

Measure the Leptonic Dirac CP Phase with Muon Decay at Rest

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SFG, Alexei Smirnov, JHEP **1610** (2016) 138 [arXiv:1607.08513]

SFG, Pedro Pasquini, M. Tortola, J. W. F. Valle, [arXiv:1605.01670]

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

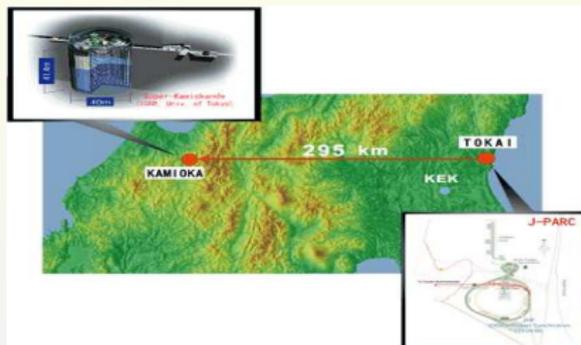
ν Oscillation Data

(for NH)	-1σ	Best Value	$+1\sigma$
$\delta m_s^2 \equiv \delta m_{12}^2$ (10^{-5}eV^2)	7.42	7.60	7.79
$ \delta m_a^2 \equiv \delta m_{13}^2 $ (10^{-3}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	?	?	?

Forero, Tortola & Valle, [arXiv:1405.7540]

CP Measurement @ Accelerator Exps

- T2K



- NO ν A



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

The Dirac CP Phase δ_D @ Accelerator Exp

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

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

$$\bar{P}_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}$$

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

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

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

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

The Dirac CP Phase δ_D @ Accelerator Exp

Accelerator experiment, such as **T2K**, uses off-axis beam to compare ν_e & $\bar{\nu}_e$ appearance @ the oscillation maximum.

- **Disadvantages:**

- **Efficiency:**

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

- **Degeneracy:**

- Only **$\sin \delta_D$** appears in $P_{\nu_\mu \rightarrow \nu_e}$ & $P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}$.
- Cannot distinguish δ_D from $\pi - \delta_D$.

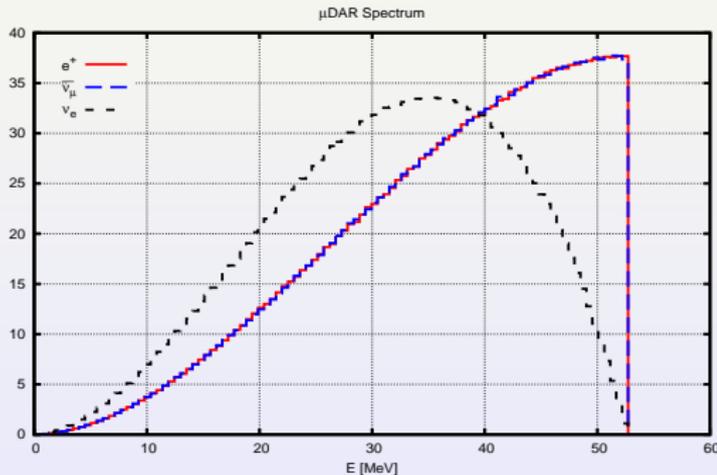
- **CP Uncertainty** $\frac{\partial P_{\mu e}}{\partial \delta_D} \propto \cos \delta_D \Rightarrow \Delta(\delta_D) \propto \mathbf{1 / \cos \delta_D}$.

