

Leptonic CP Measurement & New Physics Alternatives

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Jarah Evslin, **SFG**, Kaoru Hagiwara, JHEP **1602** (2016) 137 [arXiv:1506.05023]
SFG, Pedro Pasquini, M. Tortola, J. W. F. Valle, PRD **95** (2017) No.3, 033005 [arXiv:1605.01670]
SFG, Alexei Smirnov, JHEP **1610** (2016) 138 [arXiv:1607.08513]
SFG [arXiv:1704.08518]
SFG, Stephen Parke, Phys.Rev.Lett. **122** (2019) no.21, 211801 [arXiv:1812.08376]
SFG, Hitoshi Murayama [arXiv:1904.02518]

LHC & Daya Bay changed Physics in 2012

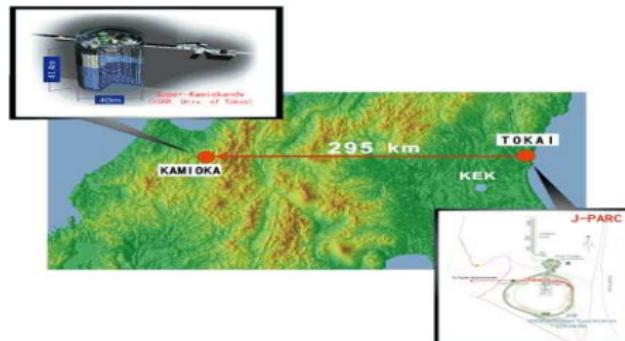
- Higgs boson \Rightarrow electroweak symmetry breaking & mass.
- Chiral symmetry breaking \Rightarrow majority of mass.
- The world seems not affected by the tiny neutrino mass?
 - Neutrino mass \Rightarrow Mixing
 - 3 Neutrino \Rightarrow possible CP violation
 - CP violation \Rightarrow Leptogenesis
 - Leptogenesis \Rightarrow Matter-Antimatter Asymmetry
 - There is something left in the Universe.
 - Baryogenesis from quark mixing is not enough.
- Majorana $\nu \Leftrightarrow$ Lepton Number Violation
- Residual \mathbb{Z}_2 Symmetries: $\cos \delta_D = \frac{(s_s^2 - c_s^2 s_r^2)(c_a^2 - s_a^2)}{4 C_a S_a C_s S_r}$

1108.0964

1104.0602

CP Measurement @ Accelerator Exps

- T2K



- NO ν A



- DUNE/T2KII/T2HK/T2HKK/T2KO; MOMENT/ADS-CI/DAE δ ALUS; Super-PINGU

The Dirac CP Phase δ_D @ Accelerator Exp

- To leading order in $\alpha = \frac{\delta M_{21}^2}{|\delta M_{31}^2|} \sim 3\%$, the oscillation probability relevant to measuring δ_D @ T2(H)K,

$$P_{\nu_\mu \rightarrow \nu_e} \approx 4 s_a^2 c_r^2 s_r^2 \sin^2 \phi_{31}$$

$$- 8 c_a s_a c_r^2 s_r c_s s_s \sin \phi_{21} \sin \phi_{31} [\cos \delta_D \cos \phi_{31} \pm \sin \delta_D \sin \phi_{31}]$$

for ν & $\bar{\nu}$, respectively. $[\phi_{ij} \equiv \frac{\delta m_{ij}^2 L}{4 E_\nu}]$

- $\nu_\mu \rightarrow \nu_\mu$ Exps measure $\sin^2(2\theta_a)$ precisely, but not $\sin^2 \theta_a$.
- Run both ν & $\bar{\nu}$ modes @ first peak $[\phi_{31} = \frac{\pi}{2}, \phi_{21} = \alpha \frac{\pi}{2}]$,

$$P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e} + P_{\nu_\mu \rightarrow \nu_e} = 2 s_a^2 c_r^2 s_r^2,$$

$$P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e} - P_{\nu_\mu \rightarrow \nu_e} = \alpha \pi \sin(2\theta_s) \sin(2\theta_r) \sin(2\theta_a) \cos \theta_r \sin \delta_D.$$

The Dirac CP Phase δ_D @ Accelerator Exp

Accelerator experiment, such as **T2(H)K**, uses off-axis beam to compare ν_e & $\bar{\nu}_e$ appearance @ the oscillation maximum.

- **Disadvantages:**

- **Efficiency:**

- Proton accelerators produce ν more efficiently than $\bar{\nu}$ ($\sigma_\nu > \sigma_{\bar{\nu}}$).
 - The $\bar{\nu}$ mode needs more beam time [$\mathbf{T}_{\bar{\nu}} : \mathbf{T}_\nu = 2 : 1$].
 - Undercut statistics \Rightarrow Difficult to reduce the uncertainty.

- **Degeneracy:**

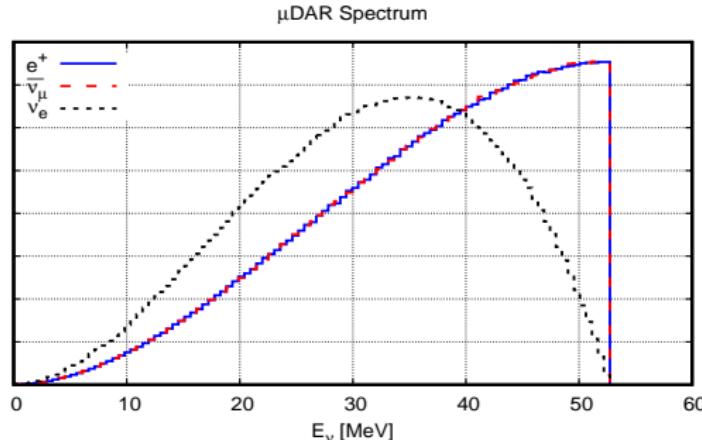
- Only $\sin \delta_D$ appears in $P_{\nu_\mu \rightarrow \nu_e}$ & $P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}$.
 - Cannot distinguish δ_D from $\pi - \delta_D$.
- **CP Uncertainty** $\frac{\partial P_{\mu e}}{\partial \delta_D} \propto \cos \delta_D \Rightarrow \Delta(\delta_D) \propto 1/\cos \delta_D$.

- **Solution:**

Measure $\bar{\nu}$ mode with μ^+ decay @ rest (μ DAR)

μ DAR $\bar{\nu}$ Oscillation Experiments

- A cyclotron produces 800 MeV proton beam @ fixed target.
- Produce π^\pm which stops &
 - π^- is absorbed,
 - π^+ decays @ rest: $\pi^+ \rightarrow \mu^+ + \nu_\mu$.
- μ^+ stops & decays @ rest: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$.



- $\bar{\nu}_\mu$ travel in all directions, oscillating as they go.
- A detector measures the $\bar{\nu}_e$ from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation.

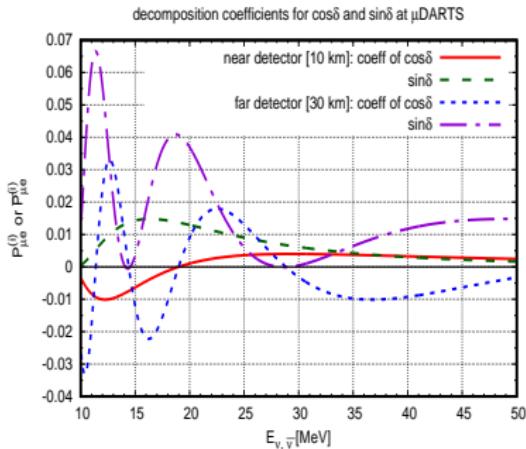
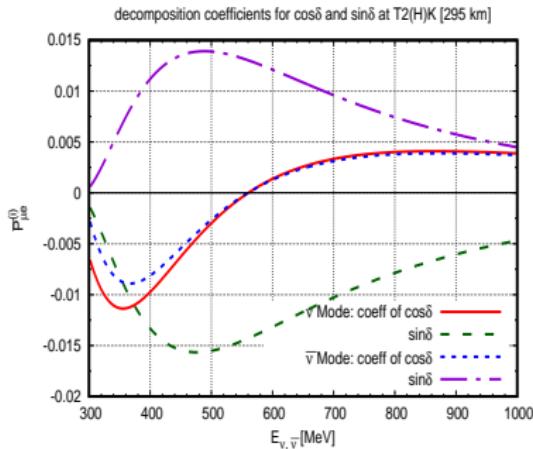
Accelerator + μ DAR Experiments

Combining $\nu_\mu \rightarrow \nu_e$ @ accelerator [narrow peak @ 550 MeV] & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ @ μ DAR [wide peak ~ 45 MeV] solves the 2 problems:

- **Efficiency:**

- $\bar{\nu}$ @ high intensity, μ DAR is plentiful enough.
- Accelerator Exps can devote all run time to the ν mode. With same run time, the statistical uncertainty drops by $\sqrt{3}$.

