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

Aman Gupta

Saha Institute of Nuclear Physics, Kolkata, India

in collaboration with **Supriya Pan, Sushant Raut, Poonam Mehta & Atika Fatima**

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Introduction: neutrino oscillation and new physics

- Neutrino flavour oscillation arises from mixing between flavour states (ν_e, ν_μ, ν_τ) 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 violating 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 three 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

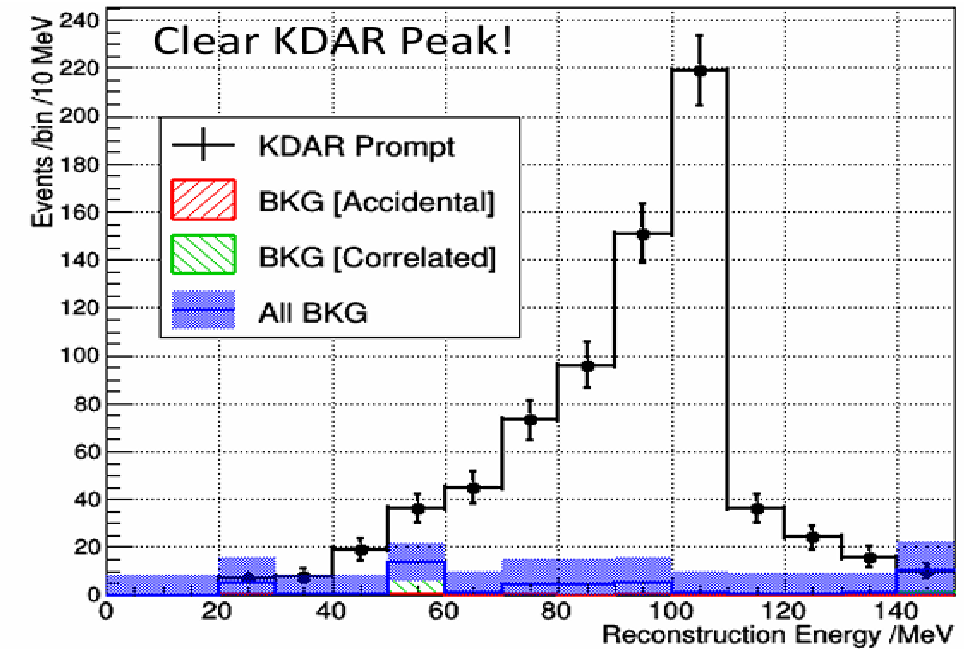
- New Physics:

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

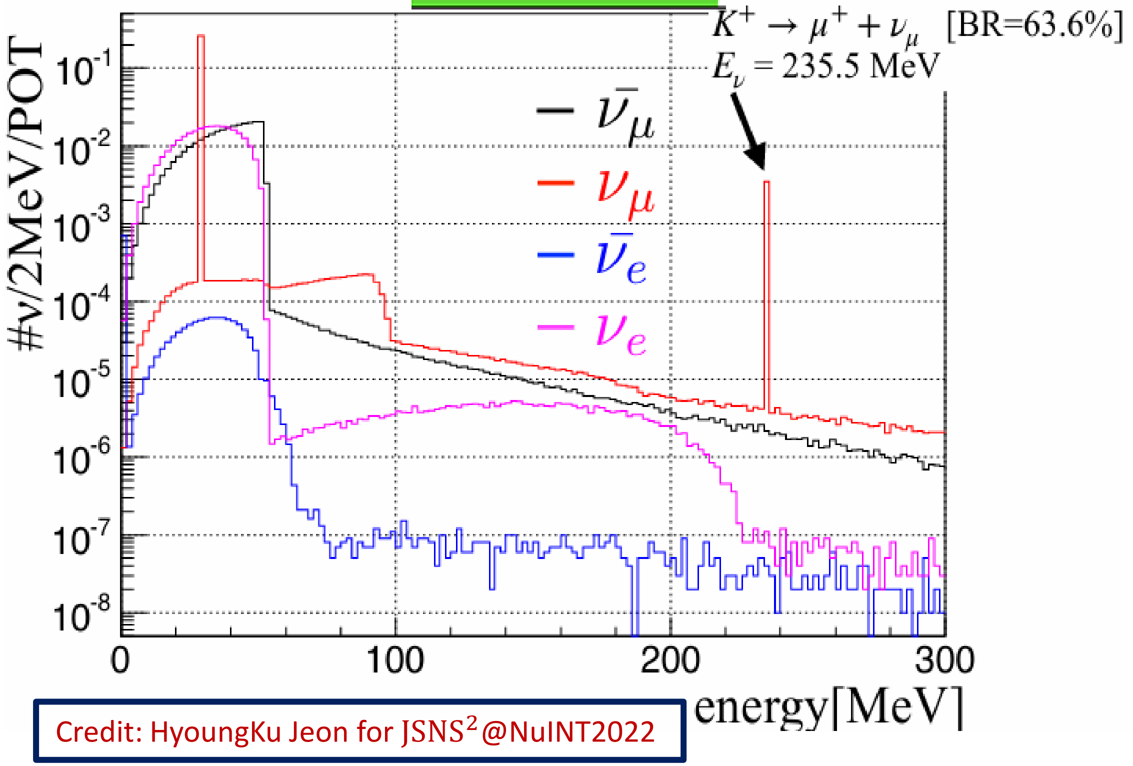
Neutrino flavour transition provides unique opportunity to search for physics beyond the Standard Model in oscillation experiments

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 `expected` data from JSNS^2 (0.7-0.8 MW beam)
- 730 muon events including 692 signal + 38 background



