Leptonic CP Phase Measurement & New Physics

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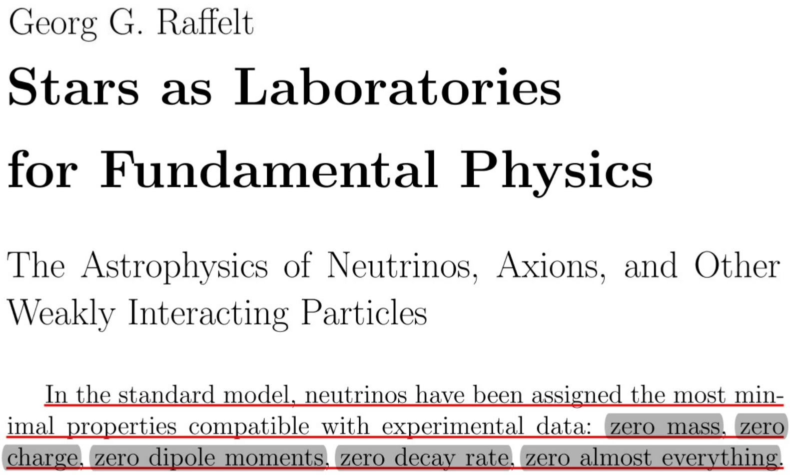
Jarah Evslin, **SFG**, Kaoru Hagiwara, JHEP **1602** (2016) 137 [arXiv:1506.05023]
SFG, Pedro Pasquini, M. Tortola, J. W. F. Valle, PRD **95** (2017) No.3, 033005 [arXiv:1605.01670]
SFG, Alexei Smirnov, JHEP **1610** (2016) 138 [arXiv:1607.08513]
SFG [arXiv:1704.08518]
SFG, Stephen Parke [arXiv:1812.08376]

Minimal Neutrinos



Georg G. Raffelt

Stars as Laboratories for Fundamental Physics

The Astrophysics of Neutrinos, Axions, and Other Weakly Interacting Particles

In the standard model, neutrinos have been assigned the most minimal properties compatible with experimental data: zero mass, zero charge, zero dipole moments, zero decay rate, zero almost everything.

Neutrinos are not just invisible but very boring!

Lazy Neutrino

Nothing can interest me!!!

Why neutrino mass & oscillation?

- **Higgs boson** ⇒ electroweak symmetry breaking & mass.
- **Chiral symmetry breaking** ⇒ majority of mass.
- **The world seems not affected by the tiny neutrino mass?**
  - Neutrino mass ⇒ Mixing
  - 3 Neutrino ⇒ possible **CP violation**
  - CP violation ⇒ **Leptogenesis**
  - **Leptogenesis** ⇒ **Matter-Antimatter Asymmetry**
  - There is something left in the Universe.
  - Baryogenesis from quark mixing is not enough.
- Majorana ν ⇔ **Lepton Number Violation**
- **Residual $\mathbb{Z}_2$ Symmetries:** $\cos\delta_{\mathbf{D}} = \frac{(s_s^2 - c_s^2 s_r^2)(\mathbf{c}_{\mathbf{a}}^2 - \mathbf{s}_{\mathbf{a}}^2)}{4 c_a s_a c_s s_s \mathbf{s}_{\mathbf{r}}}$ 1108.0964 1104.0602

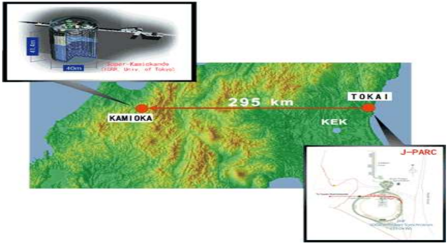
ν Oscillation Data

(for NH)	-1σ	Best Value	$+1\sigma$
$\mathbf{\Delta m_s^2} \equiv \Delta m_{12}^2\,(\mathbf{10^{-5}}\mathrm{eV}^{\mathbf{2}})$	7.37	**7.56**	7.75
$\left\lvert \mathbf{\Delta m_a^2} \equiv \Delta m_{13}^2 \right\rvert\ (\mathbf{10^{-3}}\mathrm{eV}^{\mathbf{2}})$	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

CP Measurement @ Accelerator Exps

- T2K



- NOνA

- DUNE/T2KII/T2HK/T2HKK/T2KO; MOMENT/ADS-CI/DAEδALUS; Super-PINGU

The Dirac CP Phase δ_D @ Accelerator Exp

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

$$
\begin{aligned}
P_{\substack{\nu_\mu \to \nu_e \\ \overline{\nu}_\mu \to \overline{\nu}_e}} \approx\, & 4 s_a^2 c_r^2 s_r^2 \sin^2 \phi_{31} \\
& - 8 c_a s_a c_r^2 s_r c_s s_s \sin \phi_{21} \sin \phi_{31} \left[\cos \delta_D \cos \phi_{31} \pm \sin \delta_D \sin \phi_{31} \right]
\end{aligned}
$$

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

- $\nu_\mu \to \nu_\mu$ Exps measure $\sin^2(2\theta_a)$ precisely, but not $\sin^2 \theta_a$.

