

Future Opportunities in Neutrino Physics

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- 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?

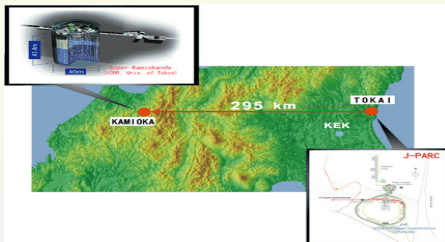
- Higgs boson for electroweak symmetry breaking & mass.
- Chiral symmetry breaking for majority of mass.
- **The world seems not affected by the tiny neutrino mass!**
 - Neutrino mass \Rightarrow Mixing
 - 3 Neutrino \Rightarrow possible **CP violation**
 - CP violation \Rightarrow Leptogenesis
 - Leptogenesis \Rightarrow **Matter-Antimatter Asymmetry**
 - There is something left in the Universe.
 - Baryogenesis from quark mixing is not enough.
- Majorana $\nu \Leftrightarrow$ **Lepton Number Violation**
- Neutrino Oscillation Experiment \Rightarrow **Neutrino Collider**

Dirac CP Phase Measurement

Jarah Evslin, **SFG**, Kaoru Hagiwara, JHEP **1602** (2016) 137 [arXiv:1506.05023]
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SFG, Alexei Smirnov, JHEP **1610** (2016) 138 [arXiv:1607.08513]
SFG, NuPhys2016 [arXiv:1704.08518]

CP Measurement @ Accelerator Exps

- T2K



- NO ν A



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

The Dirac CP Phase δ_D @ Accelerator Exp

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

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

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 **T2(H)K**, 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 $\pi - \delta_D$.

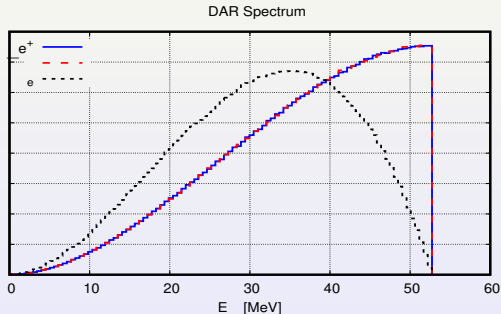
- **CP Uncertainty** $\frac{\partial P_{\mu e}}{\partial \delta_D} \propto \cos \delta_D \Rightarrow \Delta(\delta_D) \propto \frac{1}{\cos \delta_D}$.

- **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 which stops &
 - π^- is absorbed,
 - π^+ decays @ rest: $\pi^+ \rightarrow \mu^+ + \nu_\mu$.
- μ^+ stops & decays @ rest: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$.

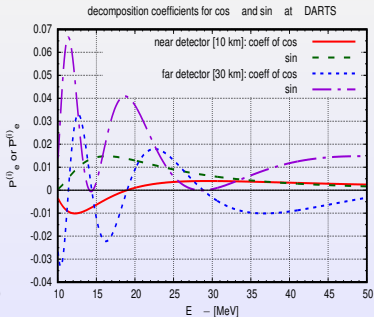
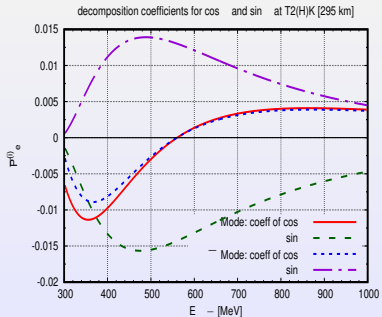


- $\bar{\nu}_\mu$ travel in all directions, oscillating as they go.
- A detector measures the $\bar{\nu}_e$ from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ **oscillation**.

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 \sim 45 MeV] solves the 3 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 Project

- 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:

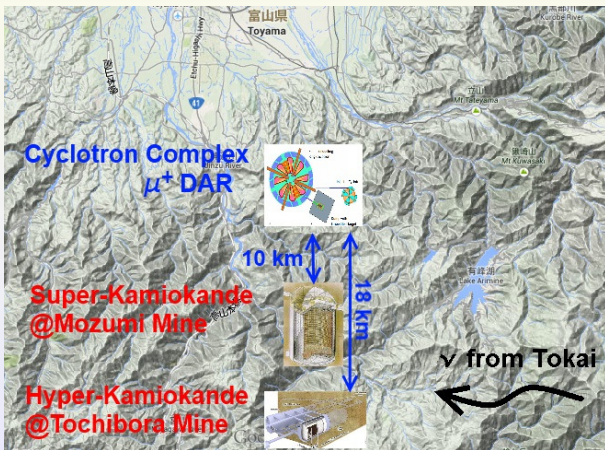
- Full (**100%**) duty factor!
- **Lower** intensity: $\sim 9\text{mA}$ [$\sim 4\times$ lower than DAE δ ALUS]
- Not far beyond the current state-of-art technology of cyclotron [2.2mA @ Paul Scherrer Institute]
- MUCH **cheaper** & technically **easier**.
 - Only one cyclotron.
 - Lower intensity.

