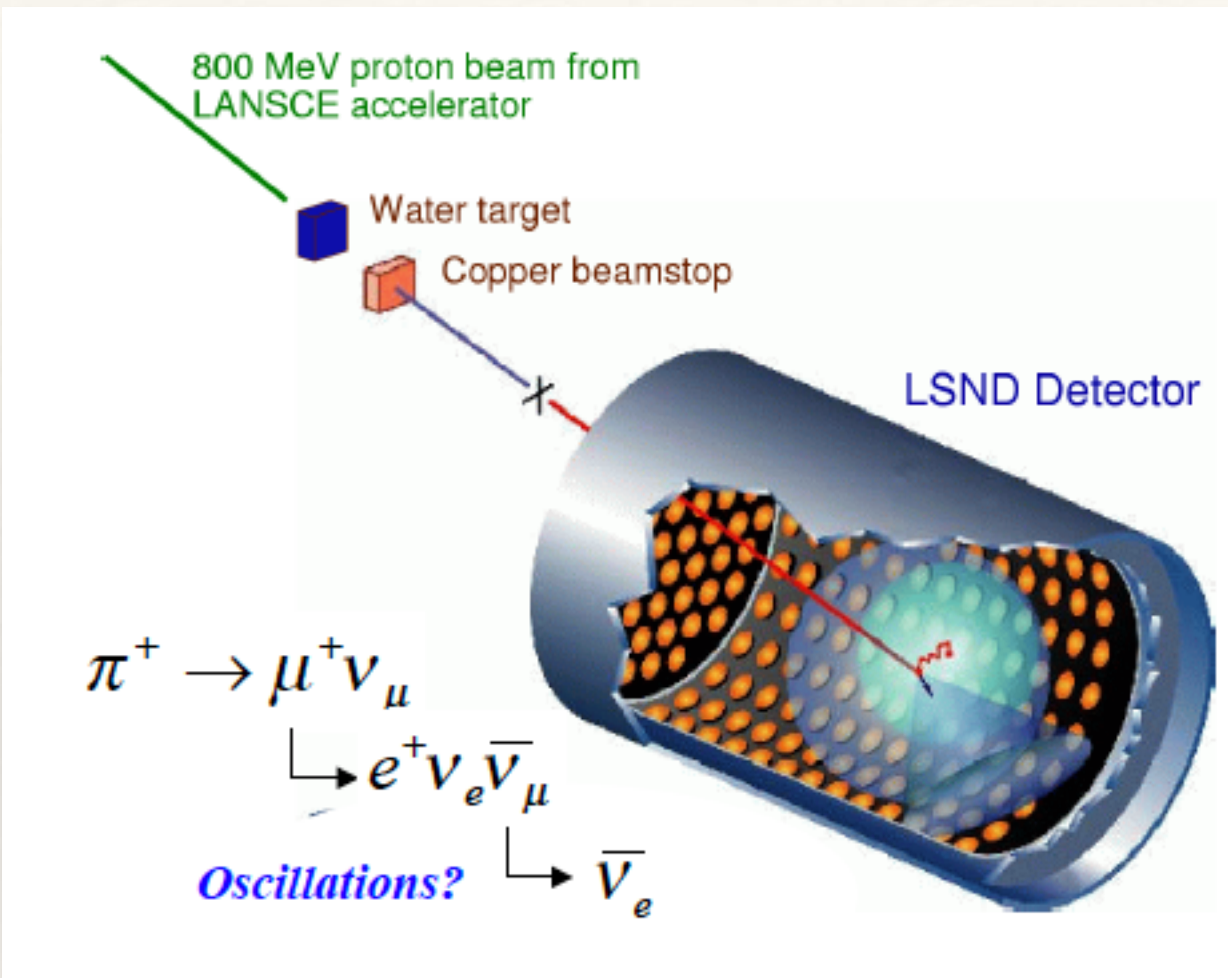
#4

Abhijit Bandyopadhyay (Saha Inst.), Sandhya Choubey (INFN, Trieste and SISSA, Trieste), Srubabati Goswami (Harish-Chandra Res. Inst.), S.T. Petcov (SISSA, Trieste and INFN, Trieste and Sofiya, Inst. Nucl. Res.) (Dec, 2004)

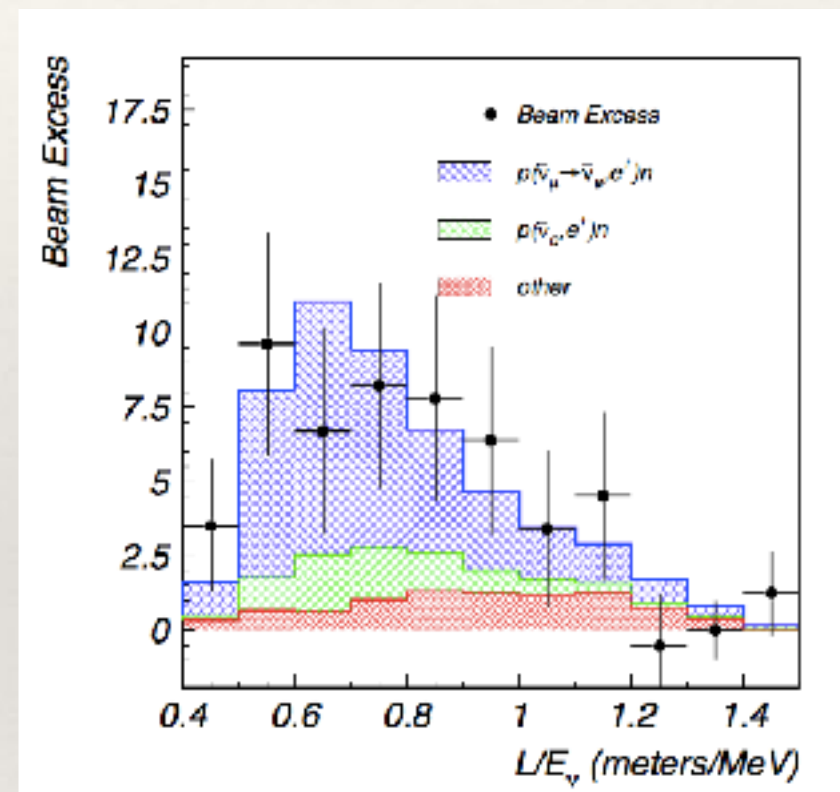
Published in: *Phys.Rev.D* 72 (2005) 033013 • e-Print: hep-ph/0410283 [hep-ph]

SISSA, 2017

LSND results



LSND PRL 1995,
PRD 2001



$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\quad L \simeq 30\,\mathrm{m}$ $\quad 20\,\mathrm{MeV} \leq E \leq 200\,\mathrm{MeV}$

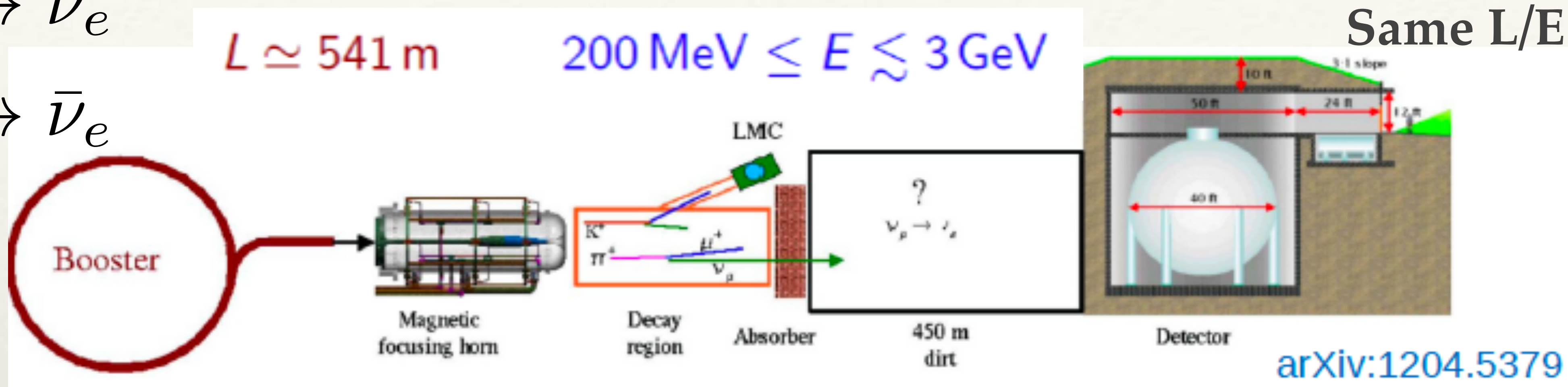
3.8σ excess $\quad \Delta m^2 \gtrsim 0.2\,\mathrm{eV}^2$