- **Solution:**

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

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

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

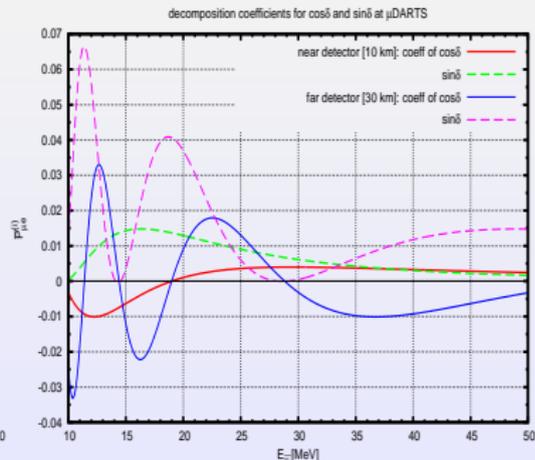
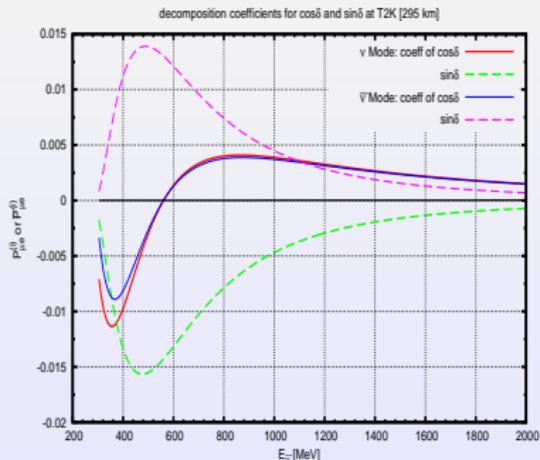


- $\bar{\nu}_\mu$ travel in all directions, oscillating as they go.
- A detector measures the $\bar{\nu}_e$ from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation.

Accelerator + μ DAR Experiments

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

- **Efficiency:**
 - $\bar{\nu}$ @ high intensity, μ DAR is plentiful enough.
 - Accelerator Exps can devote all run time to the ν mode. With same run time, the statistical uncertainty drops by $\sqrt{3}$.
- **Degeneracy: (decomposition in propagation basis [1309.3176])**



DAE δ ALUS

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

New Proposals

1 μ DAR source + 2 detectors

Advantages:

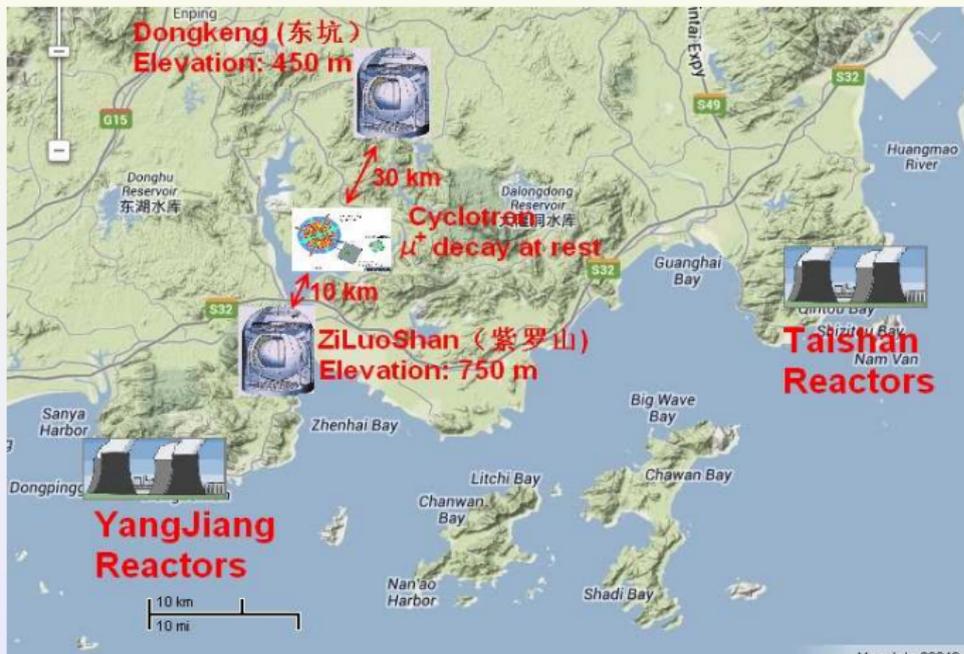
- Full (**100%**) duty factor!
- **Lower** intensity: $\sim 9\text{mA}$ [$\sim 4\times$ lower than DAE δ ALUS]
- Not far beyond the current state-of-art technology of cyclotron [**2.2mA** @ Paul Scherrer Institute]
- MUCH **cheaper** & technically **easier**.
 - Only one cyclotron.
 - Lower intensity.

