Neutrino Matter Effect & Non-Standard Interactions

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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 [arXiv:1704.08518]
SFG, Stephen J. Parke [arXiv:1812.08376]

Why neutrino mass & oscillation?

- Higgs boson ⇒ electroweak symmetry breaking & mass.
- Chiral symmetry breaking ⇒ majority of mass.
- **The world 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.
- Majorana ν ⇔ **Lepton Neumber Violation**
- **Residual $\mathbb{Z}_2$ Symmetries:** $\cos\delta_{\mathrm{D}} = \dfrac{(s_s^2 - c_s^2 s_r^2)(\mathbf{c}_\mathbf{a}^2 - \mathbf{s}_\mathbf{a}^2)}{4 c_a s_a c_s s_s \mathbf{s}_\mathbf{r}}$ 1108.0964 1104.0602

ν Mass & Mixing [Majorana ν]

- **Correlated Mass Matrix:**

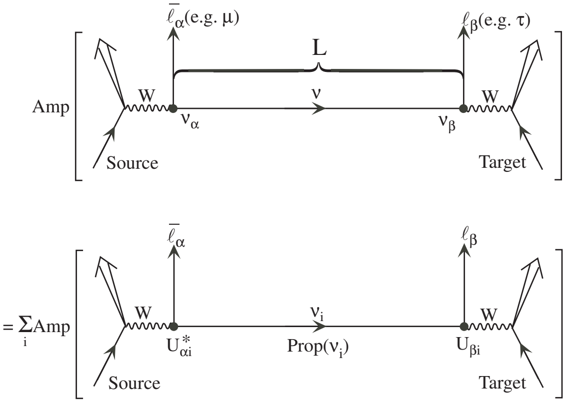
$$\mathcal{L}_\nu = -\frac{1}{2} \begin{pmatrix} \nu_e^T & \nu_\mu^T & \nu_\tau^T \end{pmatrix} \mathcal{C} \begin{pmatrix} \mathbf{A} & \mathbf{B_1} & \mathbf{B_2} \\ & \mathbf{C_1} & \mathbf{D} \\ & & \mathbf{C_2} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} + \cdots$$

- **Mass Diagonalization:**

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = U^\dagger \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$\begin{pmatrix} \mathbf{m_1} & & \\ & \mathbf{m_2} & \\ & & \mathbf{m_3} \end{pmatrix} = U^T \begin{pmatrix} \mathbf{A} & \mathbf{B_1} & \mathbf{B_2} \\ & \mathbf{C_1} & \mathbf{D} \\ & & \mathbf{C_2} \end{pmatrix} U$$

ν Oscillation



[Kayser, hep-ph/0506165]

$$\nu_\alpha = \sum_i \mathbf{U}_{\alpha i} \nu_i \rightarrow \boxed{\sum_i \mathbf{U}_{\alpha i} e^{i(E_i t - \vec{P}_i \cdot \vec{x})} \nu_i} = \boxed{\sum_i \mathbf{U}_{\alpha i} \mathbf{P}_i \mathbf{U}^\dagger_{i\beta} \nu_\beta} \equiv \sum_\beta \mathbf{A}_{\alpha\beta} \nu_\beta$$

ν Mass & Mixing

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

$$\nu_\alpha(t, L) = \sum_{i\beta} \mathbf{U}_{\alpha i} e^{-i(E_i t - p_i L)} \mathbf{U}^*_{\beta i} \nu_\beta \equiv \sum_\beta \mathbf{A}_{\alpha\beta} \nu_\beta$$

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

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

$$\nu_\alpha = \sum_i \mathbf{U}_{\alpha i}\, \nu_i$$

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

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

ν Oscillation Data

(for NH)	-1σ	Best Value	$+1\sigma$
$\boldsymbol{\Delta m^2_s} \equiv \Delta m^2_{12}\,(\mathbf{10^{-5}}\mathrm{eV}^{\mathbf{2}})$	7.37	**7.56**	7.75
$\lvert\boldsymbol{\Delta m^2_a} \equiv \Delta m^2_{13}\rvert\ (\mathbf{10^{-3}}\mathrm{eV}^{\mathbf{2}})$	2.51	**2.55**	2.59
$\sin^2\theta_s\ (\theta_s \equiv \theta_{12})$	0.305 (33.5°)	0.321 (**34.5°**)	0.339 (35.6°)
$\sin^2\theta_a\ (\theta_a \equiv \theta_{23})$	0.412 (39.9°)	0.430 (**41.0°**)	0.450 (42.1°)
$\sin^2\theta_r\ (\theta_r \equiv \theta_{13})$	0.02080 (8.29°)	0.02155 (**8.44°**)	0.02245 (8.62°)
δ_D, δ_{Mi}	?, **??**	?, **??**	?, **??**

