Physics opportunities with kaon decay-at-rest neutrinos: search for sterile neutrino and non-standard interactions

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Introduction: neutrino oscillation and new physics

- Neutrino flavour oscillation arises from mixing between flavour states $(\nu_e, \nu_\mu, \nu_\tau)$ and mass eigenstates (ν_1, ν_2, ν_3) of neutrinos.
- The 3-flavour oscillation probability depends upon 3 mixing angles $(\theta_{12}, \theta_{13}, \theta_{23})$, 2 independent mass squared differences $(\Delta m^2_{21}, \Delta m^2_{31})$ and 1 CP phase δ_{CP}.
- In three flavour standard neutrino oscillation picture the important unknown parameters are

  1. Sign of Δm^2_{31} (Neutrino mass ordering)
  2. δ_{CP} (CP violating phase)
  3. Octant of θ_{23} $(\theta_{23} > 45^0$ or $\theta_{23} < 45^0)$

- While the standard there flavour oscillation framework is firmly established by current data; **subdominant effects can not be ruled out completely**
- Current and future neutrino oscillation experiments are aimed to measure these parameters. But…
- There are several ***"New Physics"*** scenarios which can significantly impact the determination of these unknowns

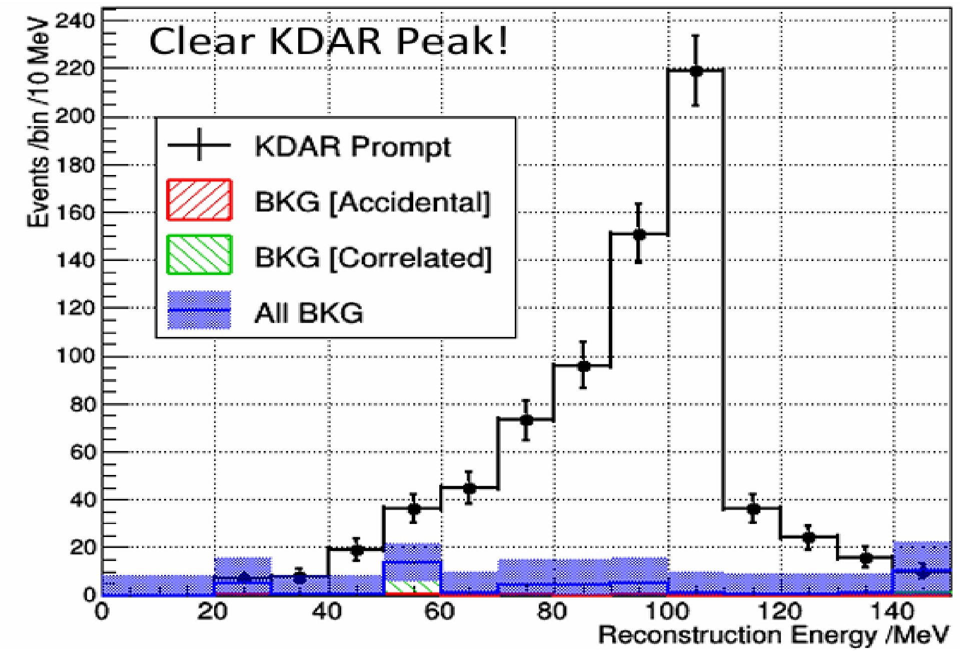
http://dx.doi.org/10.21468/SciPostPhysProc.2.001

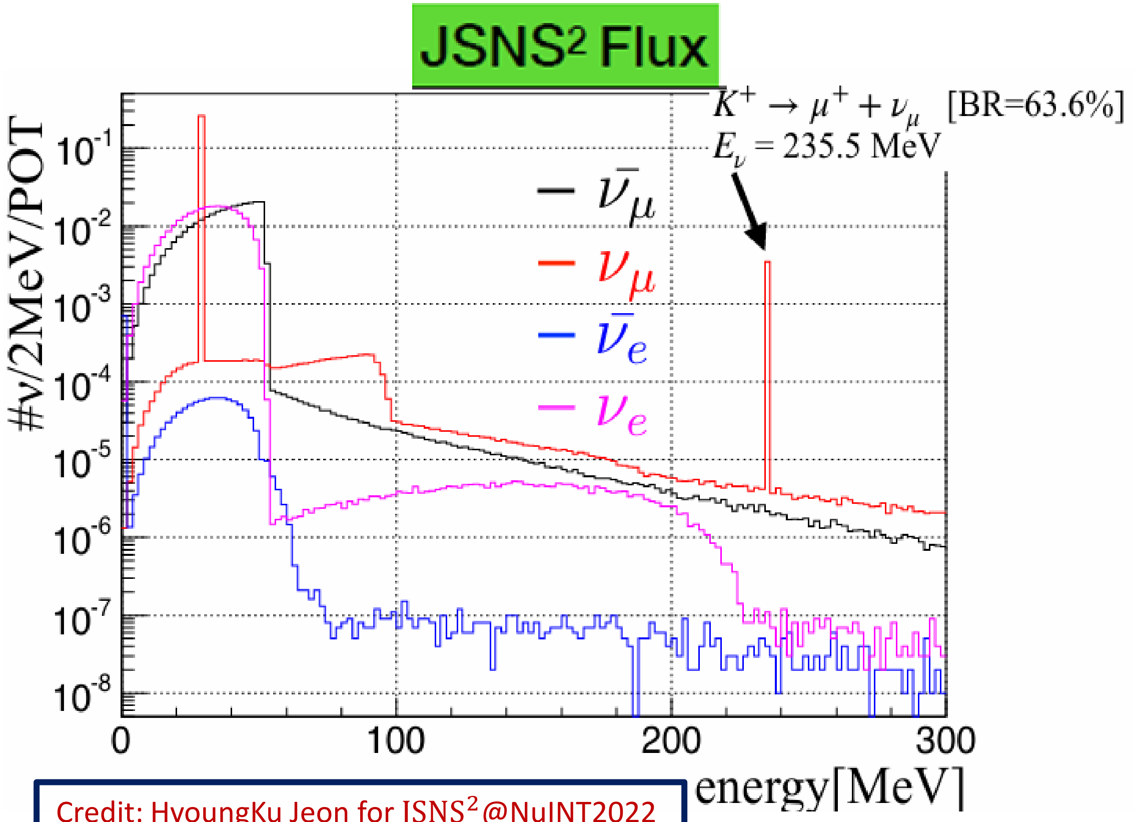
- New Physics:
  1. **Sterile neutrinos**
  2. **Non-standard interactions (NSIs)**
  3. Neutrino decoherence and decay
  4. Unitarity violation
  5. LIV/CPT, etc...

