The Leptonic CP Phases: Dirac vs Majorana

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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, Manfred Lindner, PRD **95** (2017) No.3, 033003 [arXiv:1608.01618]

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:** $\cos\delta_{\mathbf{D}} = \dfrac{(s_s^2 - c_s^2 s_r^2)(\mathbf{c_a^2} - \mathbf{s_a^2})}{4 c_a s_a c_s s_s \mathbf{s_r}}$ 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
$\lvert\mathbf{\Delta m_a^2} \equiv \Delta m_{13}^2\rvert\;(\mathbf{10^{-3}}\mathrm{eV}^\mathbf{2})$	2.51	**2.55**	2.59
$\sin^2 \boldsymbol{\theta_s}\;(\boldsymbol{\theta_s} \equiv \boldsymbol{\theta_{12}})$	0.305 (33.5°)	0.321 (**34.5°**)	0.339 (35.6°)
$\sin^2 \boldsymbol{\theta_a}\;(\boldsymbol{\theta_a} \equiv \boldsymbol{\theta_{23}})$	0.412 (39.9°)	0.430 (**41.0°**)	0.450 (42.1°)
$\sin^2 \boldsymbol{\theta_r}\;(\boldsymbol{\theta_r} \equiv \boldsymbol{\theta_{13}})$	0.02080 (8.29°)	0.02155 (**8.44°**)	0.02245 (8.62°)
$\delta_{\mathrm{D}}, \delta_{\mathrm{Mi}}$	?, **??**	?, **??**	?, **??**

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

Dirac CP Phase Measurement

Jarah Evslin, **SFG**, Kaoru Hagiwara, JHEP **1602** (2016) 137 [arXiv:1506.05023]
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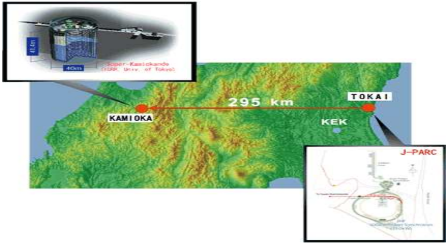
SFG [arXiv:1704.08518]

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

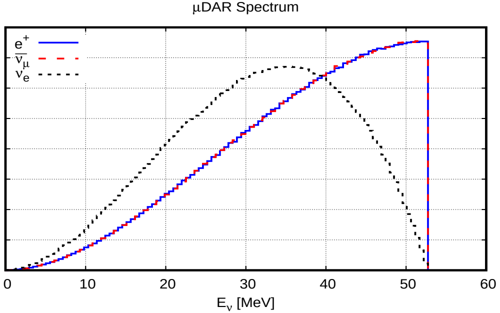
Accelerator experiment, such as **T2(H)K**, uses off-axis beam to compare ν_e & $\overline{\nu}_e$ appearance @ the oscillation maximum.

- **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 $\Rightarrow$ 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: $\boldsymbol{\mu}^+ \to \mathbf{e}^+ + \overline{\boldsymbol{\nu}}_{\boldsymbol{\mu}} + \boldsymbol{\nu}_{\mathbf{e}}$.

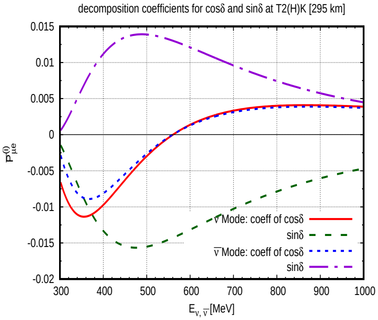


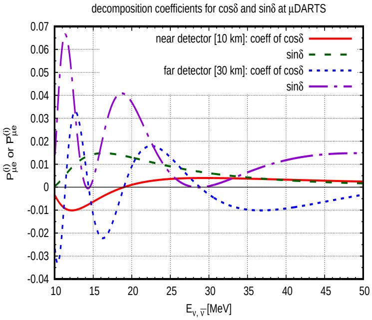
- $\overline{\nu}_\mu$ travel in all directions, oscillating as they go.
- A detector measures the $\overline{\nu}_e$ from $\overline{\boldsymbol{\nu}}_{\boldsymbol{\mu}} \to \overline{\boldsymbol{\nu}}_{\mathbf{e}}$ **oscillation**.

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])





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∼25% duty factor).
  - **Large** statistical uncertainty.
  - **Higher intensity** is necessary.
  - **Expensive** & Technically **challenging**.