Disadvantage?

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

TNT2K

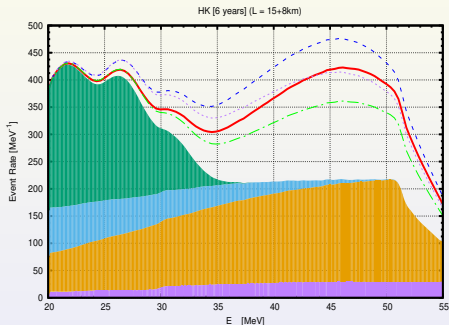
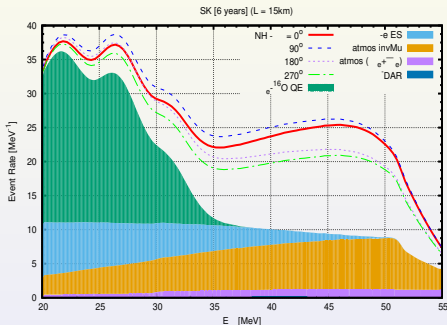
- $T2(H)K + \mu SK + \mu HK$



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

Event Shape @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]

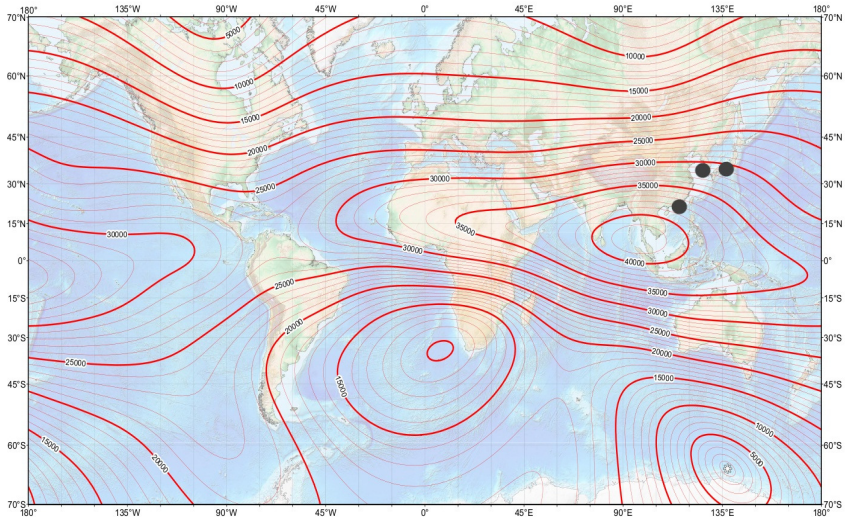


Expected μ DAR IBD signal from 6 yrs of running @ SK (15km) & HK (23km) with NH.

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

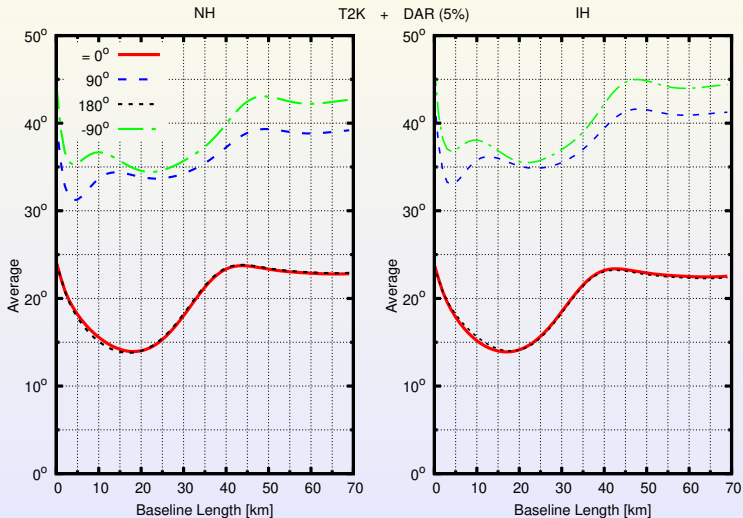
Lowest Atmospheric Neutrino Background

US/UK World Magnetic Model -- Epoch 2010.0
Main Field Horizontal Intensity (H)