- **Degeneracy: (decomposition in propagation basis [1309.3176])**



DAE δ ALUS

- It's the **FIRST** proposal along this line:
 - 3 μ DAR with 3 high-intensity cyclotron complexes.
 - 1 detector.
 - Different baselines: **1.5, 8 & 20** km to break degeneracies.
- **Disadvantages:**
 - The final-state lepton from IBD @ low energy is **isotropic**.
 - **Cannot** distinguish $\overline{\nu}_e$ from different sources
 - Baseline **cannot be measured**.
 - Cyclotrons **cannot** run simultaneously (20~25% duty factor).
 - **Large** statistical uncertainty.
 - **Higher intensity** is necessary.
 - **Expensive** & Technically **challenging**.

New Proposals

1 μ DAR source + 2 detectors

Advantages

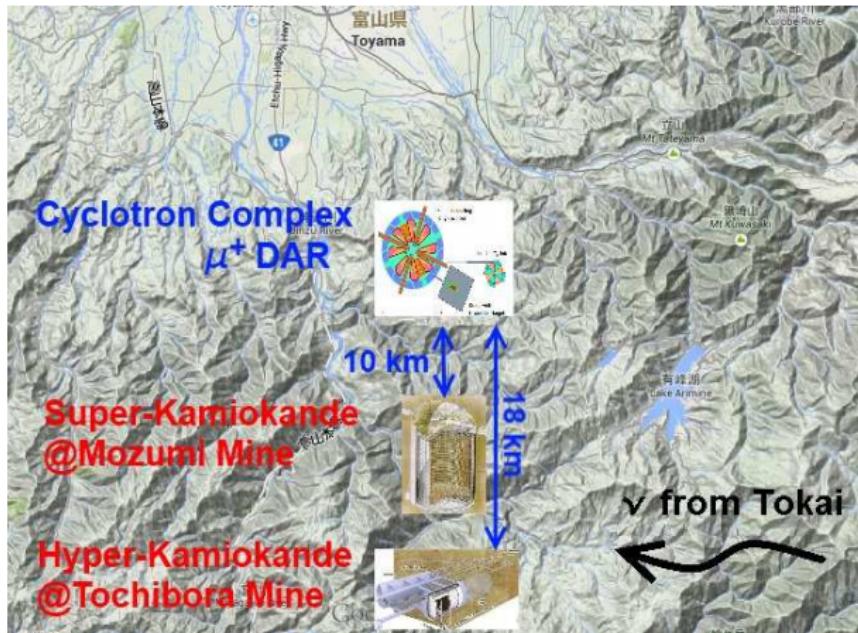
- Full (**100%**) duty factor!
- **Lower** intensity: $\sim 9\text{mA}$ [$\sim 4\times$ lower than DAE δ ALUS]
- Not far beyond the current state-of-art technology of cyclotron
[**2.2mA** @ Paul Scherrer Institute]
- MUCH **cheaper** & technically **easier**.
 - Only one cyclotron.
 - Lower intensity.

Disadvantage?

- A second detector!
 - **μ DAR** with Two Scintillators (**μ DARTS**) [Ciuffoli, Evslin & Zhang, 1401.3977] also Smirnov, Hu, Li & Ling [1802.03677, 1808.03795]
 - **Tokai 'N Toyama to(2) Kamioka (TNT2K)** [Evslin, Ge & Hagiwara, 1506.05023]