New Proposals

1 μDAR source + **2** detectors

Advantages

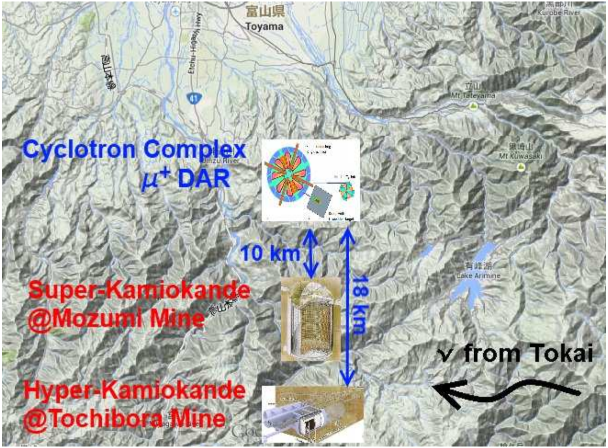
- Full (**100%**) duty factor!
- **Lower** intensity: $\sim$ **9mA** [$\sim$ **4**$\times$ lower than DAEδALUS]
- Not far beyond the current state-of-art technology of cyclotron [**2.2mA** @ Paul Scherrer Institute]
- MUCH **cheaper** & technically **easier**.
  - Only one cyclotron.
  - Lower intensity.

Disadvantage?

- A second detector! **T**okai '**N** **T**oyama to(**2**) **K**amioka (**TNT2K**) [Evslin, Ge & Hagiwara, 1506.05023]

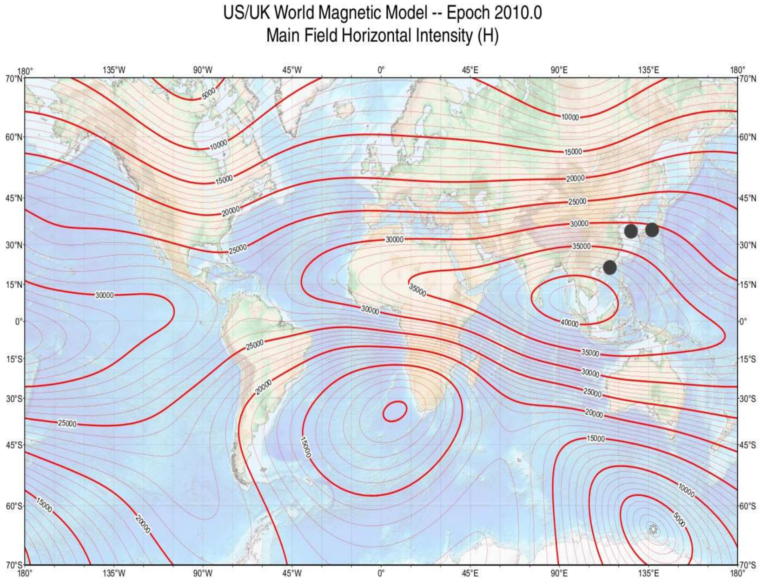
TNT2K

- T2(H)K + μSK + μHK



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

Lowest Atmospheric Neutrino Background



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

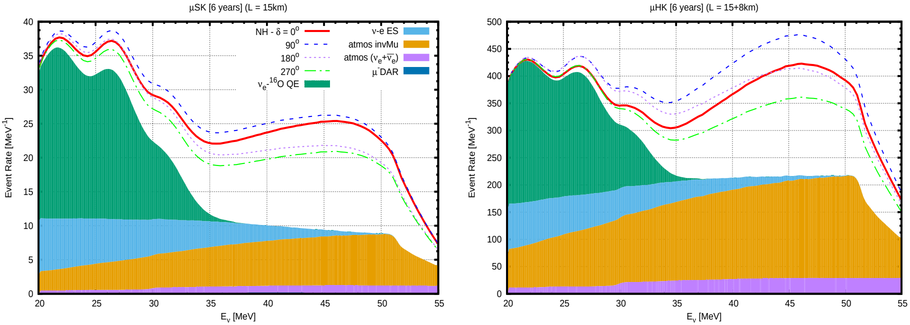
- Reactor $\overline{\nu}_e$: $E_\nu < 10$ MeV
- Accelerator ν_e: $E_\nu > 100$ MeV
- Spallation: $E_\nu \lesssim 20$ MeV
- Supernova Relic Neutrino: $E_\nu \lesssim 20$ MeV

