Leptonic Dirac CP Phase with Residual Symmetry & μDAR

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SFG, Duane A. Dicus, Wayne W. Repko, PLB **702**, 220 (2011) [arXiv:1104.0602]
SFG, Duane A. Dicus, Wayne W. Repko, PRL **108**, 041801 (2012) [arXiv:1108.0964]
Andrew D. Hanlon, **SFG**, Wayne W. Repko, PLB **729**, 185-191 (2014) [arXiv:1308.6522]
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, [arXiv:1605.01670]
SFG, Alexei Smirnov, [arXiv:1607.xxxxx]

ν Oscillation Data

(for NH)	-1σ	Best Value	$+1\sigma$
$\boldsymbol{\Delta m_s^2} \equiv \Delta m_{12}^2\, (\mathbf{10^{-5}}\mathrm{eV}^2)$	7.42	**7.60**	7.79
$\lvert\boldsymbol{\Delta m_a^2} \equiv \Delta m_{13}^2\rvert\, (\mathbf{10^{-3}}\mathrm{eV}^2)$	2.41	**2.48**	2.53
$\sin^2\theta_s$ ($\theta_s \equiv \theta_{12}$)	0.307 (33.6°)	0.323 (**34.6°**)	0.339 (35.6°)
$\sin^2\theta_a$ ($\theta_a \equiv \theta_{23}$)	0.439 (41.5°)	0.567 (**48.9°**)	0.599 (50.8°)
$\sin^2\theta_r$ ($\theta_r \equiv \theta_{13}$)	0.0214 (8.4°)	0.0234 (**8.8°**)	0.0254 (9.2°)
δ_D, δ_{Mi}	?, **??**	?, **??**	?, **??**

Forero, Tortola & Valle, arXiv:1405.7540

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:**

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

$\Rightarrow$ **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]

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

- 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 $\mathbf{d}_\ell = \mathrm{diag}(e^{i\beta_1}, e^{i\beta_2}, e^{i\beta_3})$.

Symmetry v.s. Mixing

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

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

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

- θ_s parameterized in terms of $\mathbf{k}$: $\boxed{\tan\theta_s = \sqrt{2}/k}$

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

$\mathbf{k} = 2 \quad \theta_s = 35.3^\circ$ **[TBM]**

$\mathbf{k} = \frac{3}{\sqrt{2}} \quad \theta_s = 33.7^\circ$

$\mathbf{k} = \sqrt{6} \quad \theta_s = 30.0^\circ$

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

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

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

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 $\Uparrow$ $\Downarrow$ **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 $d_\nu^i = \text{diag}\,(\pm 1, \pm 1, \pm 1)$

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

Residual Symmetry as Effective Theory

- **Full symmetry HAS TO be Broken!**
  - Fermion needs to acquire mass.
  - Non-trivial mixing $\boxed{V_{\rm PMNS} = V^\dagger_\ell V_\nu}$
- 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**.

Example Zee-A_4 Model

hep-ph/0508278

Lepton's Representation:

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

A_4 invariant Lagrangian:

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

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

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

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

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

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

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

$\mathbb{Z}_2^s$ (G_1)	$\overline{\mathbb{Z}}_2^s$ (G_2)
$\cos\delta_D = \frac{(s_s^2 - c_s^2 s_r^2)(c_a^2 - s_a^2)}{4 c_a s_a c_s s_s s_r}$	$\cos\delta_D = \frac{(s_s^2 s_r^2 - c_s^2)(c_a^2 - s_a^2)}{4 c_a s_a c_s s_s s_r}$
$\sin\theta_r = \pm\left[\pm\sqrt{c_D^2 + \cot^2 2\theta_a} - c_D\right]\tan 2\theta_a (\tan\theta_s)^{\pm 1}$	
$\frac{\delta_r}{\delta_a} = -\frac{\tan\theta_s}{\cos\delta_D}$	$\frac{\delta_r}{\delta_a} = +\frac{\cot\theta_s}{\cos\delta_D}$

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]