TNT2K

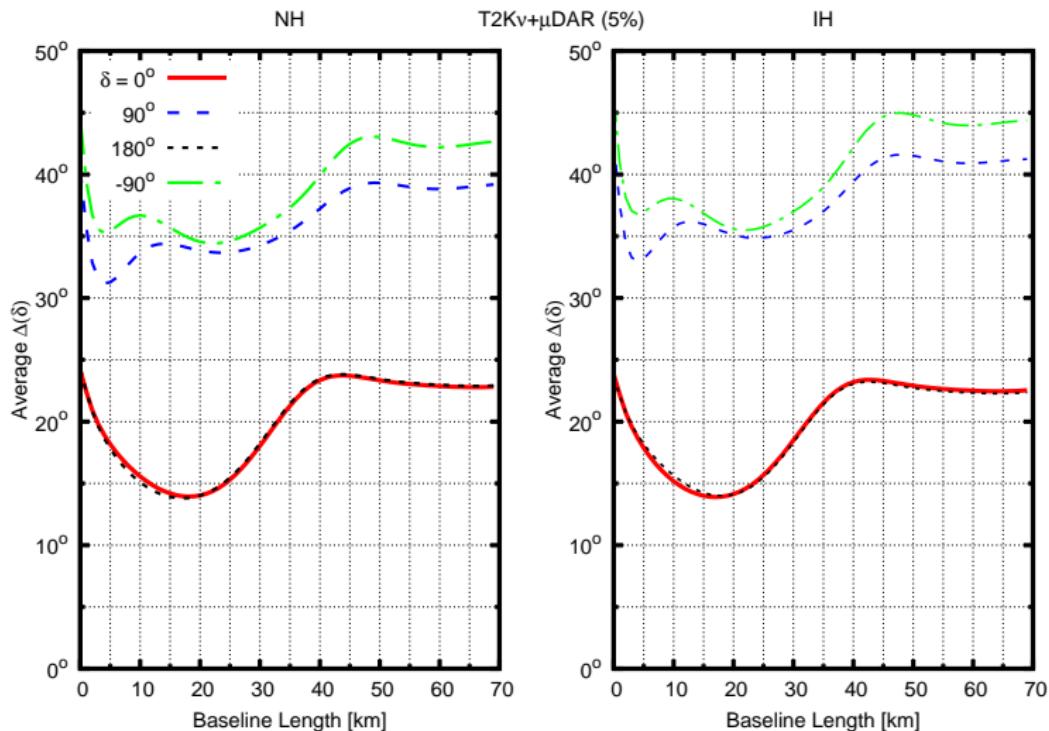
- T2(H)K + μ SK + μ HK



- μ DAR is also useful for **material, medicine** industries in Toyama

δ_D Precision @ TNT2K

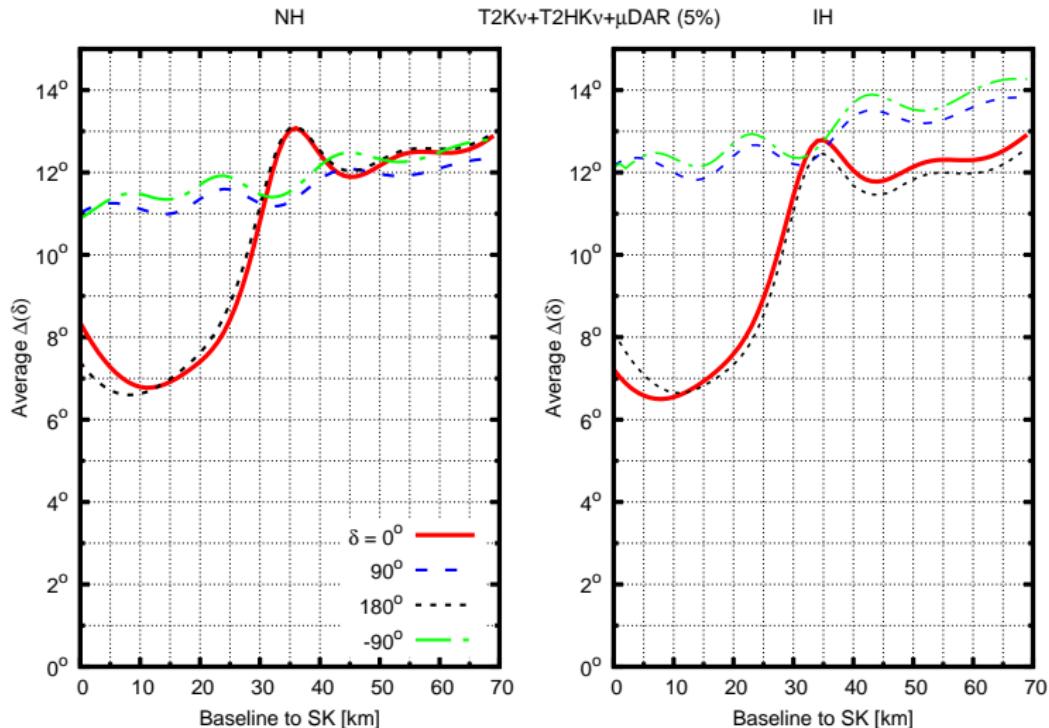
Evslin, Ge & Hagiwara [1506.05023]



Simulated by NuPro, <http://nupro.hepforge.org/>

δ_D Precision @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]



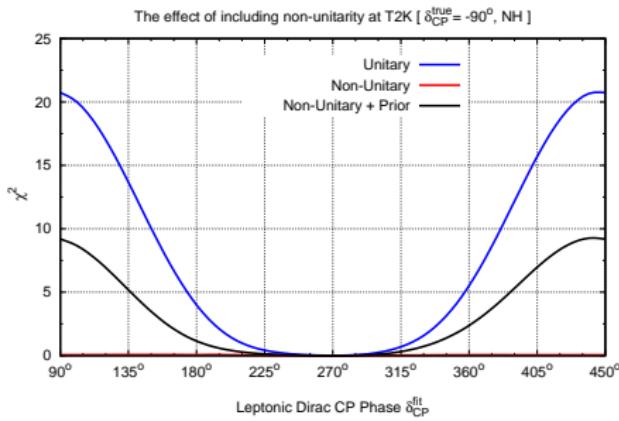
Simulated by NuPro, <http://nupro.hepforge.org/>

Non-Unitarity Mixing (NUM)

Ge, Pasquini, Tortola & Valle [1605.01670]

$$N = N^{NP} U = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ |\alpha_{21}| e^{i\phi} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U .$$

$$\begin{aligned} P_{\mu e}^{NP} = & \alpha_{11}^2 \left\{ \alpha_{22}^2 \left[c_a^2 |S'_{12}|^2 + s_a^2 |S'_{13}|^2 + 2c_a s_a (\cos \delta_D \mathbb{R} - \sin \delta_D \mathbb{I}) (S'_{12} S'^{*}_{13}) \right] + |\alpha_{21}|^2 P_{ee} \right. \\ & \left. + 2\alpha_{22}|\alpha_{21}| \left[c_a (c_\phi \mathbb{R} - s_\phi \mathbb{I}) (S'_{11} S'^{*}_{12}) + s_a (c_{\phi+\delta_D} \mathbb{R} - s_{\phi+\delta_D} \mathbb{I}) (S'_{11} S'^{*}_{13}) \right] \right\} . \end{aligned}$$



NUM vs Seesaw Mechanism

- Heavy neutrinos

$$\bar{\nu} M_D \mathcal{N} + h.c. + \overline{\mathcal{N}} M_N \mathcal{N} = \begin{pmatrix} \bar{\nu} & \overline{\mathcal{N}} \end{pmatrix} \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \begin{pmatrix} \nu \\ \mathcal{N} \end{pmatrix}$$

- Seesaw Mechanism

$$M_\nu = -M_D M_N^{-1} M_D^T, \quad \nu' = \nu + M_D M_N^{-1} \mathcal{N}$$

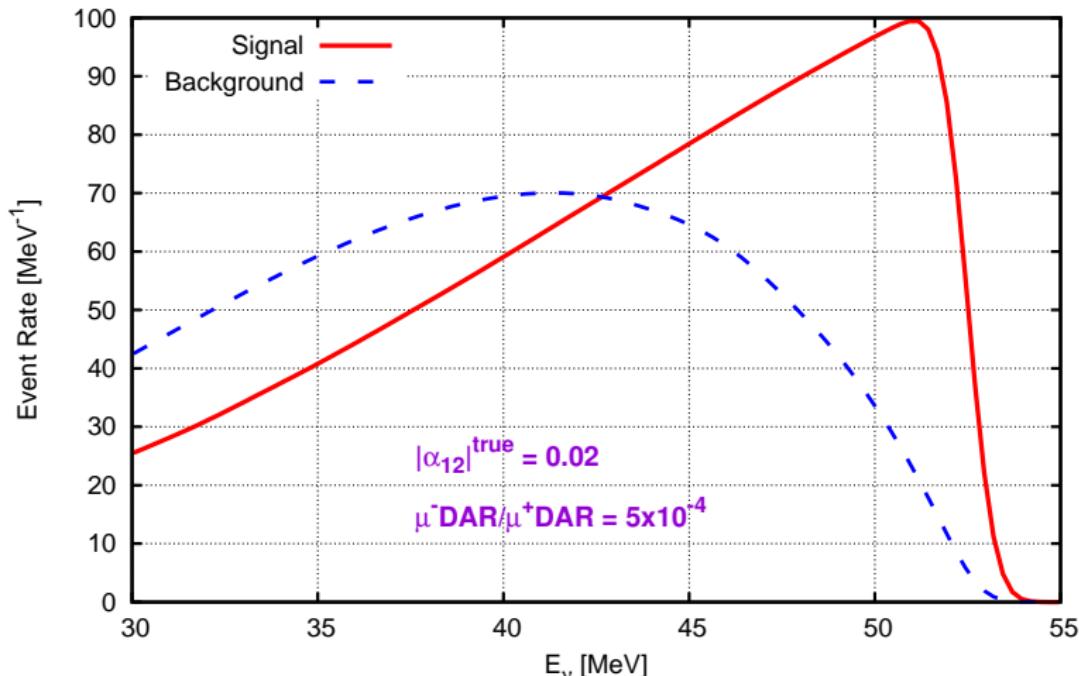


μ Near at μ DAR

Ge, Pasquini, Tortola & Valle [1605.01670]

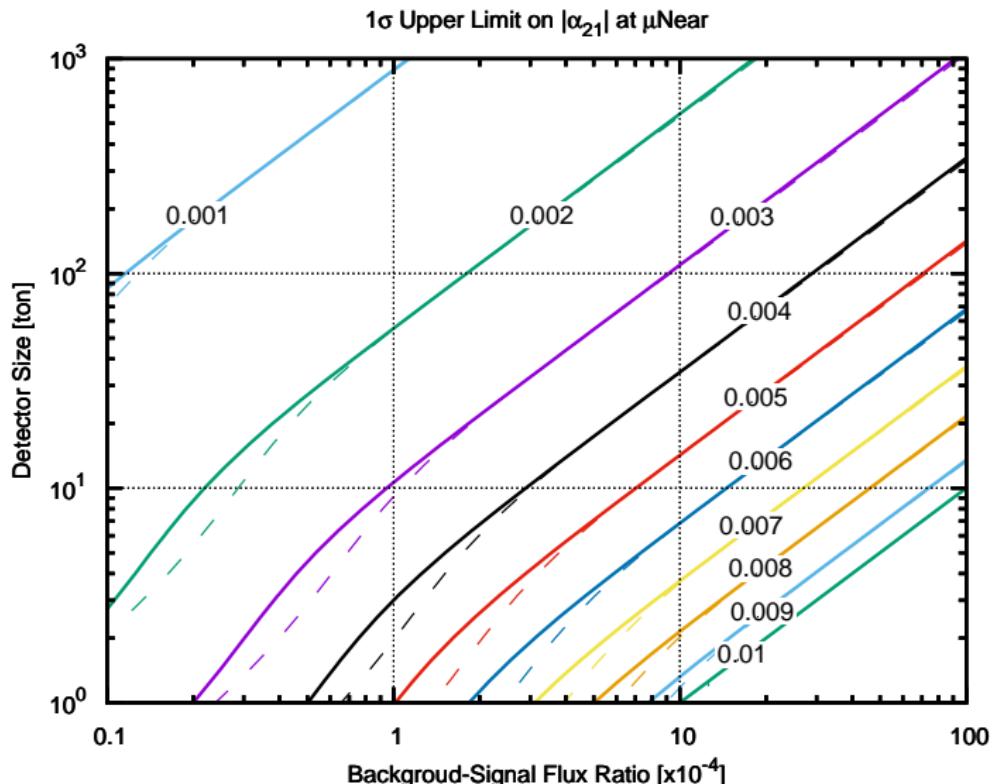
$$P_{\mu e}^{NP}(L \rightarrow 0) = \alpha_{11}^2 |\alpha_{21}|^2 P_{ee} \approx \alpha_{11}^2 |\alpha_{21}|^2 \approx |\alpha_{21}|^2$$