δ_D Precision @ TNT2K

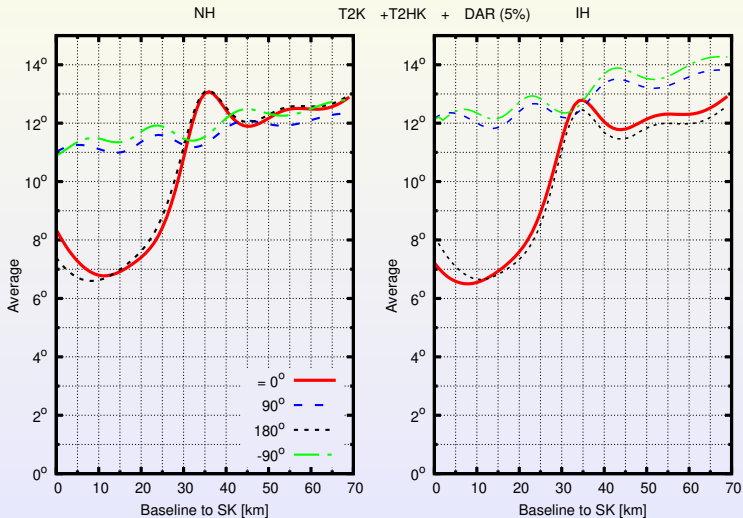
Evslin, Ge & Hagiwara [1506.05023]



Simulated by NuPro, <http://nupro.hepforge.org/>

δ_D Precision @ TNT2K

Evslin, Ge & Hagiwara [1506.05023]



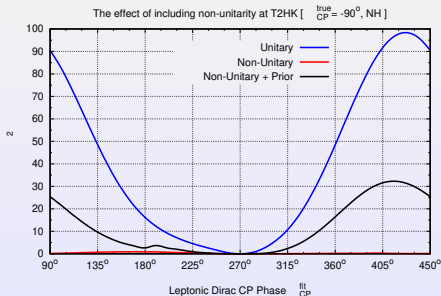
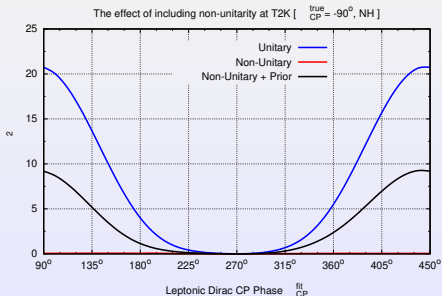
Simulated by [NuPro](http://nupro.hepforge.org/), <http://nupro.hepforge.org/>

Non-Unitarity Mixing (NUM)

Ge, Pasquini, Tortola & Valle [1605.01670]

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

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



NUM vs Seesaw Mechanism

- Heavy neutrinos

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

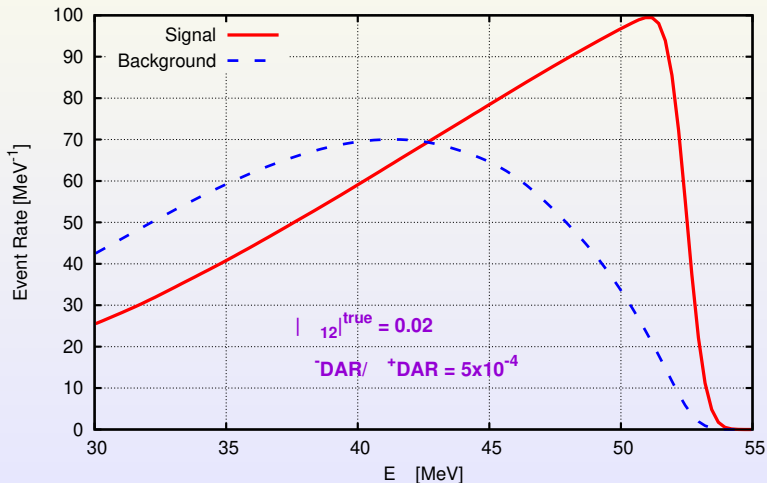
- Seesaw Mechanism

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

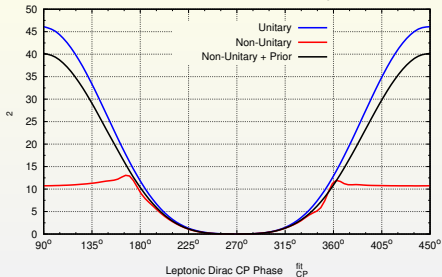


$$P_{\mu e}^{NP}(L \rightarrow 0) = \alpha_{11}^2 |\alpha_{21}|^2 P_{ee} \approx \alpha_{11}^2 |\alpha_{21}|^2 \approx |\alpha_{21}|^2$$

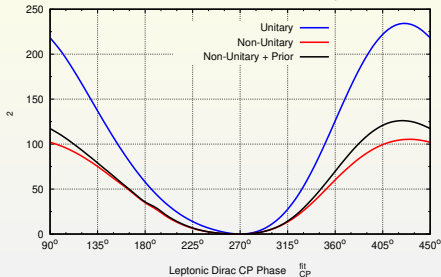
Event Spectrum at Near [20ton, L = 20m]