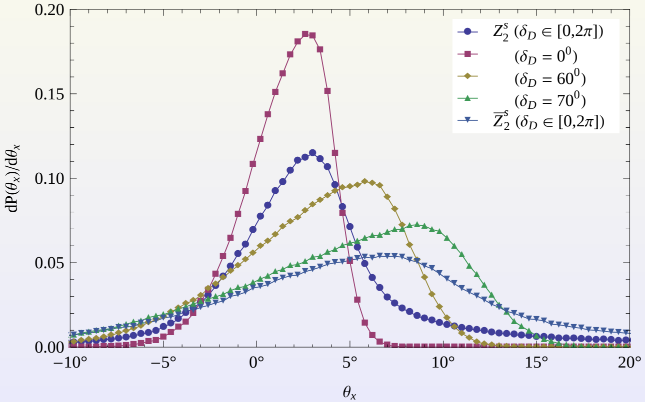
$$\sqrt{2}s_a - 1 = -\frac{1}{\sqrt{2}} s_r \cos\delta_D$$

- **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 θ_r (θ_x)

$$\sin\theta_r = \pm\left[\pm\sqrt{\cos^2\delta_D + \cot^2 2\theta_a} - \cos\delta_D\right]\tan 2\theta_a \tan^{\pm}\theta_s$$

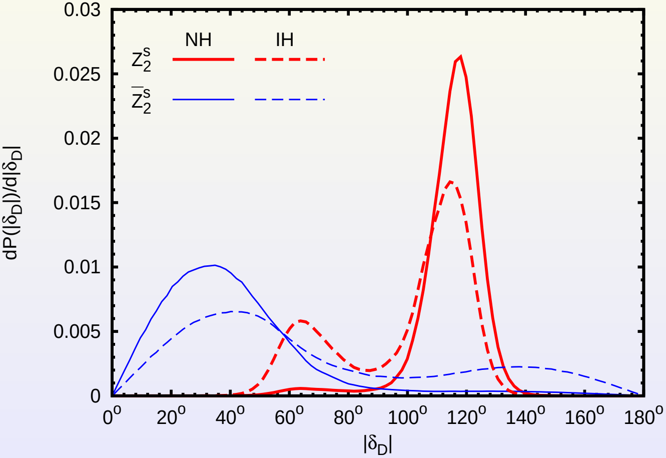


MINOS ($\theta_r \in [3^\circ, 9^\circ]/[5^\circ, 11^\circ]$)

T2K ($\theta_r \in [5^\circ, 16^\circ]/[6^\circ, 18^\circ]$) @ 90% C.L.

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!

$$G_\nu = V_\nu d_\nu V_\nu^\dagger$$

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

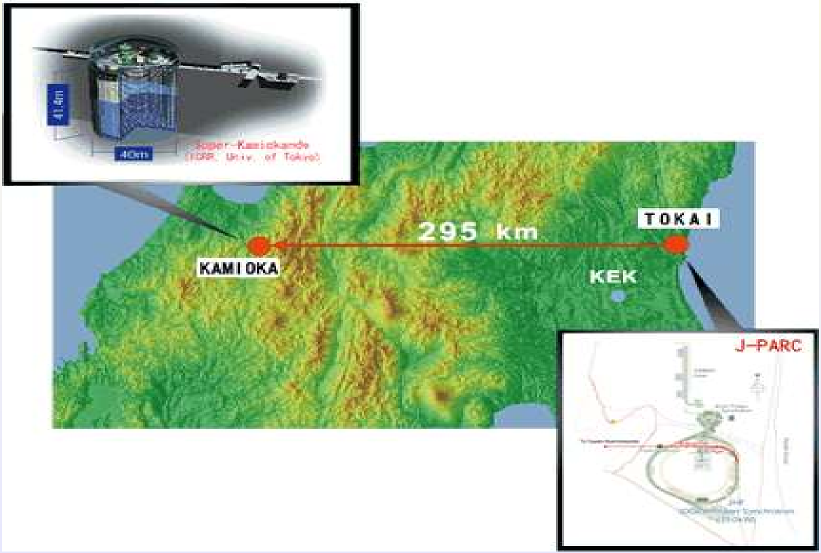
(for NH)	-1σ	Best Value	$+1\sigma$
$\sin^2\theta_s$ ($\theta_s \equiv \theta_{12}$)	0.307 (33.6°)	0.323 (**34.6°**)	0.339 (35.6°)
$\sin^2\theta_a$ ($\theta_a \equiv \theta_{23}$)	0.439 (41.5°)	0.567 (**48.9°**)	0.599 (50.8°)
$\sin^2\theta_r$ ($\theta_r \equiv \theta_{13}$)	0.0214 (8.4°)	0.0234 (**8.8°**)	0.0254 (9.2°)
δ_D	?	?	?

Forero, Tortola & Valle, arXiv:1405.7540

Why neutrino mass & oscillation?