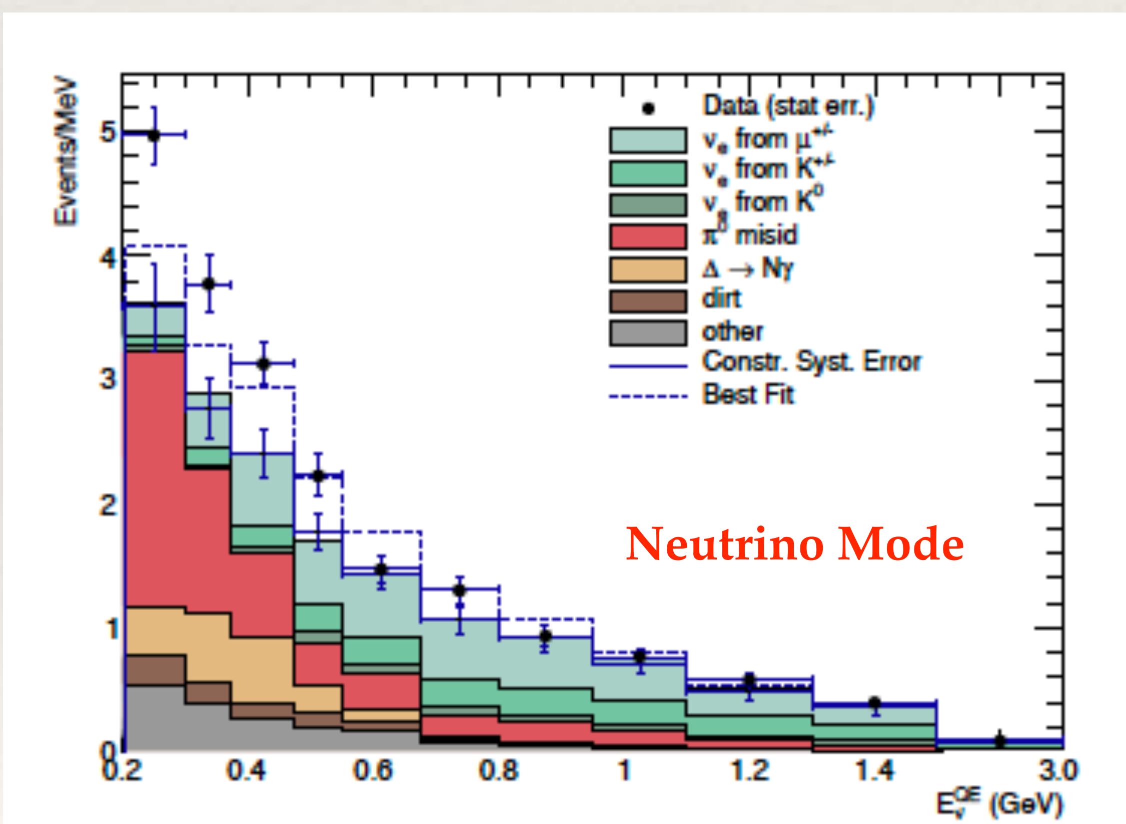
MiniBoone

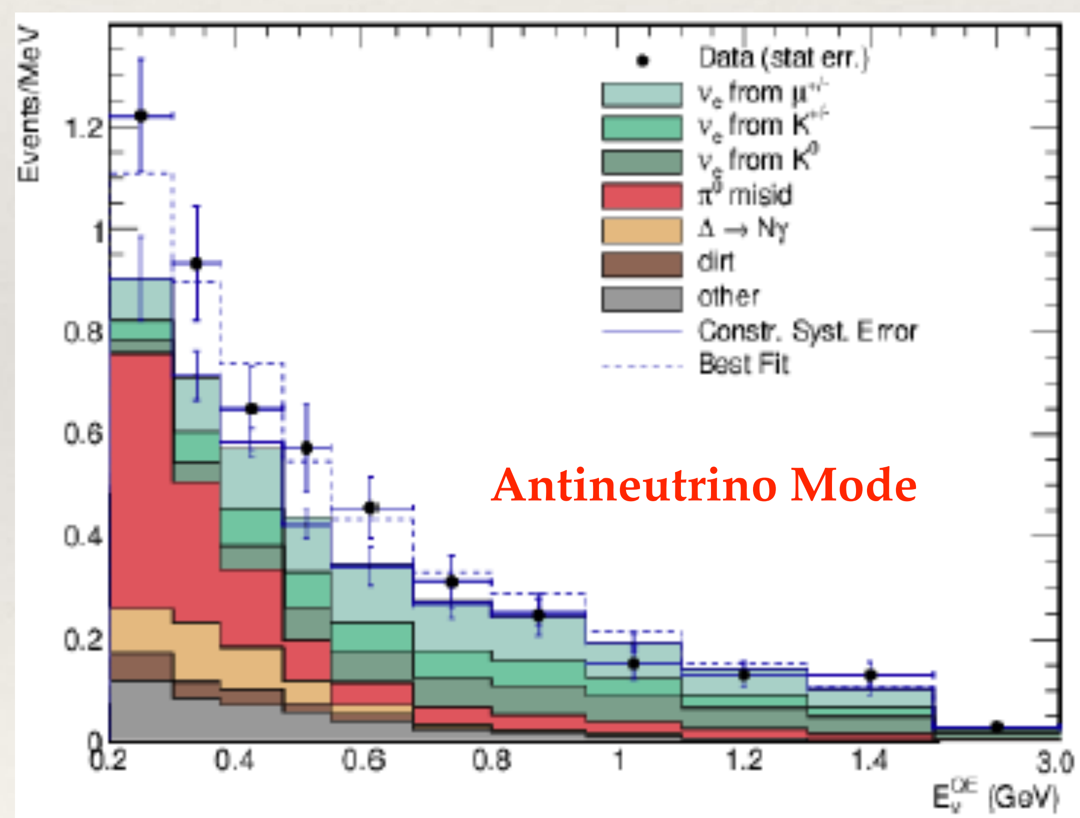
$$\nu_\mu \to \nu_e$$

$$\bar{\nu}_\mu \to \bar{\nu}_e$$

Same L/E as LSND

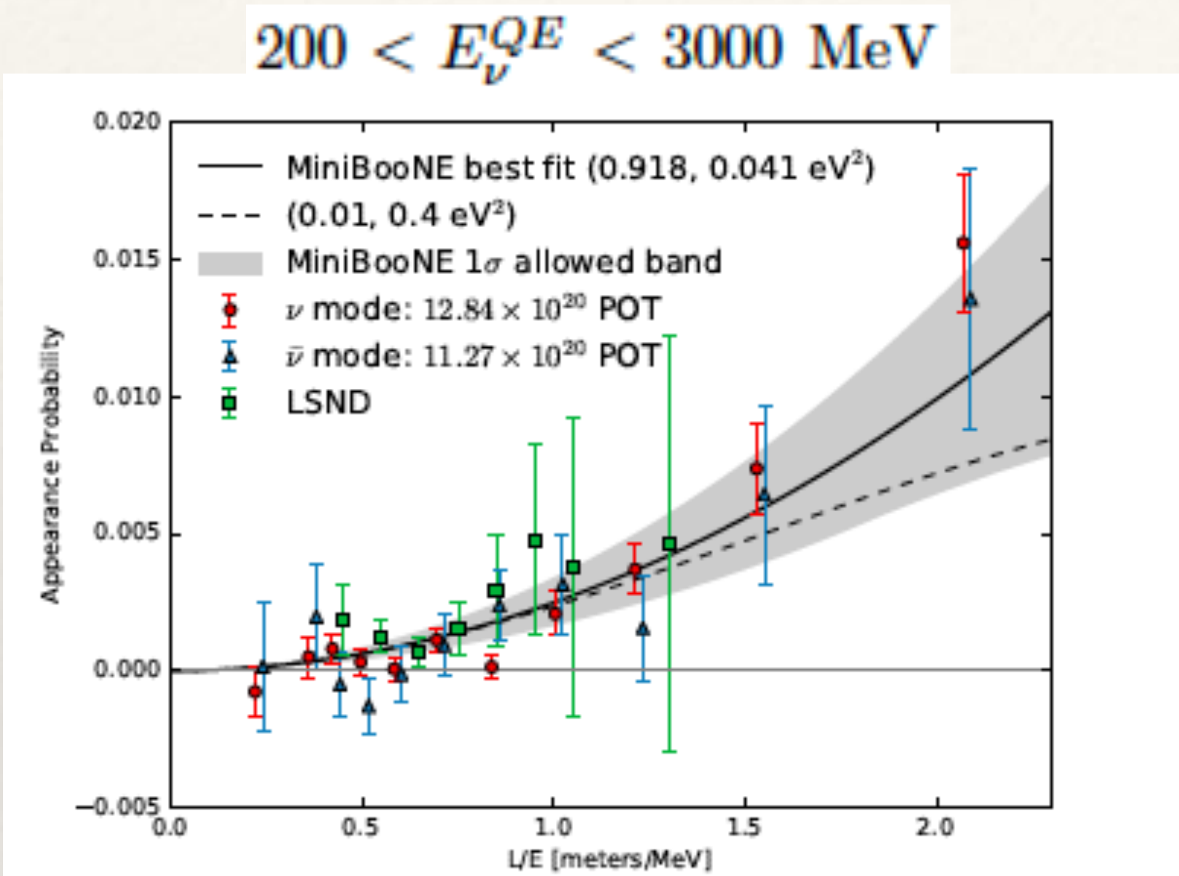


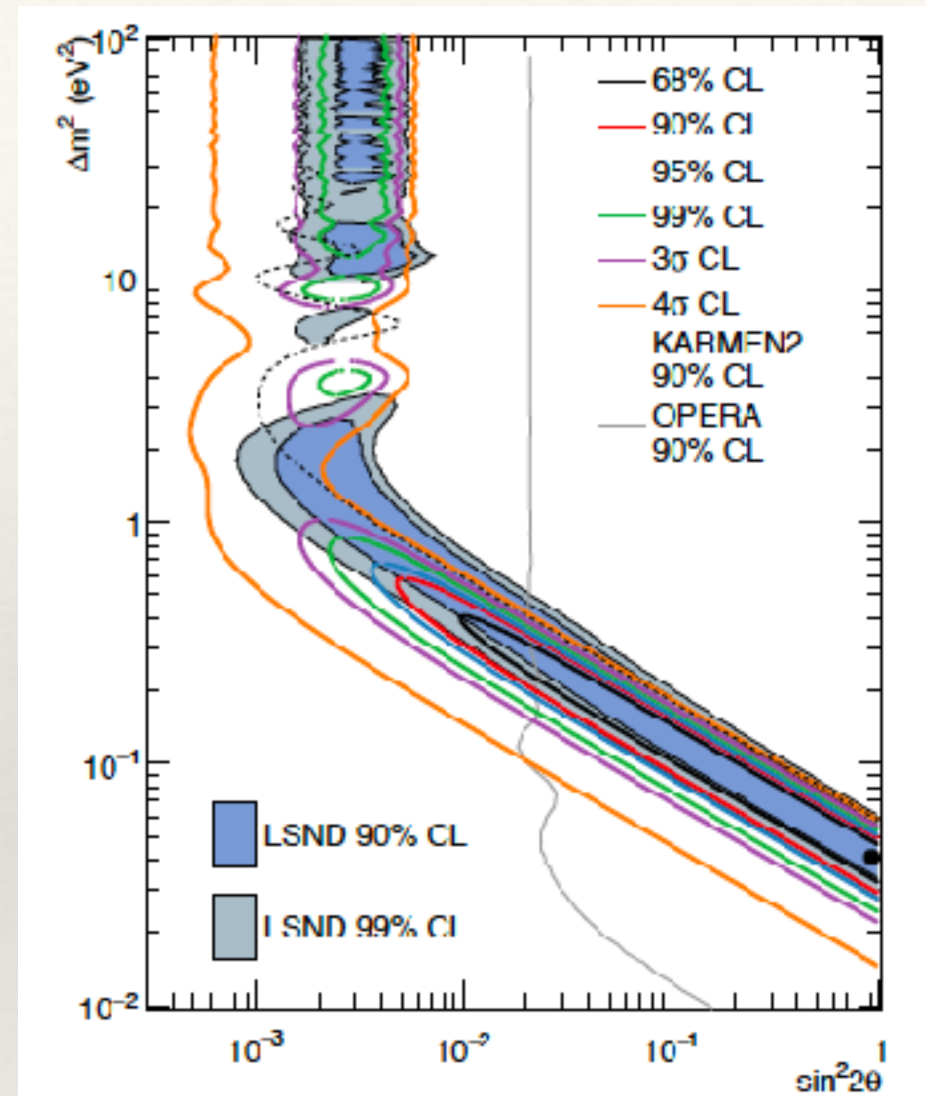




A.A. Aguilar Arevalo, PRL 121, 221801, 2018.

LSND and MiniBoone





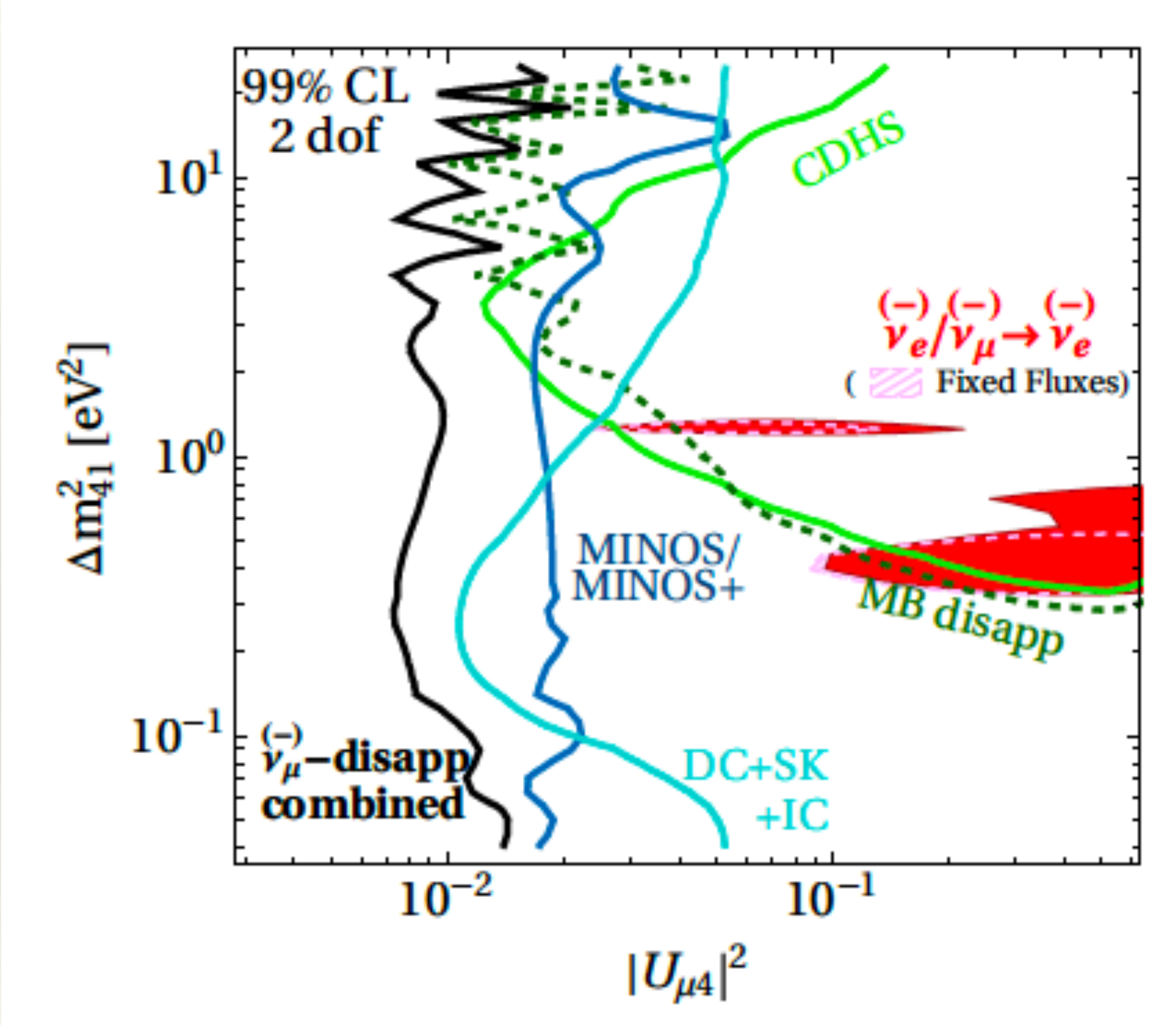
Combined significance $\sim 6\sigma$

A.A. Aguilar Arevalo, PRL 121, 221801, 2018.

