Future Opportunities in Neutrino Physics

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2018-01-10

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, NuPhys2016 [arXiv:1704.08518]
SFG, Manfred Lindner, Phys.Rev. **D95** (2017) no.3, 033003 [arXiv:1608.01618]
SFG, Manfred Lindner, Werner Rodejohann, Phys.Lett. **B772** (2017) 164-168 [arXiv:1702.02617]

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 $\Rightarrow$ Mixing
  - 3 Neutrino $\Rightarrow$ possible **CP violation**
  - CP violation $\Rightarrow$ Leptogenesis
  - Leptogenesis $\Rightarrow$ **Matter-Antimatter Asymmetry**
  - There is something left in the Universe.
  - Baryogenesis from quark mixing is not enough.
- Majorana $\nu \Leftrightarrow$ **Lepton Neumber Violation**
- Neutrino Oscillation Experiment $\Rightarrow$ **Neutrino Collider**

Dirac CP Phase Measurement

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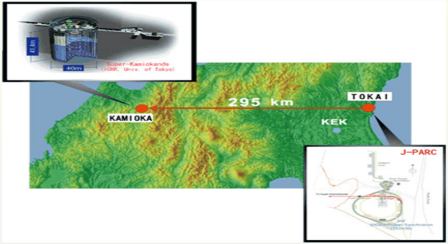
CP Measurement @ Accelerator Exps

- 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. $[\phi_{ij} \equiv \frac{\delta m^2_{ij} L}{4E_\nu}]$

- $\nu_\mu \to \nu_\mu$ 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 $\delta_{\mathbf{D}}$ @ Accelerator Exp

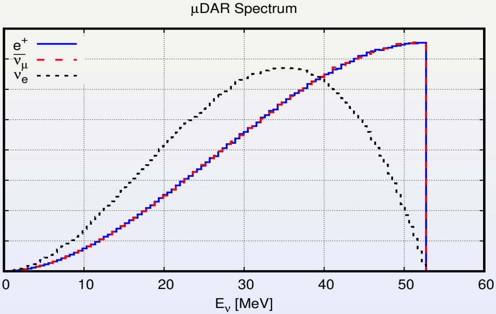
Accelerator experiment, such as **T2(H)K**, uses off-axis beam to compare ν_e & $\overline{\nu}_e$ appearance @ the oscillation maximum.

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

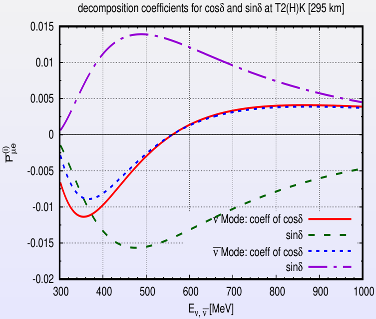


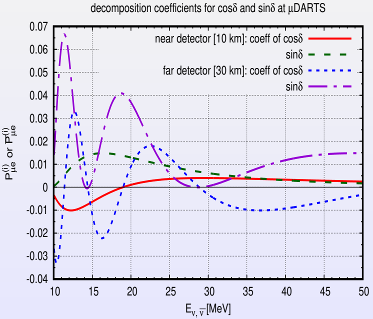
- $\overline{\nu}_{\mu}$ travel in all directions, oscillating as they go.
- A detector measures the $\overline{\nu}_{e}$ from **$\overline{\nu}_{\mu} \to \overline{\nu}_{e}$ oscillation**.

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 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])





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:

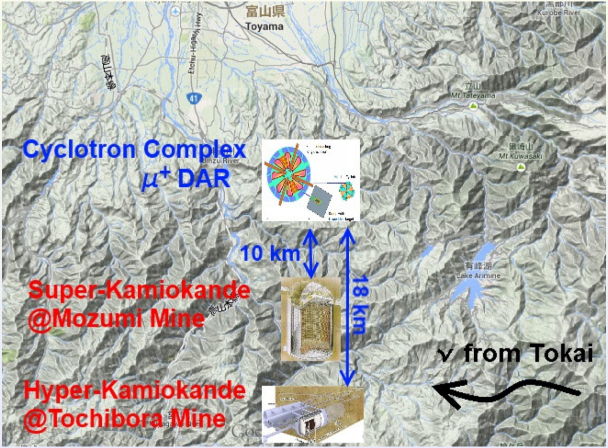
- Full (**100%**) duty factor!
- **Lower** intensity: $\sim$ **9mA** [$\sim$ **4**× lower than DAEδALUS]
- Not far beyond the current state-of-art technology of cyclotron [**2.2mA** @ Paul Scherrer Institute]
- MUCH **cheaper** & technically **easier**.
  - Only one cyclotron.
  - Lower intensity.