- Higgs boson for electroweak symmetry breaking & mass.
- Chiral symmetry breaking for mass.
- **The word 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 Exp



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**,

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

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

- $\nu_\mu \to \nu_\mu$ 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

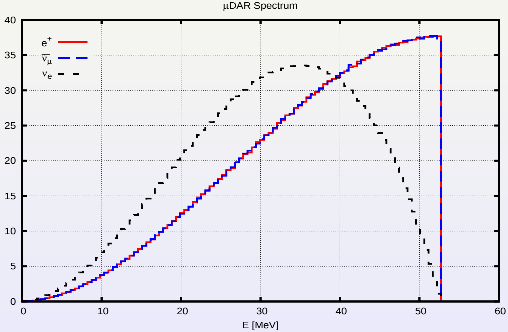
Accelerator experiment, such as **T2(H)K**, uses off-axis beam to compare ν_e & $\overline{\nu}_e$ appearance @ the oscillation maximum.

- **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 $\Rightarrow$ Difficult to reduce the uncertainty.
  - **Degeneracy**:
    - Only $\sin \delta_D$ appears in $P_{\nu_\mu \to \nu_e}$ & $P_{\overline{\nu}_\mu \to \overline{\nu}_e}$.
    - 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 $\overline{\nu}$ 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: $\boldsymbol{\mu^{+}} \to \mathbf{e^{+}} + \boldsymbol{\overline{\nu}_{\mu}} + \boldsymbol{\nu_{e}}$.

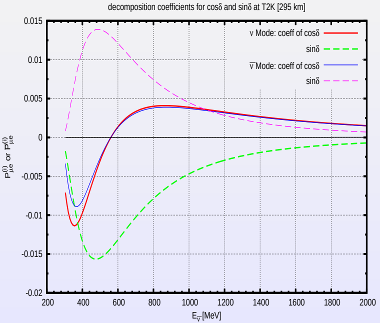


- $\overline{\nu}_{\mu}$ travel in all directions, oscillating as they go.
- A detector measures the $\overline{\nu}_{e}$ from $\boldsymbol{\overline{\nu}_{\mu} \to \overline{\nu}_{e}}$ **oscillation**.

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])



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$\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**) [1401.3977]
  - **T**okai '**N** **T**oyama to(**2**) **K**amioka (**TNT2K**) [1506.05023]

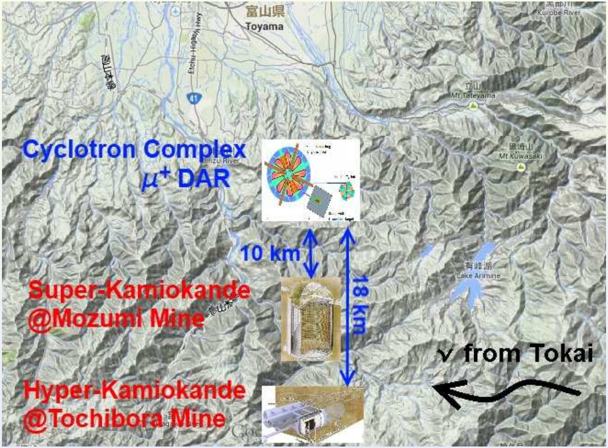
μDARTS – JUNO & RENO50

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

- China Atomic Energy Center has a proposal for cyclotron

TNT2K

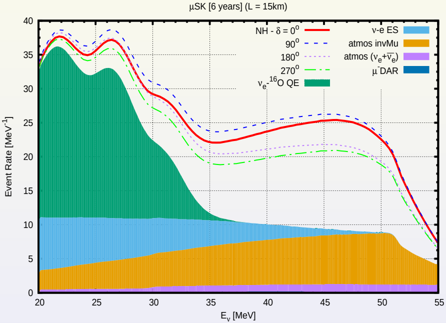
- T2(H)K + μSK + μHK

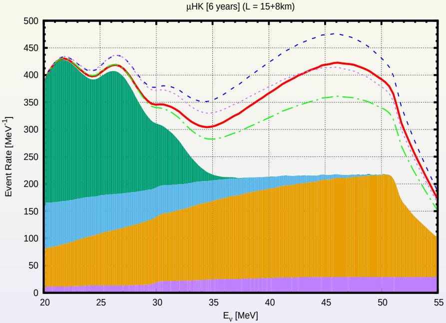


- μDAR is also useful for **material**, **medicine** industries in Toyama

Event Shape @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]