  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]

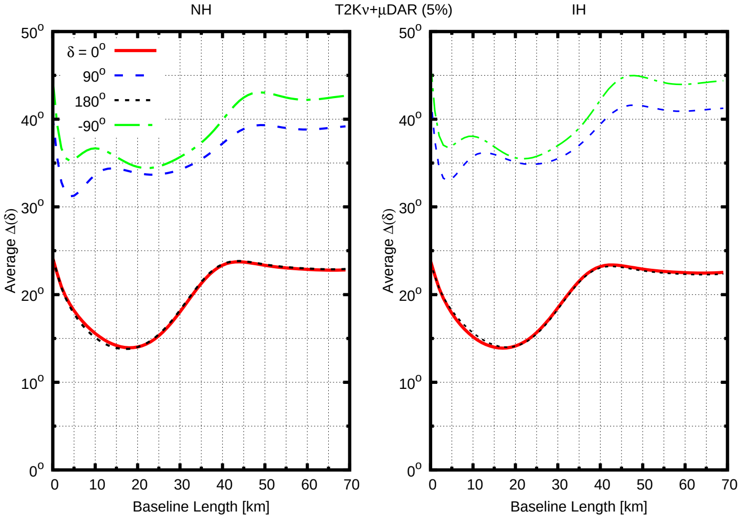


Expected μDAR IBD signal from 6 yrs of running @ SK (15km) & HK (23km) with NH.

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

δ_D Precision @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]



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δ_D Precision @ TNT2K

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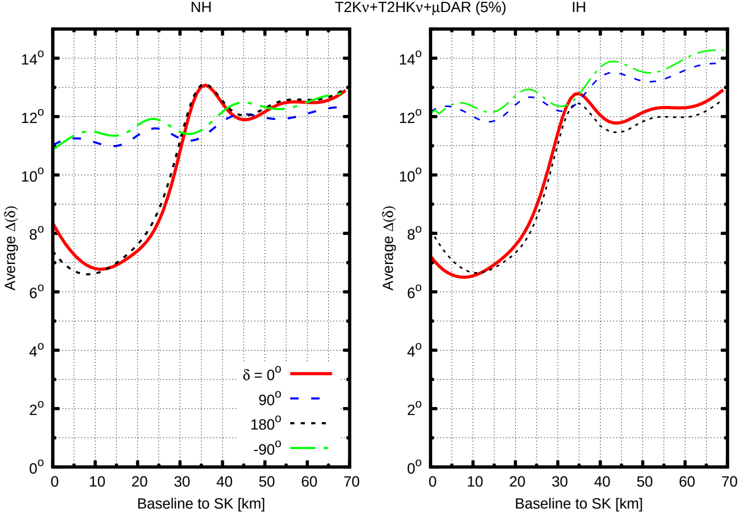


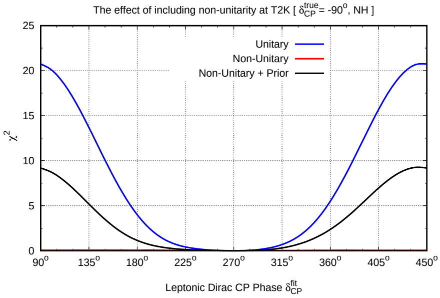
Simulated by **NuPro**, http://nupro.hepforge.org/

Non-Unitarity Mixing (NUM)

Ge, Pasquini, Tortola & Valle [1605.01670]

$$N = N^{NP} U = \left(\begin{array}{ccc} \alpha_{11} & 0 & 0 \\ |\alpha_{21}| e^{i\phi} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{array} \right) U \, .$$

