Sterile Neutrino Phenomenology

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Workshop on High Energy Physics phenomenology XVI

02, December, 2019

IIT - Guwahati

Plan

- Introduction to sterile neutrinos
- Recent developments
- Future possibilities

Standard 3+0 neutrino oscillation scenario:

Let,

ν_1, ν_2, ν_3 **mass eigenstate** ν_i

ν_e, ν_μ, ν_τ **flavour eigenstate** ν_α

$$\boxed{\nu_\alpha = U_{\alpha i}\nu_i}$$

U is the PMNS matrix

Hence, the evolution equation :

$$\boxed{i\frac{d\nu_f}{dx} = UHU^\dagger \nu_f}$$

$$H = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix}$$

2 mass-squared differences

1 CP phase

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

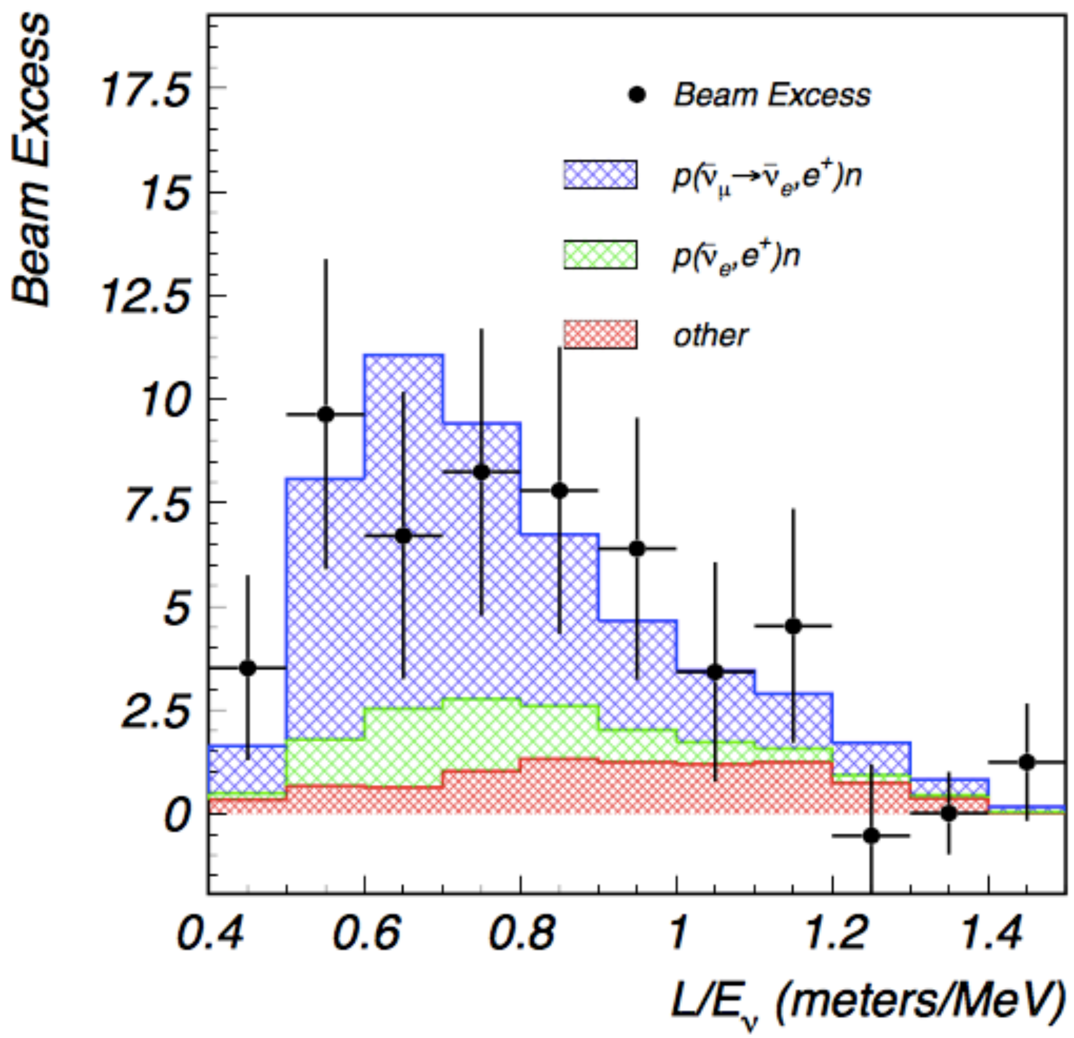
Atmospheric **Reactor** **solar**

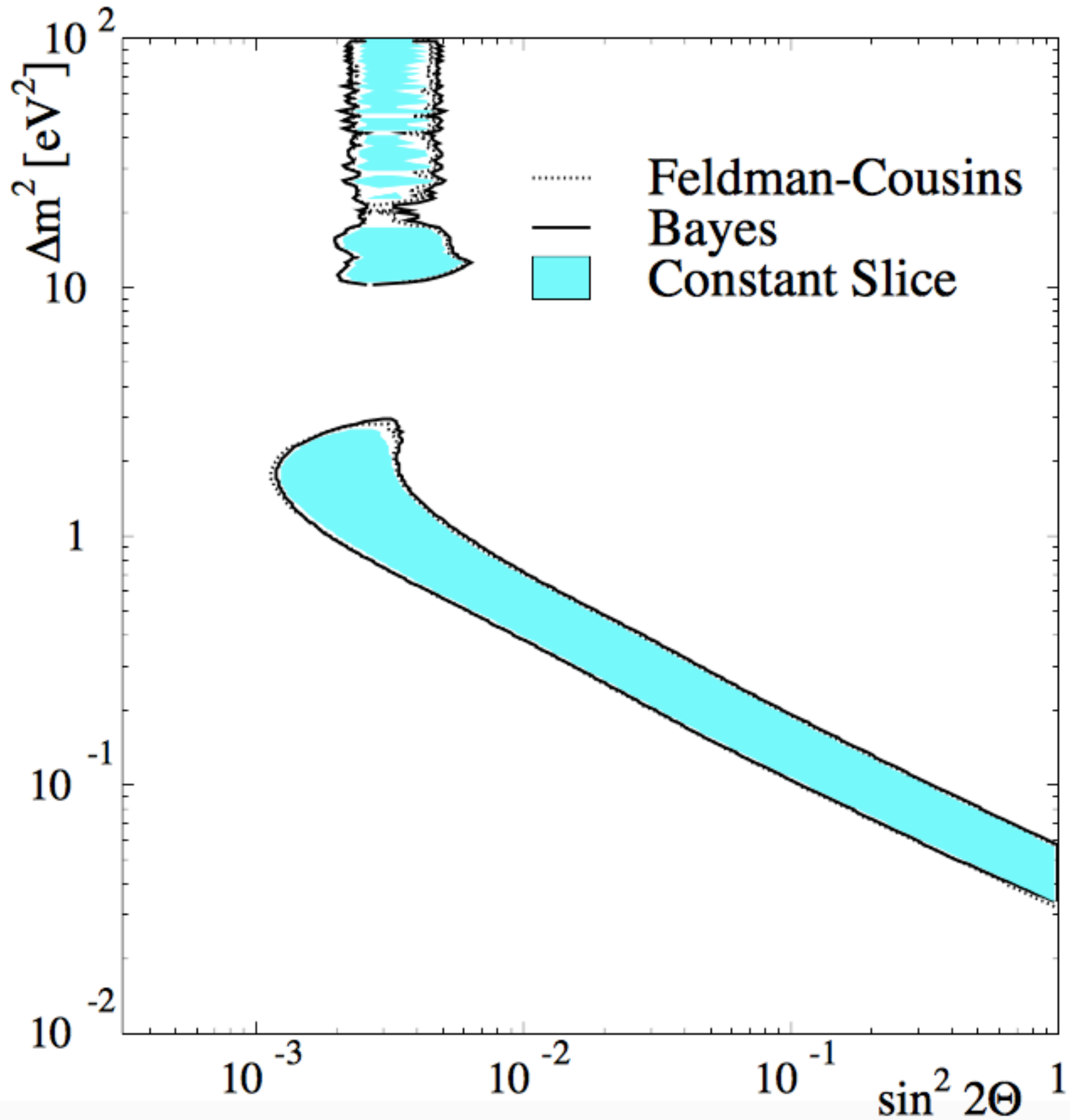
3 mixing angles

Short-Baseline Anomalies

Phys.Rev. D64 (2001) 112007

LSND anomaly





3.8 σ excess

90 % C.L.

This could only be explained in terms of neutrino oscillation

$$\Delta m^2 \sim 1eV^2$$

This is in conflict with the observed solar and atmospheric data

$\Delta m^2_{sol} \sim 8 \times 10^{-5} eV^2$ $\Delta m^2_{atm} \sim 2.5 \times 10^{3} eV^2$ $\Delta m^2_{LSND} \sim 1 eV^2$

The three generation oscillation needs two mass-squared differences

To accommodate the third mass-squared difference , we need another extra neutrino state

This extra state is called the sterile neutrino

Why sterile??

LEP measured the number of active neutrino species to be exactly three

So the new state must be a singlet of the standard model gauge group

3+1 scenario:

Four mass-states and four flavour-states

$\nu_1, \nu_2, \nu_3, \nu_4$ **mass eigenstate** ν_i

$$\nu_\alpha = U_{\alpha i}\nu_i$$

$\nu_e, \nu_\mu, \nu_\tau, \nu_s$ **flavour eigenstate** ν_α

Six mixing angles and three CP-violating phases

$$\theta_{12}, \theta_{13}, \theta_{23}, \theta_{14}, \theta_{24}, \theta_{34}, \delta_{13}, \theta_{14}, \theta_{24},$$

$$U^{3+1} = O(\theta_{34}, \delta_{34})O(\theta_{24}, \delta_{24})\boxed{R(\theta_{14})R(\theta_{23})O(\theta_{13}, \delta_{13})R(\theta_{12})} \; U_{PMNS}$$

The minimalistic sterile neutrino scenario is in conflict with Cosmology

$$n_{eff} \qquad \Sigma_{m_\nu}$$

Some way outs:

Self interaction

Decaying sterile neutrino

Alternate Cosmology??