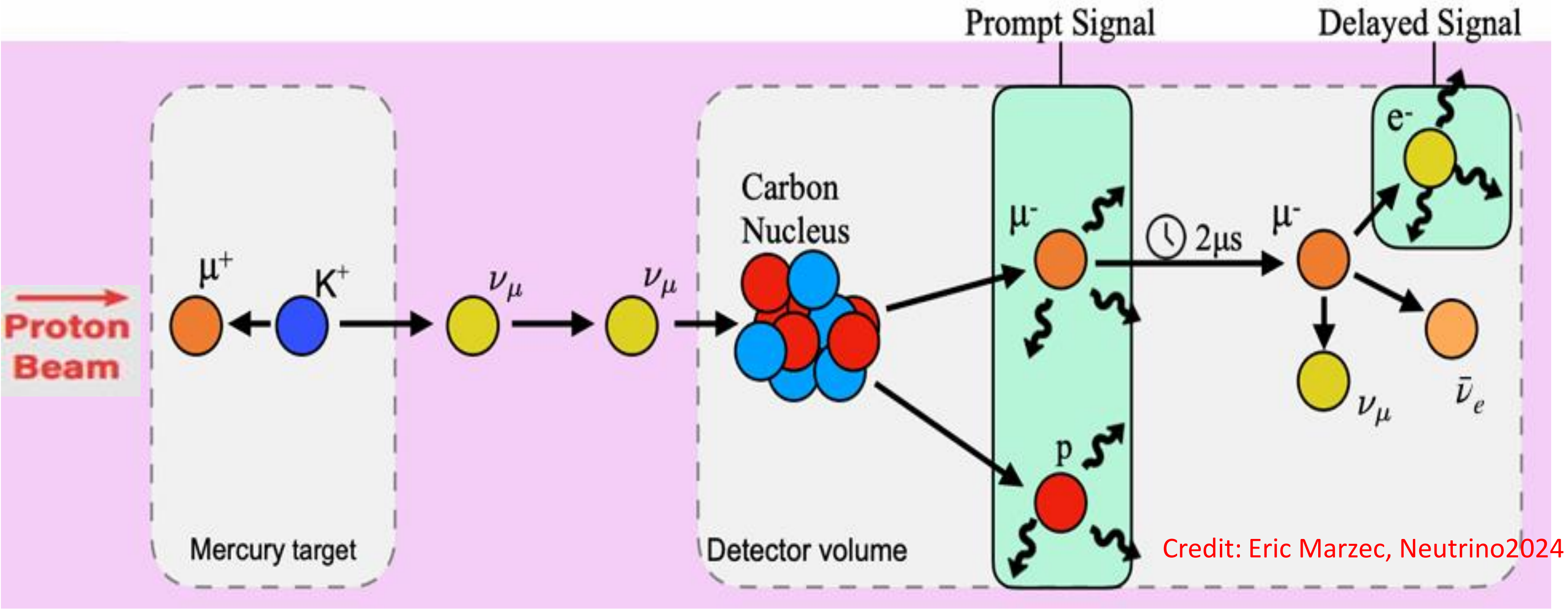
JSNS^2 Flux



Credit: HyoungKu Jeon for JSNS^2@NuINT2022

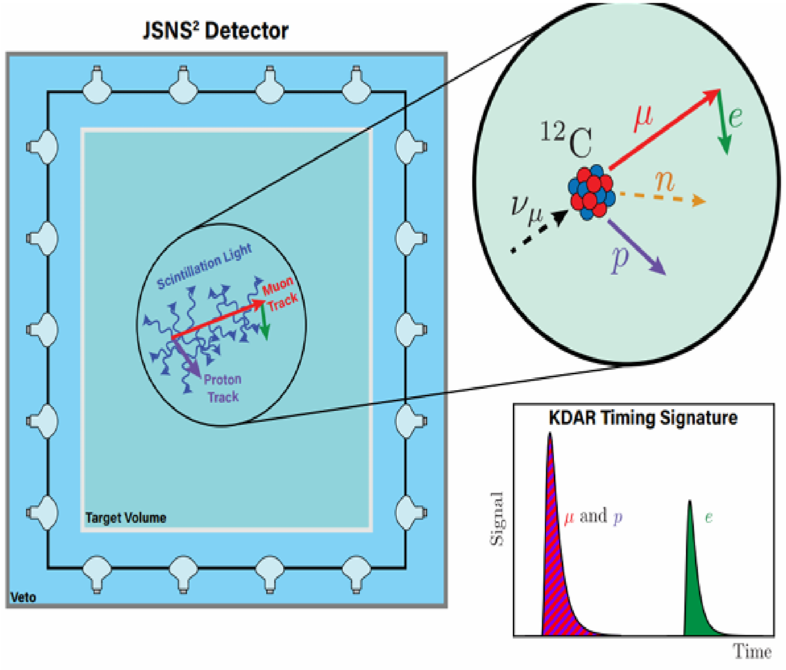
JSNS^2 as source for KDAR neutrino signal

- 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 $\Delta m^2 \sim 1\,\mathrm{eV}^2$ from $\nu_\mu \rightarrow \nu_e$** 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

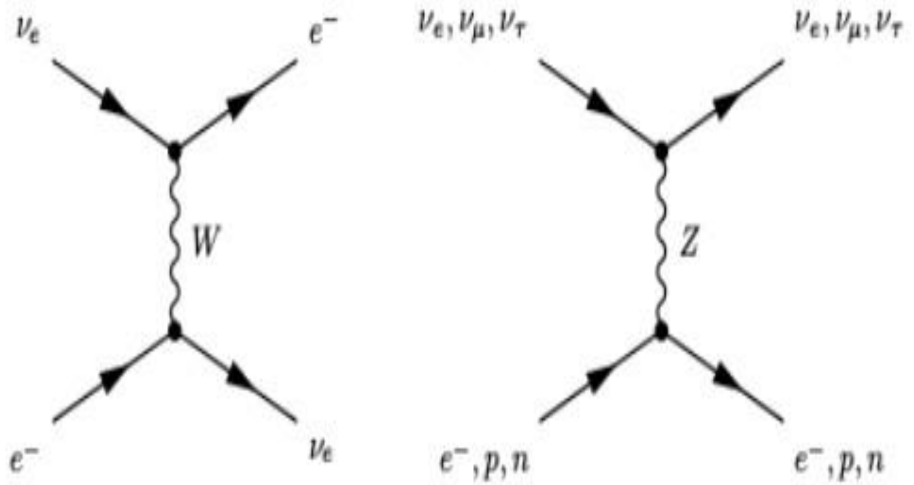
$$\mathcal{L}_{\rm cc}^{\rm eff} = -\frac{4G_F}{\sqrt{2}}[\overline{\nu_e}(p_3)\gamma_\mu P_L \nu_e(p_2)][\bar{e}(p_1)\gamma^\mu P_L e(p_4)].$$

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)

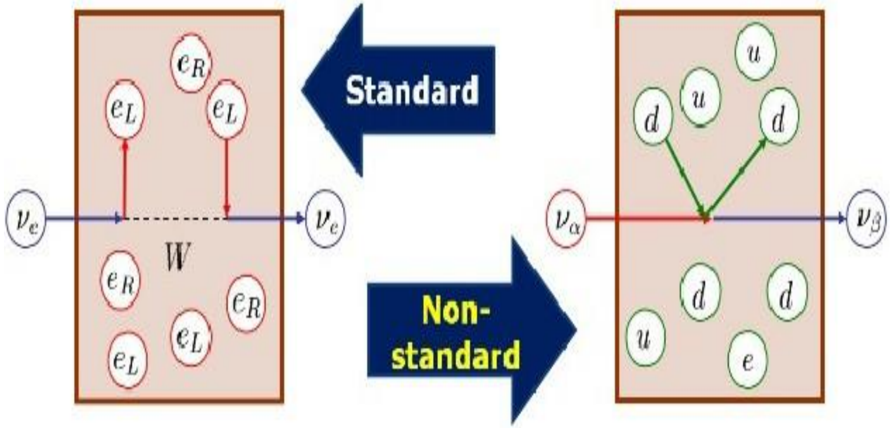
- Non-Standard neutrino interactions are the new interactions and couplings between neutrinos and matter fermions beyond those in the SM. It could be responsible for sub-leading effects in neutrino oscillation.

- **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"** $\propto E_\nu, \rho$



Credits : T. Ohlsson, MPIK'09

- 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 $\epsilon_{\alpha\beta}^{ud}$

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

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. $|\boldsymbol{\nu}_{\boldsymbol{\alpha}}^{\boldsymbol{s}}\rangle = \sum_{\boldsymbol{\beta}}\left(\boldsymbol{\delta}_{\boldsymbol{\alpha\beta}} + \boldsymbol{\epsilon}_{\boldsymbol{\alpha\beta}}^{\boldsymbol{ff'}}\right)|\boldsymbol{\nu}_{\boldsymbol{\beta}}\rangle$

- 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 →

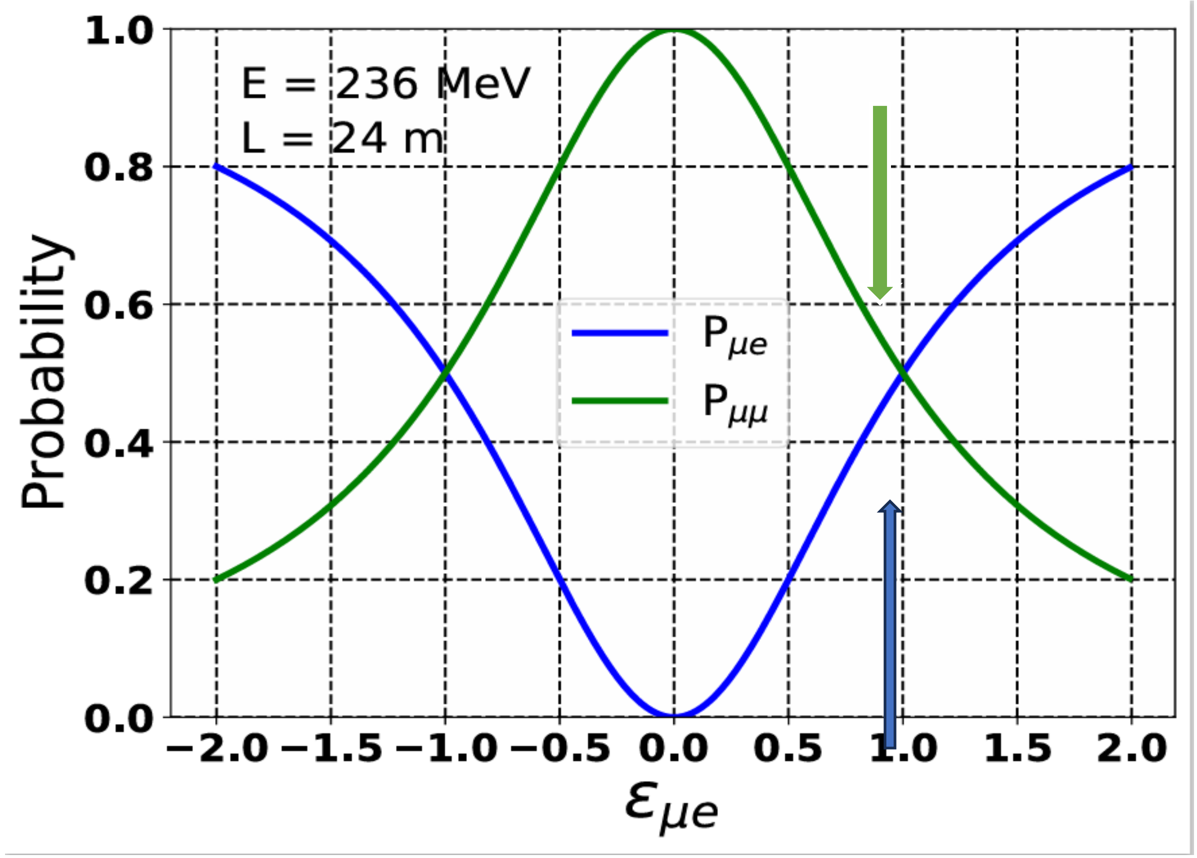
$$P_{\mu\alpha} = |\textstyle\sum_\beta (\mathbb{I} + \varepsilon^{us})_{\mu\beta}\mathcal{A}_{\beta\alpha}^{SM}|^2 \text{ (up to a normalization factor)}$$

