Leptonic Dirac CP Phase with Residual Symmetry & μDAR

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SFG [arXiv:1406.1985]
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]

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
$\sin^2 \boldsymbol{\theta}_\mathbf{s}\ (\boldsymbol{\theta}_\mathbf{s} \equiv \boldsymbol{\theta}_\mathbf{12})$	0.305 (33.5°)	0.321 (**34.5°**)	0.339 (35.6°)
$\sin^2 \boldsymbol{\theta}_\mathbf{a}\ (\boldsymbol{\theta}_\mathbf{a} \equiv \boldsymbol{\theta}_\mathbf{23})$	0.412 (39.9°)	0.430 (**41.0°**)	0.450 (42.1°)
$\sin^2 \boldsymbol{\theta}_\mathbf{r}\ (\boldsymbol{\theta}_\mathbf{r} \equiv \boldsymbol{\theta}_\mathbf{13})$	0.02080 (8.29°)	0.02155 (**8.44°**)	0.02245 (8.62°)
$\delta_\mathbf{D}, \delta_\mathbf{Mi}$	?, **??**	?, **??**	?, **??**

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

Evidence of μ–τ Symmetry

- **Two small deviations (1σ level):**

$$-3.5^\circ < \theta_a - 45^\circ < 5.8^\circ \qquad 8.4^\circ < \theta_r < 9.2^\circ$$

with **Best Fit Value**: $\boldsymbol{\theta_a - 45^\circ = -3.9^\circ}$ & $\boldsymbol{\theta_r = 8.8^\circ}$.

- **Zeroth Order Approximation:**

$$\boxed{\boldsymbol{\theta_a \approx 45^\circ}, \qquad \boldsymbol{\theta_r \approx 0^\circ}.}$$

$\Rightarrow$ **CP** & **μ–τ Symmetric** Mass Matrix:

$$M_\nu^{(0)} = \begin{pmatrix} A & \mathbf{B} & \mathbf{B} \\ & \mathbf{C} & D \\ & & \mathbf{C} \end{pmatrix}$$

Mohapatra & Nussinov [hep-ph/9809415], Lam [hep-ph/0104116]

Residual Symmetry

[Lam, PRL**101**:121602(2008), PRD**78**:073015(2008)]

- **Mass Matrix** $\mathbf{M}_\nu$ invariant under **Transformation**:

$$\mathbf{G}_\nu^T \mathbf{M}_\nu \mathbf{G}_\nu = \mathbf{M}_\nu$$

- **Diagonalization**:

$$\mathbf{V}_\nu^T \mathbf{M}_\nu \mathbf{V}_\nu = \mathbf{D}_\nu$$

- **Rephasing**:

$$\mathbf{D}_\nu = \mathbf{d}_\nu^T \mathbf{D}_\nu \mathbf{d}_\nu$$

with $\mathbf{d}_\nu^2 = \mathbf{I}_3 \quad \Rightarrow \quad \mathbf{d}_\nu = \text{diag}(\pm, \pm, \pm)$.

- Together

$$\begin{aligned} \mathbf{M}_\nu &= \mathbf{G}_\nu^T \mathbf{M}_\nu \mathbf{G}_\nu = \underline{\mathbf{G}_\nu^T \mathbf{V}_\nu^* \mathbf{D}_\nu \mathbf{V}_\nu^\dagger \mathbf{G}_\nu} \\ &= \mathbf{V}_\nu^* \mathbf{D}_\nu \mathbf{V}_\nu^\dagger = \underline{\mathbf{V}_\nu^* \mathbf{d}_\nu^T \mathbf{D}_\nu \mathbf{d}_\nu \mathbf{V}_\nu^\dagger} \end{aligned}$$

- **Consequence**: $\mathbf{V}_\nu^\dagger \mathbf{G}_\nu = \mathbf{d}_\nu \mathbf{V}_\nu^\dagger \Leftrightarrow \boxed{\mathbf{G}_\nu = \mathbf{V}_\nu \mathbf{d}_\nu \mathbf{V}_\nu^\dagger}$

- **For Leptons:** $\underline{\mathbf{F}_\ell = \mathbf{V}_\ell \mathbf{d}_\ell \mathbf{V}_\ell^\dagger}$ with $\mathbf{d}_\ell = \text{diag}(\mathbf{e}^{\mathbf{i}\beta_1}, \mathbf{e}^{\mathbf{i}\beta_2}, \mathbf{e}^{\mathbf{i}\beta_3})$.