Many many experiments after LSND

$\nu_e/\bar{\nu}_e$ disappearance data :

[JHEP 1808 (2018) 010]

Experiment	References	Comments	(Data points)
Reactor experiments			(233)
ILL	[59]		
Gösgen	[60]		
Krasnoyarsk	[61–63]		
Rovno	[64, 65]		
Bugey-3	[66]	spectra at 3 distances with free bin-by-bin normalization	
Bugey-4	[67]		
SRP	[68]		
NEOS	[23, 29]	ratio of NEOS and Daya Bay spectra	
DANSS	[26]	ratios of spectra at two baselines (updated w.r.t. [21])	
Double Chooz	[33]	near detector rate	
RENO	[69, 70]	near detector rate	
Daya Bay spectrum	[71]	spectral ratios EH3/EH1 and EH2/EH1	
Daya Bay flux	[37]	individual fluxes for each isotope (EH1, EH2)	
KamLAND	[72]	very long-baseline reactor experiment ($L \gg 1$ km)	
Solar neutrino experiments			(325)
Chlorine	[73]		
GALLEX/GNO	[74]		
SAGE	[75]		
Super-Kamiokande	[45, 76–78]	Phases I–IV	
SNO	[79–81]	Phases 1–3 (CC and NC data)	
Borexino	[46, 82, 83]	Phases I and II	
ν_e **scattering on carbon** ($\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$)			(32)
KARMEN	[84–86]		
LSND	[86, 87]		
Radioactive source experiments (gallium)			(4)
GALLEX	[74, 88]	ν_e from ^{51}Cr source	
SAGE	[89, 90]	ν_e from ^{51}Cr and ^{37}Ar sources	

This data set prefers sterile neutrino over standard case

$\nu_\mu \to \nu_e / \bar{\nu}_\mu \to \bar{\nu}_e$ **appearance data :**

[JHEP 1808 (2018) 010]

Experiment	References
LSND	[1]
LSND	[1]
MiniBooNE	[2, 99]
KARMEN	[94]
NOMAD	[95]
E776	[96]
ICARUS	[97, 98]
OPERA	[40]

Prefer sterile neutrino

The global fit prefers the sterile neutrino

$\nu_\mu/\bar{\nu}_\mu$ disappearance data

Experiment
IceCube (IC)
CDHS
MiniBooNE
Super-Kamiokande (SK)
DeepCore (DC)
NOνA
MINOS/MINOS+

[JHEP 1808 (2018) 010]

Global-fit does not prefer sterile neutrino

$$P_{\alpha\alpha}^{\rm SBL} = 1 - 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)\,\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P_{\alpha\beta}^{\rm SBL} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2\,\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right).$$

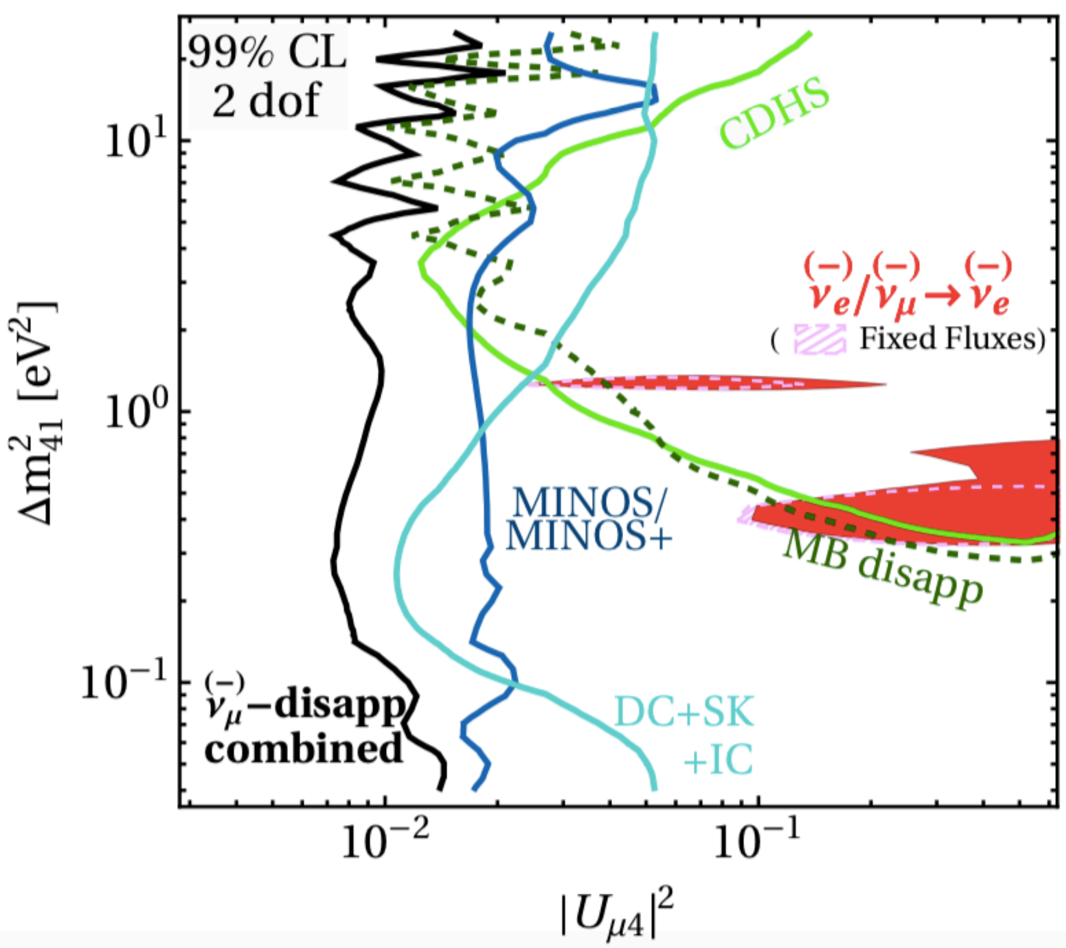
$P_{\mu e} \neq 0 \implies |U_{e4}|^2, |U_{\mu 4}|^2 \neq 0$

P_{ee} **depends on** $|U_{e4}|^2$

$P_{\mu\mu}$ **depends on** $|U_{\mu 4}|^2$

$P_{\mu e}$ **depends on** $|U_{\mu 4}|^2 |U_{e4}|^2$

Strong tension between various dataset



[JHEP 1808 (2018) 010]

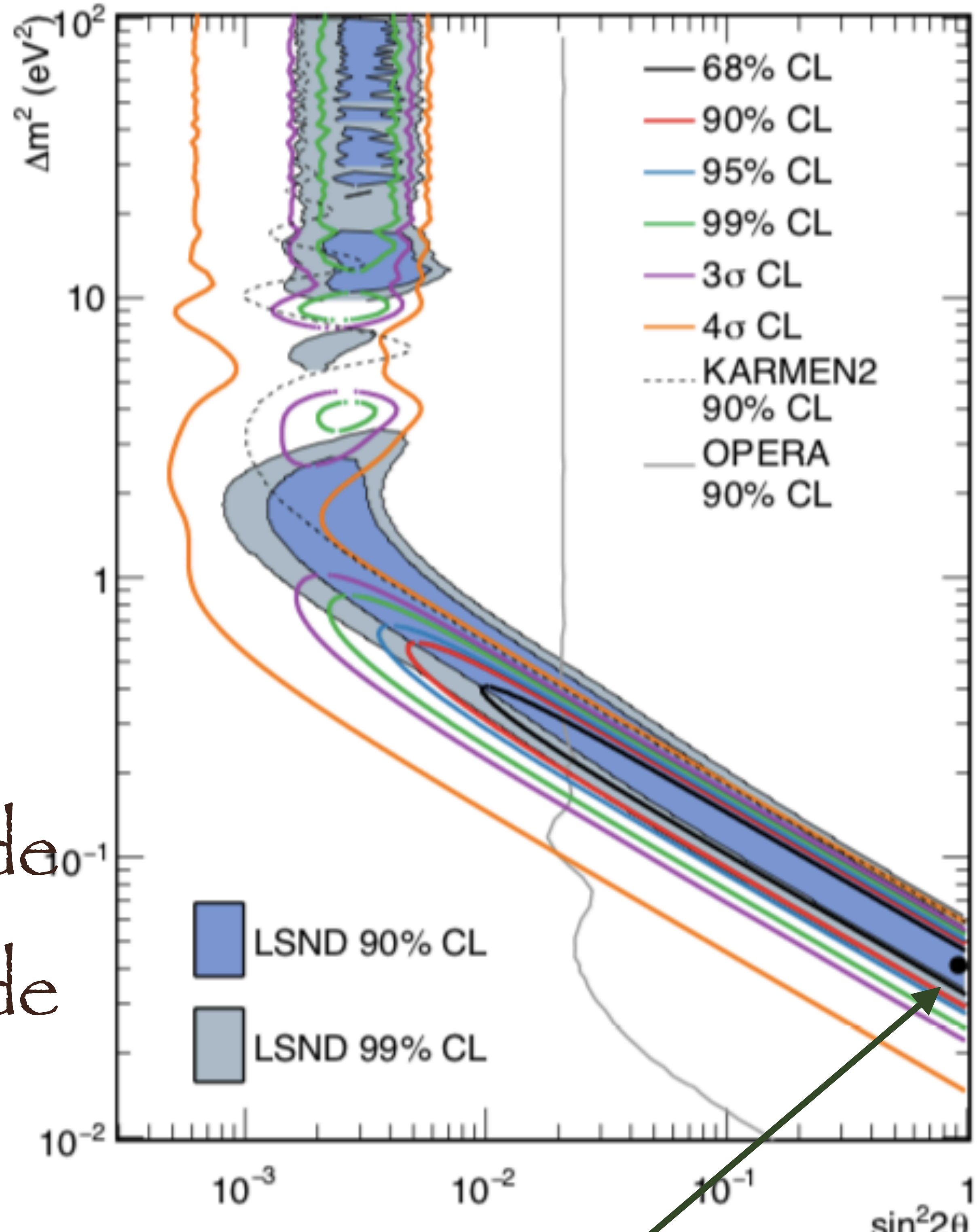
New Evidence ??!! MiniBooNe again

- 4.8 sigma excess observed for both neutrino and anti-neutrino events combined
- 6.1 sigma combined with LSND

12.84×10^{20} POT ν Mode

11.27×10^{20} POT $\bar{\nu}$ Mode

460.5 ± 95.8 excess events



[Phys.Rev.Lett. 121 (2018) no.22, 221801]

Imp. Point to note, best fit $\Delta m_{41}^2 \simeq 0.04 eV^2$

Sterile neutrino in long-baseline experiments

There are large number of papers in this area in the recent past

Mainly two directions

Prospects of measuring sterile neutrino parameters In the long-baseline experiments

Effect of sterile neutrinos in the standard physics program

Prospects of measuring sterile neutrino parameters In the long-baseline experiments

Sterile neutrino at the Deep Underground Neutrino Experiment
Jeffrey M. Berryman, André de Gouvêa, Kevin J. Kelly (Northwestern U.), Andrew Kobach (Northwestern U. & UC, San Diego). Jul 14, 2
Published in **Phys.Rev. D92 (2015) no.7, 073012**

Searches for new physics at the Hyper-Kamiokande experiment
Kevin J. Kelly (Northwestern U.). Mar 1, 2017. 14 pp.
Published in **Phys.Rev. D95 (2017) no.11, 115009**

Signatures of a Light Sterile Neutrino in T2HK
Sanjib Kumar Agarwalla (Bhubaneswar, Inst. Phys. & HBNI, Mumbai & ICTP, Trieste), Sabya Sachi Chatterjee (Bhubaneswar, Inst. Phys. & HBNI, Mur
Published in **JHEP 1804 (2018) 091**

Measuring the Sterile Neutrino CP Phase at DUNE and T2HK
Sandhya Choubey (Harish-Chandra Res. Inst. & HBNI, Mumbai & Royal Inst. Tech., Stockholm), Debajyoti Dutta, Dipyaman Pramanik (Harish-Chandra
Published in **Eur.Phys.J. C78 (2018) no.4, 339**