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



NUM vs Seesaw Mechanism

- **Heavy neutrinos**

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

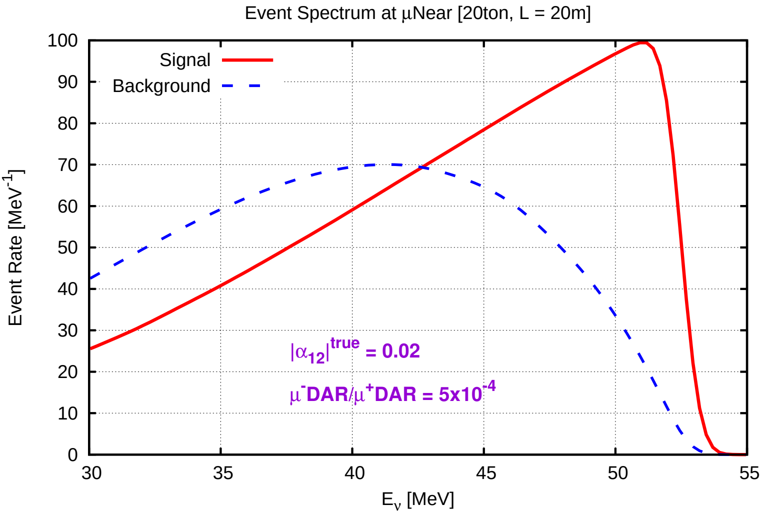
- **Seeaw Mechanism**

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

μNear at μDAR

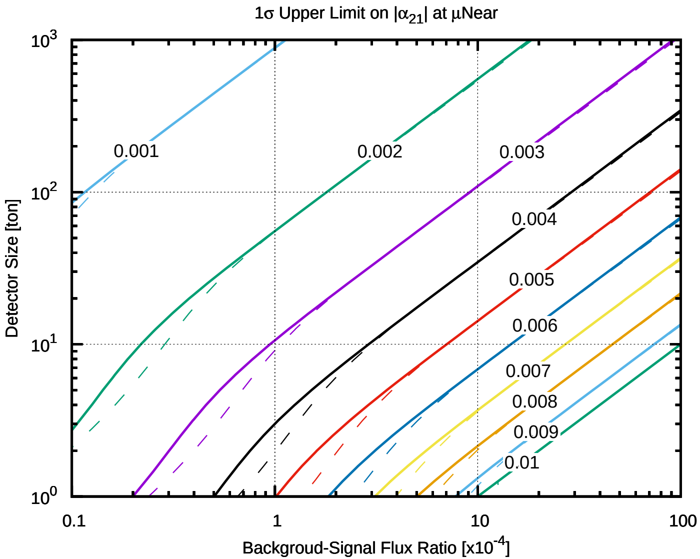
Ge, Pasquini, Tortola & Valle [1605.01670]

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



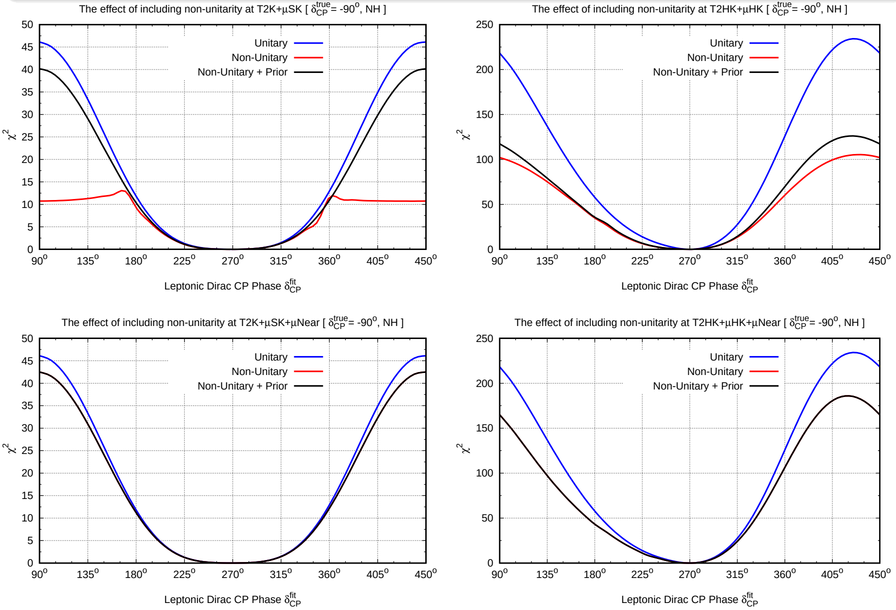
μNear at μDAR

Ge, Pasquini, Tortola & Valle [1605.01670]



TNT2K+μNear

Ge, Pasquini, Tortola & Valle [1605.01670]



Non-Standard Interaction

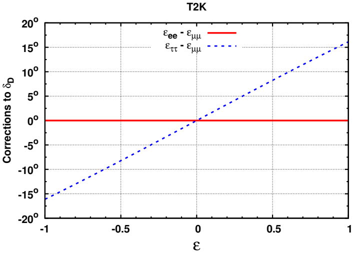
SFG & Alexei Smirnov [arXiv:1607.08513]