Disadvantage?

- A second detector!
 - μ DAR with Two Scintillators (μ DARTS) [1401.3977]
 - Tokai 'N Toyama to(2) Kamioka (TNT2K) [1506.05023]

μ DARTS – JUNO & RENO50

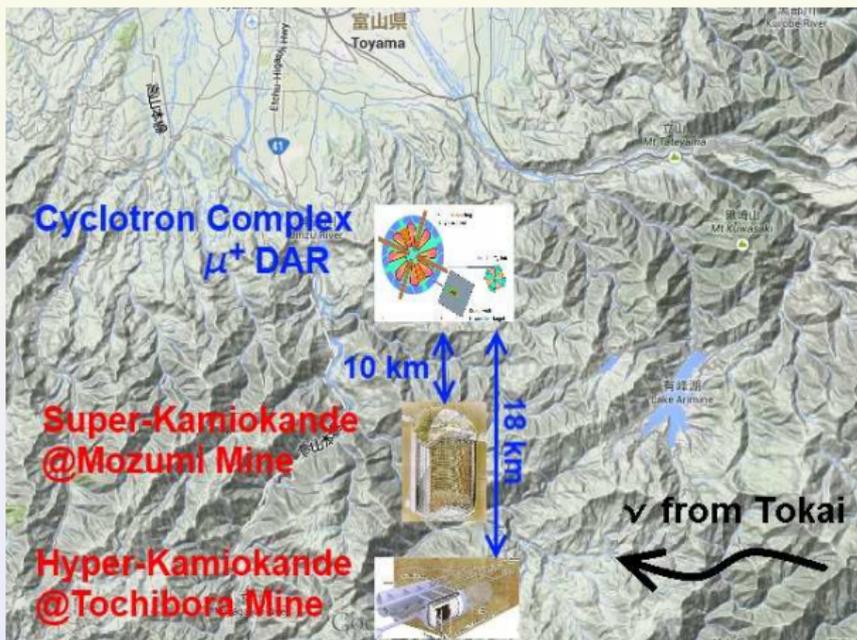
- **Two detectors** are suggested to overcome the **unknown energy response**. [Ciuffoli et al., PRD 2014; 1307.7419]



- China Atomic Energy Center is proposing a cyclotron.

TNT2K

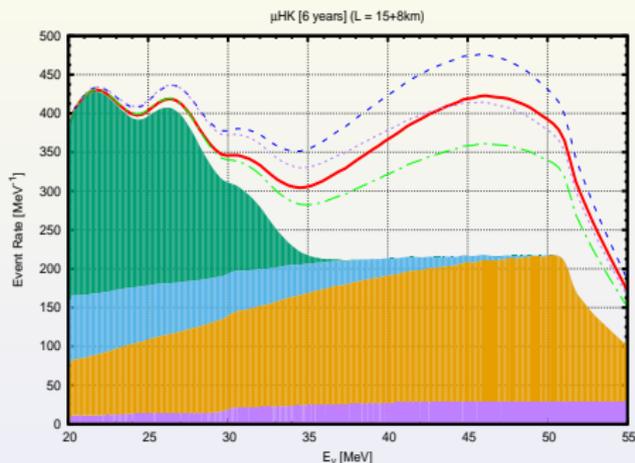
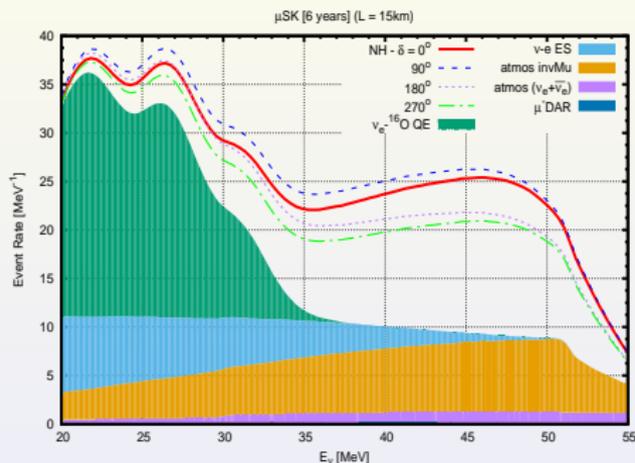
- $T2(H)K + \mu SK + \mu HK$