Two neutrino fit

MiniBoone : neutrino + antineutrino

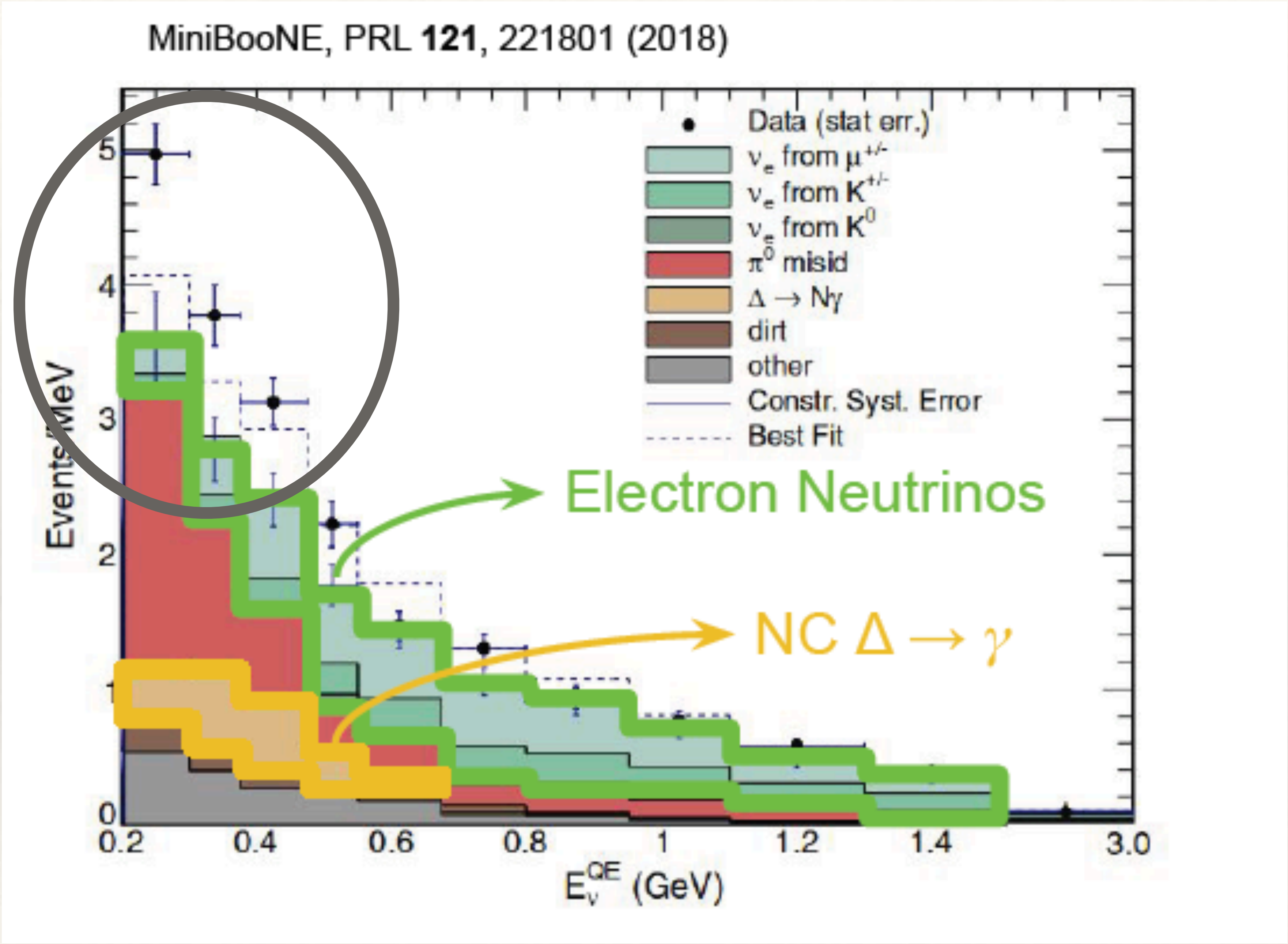
Disagreement among experiments



Low Energy Excess in MiniBoone

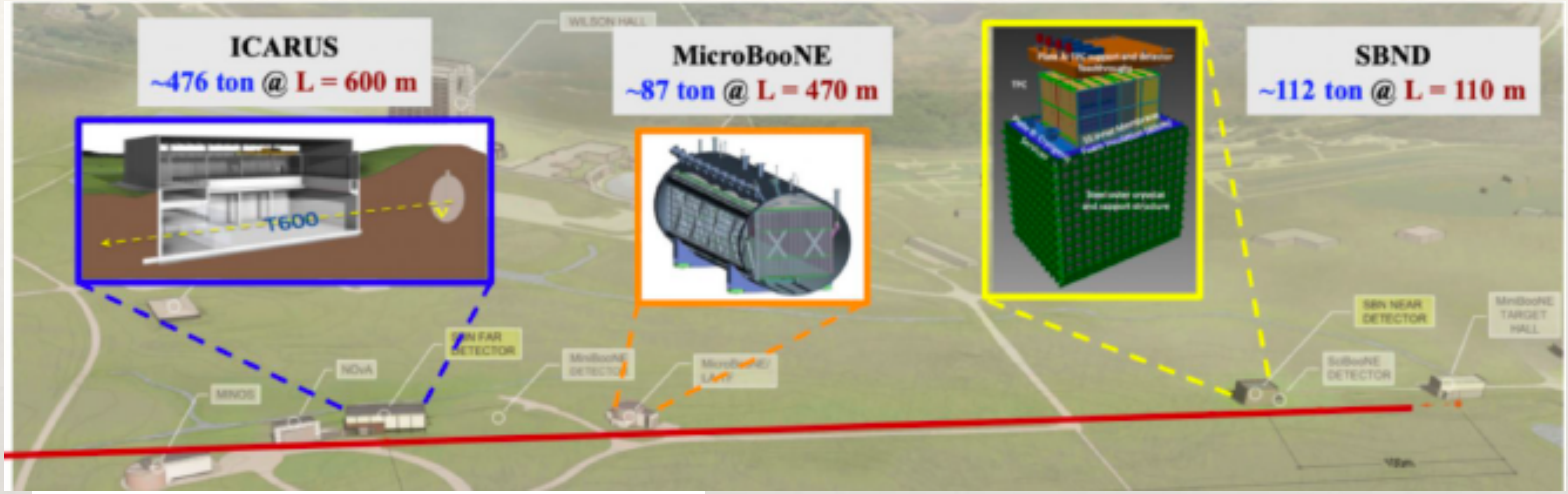
4.5σ

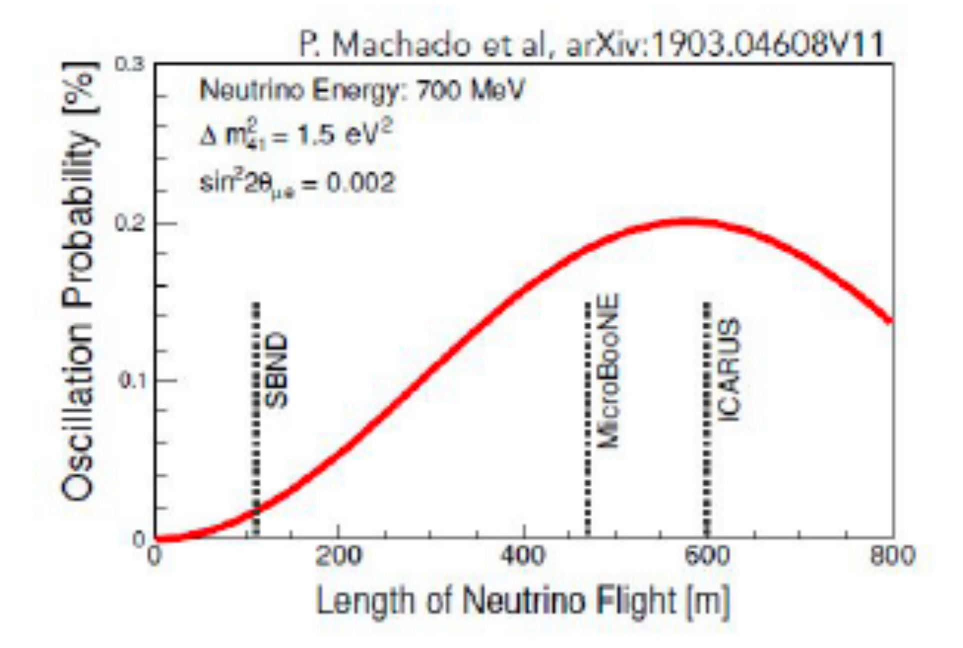
Excess



Cannot be explained in terms of 3+N scenarios

SBN@FermiLab

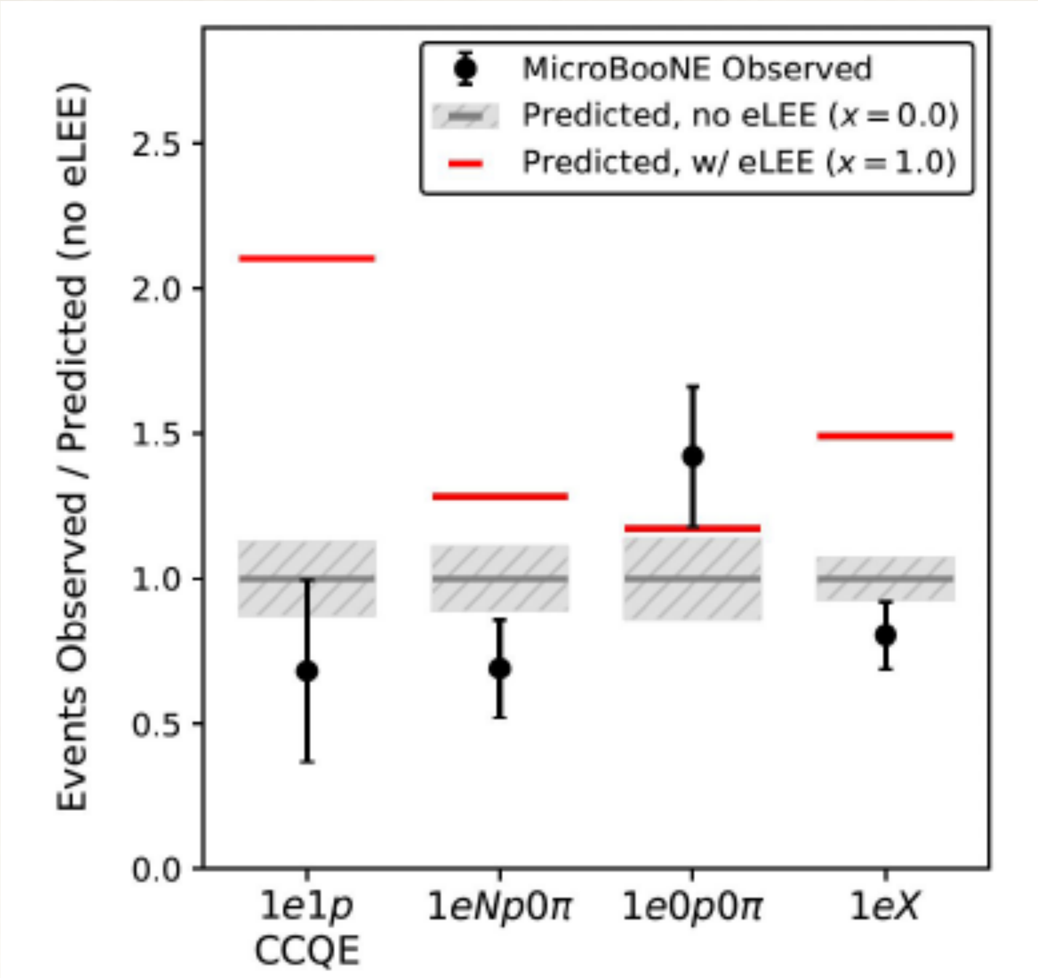




3 Liquid Argon TPCs located along the Booster Neutrino Beamline in FERMILAB

MicroBoone Results

- Disfavour NC $\Delta \rightarrow \gamma$ as origin of LEE 94.8% C.L.
- No electron neutrino excess in data