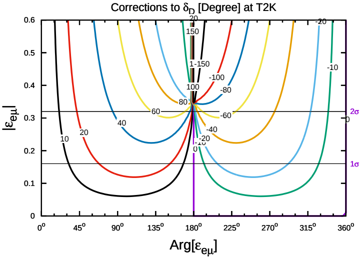
$$\mathcal{H} \equiv \frac{1}{2\mathbf{E}_\nu} U \begin{pmatrix} 0 & & \\ & \Delta m_s^2 & \\ & & \Delta m_a^2 \end{pmatrix} U^\dagger + V_{cc} \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} &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

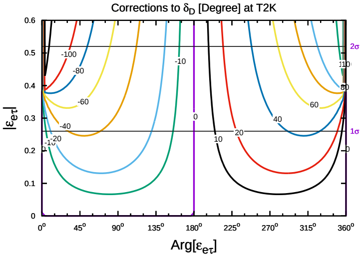
- Standard Interaction – V_{cc} (also V_{nc})
- Non-Standard Interaction – $\epsilon_{\alpha\beta}$
  - **Diagonal $\epsilon_{\alpha\alpha}$ are real**
  - **Off-diagonal $\epsilon_{\alpha\neq\beta}$ are complex**
  - **Both can fake CP**
- Z' in LMA-Dark model with $L_\mu - L_\tau$ gauged as $U(1)$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

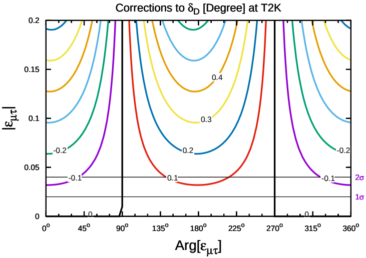
Faked CP with NSI

SFG & Alexei Smirnov [arXiv:1607.08513]



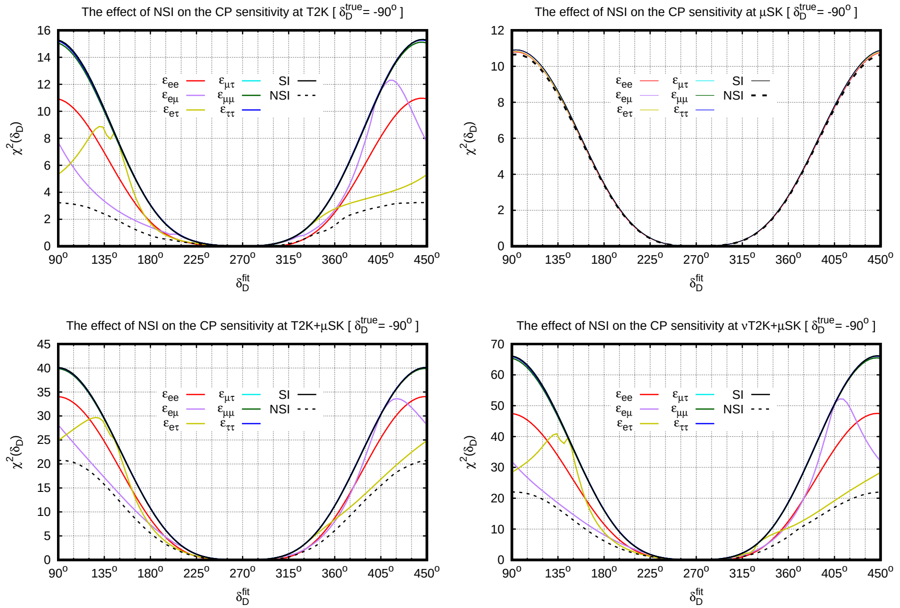






CP Sensitivity at T2K & μSK

SFG & Alexei Smirnov [arXiv:1607.08513]



Summary (1)

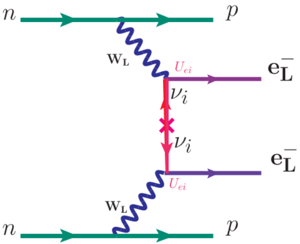
- **Better CP measurement than T2K**
  - Much larger event numbers
  - Much better CP sensitivity around maximal CP
  - Solve degeneracy between δ_D & $\pi - \delta_D$
  - Guarantee CP sensitivity against NUM
  - Guarantee CP sensitivity against NSI
- **Better configuration than DAEδALUS**
  - Only one cyclotron
  - 100% duty factor
  - Much lower flux intensity
  - Much easier
  - Much cheaper
  - Single near detector