Neutrino flavour transition provides unique opportunity to search for physics beyond the Standard Model in oscillation experiments

Neutrinos from kaon-decay-at-rest (KDAR)

- **Two-body decay of charged kaons at rest produce mono-energetic beam of muon neutrinos at ~236 MeV**
- **Because of their KNOWN energy KDAR neutrinos are ideal for a cross section measurement**
- **MiniBOONE (PRL 120, 141802), and JSNS^2 experiments (arXiv:1705.08629) have observed KDAR neutrinos so far**
- We use data from JSNS^2 (0.7-0.8 MW beam)
- 730 muon events including 692 signal + 38 background

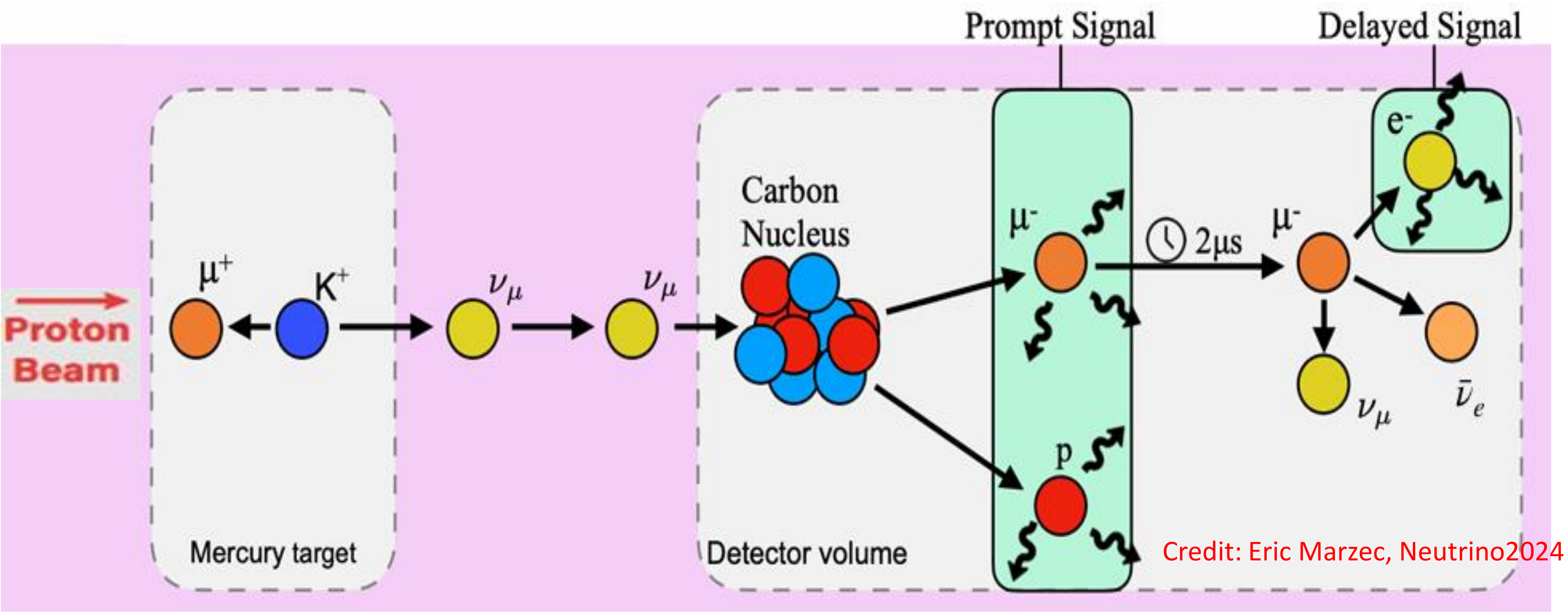




Credit: HyoungKu Jeon for JSNS^2@NuINT2022

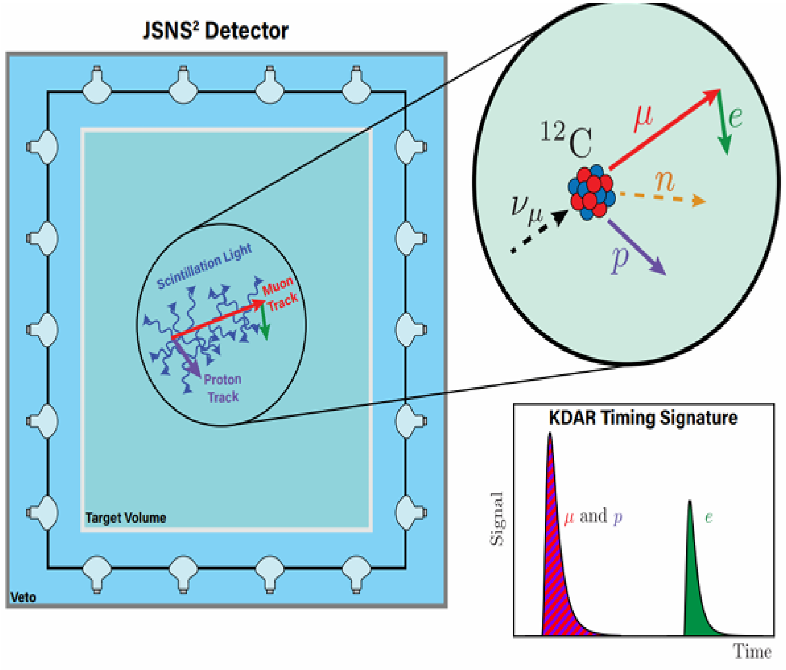
JSNS^2 as source for KDAR neutrino signal

- The J-PARC Sterile Neutrino Search at the J-PARC Spallation Neutron Source (**JSNS^2**) experiment will produce such types of neutrinos with decay-at-rest processes of pions, muons, and kaons.
- Primary aim of the experiment: Probe **sterile neutrinos with $\Delta m^2 \sim 1\,\text{eV}^2$ from $\nu_\mu \to \nu_e$** oscillations at a short baseline (24 meters)
- **17 t Gd-loaded liquid scintillator detector**
- Coincident signal between initial neutrino interaction and subsequent decay provides **excellent background rejection**



Credit: Eric Marzec, Neutrino2024

JSNS² TDR arXiv:1705.08629



Neutrino-matter interactions: Standard (SI) and non standard (NSI)

➤ In the SM there are two ways of interacting neutrinos with matter; Charged Current and Neutral Current

➤ The Charged Current Lagrangian is given by

$$\mathcal{L}_{\rm cc}^{\rm eff} = -\frac{4G_F}{\sqrt{2}}[\overline{\nu_e}(p_3)\gamma_\mu P_L \nu_e(p_2)][\bar{e}(p_1)\gamma^\mu P_L e(p_4)].$$

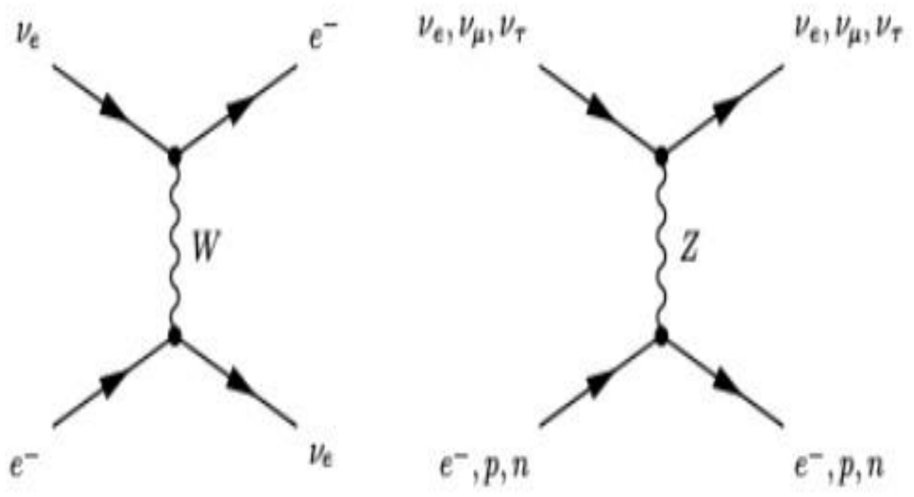
Flavour-dependent

$$V_{cc} = -\langle \nu_e e(p_e, s_e)|\mathcal{L}_{\rm eff}^{\rm cc}|\nu_e e(p_e, s_e)\rangle$$

$$V_{CC} = -\frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu(1-\gamma_5)\nu_e][\bar{\nu_e}\gamma_\mu(1-\gamma_5)e]$$

