Sensitivity of μDAR Experiment to CP Violation

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SFG, Alexei Smirnov, [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 Mass & Mixing

- **Mass & Mixing $\Rightarrow$ Oscillation:**

$$\nu_\alpha(t,L) = \sum_{i\beta} V_{\alpha i} e^{-i(E_i t - p_i L)} V^*_{\beta i} \nu_\beta \equiv \sum_\beta A_{\alpha\beta}\nu_\beta$$

$$P_{\alpha\beta}\big|_{\alpha\neq\beta} \equiv |A_{\alpha\beta}|^2 = \sin^2 2\theta \sin^2\left(\delta m^2 \frac{L}{4E}\right)$$

- **Flavor v.s. Mass** Eigenstates:

$$\nu_\alpha = \sum_i V_{\alpha i}\, \nu_i$$

$$V = \begin{pmatrix} c_s c_r & s_s c_r & s_r e^{-i\delta_D} \\ -s_s c_a - c_s s_a s_r e^{i\delta_D} & +c_s c_a - s_s s_a s_r e^{i\delta_D} & s_a c_r \\ +s_s s_a - c_s c_a s_r e^{i\delta_D} & -c_s s_a - s_s c_a s_r e^{i\delta_D} & c_a c_r \end{pmatrix}$$

[$(s,a,r) \equiv (12,23,13)$ for (**solar, atmospheric, reactor**) angles]

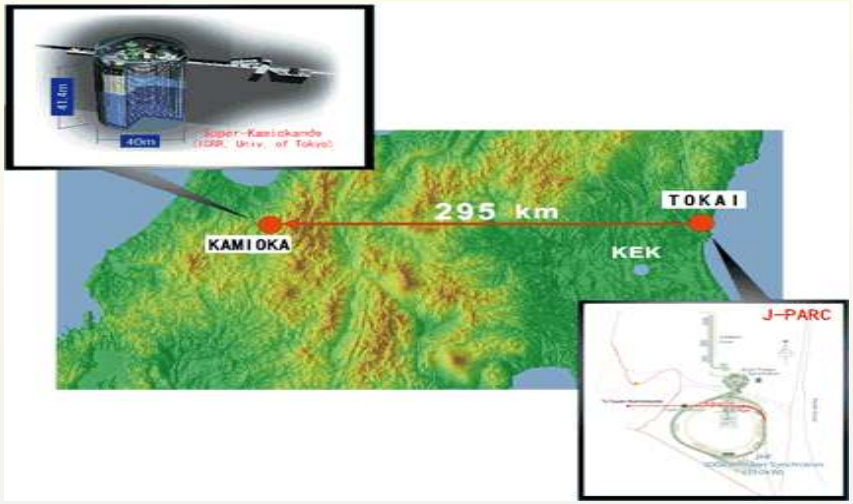
ν Oscillation Data

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

Forero, Tortola & Valle, arXiv:1405.7540

CP Measurement @ Accelerator Exps

- T2K



- NOνA

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

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**,

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

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

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

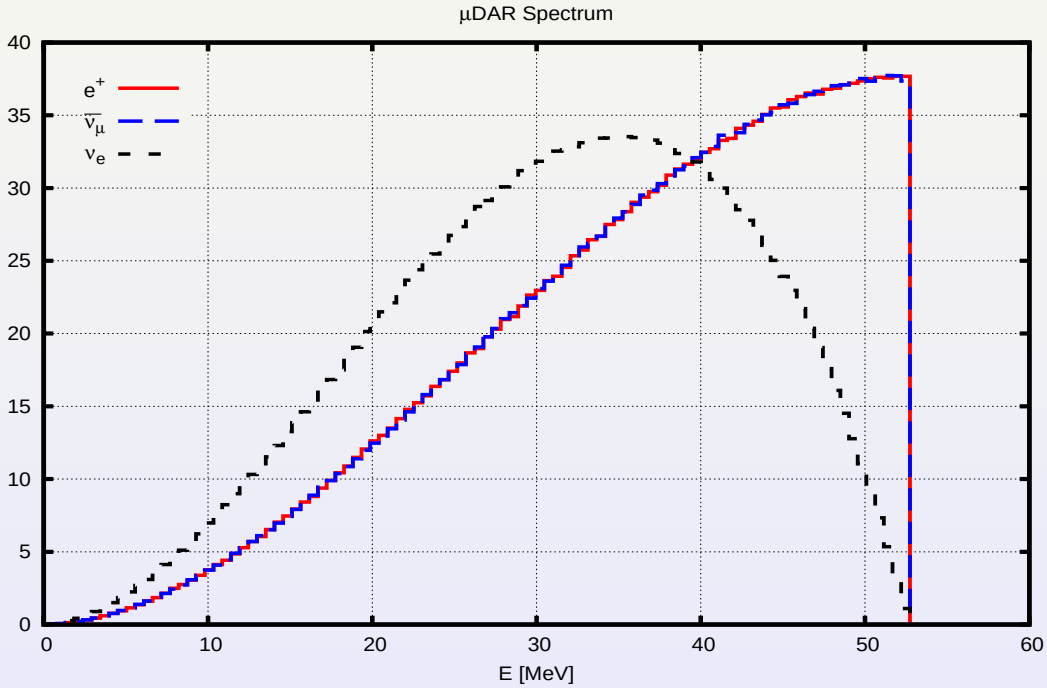
Accelerator experiment, such as **T2(H)K**, uses off-axis beam to compare ν_e & $\overline{\nu}_e$ appearance @ the oscillation maximum.

- **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** $\frac{\partial P_{\mu e}}{\partial \delta_D} \propto \cos \delta_D \Rightarrow \Delta(\delta_D) \propto \mathbf{1}/\cos \delta_D$.
- **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: $\boldsymbol{\mu^{+} \to e^{+} + \overline{\nu}_{\mu} + \nu_{e}}$.

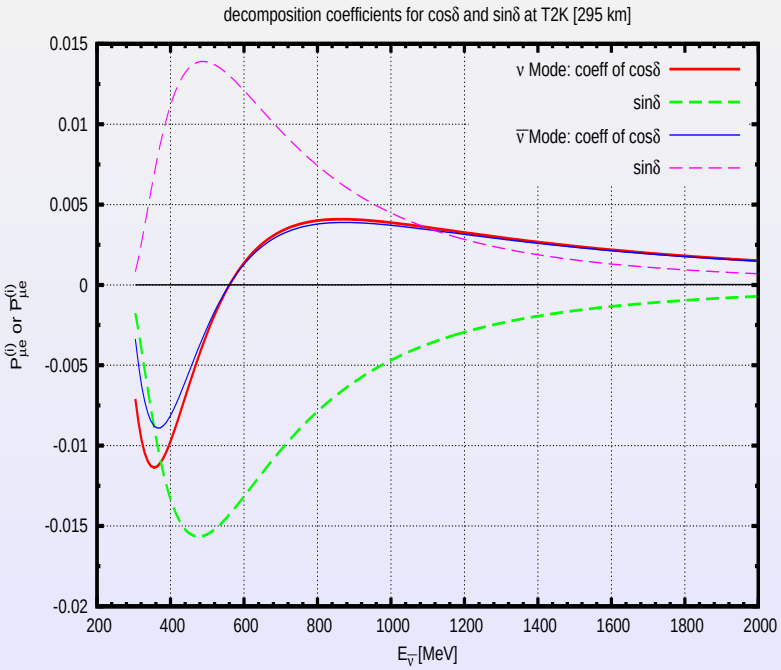


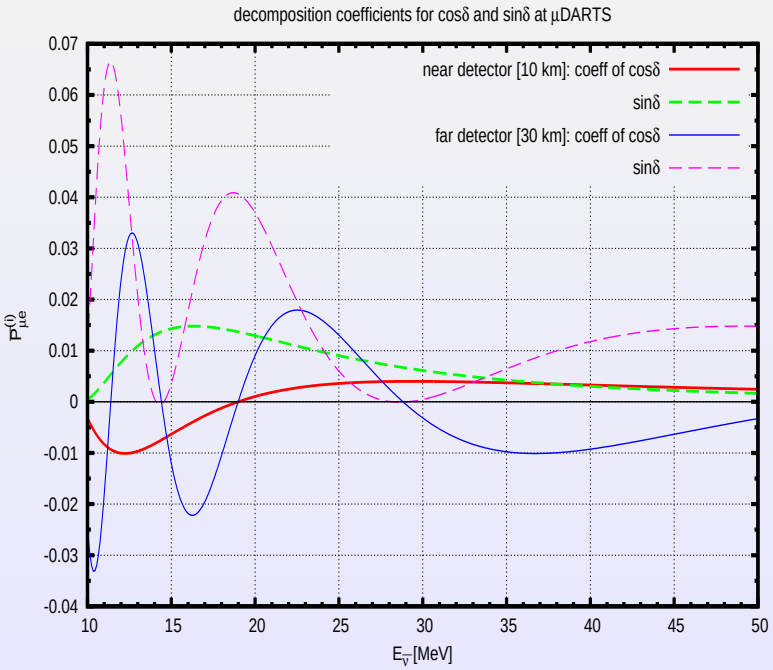
- $\overline{\nu}_{\mu}$ travel in all directions, oscillating as they go.
- A detector measures the $\overline{\nu}_{e}$ from $\boldsymbol{\overline{\nu}_{\mu} \to \overline{\nu}_{e}}$ **oscillation**.