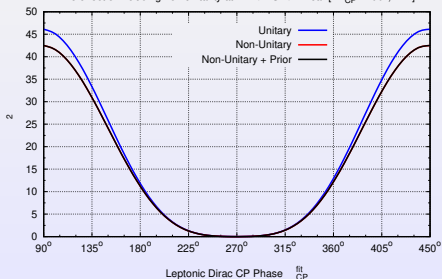
The effect of including non-unitarity at T2K+ SK [$\theta_{CP}^{true} = -90^\circ$, NH]



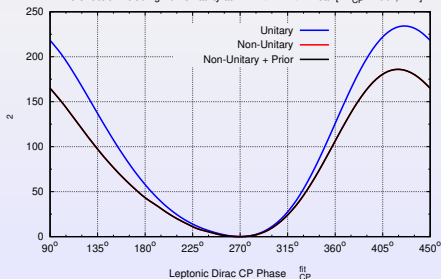
The effect of including non-unitarity at T2HK+ HK [$\theta_{CP}^{true} = -90^\circ$, NH]



The effect of including non-unitarity at T2K+ SK+ Near [$\theta_{CP}^{true} = -90^\circ$, NH]



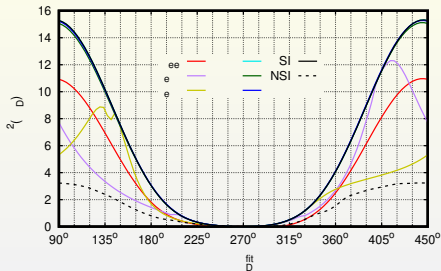
The effect of including non-unitarity at T2HK+ HK+ Near [$\theta_{CP}^{true} = -90^\circ$, NH]



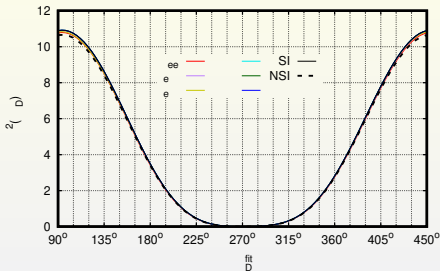
$$\mathcal{H} \equiv \frac{1}{2\mathbf{E}_\nu} \left\{ U_\nu \begin{pmatrix} 0 & & \\ & \Delta m_s^2 & \\ & & \Delta m_a^2 \end{pmatrix} U_\nu^\dagger + 2\mathbf{E}_\nu V_{CC} \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}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

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

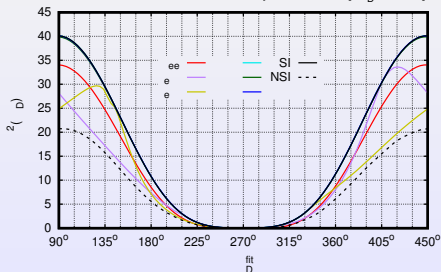
The effect of NSI on the CP sensitivity at T2K [$\text{true}_D = -90^\circ$]



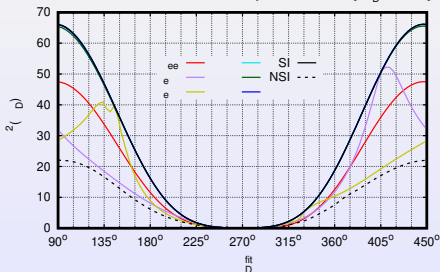
The effect of NSI on the CP sensitivity at μ SK [$\text{true}_D = -90^\circ$]



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



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



Summary – Experiment

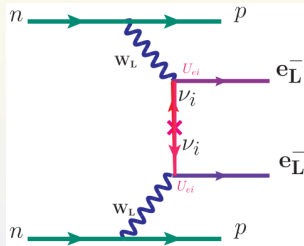
- **Better CP measurement than T2K, T2KII, T2HK, T2KK**
 - Much larger event numbers
 - Much better CP sensitivity around maximal CP
 - Solve degeneracy between δ_D & $\pi - \delta_D$
 - Guarantee CP sensitivity against NUM
 - Guarantee CP sensitivity against NSI
- **Better configuration than DAE δ ALUS**
 - 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]