Event Spectrum at μ Near [20ton, L = 20m]



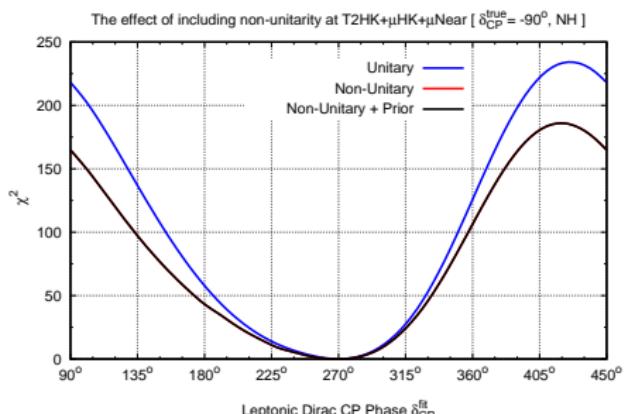
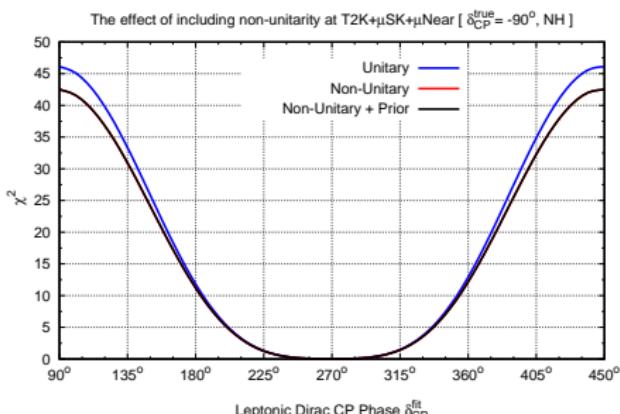
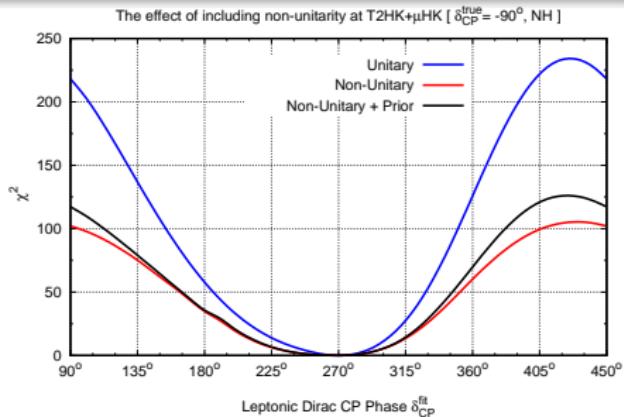
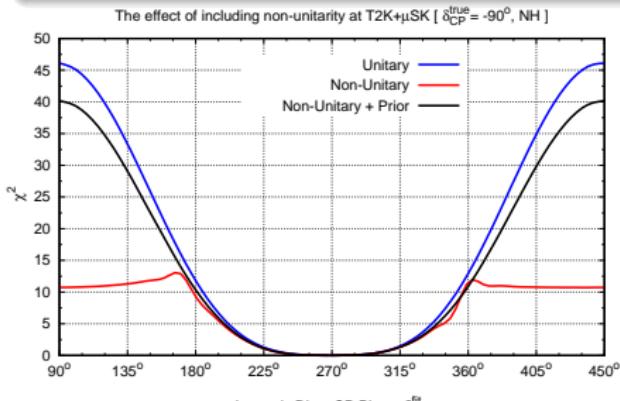
μ Near at μ DAR

Ge, Pasquini, Tortola & Valle [1605.01670]



TNT2K+ μ Near

Ge, Pasquini, Tortola & Valle [1605.01670]



Non-Standard Interaction

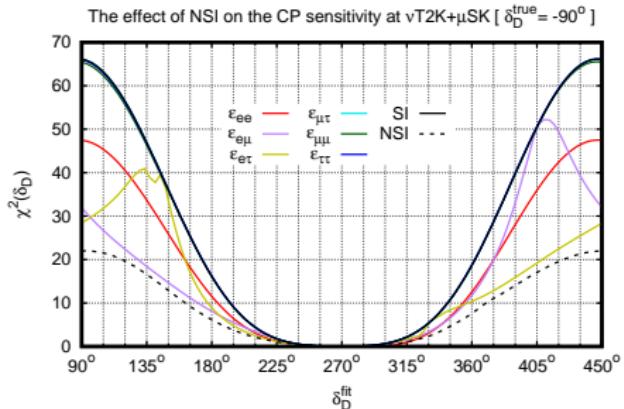
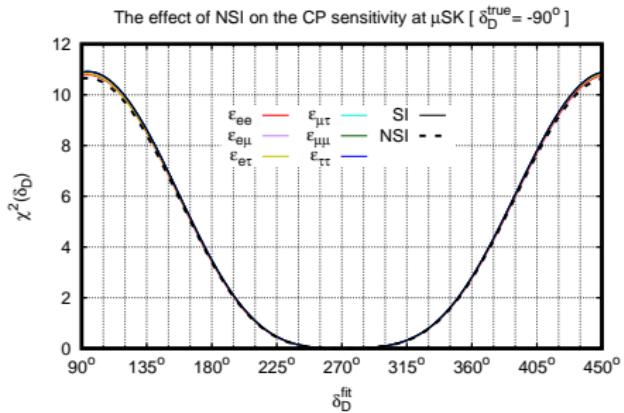
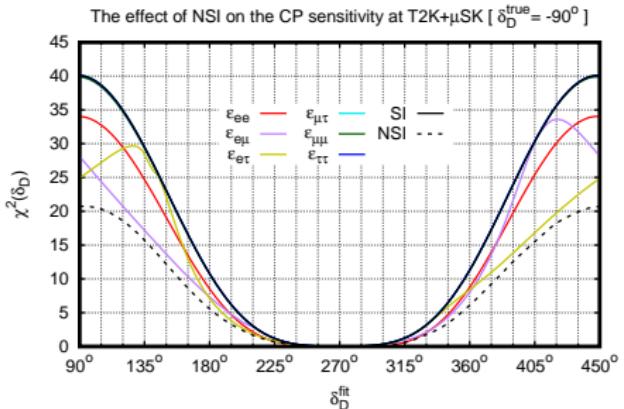
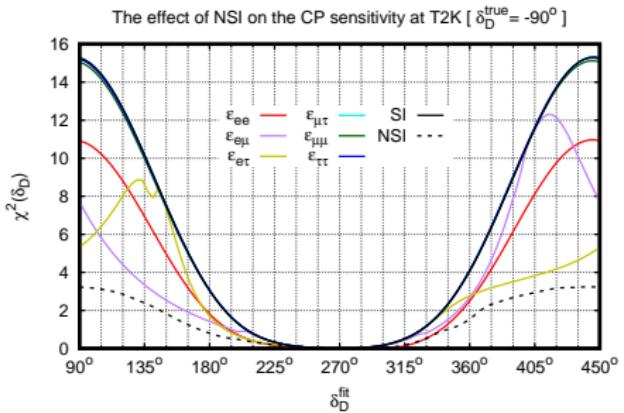
SFG & Alexei Smirnov [arXiv:1607.08513]

$$\mathcal{H} \equiv \frac{1}{2E_\nu} U \begin{pmatrix} 0 & & \\ & \Delta m_s^2 & \\ & & \Delta m_a^2 \end{pmatrix} U^\dagger + V_{cc} \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