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

Event Shape @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]

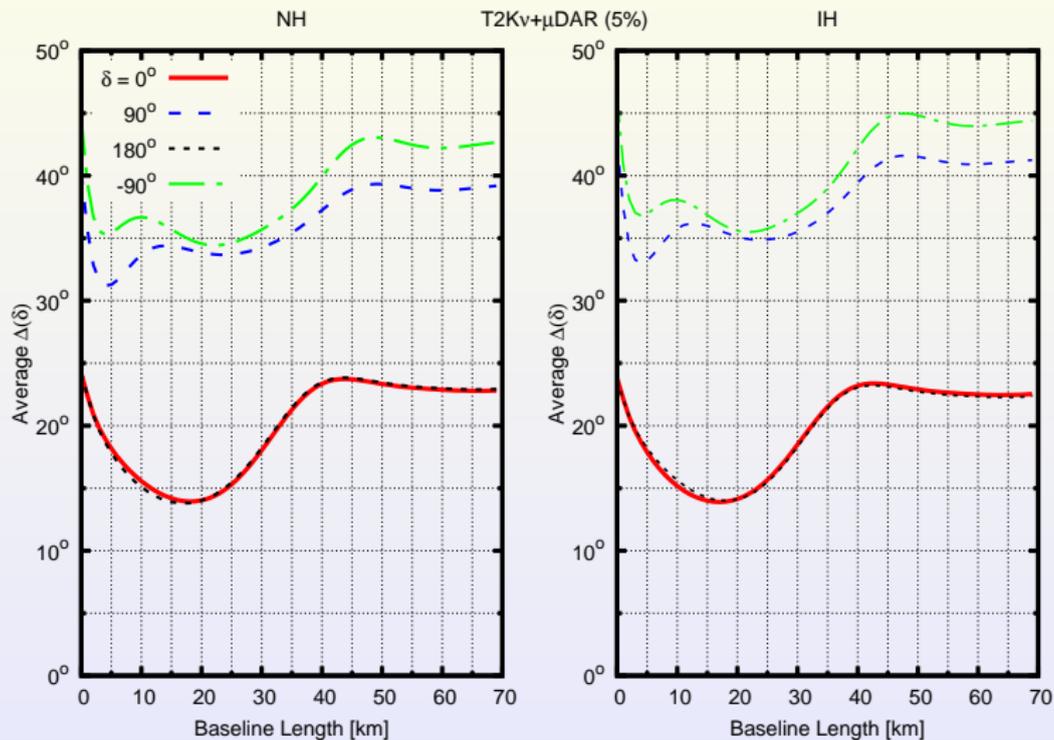


Expected μ DAR IBD signal from 6 yrs of running @ SK (15km) & HK (23km) with NH.