Symmetry v.s. Mixing

[Lam, PRL**101**:121602(2008), PRD**78**:073015(2008)]

- **Two Nontrivial Independent** possibilities of $\mathbf{d}_\nu$:

$$\mathbf{d}_\nu^{(1)} = \mathrm{diag}(-1,1,1), \quad \mathbf{d}_\nu^{(2)} = \mathrm{diag}(1,-1,1), \qquad \mathbf{d}_\nu^{(3)} = -d_\nu^{(1)} d_\nu^{(2)}\,.$$

- $\boldsymbol{\theta}_\mathbf{s}$ parameterized in terms of $\mathbf{k}$: $\boxed{\tan\theta_s = \sqrt{2}/k}$

$$V_\nu(k) = \begin{pmatrix} \frac{k}{\sqrt{2+k^2}} & \frac{\sqrt{2}}{\sqrt{2+k^2}} & 0 \\ \frac{1}{\sqrt{2+k^2}} & \frac{k}{\sqrt{2(2+k^2)}} & \frac{-1}{\sqrt{2}} \\ \frac{1}{\sqrt{2+k^2}} & \frac{k}{\sqrt{2(2+k^2)}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$\mathbf{k} = \mathbf{2}$ $\quad \boldsymbol{\theta}_\mathbf{s} = \mathbf{35.3^\circ}$ **[TBM]**

$\mathbf{k} = \frac{\mathbf{3}}{\sqrt{\mathbf{2}}}$ $\quad \boldsymbol{\theta}_\mathbf{s} = \mathbf{33.7^\circ}$

$\mathbf{k} = \sqrt{\mathbf{6}}$ $\quad \boldsymbol{\theta}_\mathbf{s} = \mathbf{30.0^\circ}$

- **Two Independent** *Symmetry Transformations* $\mathbf{G_i} = \mathbf{V}_\nu \mathbf{d}_\nu^{(\mathbf{i})} \mathbf{V}_\nu^\dagger$

$$G_1 = \frac{1}{2+k^2} \begin{pmatrix} 2-k^2 & 2k & 2k \\ & k^2 & -2 \\ & & k^2 \end{pmatrix}, \qquad G_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

- $\mathbb{Z}_\mathbf{2}^\mathbf{s}(\times \overline{\mathbb{Z}}_\mathbf{2}^\mathbf{s}) \times \mathbb{Z}_\mathbf{2}^{\boldsymbol{\mu\tau}} \equiv \mathcal{G} = \{\mathbf{E}, \mathbf{G_1}, \mathbf{G_2}(\equiv G_1 G_3), \mathbf{G_3}\}$

Full v.s. Residual

[Lam, PRL**101**:121602(2008), PRD**78**:073015(2008)]

- **Full Symmetries:**

$\mathcal{H} \equiv \mathcal{G} \times \mathcal{F}$	$\mathcal{G}$	$\mathcal{F}$
S_4	$\mathbb{Z}_2^s \times \mathbb{Z}_2^{\mu\tau}$	$\mathbb{Z}_3 \equiv \{I, F, F^2\}$
$\{G_1, G_3, F\}$	$G_1(G_2), G_3$	$F \equiv \text{diag}\,(1, \omega, \omega^2)$

Bottom-Up ⇑ ⇓ **Top-Down**

See also Smirnov et. al., 1204.0445, 1212.2149, 1510.00344

- **Residual Symmetries:**

$\boldsymbol{\nu}_\mathbf{i}$: $\mathcal{G} \equiv \mathbb{Z}_2^s(\overline{\mathbb{Z}}_2^s) \times \mathbb{Z}_2^{\mu\tau}$ for $d^i_\nu = \text{diag}\,(\pm 1, \pm 1, \pm 1)$

$\boldsymbol{\ell}_\mathbf{i}$: $\mathcal{F} \in U(1) \times U(1)$ for $d^i_\ell = \text{diag}\,(e^{i\beta_1}, e^{i\beta_2}, e^{i\beta_3})$

Example Zee-A_4 Model

hep-ph/0508278

- **Lepton's Representation:**

$$\begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix} \sim \mathbf{3}\,, \quad \begin{matrix} e_R \sim \mathbf{1} \\ \mu_R \sim \mathbf{1}'\,, \\ \tau_R \sim \mathbf{1}'' \end{matrix} \qquad \begin{pmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \end{pmatrix} \sim \mathbf{3}\,.$$

- A_4 **invariant Lagrangian:**

$$\begin{aligned} \mathcal{L}_\ell \;=\;& \mathbf{y_1}\overline{e}_R(\mathbf{1}\varphi_1^\dagger e_L + \mathbf{1}\varphi_2^\dagger \mu_L + \mathbf{1}\varphi_3^\dagger \tau_L) \\ +\;& \mathbf{y_2}\overline{\mu}_R(\boldsymbol{\omega}\varphi_1^\dagger e_L + \mathbf{1}\varphi_2^\dagger \mu_L + \boldsymbol{\omega}^{\mathbf{2}}\varphi_3^\dagger \tau_L) \\ +\;& \mathbf{y_3}\overline{\tau}_R(\boldsymbol{\omega}^{\mathbf{2}}\varphi_1^\dagger e_L + \mathbf{1}\varphi_2^\dagger \mu_L + \boldsymbol{\omega}\varphi_3^\dagger \tau_L)\,. \end{aligned}$$