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]

TNT2K

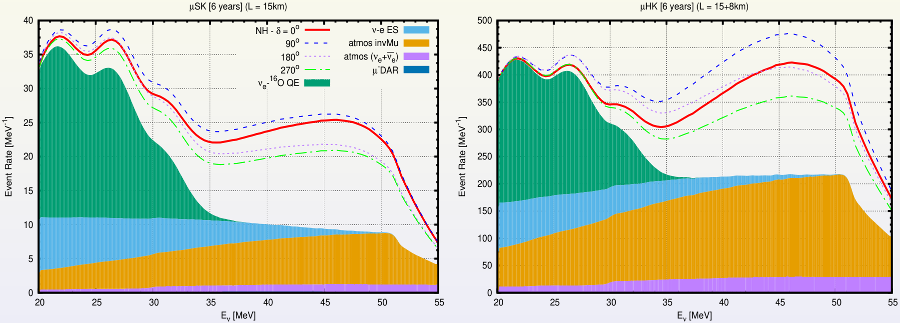
- T2(H)K + μSK + μHK



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

Event Shape @ TNT2K

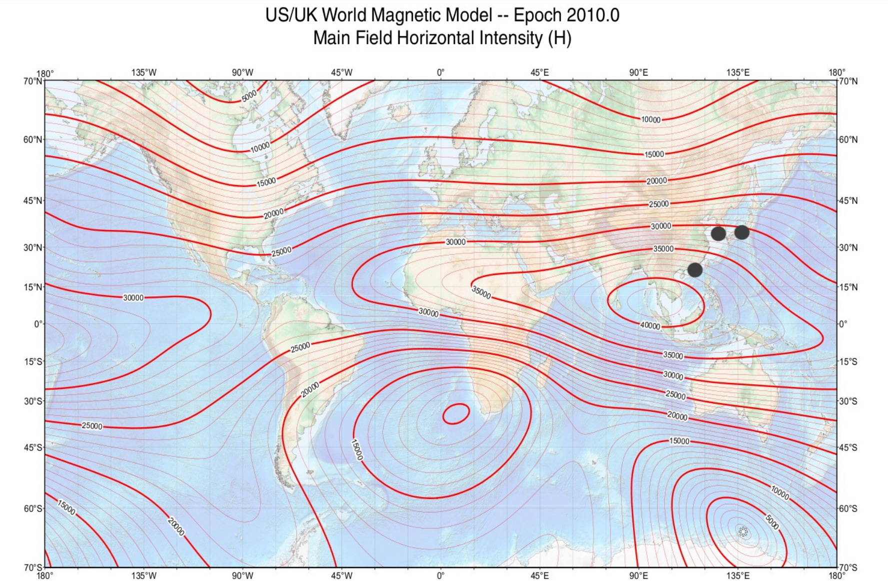
Evslin, Ge & Hagiwara [1506.05023]



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

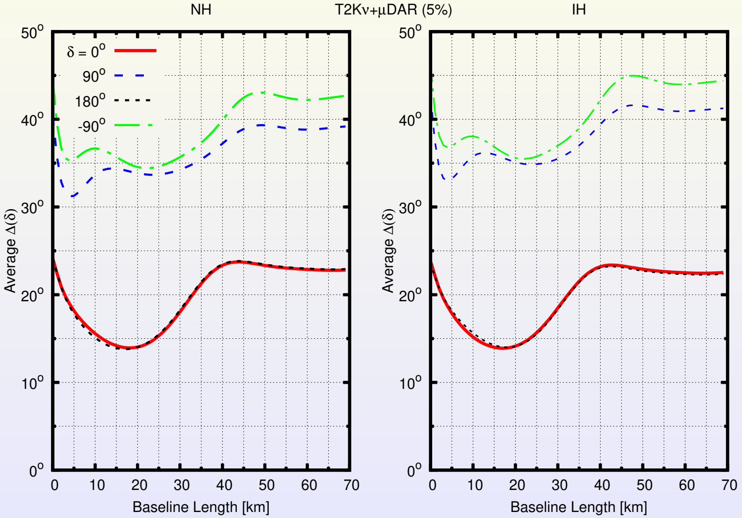
Simulated by **NuPro**, http://nupro.hepforge.org/

Lowest Atmospheric Neutrino Background



δ_D Precision @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]