Simulated by [NuPro](http://nupro.hepforge.org/), <http://nupro.hepforge.org/>

δ_D Precision @ TNT2K

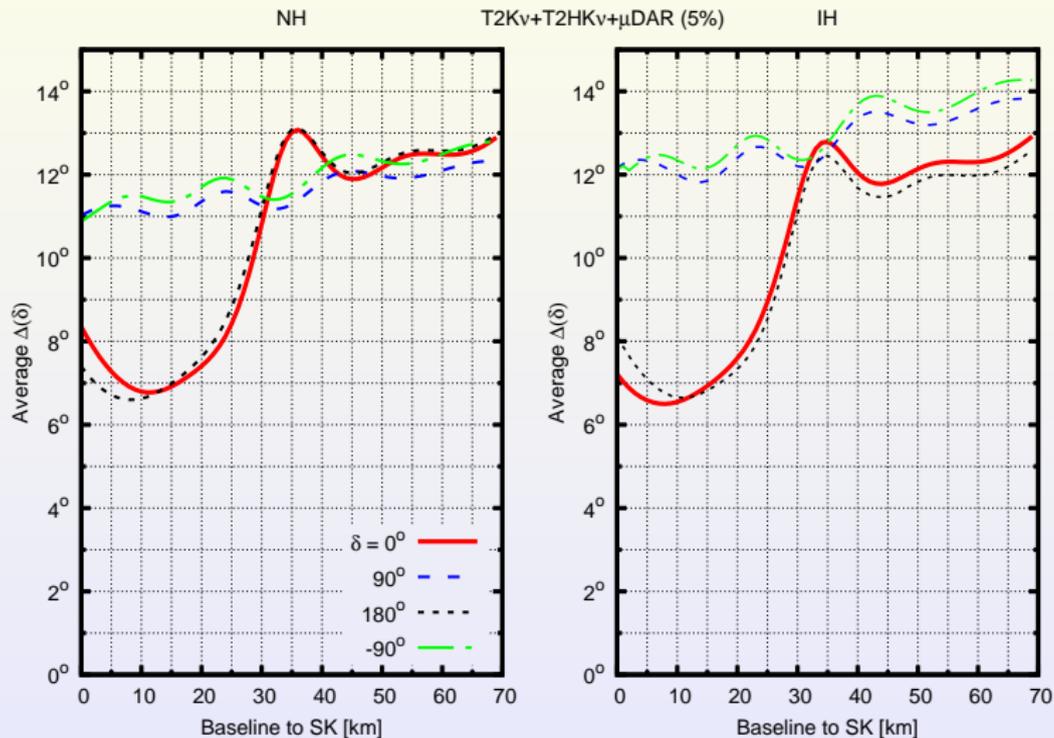
Evslin, Ge & Hagiwara [1506.05023]



Simulated by [NuPro](http://nupro.hepforge.org/), <http://nupro.hepforge.org/>

δ_D Precision @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]



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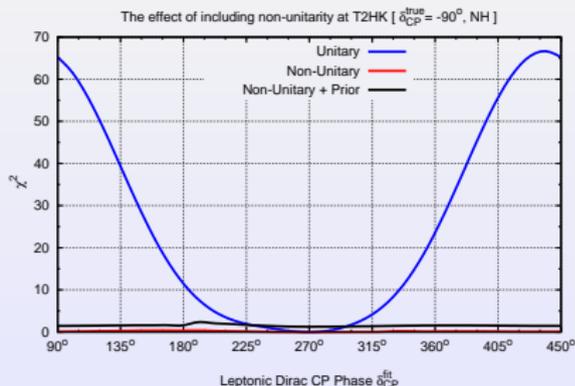
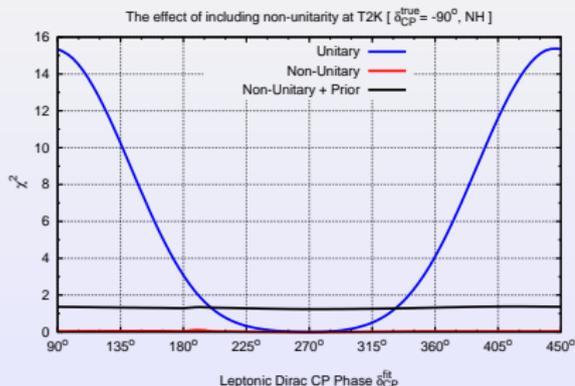
Non-Unitarity Mixing (NUM)