- **Mass term** with $\langle \varphi_i \rangle = v_i$:

$$\mathcal{L}_\ell = \begin{pmatrix} \overline{e}_R & \overline{\mu}_R & \overline{\tau}_R \end{pmatrix} \begin{pmatrix} \mathbf{y_1} & & \\ & \mathbf{y_2} & \\ & & \mathbf{y_3} \end{pmatrix} \underset{\|}{\begin{pmatrix} \mathbf{1} & \mathbf{1} & \mathbf{1} \\ \omega & \mathbf{1} & \omega^2 \\ \omega^2 & \mathbf{1} & \omega \end{pmatrix}} \begin{pmatrix} \mathbf{v_1} & & \\ & \mathbf{v_2} & \\ & & \mathbf{v_3} \end{pmatrix} \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix} \,.$$

$$\mathbf{v_1} = \mathbf{v_2} = \mathbf{v_3} = \mathbf{v} \Rightarrow U_{\ell,R} = I,\, \mathbf{U_{\ell,L}}(\omega),\; m_{\ell,i} = \mathbf{y_i v}.$$

$$\mathbf{y_1} = \mathbf{y_2} = \mathbf{y_3} = \mathbf{y} \Rightarrow U_{\ell,L} = I,\, \mathbf{U_{\ell,R}}(\omega),\; m_{\ell,i} = \mathbf{y v_i}.$$

Residual Symmetry as Effective Theory

- **Full symmetry HAS TO be Broken!**
  - Fermion needs to acquire mass.
  - Non-trivial mixing $\boxed{V_{\rm PMNS} = V_\ell^\dagger V_\nu}$
- If mixing is **TRUELY determined by symmetry**, it has to be **residual symmetry**
  - VEVs
  - Yukawa couplings
- **Residual Symmetry** as **Custodial Symmetry**
  - **Gauge symmetry has to be broken**. Otherwise, no mixing.
  - **Weak mixing angle** is a function of gauge couplings, which **cannot be dictated by gauge symmetry** (and VEV).
  - **Weak mixing angle is related to** the physical observables, the **gauge boson masses**, by **custodial symmetry**.

Partial Residual Symmetry $\mathbb{Z}_2^s$ or $\overline{\mathbb{Z}}_2^s$

- Although $\mathbb{Z}_2^{\mu\tau}$, represented by $\mathbf{G_3}$, is Broken!
- **No particular reason** for $\mathbb{Z}_2^s$ or $\overline{\mathbb{Z}}_2^s$ to be Broken!

$$
\begin{aligned}
\mathbb{Z}_2^s \quad &: \quad \mathbf{G_1(k)} = \frac{1}{2+k^2}\begin{pmatrix} 2-k^2 & 2k & 2k \\ & k^2 & -2 \\ & & k^2 \end{pmatrix} \, , \\
\overline{\mathbb{Z}}_2^s \quad &: \quad \mathbf{G_2(k)} = \frac{1}{2+k^2}\begin{pmatrix} 2-k^2 & 2k & 2k \\ & -2 & k^2 \\ & & -2 \end{pmatrix} \, .
\end{aligned}
$$

- $\mathbb{Z}_2^s$ & $\overline{\mathbb{Z}}_2^s$ are **Dependent**

$$\mathbf{G_1(k)} = \mathbf{G_2(k)G_3}$$

- **DIFFERENT Consequences!!!**

Correlation between Physical Observables

$$\mathbf{G}_\nu = \mathbf{V}_\nu \mathbf{d}_\nu \mathbf{V}_\nu^\dagger$$

$\mathbb{Z}_\mathbf{2}^\mathbf{s}$ (G_1)	$\overline{\mathbb{Z}}_\mathbf{2}^\mathbf{s}$ (G_2)
$\cos \boldsymbol{\delta}_\mathbf{D} = \frac{(s_s^2 - c_s^2 s_r^2)(\mathbf{c}_\mathbf{a}^\mathbf{2} - \mathbf{s}_\mathbf{a}^\mathbf{2})}{4 c_a s_a c_s s_s \mathbf{s}_\mathbf{r}}$	$\cos \boldsymbol{\delta}_\mathbf{D} = \frac{(s_s^2 s_r^2 - c_s^2)(\mathbf{c}_\mathbf{a}^\mathbf{2} - \mathbf{s}_\mathbf{a}^\mathbf{2})}{4 c_a s_a c_s s_s \mathbf{s}_\mathbf{r}}$
$\sin \boldsymbol{\theta}_\mathbf{r} = \pm \left[\pm \sqrt{\mathbf{c}_\mathbf{D}^\mathbf{2} + \cot^2 2\theta_a} - \mathbf{c}_\mathbf{D} \right] \tan 2\boldsymbol{\theta}_\mathbf{a} (\tan \theta_s)^{\pm 1}$	
$\frac{\boldsymbol{\delta}_\mathbf{r}}{\boldsymbol{\delta}_\mathbf{a}} = -\frac{\tan \theta_s}{\cos \boldsymbol{\delta}_\mathbf{D}}$	$\frac{\boldsymbol{\delta}_\mathbf{r}}{\boldsymbol{\delta}_\mathbf{a}} = +\frac{\cot \theta_s}{\cos \boldsymbol{\delta}_\mathbf{D}}$

Model-Independence

$$\frac{\delta_r}{\delta_a} = -\frac{\tan\theta_s}{\cos\delta_D} \qquad \cos\delta_D = \frac{(s_s^2 - c_s^2 s_r^2)(c_a^2 - s_a^2)}{4 c_a s_a c_s s_s s_r},$$