$$V_{CC} = \pm\sqrt{2}G_F N_e$$

→ Affect neutrino oscillation significantly



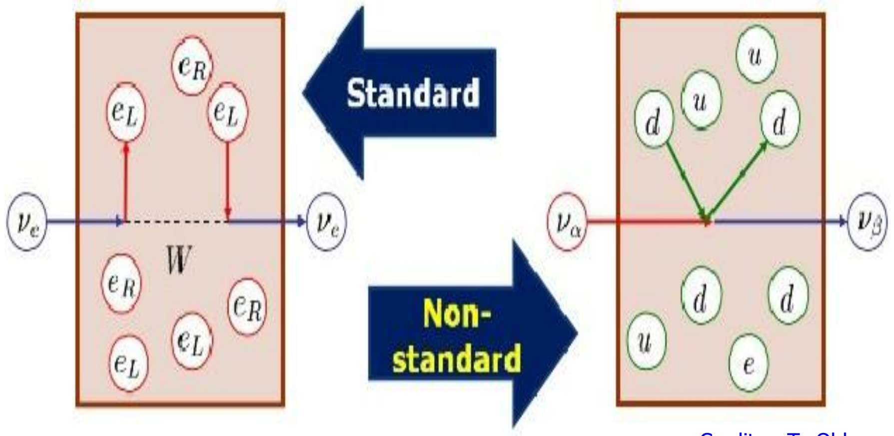
$\nu_e(\overline{\nu_e})$ only

Flavour-independent

Similar term for V_{NC} but due to flavour universal it does not affect neutrino oscillation

Neutrino-matter interactions: Standard (SI) and non standard (NSI)

- Non-Standard neutrino interactions are the new interactions and couplings between neutrinos and matter fermions beyond those in the SM. It could be responsible for sub-leading effects in neutrino oscillation.



Credits : T. Ohlsson, MPIK'09

- **NSI Lagrangian:**

10.1103/PhysRevD.78.053007

$$\mathcal{L}_{NSI}^{NC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon_{\alpha\beta}^{f,P} (\bar{\nu_\alpha}\gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f),$$

- Modify the neutrino coherent-forward scattering with matter over long-baselines aka **"Propagation NSI"** $\propto \boldsymbol{E_\nu, \rho}$

- NSIs which affect neutrino production or detection involve **Charged Current** processes

$$\mathcal{L}_{NSI}^{CC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon_{\alpha\beta}^{f,P} (\bar{\nu_\alpha}\gamma^\mu P_L l_\beta)(\bar{f}\gamma_\mu P f'),$$

For most experiments, neutrinos are produced from pion decay and detected through their interactions with nucleons, i.e. they are sensitive to the source/detector NSI parameters $\boldsymbol{\epsilon_{\alpha\beta}^{ud}}$

In this work we use neutrinos from kaon decay to probe a different family of NSI parameters: $\boldsymbol{\epsilon_{\alpha\beta}^{us}}$

Neutrino oscillations with source NSI

- In the SM, interactions of charged leptons with neutrinos are flavour-diagonal, i.e. $|\nu_\alpha^s\rangle = |\nu_\alpha\rangle$.
- **However, the inclusion of CC-NSI can alter this and the neutrino produced in association with the charged lepton l_α can also have an admixture of other flavour ν_β**, i.e. $|\nu_\alpha^s\rangle = \sum_\beta \left(\delta_{\alpha\beta} + \epsilon_{\alpha\beta}^{ff'}\right) |\nu_\beta\rangle$

- Source NSIs induce non-unitarity: Non-trivial normalization of the states
- For KDAR neutrinos $|\nu_\mu^s\rangle$ will be modified as

$$|\nu_\mu^s\rangle = (\mathbb{I} + \varepsilon^{ff'})_{\mu\alpha} |\nu_\alpha\rangle = (\mathbb{I} + \varepsilon^{ff'})_{\mu\alpha} U_{\alpha i} |\nu_i\rangle$$

- The source NSI parameters relevant for this work

$$\varepsilon_{\alpha\beta}^{us} = \begin{bmatrix} \varepsilon_{ee}^s & \varepsilon_{e\mu}^s & \varepsilon_{e\tau}^s \\ \varepsilon_{\mu e}^s & \varepsilon_{\mu\mu}^s & \varepsilon_{\mu\tau}^s \\ \varepsilon_{\tau e}^s & \varepsilon_{\tau\mu}^s & \varepsilon_{\tau\tau}^s \end{bmatrix}$$

- **For very short baselines (L/E << 1)**, only (standard) survival amplitudes contribute, giving rise to **'zero-distance flavour conversion'**

Oscillation Probabilities →

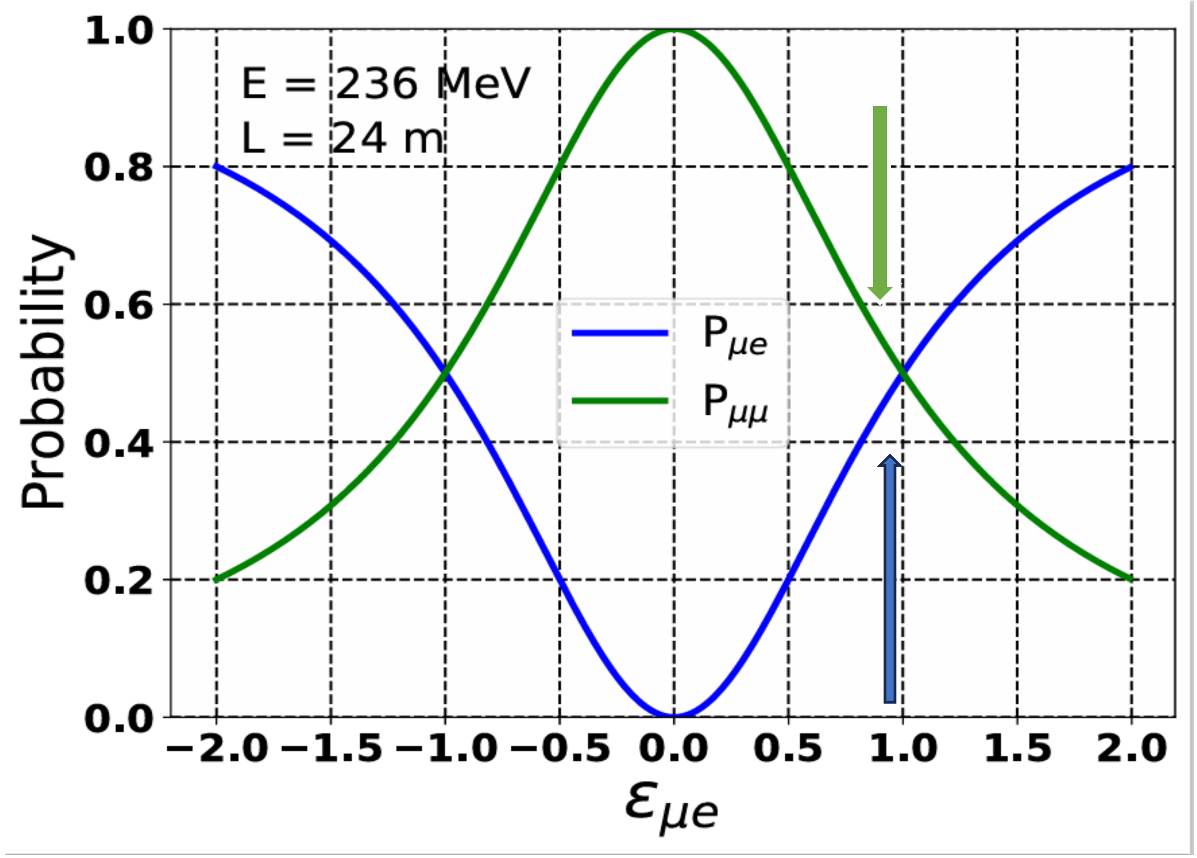
$$P_{\mu\alpha} = |\textstyle\sum_\beta (\mathbb{I} + \varepsilon^{us})_{\mu\beta} \mathcal{A}_{\beta\alpha}^{SM}|^2 \text{ (up to a normalization factor)}$$