Ge, Pasquini, Tortola & Valle

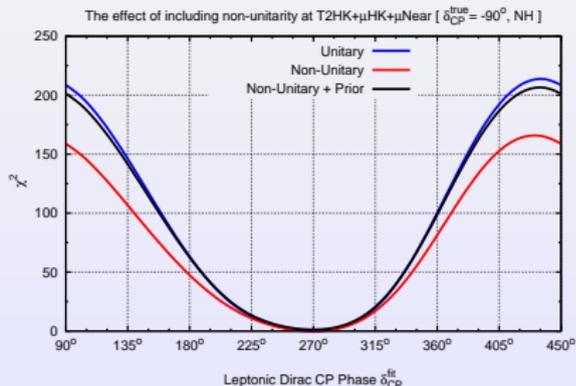
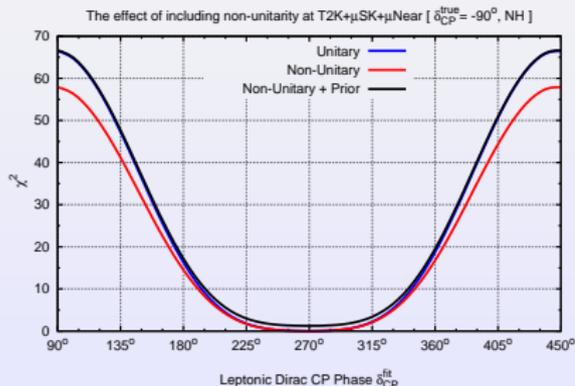
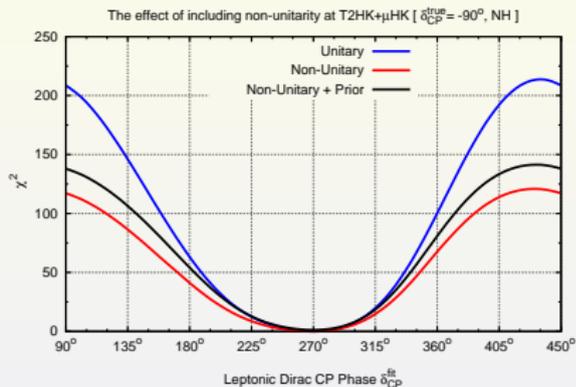
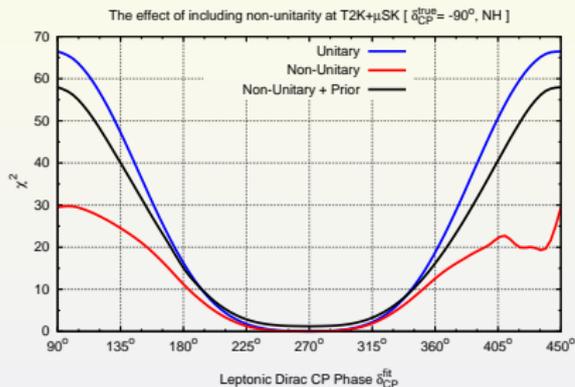
[1605.01670]

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

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



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

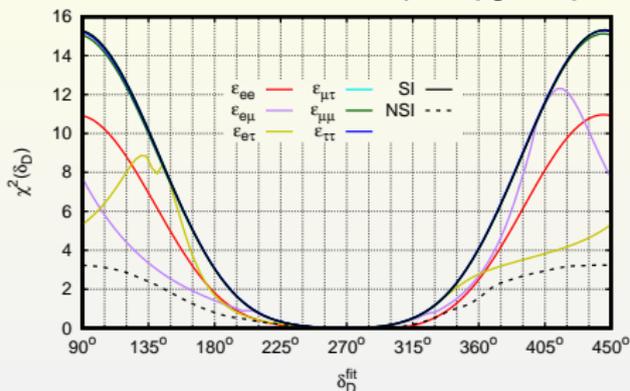


$$\mathcal{H} \equiv \frac{1}{2\mathbf{E}_\nu} U \begin{pmatrix} 0 & & \\ & \Delta m_s^2 & \\ & & \Delta m_a^2 \end{pmatrix} U^\dagger + V_{CC} \begin{pmatrix} \mathbf{1} + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^*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

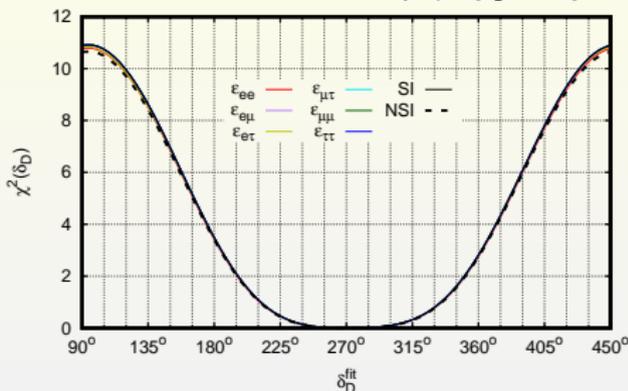
- **Standard Interaction** – V_{CC} (also V_{nc})
- **Non-Standard Interaction** – $\epsilon_{\alpha\beta}$
 - Diagonal $\epsilon_{\alpha\alpha}$ are real
 - Off-diagonal $\epsilon_{\alpha\neq\beta}$ are complex
 - Both can fake CP
- Z' in **LMA-Dark** model with $L_\mu - L_\tau$ gauged as $U(1)$
 -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