- Standard Interaction – V_{cc} (also V_{nc})
- Non-Standard Interaction – $\epsilon_{\alpha\beta}$
 - Diagonal $\epsilon_{\alpha\alpha}$ are real
 - Off-diagonal $\epsilon_{\alpha\neq\beta}$ are complex
 - Both can fake CP
- Z' in LMA-Dark model with $L_\mu - L_\tau$ gauged as $U(1)$
 - $M_{Z'} \sim \mathcal{O}(10)\text{MeV}$
 - $g_{Z'} \sim 10^{-5}$

CP Sensitivity at T2K & μ SK

SFG & Alexei Smirnov [arXiv:1607.08513]



- **Vector NSI**

$$\mathcal{L}_{cc}^{\text{eff}} = \frac{g_{\alpha\rho} g_{\beta\sigma}^*}{2} \frac{1}{-m_V^2} (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta) (\bar{\ell}_\sigma \gamma^\mu P_L \ell_\rho) ,$$

which is **vector-vector type vertex**.

- **Scalar Mediator**

$$-\mathcal{L} = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} M_{\alpha\beta} \bar{\nu}_\alpha \nu_\beta + y_{\alpha\beta} \phi \bar{\nu}_\alpha \nu_\beta + Y_{\alpha\beta} \phi \bar{f}_\alpha f_\beta + h.c. ,$$

Due to **forward scattering**, the **effective Lagrangian** is

$$\mathcal{L}_{\text{eff}}^s \propto y_{\alpha\beta} Y_{ee} [\bar{\nu}_\alpha(p_3) \nu_\beta(p_2)] [\bar{e}(p_1) e(p_4)] ,$$

which is a **scalar-scalar type vertex** \Rightarrow **significant phenomenological consequences**.

EOM & Effective Hamiltonian with Scalar NSI

- Two-Point Correlation Function

$$\begin{aligned}\delta\Gamma_S &= \frac{y_{\alpha'\beta'}y_{ee}}{m_\phi^2} \langle \nu_\alpha | \bar{\nu}_{\alpha'} \nu_{\beta'} | \nu_\beta \rangle \langle e | \bar{e} e | e \rangle, \\ \delta\bar{\Gamma}_S &= \frac{y_{\beta'\alpha'}y_{ee}}{m_\phi^2} \langle \bar{\nu}_\alpha | \bar{\nu}_{\alpha'} \nu_{\beta'} | \bar{\nu}_\beta \rangle \langle e | \bar{e} e | e \rangle.\end{aligned}$$

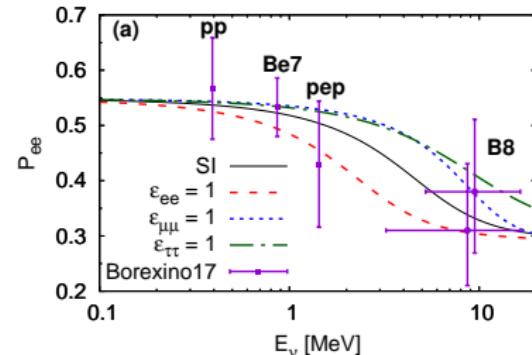
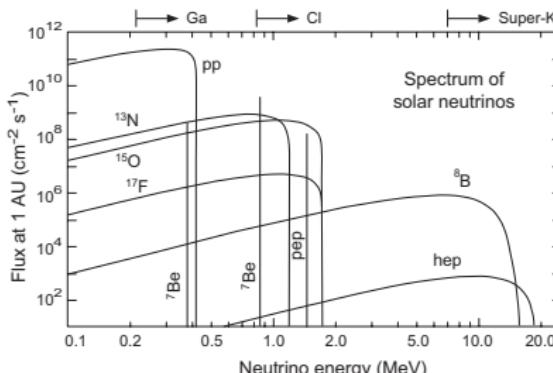
- Equation of Motion

$$\bar{\nu}_\beta \left[i\partial_\mu \gamma^\mu + \left(M_{\beta\alpha} + \frac{\mathbf{n}_e \mathbf{y}_e \mathbf{Y}_{\alpha\beta}}{\mathbf{m}_\phi^2} \right) \right] \nu_\alpha = 0,$$

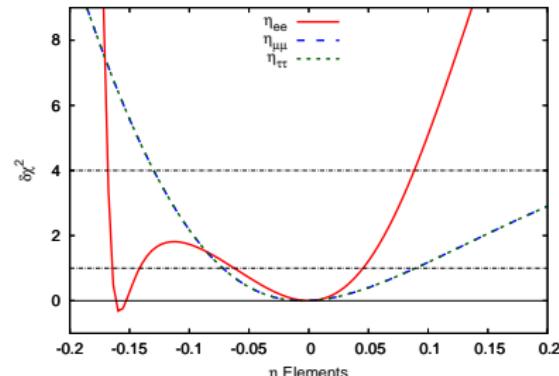
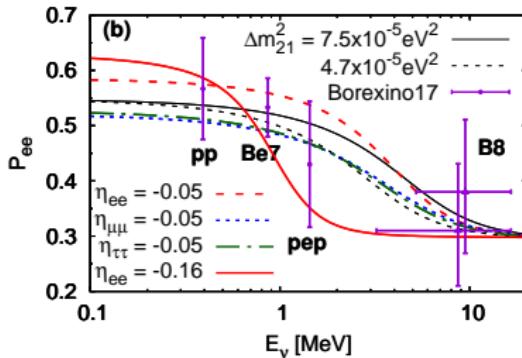
- Effective Hamiltonian

$$\mathcal{H} \approx E_\nu + \frac{(M + \mathbf{M}_S)(M + \mathbf{M}_S)^\dagger}{2E_\nu} \pm V_{SI},$$