- **Minimal Seesaw** [**SFG**, He, Yin, JCAP2010]

$$\frac{\delta_r}{\delta_a} = -\frac{\tan\theta_s}{\cos\delta_D}$$

Common origin of soft μ–τ & CP breaking

- **Trimaximal Mixing** $(k = 2)$ @ A_4/S_4 [King, Luhn, 1107.5332]

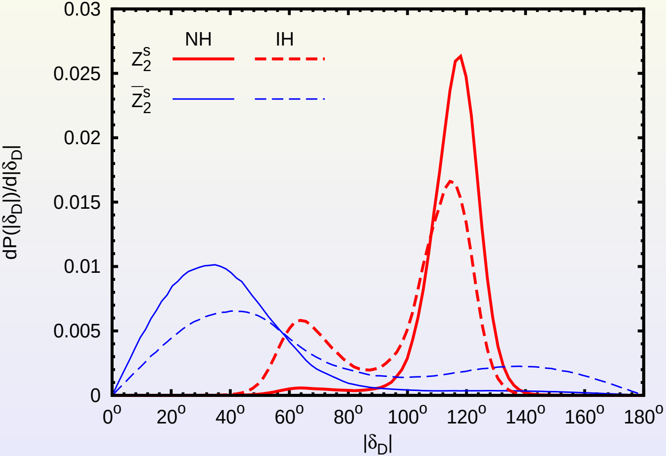
$$\sqrt{2}s_a - 1 = -\frac{1}{\sqrt{2}} s_r \cos\delta_D$$

- **Unrealistic Bimaximal Mixing** [Lam, 1105.5166]

$$\left\langle s_s, s_a, s_r e^{i\delta_D} \right\rangle = \left\langle \frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, \frac{1}{\sqrt{3}} e^{-\frac{i}{2}\pi} \right\rangle$$

Prediction of Large δ_D

$$\cos \delta_D = \frac{(s_s^2 - c_s^2 s_r^2)(c_a^2 - s_a^2)}{4 c_a s_a c_s s_s s_r} \qquad \cos \delta_D = \frac{(s_s^2 s_r^2 - c_s^2)(c_a^2 - s_a^2)}{4 c_a s_a c_s s_s s_r}$$



1σ Indication for $\delta_D = -74^\circ(-110^\circ)$ [Schwetz et.al. 1108.1376]

Precision Measurement of CP δ_D is Needed!

$$\mathbf{G}_\nu = \mathbf{V}_\nu \mathbf{d}_\nu \mathbf{V}_\nu^\dagger$$

$\mathbb{Z}_2^s$ (G_1)	$\overline{\mathbb{Z}}_2^s$ (G_2)
$\cos\delta_D = \frac{(s_s^2 - c_s^2 s_r^2)(\mathbf{c_a^2} - \mathbf{s_a^2})}{4 c_a s_a c_s s_s \mathbf{s_r}}$	$\cos\delta_D = \frac{(s_s^2 s_r^2 - c_s^2)(\mathbf{c_a^2} - \mathbf{s_a^2})}{4 c_a s_a c_s s_s \mathbf{s_r}}$

(for NH)	-1σ	Best Value	$+1\sigma$
$\sin^2\theta_s$ $(\theta_s \equiv \theta_{12})$	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	**?**	**?**	**?**

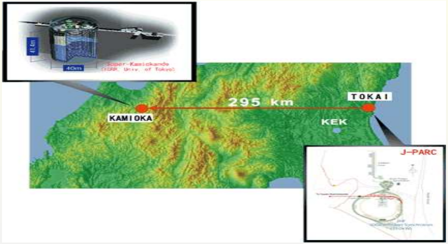
Salas, Forero, Ternes, Tortola & Valle, arXiv:1708.01186

Why neutrino mass & oscillation?

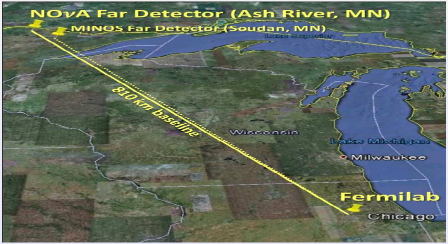
- Higgs boson for electroweak symmetry breaking & mass.
- Chiral symmetry breaking for majority of mass.
- **The world seems not affected by the tiny neutrino mass!**
  - Neutrino mass ⇒ Mixing
  - 3 Neutrino ⇒ possible CP violation
  - CP violation ⇒ Leptogenesis
  - Leptogenesis ⇒ **Matter-Antimatter Asymmetry**
  - There is something left in the Universe.
  - Baryogenesis from quark mixing is not enough.

CP Measurement @ Accelerator Exps

- T2K



- NOνA



- DUNE,T2KII/T2HK/T2KK/T2KO, MOMENT/ADS-CI, 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**,

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

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 $[\phi_{31} = \frac{\pi}{2}, \phi_{21} = \alpha\frac{\pi}{2}]$,

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

The Dirac CP Phase δ_D @ Accelerator Exp

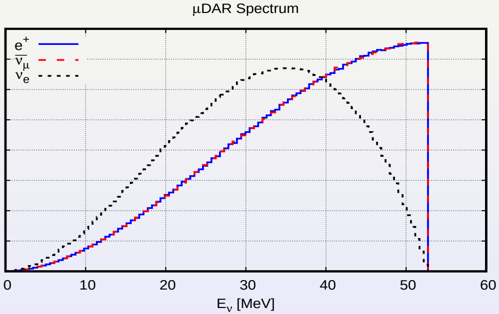
Accelerator experiment, such as **T2(H)K**, uses off-axis beam to compare ν_e & $\overline{\nu}_e$ appearance @ the oscillation maximum.