- Run both ν & $\overline{\nu}$ modes @ first peak $[\phi_{31} = \frac{\pi}{2}, \phi_{21} = \alpha \frac{\pi}{2}]$,

$$
\begin{aligned}
P_{\overline{\nu}_\mu \to \overline{\nu}_e} + P_{\nu_\mu \to \nu_e} &= 2 s_a^2 c_r^2 s_r^2 \,, \\
P_{\overline{\nu}_\mu \to \overline{\nu}_e} - P_{\nu_\mu \to \nu_e} &= \alpha \pi \sin(2\theta_s) \sin(2\theta_r) \sin(2\theta_a) \cos \theta_r \sin \delta_D \,.
\end{aligned}
$$

The Dirac CP Phase δ_D @ Accelerator Exp

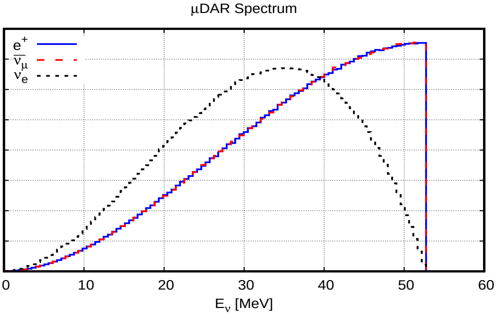
Accelerator experiment, such as **T2(H)K**, uses off-axis beam to compare ν_e & $\overline{\nu}_e$ appearance @ the oscillation maximum.

- **Disadvantages**:
  - **Efficiency**:
    - Proton accelerators produce ν more efficiently than $\overline{\nu}$ $(\sigma_\nu > \sigma_{\overline{\nu}})$.
    - The $\overline{\nu}$ mode needs more beam time $[\mathbf{T}_{\overline{\nu}} : \mathbf{T}_\nu = \mathbf{2} : \mathbf{1}]$.
    - Undercut statistics ⇒ Difficult to reduce the uncertainty.
  - **Degeneracy**:
    - Only $\sin \boldsymbol{\delta}_{\mathbf{D}}$ appears in $P_{\nu_\mu \to \nu_e}$ & $P_{\overline{\nu}_\mu \to \overline{\nu}_e}$.
    - Cannot distinguish $\boldsymbol{\delta}_{\mathbf{D}}$ from $\boldsymbol{\pi} - \boldsymbol{\delta}_{\mathbf{D}}$.
  - **CP Uncertainty** $\frac{\partial P_{\mu e}}{\partial \delta_D} \propto \cos \delta_D \Rightarrow \Delta(\delta_D) \propto \mathbf{1}/\cos \boldsymbol{\delta}_{\mathbf{D}}$.
- **Solution**:

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

μDAR $\bar{\nu}$ Oscillation Experiments

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

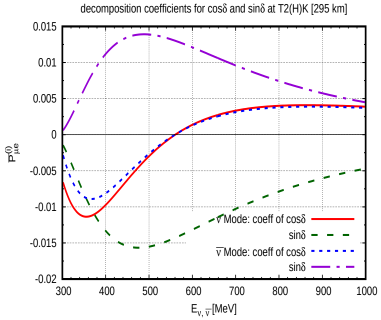


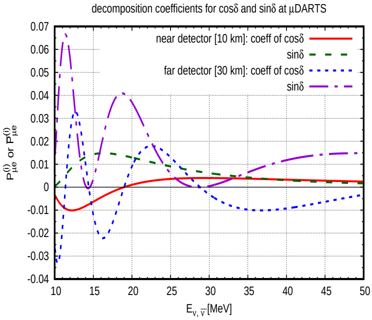
- $\overline{\nu}_{\mu}$ travel in all directions, oscillating as they go.
- A detector measures the $\overline{\nu}_{e}$ from $\boldsymbol{\overline{\nu}_{\mu} \to \overline{\nu}_{e}}$ **oscillation**.