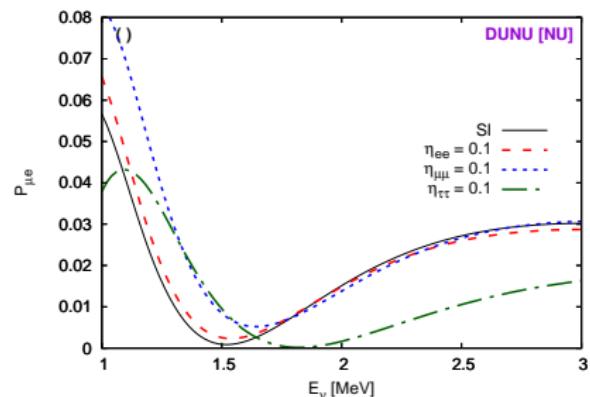
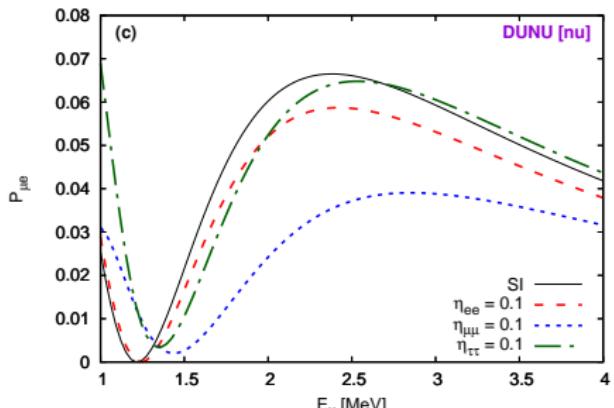
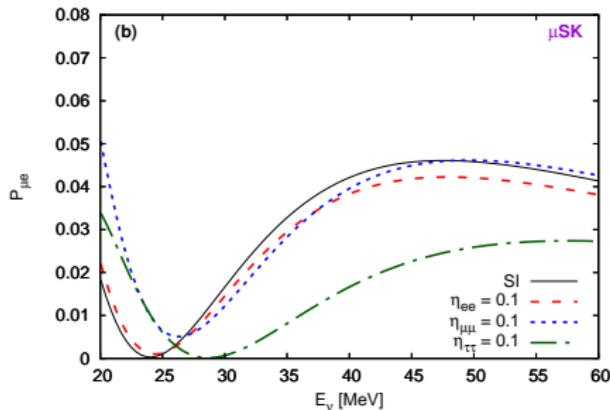
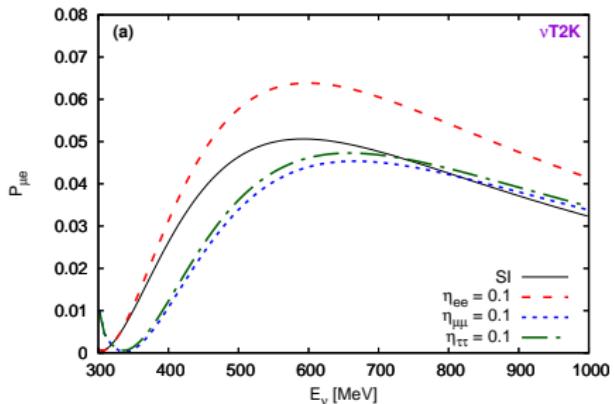
Solar Neutrino



$$P_{ee}^{\text{sun}} = \left| U_{ei}^{\text{prod}} (U_{ei}^{\text{vac}})^* \right|^2$$



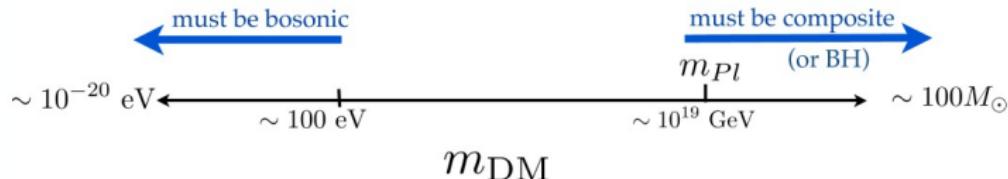
Scalar NSI @ Accelerator Neutrino Oscillation



Light Dark Matter

SFG, Hitoshi Murayama [arXiv:1904.02518]

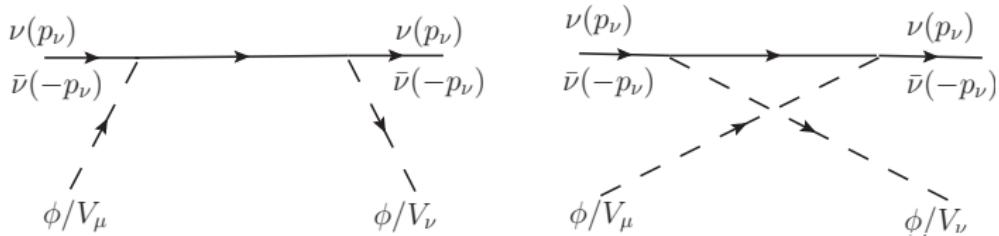
- The DM mass can span almost 100 orders



- For light bosonic DM

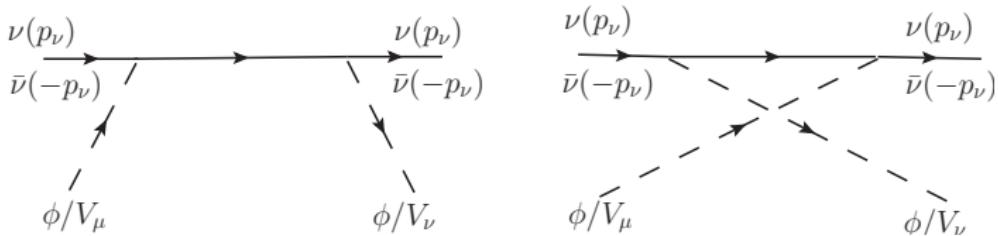
$$-\mathcal{L} = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} M_{\alpha\beta} \bar{\nu}_\alpha \nu_\beta + y_{\alpha\beta} \phi \bar{\nu}_\alpha \nu_\beta + h.c.,$$

leading to **forward scattering**



Effective Mass Correction from Dark Matter

- The **forward scattering** with the **DM background**



- modifies the neutrino **kinetic term**

$$i\delta\Gamma_{\alpha\beta} = \frac{i\rho_\phi(\mathbf{v}_\phi)}{m_\phi^2} \sum_j y_{\alpha j} y_{j\beta}^* \left[\frac{\not{p}_\nu + \not{\mathbf{p}}_\phi + m_\nu}{\not{p}_\phi^2 + 2\not{\mathbf{p}}_\nu \cdot \not{\mathbf{p}}_\phi} + \frac{\not{p}_\nu - \not{\mathbf{p}}_\phi + m_\nu}{\not{p}_\phi^2 - 2\not{\mathbf{p}}_\nu \cdot \not{\mathbf{p}}_\phi} \right]$$

with $\mathbf{p}_\phi \sim \mathbf{m}_\phi(1, \tilde{\mathbf{v}}_\phi)$, the correction

$$\delta\Gamma_{\alpha\beta} \approx \sum_j y_{\alpha j} y_{j\beta}^* \frac{\rho_\chi}{m_\phi^2 \mathbf{E}_\nu} \gamma_0$$

appears as **dark potential**.

SFG, Hitoshi Murayama [arXiv:1904.02518]

- The dark potential

$$\delta\Gamma_{\alpha\beta} \approx \sum_j y_{\alpha j} y_{j\beta}^* \frac{\rho_\chi}{m_\phi^2 E_\nu} \gamma_0$$

is a correction to the Hamiltonian, same as the matter potential.

- Due to $1/E_\nu$ dependence, the dark potential is promoted to mass correction

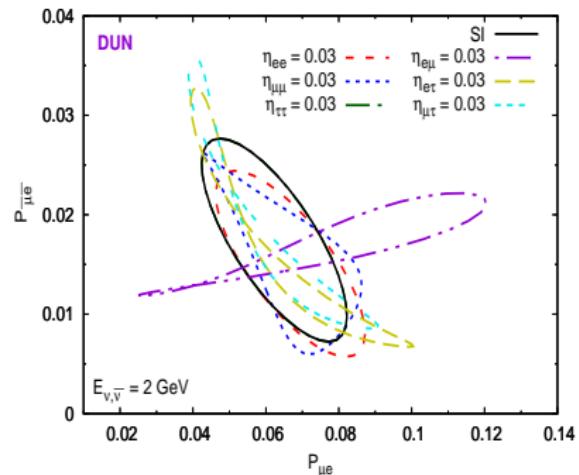
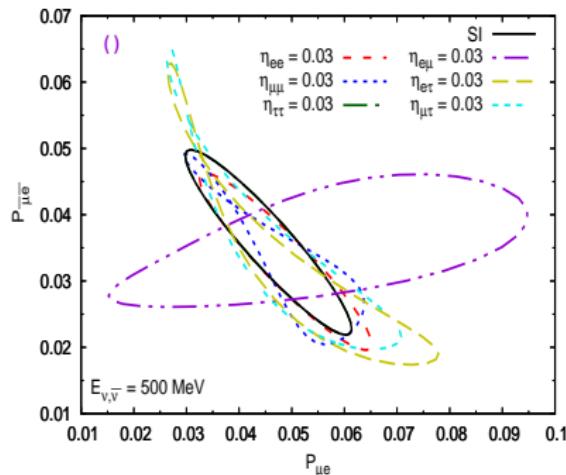
$$H = \frac{M^2}{2E_\nu} - \frac{1}{E_\nu} \sum_j y_{\alpha j} y_{j\beta}^* \frac{\rho_\chi}{m_\phi^2} \equiv \frac{M^2 + \delta M^2}{2E_\nu}$$

which is totally different from the scalar NSI.