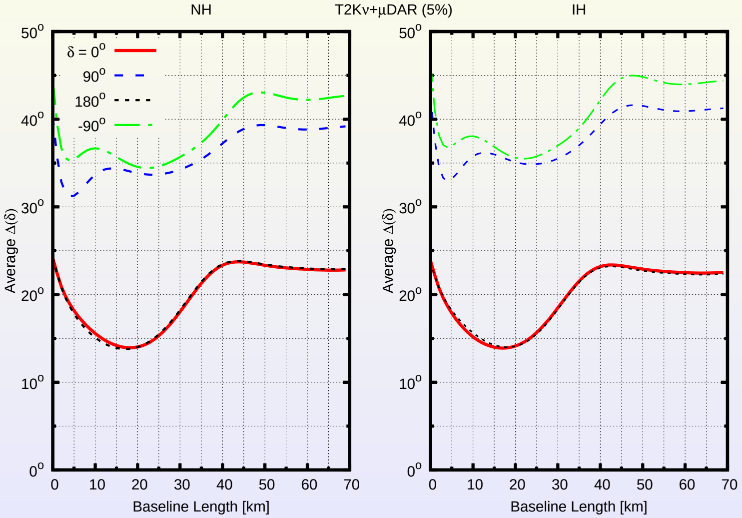


Expected μDAR IBD signal from 6 yrs of running @ SK (15km) & HK (23km) with NH.

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

δ_D Precision @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]



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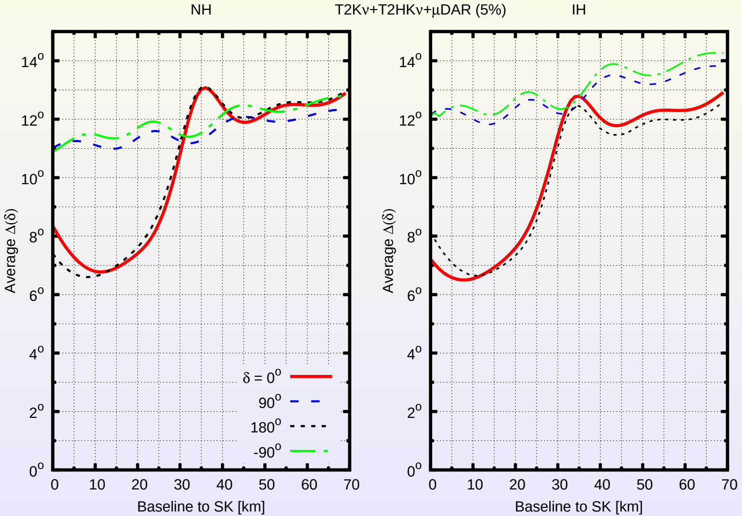

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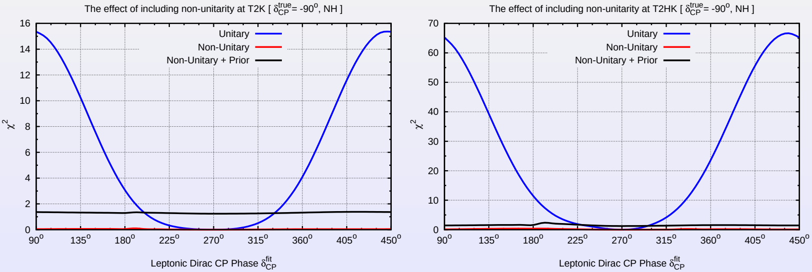
Non-Unitarity Mixing (NUM)

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**

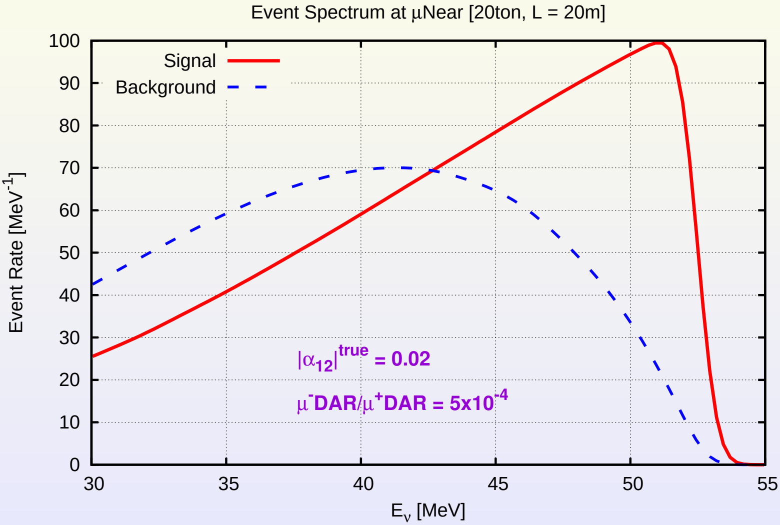
$$\bar{\nu} M_D \mathcal{N} + h.c. + \overline{\mathcal{N}} M_N \mathcal{N} = \begin{pmatrix} \bar{\nu} & \overline{\mathcal{N}} \end{pmatrix} \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \begin{pmatrix} \nu \\ \mathcal{N} \end{pmatrix}$$