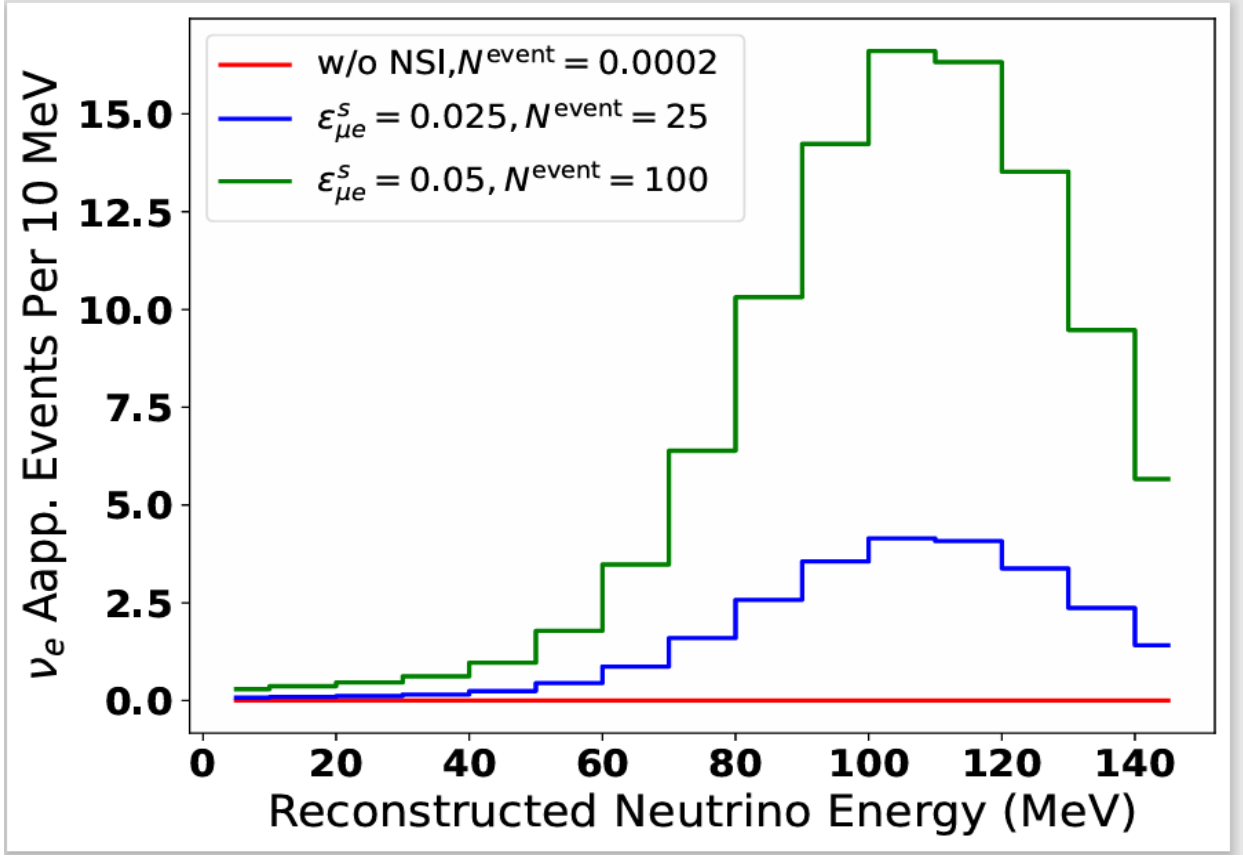
$$P_{\mu e} = |\varepsilon_{\mu e}^{us}|^2 / \left(|\varepsilon_{\mu e}^{us}|^2 + |1 + \varepsilon_{\mu\mu}^{us}|^2\right)$$

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

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.