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



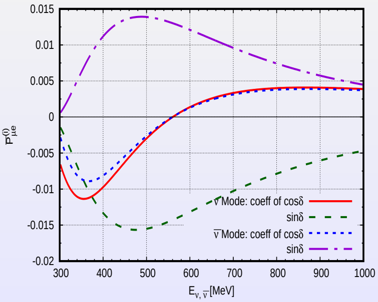
- $\overline{\nu}_\mu$ travel in all directions, oscillating as they go.
- A detector measures the $\overline{\nu}_e$ from $\overline{\boldsymbol{\nu}}_{\boldsymbol{\mu}} \to \overline{\boldsymbol{\nu}}_{\mathbf{e}}$ **oscillation**.

Accelerator + μDAR Experiments

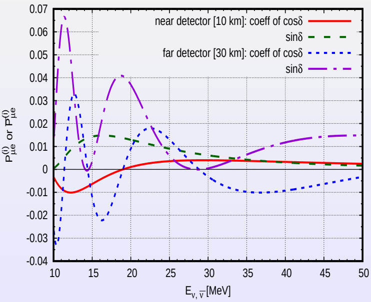
Combining $\nu_\mu \to \nu_e$ **@ accelerator** [narrow **peak @ 550 MeV**] & $\overline{\nu}_\mu \to \overline{\nu}_e$ **@ μDAR** [wide **peak $\sim$ 45 MeV**] solves the 3 problems:

- **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 Project

- 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!
  - **μDAR** with **T**wo **S**cintillators (**μDARTS**) [1401.3977]
  - **T**okai '**N** **T**oyama to(**2**) **K**amioka (**TNT2K**) [1506.05023]

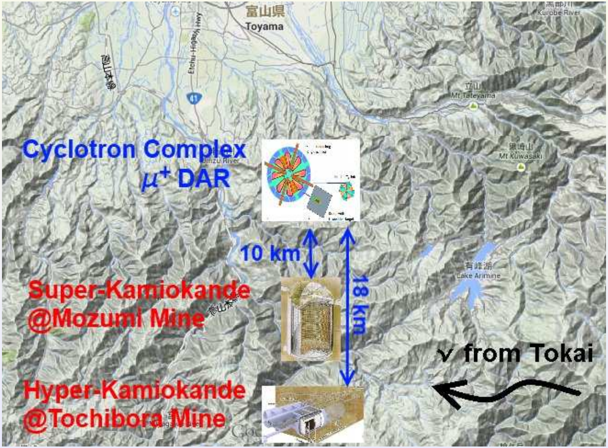
μDARTS – JUNO/RENO-50

- **Two detectors** are suggested to overcome the **unknown energy response**. [Ciuffoli et al., PRD 2014; 1307.7419, 1401.3977]