Accelerator + μDAR Experiments

Combining $\nu_\mu \to \nu_e$ **@ accelerator** [narrow **peak @ 550 MeV**] & $\overline{\nu}_\mu \to \overline{\nu}_e$ **@ μDAR** [wide **peak $\sim$ 45 MeV**] solves the 2 problems:

- **Efficiency**:
  - $\overline{\nu}$ @ high intensity, μDAR 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])


decomposition coefficients for cosδ and sinδ at T2(H)K [295 km]


decomposition coefficients for cosδ and sinδ at μDARTS

DAEδALUS

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

New Proposals

1 μDAR source + **2** detectors

Advantages

- Full (**100%**) duty factor!
- **Lower** intensity: $\sim$ **9mA** [$\sim$ **4**$\times$ lower than DAEδALUS]
- 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!
  - **μDAR** with **T**wo **S**cintillators (**μDARTS**) [Ciuffoli, Evslin & Zhang, 1401.3977] also Smirnov, Hu, Li & Ling [1802.03677, 1808.03795]
  - **T**okai '**N** **T**oyama to(**2**) **K**amioka (**TNT2K**) [Evslin, Ge & Hagiwara, 1506.05023]

μDARTS – JUNO & RENO50

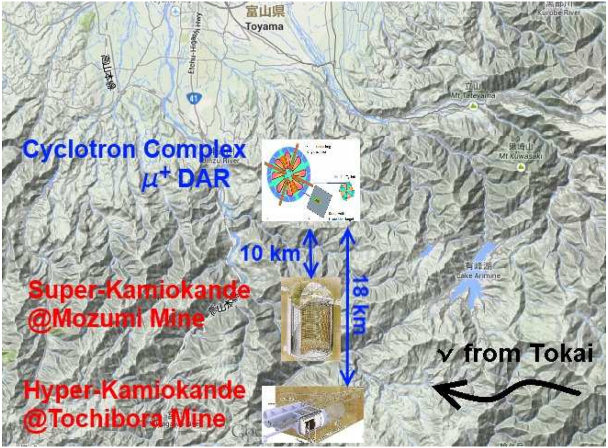
- **Two detectors** are suggested to overcome the **unknown energy response**. [Ciuffoli et al., PRD 2014; 1307.7419]

See also Smirnov, Hu, Li & Ling [1802.03677, 1808.03795]

- China Atomic Energy Center is proposing a cyclotron.

TNT2K

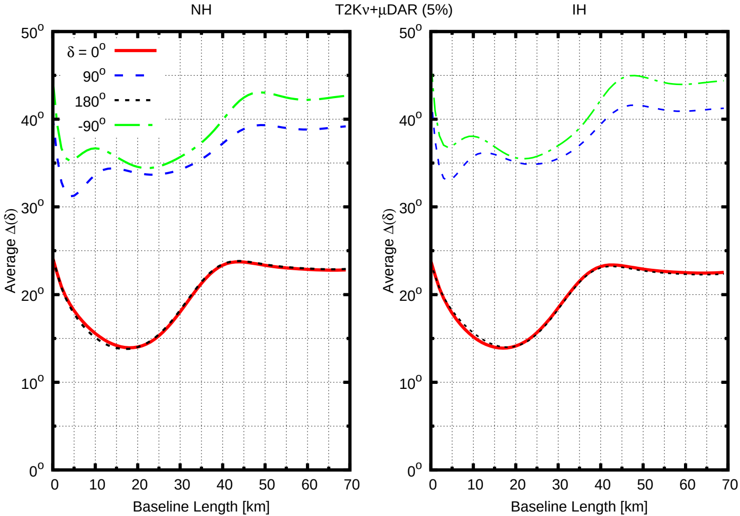
- T2(H)K + μSK + μHK



- μDAR 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

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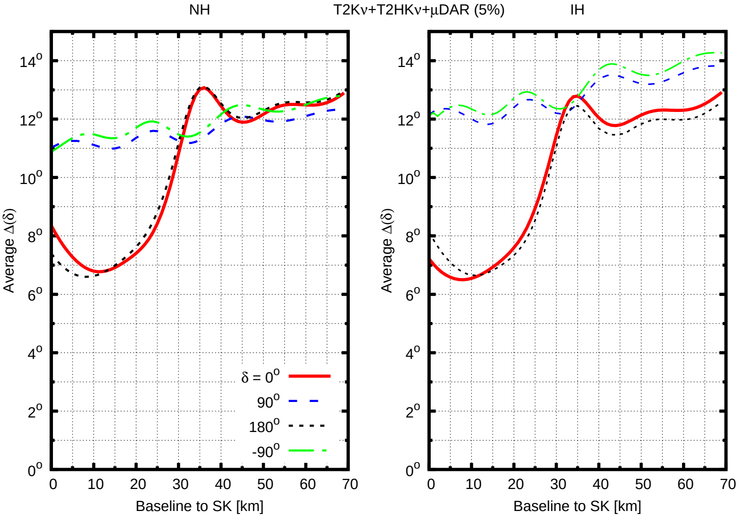