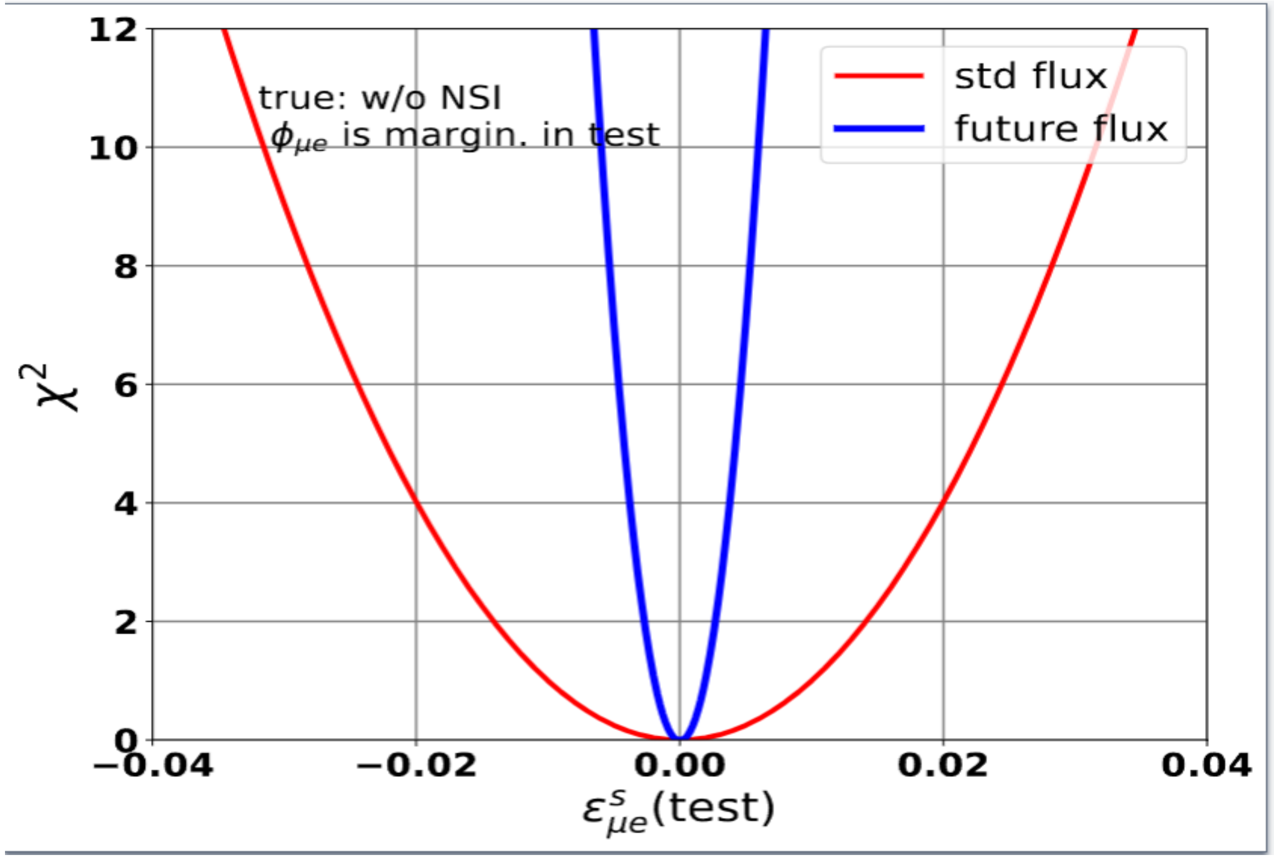


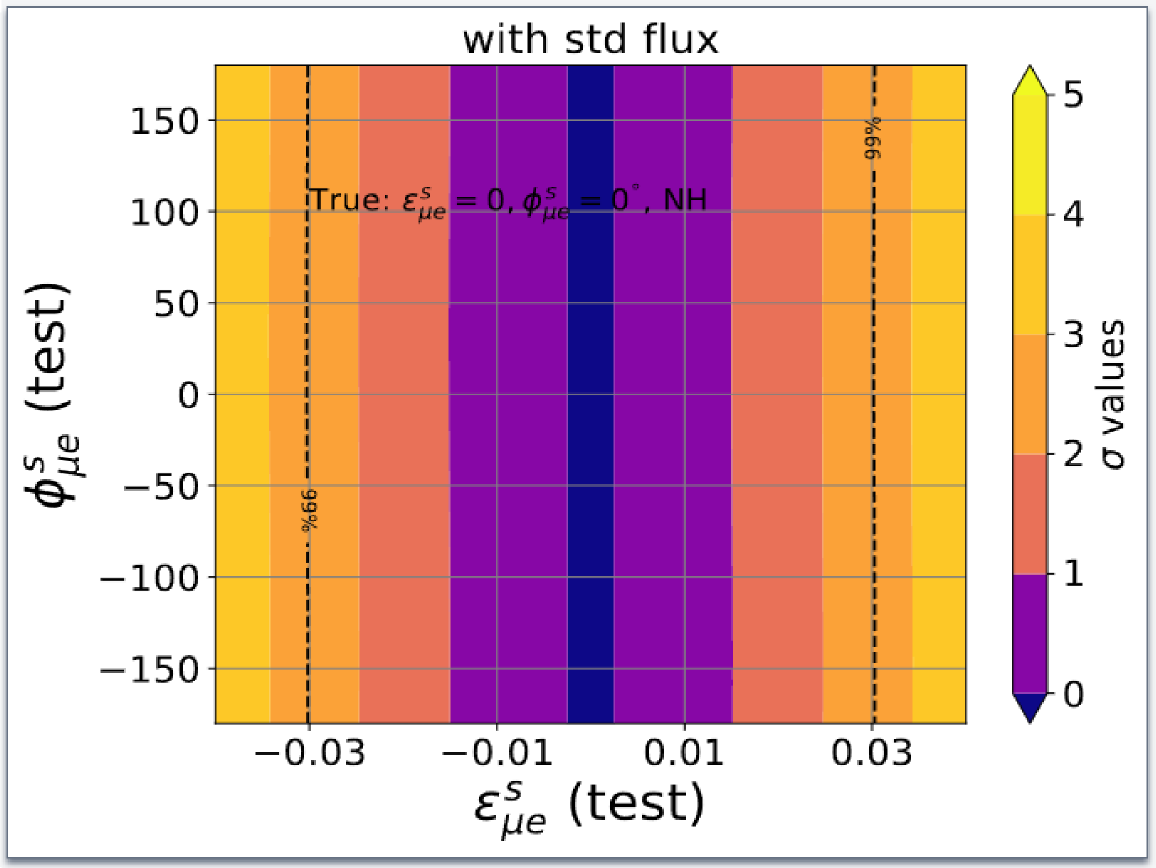


- The effect of only $\epsilon^{us}_{\mu\mu}$ is wiped out due to the probability normalization by ν_μ disappearance events

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"

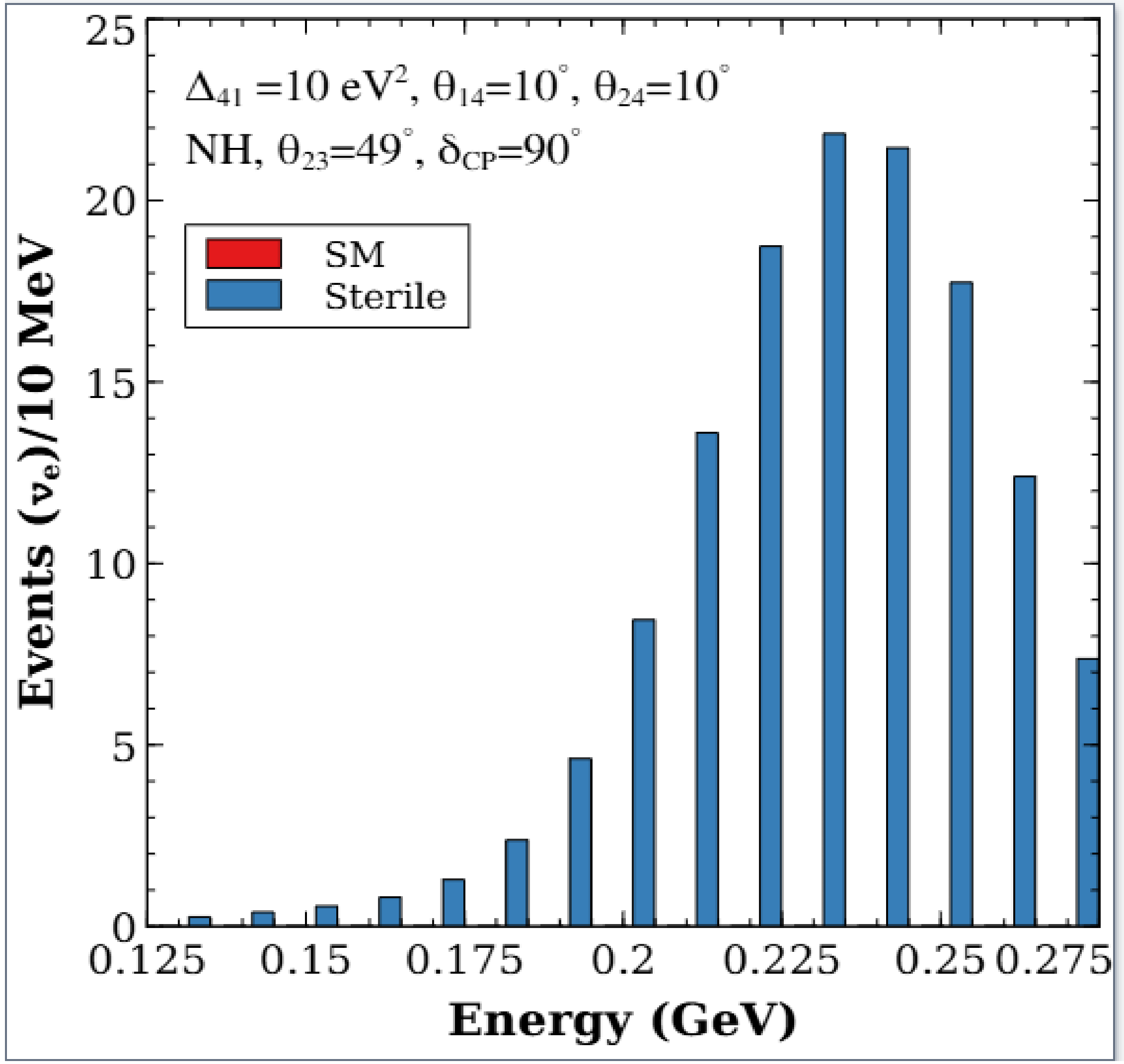
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2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

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

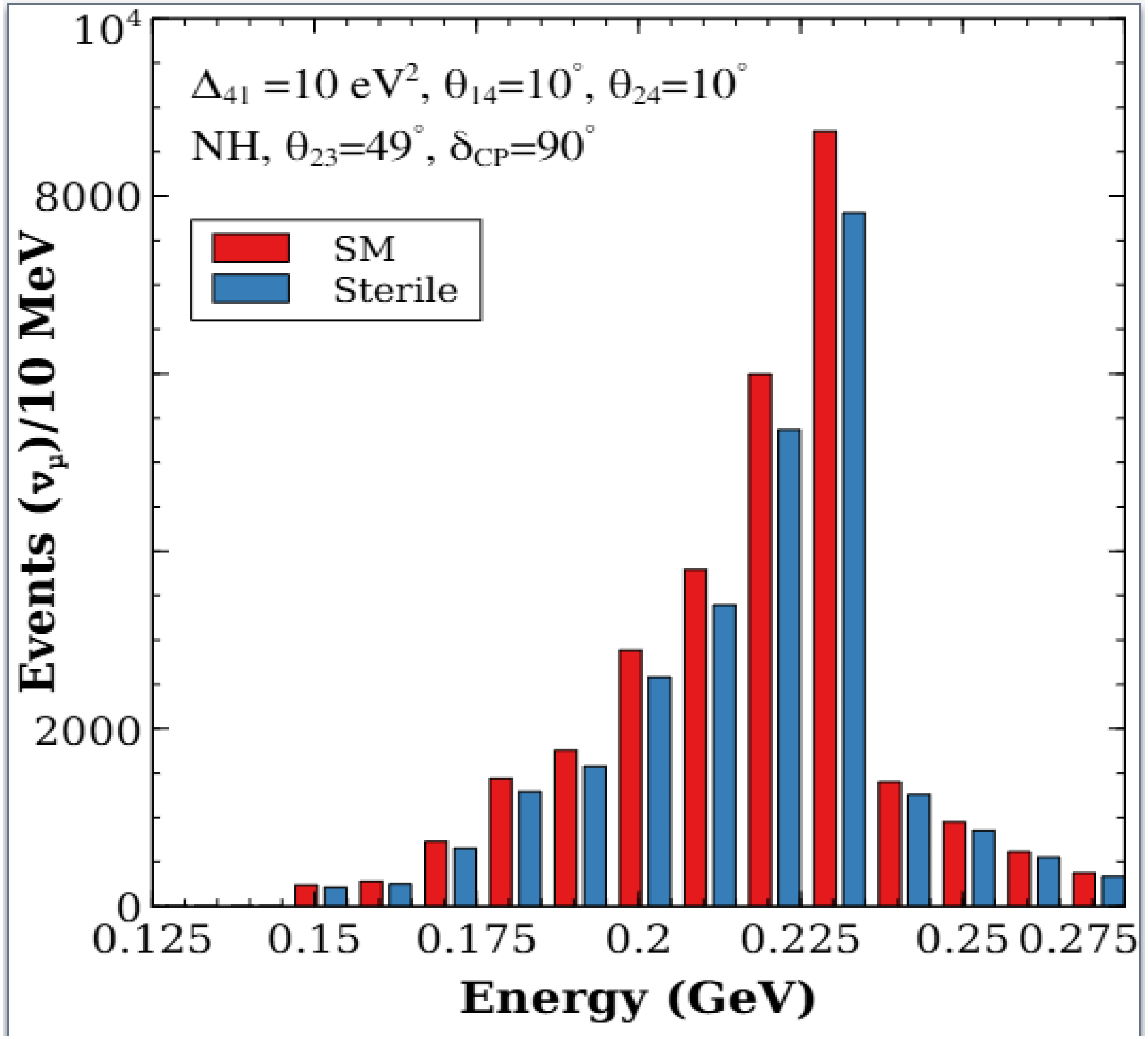
$$P_{\mu e}^{\mathrm{sbl}} \simeq 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \frac{\Delta m_{41}^2 L}{4E}$$