$0\nu 2\beta$ Decay

- Mediated by **Majorana Neutrino** + **Lepton # Violation**



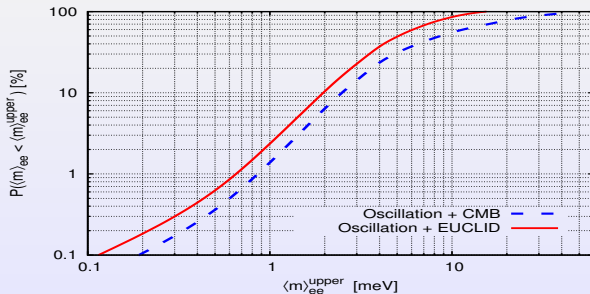
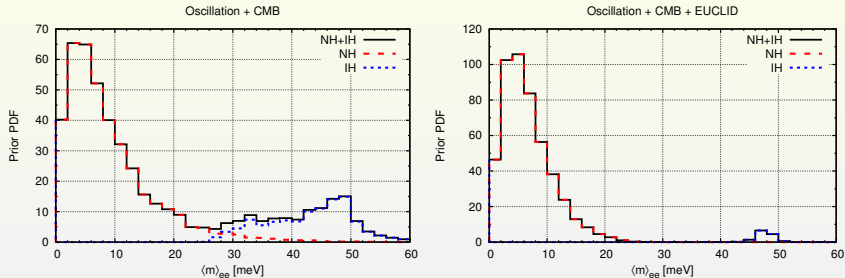
- Helicity Suppression** → **Mass Suppression**

$$\mathcal{M} \propto \sum_i U_{ei} \frac{i}{\not{p} - m_i} U_{ei} \approx \sum_i U_{ei} \frac{m_i}{p^2} U_{ei}$$

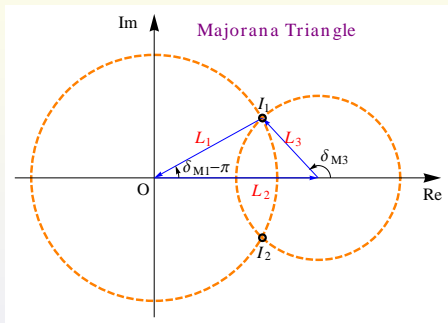
- Effective Mass**

$$m_{ee}^\nu \equiv \left| \sum_i m_i U_{ei}^2 \right| = \left| c_s^2 c_r^2 m_1 e^{i\delta_{M1}} + s_s^2 c_r^2 m_2 + s_r^2 m_3 e^{i\delta_{M3}} \right|$$

Preference of NH \Rightarrow Non-Observation of $0\nu 2\beta$



Any chance of obtaining some information?



$$\langle m \rangle_{ee} \equiv \vec{L}_1 + \vec{L}_2 + \vec{L}_3,$$

with

$$\vec{L}_1 \equiv m_1 U_{e1}^2 = m_1 c_r^2 c_s^2 e^{i\delta_{M1}},$$

$$\vec{L}_2 \equiv m_2 U_{e2}^2 = \sqrt{m_1^2 + \Delta m_s^2} c_r^2 s_s^2,$$

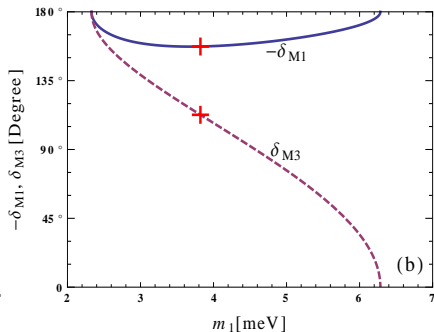
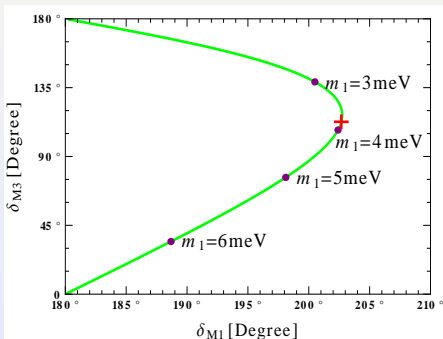
$$\vec{L}_3 \equiv m_3 U_{e3}^2 = \sqrt{m_1^2 + \Delta m_a^2} s_r^2 e^{i\delta_{M3}}.$$