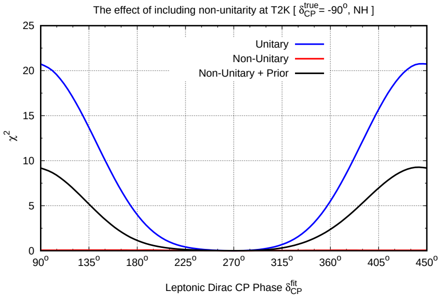
Simulated by **NuPro**, http://nupro.hepforge.org/

Non-Unitarity Mixing (NUM)

Ge, Pasquini, Tortola & Valle [1605.01670]

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

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



NUM vs Seesaw Mechanism

- **Heavy neutrinos**

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

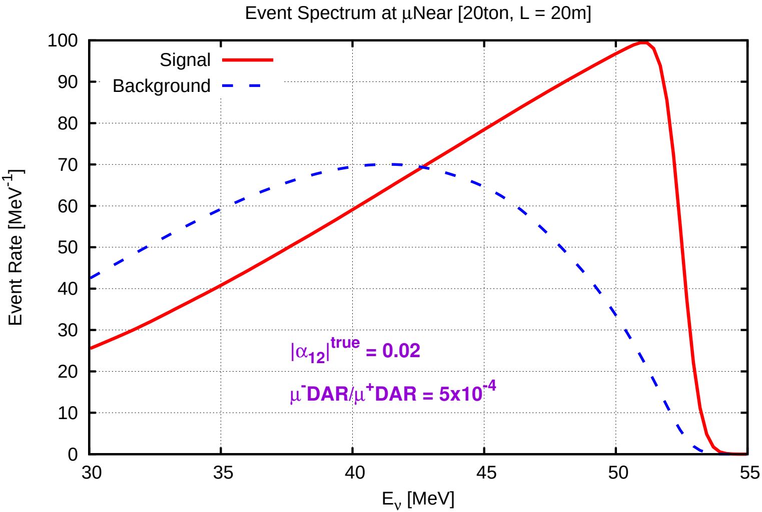
- **Seeaw Mechanism**

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

μNear at μDAR

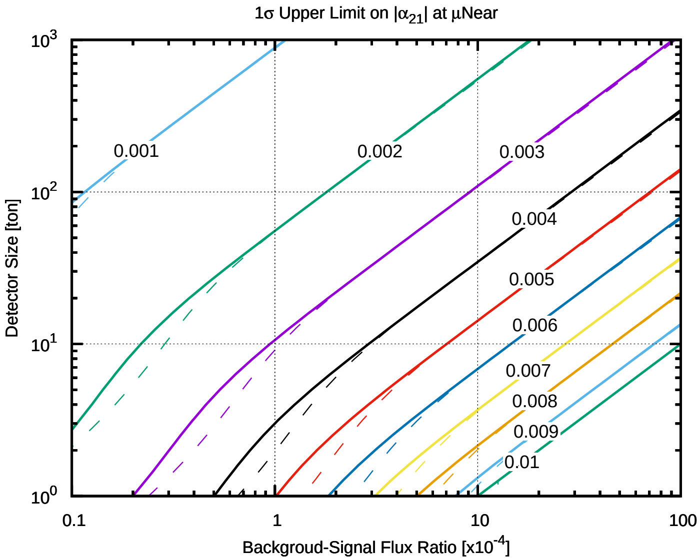
Ge, Pasquini, Tortola & Valle [1605.01670]

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



μNear at μDAR

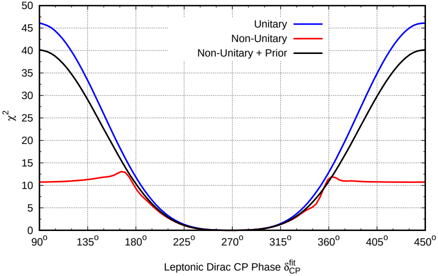
Ge, Pasquini, Tortola & Valle [1605.01670]



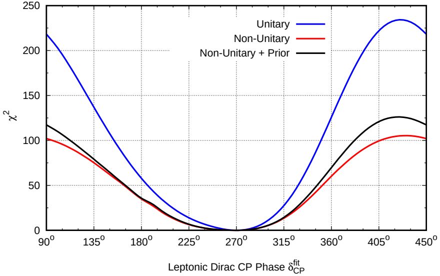
TNT2K+μNear

Ge, Pasquini, Tortola & Valle [1605.01670]