- China Atomic Energy Center has a proposal for cyclotron

TNT2K

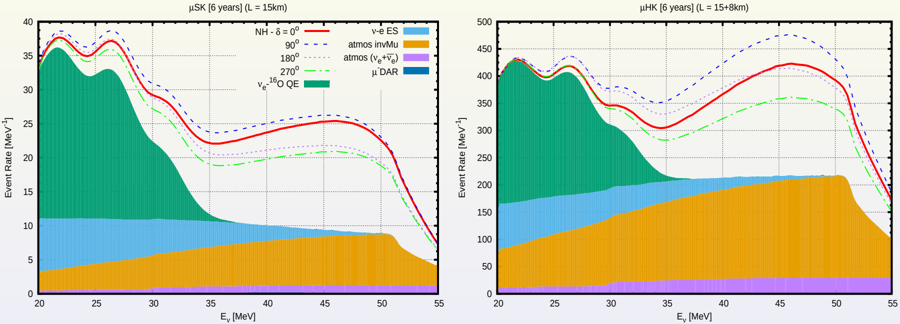
- T2(H)K + μSK + μHK



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

Event Shape @ TNT2K

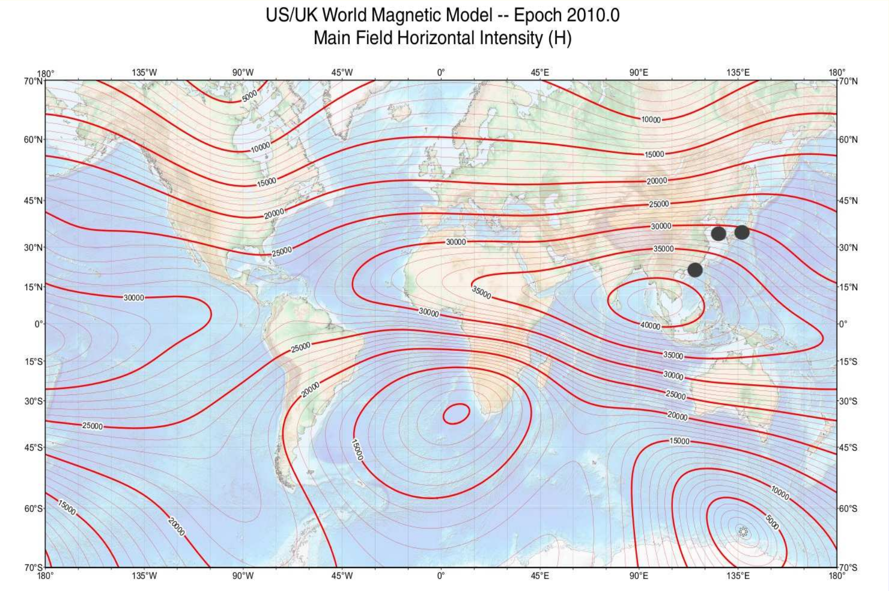
Evslin, Ge & Hagiwara [1506.05023]



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

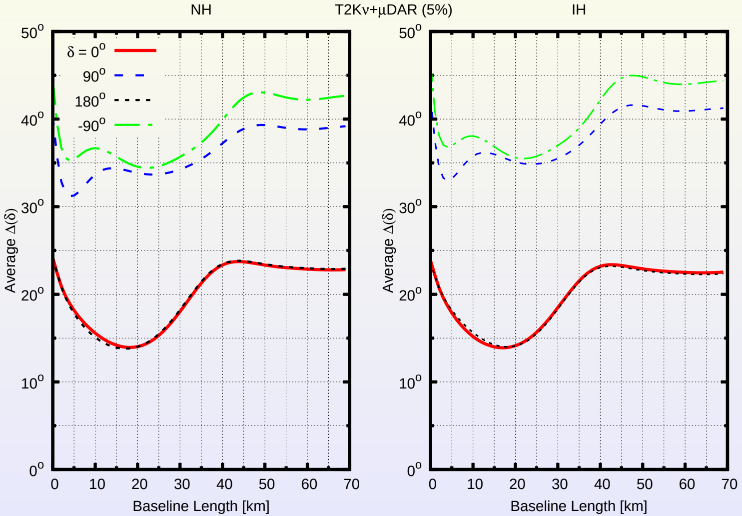
Simulated by **NuPro**, http://nupro.hepforge.org/

Lowest Atmospheric Neutrino Background



δ_D Precision @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]



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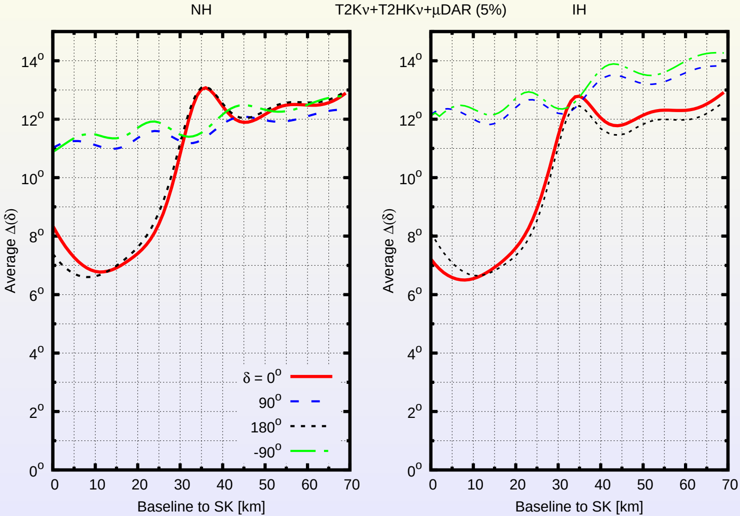
δ_D Precision @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]



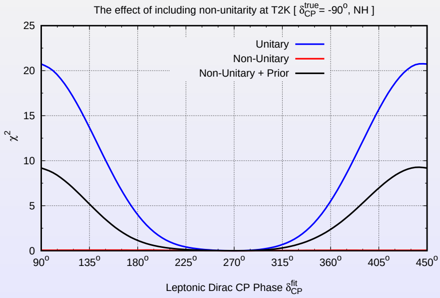
Simulated by **NuPro**, http://nupro.hepforge.org/

Non-Unitarity Mixing (NUM)

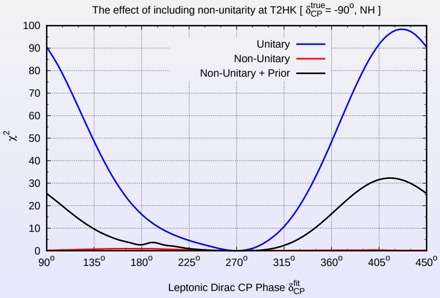
Ge, Pasquini, Tortola & Valle [1605.01670]