- With mass term correction, any neutrino oscillation cannot see the original variables. Neutrino oscillation can happen even if the original mass term M^2 vanishes.

Dark NSI & Faked CP

- With just 3% of dark NSI



- The biprobability contour can totally change.

SFG, Hitoshi Murayama [arXiv:1904.02518]

Summary

- **Better CP measurement than T2K**

- Much larger event numbers
- Much better CP sensitivity around maximal CP
- Solve degeneracy between δ_D & $\pi - \delta_D$
- Guarantee CP sensitivity against NUM
- Guarantee CP sensitivity against NSI (vector, scalar, dark)

- **Better configuration than DAE δ ALUS**

- Only one cyclotron
- 100% duty factor
- Much lower flux intensity
- Much easier
- Much cheaper
- Single near detector

Thank You!

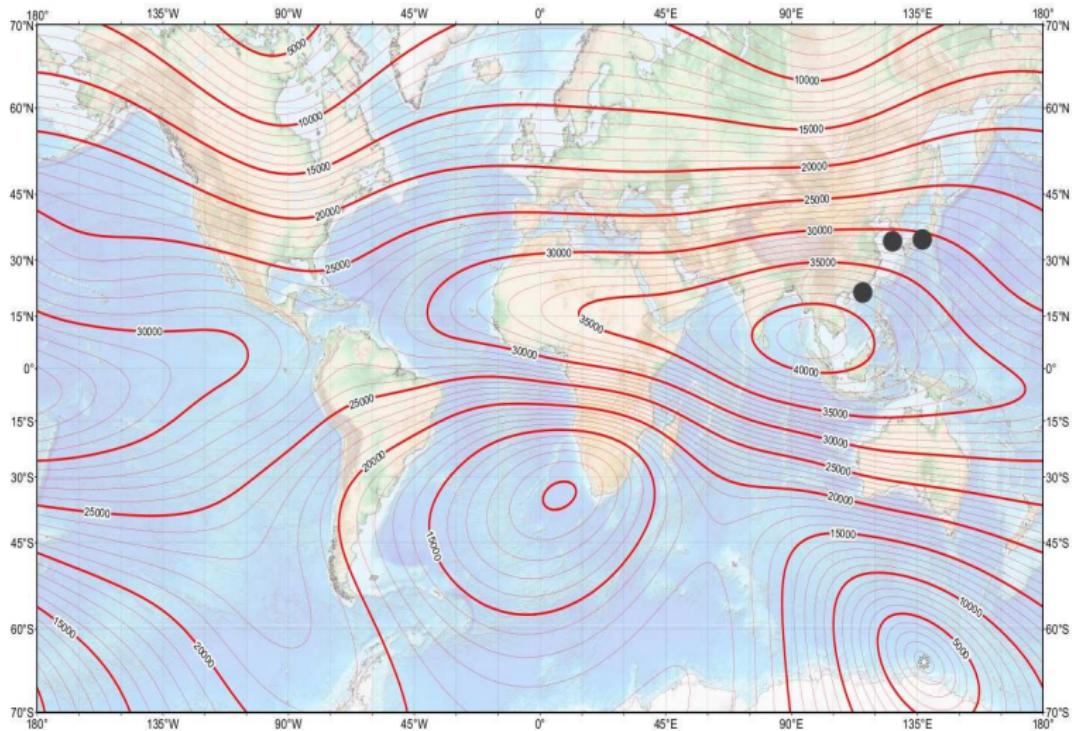
ν Oscillation Data

(for NH)	-1σ	Best Value	$+1\sigma$
$\Delta m_s^2 \equiv \Delta m_{12}^2$ (10^{-5} eV 2)	7.37	7.56	7.75
$ \Delta m_a^2 \equiv \Delta m_{13}^2$ (10^{-3} eV 2)	2.51	2.55	2.59
$\sin^2 \theta_s$ ($\theta_s \equiv \theta_{12}$)	0.305 (33.5°)	0.321 (34.5°)	0.339 (35.6°)
$\sin^2 \theta_a$ ($\theta_a \equiv \theta_{23}$)	0.412 (39.9°)	0.430 (41.0°)	0.450 (42.1°)
$\sin^2 \theta_r$ ($\theta_r \equiv \theta_{13}$)	0.02080 (8.29°)	0.02155 (8.44°)	0.02245 (8.62°)
δ_D, δ_{Mi}	?, ??	?, ??	?, ??

Salas, Forero, Ternes, Tortola & Valle, arXiv:1708.01186

Lowest Atmospheric Neutrino Background

US/UK World Magnetic Model -- Epoch 2010.0
Main Field Horizontal Intensity (H)



Backgrounds to IBD ($\bar{\nu}_e + p \rightarrow e^+ + n$)

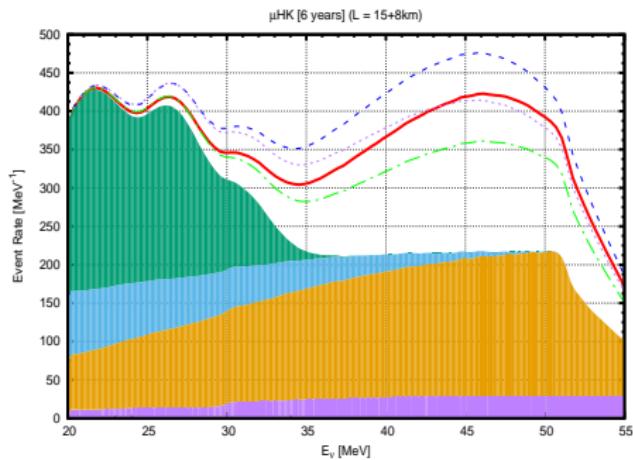
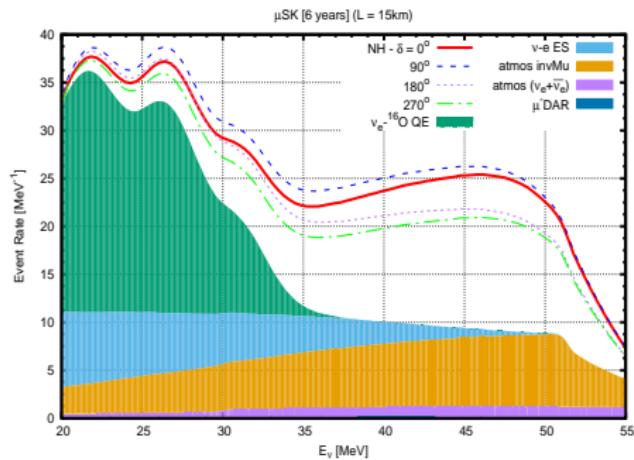
- Reactor $\bar{\nu}_e$: $E_\nu < 10$ MeV
- Accelerator ν_e : $E_\nu > 100$ MeV
- Spallation: $E_\nu \lesssim 20$ MeV
- Supernova Relic Neutrino: $E_\nu \lesssim 20$ MeV

Cut with $30 \text{ MeV} < E_\nu < 55 \text{ MeV}$

- Accelerator $\nu_\mu \rightarrow$ **Invisible muon**
- Atmospheric Neutrino Background
 - **Invisible muon** (below Cherenkov limit)
 - $E_\mu \lesssim 1.5 \times m_\mu$, $\mu^\pm \rightarrow e^\pm$
 - $E_\pi \lesssim 1.5 \times m_\pi$, $\pi^+ \rightarrow \mu^+ \rightarrow e^+$
 - **1 neutron**
 - **No prompt photon**
 - Irreducible $\bar{\nu}_e$: $30 \text{ MeV} \lesssim E_\nu \lesssim 55 \text{ MeV}$
 - Reducible ν_e : $60 \text{ MeV} \lesssim E_\nu \lesssim 100 \text{ MeV}$
 - **1 neutron**
 - **No prompt photon**
 - **Lowest** at μ DARTS & TNT2K sites