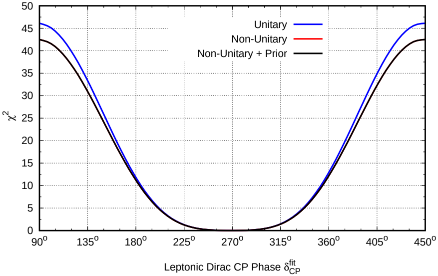
The effect of including non-unitarity at T2K+μSK [δ_{CP}^{true}= -90°, NH]



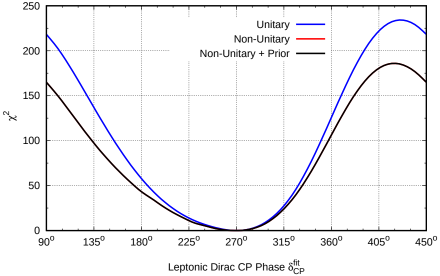
The effect of including non-unitarity at T2HK+μHK [δ_{CP}^{true}= -90°, NH]



The effect of including non-unitarity at T2K+μSK+μNear [δ_{CP}^{true}= -90°, NH]



The effect of including non-unitarity at T2HK+μHK+μNear [δ_{CP}^{true}= -90°, NH]



Non-Standard Interaction

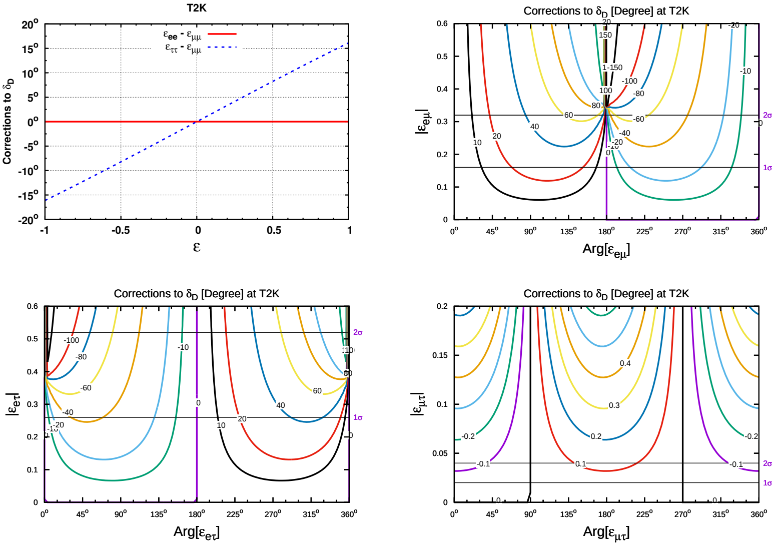
SFG & Alexei Smirnov [arXiv:1607.08513]

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

- 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 $U(1)$
  - $M_{Z'} \sim \mathcal{O}(10)$MeV
  - $g_{Z'} \sim 10^{-5}$

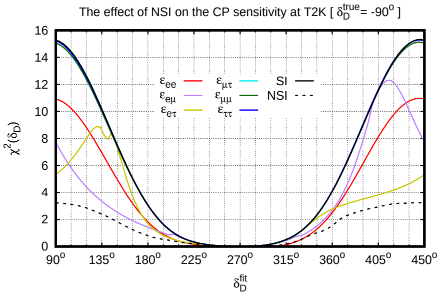
Faked CP with NSI

SFG & Alexei Smirnov [arXiv:1607.08513]

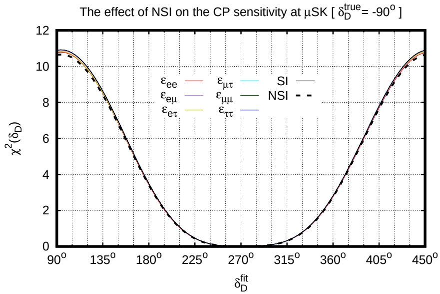


CP Sensitivity at T2K & μSK

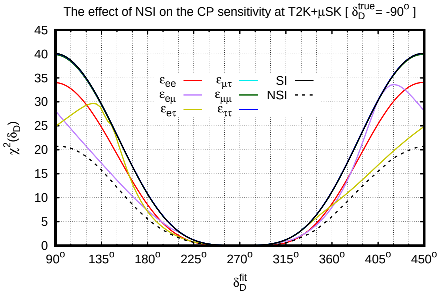
SFG & Alexei Smirnov [arXiv:1607.08513]