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])





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

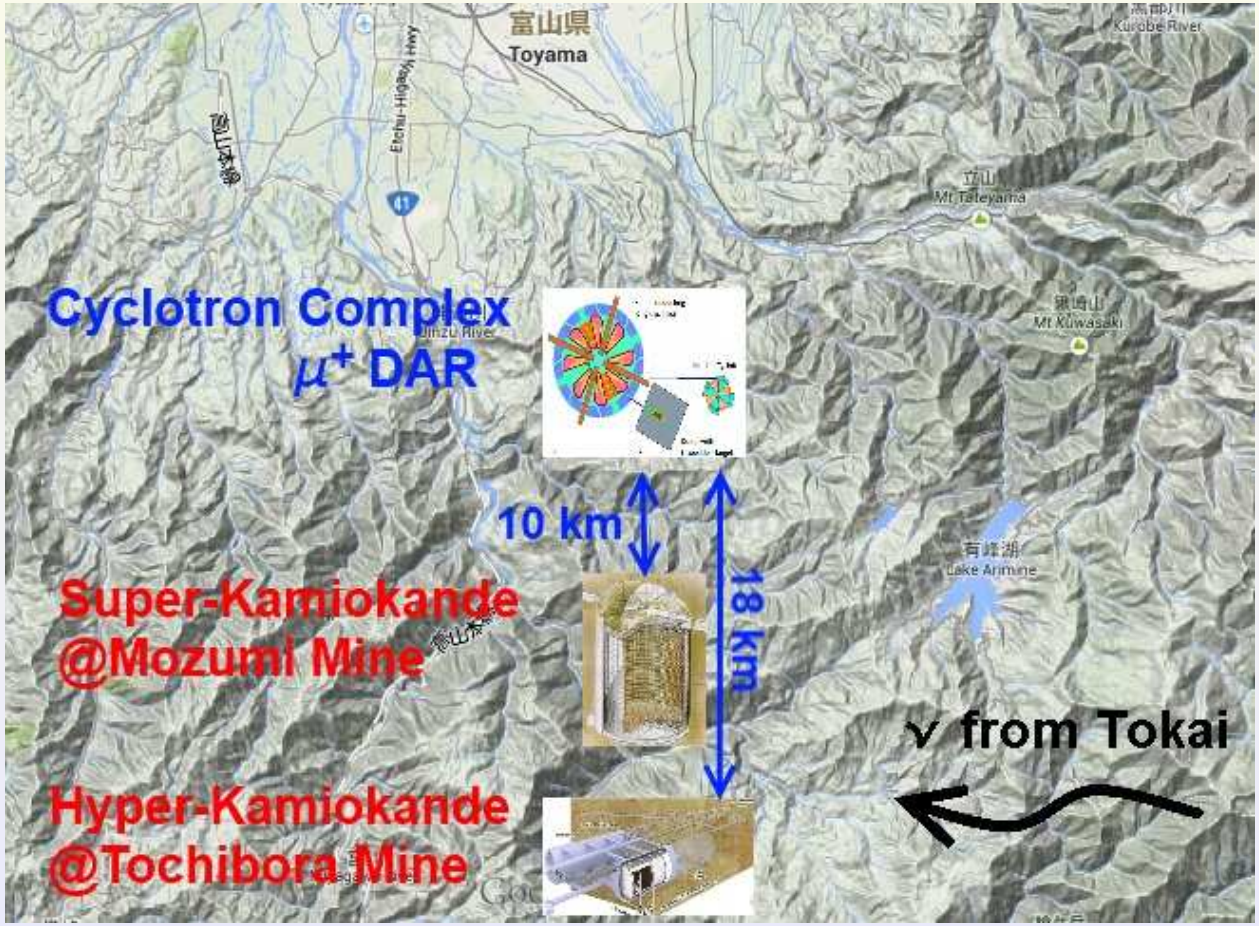
μDARTS – JUNO & RENO50

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

- China Atomic Energy Center is proposing a cyclotron.

TNT2K

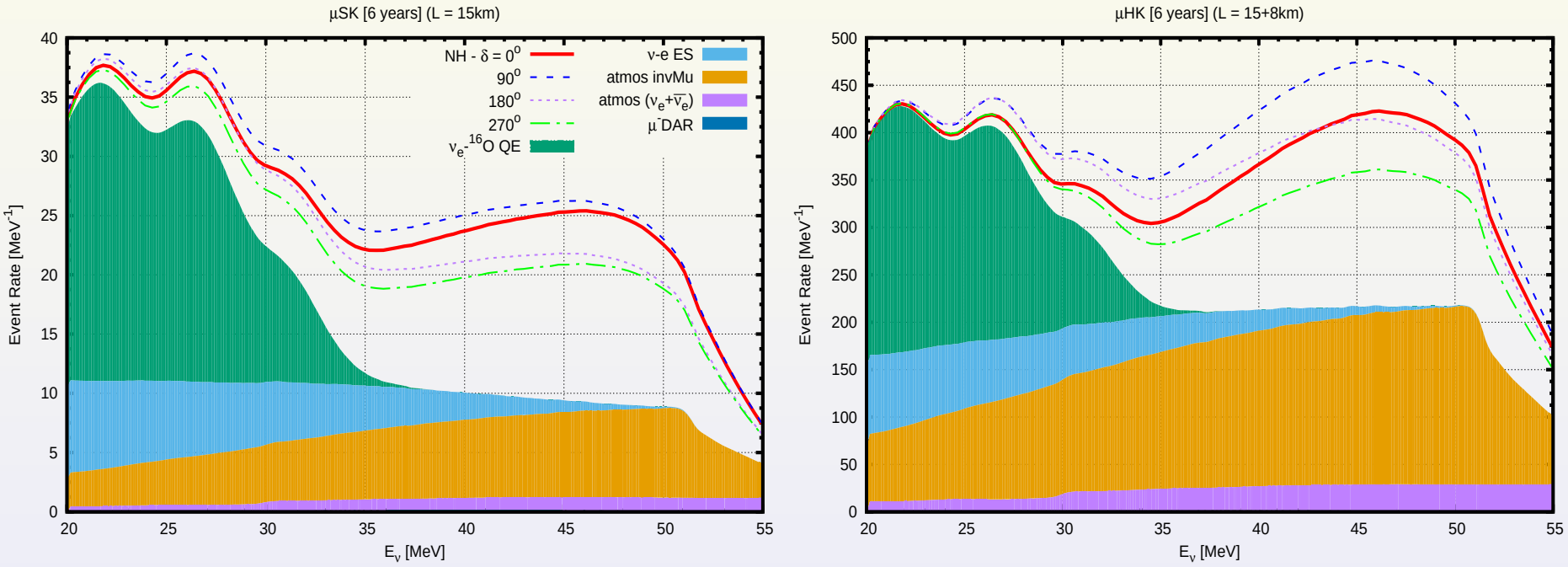
- T2(H)K + μSK + μHK



- 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.

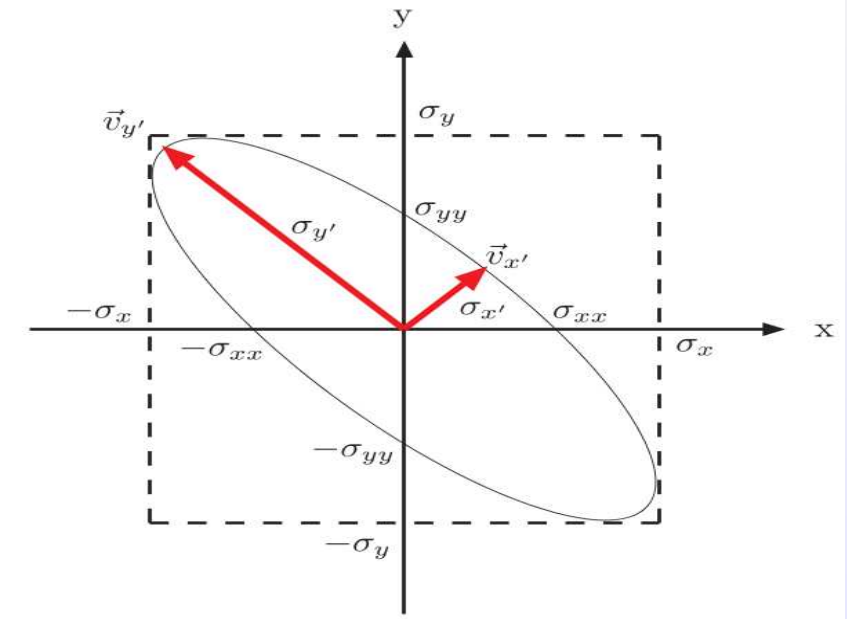
Simulated by **NuPro**, http://nupro.hepforge.org/