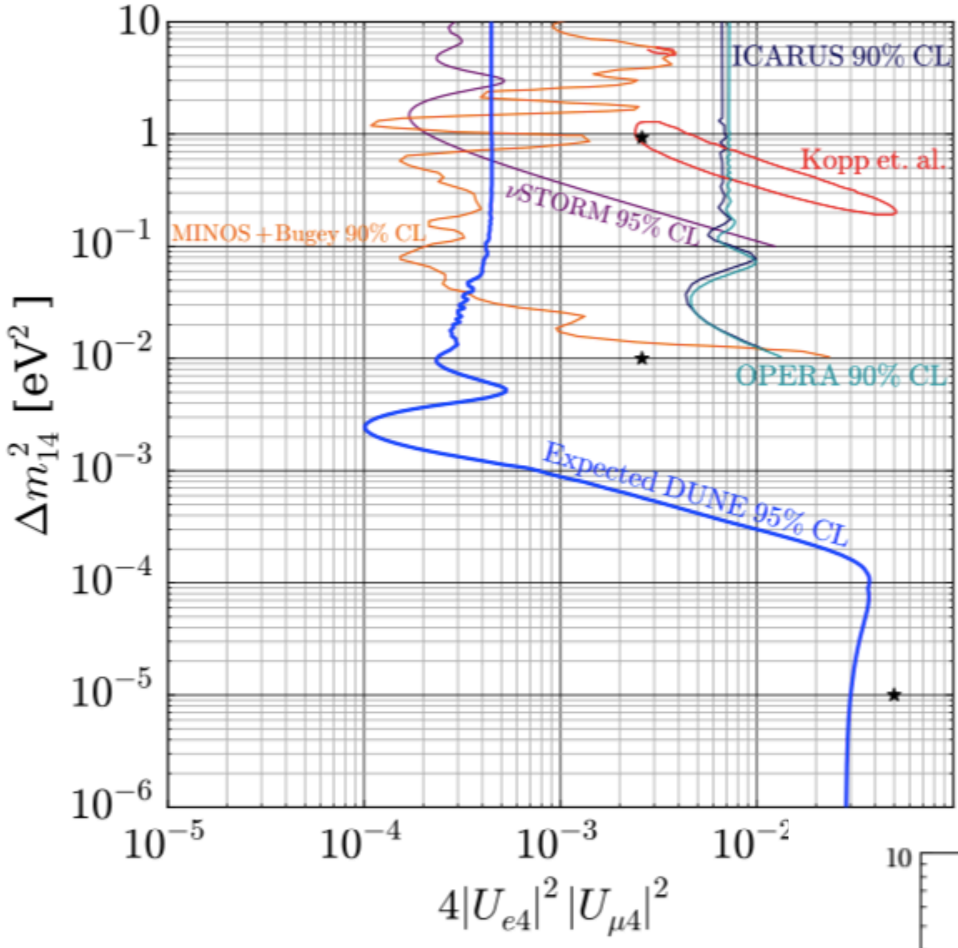
DUNE Sensitivities to the Mixing between Sterile and Tau Neutrinos
Pilar Coloma (Fermilab), David V. Forero (Campinas State U. & Virginia Tech.), Stephen J. Parke (Fermilab). Jul 17, 2017. 18 pp.
Published in **JHEP 1807 (2018) 079**

What measurements of neutrino neutral current events can reveal
Raj Gandhi (Harish-Chandra Res. Inst.), Boris Kayser (Fermilab), Suprabh Prakash (Campinas State U.), Samiran Roy (Harish-Chai
Published in **JHEP 1711 (2017) 202**

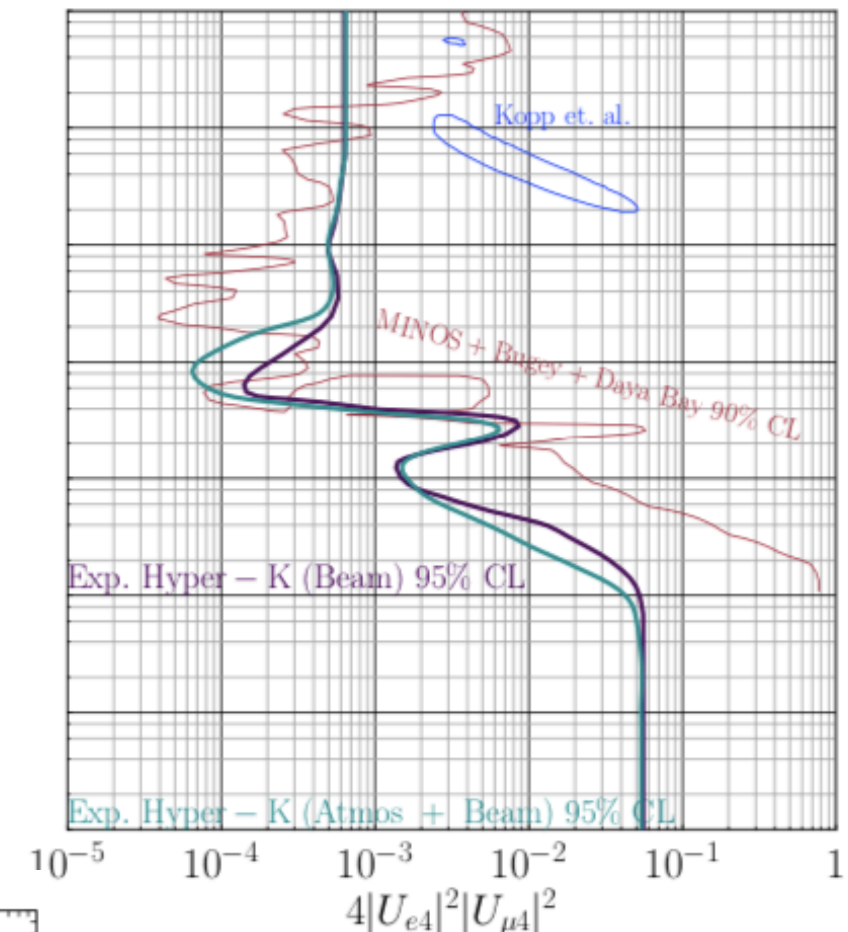
Physics with Beam Tau-Neutrino Appearance at DUNE
André De Gouvêa (Northwestern U.), Kevin J. Kelly (Northwestern U. & Fermilab), G.V. Stenico (Northwestern U. & Campinas State U.), Pedro Pasquini (Ferm
Published in **Phys.Rev. D100 (2019) no.1, 016004**
FERMILAB-PUB-19-146-T, NUHEP-TH/19-04

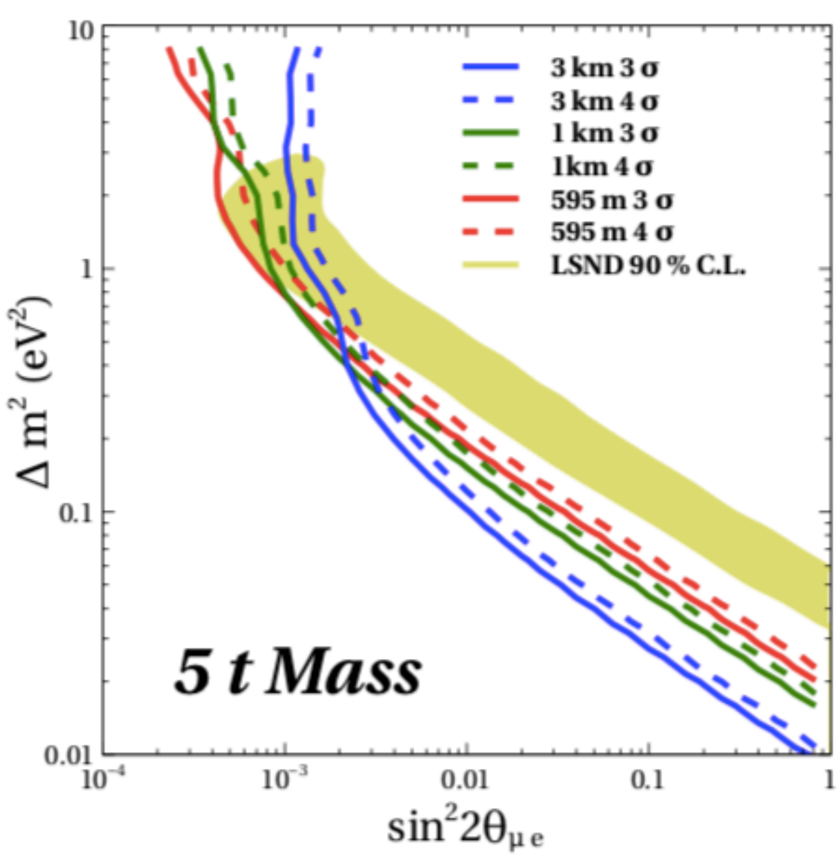
Prospects of measuring sterile neutrino parameters In the long-baseline experiments

[Phys.Rev. D92 (2015) no.7, 073012]



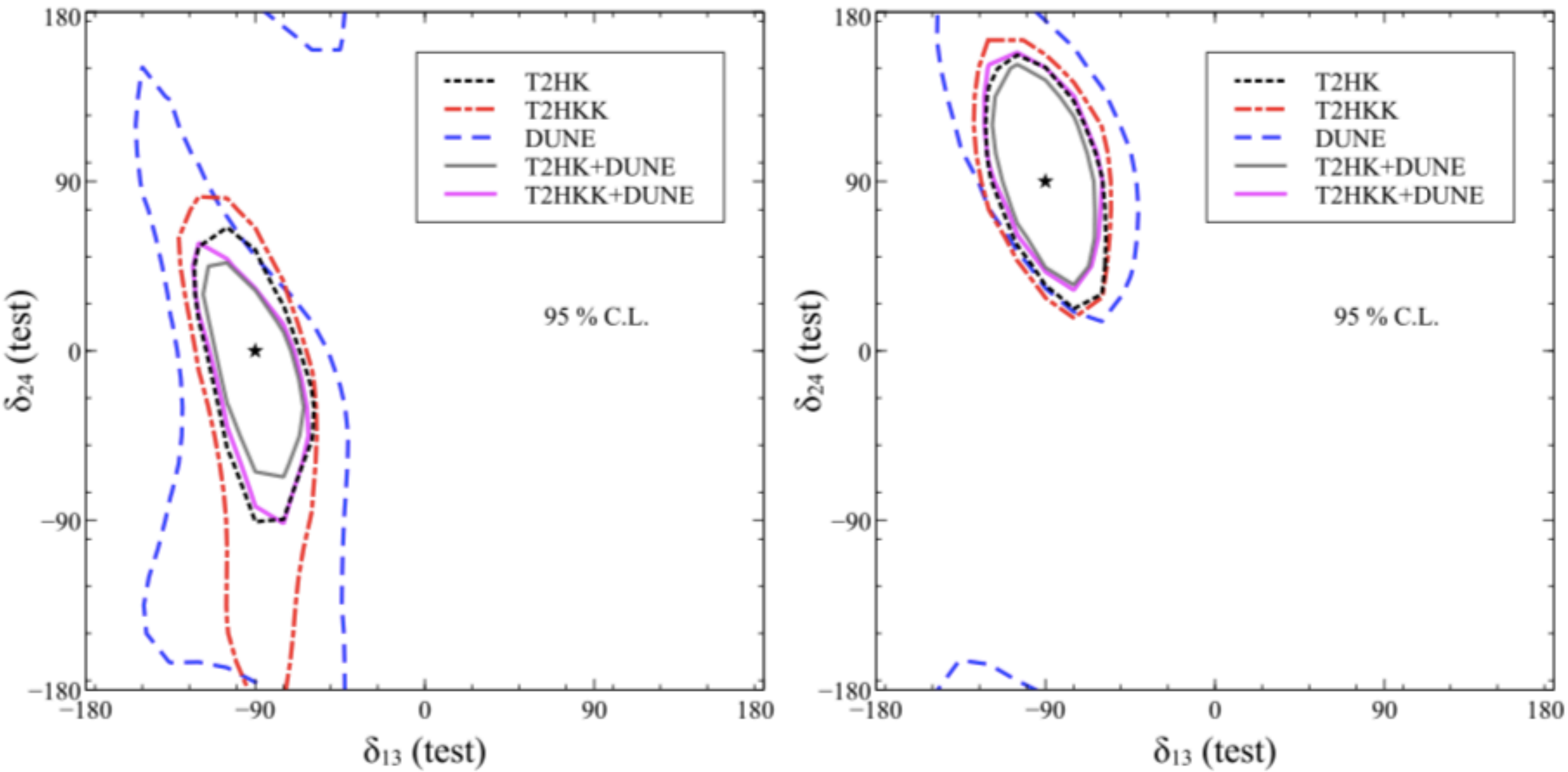
[Phys.Rev. D95 (2017) no.11, 115009]