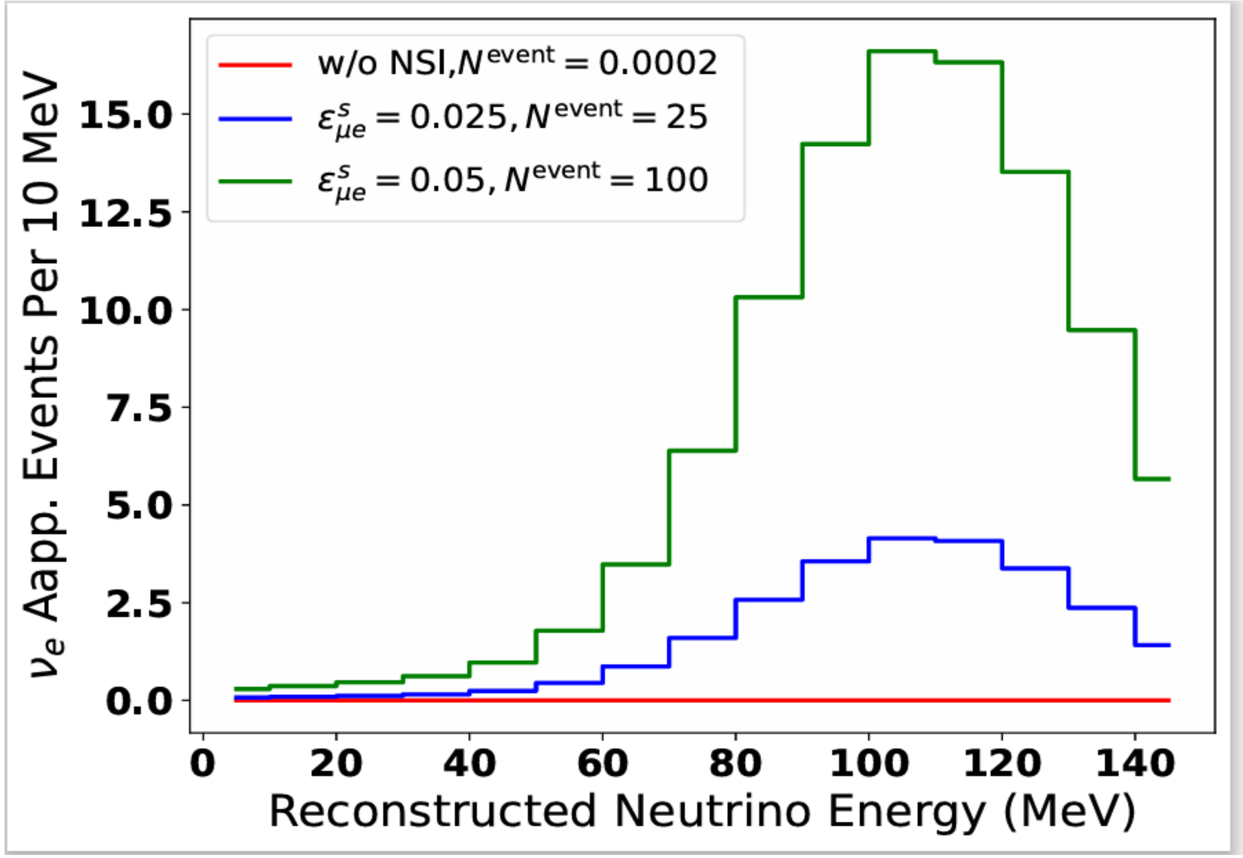
$$P_{\mu e} = |\varepsilon_{\mu e}^{us}|^2 / \left(|\varepsilon_{\mu e}^{us}|^2 + |1 + \varepsilon_{\mu\mu}^{us}|^2\right)$$

$$P_{\mu\mu} = |1 + \varepsilon_{\mu\mu}^{us}|^2 / \left(|\varepsilon_{\mu e}^{us}|^2 + |1 + \varepsilon_{\mu\mu}^{us}|^2\right)$$

Results: oscillation probability and event spectrum

- We use GLoBES to compute the event spectrum and sensitivity of $JSNS^2$ by implementing our own NSI probability engine.
- Only one NSI parameter is considered at a time.