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 JSNS^2 with sterile neutrino

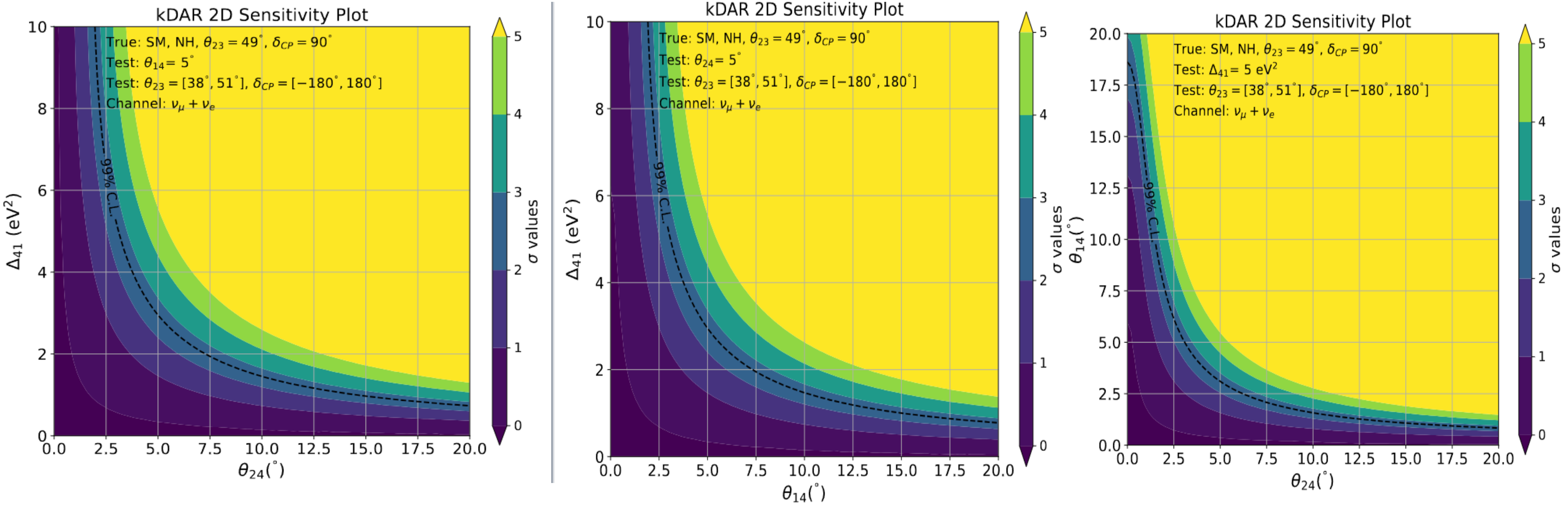


Appearance



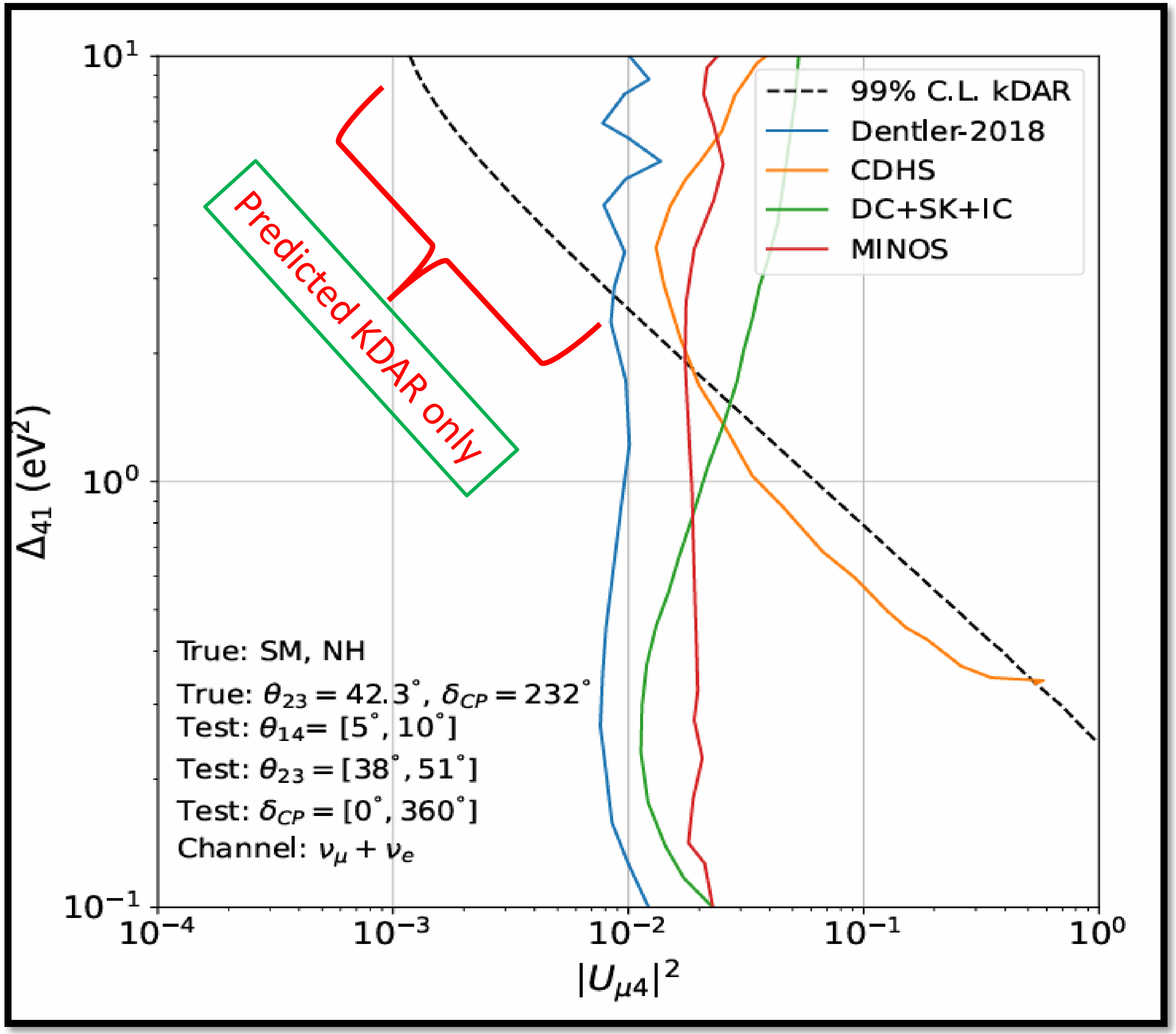
Disappearance

Results: constraints on sterile neutrino parameter space



Sensitivity of JSNS^2 (with KADAR only data) in constraining θ_{14}, θ_{24} and Δm^2_{41} 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 $|U_{\mu4}^2|$ from future KDAR data (black, dotted), overlaid on bounds from CDHS, MINOS, and atmospheric neutrino data

The best bounds (**as small as $|U_{\mu4}^2| \sim 10^{-3}$**) are obtained for $\boldsymbol{\Delta m_{41}^2 > 2\ \mathrm{eV}^2}$ 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:**