[Phys.Lett. B764 (2017) 135-141]

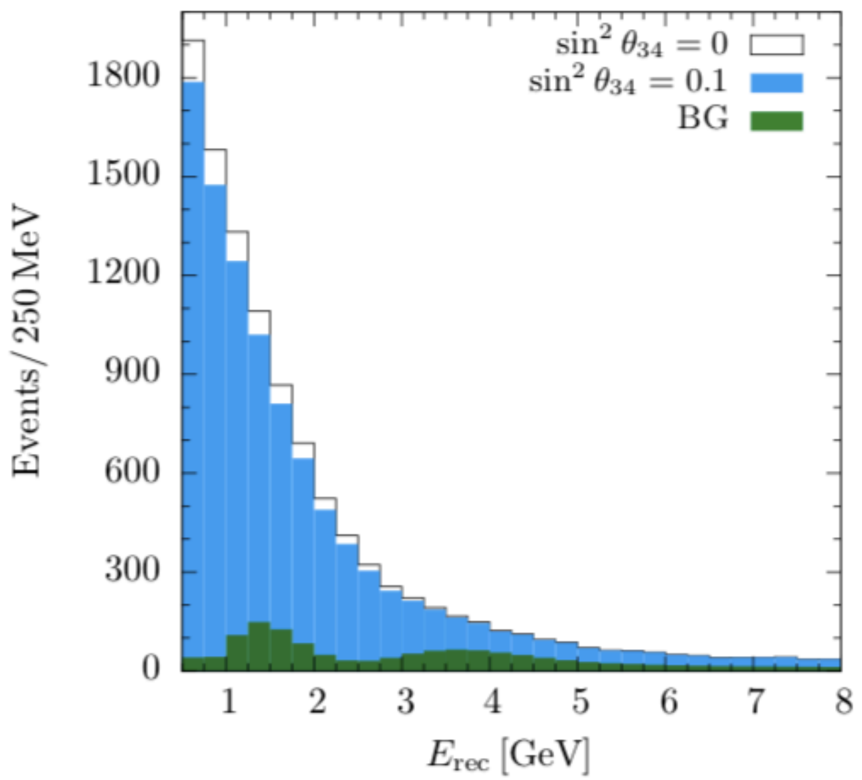
Prospects of measuring sterile neutrino parameters In the long-baseline experiments



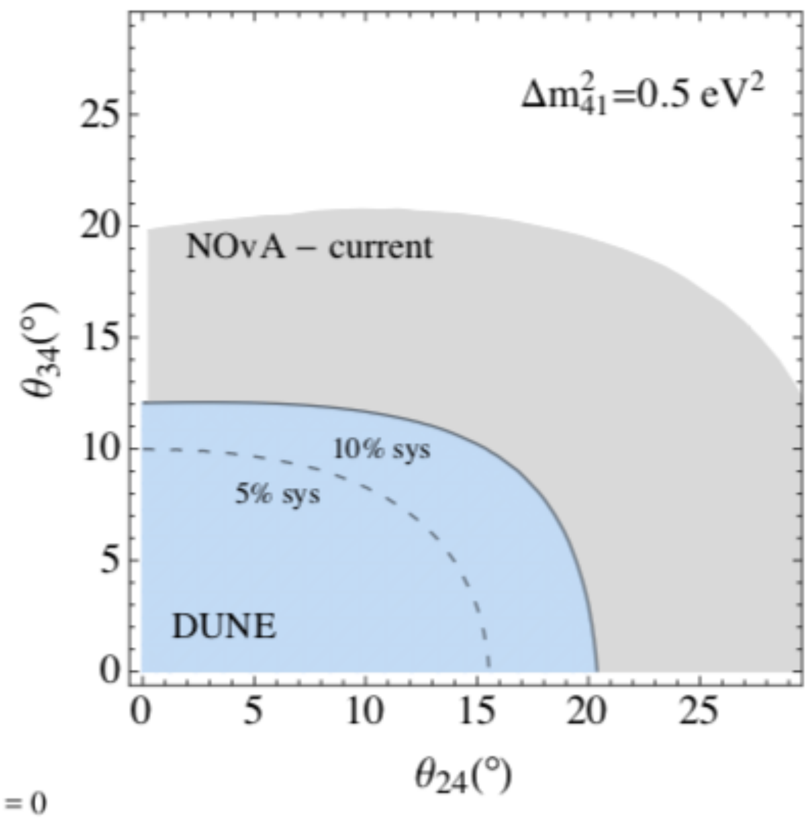
[Eur.Phys.J. C78 (2018) no.4, 339]

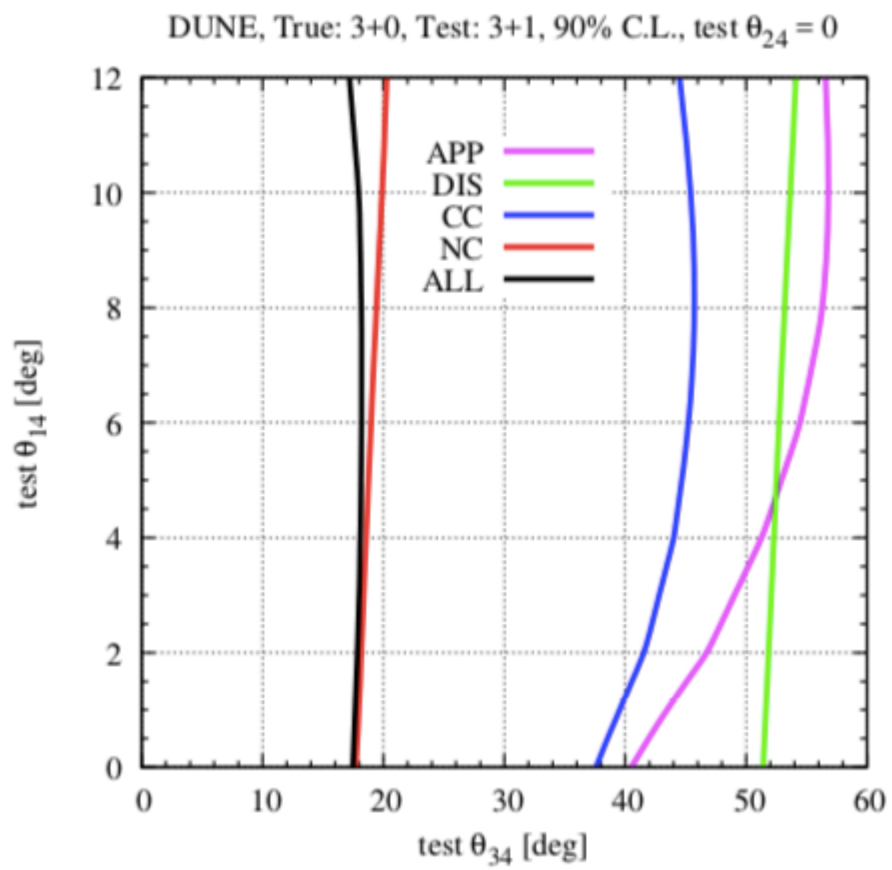
Prospects of measuring sterile neutrino parameters In the long-baseline experiments

[JHEP 1807 (2018) 079]



[JHEP 1807 (2018) 079]



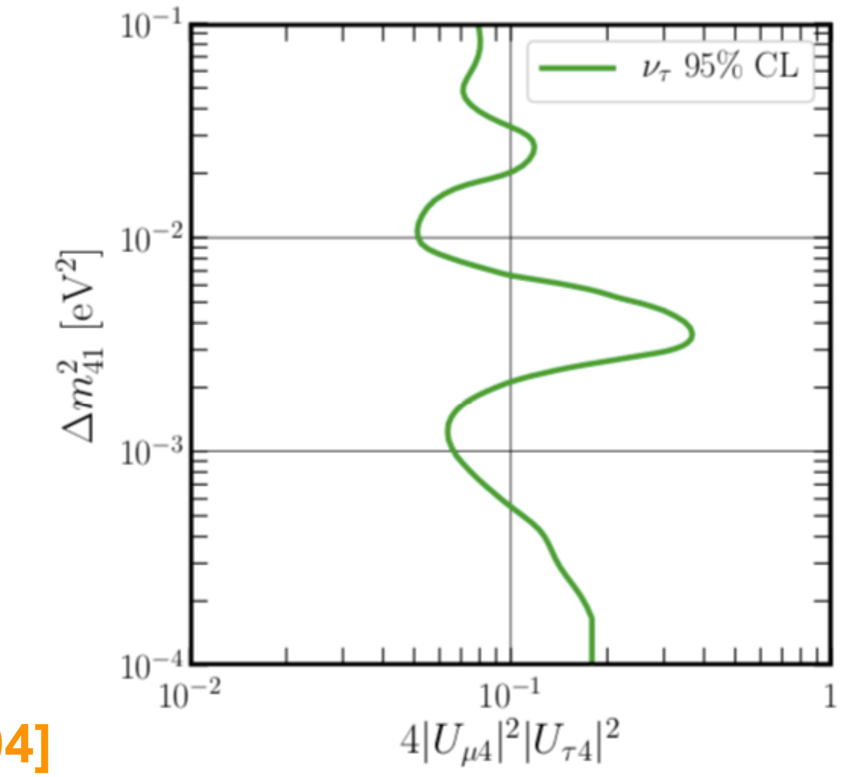


[JHEP 1711 (2017) 202]

Prospects of measuring sterile neutrino parameters In the long-baseline experiments