- **Seeaw Mechanism**

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

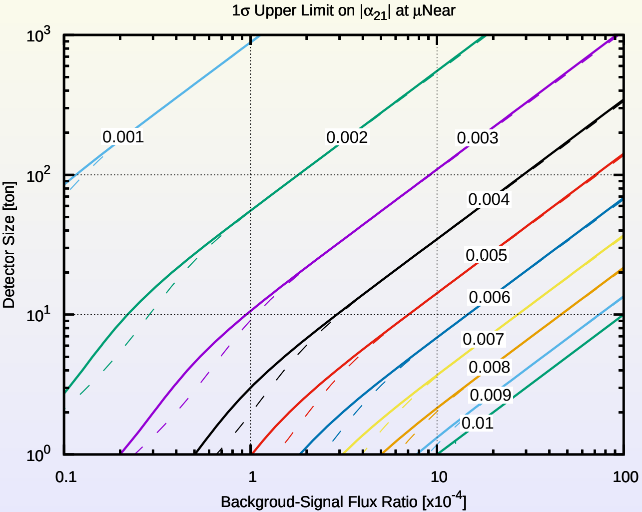
μNear at μDAR

Ge, Pasquini, Tortola & Valle [1605.01670]



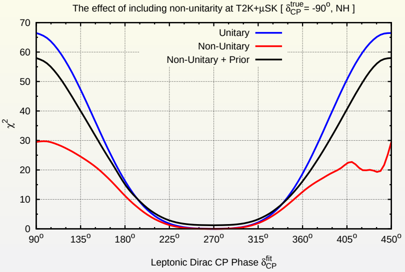
μNear at μDAR

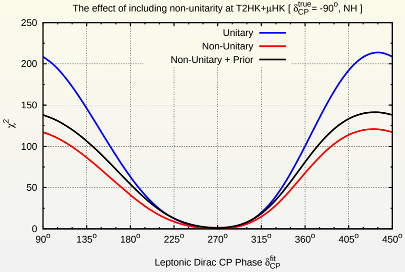
Ge, Pasquini, Tortola & Valle [1605.01670]

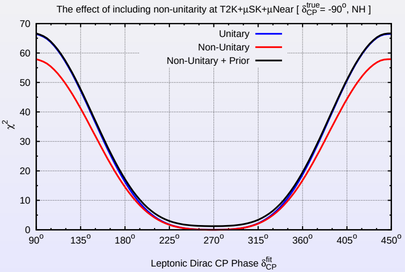


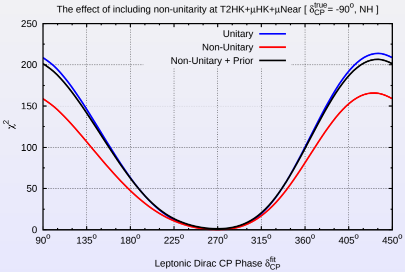
TNT2K+μNear

Ge, Pasquini, Tortola & Valle [1605.01670]









Non-Standard Interaction

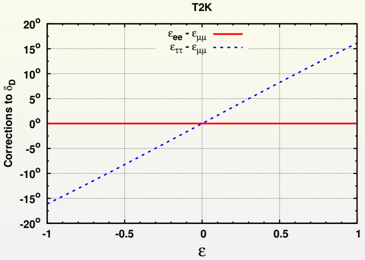
SFG & Smirnov [arXiv:1607.xxxxx]

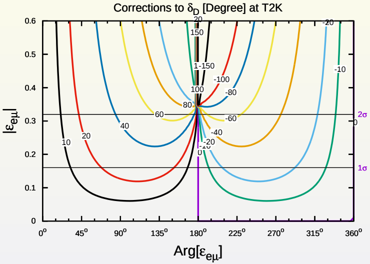
$$\mathcal{H} \equiv \frac{1}{2E_\nu} U \begin{pmatrix} 0 & & \\ & \Delta m_s^2 & \\ & & \Delta m_a^2 \end{pmatrix} U^\dagger + V_{cc} \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^*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