χ^2 & Minimization/Marginalization in NuPro

- $\chi^2 \equiv \chi^2_{\text{stat}} + \chi^2_{\text{sys}} + \chi^2_{input}$

$$\begin{aligned}\chi^2 &\equiv \sum_i \frac{(\overline{N}_i - fN_i)^2}{\overline{N}_i} + \left(\frac{f_\nu - 1}{0.05}\right)^2 + \left(\frac{f_{\bar{\nu}} - 1}{0.05}\right)^2 \\ &+ \left[\frac{\Delta m_s^2 - \overline{\Delta m_s^2}}{\delta(\Delta m_s^2)}\right]^2 + \left[\frac{\Delta m_a^2 - \overline{\Delta m_a^2}}{\delta(\Delta m_a^2)}\right]^2 \\ &+ \left[\frac{\sin^2\theta_a - \overline{\sin^2\theta_a}}{\delta(\sin^2\theta_a)}\right]^2 + \left[\frac{\sin^2 2\theta_r - \overline{\sin^2 2\theta_r}}{\delta(\sin^2 2\theta_r)}\right]^2 + \left[\frac{\sin^2\theta_s - \overline{\sin^2\theta_s}}{\delta(\sin^2\theta_s)}\right]^2 .\end{aligned}$$

- **Marginalization**
  - $\mathbb{P}(x) = \int_{-\infty}^{+\infty} \mathbb{P}(x,y)dy$
  - $\chi^2(x) = \min_y[\chi^2(x,y)]$.
  - Sampling $\mathbb{P}(x_i) = \sum_j w(x_i, y_j)$



Analytical Linear χ^2 Minimization/Marginalization

- **Measurements**: $X = (x_1, \cdots, x_m)$ & $Y = (y_1, \cdots, y_n)$

$$\begin{aligned} \chi^2(X) &= \sum_i \left[\frac{Y_i^{exp} - Y_i^{th}(X)}{\sigma_i}\right]^2 \\ &= \left[Y^{exp} - Y^{th}(X)\right]^T \overline{\Sigma}^{-1} \left[Y^{exp} - Y^{th}(X)\right] \end{aligned}$$

- **Linear Expansion**

$$Y^{th}(X) \approx Y^{th0} + AX \quad \Rightarrow \quad \chi^2 = \left[\delta\overline{Y} - AX\right]^T \overline{\Sigma}^{-1} \left[\delta\overline{Y} - AX\right]$$

with $\delta\overline{Y} \equiv Y^{exp} - Y^{th0}$.

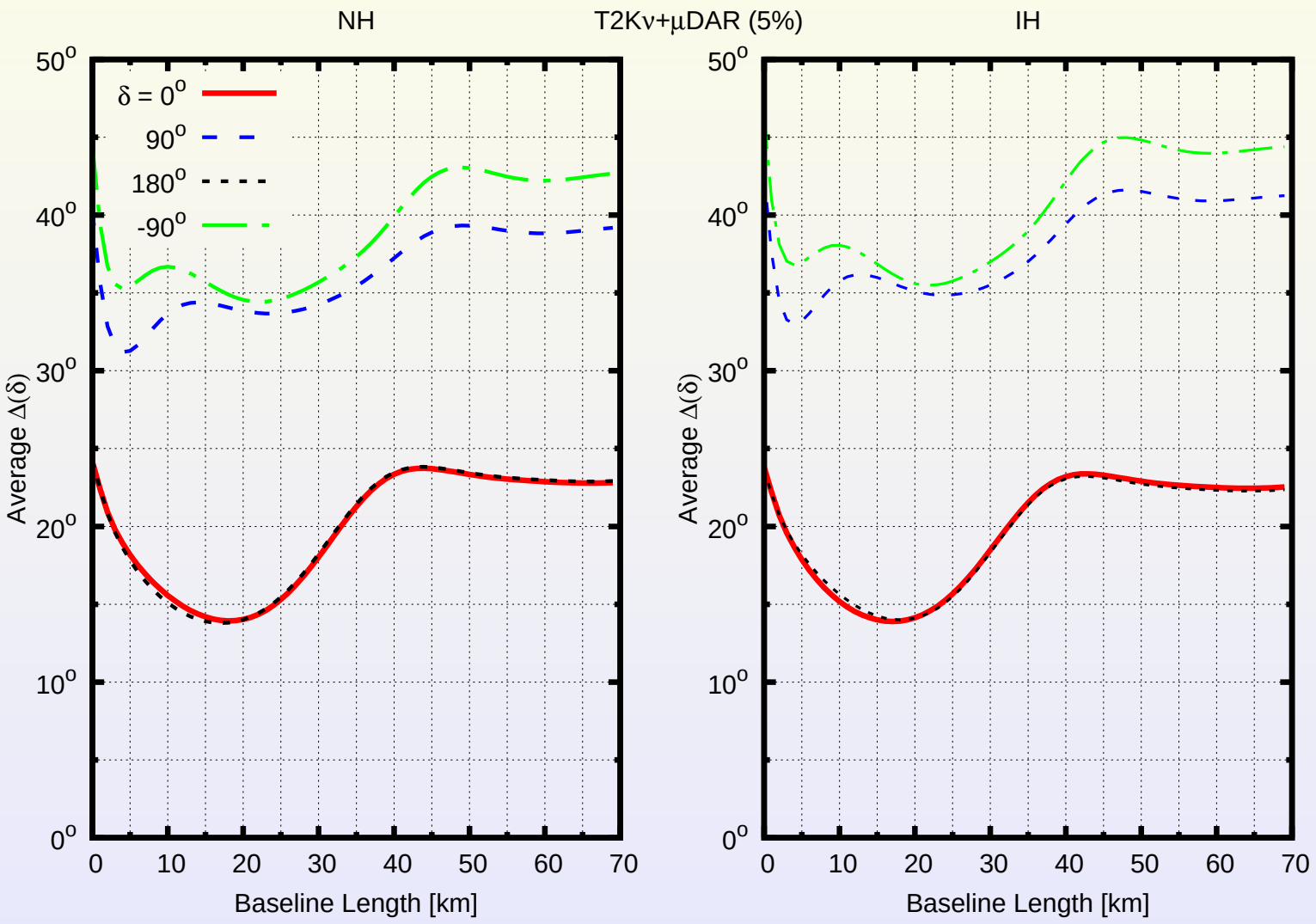
- **Minimization**

$$\begin{aligned} \delta\overline{\mathbf{X}}_{\text{best fit}} &= A^T\overline{\Sigma}^{-1}\delta\overline{Y}, \qquad \boldsymbol{\Sigma}^{-1} = A^T\overline{\Sigma}^{-1}A, \\ \chi^2_{\text{min}}(\mathbf{X}) &= \left[X - \Sigma\delta\overline{X}\right]^T \Sigma^{-1} \left[X - \Sigma\delta\overline{X}\right]. \end{aligned}$$

Sec.5 of 1210.8141 & Appendix B of 1603.03385.

δ_D Precision @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]



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

δ_D Precision @ TNT2K

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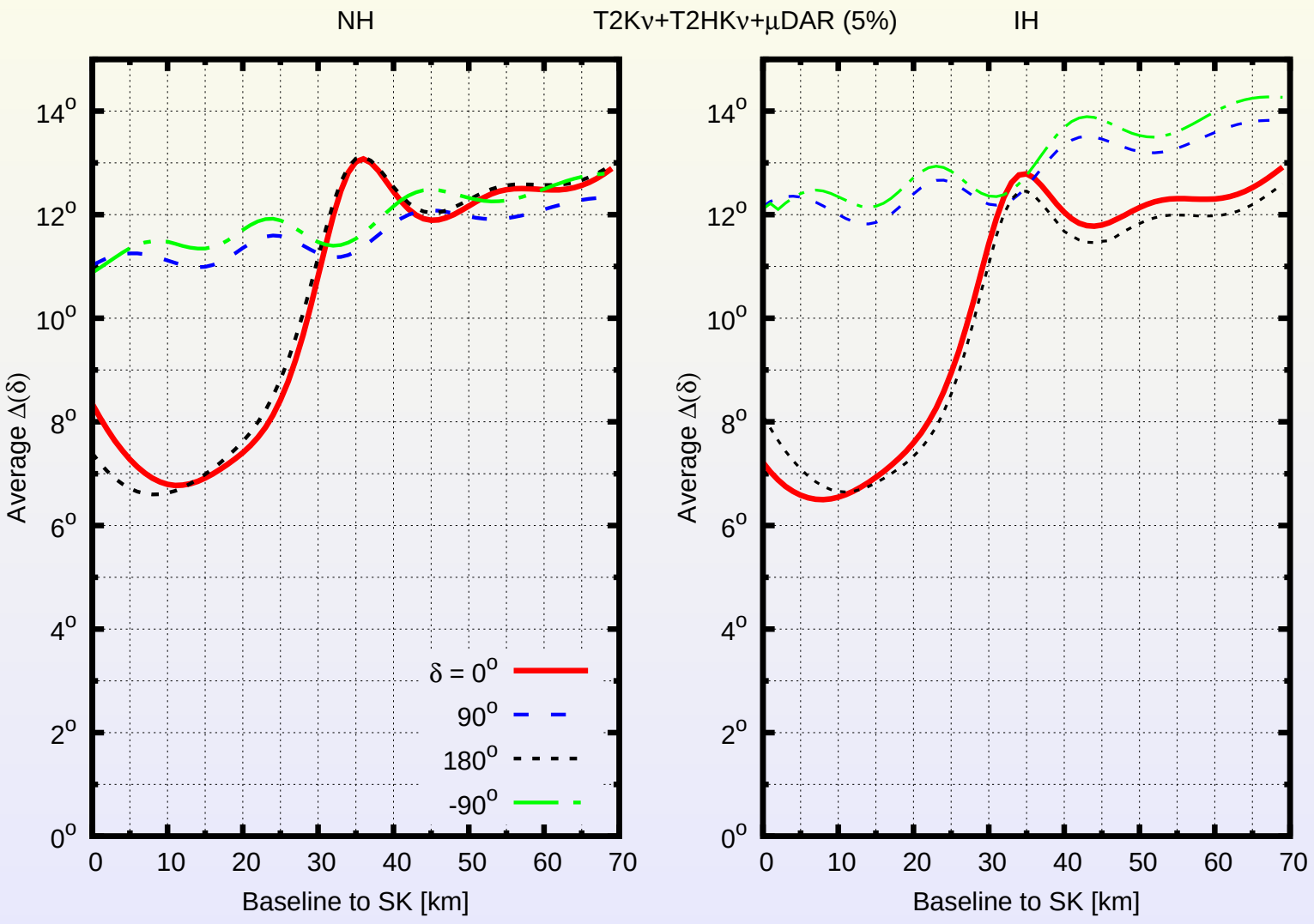