Event Shape @ TNT2K

Evselin, Ge & Hagiwara [1506.05023]

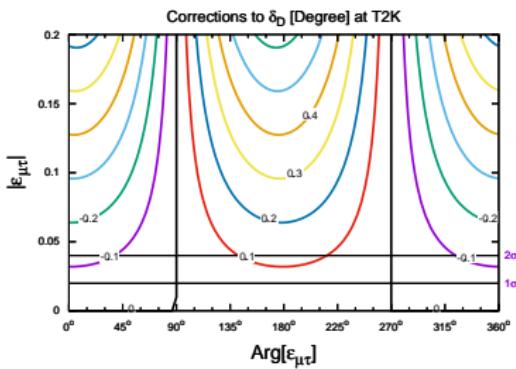
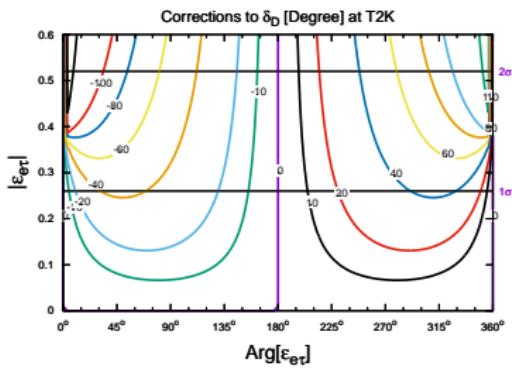
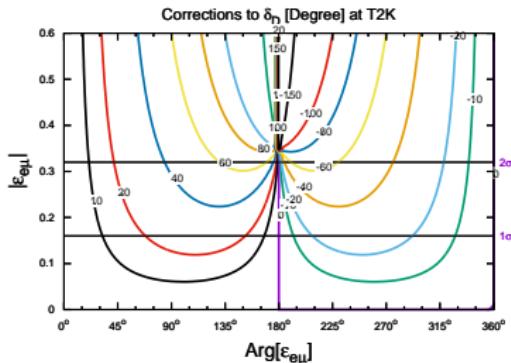
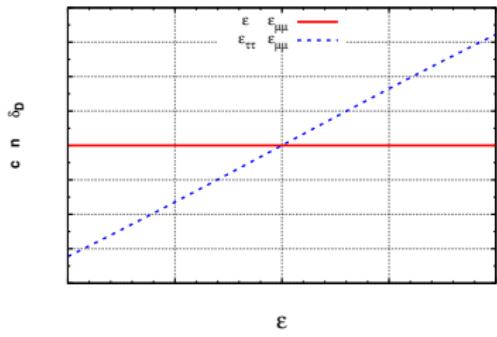


Expected μ DAR IBD signal from 6 yrs of running @ SK (15km) & HK (23km) with NH.

Simulated by NuPro, <http://nupro.hepforge.org/>

Faked CP with NSI

SFG & Alexei Smirnov [arXiv:1607.08513]



Mass Scale & Unphysical CP Phases in Oscillation

- The **effective mass term** is a combination

$$\mathbf{M}\mathbf{M}^\dagger \rightarrow (\mathbf{M} + \mathbf{M}_S)(\mathbf{M} + \mathbf{M}_S)^\dagger = \mathbf{M}\mathbf{M}^\dagger + \mathbf{M}\mathbf{M}_S^\dagger + \mathbf{M}_S\mathbf{M}^\dagger + \mathbf{M}_S\mathbf{M}_S^\dagger$$

- The **absolute neutrino mass** can enter neutrino oscillation!

$$\mathbf{M}\mathbf{M}_S^\dagger + \mathbf{M}_S\mathbf{M}^\dagger$$

- The **unphysical CP phases** can also enter neutrino oscillation!

$$M \equiv R_\nu D_\nu R_\nu^\dagger \quad \& \quad R_\nu \equiv P_\nu U_\nu Q_\nu$$

The **Majorana rephasing matrix** $Q_\nu = \{e^{i\delta_{M1}/2}, 1, e^{i\delta_{M3}/2}\}$ can be absorbed, $Q_\nu D_\nu Q_\nu^\dagger = D_\nu$ while the **unphysical rephasing matrix** $P_\nu \equiv \{e^{i\alpha}, e^{i\beta}, e^{i\gamma}\}$ can not be simply rotated away now:

$$M \rightarrow \widetilde{\mathbf{M}} = \mathbf{U}_\nu \mathbf{D}_\nu \mathbf{U}_\nu^\dagger, \quad M_S \rightarrow \widetilde{\mathbf{M}}_S = \mathbf{P}_\nu^\dagger \mathbf{M}_S \mathbf{P}_\nu$$

Parametrization & Constant Density Subtraction

- Use characteristic scale Δm_a^2 to parametrize scalar NSI

$$\tilde{\mathbf{M}}_S \equiv \sqrt{\Delta m_a^2} \begin{pmatrix} \eta_{ee} & \eta_{\mu e}^* & \eta_{\tau e}^* \\ \eta_{\mu e} & \eta_{\mu \mu} & \eta_{\tau \mu}^* \\ \eta_{\tau e} & \eta_{\tau \mu} & \eta_{\tau \tau} \end{pmatrix},$$

where $\Delta m_a^2 \equiv \Delta m_{31}^2 = 2.7 \times 10^{-3} \text{ eV}^2$.

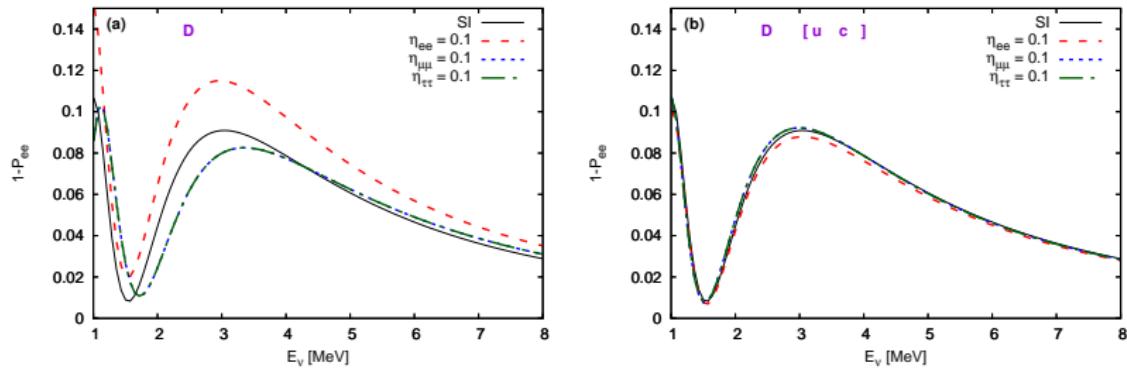
- We first need **input** for $\tilde{\mathbf{M}}$ which is not directly measured.
- However, the directly measured from terrestrial experiments is always a combination, $\tilde{\mathbf{M}} + \tilde{\mathbf{M}}_S (\rho_s \approx 3 \text{ g/cm}^3)$. It is then necessary to first subtract a constant term:

$$\tilde{\mathbf{M}} \rightarrow \tilde{\mathbf{M}} + \tilde{\mathbf{M}}_S \frac{\rho - \rho_s}{\rho_s}$$

where $\tilde{\mathbf{M}} = \mathbf{U}_\nu \mathbf{D}_\nu \mathbf{U}_\nu^\dagger$ is **reconstructed** in terms of the measured mixing matrix while $\tilde{\mathbf{M}}_S$ is the scalar NSI @ typical constant **subtraction density ρ_s** .

Density Subtraction for Reactor Anti-Neutrinos

- Since the reactor anti-neutrino experiments (**Daya Bay & JUNO**) are the most precise ones, we do subtraction according to them:



$$\tilde{M} \rightarrow \tilde{M} + \tilde{\mathbf{M}}_S \frac{\rho - \rho_s}{\rho_s}$$

- Then **no constraint** on **scalar NSI** from reactor experiments!

Scalar NSI @ Atmospheric Neutrino Oscillation