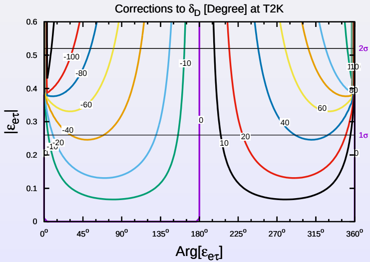
- Standard Interaction – V_{cc} (also V_{nc})
- Non-Standard Interaction – $\epsilon_{\alpha\beta}$
  - Diagonal $\epsilon_{\alpha\alpha}$ are real
  - Off-diagonal $\epsilon_{\alpha\neq\beta}$ are complex
  - Both can fake CP
- Z' in LMA-Dark model with $L_\mu - L_\tau$ gauged as $U(1)$
  - $M_{Z'}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

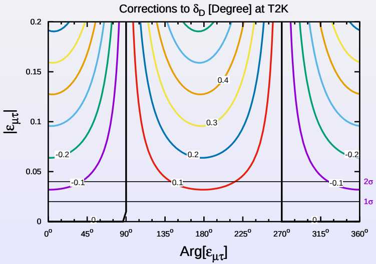
Faked CP with NSI

SFG & Smirnov [arXiv:1607.xxxxx]



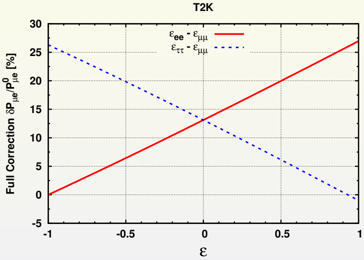


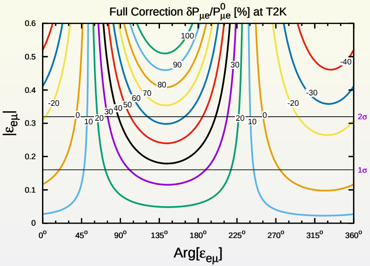


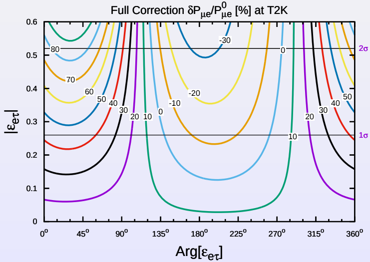


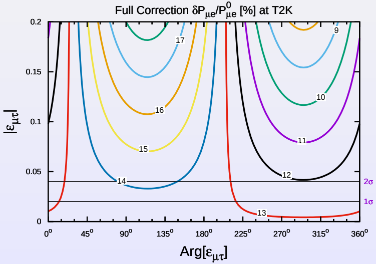
The effect of NSI @ T2K

SFG & Smirnov [arXiv:1607.xxxxx]