Simulated by **NuPro**, http://nupro.hepforge.org/

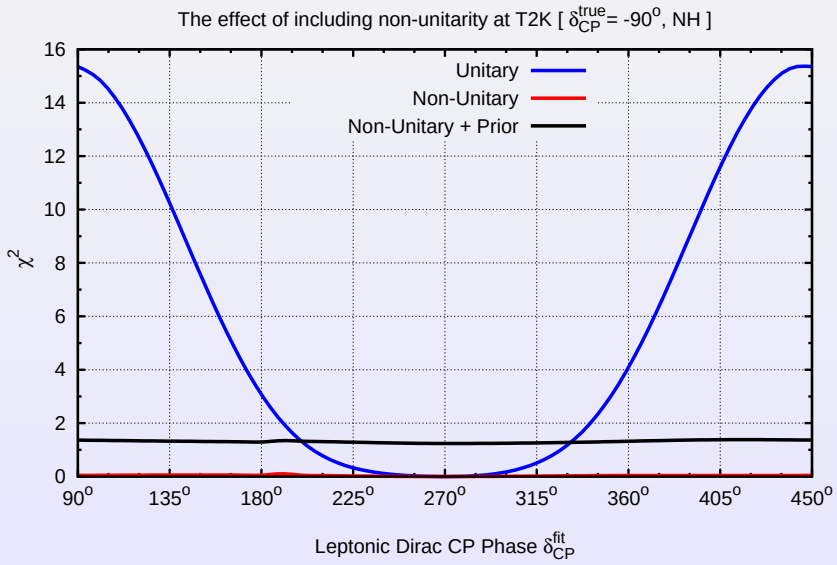
Non-Unitarity Mixing (NUM)

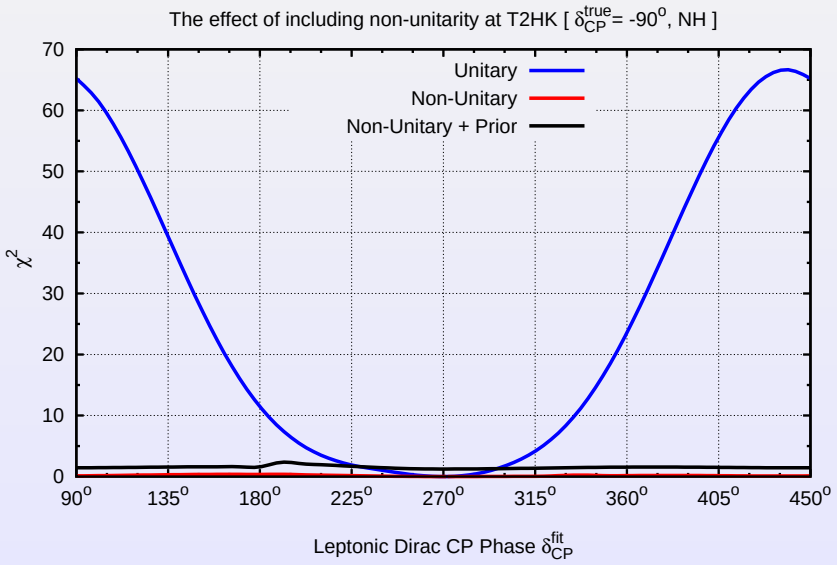
Ge, Pasquini, Tortola & Valle

[1605.01670]

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

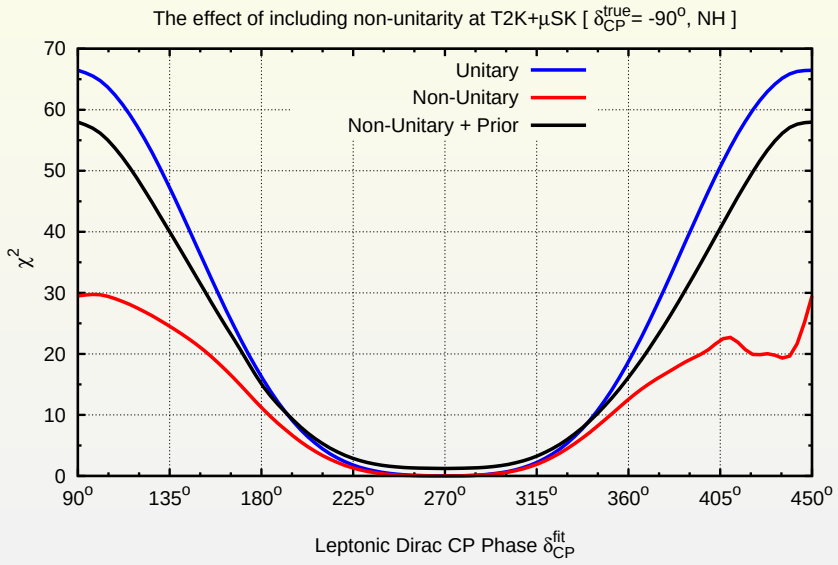
$$P^{NP}_{\mu e} = \alpha_{11}^2 \left\{ \alpha_{22}^2 \left[c_a^2 |S'_{12}|^2 + s_a^2 |S'_{13}|^2 + 2 c_a s_a (\cos\delta_D \mathbb{R} - \sin\delta_D \mathbb{I})(S'_{12} S'^*_{13}) \right] + |\alpha_{21}|^2 P_{ee} \right.$$
$$\left. + 2\alpha_{22} |\alpha_{21}| \left[c_a \left(c_\phi \mathbb{R} - s_\phi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