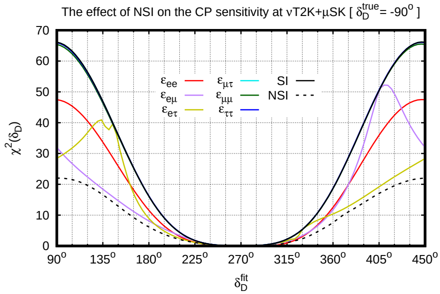
The effect of NSI on the CP sensitivity at T2K [δ_D^{true}= -90^o]



The effect of NSI on the CP sensitivity at μSK [δ_D^{true}= -90^o]



The effect of NSI on the CP sensitivity at T2K+μSK [δ_D^{true}= -90^o]



The effect of NSI on the CP sensitivity at νT2K+μSK [δ_D^{true}= -90^o]

Scalar NSI

SFG & Stephen Parke [1812.08376]

- Vector NSI

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

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

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

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

EOM & Effective Hamiltonian with Scalar NSI

- **Two-Point Correlation Function**

$$\delta\Gamma_S = \frac{y_{\alpha'\beta'} y_{ee}}{m_\phi^2} \langle \nu_\alpha | \bar\nu_{\alpha'} \nu_{\beta'} | \nu_\beta \rangle \langle e | \bar e e | e \rangle \,,$$

$$\delta\overline{\Gamma}_S = \frac{y_{\beta'\alpha'} y_{ee}}{m_\phi^2} \langle \bar\nu_\alpha | \bar\nu_{\alpha'} \nu_{\beta'} | \bar\nu_\beta \rangle \langle e | \bar e e | e \rangle \,.$$

- **Equation of Motion**

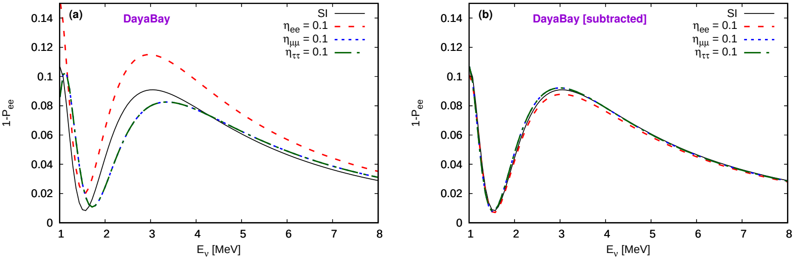
$$\bar\nu_\beta \left[i\partial_\mu \gamma^\mu + \left(M_{\beta\alpha} + \frac{n_e y_e Y_{\alpha\beta}}{m_\phi^2} \right) \right] \nu_\alpha = 0 \,,$$

- **Effective Hamiltonian**

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

Density Subtraction for Reactor Anti-Neutrinos

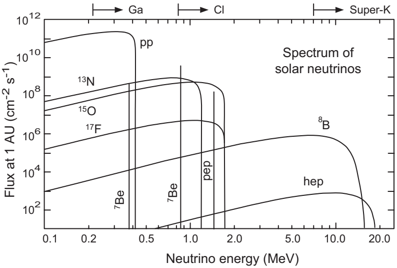
- Since the reactor anti-neutrino experiments (**Daya Bay** & **JUNO**) are the most precise ones, we do substraction according to them:

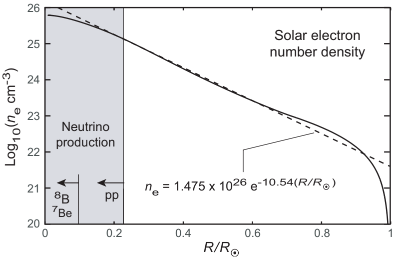


$$\widetilde{M} \to \widetilde{M} + \widetilde{\mathbf{M}}_{\mathbf{S}} \frac{\rho - \rho_{\mathbf{s}}}{\rho_{\mathbf{s}}}$$

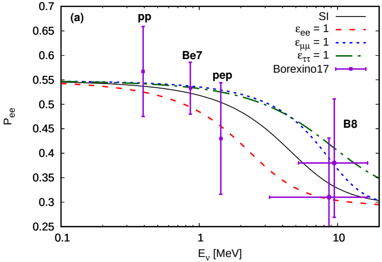
- Then **no constraint** on **scalar NSI** from reactor experiments!