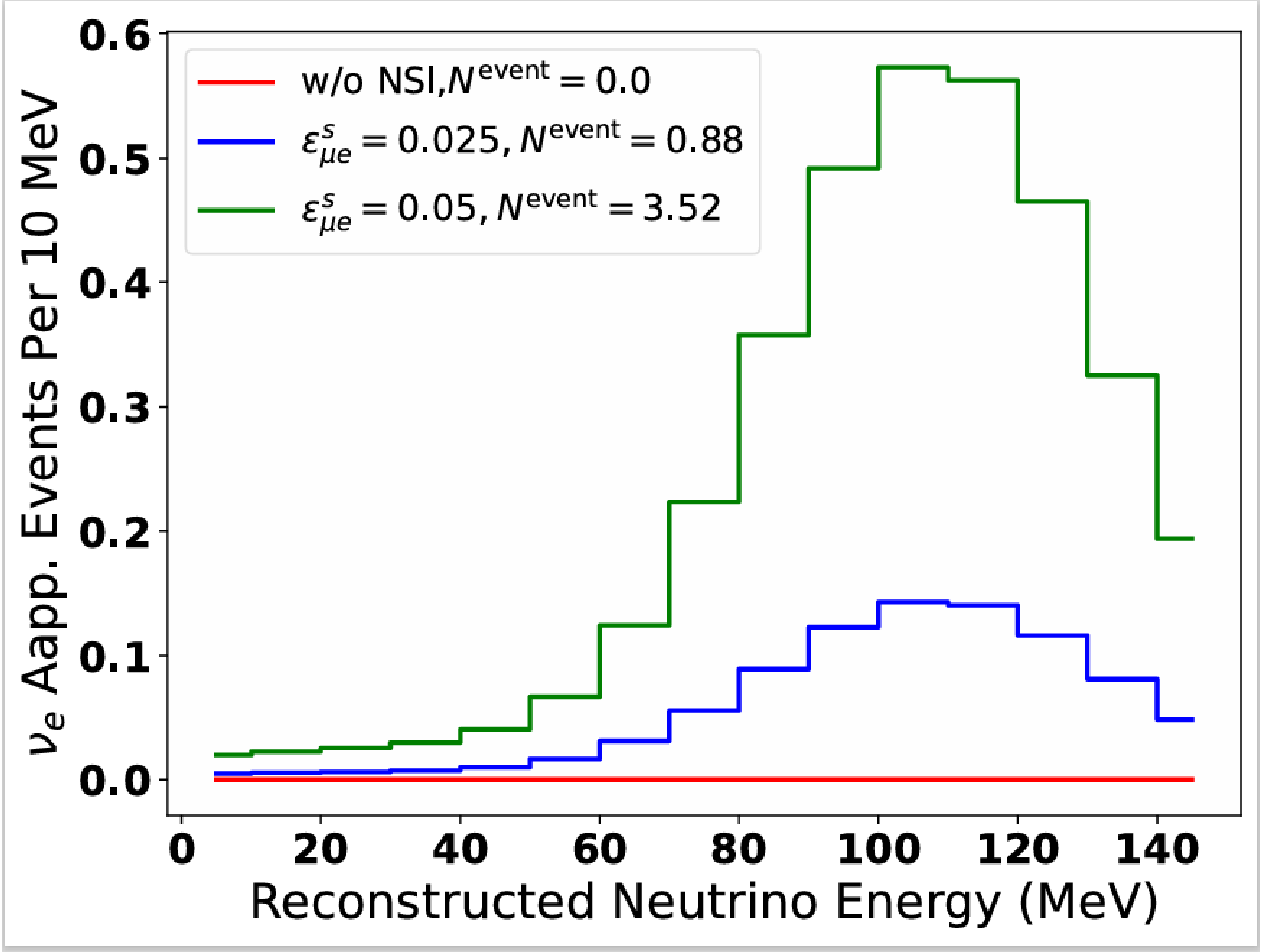
$|\varepsilon_{\mu e}^{us}| < 0.03$ (0.005) at 99% C.L. with current (future) statistics

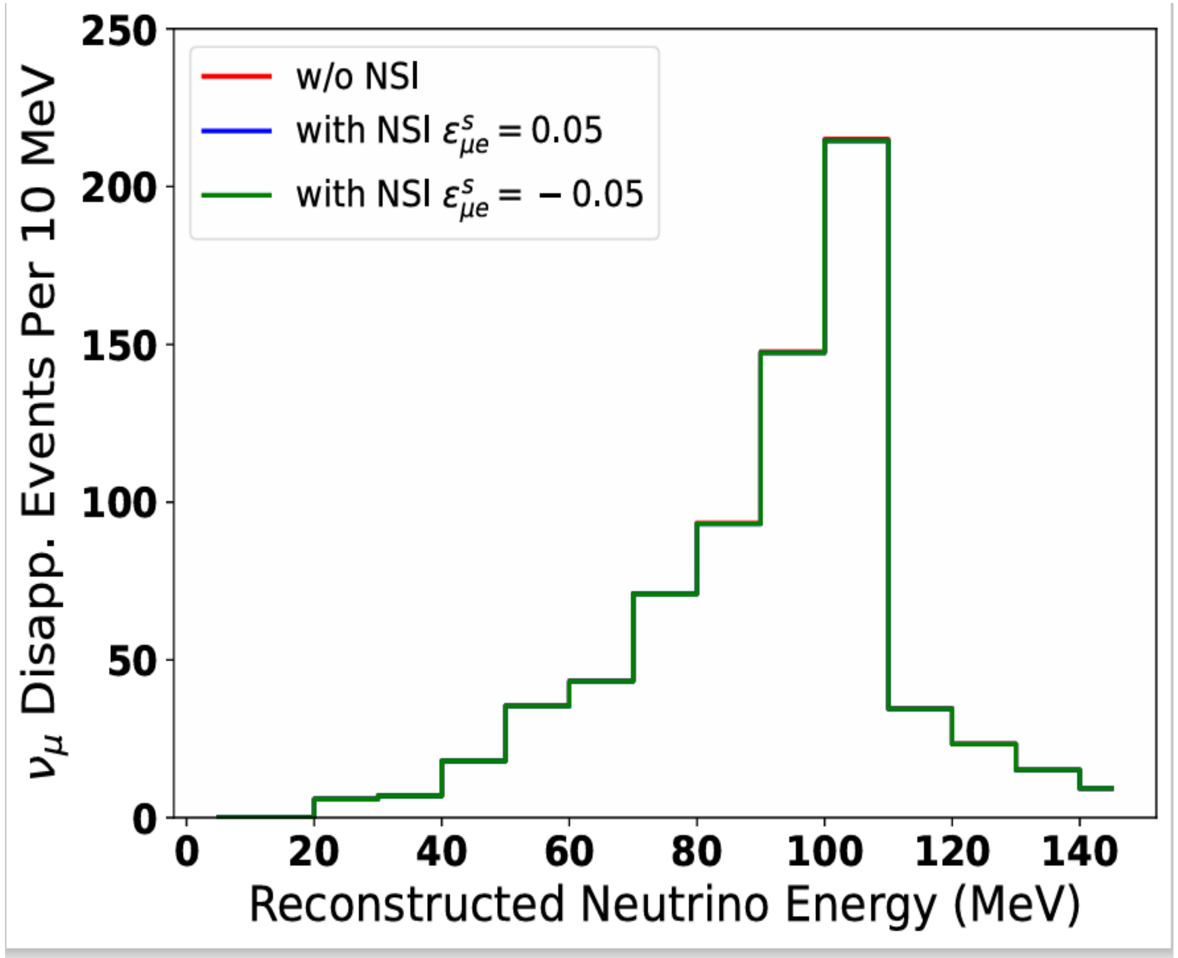
- We also find that with the JSNS^2 experiment and future KDAR only data