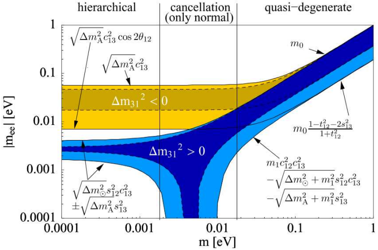
Majorana CP Phase Measurement

SFG, Manfred Lindner, PRD **95** (2017) No.3, 033003 [arXiv:1608.01618]

$0\nu 2\beta$ Decay

- Mediated by **Majorana Neutrino** + **Lepton # Violation**





- **Helicity Suppression → Mass Suppression**

$$\mathcal{M} \propto \sum_i U_{ei} \frac{i}{\not{p} - m_i} U_{ei} \approx \sum_i U_{ei} \frac{m_i}{p^2} U_{ei}$$

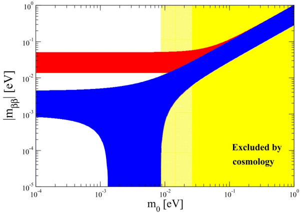
- **Effective Electron Neutrino Mass**

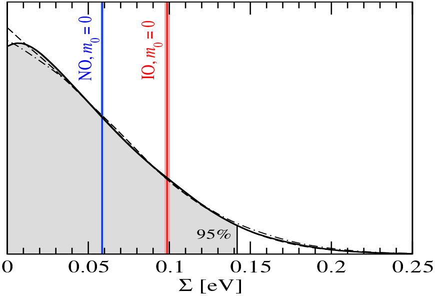
$$\langle m \rangle_{ee} \equiv \left| \sum_i m_i U^2_{ei} \right| = \left| c^2_s c^2_r m_1 e^{i\delta_{M1}} + s^2_s c^2_r m_2 + s^2_r m_3 e^{i\delta_{M3}} \right|$$

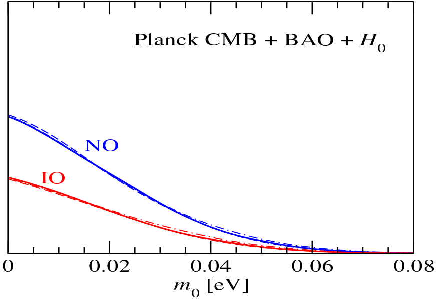
see also SFG & Werner Rodejohann [1507.05514]

Cosmological Data on Mass Sum

$$\Sigma \equiv m_1 + m_2 + m_3$$

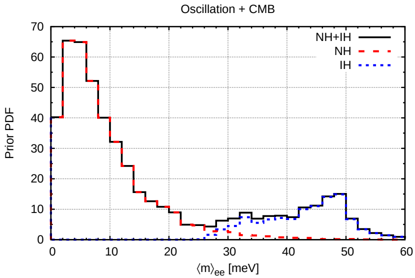


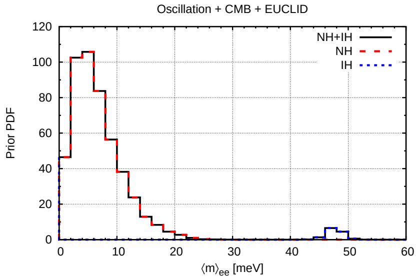


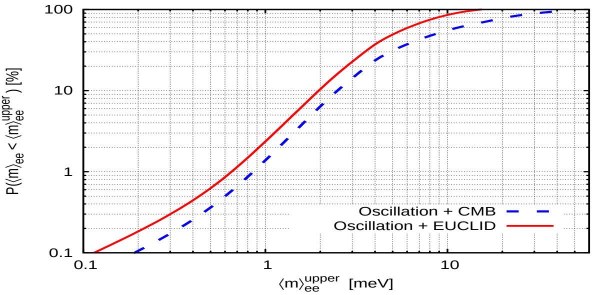


Hannestad & Schwetz [1606.04691]

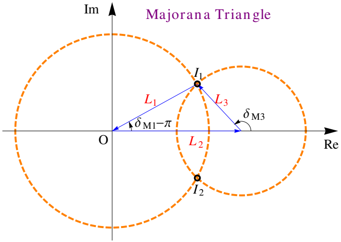
Preference of NH ⇒ Non-Observation of $0\nu2\beta$?