Salas, Forero, Ternes, Tortola & Valle, arXiv:1708.01186

Neutrino Oscillation = Mass + Interaction

PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

Neutrino oscillations in matter

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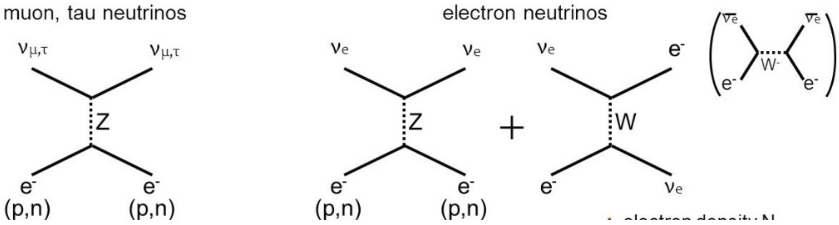
(Received 6 October 1977; revised manuscript received 5 December 1977)

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

$$\mathcal{H} = \frac{\mathbf{MM}^\dagger}{2E_\nu} \pm \mathbf{V}\,.$$



Forward Scattering & Effective Lagrangian

- **Standard Model Lagrangian**

$$\mathcal{L}_{\rm cc} = \frac{\mathbf{g}_{\alpha\rho}}{\sqrt{2}} V^+_\mu \bar{\nu}_\alpha \gamma^\mu P_L \ell_\rho + h.c.$$

To be general, let's keep **non-universal couplings $\mathbf{g}_{\alpha\rho}$**.

- The **effective Lagrangian** for **forward scattering without momentum transfer**

$$\mathcal{L}^{\rm eff}_{\rm cc} = \frac{\mathbf{g}_{\alpha\rho}\mathbf{g}^*_{\beta\sigma}}{2} \frac{\mathbf{1}}{-\mathbf{m}^2_V} \left(\bar{\nu}_\alpha \gamma^\mu P_L \ell_\rho \right) \left(\bar{\ell}_\sigma \gamma_\mu P_L \nu_\beta \right) ,$$

where $\boxed{\frac{\mathbf{1}}{\mathbf{p}^2_V - \mathbf{m}^2_V} = \frac{\mathbf{1}}{-\mathbf{m}^2_V}}$ from the V propagator with **vanishing $\mathbf{p}_V$**.

Fierz Transformation Matter Potentials

- Using **Fierz transformation**, the effective Lagrangian becomes

$$\mathcal{L}^{\rm eff}_{\rm cc} = \frac{g_{\alpha\rho} g^*_{\beta\sigma}}{2} \frac{1}{-m^2_V} \left(\overline{\nu_\alpha} \gamma_\mu P_L \nu_\beta\right) \left(\overline{\ell}_\sigma \gamma^\mu P_L \ell_\rho\right) \,,$$

  which can account for both **charged & neutral current** contributions!

- **The matter potential is defined by not just Lagrangian, but also external states!** When expanding $\boxed{\langle out | \mathcal{S} \equiv e^{-i \int \mathcal{L}^{\rm eff}_{\rm cc}} | in \rangle}$ to leading order

$$\boldsymbol{\delta \Gamma_{\alpha\beta}} = - \langle \nu_\alpha e | \mathcal{L}^{\rm cc}_{\rm eff} | \nu_\beta e \rangle \,,$$

  for **neutrino modes** &

$$\boldsymbol{\delta \overline{\Gamma}_{\alpha\beta}} = - \langle \bar\nu_\alpha e | \mathcal{L}^{\rm cc}_{\rm eff} | \bar\nu_\beta e \rangle \,,$$

  for **anti-neutrino modes**.