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δ_D Precision @ TNT2K

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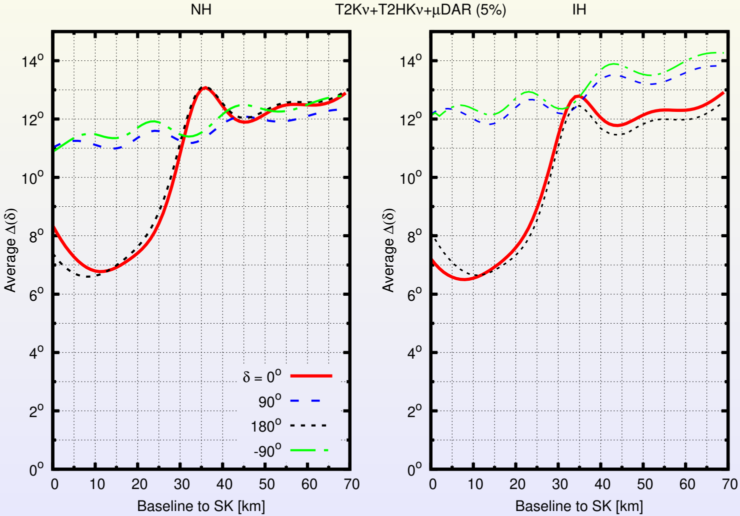


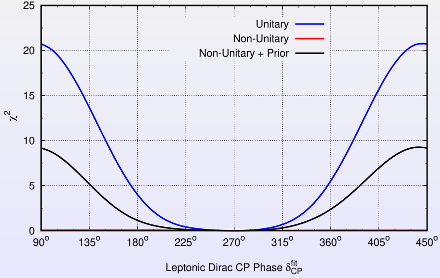
Simulated by **NuPro**, http://nupro.hepforge.org/

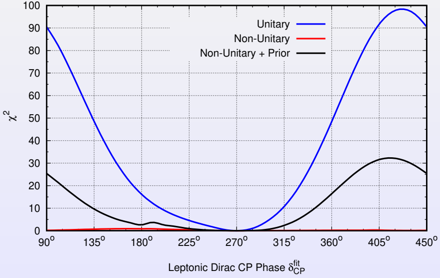
Non-Unitarity Mixing (NUM)

Ge, Pasquini, Tortola & Valle [1605.01670]

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

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


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


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

NUM vs Seesaw Mechanism

- **Heavy neutrinos**

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

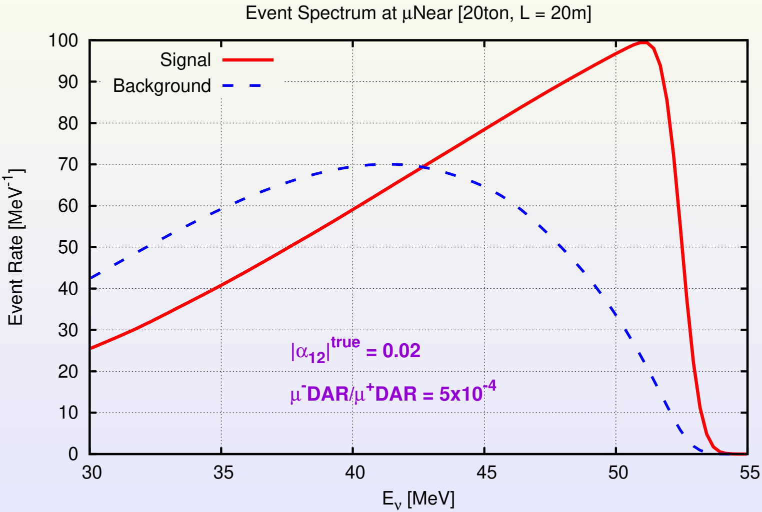
- **Seeaw Mechanism**

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

μNear at μDAR

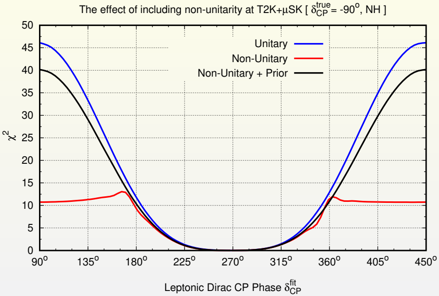
Ge, Pasquini, Tortola & Valle [1605.01670]

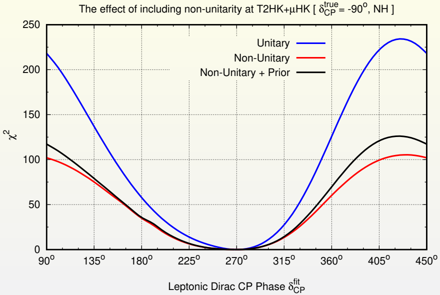
$$P^{NP}_{\mu e}(L \to 0) = \alpha^2_{11}|\alpha_{21}|^2 P_{ee} \approx \alpha^2_{11}|\alpha_{21}|^2 \approx |\alpha_{21}|^2$$