Any chance of obtaining some information?



$$\langle m \rangle_{ee} \equiv \overrightarrow{L_1} + \overrightarrow{L_2} + \overrightarrow{L_3} \,,$$

with

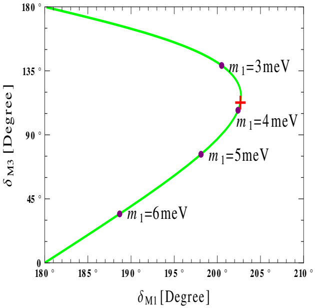
$$\overrightarrow{L_1} \equiv m_1 U_{e1}^2 = m_1 c_r^2 c_s^2 e^{i\boldsymbol{\delta_{\mathrm{M1}}}} \,,$$
$$\overrightarrow{L_2} \equiv m_2 U_{e2}^2 = \sqrt{m_1^2 + \Delta m_s^2} c_r^2 s_s^2 \,,$$
$$\overrightarrow{L_3} \equiv m_3 U_{e3}^2 = \sqrt{m_1^2 + \Delta m_a^2} s_r^2 e^{i\boldsymbol{\delta_{\mathrm{M3}}}} \,.$$

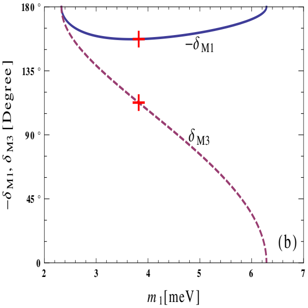
Determine 2 Majorana Phases Simultaneously

$$|L_1 - L_3| \leq L_2 \leq L_1 + L_3 \, .$$

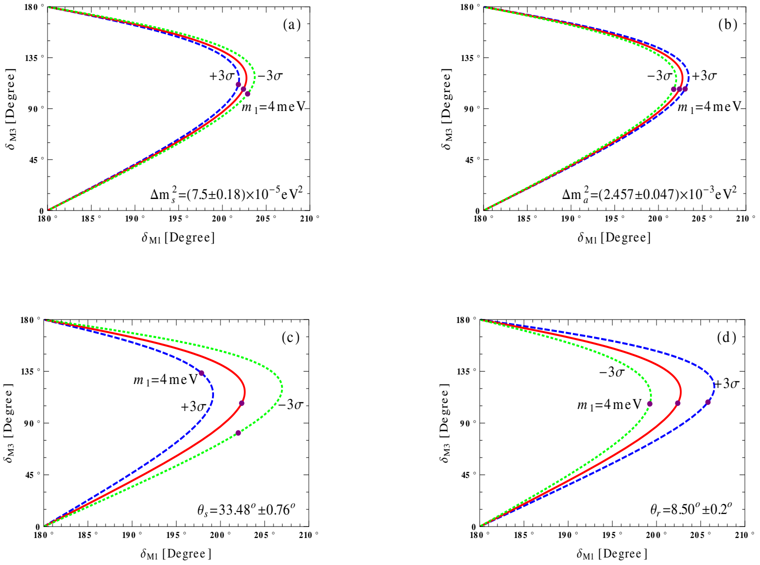
$$\cos \boldsymbol{\delta_{M1}} = -\frac{L_1^2 + L_2^2 - L_3^2}{2 L_1 L_2} = -\frac{m_1^2 c_r^4 c_s^4 + m_2^2 c_r^4 s_s^4 - m_3^2 s_r^4}{2 m_1 m_2 c_r^4 c_s^2 s_s^2} \, ,$$

$$\cos \boldsymbol{\delta_{M3}} = +\frac{L_1^2 - L_2^2 - L_3^2}{2 L_2 L_3} = +\frac{m_1^2 c_r^4 c_s^4 - m_2^2 c_r^4 s_s^4 - m_3^2 s_r^4}{2 m_2 m_3 c_r^2 s_r^2 s_s^2} \, .$$