CP Sensitivity at T2K & μ SK SFG & A. Smirnov [arXiv:1607.08513]

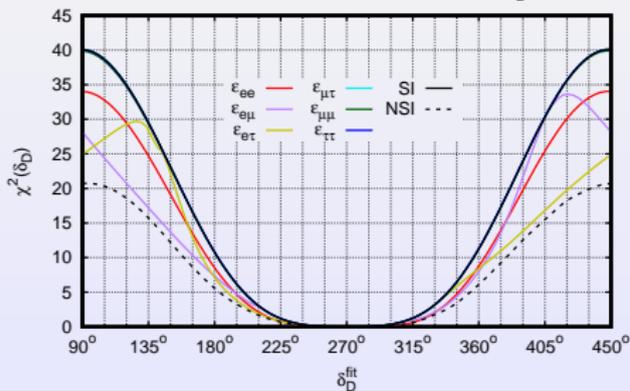
The effect of NSI on the CP sensitivity at T2K [$\delta_D^{\text{true}} = -90^\circ$]



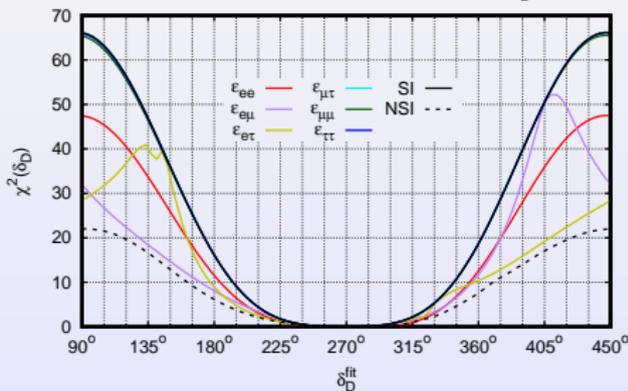
The effect of NSI on the CP sensitivity at μ SK [$\delta_D^{\text{true}} = -90^\circ$]



The effect of NSI on the CP sensitivity at T2K+ μ SK [$\delta_D^{\text{true}} = -90^\circ$]



The effect of NSI on the CP sensitivity at ν T2K+ μ SK [$\delta_D^{\text{true}} = -90^\circ$]



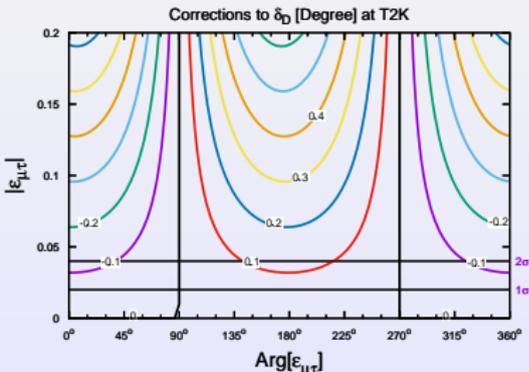
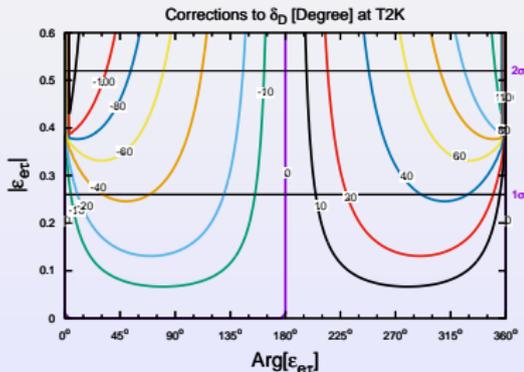
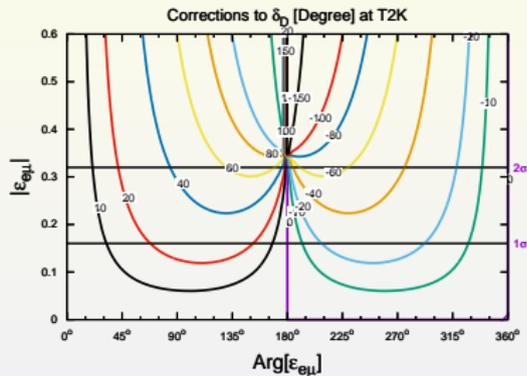
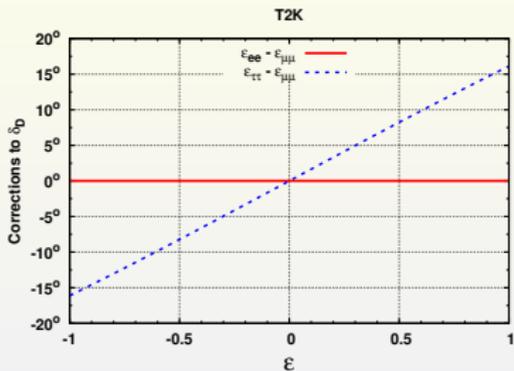
Summary