Determine 2 Majorana Phases Simultaneously

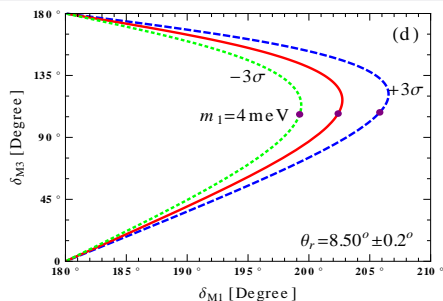
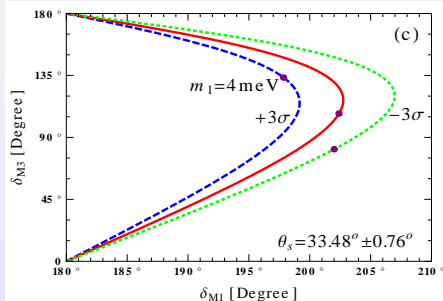
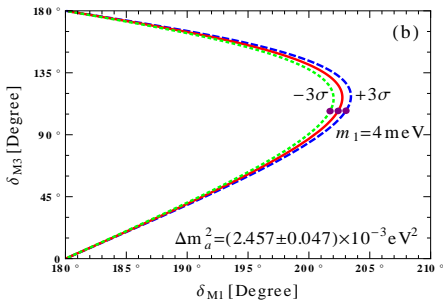
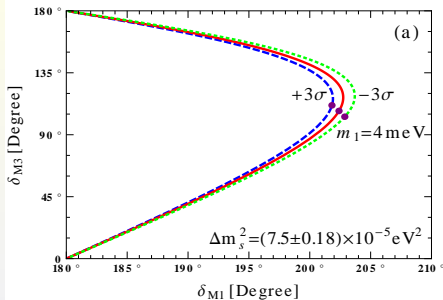
$$|L_1 - L_3| \leq L_2 \leq L_1 + L_3.$$

$$\cos \delta_{M1} = -\frac{L_1^2 + L_2^2 - L_3^2}{2L_1L_2} = -\frac{m_1^2 c_r^4 c_s^4 + m_2^2 c_r^4 s_s^4 - m_3^2 s_r^4}{2m_1 m_2 c_r^4 c_s^2 s_s^2},$$

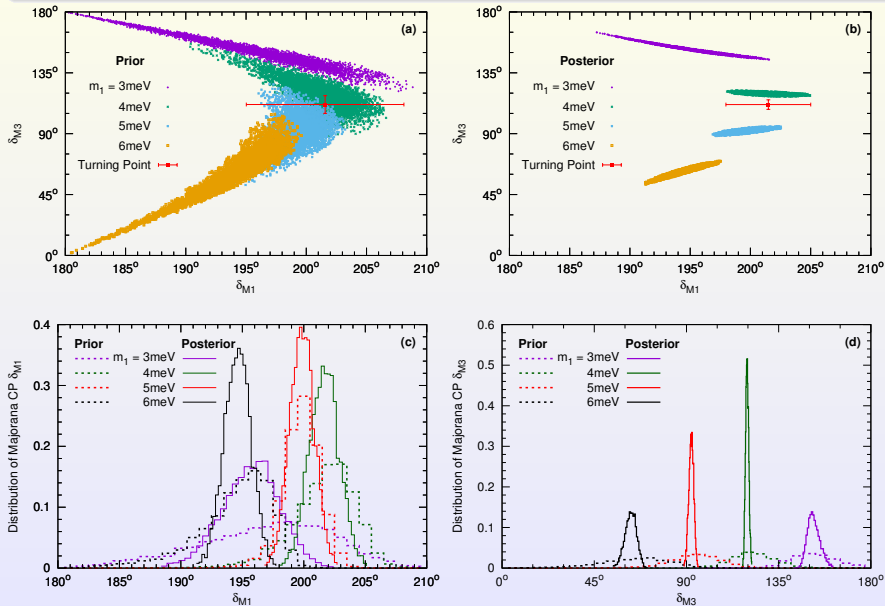
$$\cos \delta_{M3} = +\frac{L_1^2 - L_2^2 - L_3^2}{2L_2L_3} = +\frac{m_1^2 c_r^4 c_s^4 - m_2^2 c_r^4 s_s^4 - m_3^2 s_r^4}{2m_2 m_3 c_r^2 s_r^2 s_s^2}.$$



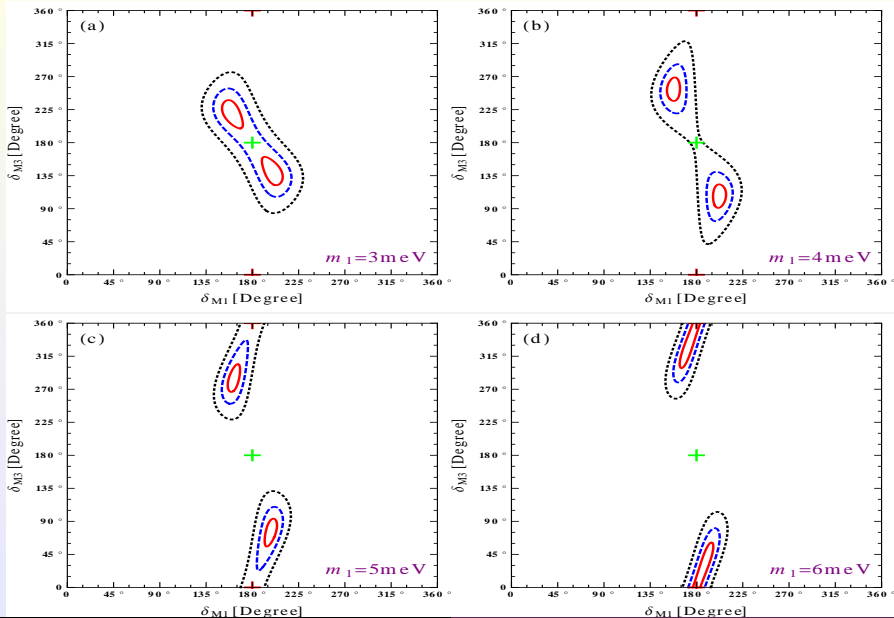
Uncertainties from Oscillation Parameters