https://arxiv.org/pdf/2110.14054.pdf

See however

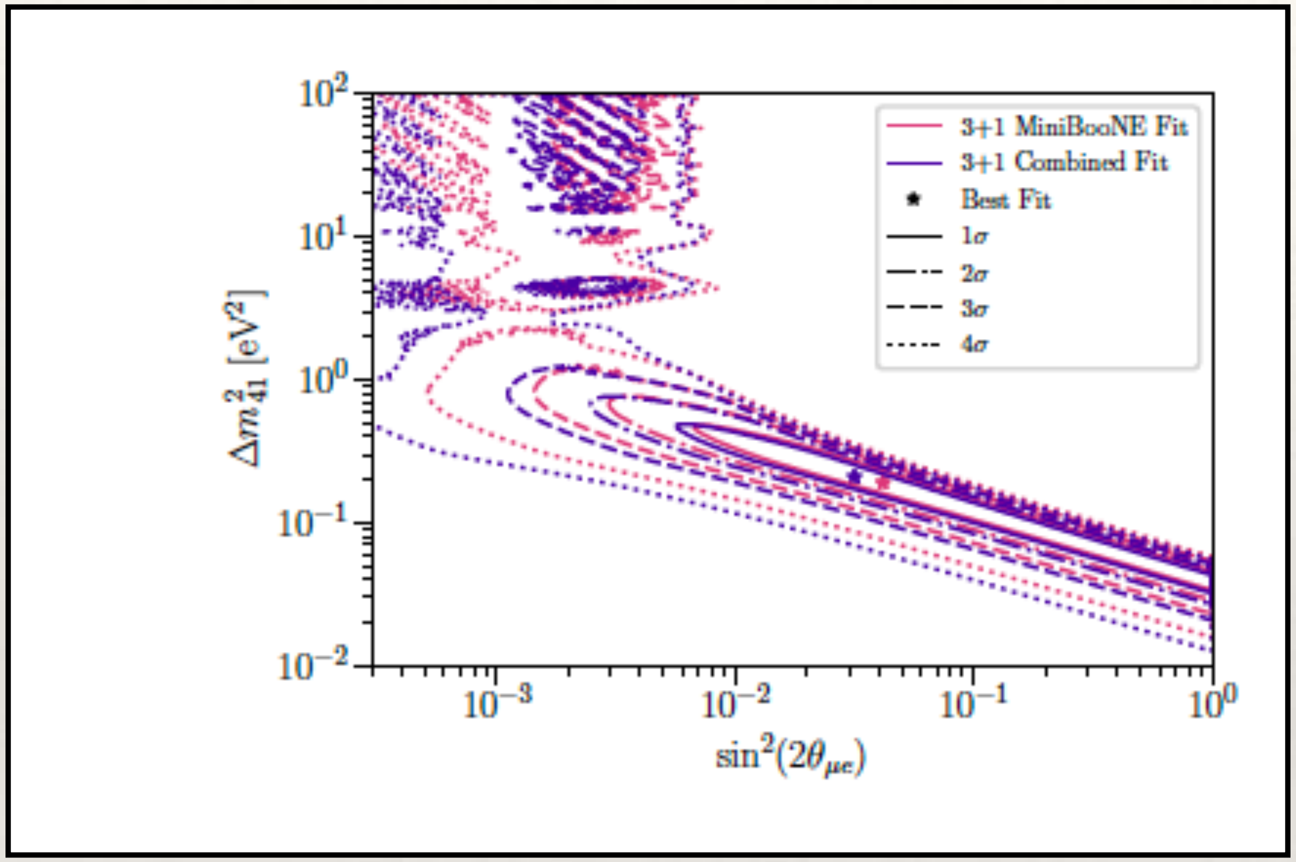
.https://arxiv.org/pdf/2111.10359.pdf

The electron neutrino excess cannot be excluded in a model independent way

New physics ?

Result from all 3 detectors in SBN

3+1 fit : MiniBoone and MicroBoone



3+1 Fit	$\lvert U_{e4}\rvert^2$	$\lvert U_{\mu 4}\rvert^2$	Δm^2	$\Delta\chi^2$/ dof
MiniBooNE only	0.508	0.0205	0.191	27.8 / 3
Combination	0.502	0.0158	0.209	24.7 / 3

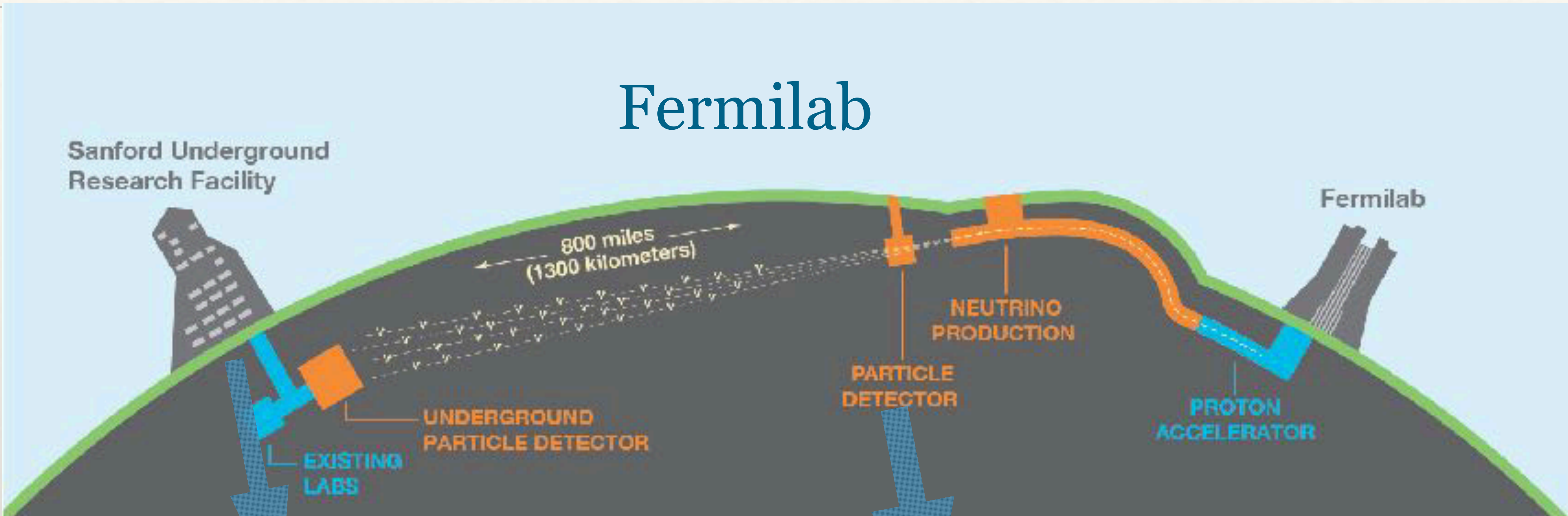
TABLE I. Summary of results. The $\Delta\chi^2$/dof in the last column compares the $3+1$ model to the no-oscillation model.

3+1 scenario preferred at 4.3σ

Phys. Rev. Lett.129 (2022)

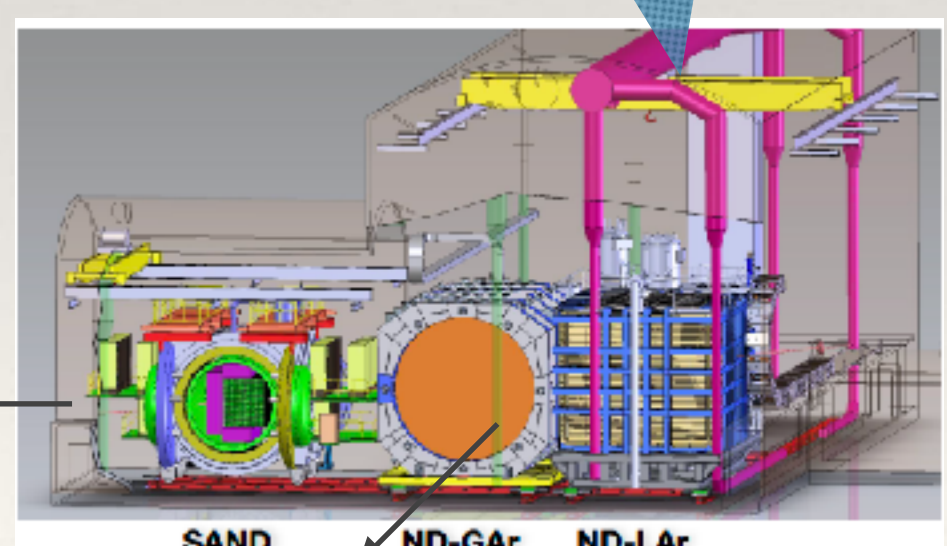
Impact on future Neutrino Oscillation Experiments

Liquid Argon Detector (DUNE)