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

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



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



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

NUM vs Seesaw Mechanism

- **Heavy neutrinos**

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

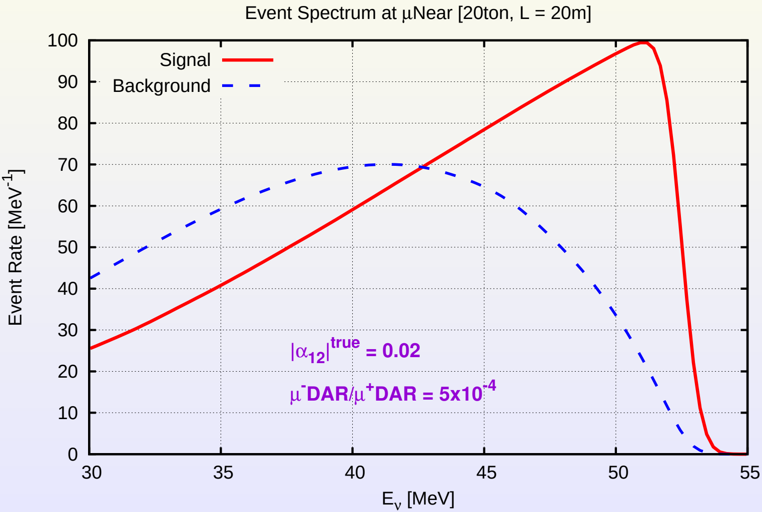
- **Seeaw Mechanism**

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

μNear at μDAR

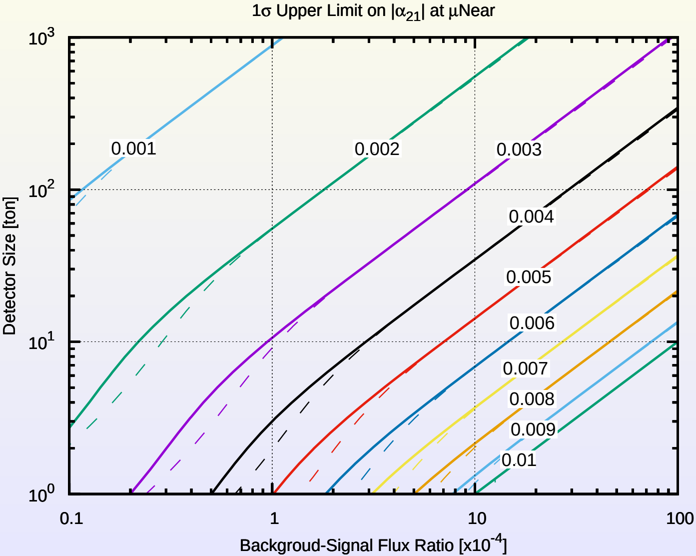
Ge, Pasquini, Tortola & Valle [1605.01670]

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



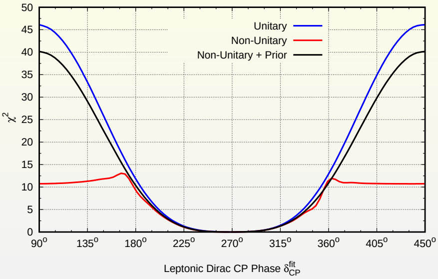
μNear at μDAR

Ge, Pasquini, Tortola & Valle [1605.01670]

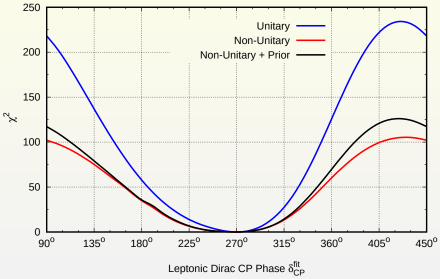


TNT2K+μNear

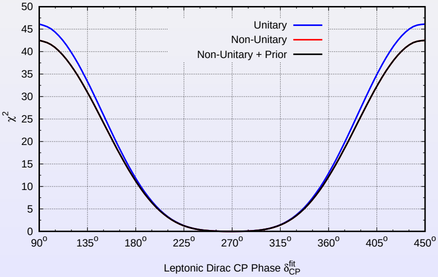
Ge, Pasquini, Tortola & Valle [1605.01670]



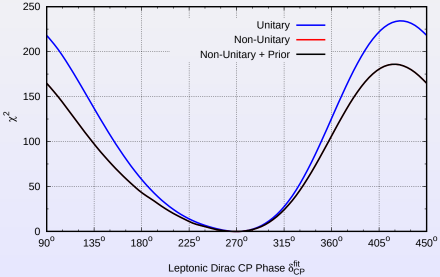
The effect of including non-unitarity at T2K+μSK [δ_{CP}^{true}= -90°, NH]



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 & Smirnov [arXiv:1607.08513]

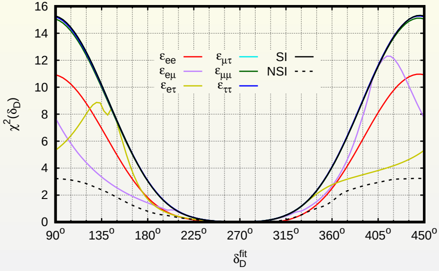
$$\mathcal{H} \equiv \frac{1}{2\mathbf{E}_\nu} U \begin{pmatrix} 0 & & \\ & \Delta m_s^2 & \\ & & \Delta m_a^2 \end{pmatrix} U^\dagger + V_{cc} \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* &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