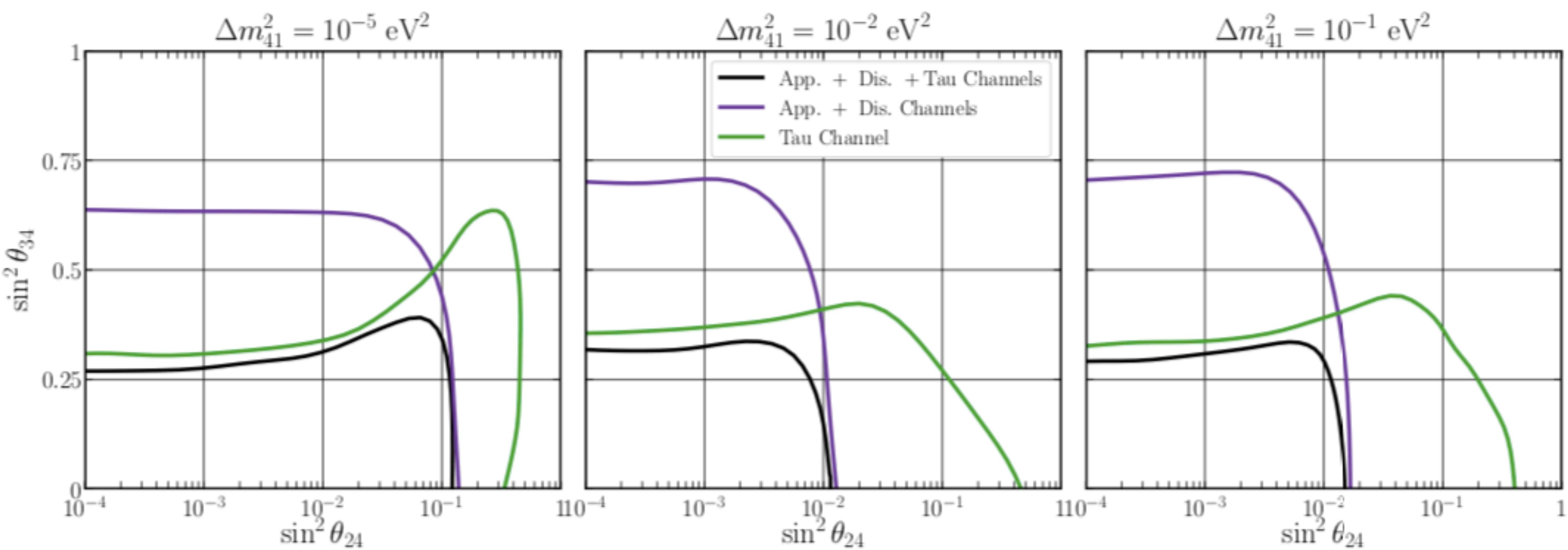
ν_τ **channel**

Weaker compared to the usual channels for θ_{14} and θ_{24}



Very useful for probing θ_{34}

[Phys.Rev. D100 (2019) no.1, 016004]



Effect of sterile neutrinos in the standard physics program

The impact of sterile neutrinos on CP measurements at long baselines
Raj Gandhi (Fermilab & Harish-Chandra Res. Inst.), Boris Kayser (Fermilab), Mehedi Masud, Suprabh Prakash (Harish-Chandra Res. Inst.). Aug 25, 2015. 16 pp.
Published in **JHEP 1511 (2015) 039**

Physics Reach of DUNE with a Light Sterile Neutrino
Sanjib Kumar Agarwalla, Sabya Sachi Chatterjee (Bhubaneswar, Inst. Phys.), Antonio Palazzo (INFN, Bari & Bari U.). Mar 11, 2016. 26 pp.
Published in **JHEP 1609 (2016) 016**

Imprints of a light Sterile Neutrino at DUNE, T2HK and T2HKK
Sandhya Choubey (Royal Inst. Tech., Stockholm & Harish-Chandra Res. Inst. & HBNI, Mumbai), Debajyoti Dutta, Dipyaman Pramanik (HBNI, Mumbai & Harish-Chandra Res. Inst.). Apr 24, 2017. 14 pp.
Published in **Phys.Rev. D96 (2017) no.5, 056026**

Octant of θ_{23} in danger with a light sterile neutrino
Sanjib Kumar Agarwalla, Sabya Sachi Chatterjee (Bhubaneswar, Inst. Phys.), Antonio Palazzo (Bari U. & INFN, Bari). May 13, 2016. 6 pp.
Published in **Phys.Rev.Lett. 118 (2017) no.3, 031804**

Capabilities of long-baseline experiments in the presence of a sterile neutrino
Debajyoti Dutta, Raj Gandhi (Harish-Chandra Res. Inst.), Boris Kayser (Fermilab), Mehedi Masud (Harish-Chandra Res. Inst.),
Published in **JHEP 1611 (2016) 122**

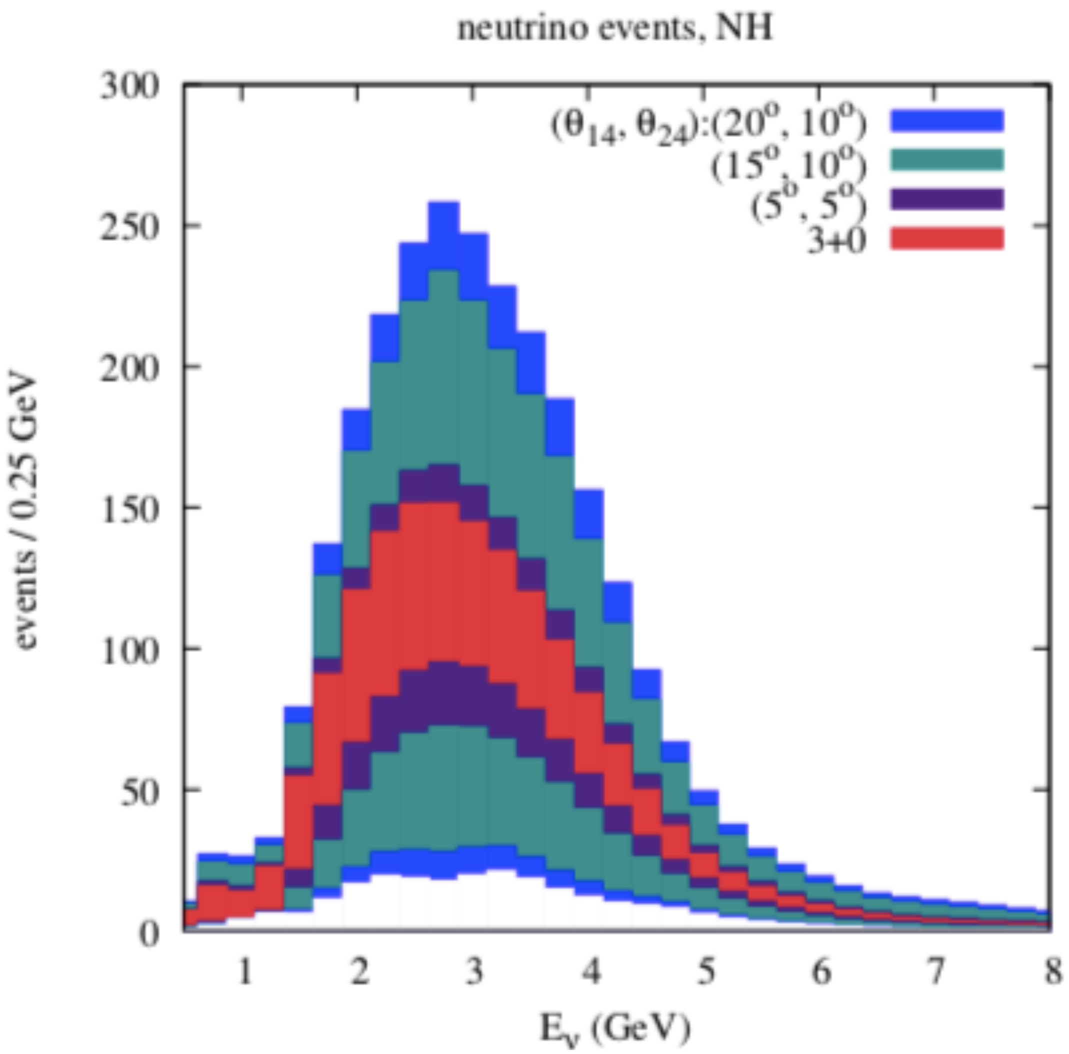
Physics Potential of ESSνSB in the presence of a Light Sterile Neutrino
Sanjib Kumar Agarwalla (Bhubaneswar, Inst. Phys. & HBNI, Mumbai & ICTP, Trieste), Sabya Sachi Chatterjee (Bhubaneswar
pp.
IP/BBSR/2019-6, IPPP/19/74
e-Print: **arXiv:1909.13746 [hep-ph]** | **PDF**

Exploring a New Degeneracy in the Sterile Neutrino Sector at Long-Baseline Experiments
Sandhya Choubey (Harish-Chandra Res. Inst. & Royal Inst. Tech., Stockholm), Debajyoti Dutta (Assam U.), Dipyaman Pramanik (Harish-Chan
e-Print: **arXiv:1811.08684 [hep-ph]** | **PDF**

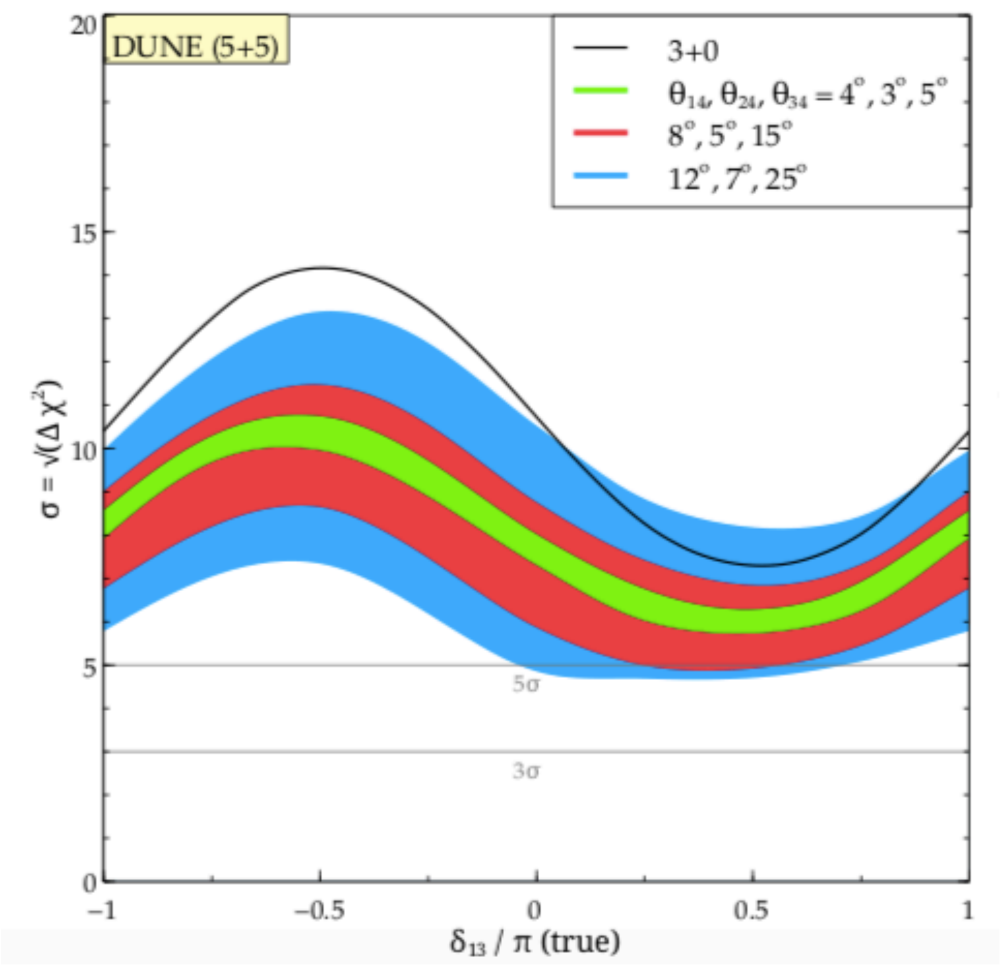
1. **Effect of light sterile neutrino on currently running long-baseline experiments**
   Rudra Majhi, Soumya C, Rukmani Mohanta. Nov 25, 2019. 23 pp.
   e-Print: **arXiv:1911.10952 [hep-ph]** | **PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
   Detailed record