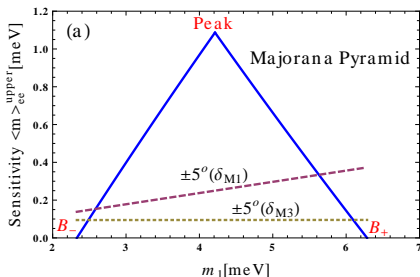
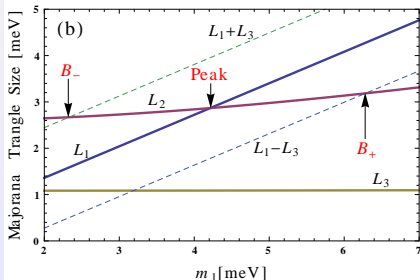
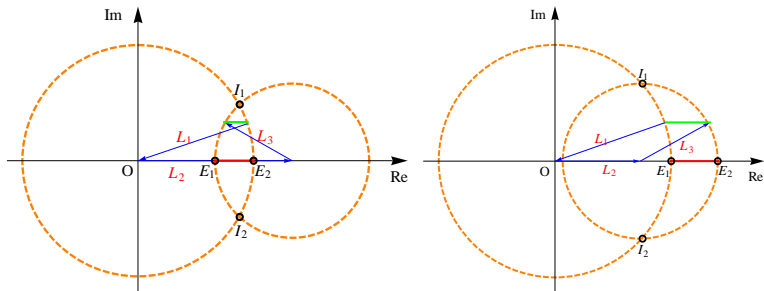
Uncertainties from Oscillation Parameters



Uncertainties from $0\nu 2\beta$ Measurement



Majorana Pyramid



Prey of Leptonic CP Phases



Dirac



Majorana 1



Majorana 2



Majorana Pyramid

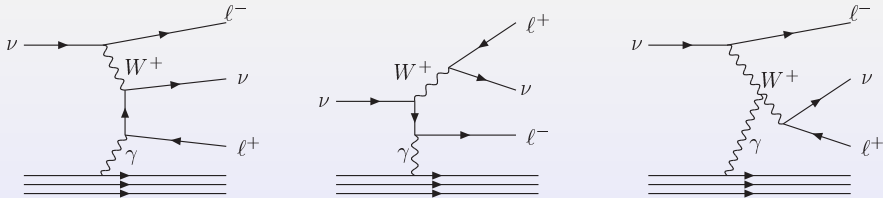
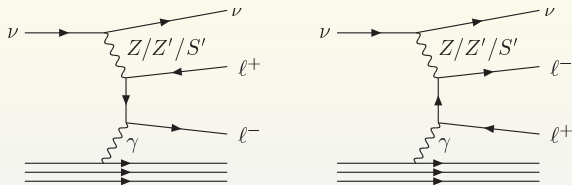
Summary

- **Null observation of $0\nu 2\beta$ is not bad at all!**
- Even better: fixing two Majorana CP phases simultaneously
- Majorana vs Dirac can be determined by other measurements

Neutrino Collider?

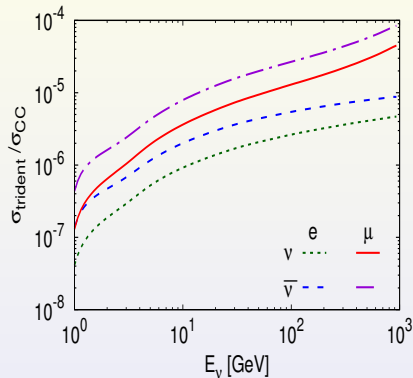
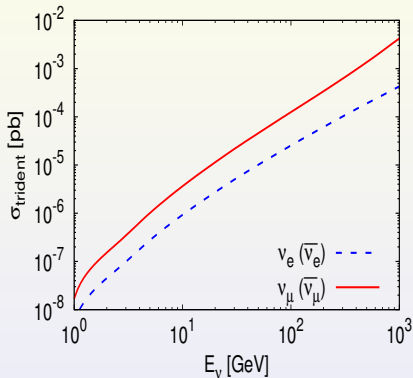
SFG, Manfred Lindner, Werner Rodejohann, Phys.Lett. **B772** (2017) 164-168 [arXiv:1702.02617]