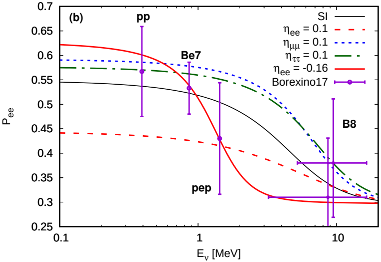
Solar Neutrino



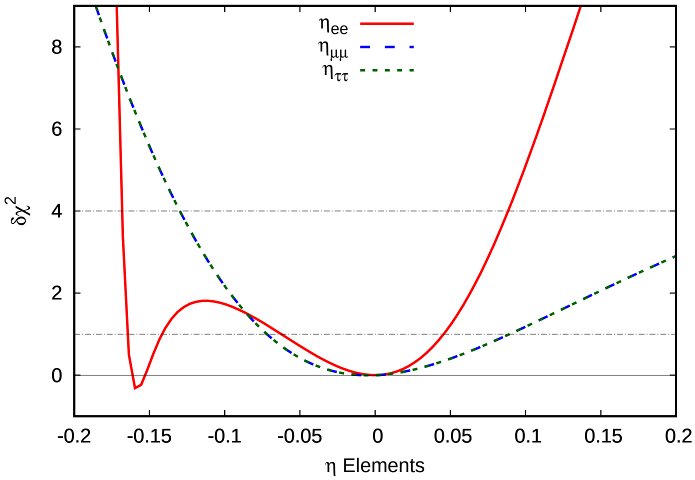


$$P_{ee}^{sun} = \left| U_{ei}^{prod} (U_{ei}^{vac})^* \right|^2$$

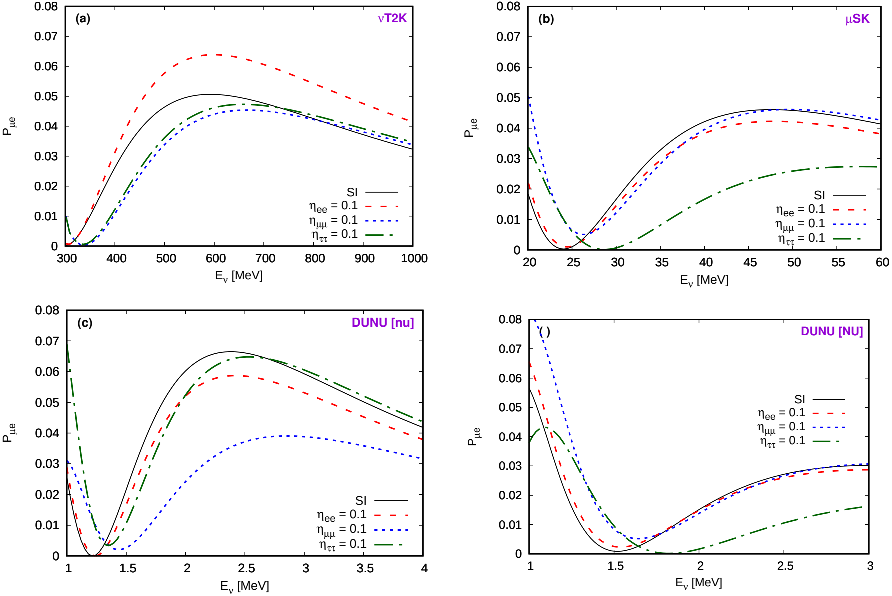




Fitting the Borexino 2017 Data



Scalar NSI @ Accelerator Neutrino Oscillation

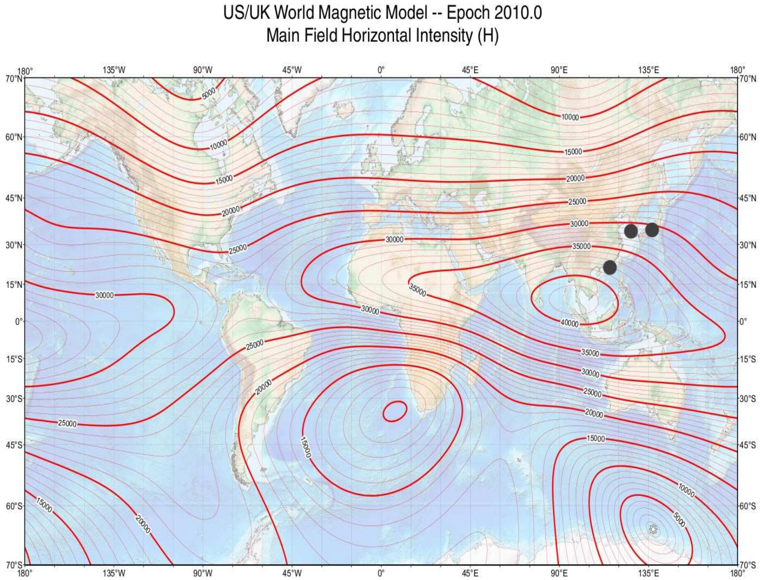


Summary

- **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)
- **Better configuration than DAEδALUS**
  - Only one cyclotron
  - 100% duty factor
  - Much lower flux intensity
  - Much easier
  - Much cheaper
  - Single near detector

Thank You!