Far Detector
Liquid Argon Time
Projection Chamber

On-axis

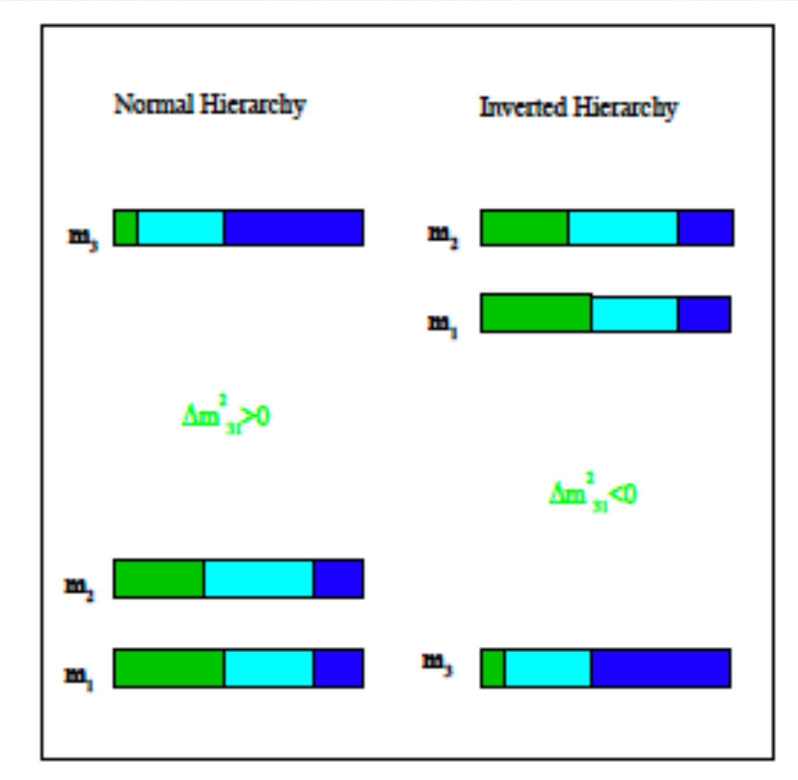


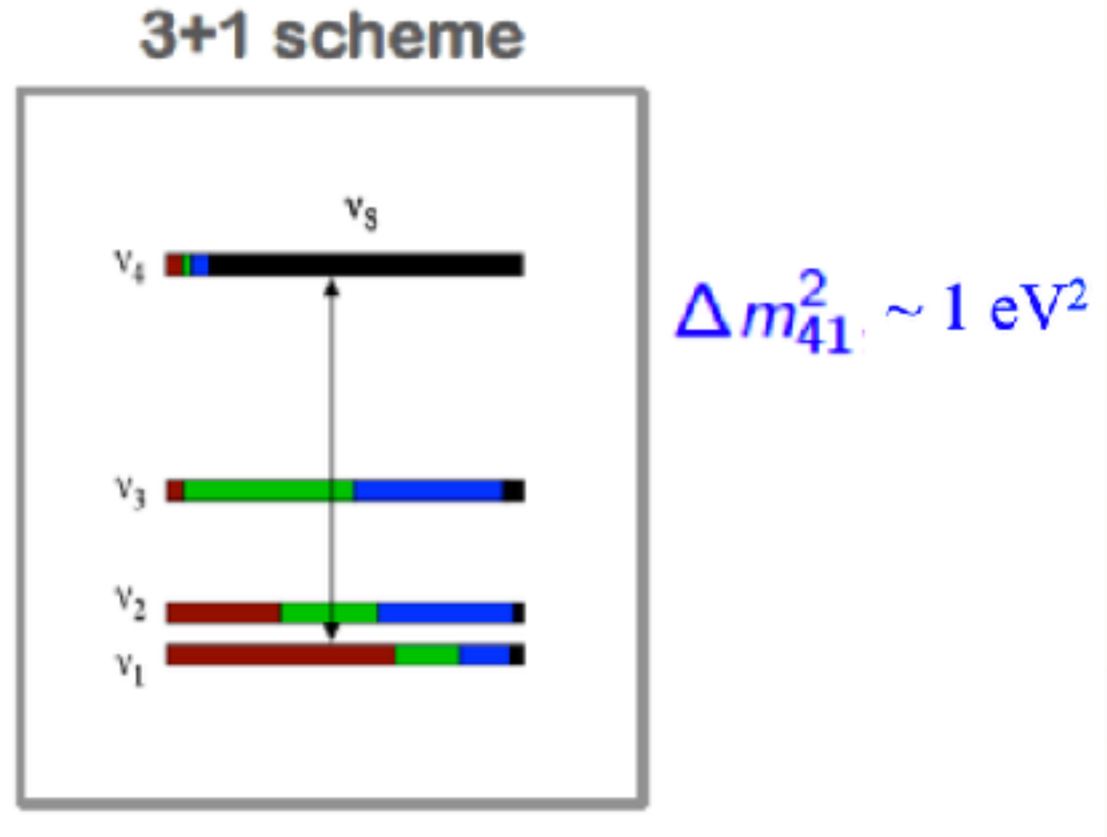
Also sensitive to
atmospheric neutrinos

Both muon and electron events in Liquid Argon

DUNE PRISM: off-axis, movable

3 and 3+1 Scheme



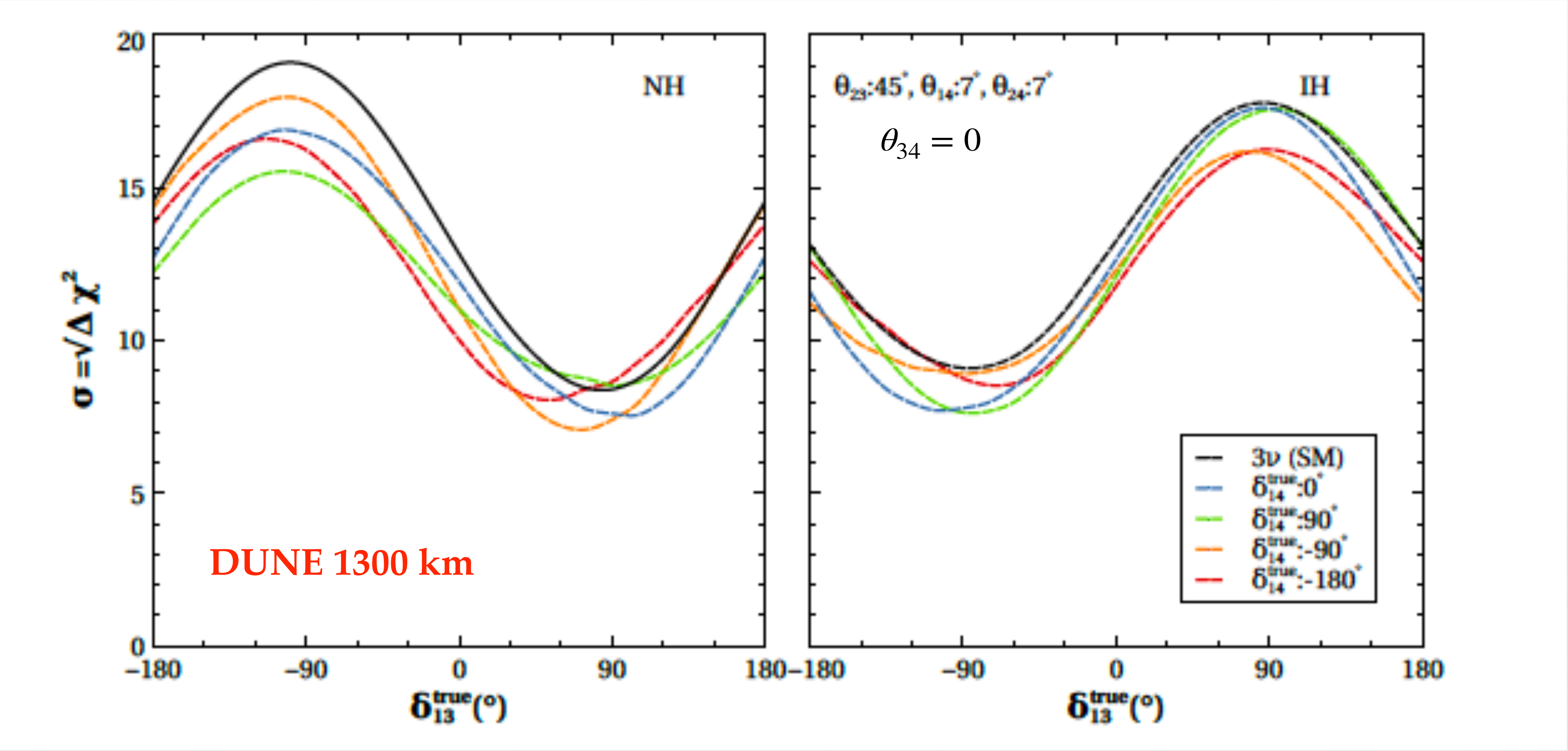


$$U_{st} = \tilde{R}_{34}(\theta_{34}, \delta_{34}) R_{24}(\theta_{24}) \tilde{R}_{14}(\theta_{14}, \delta_{14}) R_{23}(\theta_{23}) \tilde{R}_{13}(\theta_{13}, \delta_{13}) R_{12}(\theta_{12})$$

Beyond 3 flavours

- Impact of sterile neutrinos on oscillation probabilities
- Sub-leading effect
- Extra parameters and degeneracies
- How does it affect the determination of ordering, octant of 2-3 mixing and CP phase ?
- Constraints on sterile parameters

Hierarchy sensitivity in 3+1 picture



Hierarchy sensitivity reduces in presence of sterile neutrino, but still substantial

Chatterjee, Pan, Goswami, 2023

Degeneracies in presence of a sterile neutrino

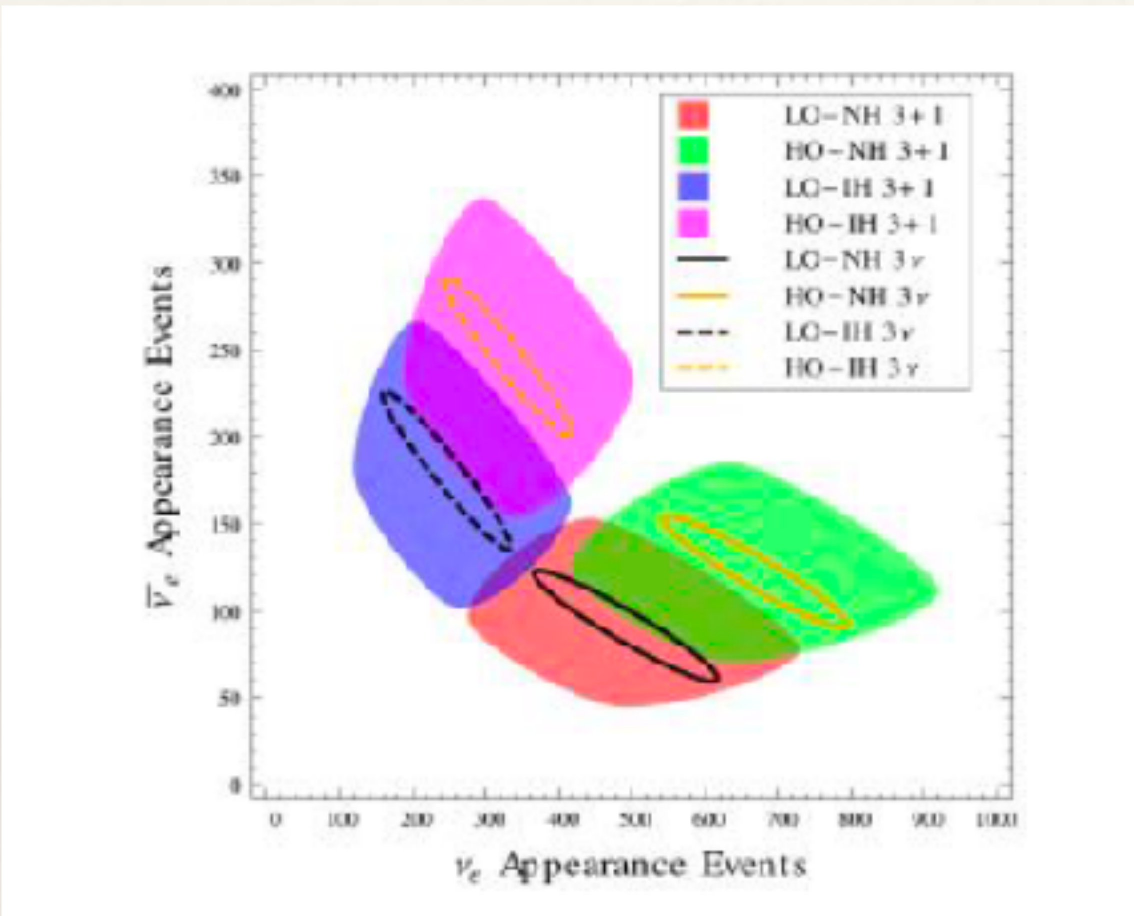
- For fixed hierarchy 8-fold degeneracy

Solution with right octant	Solution with wrong octant
RO-Rδ_{13}-Rδ_{14}	WO-Rδ_{13}-Rδ_{14}
RO-Rδ_{13}-Wδ_{14}	WO-Rδ_{13}-Wδ_{14}
RO-Wδ_{13}-Rδ_{14}	WO-Wδ_{13}-Rδ_{14}
RO-Wδ_{13}-Wδ_{14}	WO-Wδ_{13}-Wδ_{14}

- If hierarchy is unknown 16-fold degeneracy

Octant sensitivity in danger ?

eV scale sterile neutrino



Agarwalla, Chatterjee, Palazzo, PRL (2016)

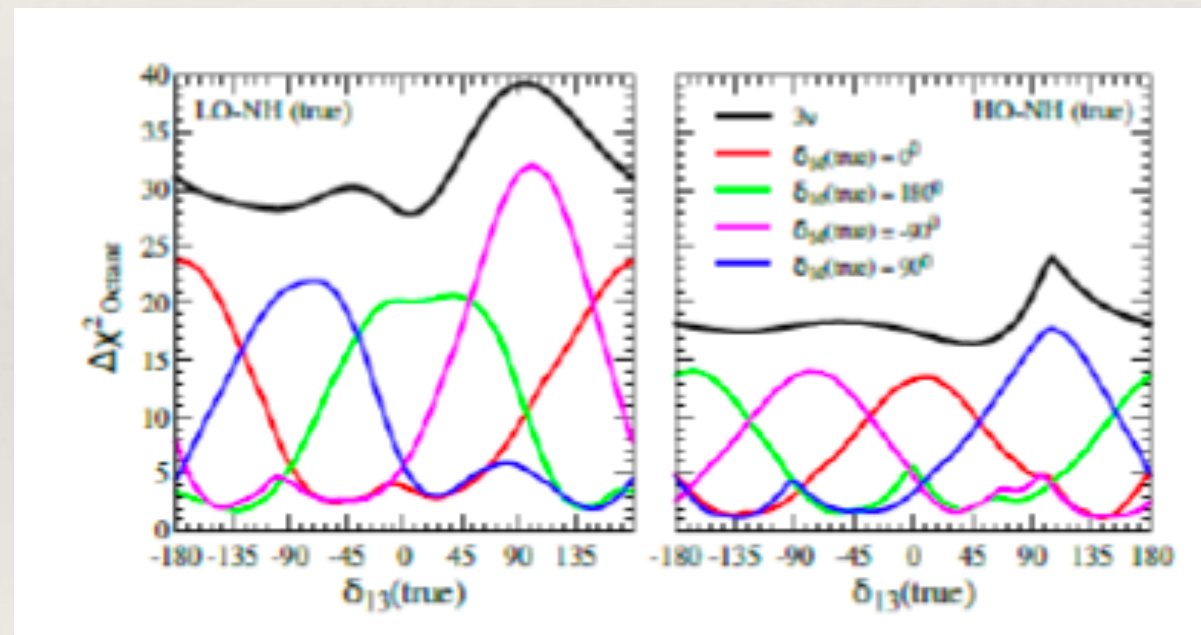
DUNE detector 1300 km baseline

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

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

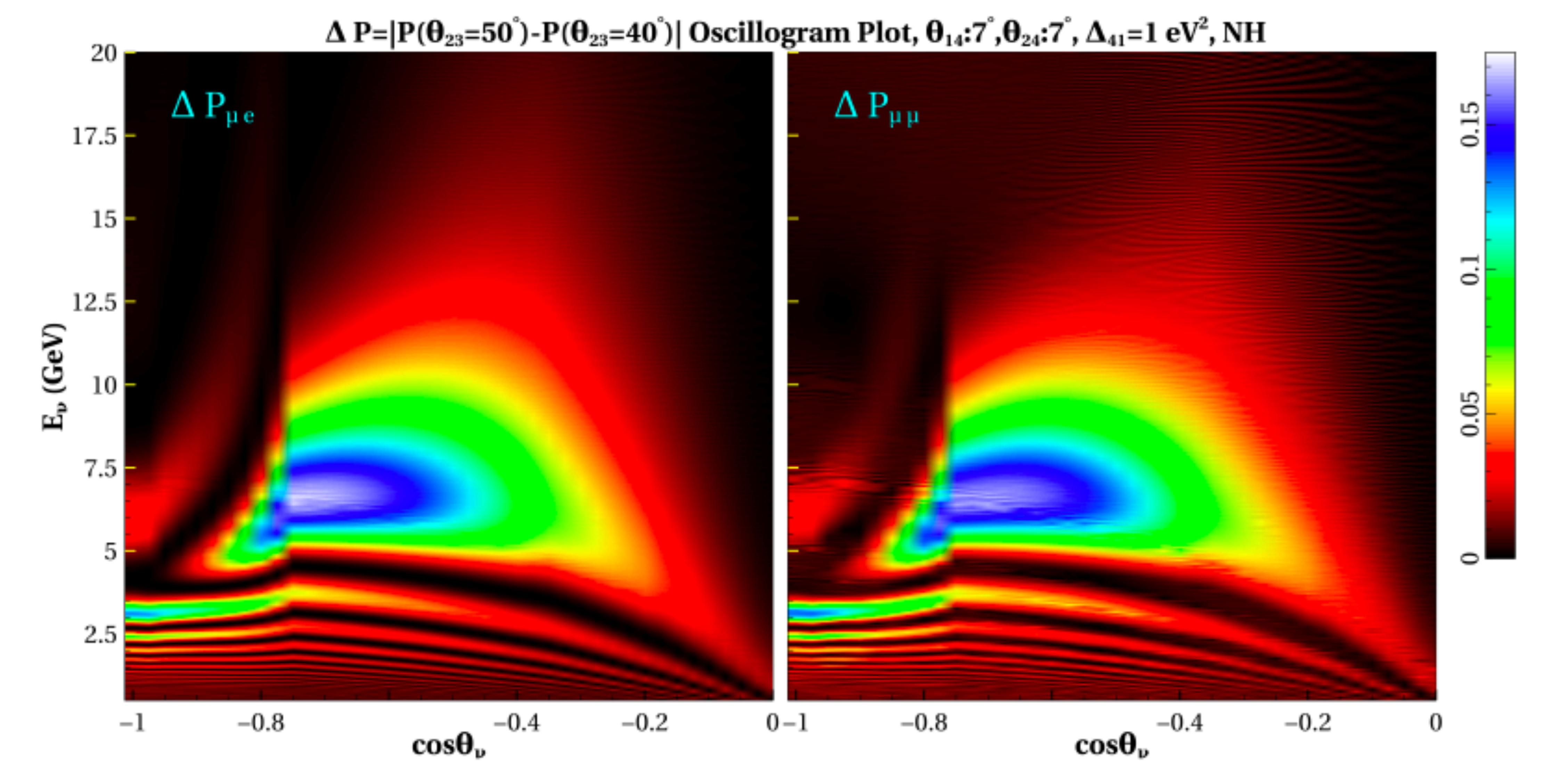
$$P_1 \simeq 8 s_{13} s_{12} c_{12} s_{23} c_{23} (\alpha\Delta) \sin\Delta \cos(\Delta \pm \delta_{13}) ,$$