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

Thank You!

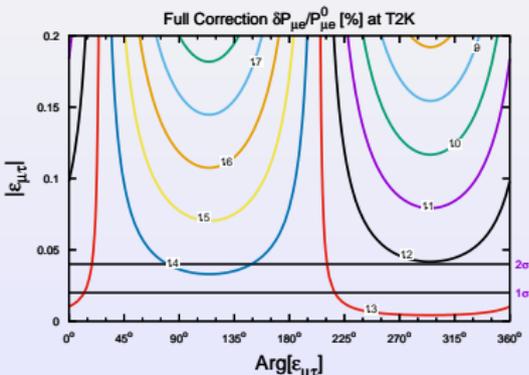
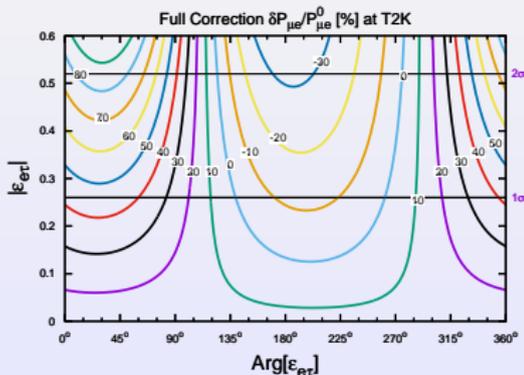
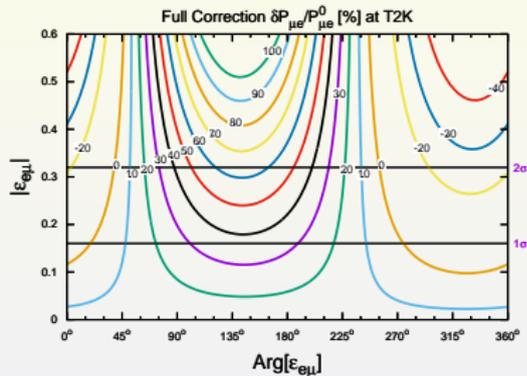
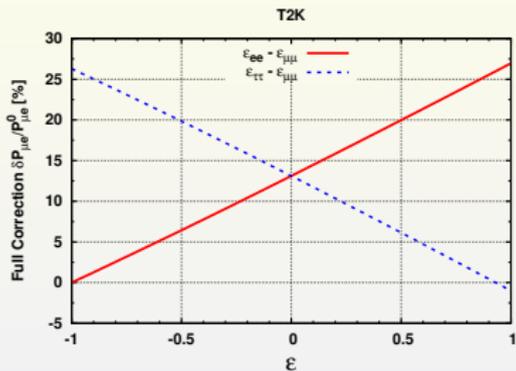
Faked CP with NSI

SFG & Alexei Smirnov [arXiv:1607.08513]



The effect of NSI @ T2K

SFG & Alexei Smirnov [arXiv:1607.08513]



The effect of NSI @ μ SK

SFG & Alexei Smirnov [arXiv:1607.08513]