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

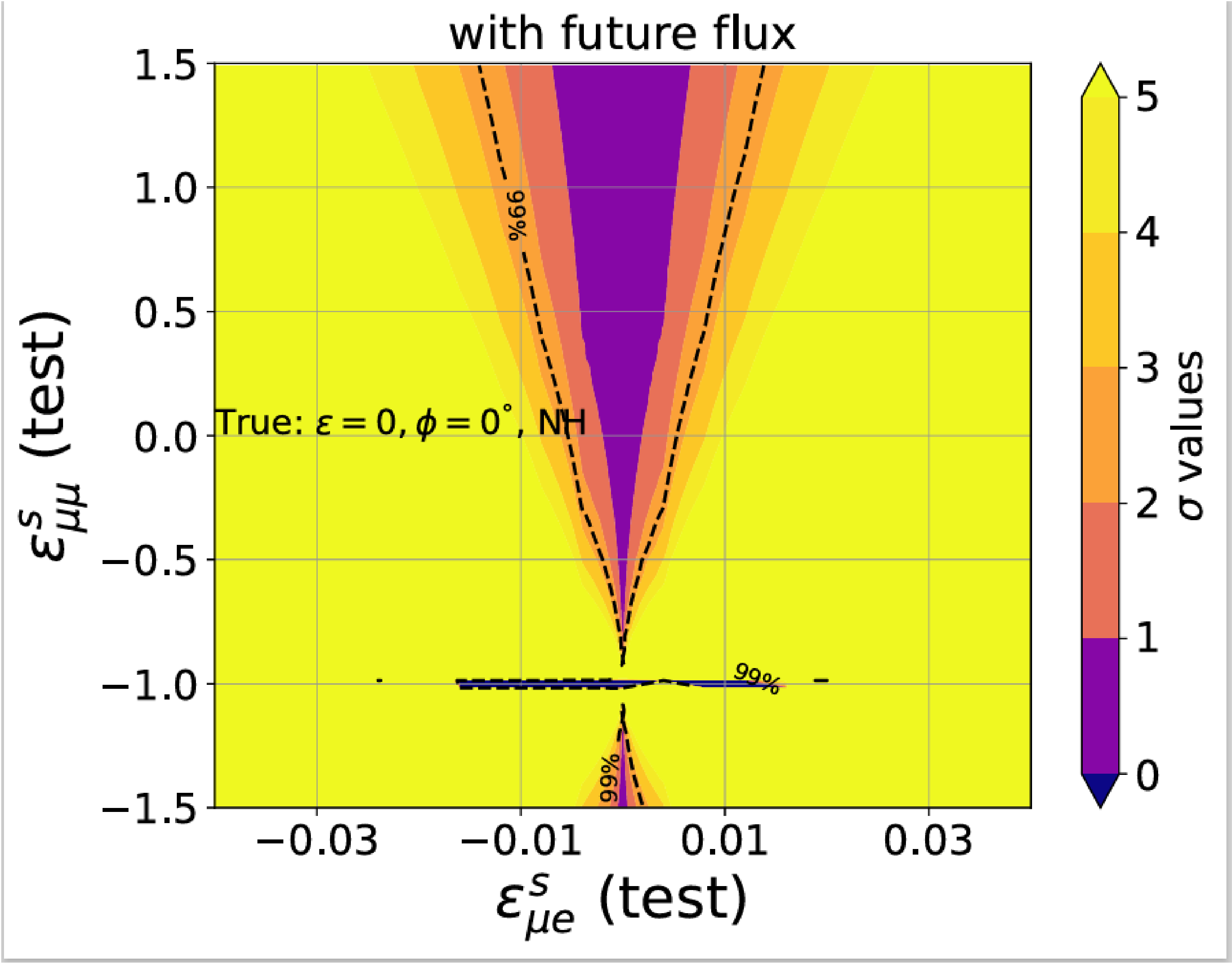
- Monoenergetic 236 MeV neutrinos from kaon decay-at-rest, can also be used to study neutrino-nucleus cross-section

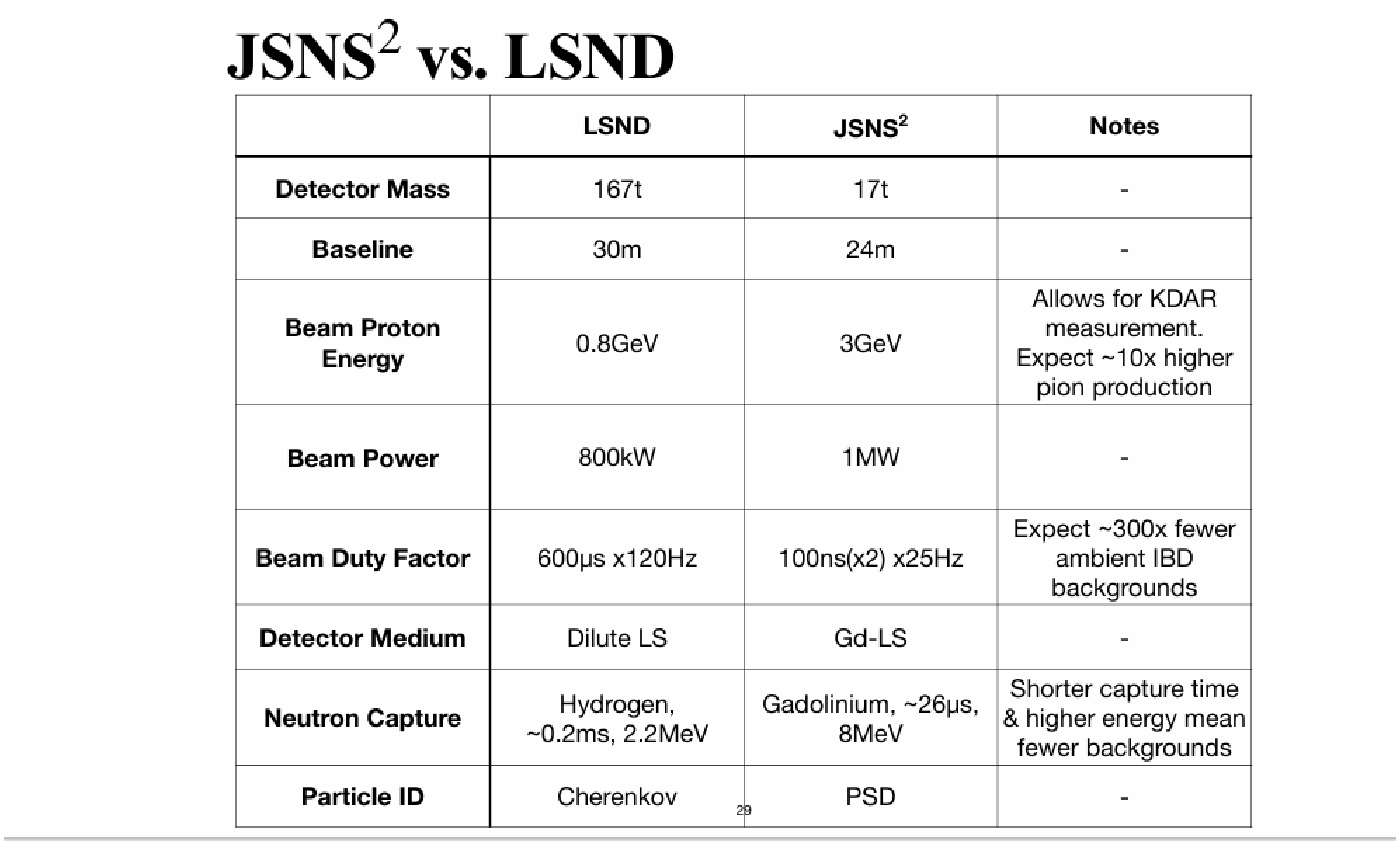
Thank you ☺





With current data; 730 ν_μ events


with future flux
True: $\varepsilon = 0, \phi = 0^\circ$, NH
99%
99%
99%
$\varepsilon^s_{\mu\mu}$ (test)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−0.03
−0.01
0.01
0.03
$\varepsilon^s_{\mu e}$ (test)
5
4
3
2
1
0
σ values



JSNS^2 vs. LSND

	LSND	JSNS^2	Notes
Detector Mass	167t	17t	-
Baseline	30m	24m	-
Beam Proton Energy	0.8GeV	3GeV	Allows for KDAR measurement. Expect ~10x higher pion production
Beam Power	800kW	1MW	-
Beam Duty Factor	600μs x120Hz	100ns(x2) x25Hz	Expect ~300x fewer ambient IBD backgrounds
Detector Medium	Dilute LS	Gd-LS	-
Neutron Capture	Hydrogen, ~0.2ms, 2.2MeV	Gadolinium, ~26μs, 8MeV	Shorter capture time & higher energy mean fewer backgrounds
Particle ID	Cherenkov	PSD	-

Indication of a sterile neutrino ($\Delta m^2 \sim 1 eV^2$)