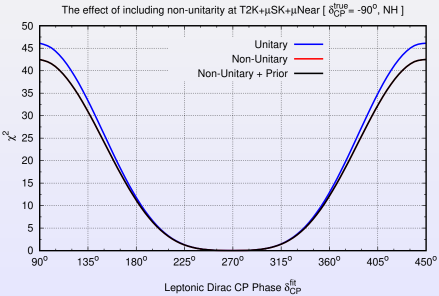


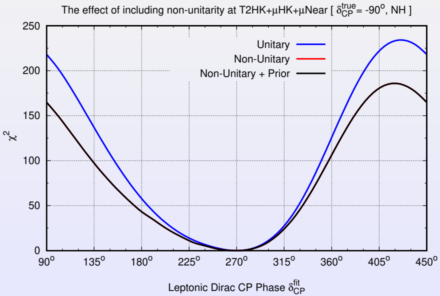
TNT2K+μNear

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

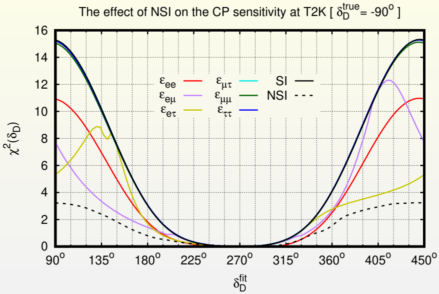
SFG & Smirnov [arXiv:1607.08513]

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

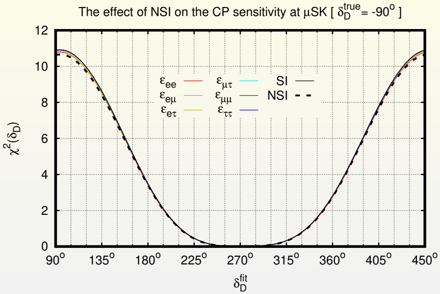
- Standard Interaction – V_{cc} (also V_{nc})
- Non-Standard Interaction – $\epsilon_{\alpha\beta}$
    - Diagonal $\epsilon_{\alpha\alpha}$ are real
    - Off-diagonal $\epsilon_{\alpha\neq\beta}$ are complex
    - Both can fake CP
- Z' in LMA-Dark model with $L_\mu - L_\tau$ gauged as $U(1)$
    -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

CP Sensitivity at T2K & μSK

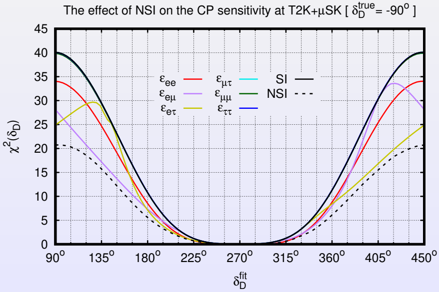
SFG & Smirnov [arXiv:1607.08513]



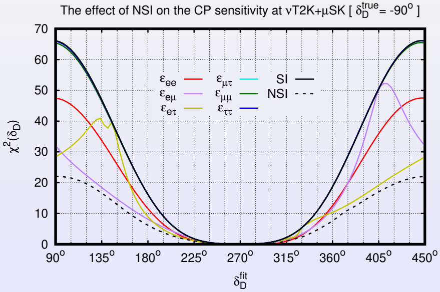
The effect of NSI on the CP sensitivity at T2K [δ_D^{true}= -90°]



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



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



The effect of NSI on the CP sensitivity at νT2K+μSK [δ_D^{true}= -90°]

Summary – Experiment

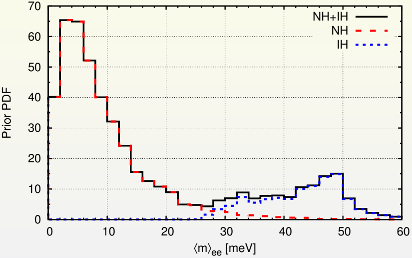
- **Better CP measurement than T2K, T2KII, T2HK, T2KK**
  - Much larger event numbers
  - Much better CP sensitivity around maximal CP
  - Solve degeneracy between δ_D & $\pi - \delta_D$
  - Guarantee CP sensitivity against NUM
  - Guarantee CP sensitivity against NSI
- **Better configuration than DAEδALUS**
  - Only one cyclotron
  - 100% duty factor
  - Much lower flux intensity
  - Much easier
  - Much cheaper
  - Single near detector

Majorana CP Phase Measurement

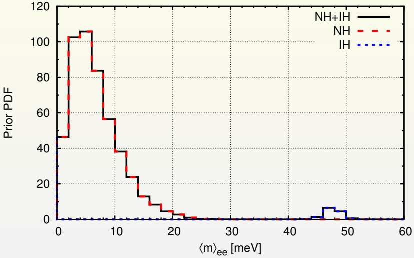
SFG, Manfred Lindner, Phys.Rev. **D95** (2017) no.3, 033003 [arXiv:1608.01618]

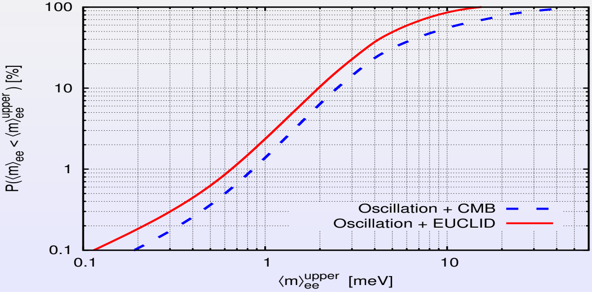
Preference of NH ⇒ Non-Observation of $0\nu2\beta$?