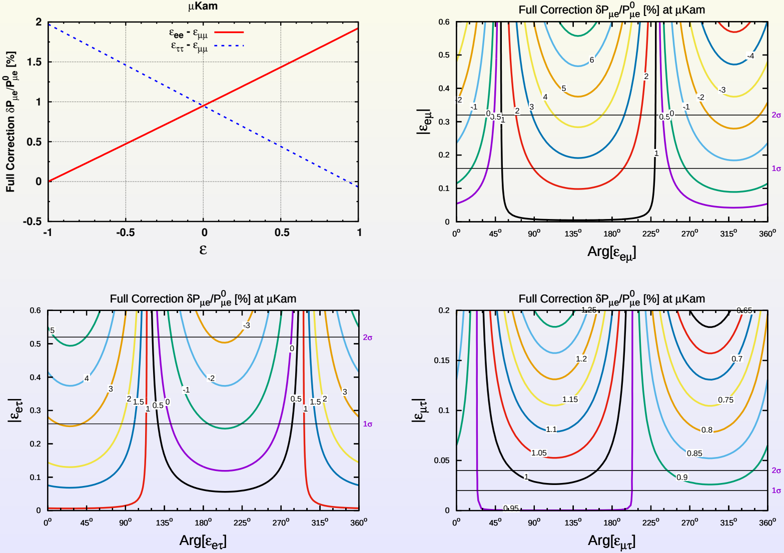






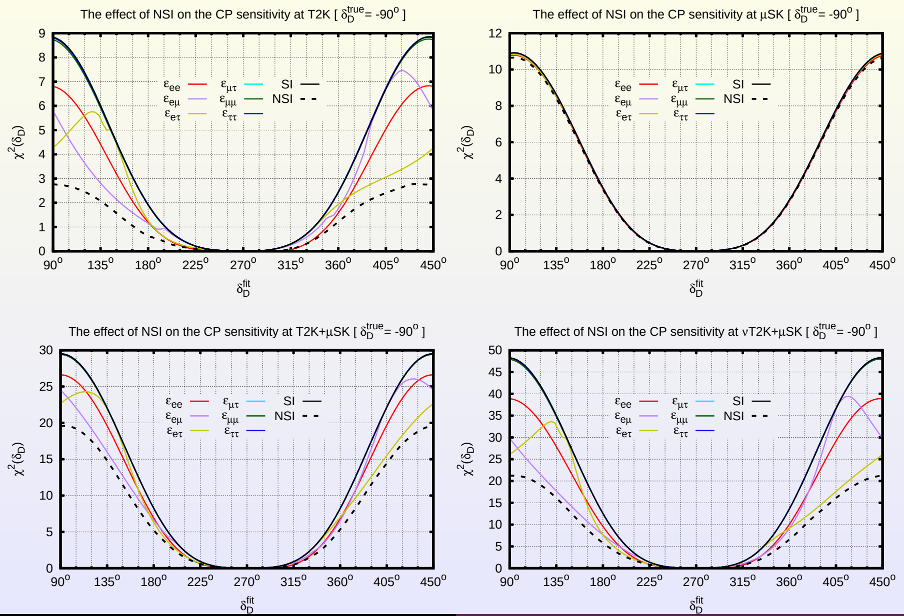
The effect of NSI @ μKam

SFG & Smirnov [arXiv:1607.xxxxx]



CP Sensitivity at T2K & μSK

SFG & Smirnov [arXiv:1607.xxxxx]



CP Sensitivities

SFG & Smirnov [arXiv:1607.xxxxx]

$\delta_D = -90^\circ$ vs 0° Event Numbers	T2K $57\nu + 28\bar{\nu}$		μSK $212\bar{\nu}$		T2K+μSK $57\nu + 240\bar{\nu}$		νT2K+μSK $171\nu + 212\bar{\nu}$	
χ^2 for **SI** & **NSI**	**2.43**	**1.21**	**4.13**	**2.75**	**8.20**	**5.33**	**13.6**	**6.60**
ϵ_{ee} χ^2	**1.58**	–	**4.09**	–	**6.81**	–	**10.1**	–
ϵ_{ee} best fit	0.60	0.55	0.47	0.47	0.69	0.65	0.90	0.69
$\epsilon_{\mu\mu}$ χ^2	**2.42**	–	**4.13**	–	**8.20**	–	**13.6**	–
$\epsilon_{\mu\mu}$ best fit	-0.02	-0.01	-0.02	-0.01	-0.02	-0.01	-0.02	0.09
$\epsilon_{\tau\tau}$ χ^2	**2.43**	–	**4.13**	–	**8.20**	–	**13.6**	–
$\epsilon_{\tau\tau}$ best fit	0.02	0.01	0.02	0.01	0.02	0.01	0.01	0.10
$\epsilon_{e\mu}$ χ^2	**1.76**	–	**4.11**	–	**6.54**	–	**9.12**	–
$\epsilon_{e\mu}$ best fit	0.10	0.04	0.02	0.01	0.15	0.11	0.19	0.10
$\epsilon_{e\tau}$ χ^2	**1.94**	–	**4.13**	–	**7.02**	–	**9.17**	–
$\epsilon_{e\tau}$ best fit	0.17	0.11	0.01	0.01	0.27	0.24	0.43	0.16
$\epsilon_{\mu\tau}$ χ^2	**2.43**	–	**4.13**	–	**8.20**	–	**13.6**	–
$\epsilon_{\mu\tau}$ best fit	0	0	0	0	0	0	0	0

Summary

- **Horizontal Symmetry**
  - $\mathbb{Z}_2^{\mu\tau}$ $\left[G_3 \text{ v.s. } d_\nu^{(3)}\right]$
  - $\mathbb{Z}_2^s$ $\left[G_1 \text{ v.s. } d_\nu^{(1)}\right]$ & $\overline{\mathbb{Z}}_2^s$ $\left[G_2 \text{ v.s. } d_\nu^{(2)}\right]$
- **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.
- **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

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

Thank You!