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



For certain combinations of phases very low octant sensitivity

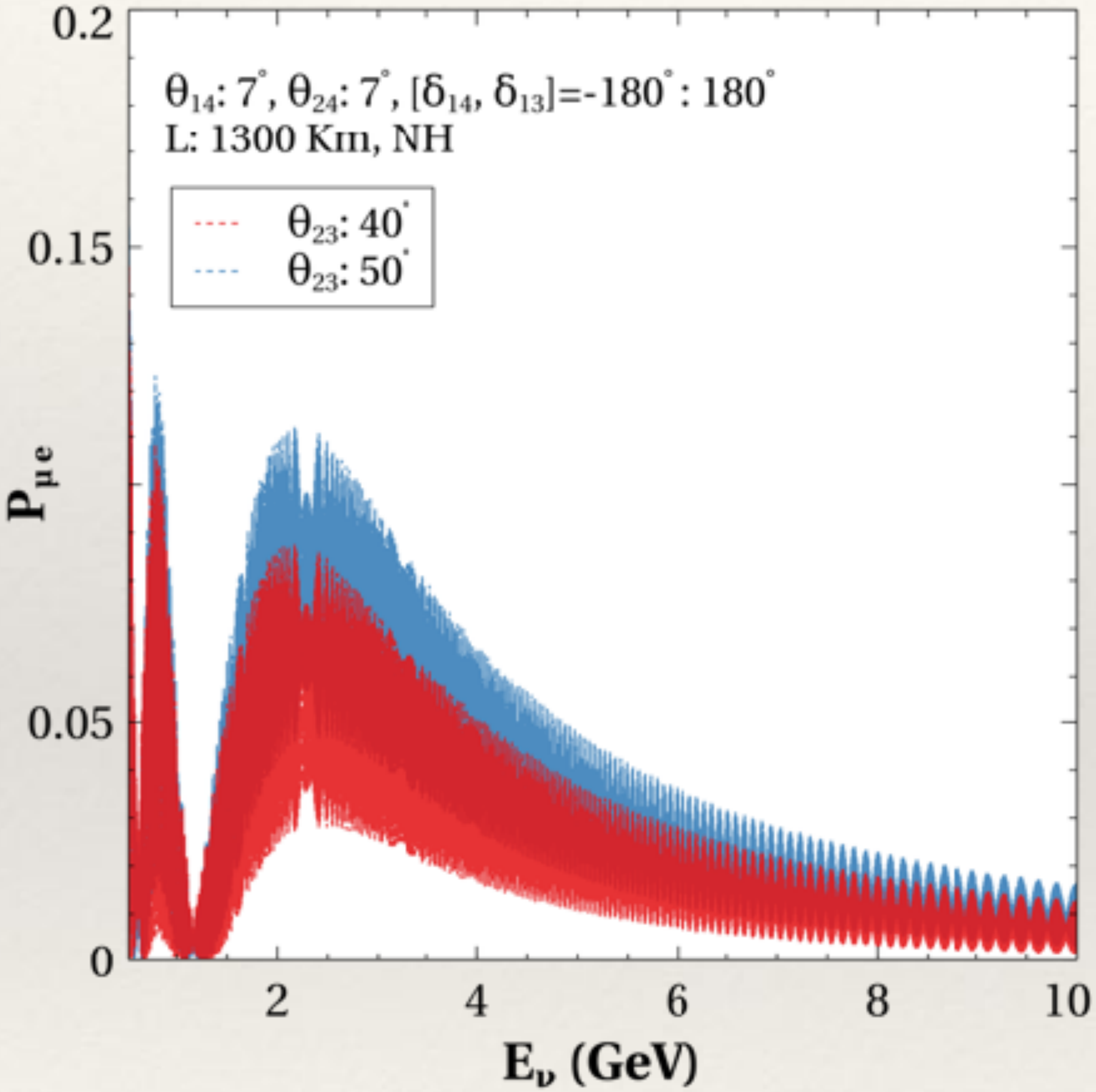
Oscillogram of Octant sensitivity

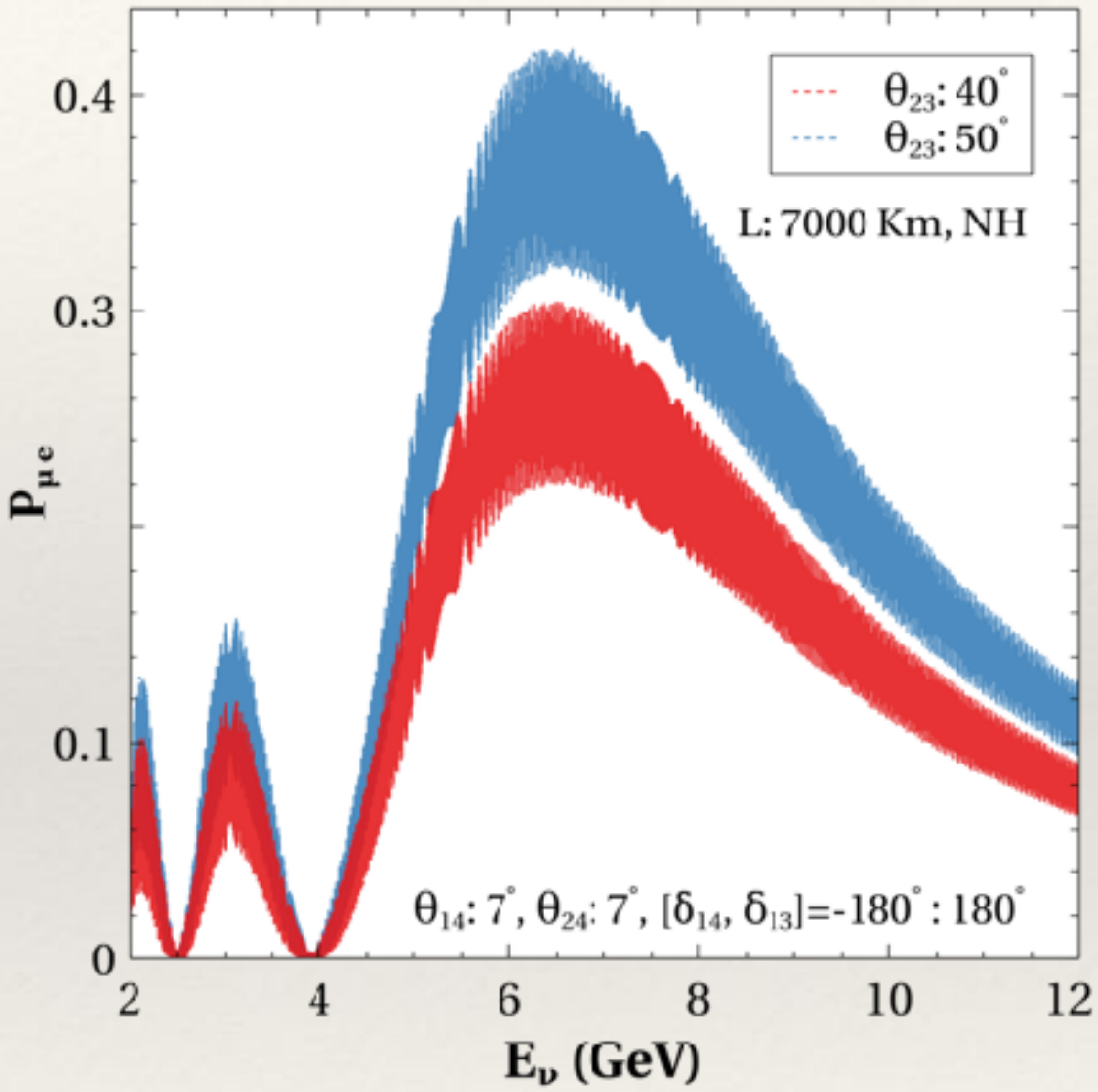


For fixed phases, variation over phases can reduce sensitivity further

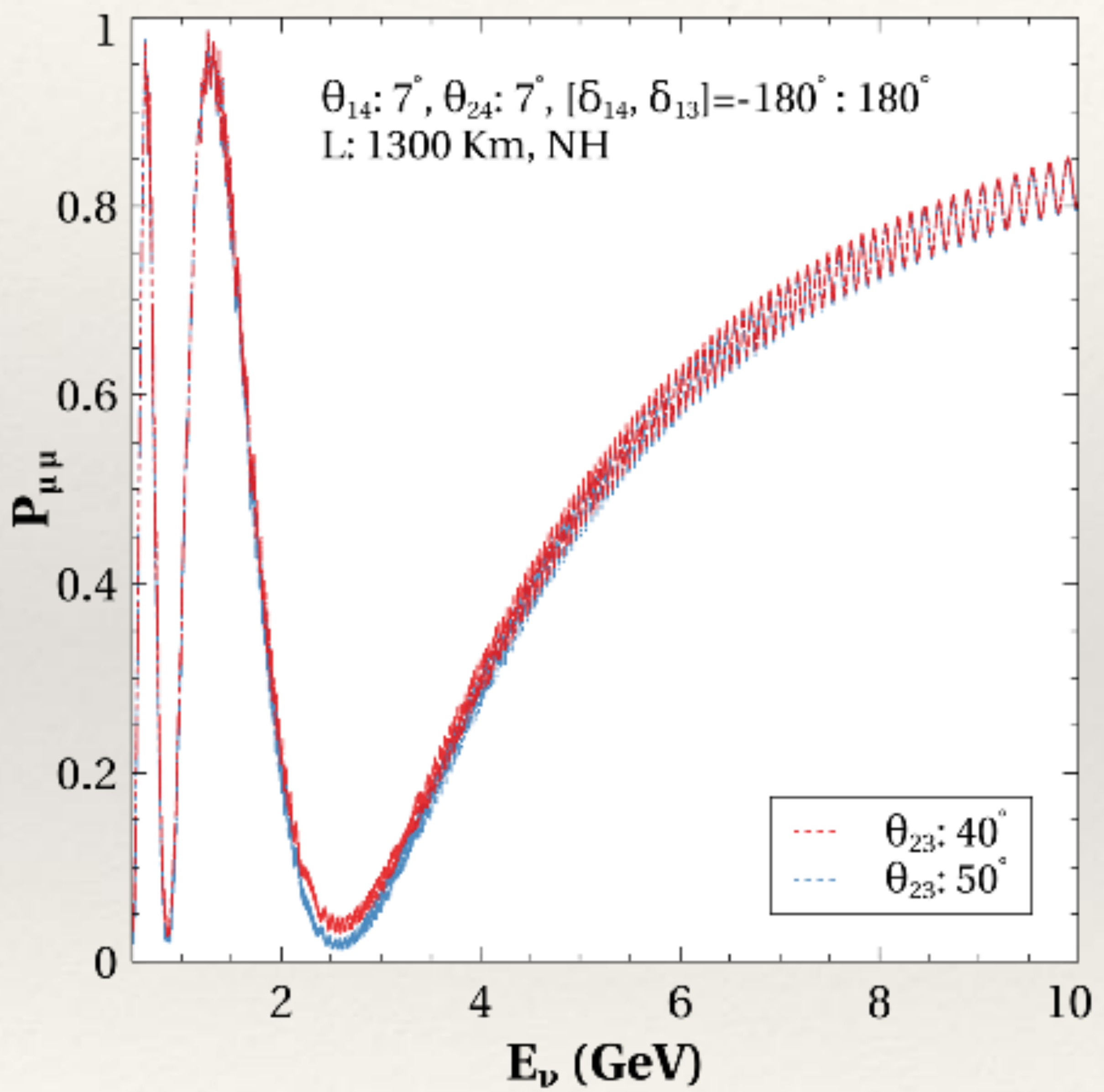
For 5-7 GeV and $\cos\theta_\nu$ in the range -0.5 - 0.9 sensitivity is more