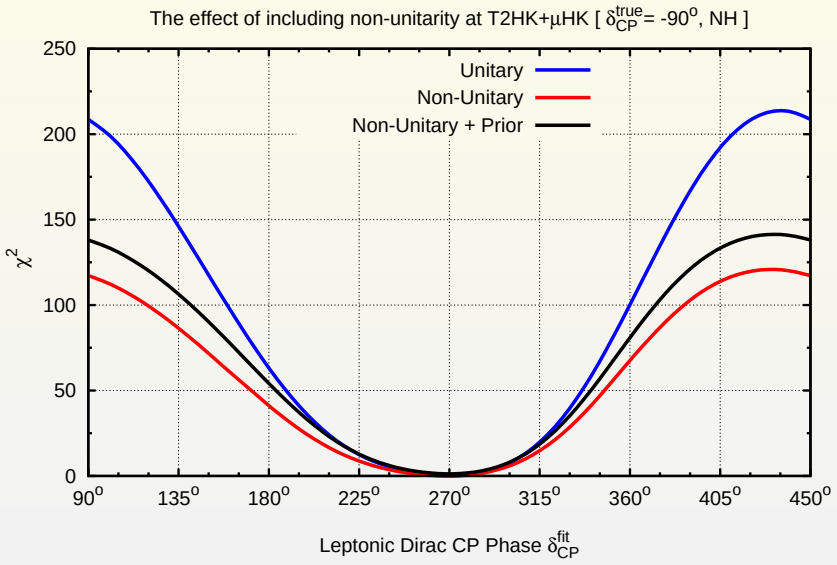


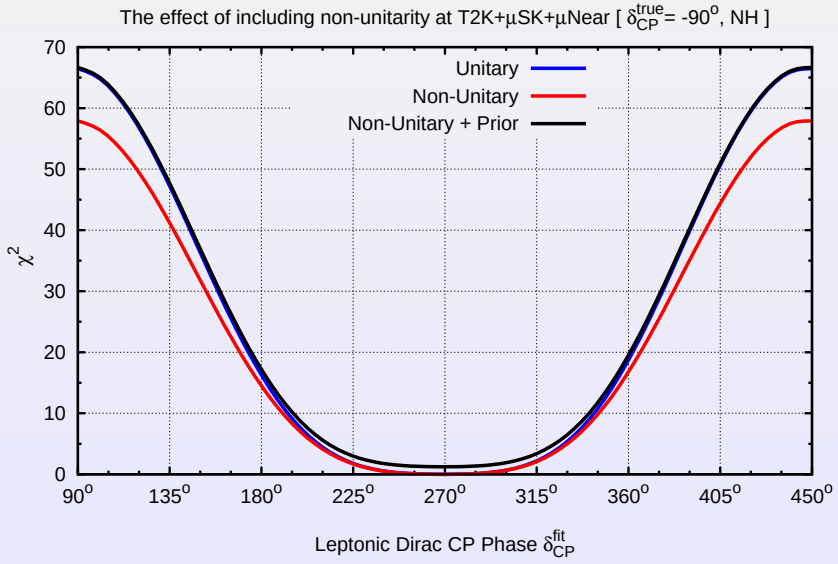


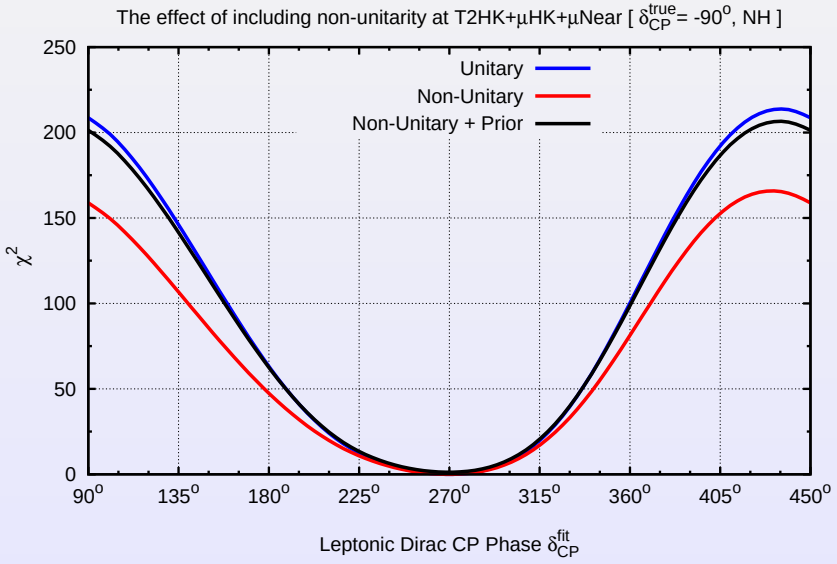
TNT2K+μNear

Ge, Pasquini, Tortola & Valle [1605.01670]









Non-Standard Interaction

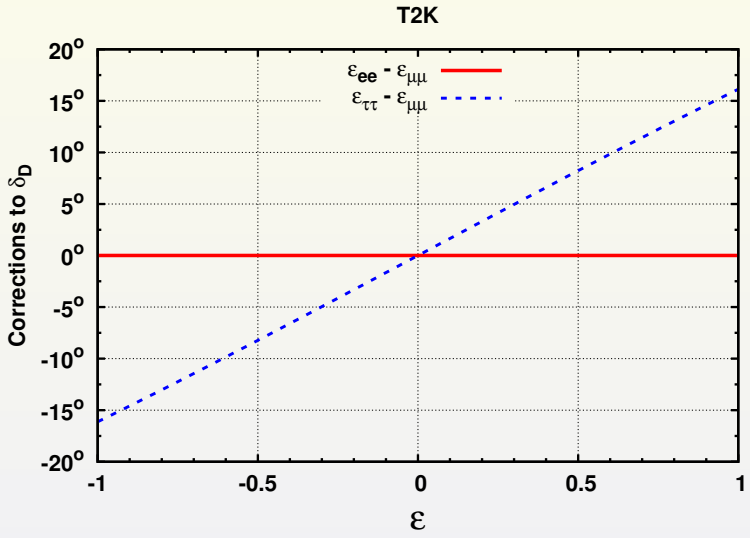
SFG & Alexei Smirnov [arXiv:1607.08513]

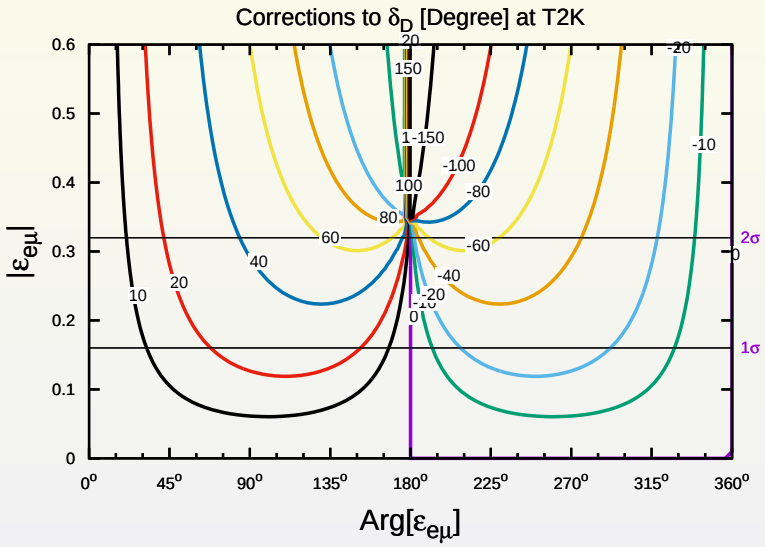
$$\mathcal{H} \equiv \frac{1}{2E_\nu} U \begin{pmatrix} 0 & & \\ & \Delta m_s^2 & \\ & & \Delta m_a^2 \end{pmatrix} U^\dagger + V_{cc} \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^*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

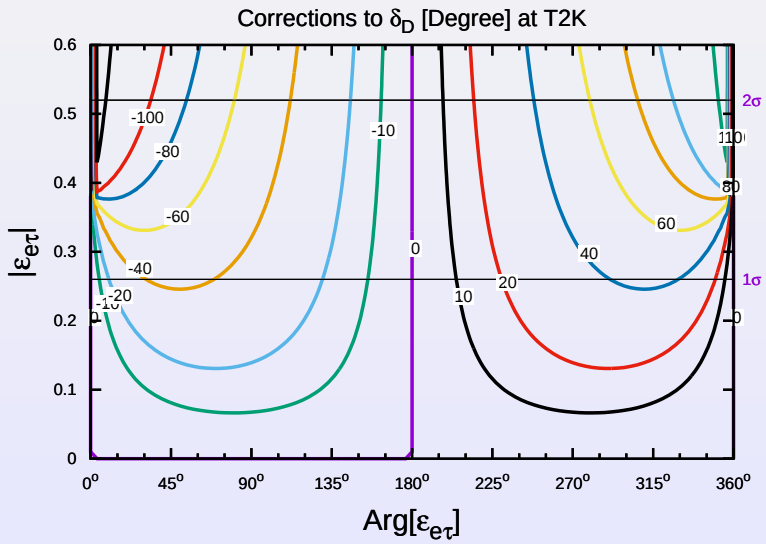
- **Standard Interaction** – V_{cc} (also V_{nc})
- **Non-Standard Interaction** – $\epsilon_{\alpha\beta}$
  - Diagonal $\epsilon_{\alpha\alpha}$ are real
  - Off-diagonal $\epsilon_{\alpha\neq\beta}$ are complex
  - Both can fake CP
- Z' in **LMA-Dark** model with $L_\mu - L_\tau$ gauged as $U(1)$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

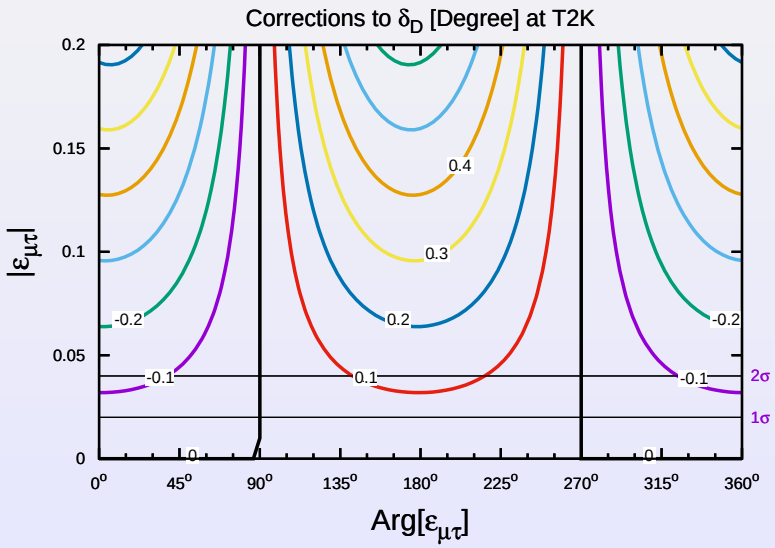
Faked CP with NSI

SFG & Alexei Smirnov [arXiv:1607.08513]