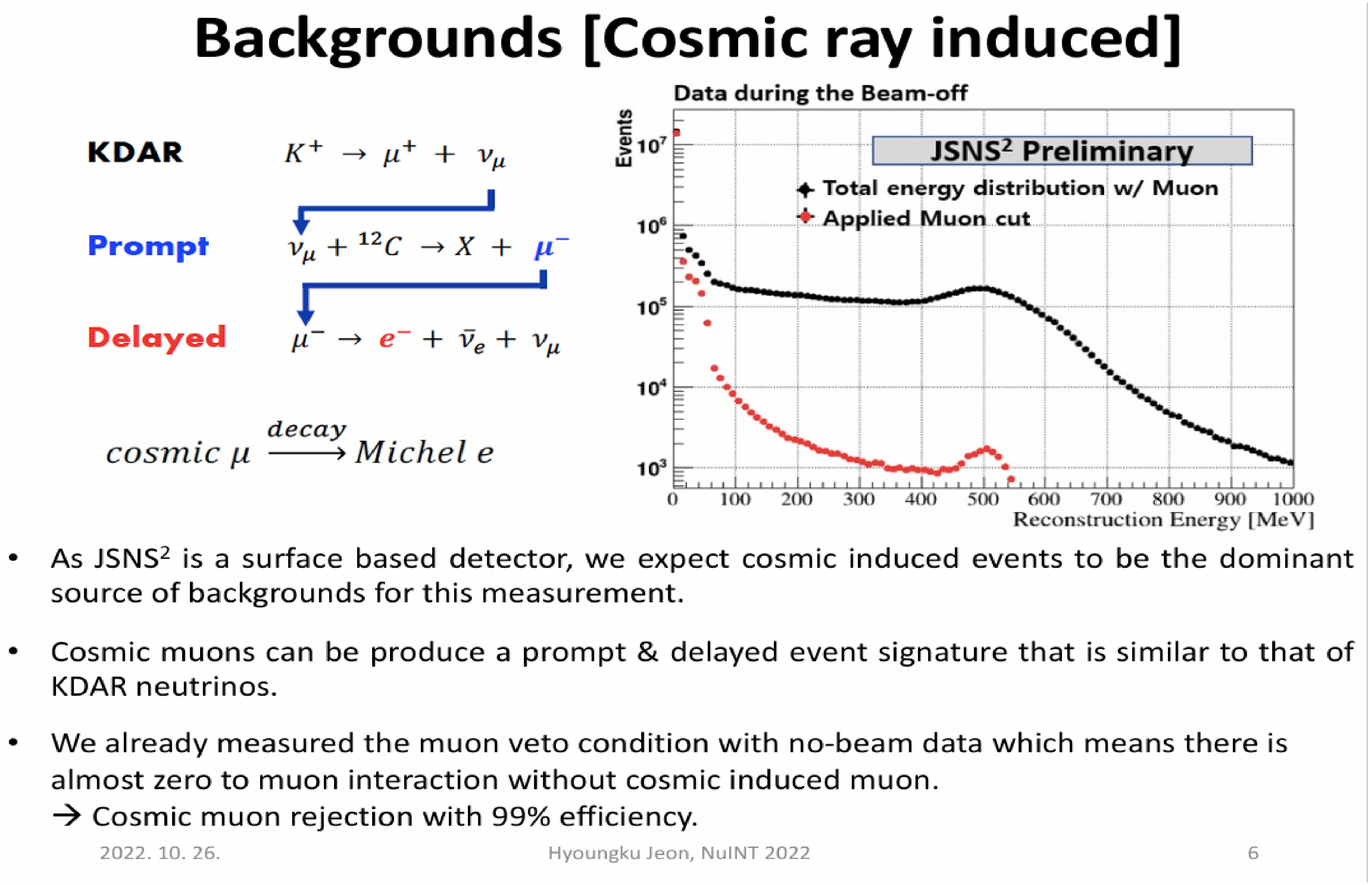
- Anomalies, which cannot be explained by standard neutrino oscillations for ~20 years are shown

Experiments	Neutrino source	Signal	Significance	E(MeV)	L(m)
LSND	μ Decay-At-Rest	$\bar{\nu}_\mu \to \bar{\nu}_e$	3.8σ	40	30
MiniBooNE	π Decay-In-Flight	$\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$	4.8σ	800	600
BEST	e capture	$\nu_e \to \nu_x$	4.2σ	<3	10
Reactors	Beta decay	$\bar{\nu}_e \to \bar{\nu}_x$	3.0σ	3	10-100

- JSNS^2 uses the same neutrino source (μ), target (H), and detection principle (IBD) as the **LSND**

- Even if the excess is not due to the oscillation, JSNS^2 can catch this directly
- two advantages : short-pulsed beam and used the gadolinium(Gd)-loaded liquid scintillator(GdLS)

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



Backgrounds [Cosmic ray induced]

KDAR $K^+ \to \mu^+ + \nu_\mu$

Prompt $\nu_\mu + {}^{12}C \to X + \mu^-$

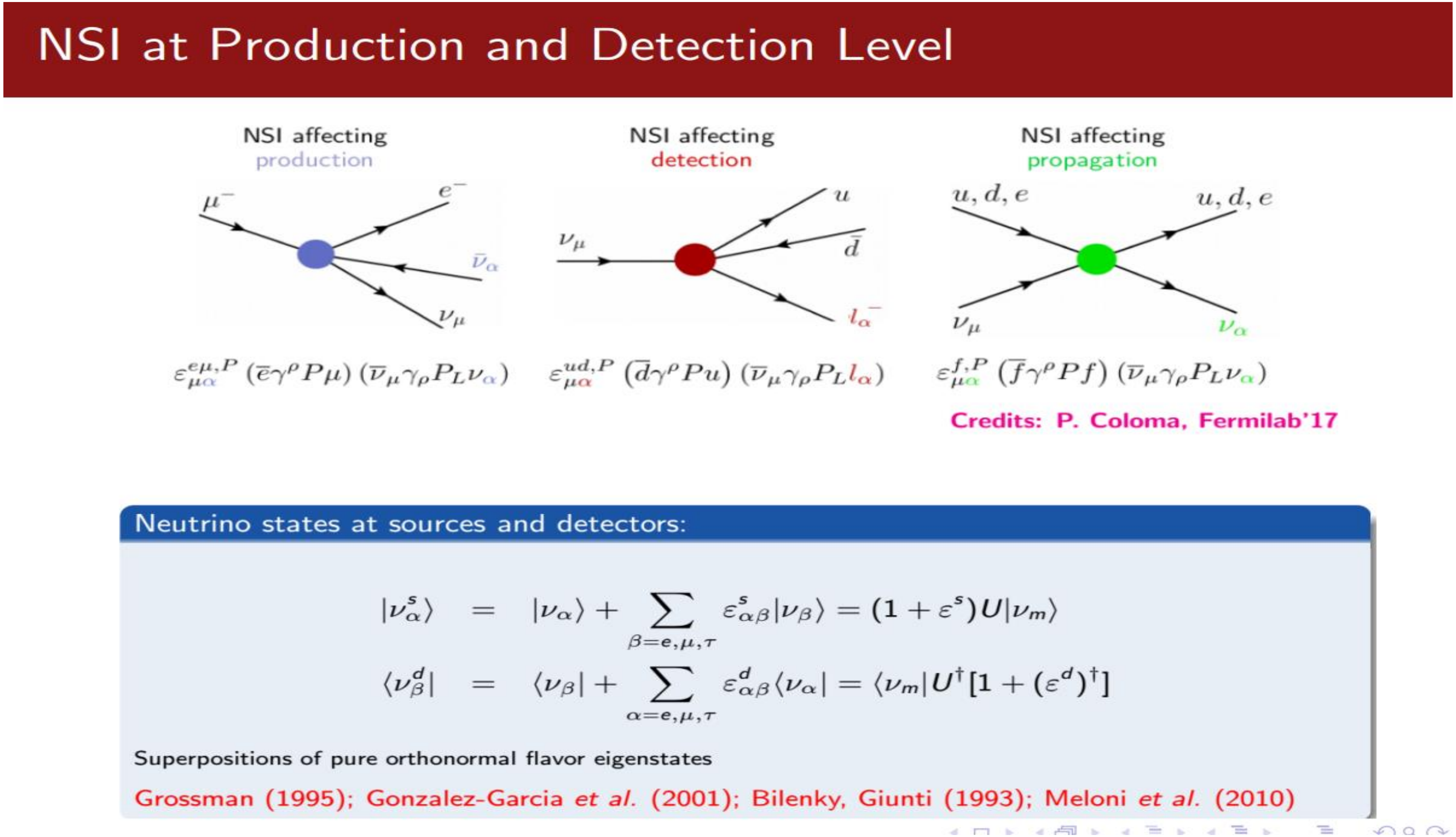
Delayed $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$

$$\text{cosmic } \mu \xrightarrow{decay} \text{Michel } e$$

Data during the Beam-off

- As JSNS² is a surface based detector, we expect cosmic induced events to be the dominant source of backgrounds for this measurement.
- Cosmic muons can be produce a prompt & delayed event signature that is similar to that of KDAR neutrinos.
- We already measured the muon veto condition with no-beam data which means there is almost zero to muon interaction without cosmic induced muon.
  → Cosmic muon rejection with 99% efficiency.

2022. 10. 26. Hyoungku Jeon, NuINT 2022 6



NSI at Production and Detection Level

NSI affecting production

NSI affecting detection

NSI affecting propagation

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

Credits: P. Coloma, Fermilab'17

Neutrino states at sources and detectors:

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

Superpositions of pure orthonormal flavor eigenstates

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