Oscillation + CMB

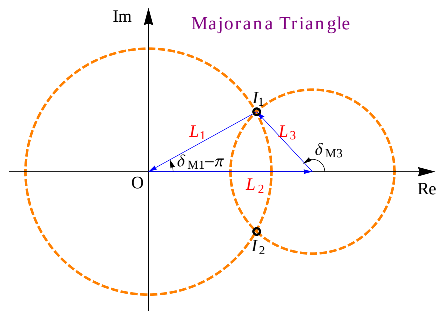


Oscillation + CMB + EUCLID





Any chance of obtaining some information?



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

with

$$\overrightarrow{L_1} \equiv m_1 U_{e1}^2 = m_1 c_r^2 c_s^2 e^{i\delta_{\rm M1}} \,,$$

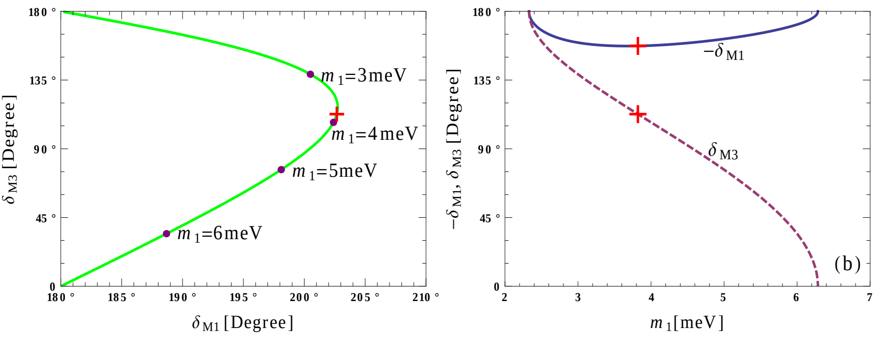
$$\overrightarrow{L_2} \equiv m_2 U_{e2}^2 = \sqrt{m_1^2 + \Delta m_s^2} c_r^2 s_s^2 \,,$$

$$\overrightarrow{L_3} \equiv m_3 U_{e3}^2 = \sqrt{m_1^2 + \Delta m_a^2} s_r^2 e^{i\delta_{\rm M3}} \,.$$

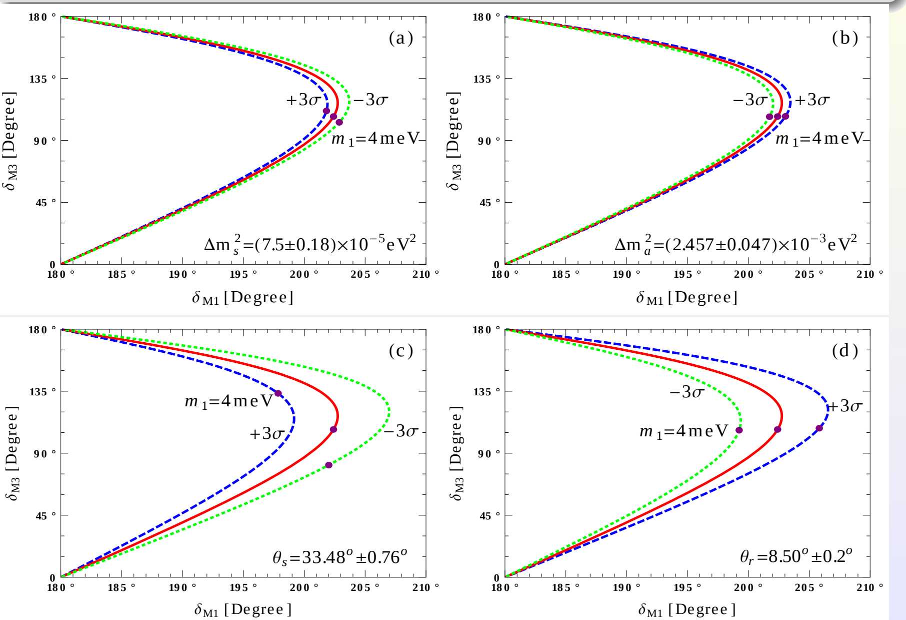
Determine 2 Majorana Phases Simultaneously