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

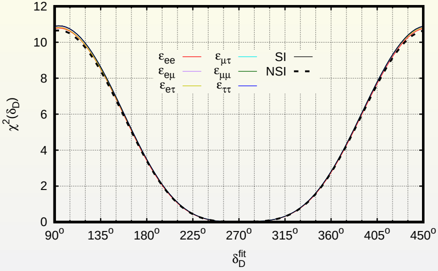
CP Sensitivity at T2K & μSK

SFG & Smirnov [arXiv:1607.08513]

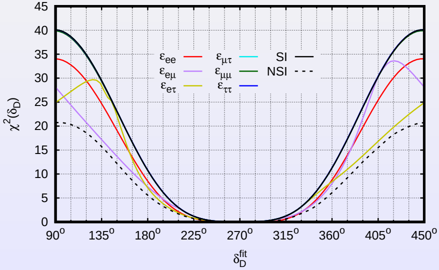
The effect of NSI on the CP sensitivity at T2K [δ_D^{true}= -90^o]



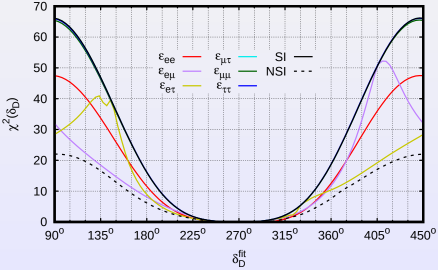
The effect of NSI on the CP sensitivity at μSK [δ_D^{true}= -90^o]



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]



CP Sensitivities

SFG & Smirnov [arXiv:1607.08513]

$\delta_D = -90^\circ$ vs 0° Event Numbers	T2K $\mathbf{114\nu + 56\bar{\nu}}$		μSK $\mathbf{212\bar{\nu}}$		T2K+μSK $\mathbf{57\nu + 268\bar{\nu}}$		νT2K+μSK $\mathbf{342\nu + 212\bar{\nu}}$	
χ^2 for **SI** & **NSI**	**4.08**	**1.54**	**2.81**	**2.75**	**11.3**	**6.10**	**18.7**	**7.59**
χ^2	**2.50**	–	**2.75**	–	**8.77**	–	**12.5**	–
$\epsilon_{ee}^{\text{bf}}$	0.69	0.57	0.48	0.47	0.81	0.63	1.07	0.70
χ^2	**4.06**	–	**2.81**	–	**11.3**	–	**18.6**	–
$\epsilon_{\mu\mu}^{\text{bf}}$	-0.02	-0.01	-0.02	-0.01	-0.02	-0.01	-0.02	-0.01
χ^2	**4.11**	–	**2.81**	–	**11.3**	–	**18.7**	–
$\epsilon_{\tau\tau}^{\text{bf}}$	0.02	0.01	0.02	0.01	0.02	0.01	0.01	0.01
χ^2	**2.68**	–	**2.81**	–	**8.01**	–	**11.7**	–
$\epsilon_{e\mu}^{\text{bf}}$	0.12	0.07	0.01	0.01	0.19	0.11	0.23	0.10
χ^2	**2.77**	–	**2.81**	–	**8.42**	–	**10.4**	–
$\epsilon_{e\tau}^{\text{bf}}$	0.25	0.14	0.01	0.01	0.37	0.21	0.51	0.30
χ^2	**4.08**	–	**2.81**	–	**11.3**	–	**18.7**	–
$\epsilon_{\mu\tau}^{\text{bf}}$	0	0	0	0	0	0	0	0

Summary – Theory

- **Horizontal Symmetry**
  - $\mathbb{Z}_2^{\mu\tau}$ $\left[G_3 \text{ v.s. } d_\nu^{(3)}\right]$
  - $\mathbb{Z}_2^{\mathrm{s}}$ $\left[G_1 \text{ v.s. } d_\nu^{(1)}\right]$ & $\overline{\mathbb{Z}}_2^{\mathrm{s}}$ $\left[G_2 \text{ v.s. } d_\nu^{(2)}\right]$
- **Residual Symmetry** as **Custodial Symmetry**
  - Full symmetry has to be broken. Otherwise, no mixing.
  - Mixing angles dictated by residual symmetry.
  - Physical observables, mixing angles & CP phase, are correlated.

$$\cos\boldsymbol{\delta}_{\mathbf{D}} = \frac{(s_s^2 - c_s^2 s_r^2)(c_a^2 - s_a^2)}{4 c_a s_a c_s s_s s_r} \qquad \cos\boldsymbol{\delta}_{\mathbf{D}} = \frac{(s_s^2 s_r^2 - c_s^2)(c_a^2 - s_a^2)}{4 c_a s_a c_s s_s s_r}$$

- **Phenomenological consequences**
  - Nonzero θ_r
  - Large δ_D
  - Non-maximal θ_a
  - Distinguishing $\mathbb{Z}_2^s$ & $\overline{\mathbb{Z}}_2^s$ with NOνA, T2K, μDAR

Summary – Experiment

- **Better CP measurement than T2K, T2KII, T2HK, T2KK**
  - 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

Thank You!