Mixing Dictated by $\mathbb{Z}_2^s$

- Mixing matrix,

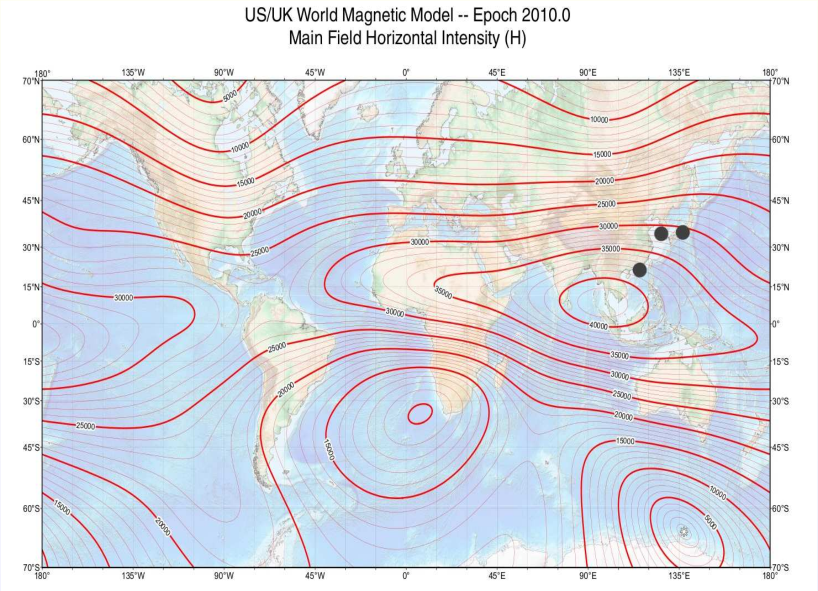
$$\mathbf{V}_\nu \equiv \mathcal{P}_\nu \mathcal{U}_\nu \mathcal{Q}_\nu$$

- $\mathbf{G}_\nu = \mathbf{V}_\nu \mathbf{d}_\nu \mathbf{V}_\nu^\dagger \quad \Rightarrow \quad \widetilde{G} \equiv \mathcal{P}_\nu^\dagger \mathbf{G_1} \mathcal{P}_\nu = \mathcal{U}_\nu \mathbf{d}_\nu^{(1)} \mathcal{U}_\nu^\dagger$

$$\widetilde{G}_1 = \frac{1}{2+k^2} \begin{pmatrix} \mathbf{2-k^2} & 2ke^{-i(\phi_1-\phi_2)} & 2ke^{-i(\phi_1-\phi_3)} \\ 2ke^{i(\phi_1-\phi_2)} & \mathbf{k^2} & -2e^{-i(\phi_2-\phi_3)} \\ 2ke^{i(\phi_1-\phi_3)} & -2e^{i(\phi_2-\phi_3)} & \mathbf{k^2} \end{pmatrix}$$

$$\begin{aligned}
\widetilde{\mathbf{G}}_{11} &= s_r^2 - c_r^2(c_s^2 - s_s^2)\,, \\
\widetilde{G}_{12} = \widetilde{G}_{21}^* &= 2c_r c_s \left(c_s s_a s_r e^{i\delta_D} - c_a s_s \right)\,, \\
\widetilde{G}_{13} = \widetilde{G}_{31}^* &= -2c_r c_s \left(c_s c_a s_r e^{i\delta_D} + s_a s_s \right)\,, \\
\widetilde{\mathbf{G}}_{22} &= (c_s^2 - s_s^2)c_a^2 + 4c_a s_a c_s s_s s_r \cos\delta_D + \left[c_r^2 - (c_s^2 - s_s^2)s_r^2 \right] s_a^2\,, \\
\widetilde{G}_{23} = \widetilde{G}_{32}^* &= \left[3c_s^2 - 2 - c_s^2(c_r^2 - s_r^2) \right] c_a s_a - 2\left[(c_a^2 - s_a^2)\cos\delta_D + i\sin\delta_D \right] c_s s_s s_r\,, \\
\widetilde{\mathbf{G}}_{33} &= (c_s^2 - s_s^2)s_a^2 - 4c_a s_a c_s s_s s_r \cos\delta_D + \left[c_r^2 - (c_s^2 - s_s^2)s_r^2 \right] c_a^2\,.
\end{aligned}$$

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