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

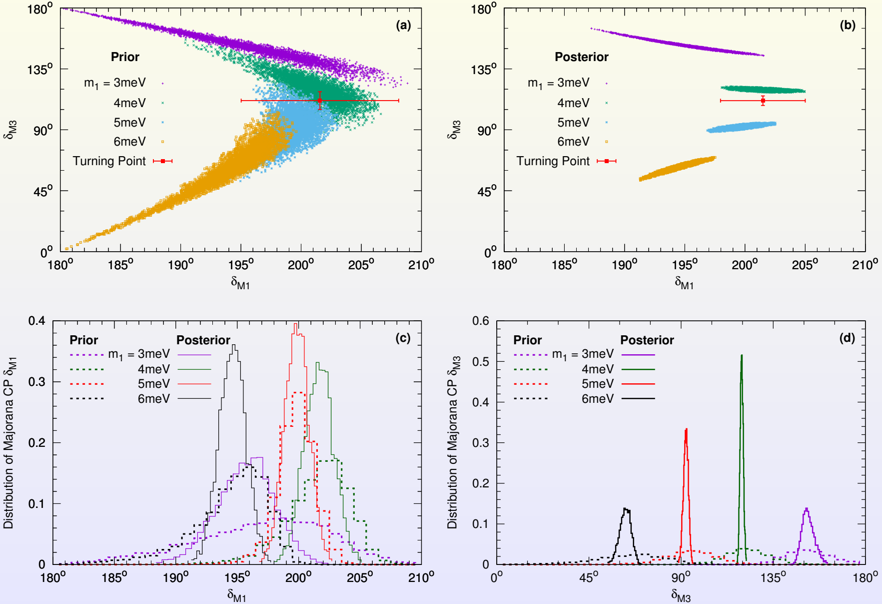
$$\begin{aligned} \cos\delta_{\rm M1} &= -\frac{L_1^2 + L_2^2 - L_3^2}{2L_1L_2} = -\frac{m_1^2 c_r^4 c_s^4 + m_2^2 c_r^4 s_s^4 - m_3^2 s_r^4}{2 m_1 m_2 c_r^4 c_s^2 s_s^2} \,, \\ \cos\delta_{\rm M3} &= +\frac{L_1^2 - L_2^2 - L_3^2}{2L_2L_3} = +\frac{m_1^2 c_r^4 c_s^4 - m_2^2 c_r^4 s_s^4 - m_3^2 s_r^4}{2 m_2 m_3 c_r^2 s_r^2 s_s^2} \,. \end{aligned}$$



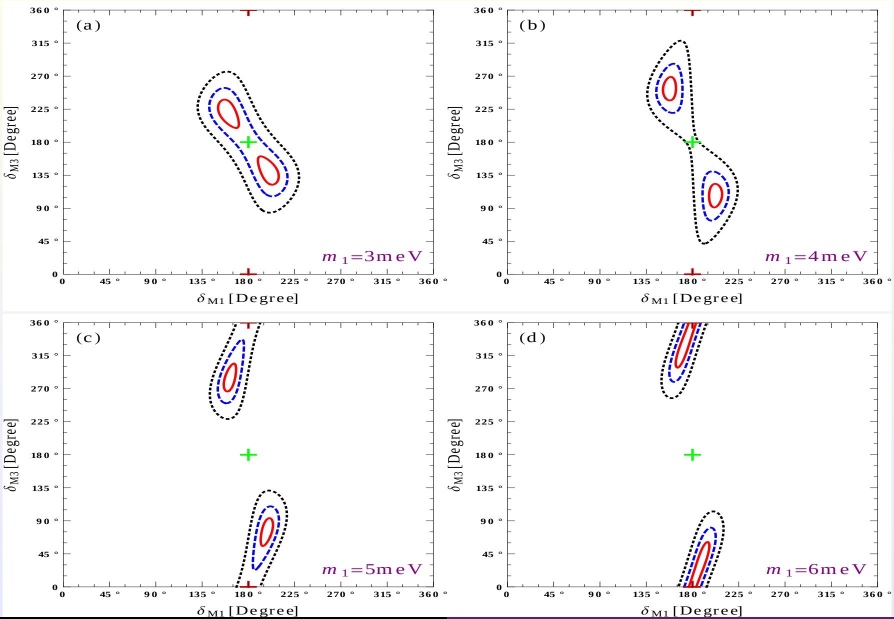
Uncertainties from Oscillation Parameters



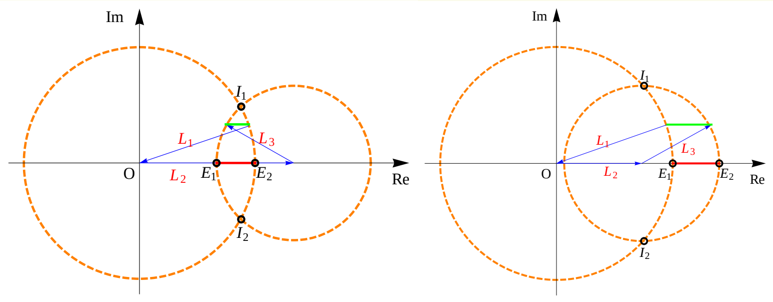
Uncertainties from Oscillation Parameters