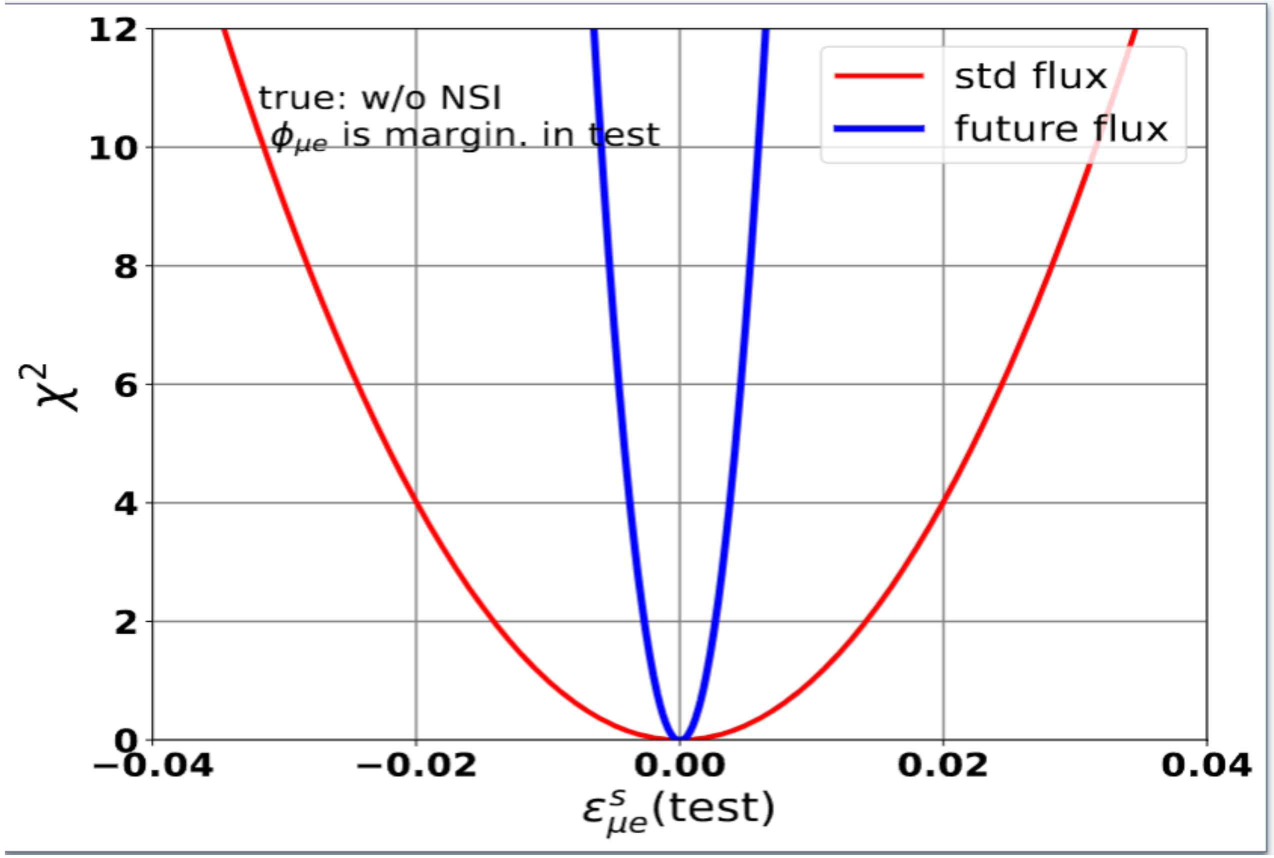


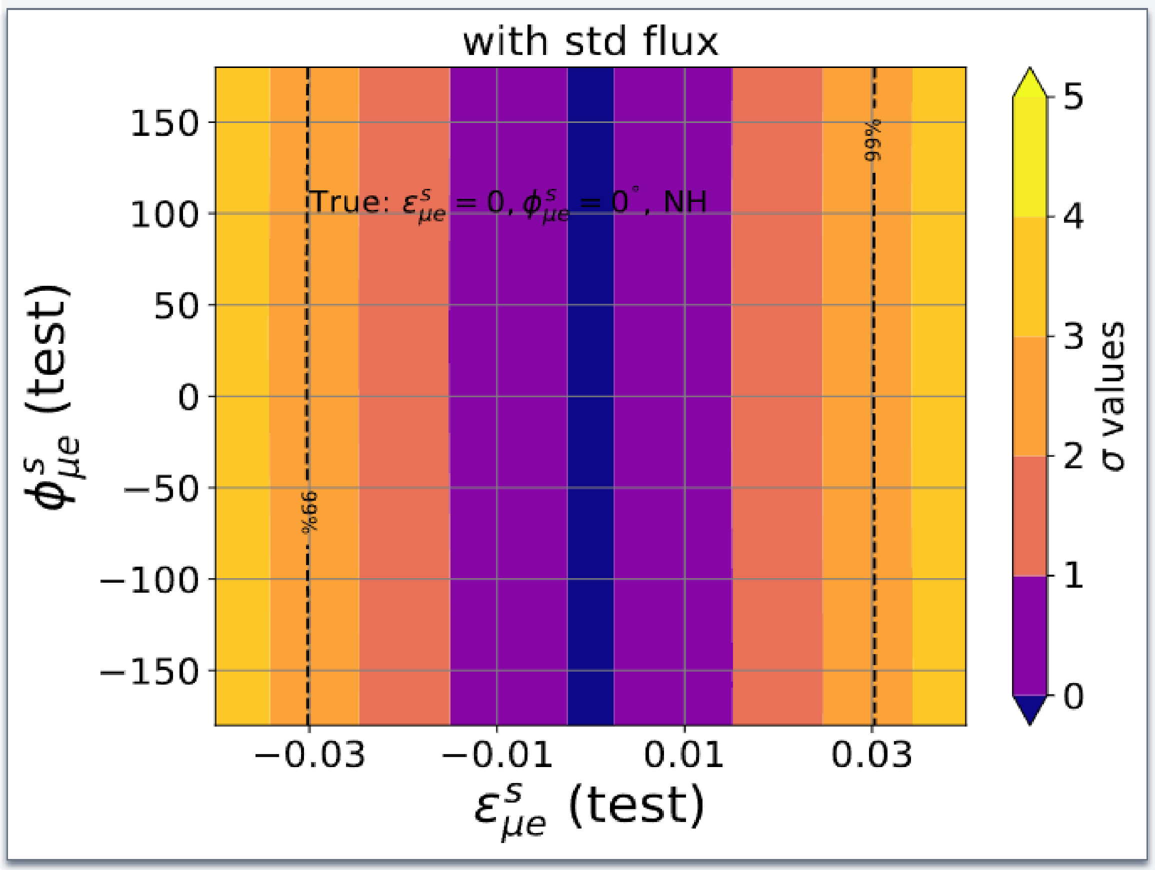


- The effect of only $\epsilon^{us}_{\mu\mu}$ is wiped out due to the probability normalization by ν_μ disappearance events

Results: source NSI constraint from KDAR

- We present the result for both Current data (calibrated to 730 ν_μ events) and future data (calibrated to 40,000 ν_μ events)





The bounds by JSNS^2 on NSI parameter $|\epsilon^{us}_{\mu e}| < 0.03\ (0.005)$ at 99% C.L. with current (future) statistics

Search for Sterile neutrinos from KDAR

- Over the past few decades, several anomalous results have been observed in experiments involving the production and detection of neutrinos over short baselines (less than 1 km). **To explain these anomalies, sterile neutrino oscillations with a mass of around 1 eV have been proposed as a key solution.**

- The short-baseline oscillation behaviour of KDAR neutrinos will be altered in the presence of eV-scale sterile neutrino: **new mixing angles, phases, mass-squared difference**

In "3+1 model"

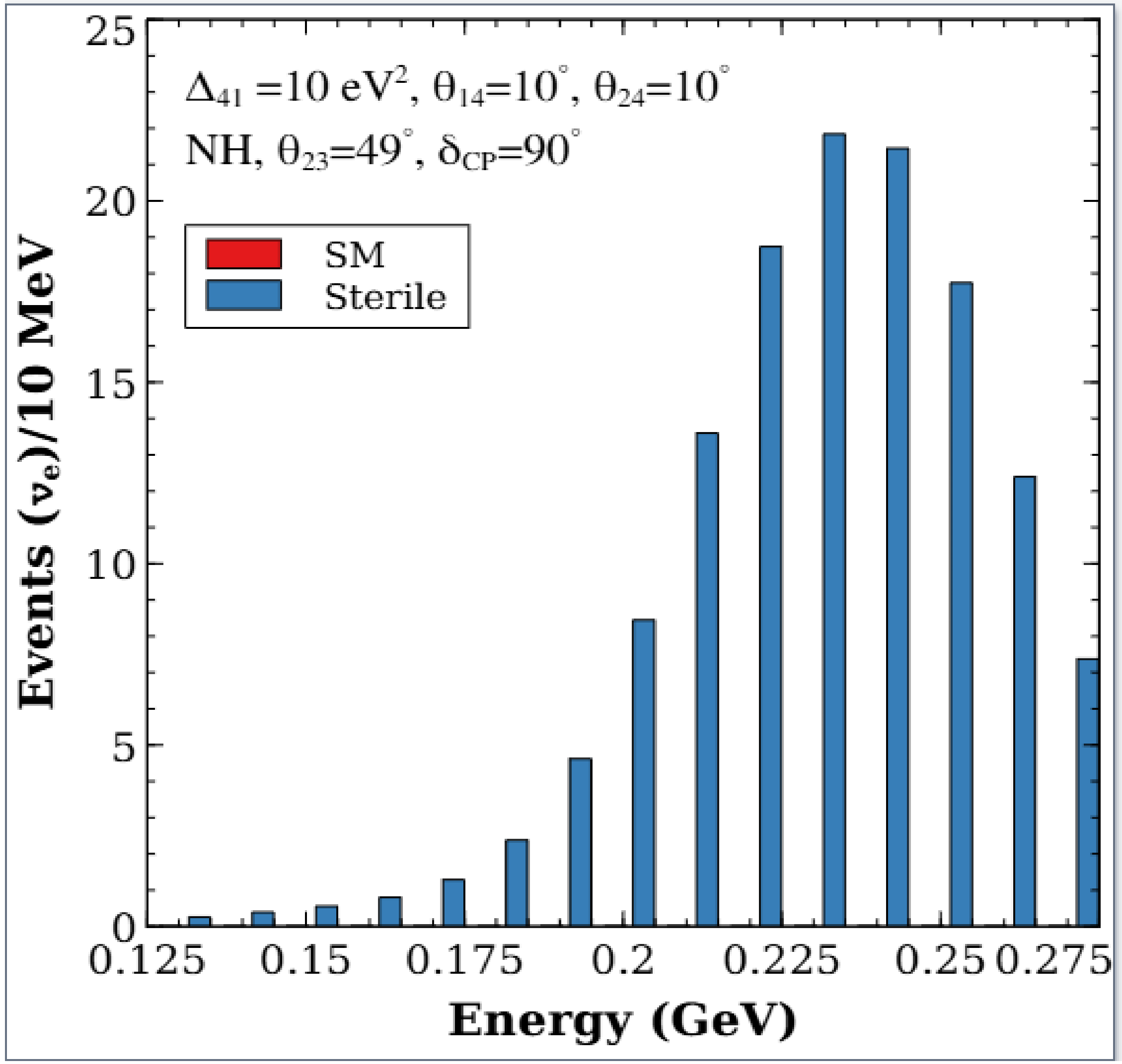
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