Neutrino Trident Production



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

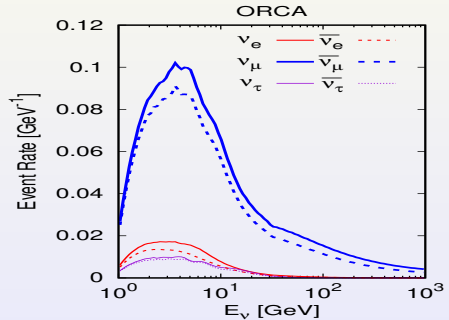
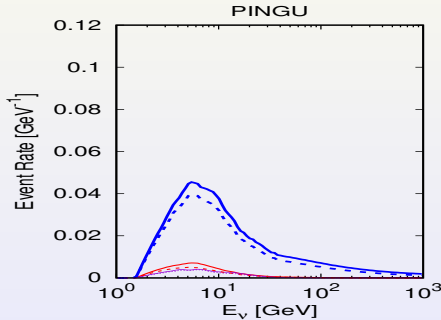
Neutrino Trident Production



- Typically $\sigma_{\text{trident}} \sim (10^{-6} \sim 10^{-5})\sigma_{\text{CC}}$.
- 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

- $\nu + N \rightarrow \mu^+ \mu^- \nu' N^*$
- **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

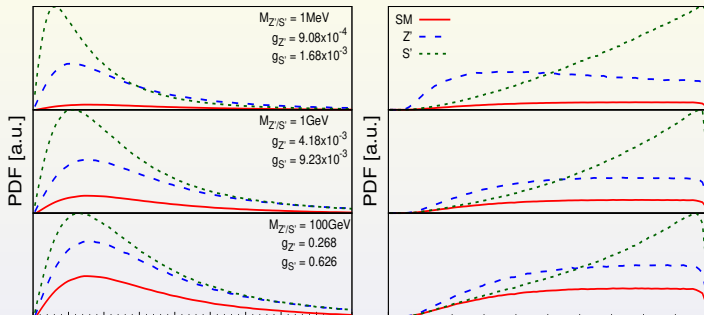
$$C_{N_{CC}}^2 (\Delta t/T)^2 \lesssim 1 \quad \Rightarrow \quad \Delta t \approx \frac{\sqrt{2}T}{N_{CC}} \approx 500s.$$

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

- **High- p_T pion**

- $\nu + N \rightarrow \ell + \pi^\pm + X \rightarrow \ell + \mu^\pm + X'$
- 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

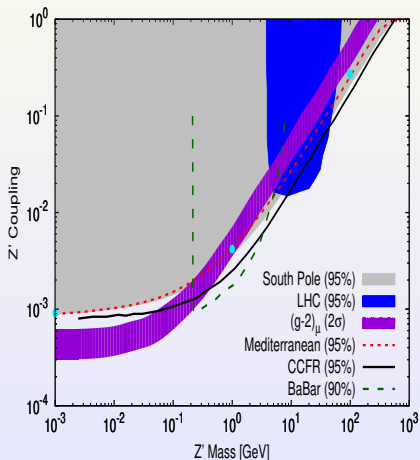
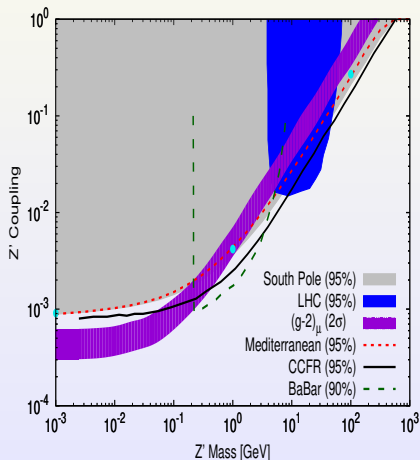


- **ORCA can do better than PINGU in angular resolution.**
- **Angular opening is not necessary** for recognizing double muon!
 - **Edepillim** can reconstruct energy from **radiation rate**
 - **Track length** can also tell the muon energy.
 - **Mismatch** between the two estimations for overlapping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

Z'/S' Sensitivities

$$\mathcal{L}_{Z'} \equiv g_{Z'} Q_{\alpha\beta} \left[\bar{L}_\alpha \gamma^\mu L_\beta + \bar{\ell}_{R\alpha} \gamma^\mu \ell_{R\beta} \right] Z'_\mu + h.c.$$

$$\mathcal{L}_{S'} \equiv g_{S'} Q_{\alpha\beta} \left[\bar{\ell}_{R\alpha} \ell_{L\beta} + \bar{\nu}_{L\alpha}^c \nu_{L\beta} \right] S' + h.c.$$



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 initial state:
 - **Momentum**
 - **Flavor**
- **Neutrino collider** reconstructs NP with final-state particles.

Thank You!