Effect of sterile neutrinos in the standard physics program

[JHEP 1611 (2016) 122]

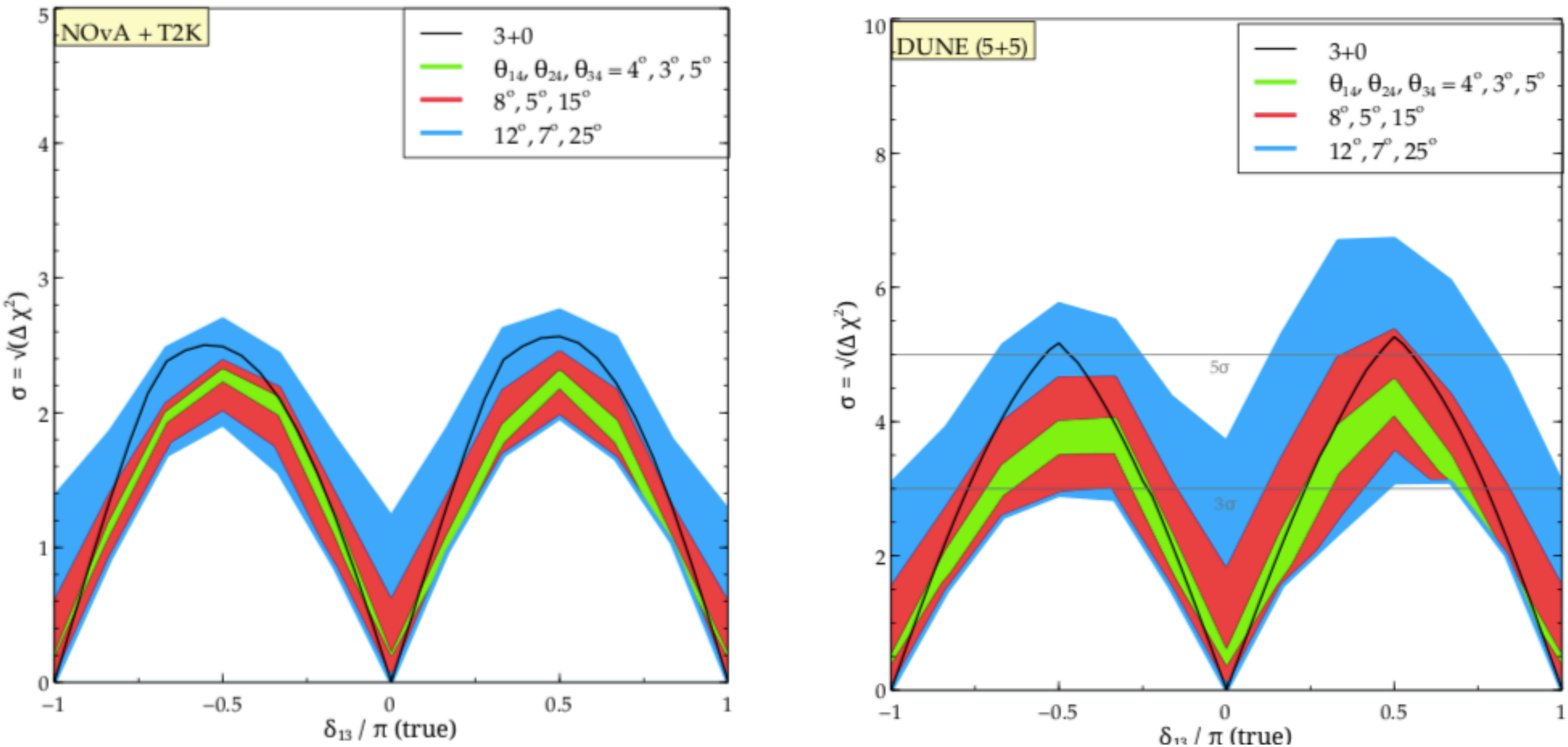


[JHEP 1511 (2015) 039]



Effect of sterile neutrino in mass-hierarchy sensitivity

[JHEP 1611 (2016) 122]

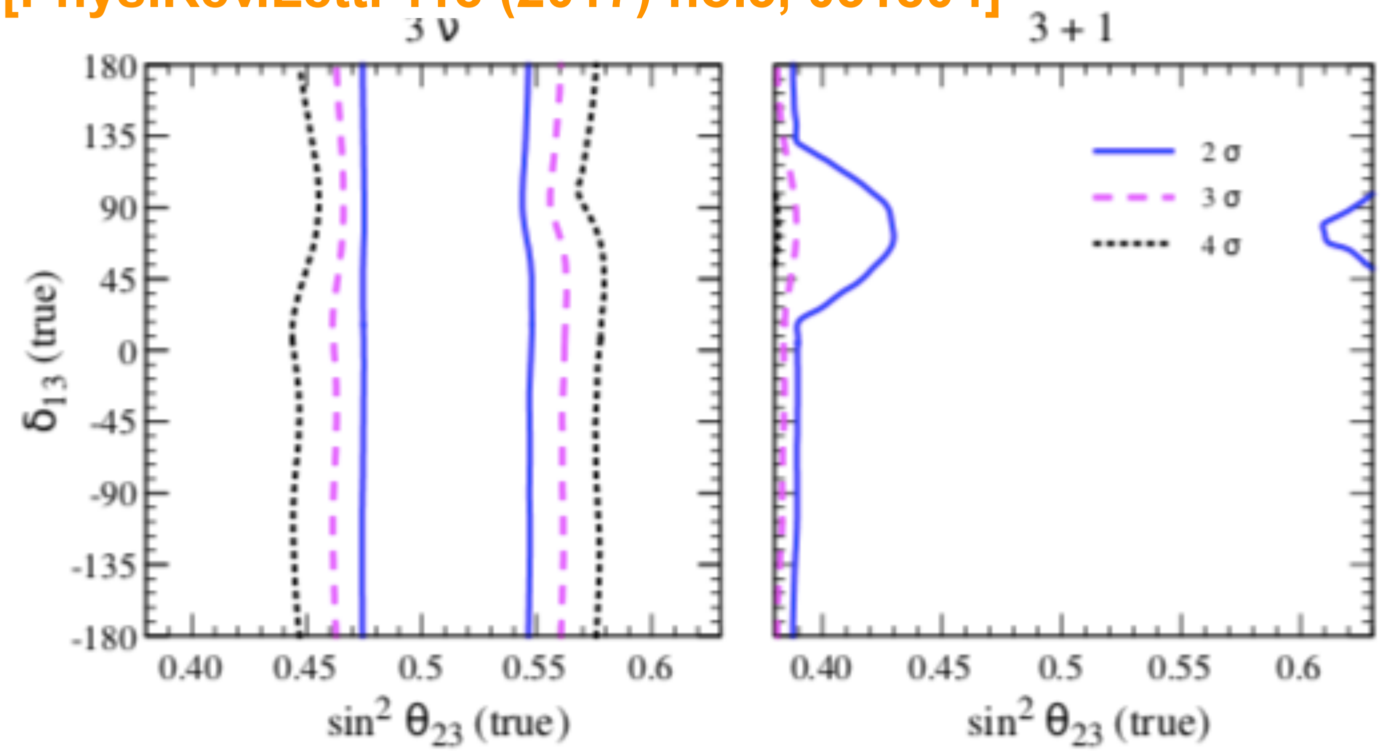


Effect of sterile neutrino in CP-violation sensitivity

[JHEP 1609 (2016) 016]

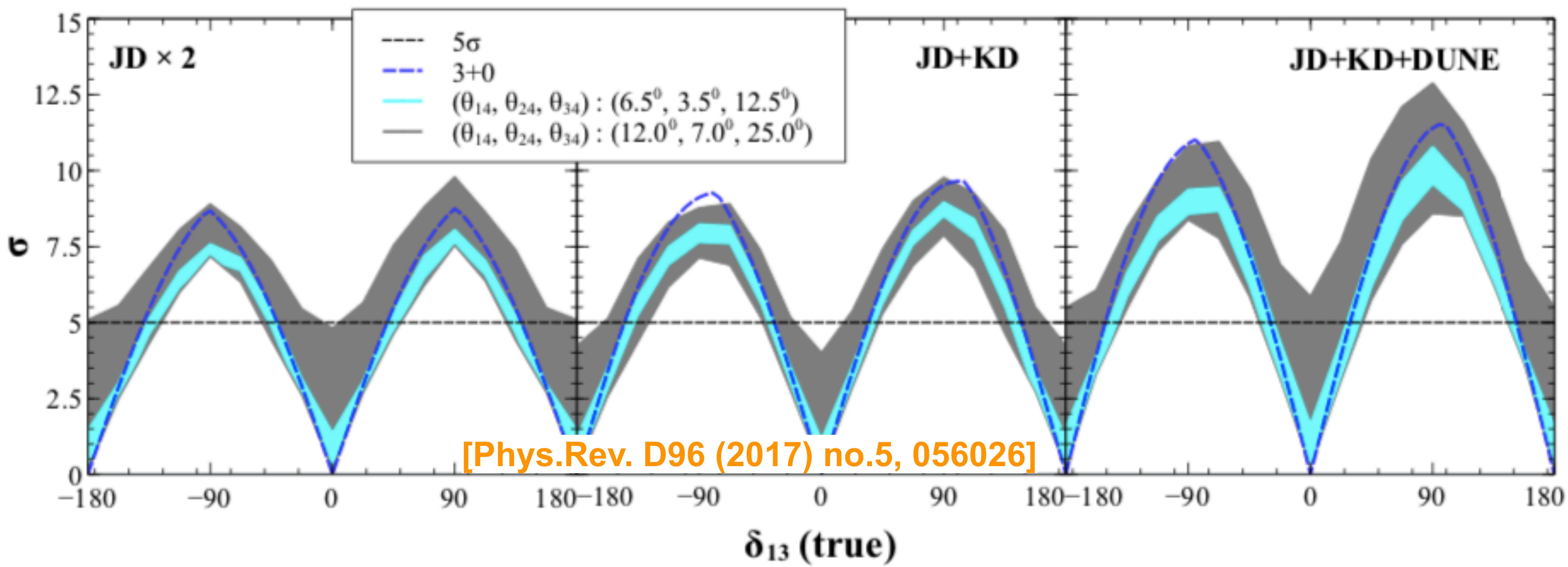
Effect of sterile neutrinos in the standard physics program

[Phys.Rev.Lett. 118 (2017) no.3, 031804]