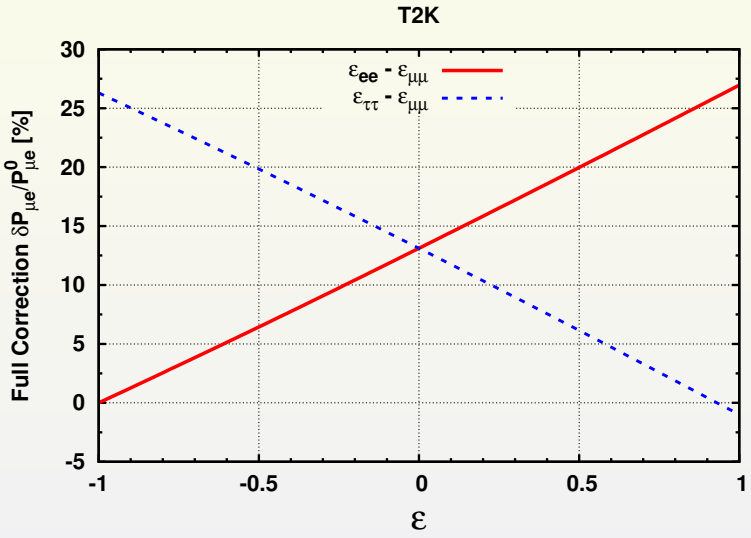


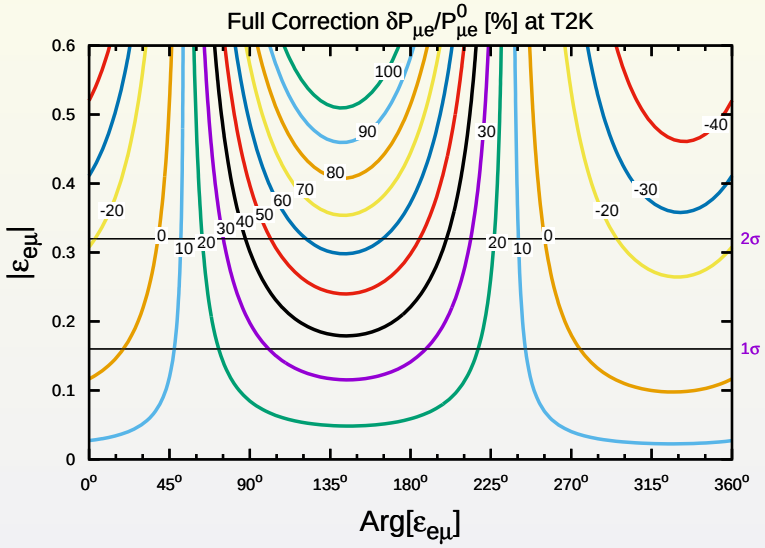


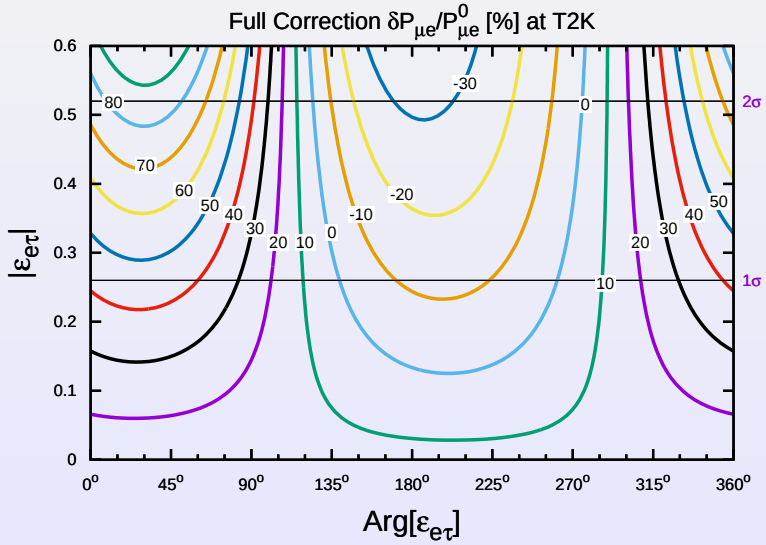


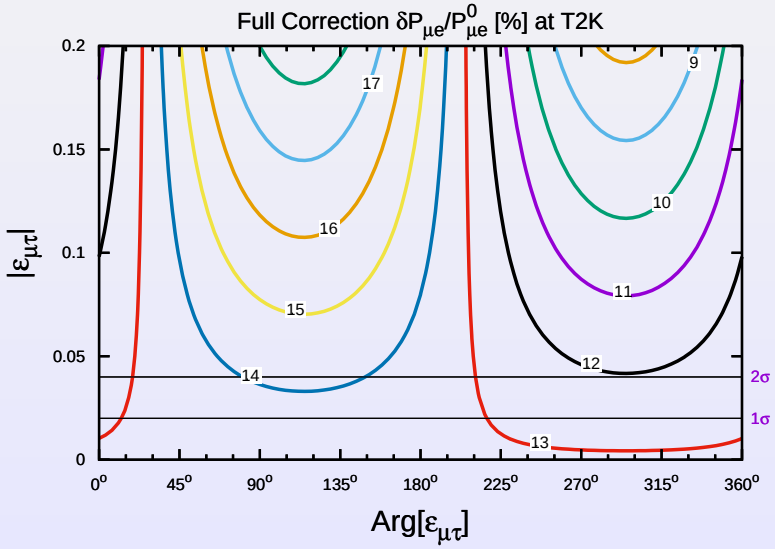
The effect of NSI @ T2K

SFG & Alexei Smirnov [arXiv:1607.08513]



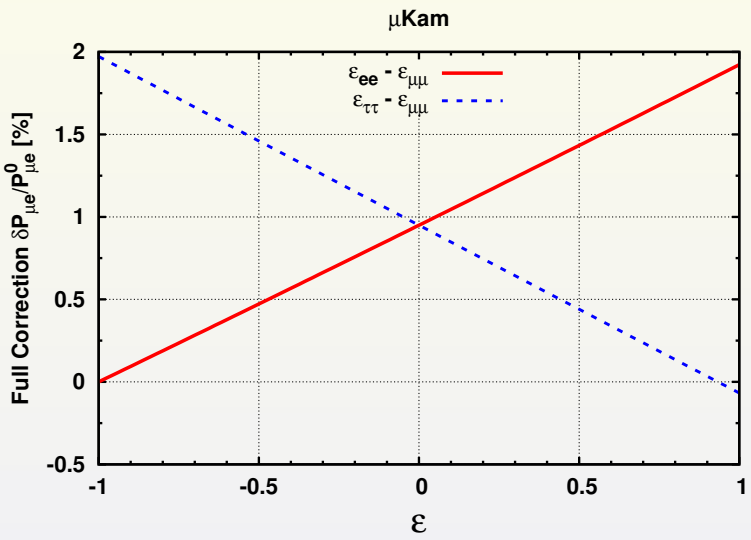


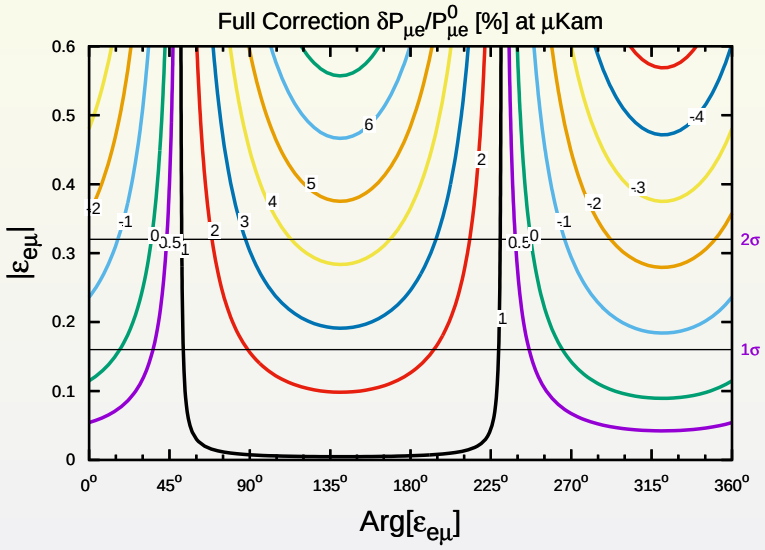


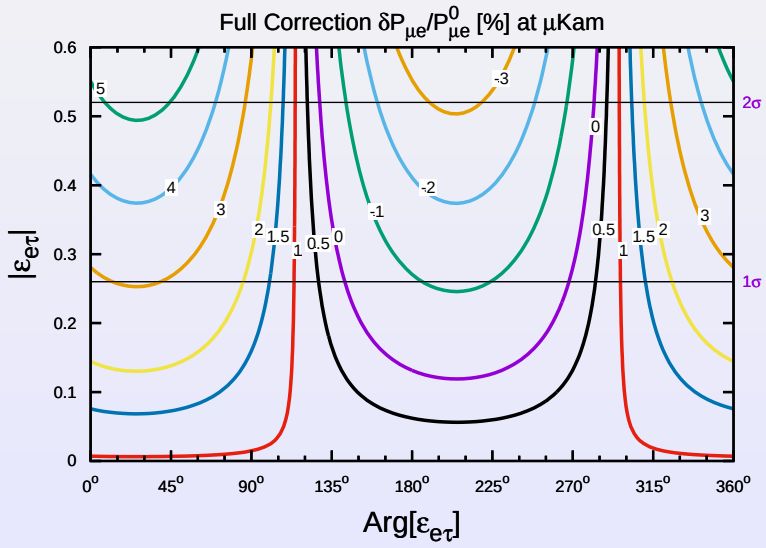


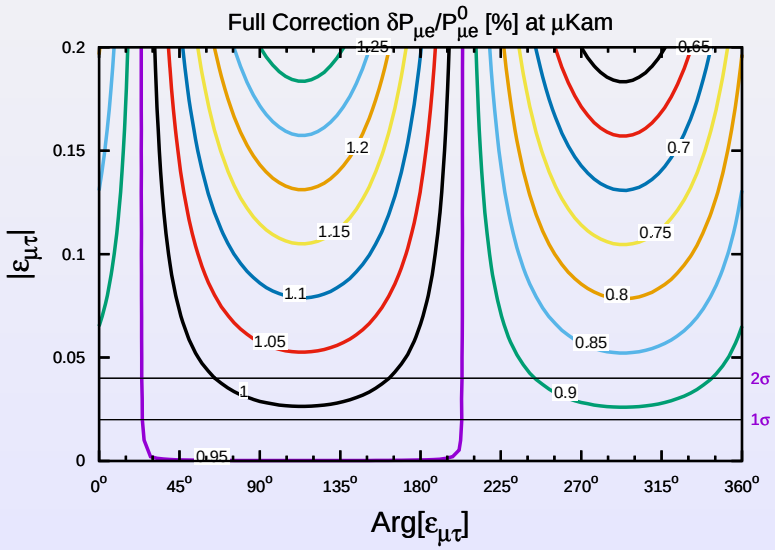
The effect of NSI @ μSK

SFG & Alexei Smirnov [arXiv:1607.08513]