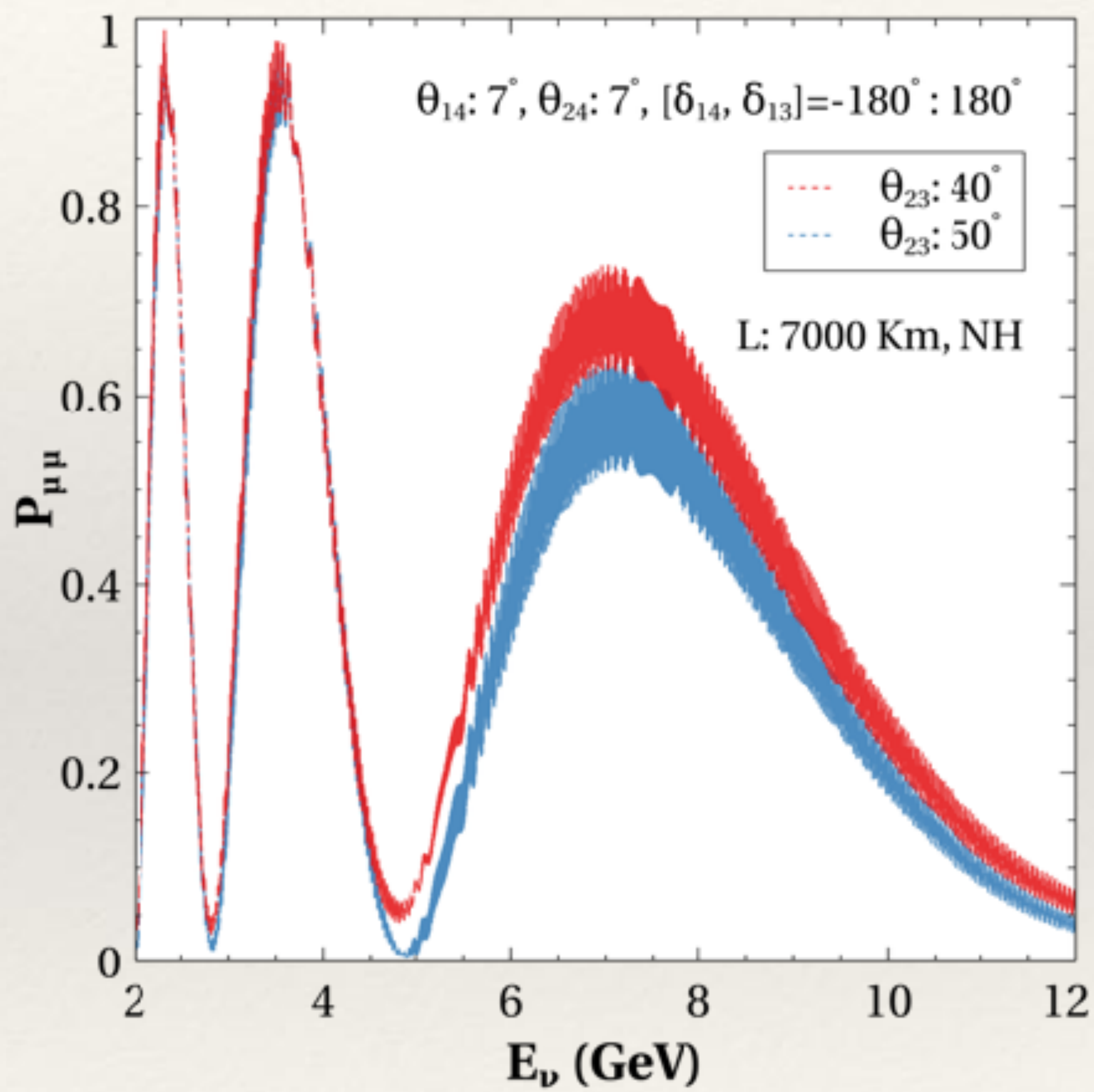
Effect of Phases : $P_{\mu e}$



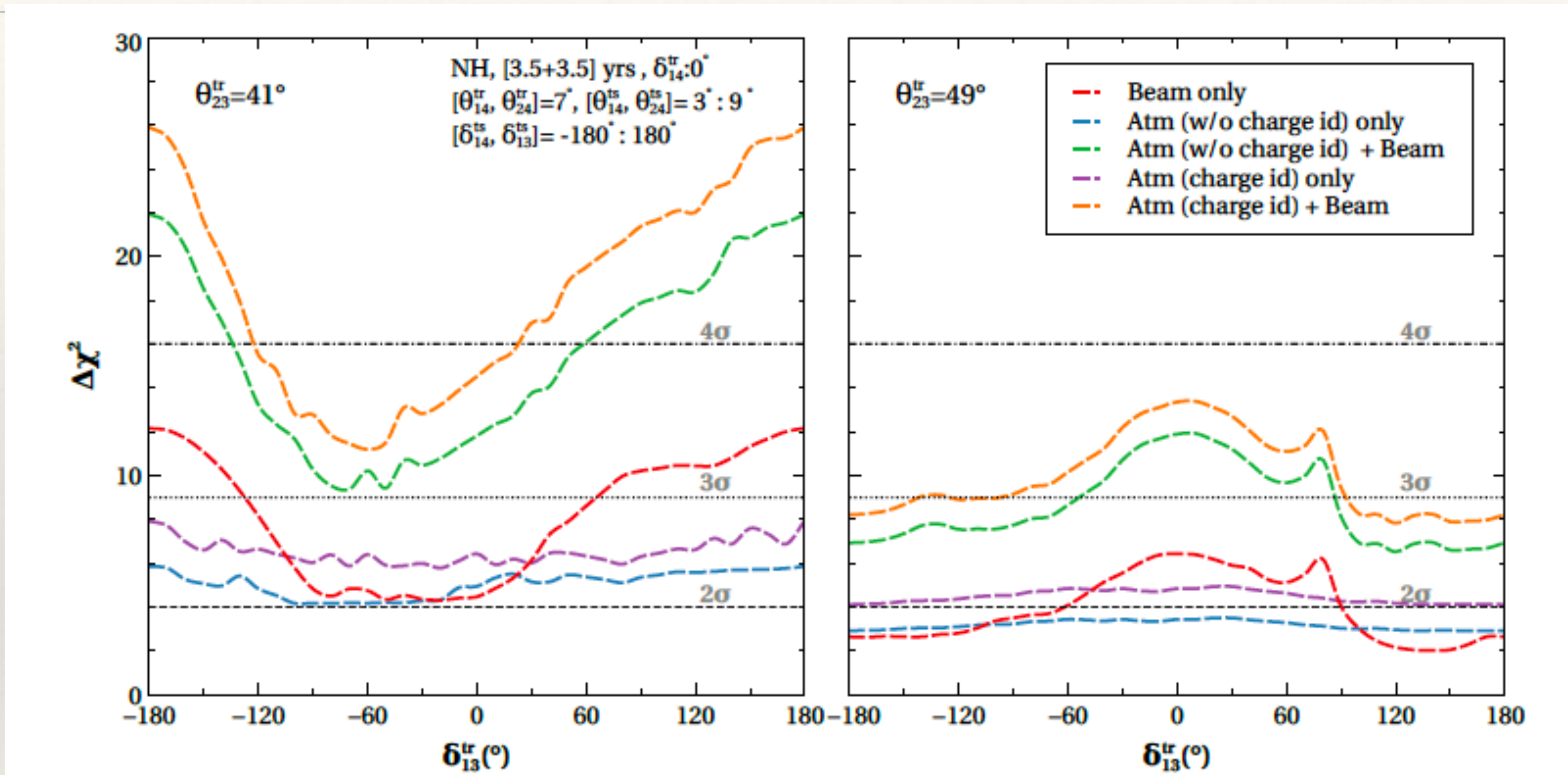


Effect of Phases : $P_{\mu\mu}$





Can atmospheric neutrinos help ?