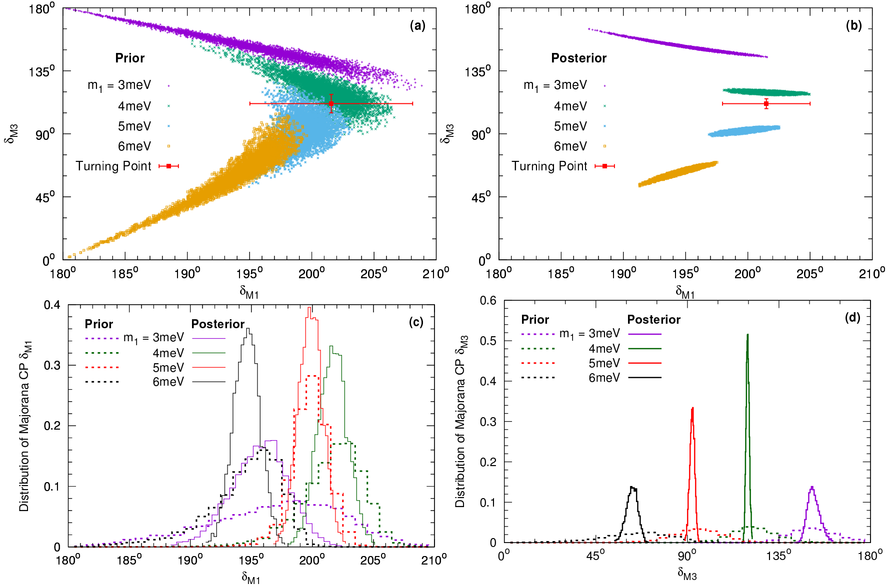




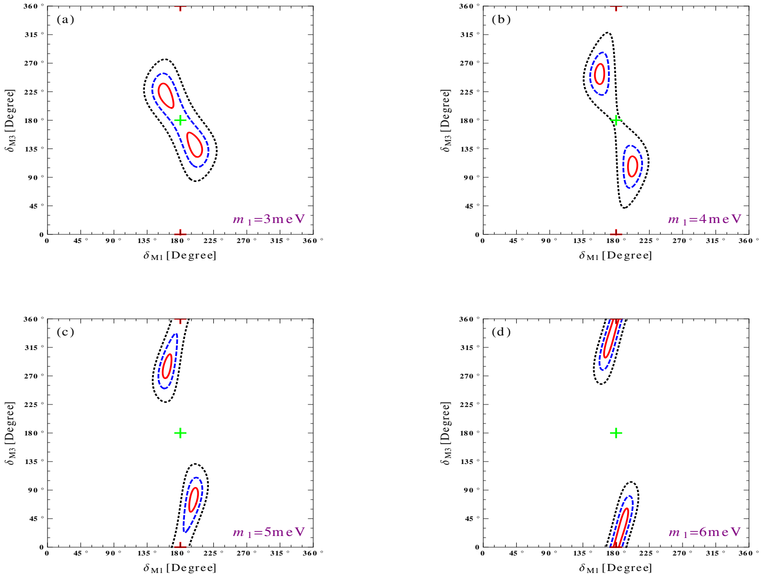
Uncertainties from Oscillation Parameters



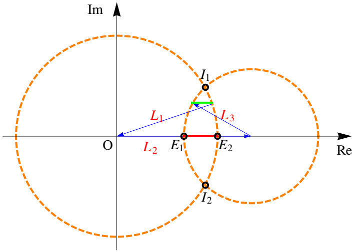
Uncertainties from Oscillation Parameters

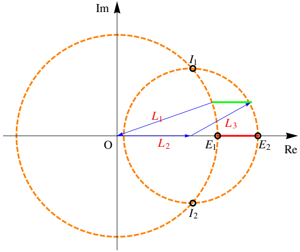


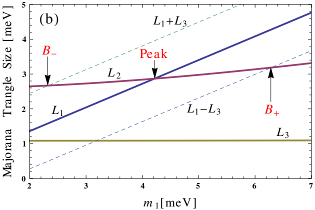
Uncertainties from $\langle m \rangle_{ee}$

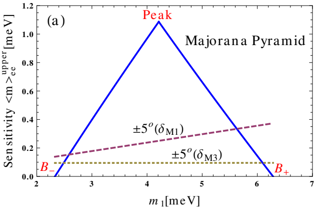


Majorana Pyramid









Prey of Leptonic CP Phases

Summary

- **CP is fundamentally important**
  - Matter-Antimatter Asymmetry
  - Test of Discrete Symmetries
- **Better Dirac CP measurement at TNT2K**
  - 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
- **Elusive Majorana CP Phases**
  - Observing nothing is not bad at all
  - Even better: fixing two Majorana CP phases simultaneously

Thank You!