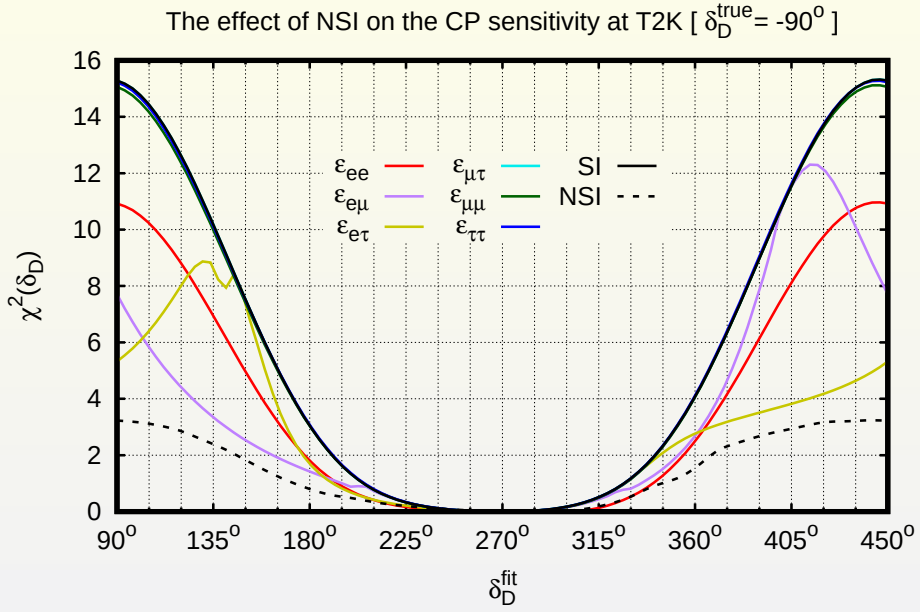


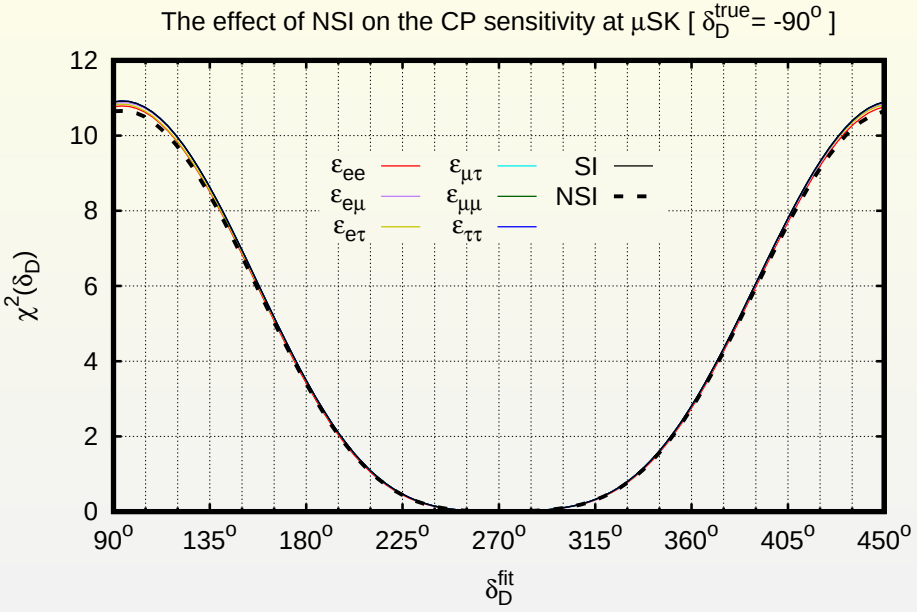


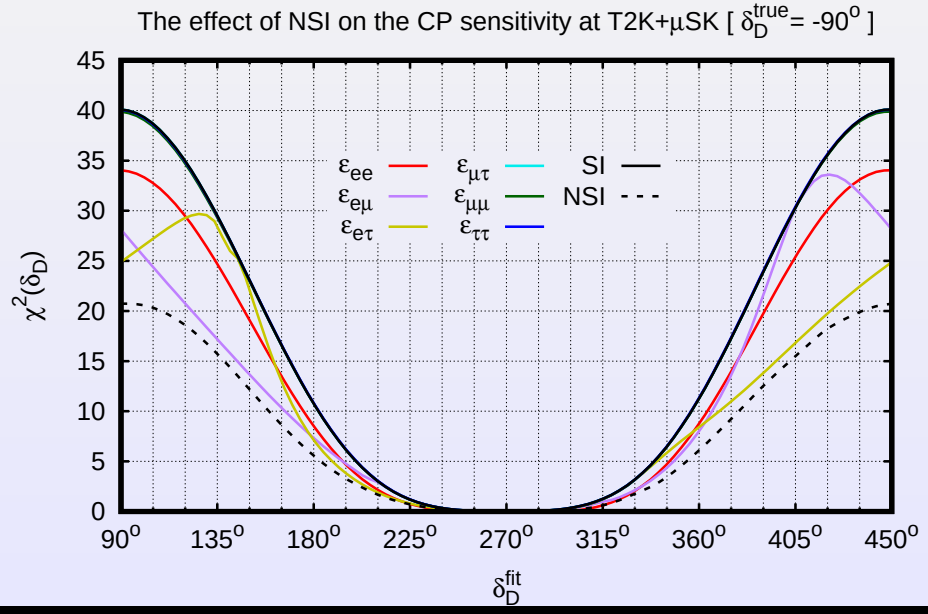


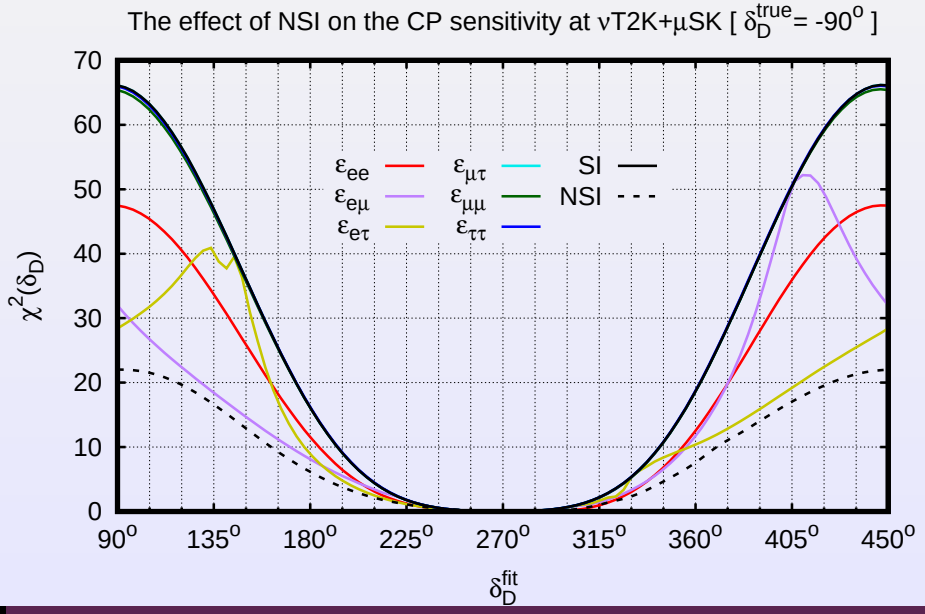


CP Sensitivity at T2K & μSK SFG & A. Smirnov [arXiv:1607.08513]