θ_{23} **octant is in danger!!**

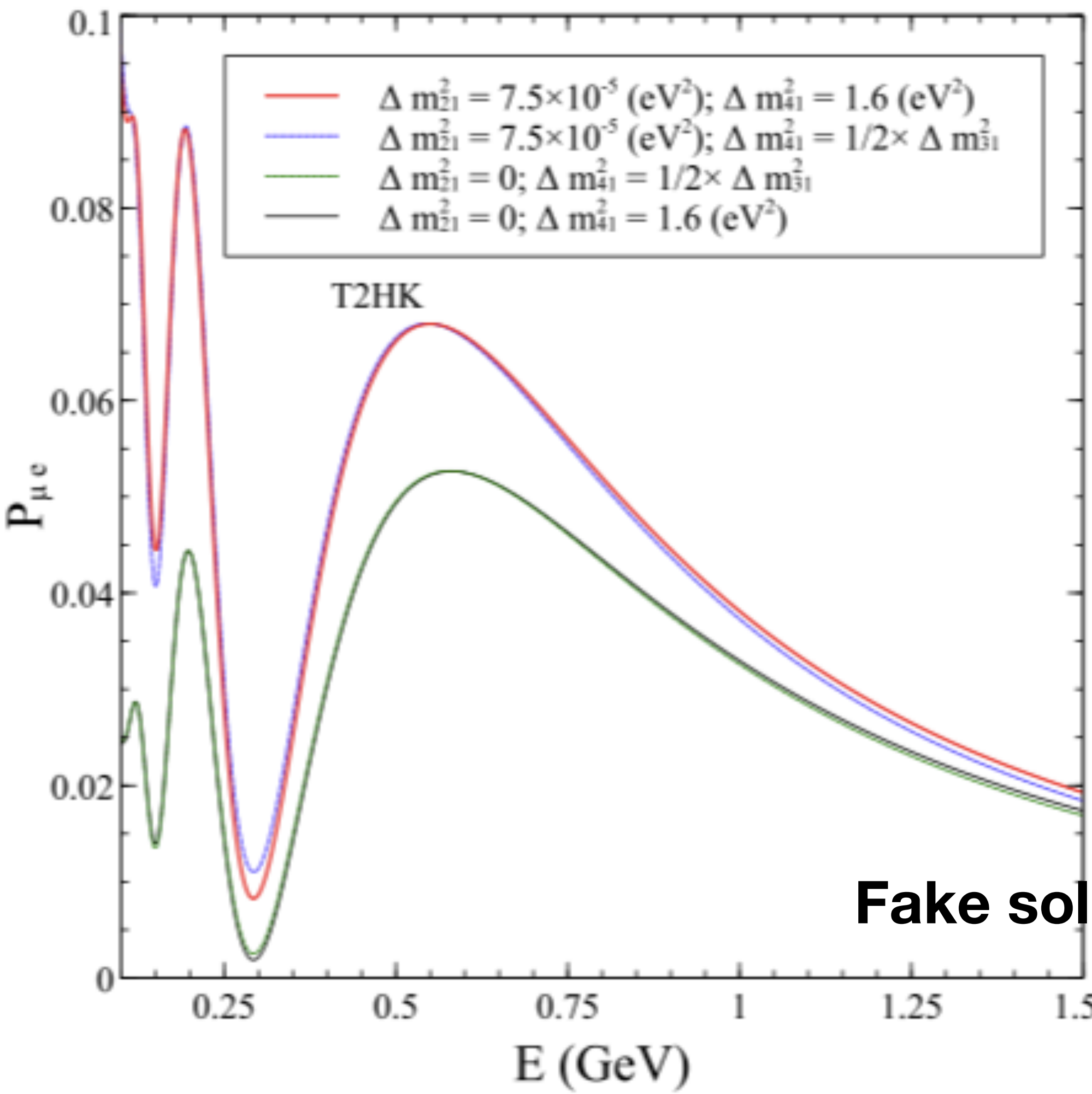
Combination of two experiments

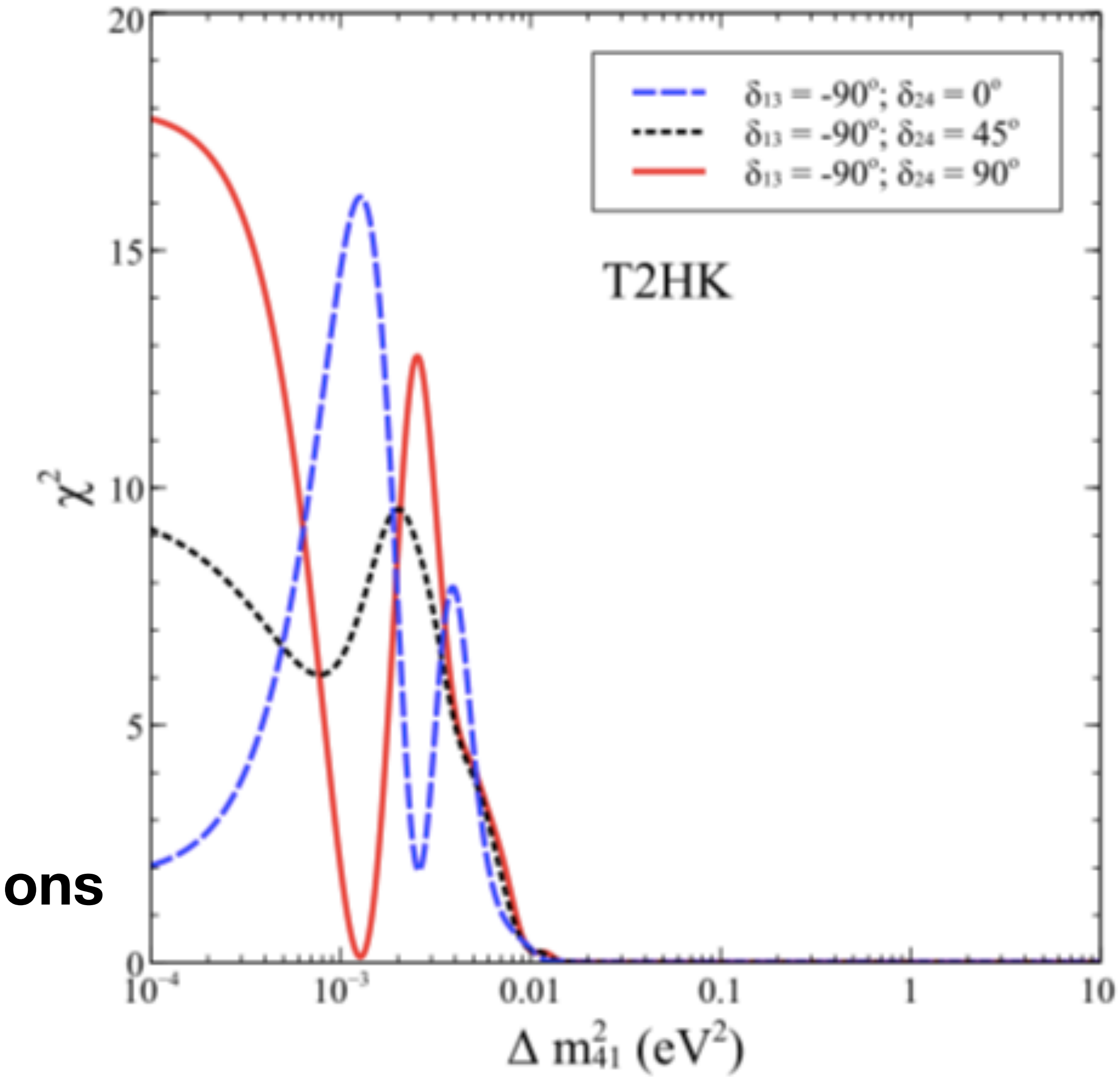


[Phys.Rev. D96 (2017) no.5, 056026]

Effect of sterile neutrinos in the standard physics program

[Eur. Phys. J C (2019) 79: 968]





Fake solutions

The condition of fake solution : $\Delta m^2_{41} = \frac{1}{2}\Delta m^2_{31}$

$$\delta_{13} + \delta_{24} = 0^o$$

Explaining LSND/MiniBooNe using non-oscillation mechanism??!!

Dark Neutrino Portal to Explain MiniBooNE excess
Enrico Bertuzzo (Sao Paulo U.), Sudip Jana (Oklahoma Ctr. High Energy Phys. & Oklahoma State
Published in **Phys.Rev.Lett. 121 (2018) no.24, 241801**

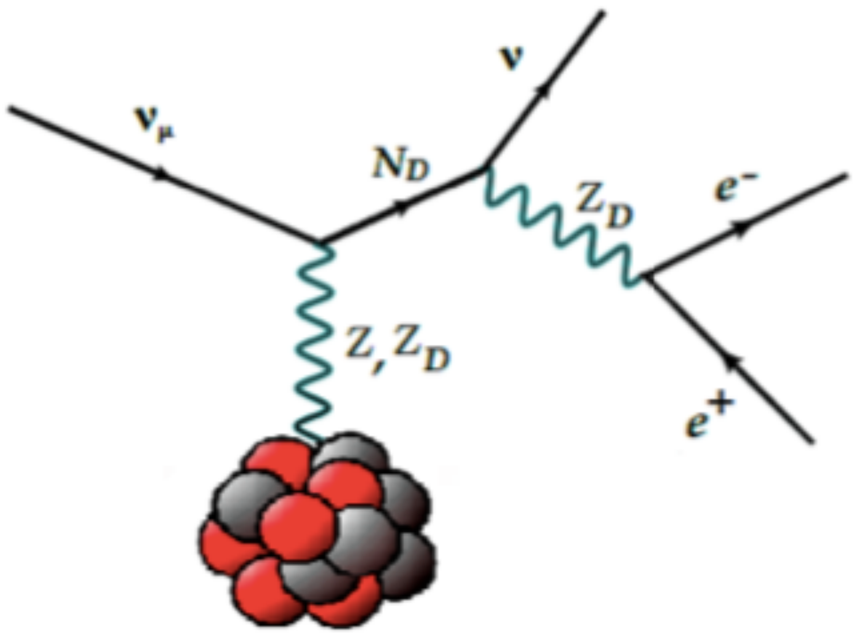
Explaining the MiniBooNE excess by a decaying sterile neutrino with mass in the 250 MeV range
Oliver Fischer, Álvaro Hernández-Cabezudo, Thomas Schwetz (KIT, Karlsruhe, IKP). Sep 20, 2019. 26 pp.
e-Print: **arXiv:1909.09561 [hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service

U(1)' mediated decays of heavy sterile neutrinos in MiniBooNE
Peter Ballett, Silvia Pascoli (Durham U., IPPP), Mark Ross-Lonergan (Nevis Labs, Columbia U.). Aug 8, 2018. 8 pp.
Published in **Phys.Rev. D99 (2019) 071701**
IPPP/18/70