Lowest Atmospheric Neutrino Background



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

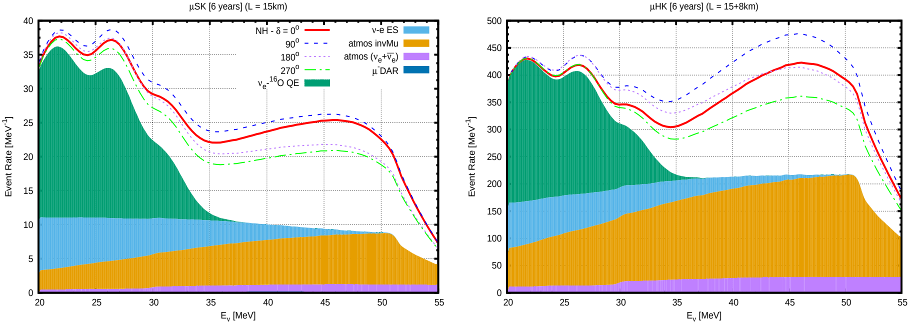
- Reactor $\overline{\nu}_e$: $E_\nu < 10$ MeV
- Accelerator ν_e: $E_\nu > 100$ MeV
- Spallation: $E_\nu \lesssim 20$ MeV
- Supernova Relic Neutrino: $E_\nu \lesssim 20$ MeV

Cut with 30 MeV $< E_\nu <$ 55 MeV

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

Event Shape @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]



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

Simulated by **NuPro**, http://nupro.hepforge.org/

Mass Scale & Unphysical CP Phases in Oscillation

- The effective mass term is a combination

$$\mathbf{M}\mathbf{M}^\dagger \to (\mathbf{M}+\mathbf{M}_\mathbf{S})(\mathbf{M}+\mathbf{M}_\mathbf{S})^\dagger = \mathbf{M}\mathbf{M}^\dagger + \mathbf{M}\mathbf{M}_\mathbf{S}^\dagger + \mathbf{M}_\mathbf{S}\mathbf{M}^\dagger + \mathbf{M}_\mathbf{S}\mathbf{M}_\mathbf{S}^\dagger$$

- The absolute neutrino mass can enter neutrino oscillation!

$$\mathbf{M}\mathbf{M}_\mathbf{S}^\dagger + \mathbf{M}_\mathbf{S}\mathbf{M}^\dagger$$

- 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 matrice** $Q_\nu = \{e^{i\delta_{\mathrm{M1}}/2}, 1, e^{i\delta_{\mathrm{M3}}/2}\}$ 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:

$$M \to \widetilde{\mathbf{M}} = \mathbf{U}_\nu \mathbf{D}_\nu \mathbf{U}_\nu^\dagger\,, \qquad M_S \to \widetilde{\mathbf{M}}_\mathbf{S} = \mathbf{P}_\nu^\dagger \mathbf{M}_\mathbf{S} \mathbf{P}_\nu$$

Parametrization & Constant Density Subtraction

- Use **characteristic scale** $\mathbf{\Delta m_a^2}$ to parametrize scalar NSI

$$\widetilde{\mathbf{M}}_\mathbf{S} \equiv \sqrt{\mathbf{\Delta m_a^2}} \begin{pmatrix} \eta_{ee} & \eta^*_{\mu e} & \eta^*_{\tau e} \\ \eta_{\mu e} & \eta_{\mu\mu} & \eta^*_{\tau\mu} \\ \eta_{\tau e} & \eta_{\tau\mu} & \eta_{\tau\tau} \end{pmatrix},$$

  where $\mathbf{\Delta m_a^2} \equiv \Delta m^2_{31} = 2.7 \times 10^{-3}\,\mathrm{eV}^2$.

- We first need **input** for $\widetilde{\mathbf{M}}$ which is not directly measured.

- However, the directly measured from terrestial experiments is always a combination, $\widetilde{\mathbf{M}} + \widetilde{\mathbf{M}}_\mathbf{S}(\rho_\mathbf{s} \approx \mathbf{3}\mathrm{g/cm}^\mathbf{3})$. It is then necessary to first substract a constant term:

$$\widetilde{M} \to \widetilde{M} + \widetilde{\mathbf{M}}_\mathbf{S} \frac{\rho - \rho_\mathbf{s}}{\rho_\mathbf{s}}$$

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

Scalar NSI @ Atmospheric Neutrino Oscillation