In the short-baseline limit $\left(\frac{\Delta m_{21}^2 L}{E} \ll 1, \frac{\Delta m_{31}^2 L}{E} \ll 1\right)$, where standard oscillations are suppressed, the $\nu_\mu \to \nu_e$ probability is

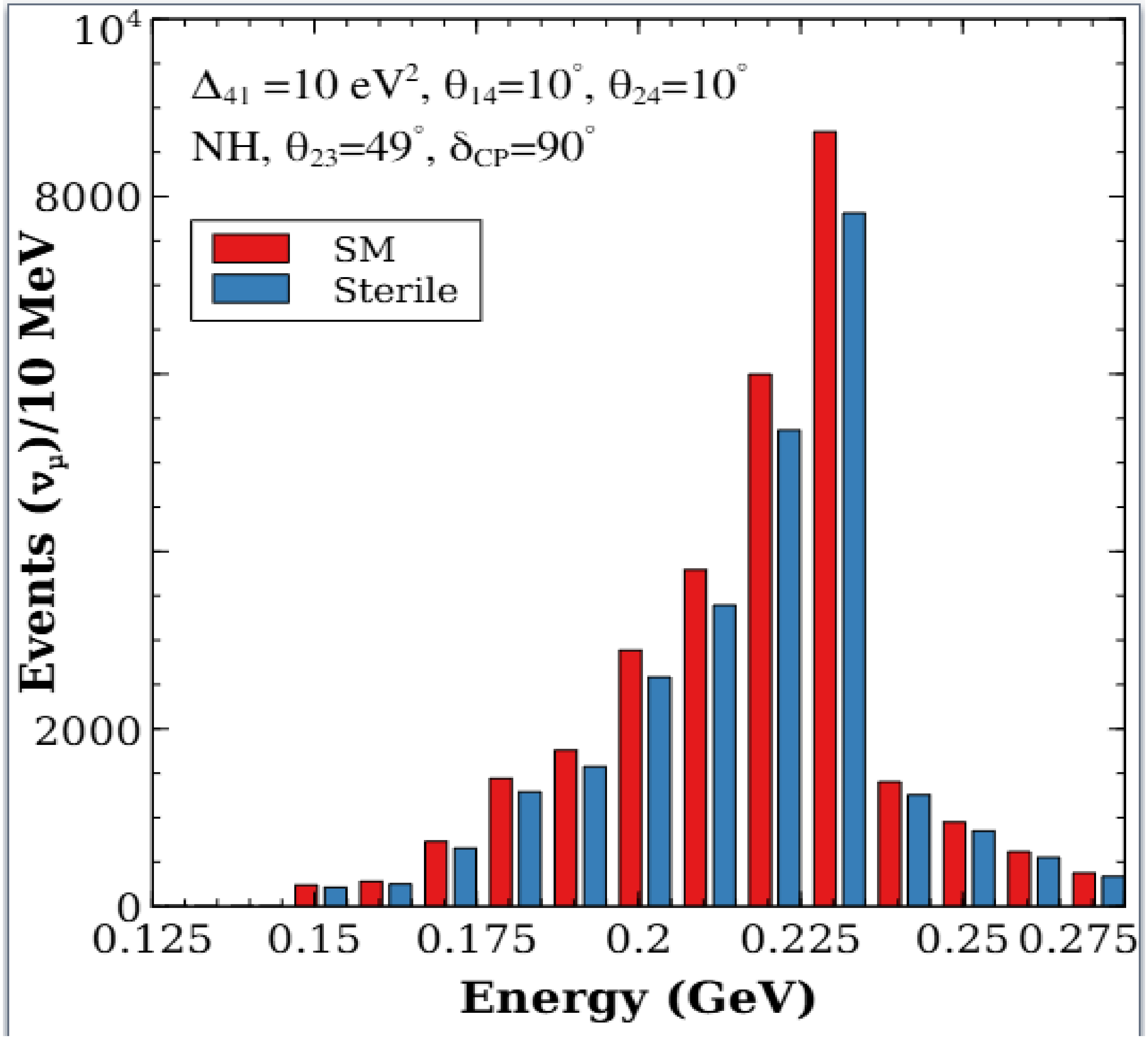
$$P_{\mu e}^{\text{sbl}} \simeq 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \frac{\Delta m_{41}^2 L}{4E}$$

We compare the **KDAR neutrino** spectra with standard oscillations versus with sterile neutrinos to put bounds on the sterile parameter space