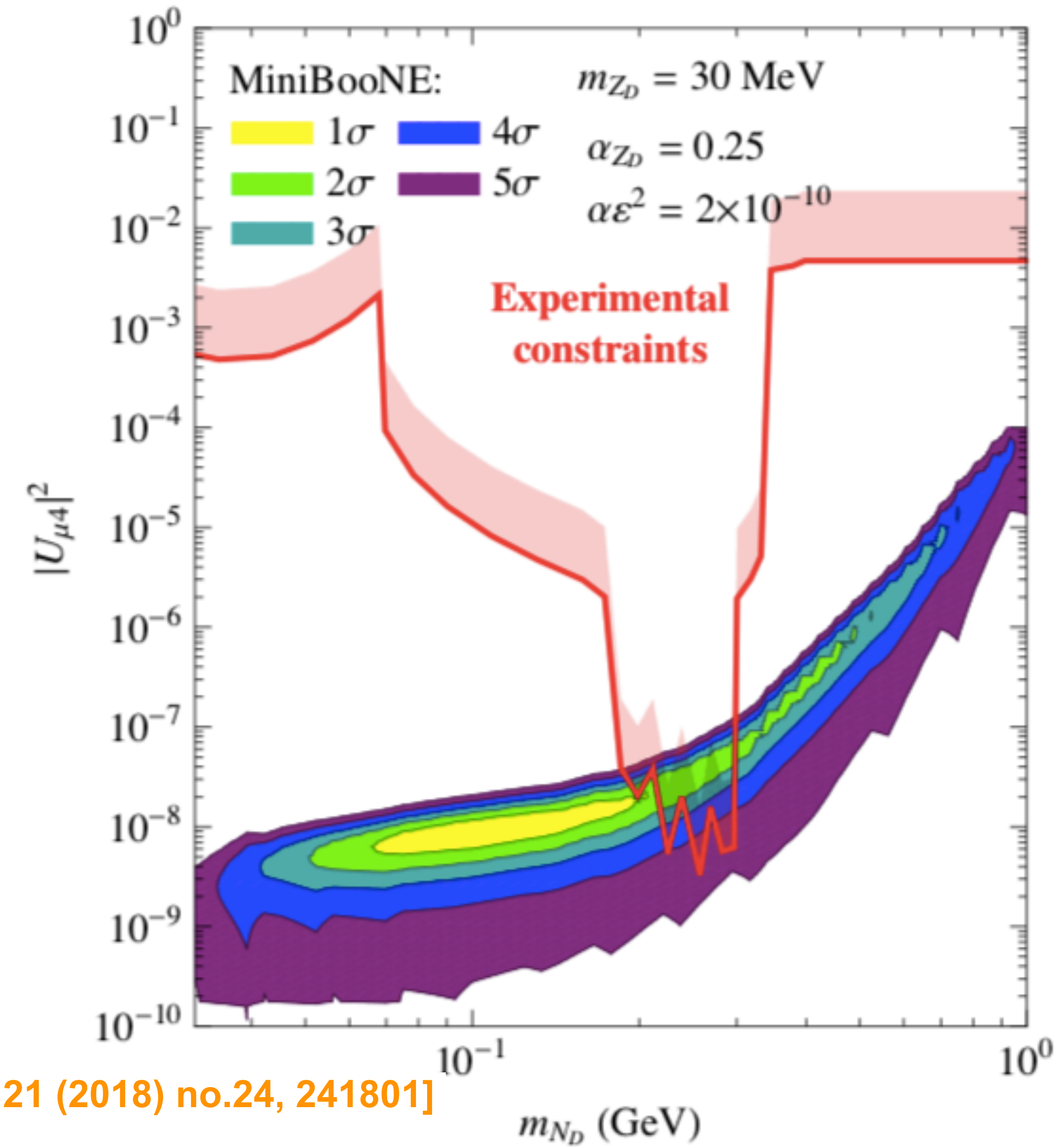
Testing New Physics Explanations of MiniBooNE Anomaly at Neutrino Scattering Experiments
Carlos A. Argüelles (MIT, Cambridge, Dept. Phys.), Matheus Hostert (Durham U., IPPP), Yu-Dai Tsai (Fermilab). Dec 20, 2018. 7 pp.
IPPP/18/113, FERMILAB-PUB-18-686-A-ND-PPD-T
e-Print: **arXiv:1812.08768 [hep-ph]** | **PDF**

Severe Constraints on New Physics Explanations of the MiniBooNE Excess
Johnathon R. Jordan (Michigan U.), Yonatan Kahn (Princeton U. & Chicago U., KICP & Illinois U., Urbana (main)).
2018. 7 pp.
Published in **Phys.Rev.Lett. 122 (2019) no.8, 081801**

Explaining LSND/MiniBooNe using non-oscillation mechanism??!!



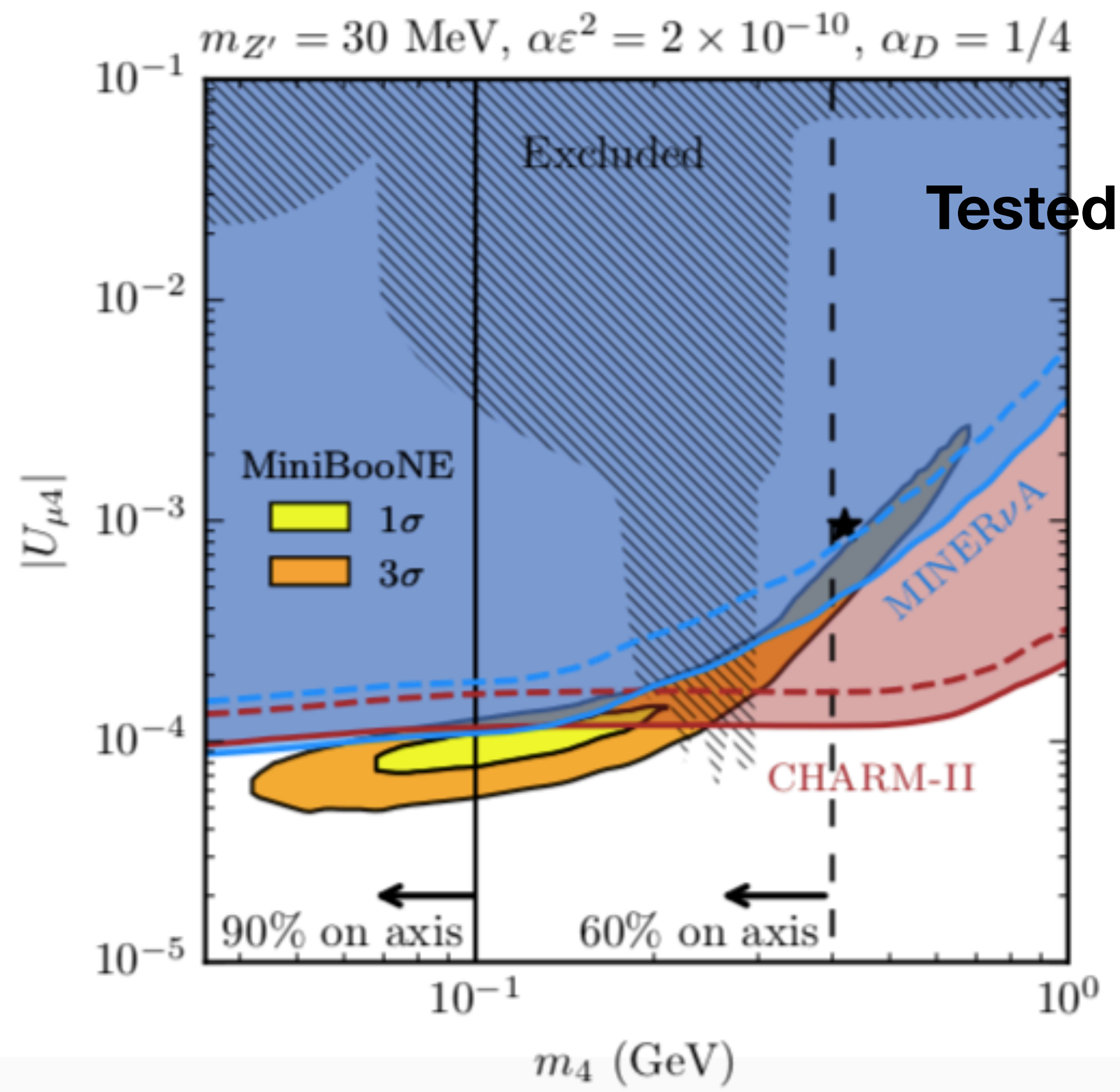
Collimated e^+e^- signal, that can be identified as a single ν_e event



[Phys.Rev.Lett. 121 (2018) no.24, 241801]

Testing the new-physics hypothesis

[arXiv:1812.08768]



Tested the hypothesis with charm-II and MinervA data

Some other ideas

[arXiv:1909.09561]

Kaons are decayed into N and muons in the decay pipe. Then N decays into ν and γ

These photons can not be distinguished from the electromagnetic shower of the ν_e

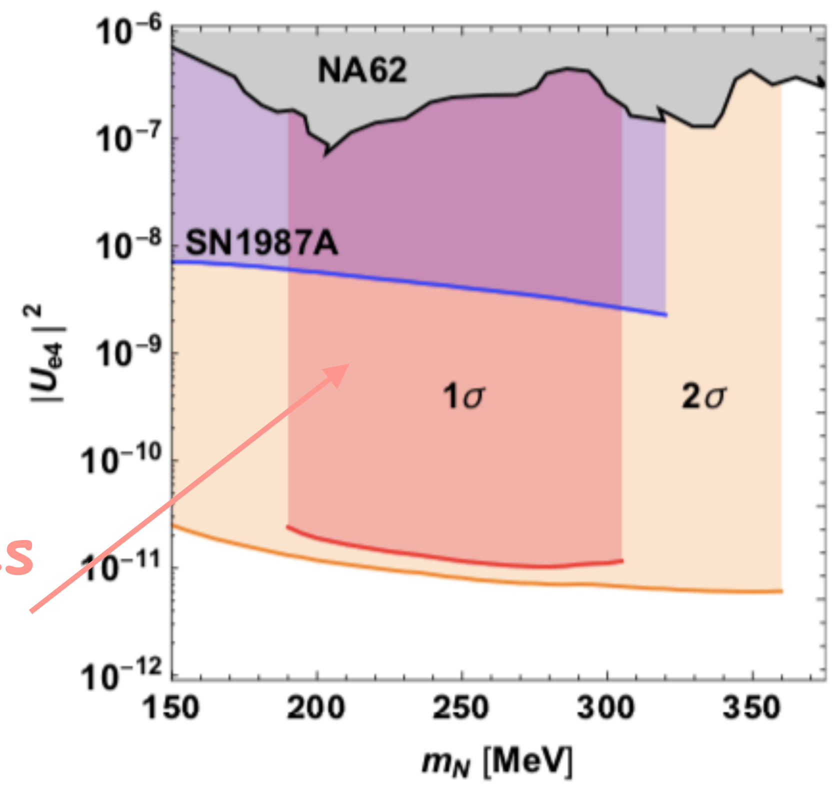
$$\mathcal{O}_{\ell N q_u q_d} = U_{\ell 4} V_{q_u q_d} G_F \, [\bar{q}_u \gamma^\mu (1-\gamma_5) q_d] \, \left[\bar{\ell} \gamma_\mu (1-\gamma_5) N\right] + \mathrm{h.c.}$$

$$K \to N\mu$$

$$\mathcal{O}_{N\nu\gamma} = \frac{1}{\Lambda} \bar{N} \sigma^{\alpha\beta} \nu F_{\alpha\beta}$$

$$N \to \nu\gamma$$

This region gives the MiniBooNe excess



Some ideas for the workshop??

1. **Can we test the new physics explanations of the LSND/MiniBooNe excess in the future experiments?**

2. **What are other possible new physics explanations for the LSND/MiniBooNe excess?**

3. **Are there any general degeneracies between the sterile 3+1 sector and 3+0 sector?**

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