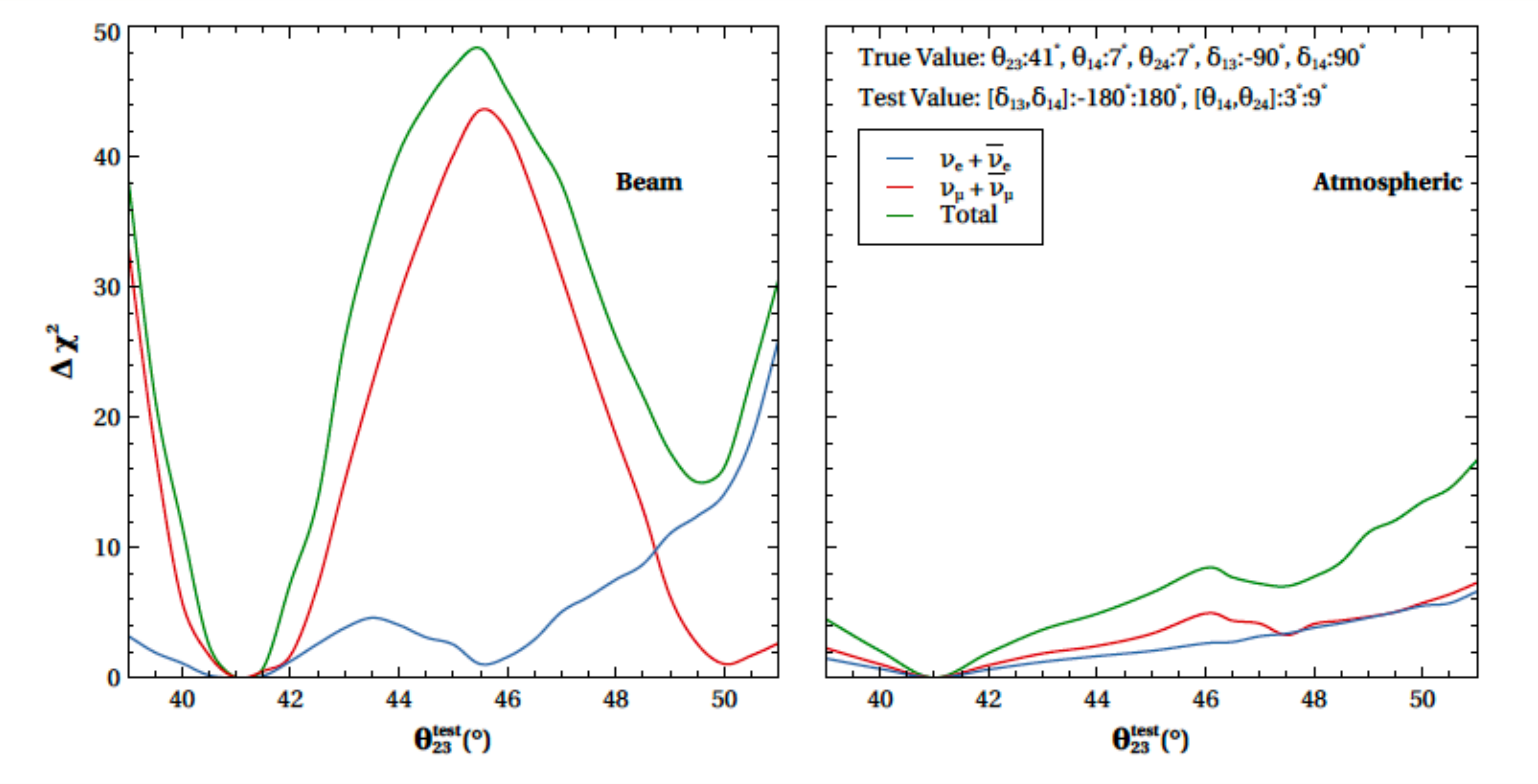


Animesh Chatterjee, Supriya Pan, SG, 2212.02949

Beam and atmospheric neutrinos combined for a Liquid Argon detector

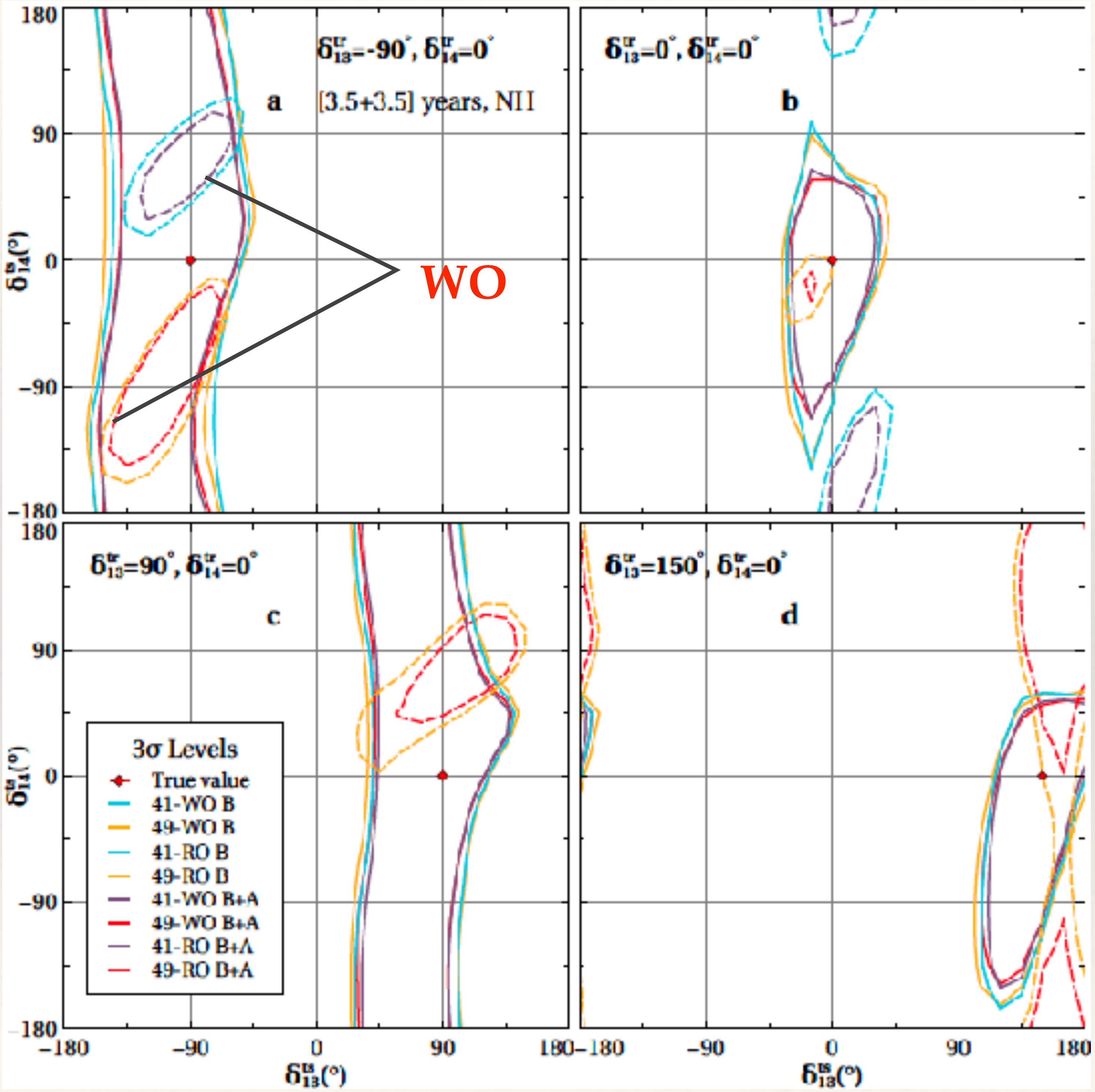
Beam 3.5 + 3.5 years   Atmospheric : 40 kt X 7 years = 280 kty

Synergy



True Value: θ23:41°, θ14:7°, θ24:7°, δ13:-90°, δ14:90°
Test Value: [δ13,δ14]:-180°:180°, [θ14,θ24]:3°:9°
Beam
Atmospheric
Total
Δχ²
θ23test(°)

Degenerate solutions



Wrong Octant solutions in $\delta_{13} - \delta_{14}$ plane

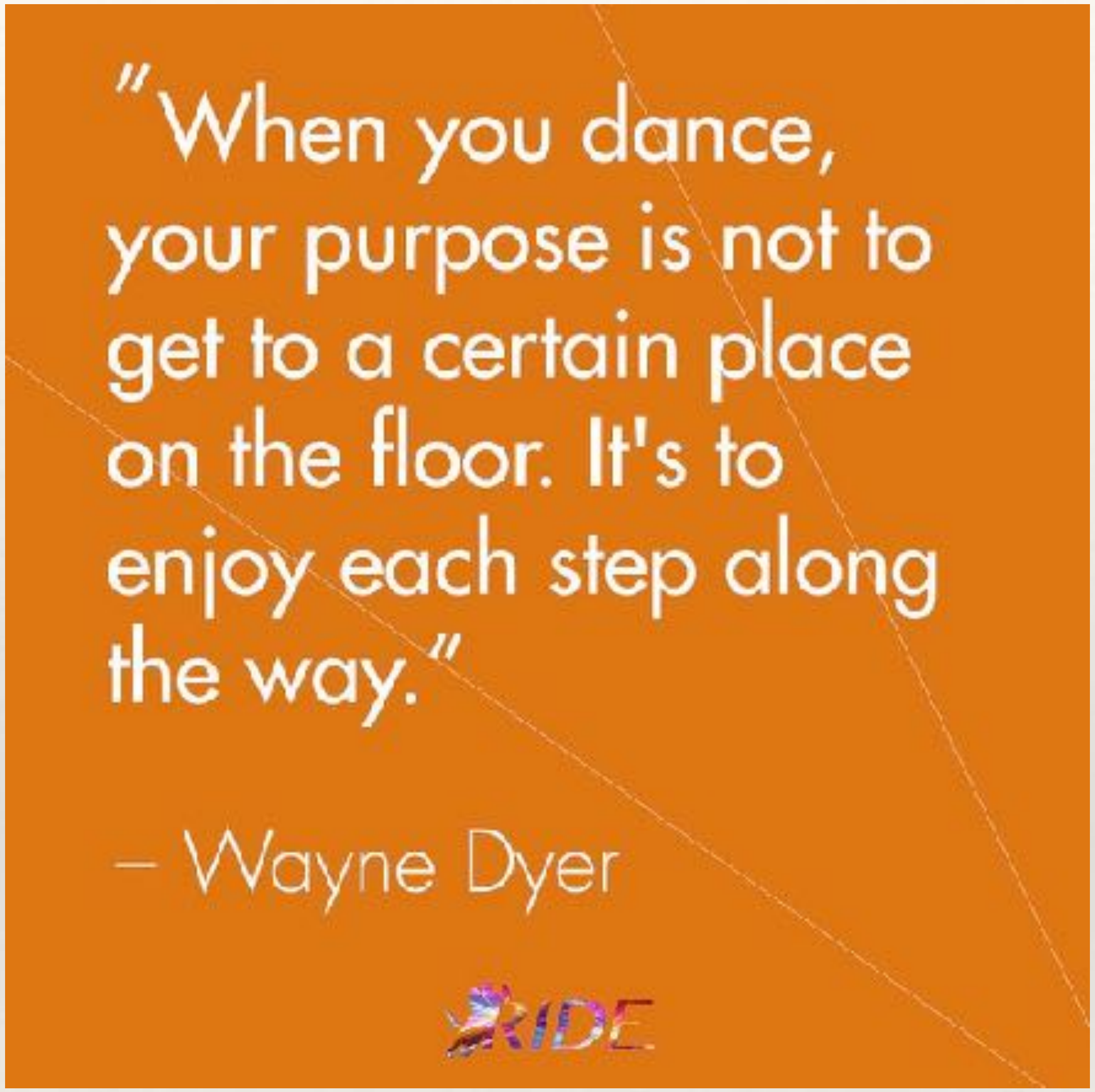
Poor precision of δ_{14}

Animesh Chatterjee, Supriya Pan, SG, 2212.02949

Summary

- Increased parameters in 3+1 picture give rise to additional degeneracies
- Precision of 3 generation parameters can become worse
- Octant sensitivity can be very low for 1300 km beam experiment
- Adding beam + atmospheric neutrinos can help in increasing the sensitivity

NOW 2022, Ostuni



Raising a toast for more physics and more fun


TACK
spas
TESEKKUR EDERIM
asante
tesekkur ederim
GRATIAS AGO
grazie
merci
asante
TACK
dziekuje
spas
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tak
dziekuje
NGIYABONGA
THANK YOU
GRACIAS
grazie
dankon
tesekkur ederim
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gracias
GRACIAS
asante
danke
gracias
xièxie
GRACIAS
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BAYARLALAA
TODA
dankon
gracias
NGIYABONGA
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DZIEKUJE
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BACKUP SLIDES

Charge ID in Liquid Argon

μ^- can get captured in liquid Argon

$$\tau = (\frac{1}{\tau_{cap}} + \frac{Q}{\tau_{free}})^{-1}$$

Lifetime of the muon resulting in capture and decay

$$\epsilon^{cap} = \frac{\tau}{\tau_{cap}} = 1 - \frac{\tau}{\tau_{free}}$$

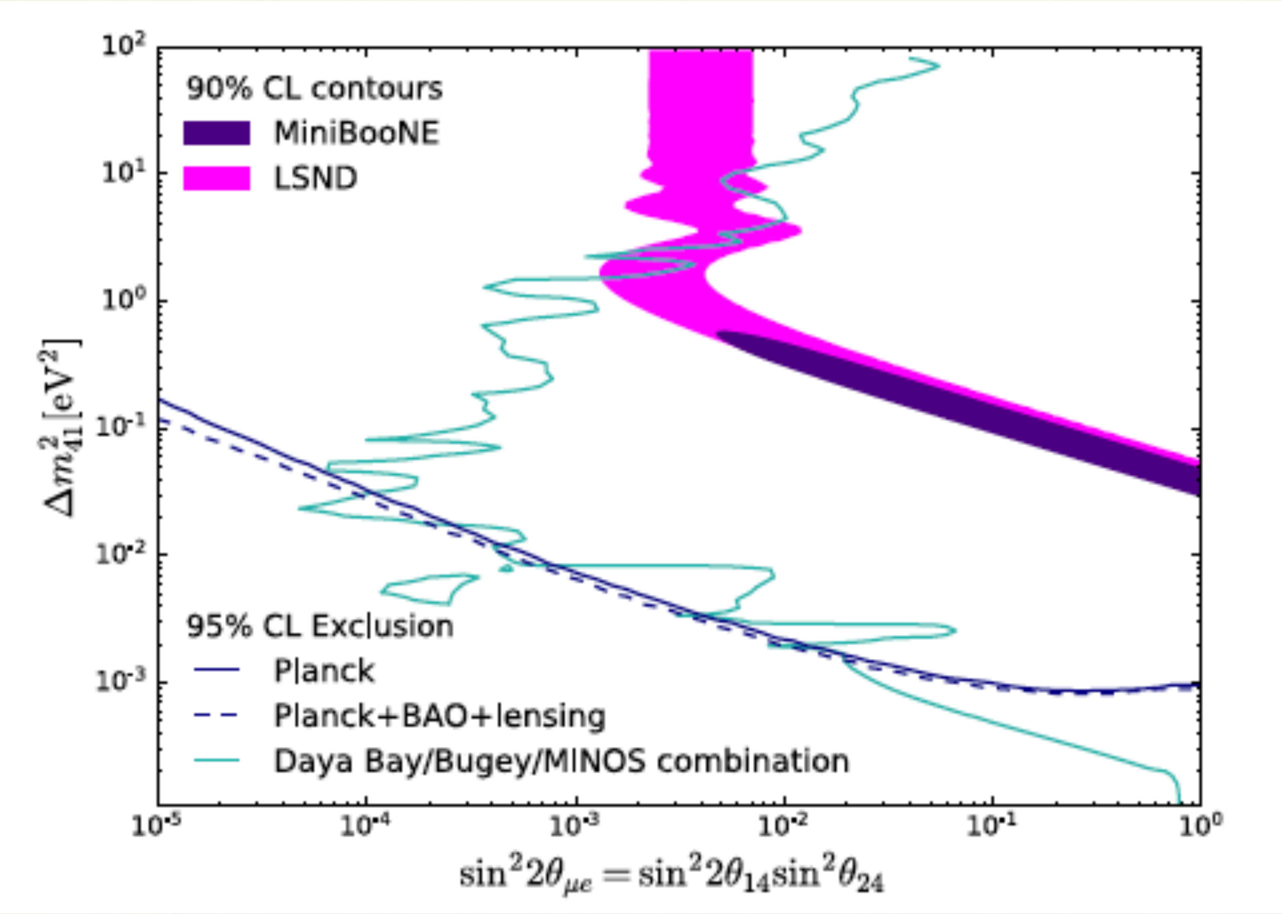
$$N_{i,j,\mu^-}{}^{cap} = \epsilon^{cap} \times N_{\mu^-}$$

$$N^{rest}_{i,j,\mu^+} = (1 - \epsilon^{cap}) N_{i,j,\mu^-} + N_{i,j,\mu^+}$$

$$\chi^2_{w/o\ charge-id} = \chi^2_{\mu^- + \mu^+} + \chi^2_{e^- + e^+}$$

$$\chi^2_{charge-id} = \chi^2_{\mu^-} + \chi^2_{\mu^+} + \chi^2_{e^- + e^+}$$

Cosmological constraints



M.Adams et al. Eur. Phys. J.80 (2020)

Interactions with an ultralight scalar

Y. Farzan, Phys. Lett. B. 2019
J.M. Cline, Phys. Lett. B 2020

Large lepton anti-lepton asymmetry in the Universe

Foot and Volkas, PRL 1995

Low reheating temperature

Gelmini, Palomarez-Ruis, Pascoli, PRL 2004