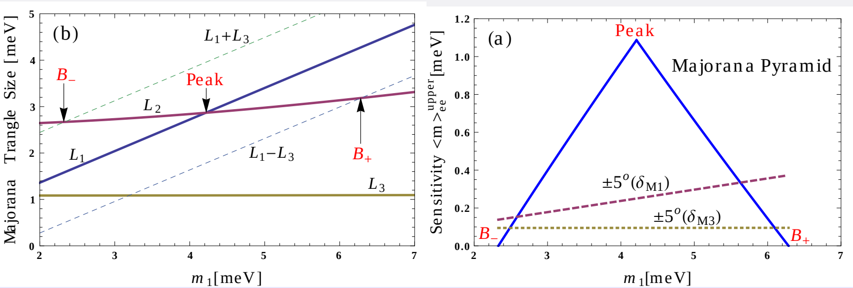


Uncertainties from $0\nu2\beta$ Measurement



Majorana Pyramid





Prey of Leptonic CP Phases

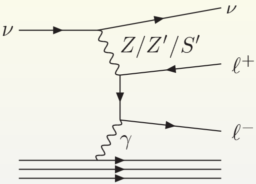
Summary

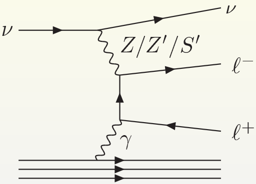
- **Null observation of $0\nu2\beta$ is not bad at all!**
- Even better: fixing two Majorana CP phases simultaneously
- Majorana vs Dirac can be determined by other measurements

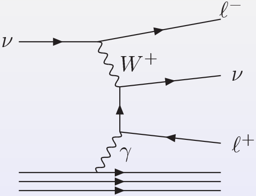
Neutrino Collider?

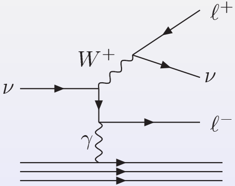
SFG, Manfred Lindner, Werner Rodejohann, Phys.Lett. **B772** (2017) 164-168 [arXiv:1702.02617]

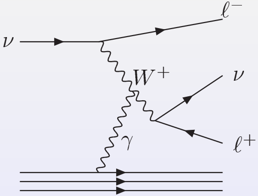
Neutrino Trident Production





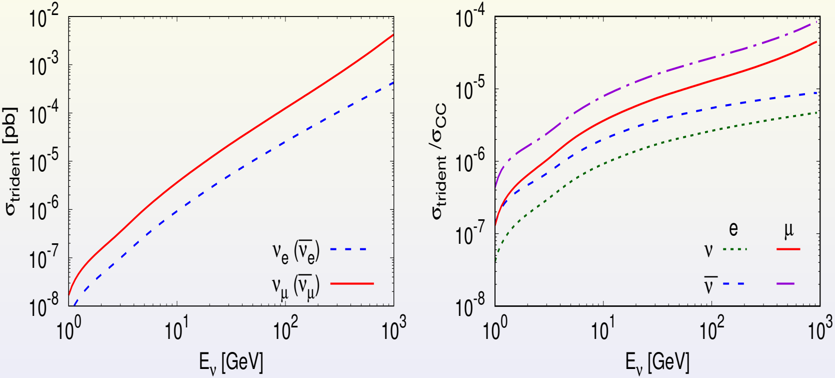






- Produce particles (**$Z/Z'/S'$**) in *t* channel.

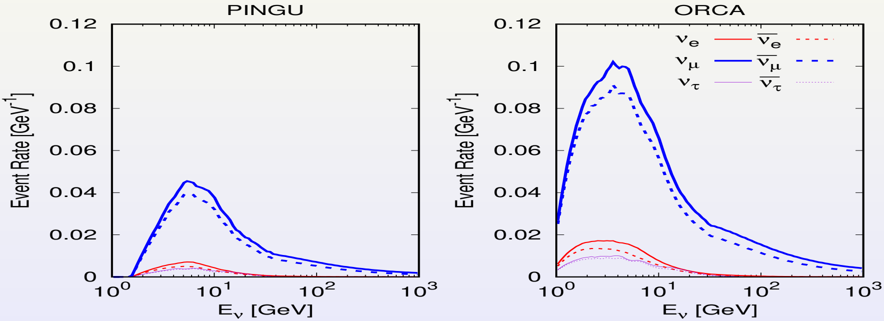
Neutrino Trident Production



- Typically $\sigma_{\rm trident} \sim (\mathbf{10^{-6} \sim 10^{-5}})\sigma_{\rm CC}$.
- To collect a handful of events, at least **10^6** CC events.
- **ARCA+ORCA** & **IceCube+DeepCore+PINGU** are perfect candidates.