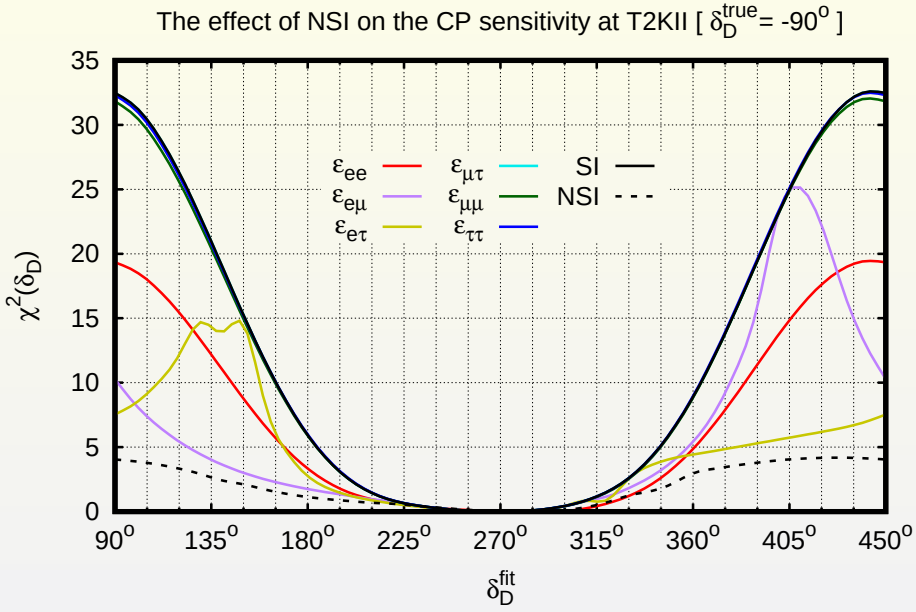


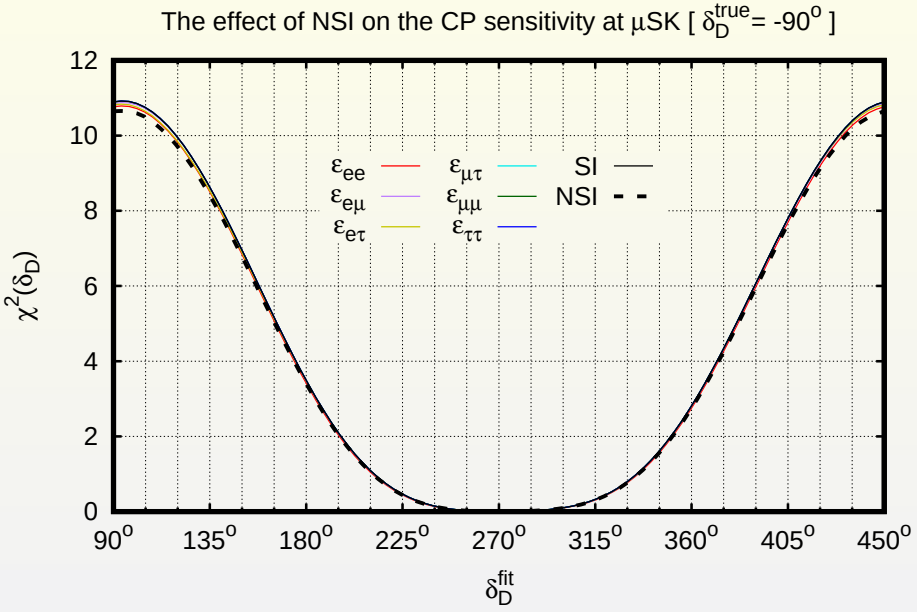


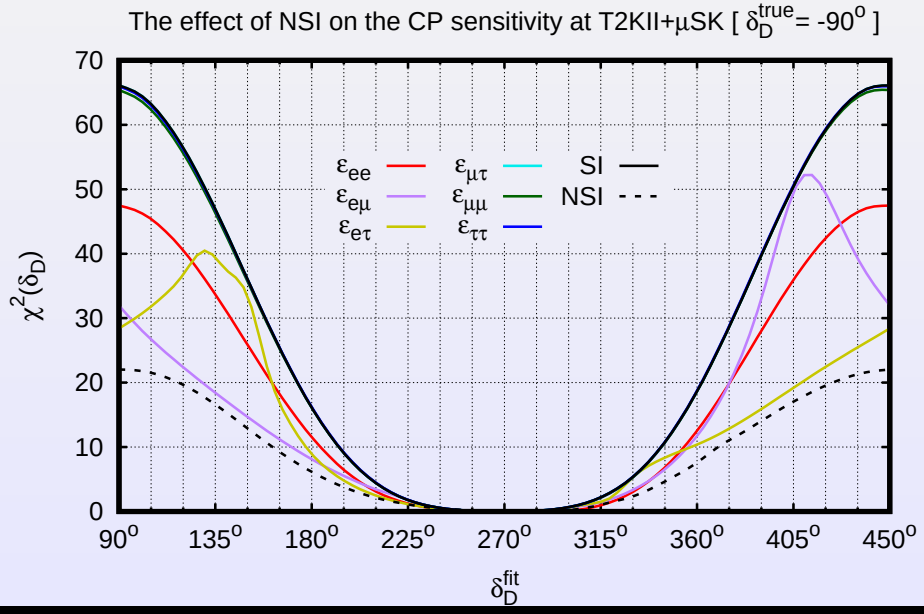


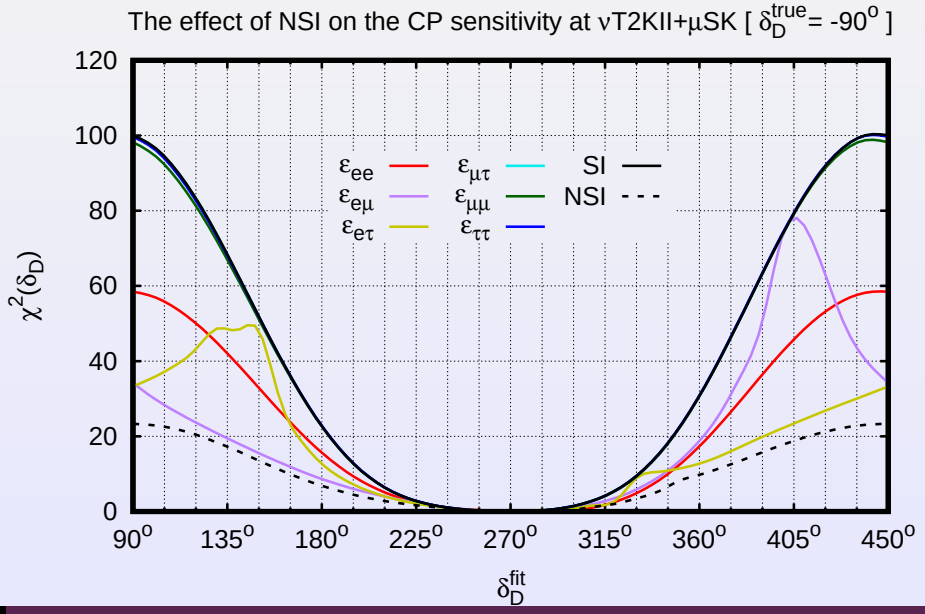


CP Sensitivity at T2KII & μSK









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

nupro.hepforge.org

Search

NuPro is hosted by Hepforge, IPPP Durham

- Home
- Source Code
- Tracker
- Wiki

NuPro - A Simulation Package for Neutrino Properties

NuPro is a C++ package developed to simulate neutrino physics:

- **Fixed Baseline Experiments:**
  - Reactor
  - Accelerator
- **Free Baseline Experiments:**
  - Atmospheric
  - Solar
- **Decay Experiments:**
  - Beta Decay
  - Two Neutrino Double Beta Decay
  - Neutrinoless Double Beta Decay
  - Majoron-Emitting Neutrinoless Double Beta Decay
- **Cosmological Measurements:**
  - Global Fit on the Mass Sum
  - Cosmic Neutrino Background

NuPro has already been used for several papers:

- **Extracting Majorana Properties in the Throat of Neutrinoless Double Beta Decay**,
  Shao-Feng Ge, Manfred Lindner, arXiv:1608.01618
- **Non-standard interactions and CP phase measurements in neutrino oscillations at low energies**,
  Shao-Feng Ge, Alexei Yu. Smirnov, arXiv:1607.08513
- **Measuring the Leptonic CP Phase in Neutrino Oscillations with Non-Unitary Mixing**,
  Shao-Feng Ge, Pedro Pasquini, M. Tortola, J. W. F. Valle, arXiv:1605.01670
- **New physics effects on neutrinoless double beta decay from right-handed current**,
  Shao-Feng Ge, Manfred Lindner, Sudhanwa Patra, arXiv:1508.07286
- **JUNO and Neutrinoless Double Beta Decay**,
  Shao-Feng Ge, Werner Rodejohann, arXiv:1507.05514
- **The Leptonic CP Phase from T2(H)K and Muon Decay at Rest**,
  Jarah Evslin, Shao-Feng Ge, Kaoru Hagiwara, arXiv:1506.05023

Nevertheless, it is still under development and will be made publicly avaible when ready. For more information, please contact Shao-Feng Ge (gesf02[@]gmail.com).

Coverage of NuPro & Unsolved Issues

- **Simulation of experiments**
- **χ^2 minimization + marginalization**
- **Bayesian sampling**
  - full correlation without marginalization
  - customized use
- **Plot any function from Bayesian sample**
- **Resampling from Bayesian sample?**
  - when new data is avaible
  - just simulate the experiments providing new data
- **Model selection**
- **Global fit**

Thank You!