KDAR event spectra at $\mathbf{JSNS^2}$ with sterile neutrino

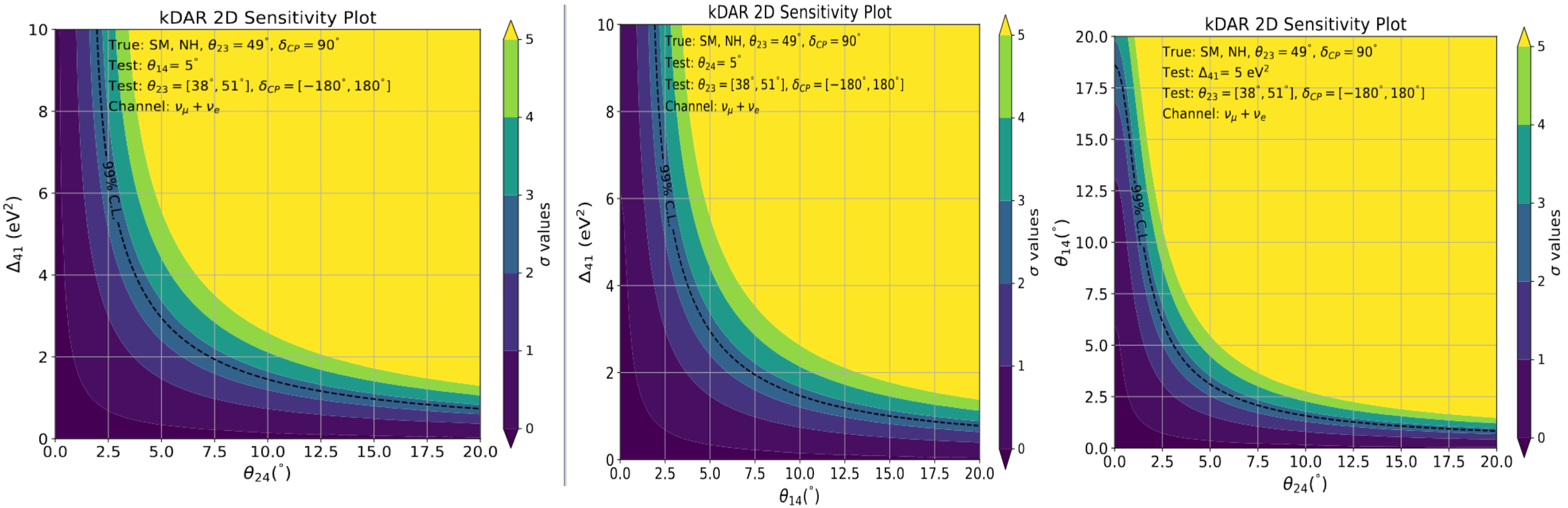


Appearance



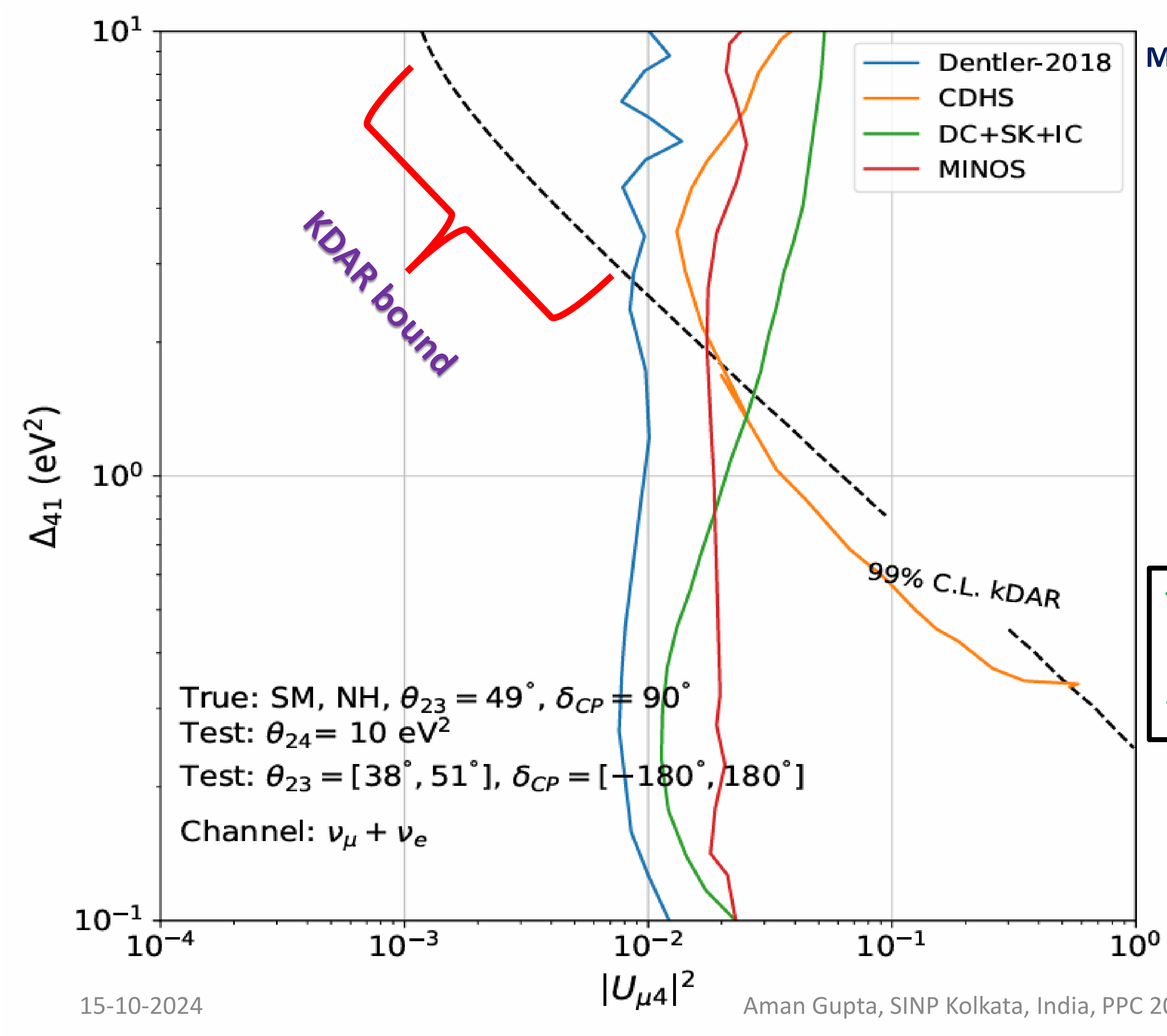
Disappearance

Results: constraints on sterile neutrino parameter space



Sensitivity of JSNS^2 (with KADAR only data) in constraining θ_{14}, θ_{24} and Δm_{41}^2 from appearance and disappearance channel data

Results: constraints on sterile neutrino parameter space



M. Dentler et al., JHEP 08 (2018) 010

Constraints on the active-sterile mixing matrix element $|U_{\mu 4}^2|$ from future KDAR data (black, dotted), overlaid on bounds from CDHS, MINOS, and atmospheric neutrino data

The best bounds (**as small as $|U_{\mu 4}^2| \sim 10^{-3}$**) are obtained for $\Delta m_{41}^2 > 2\ \mathrm{eV}^2$ which is consistent with the baseline and energy of this experiment

Concluding Remarks

- The possibility of new physics searches such as **source NSI** and **sterile neutrino** have been explored exploiting KDAR neutrino facility at $JSNS^2$ experiment

- Unlike propagation NSI, source (or production) NSI is independent of matter potential and neutrino energy and can give rise to **'zero-distance flavour conversion'**

- **Constraints on the non-standard coupling, for the first time in us sector (strange quark) have been obtained:**

$|\varepsilon_{\mu e}^{us}| < 0.03$ (0.005) at 99% C.L. with current (future) statistics

- We also find that with the $JSNS^2$ experiment and future KDAR only data

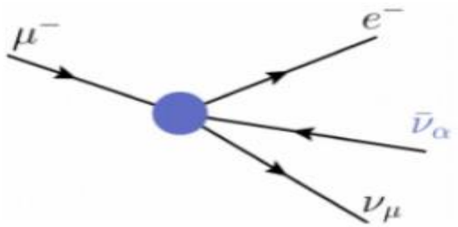
Active sterile mixing can be probed down to $|U_{\mu 4}^2| \sim 10^{-3}$ for $\Delta m_{41}^2 \sim 10\ eV^2$

- Monoenergetic 236 MeV neutrinos from kaon decay-at-rest, can also be used to study neutrino-nucleus cross-section

Thank you ☺

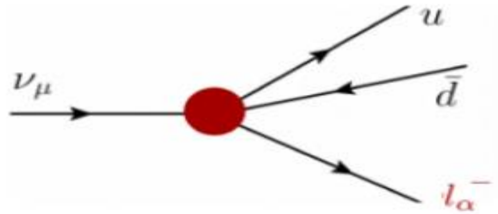
NSI at Production and Detection Level

NSI affecting production



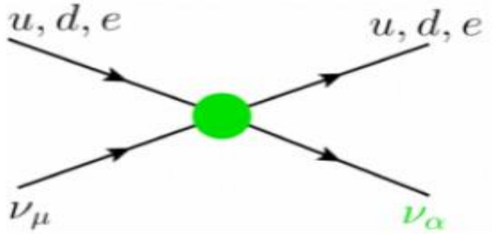
$\varepsilon^{e\mu,P}_{\mu\alpha}\,(\overline{e}\gamma^\rho P\mu)\,(\overline{\nu}_\mu\gamma_\rho P_L\nu_\alpha)$

NSI affecting detection



$\varepsilon^{ud,P}_{\mu\alpha}\,(\overline{d}\gamma^\rho Pu)\,(\overline{\nu}_\mu\gamma_\rho P_L l_\alpha)$