Trident Production Event @ PINGU/ORCA

- $\nu + N \to \mu^+ \mu^- \nu' N^*$
- **Double muon tracks simultaneously produced at the same vertex!**



- **South Pole** (PINGU+DeepCore+IceCube) - **87** events
- **Mediterranean** (ORCA+ARCA) - **39** events

Backgrounds to Trident Production

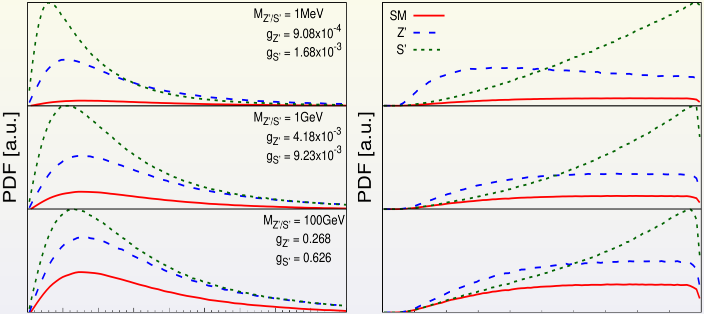
- **Coincident Double CC muons**
  - Using only **time-window cut**
    - $N_{CC} \sim 10^5$ per year ($T = 3 \times 10^7 s$)
    - Rate of coincidence within time-window Δt

$$C^2_{N_{CC}} (\Delta t / T)^2 \lesssim 1 \quad \Rightarrow \quad \Delta t \approx \frac{\sqrt{2} T}{N_{CC}} \approx 500 s\,.$$

    - Large enough to cut off all coincident background!
  - **Vertex cut**

- **High-p_T pion**
  - $\nu + N \to \ell + \pi^\pm + X \to \ell + \mu^\pm + X'$
  - The muon from pion decay tends to be soft.
  - Momentum transfer to N is highly suppressed in trident production.
  - Much cleaner hadronic shower in trident event.

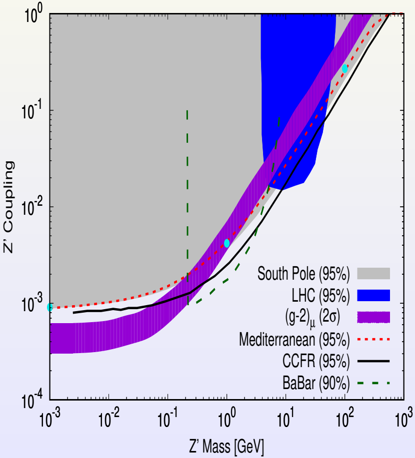
Event Reconstruction

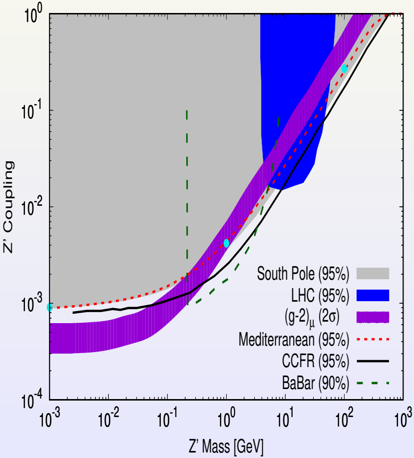


- **ORCA can do better than PINGU** in **angular resolution**.
- **Angular opening is not necessary** for recognizing double muon!
  - **Edepillim** can reconstruct energy from **radiation rate**
  - **Track length** can also tell the muon energy.
  - **Mismatch** between the two estimations for overlapping double muon.

Z'/S' **Sensitivities**

$$
\begin{aligned}
\mathcal{L}_{Z'} &\equiv g_{Z'} Q_{\alpha\beta} \left[\overline{L}_\alpha \gamma^\mu L_\beta + \overline{\ell}_{R\alpha} \gamma^\mu \ell_{R\beta} \right] \mathbf{Z}'_{\boldsymbol{\mu}} + h.c. \\
\mathcal{L}_{S'} &\equiv g_{S'} Q_{\alpha\beta} \left[\overline{\ell_{R\alpha}} \ell_{L\beta} + \overline{\nu^c_{L\alpha}} \nu_{L\beta} \right] \mathbf{S}' + h.c.
\end{aligned}
$$





Probing New Physics @ Neutrino Collider

- Trident event can produce **new particles** as **intermediate state**.
- This provides an opportunity to *directly* probe **new physics beyond the SM**.
- It essentially turns **neutrino oscillation experiment** to **neutrino collider**.
- **Neutrino oscillation experiments** reconstruct the intial state:
  - **Momentum**
  - **Flavor**
- **Neutrino collider** reconstructs NP with final-state particles.

Thank You!