NSI affecting propagation



$\varepsilon^{f,P}_{\mu\alpha}\,(\overline{f}\gamma^\rho Pf)\,(\overline{\nu}_\mu\gamma_\rho P_L\nu_\alpha)$

Credits: P. Coloma, Fermilab'17

Neutrino states at sources and detectors:

$$|\nu^s_\alpha\rangle = |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau}\varepsilon^s_{\alpha\beta}|\nu_\beta\rangle = (1+\varepsilon^s)U|\nu_m\rangle$$

$$\langle\nu^d_\beta| = \langle\nu_\beta| + \sum_{\alpha=e,\mu,\tau}\varepsilon^d_{\alpha\beta}\langle\nu_\alpha| = \langle\nu_m|U^\dagger[1+(\varepsilon^d)^\dagger]$$

Superpositions of pure orthonormal flavor eigenstates

Grossman (1995); Gonzalez-Garcia *et al.* (2001); Bilenky, Giunti (1993); Meloni *et al.* (2010)

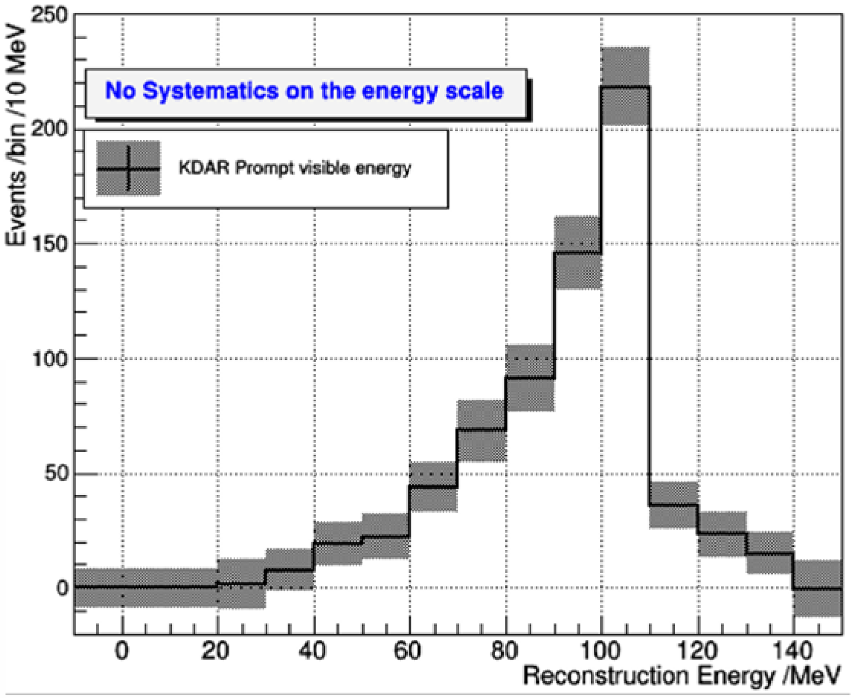
First clear KDAR signal

(Toward first precise KDAR measurement)

- **KDAR peak is clearly seen**
- **High purity (95%)** KDAR signal
  - Background: 5.2 %

- Note that **the systematics on the energy scale are not included yet**.

BKG ID	Correlated/ Accidental	BKG (# of events)	
1	Correlated	36.6 +- 34.8	5.0 +- 5.1%
2	Accidental	1.5 +- 0.1	0.2 +- 0.01%
KDAR Candidates : 730 events		38.1 +- 38.4	5.2 +- 5.3%



ChangDong Shin

NuFACT 2023, Seoul, Korea

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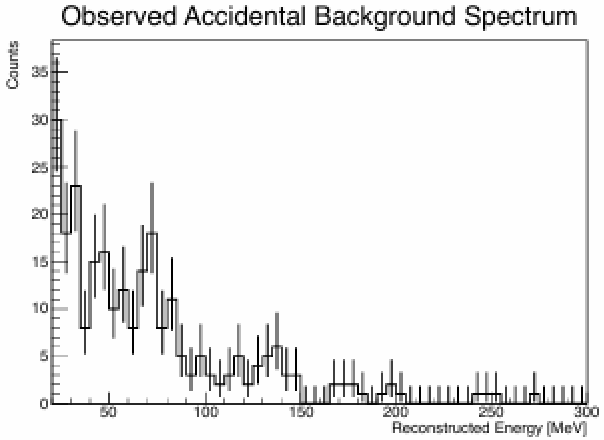
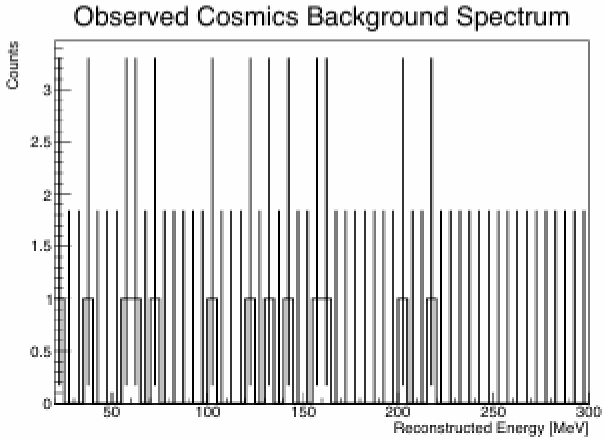
KDAR Backgrounds

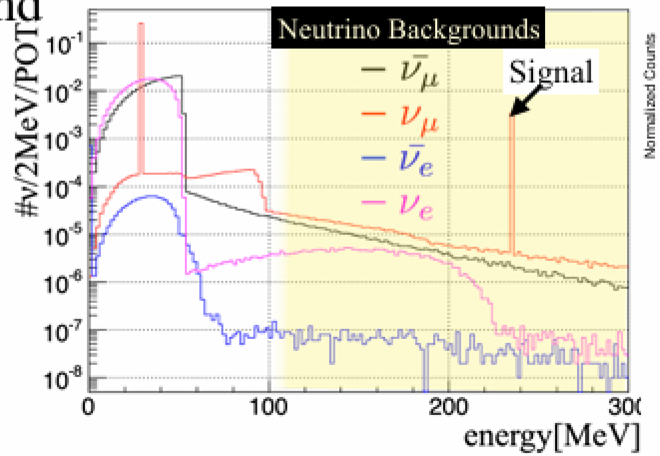
- **Dominant background source is pion decay-in-flight (DIF) neutrinos**
- DIF background spectral shape estimated with MC
- Both NuWro & GiBUU event generators are used for DIF background simulation
- Normalization estimated using the kinematically disallowed (>150MeV) portion of the KDAR spectrum

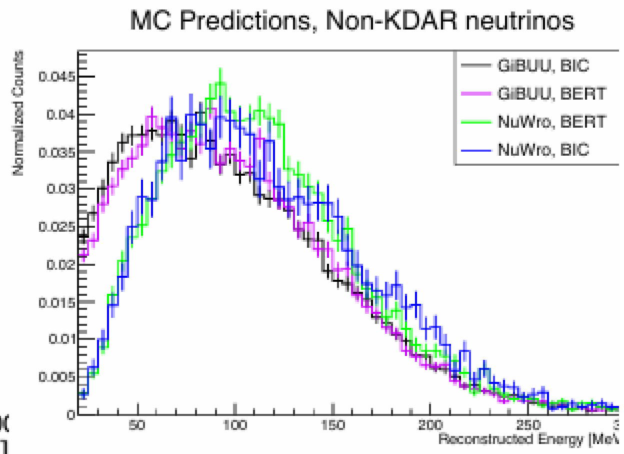


< 1.14 events in KDAR dataset



< 6.57 events in KDAR dataset





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