Second Quantization

Two-point correlation function

$$\delta\Gamma_{\alpha\beta} = -\langle \nu_\alpha e | \mathcal{L}^{\rm cc}_{\rm eff} | \nu_\beta e \rangle \,, \qquad \delta\overline{\Gamma}_{\alpha\beta} = -\langle \bar\nu_\alpha e | \mathcal{L}^{\rm cc}_{\rm eff} | \bar\nu_\beta e \rangle \,,$$

- **Second Quantization**

$$\nu_\alpha = a_\alpha u_\alpha e^{-ip\cdot x} + b^\dagger_\alpha v_\alpha e^{ip\cdot x} \,, \qquad |\nu_\alpha\rangle = a^\dagger_\alpha |0\rangle \,, \qquad |\bar\nu_\alpha\rangle = b^\dagger_\alpha |0\rangle \,.$$

- Apply to the neutrino & lepton parts separately:

$$\delta\Gamma_{\alpha\beta} = \frac{g_{\alpha' e} g^*_{\beta' e}}{2 m_V^2} \langle \nu_\alpha | \bar\nu_{\alpha'} \gamma_\mu P_L \nu_{\beta'} | \nu_\beta \rangle \langle e | \bar\ell \gamma_\mu P_L \ell | e \rangle \,,$$

$$\delta\overline{\Gamma}_{\alpha\beta} = \frac{g_{\alpha' e} g^*_{\beta' e}}{2 m_V^2} \langle \bar\nu_\alpha | \bar\nu_{\alpha'} \gamma_\mu P_L \nu_{\beta'} | \bar\nu_\beta \rangle \langle e | \bar\ell \gamma_\mu P_L \ell | e \rangle \,,$$

- The contraction of operators are

$$\nu_\alpha | \nu_\beta \rangle = u_\alpha \delta_{\alpha\beta} \,, \quad \bar\nu_\alpha | \bar\nu_\beta \rangle = \bar v_\alpha \delta_{\alpha\beta} \,, \quad \langle \nu_\alpha | \bar\nu_\beta = \bar u_\alpha \delta_{\alpha\beta} \,, \quad \langle \bar\nu_\alpha | \nu_\beta = v_\alpha \delta_{\alpha\beta}$$

Sign Difference between Neutrino & Anti-Neutrino

- Altogether

$$\delta\Gamma_{\alpha\beta} \propto \langle 0| a_\alpha (a^\dagger_{\alpha'} \bar{u}_{\alpha'} + b_{\alpha'} \bar{v}_{\alpha'}) \gamma_\mu P_L (a_{\beta'} u_{\beta'} + b^\dagger_{\beta'} v_{\beta'}) a^\dagger_\beta |0\rangle$$
$$= \langle 0| a_\alpha a^\dagger_{\alpha'} \bar{u}_{\alpha'} \gamma_\mu P_L a_{\beta'} u_{\beta'} a^\dagger_\beta |0\rangle \,,$$

$$\delta\overline{\Gamma}_{\alpha\beta} \propto \langle 0| b_\alpha (a^\dagger_{\alpha'} \bar{u}_{\alpha'} + b_{\alpha'} \bar{v}_{\alpha'}) \gamma_\mu P_L (a_{\beta'} u_{\beta'} + b^\dagger_{\beta'} v_{\beta'}) b^\dagger_\beta |0\rangle$$
$$= \langle 0| b_\alpha b_{\alpha'} \bar{v}_{\alpha'} \gamma_\mu P_L b^\dagger_{\beta'} v_{\beta'} b^\dagger_\beta |0\rangle \,.$$

- **0** permutation for **neutrino** vs **1** permutation for **anti-neutrino**

$$\delta\Gamma_{\alpha\beta} = +\frac{g_{\alpha e} g^*_{\beta e}}{2 m_V^2} (\bar{u}_\alpha \gamma_\mu P_L u_\beta) \langle e| \bar{e} \gamma_\mu P_L e |e\rangle \,,$$

$$\delta\overline{\Gamma}_{\alpha\beta} = -\frac{g_{\beta e} g^*_{\alpha e}}{2 m_V^2} (\bar{v}_\beta \gamma_\mu P_L v_\alpha) \langle e| \bar{e} \gamma_\mu P_L e |e\rangle \,,$$

Matter Effect

- The **total matter effect** is an **integration** over electron **momentum** & **spin**

$$\delta\Gamma = \frac{g_{\alpha e} g^*_{\beta e}}{2 m_V^2} \left(\bar{u}_\alpha \gamma_\mu P_L u_\beta \right) \times \int \frac{\mathbf{d^3 p_e}}{\mathbf{N}} \frac{\mathbf{1}}{\mathbf{2}} \sum_{\mathbf{s}} \bar{u}^e_s(\mathbf{p}_e) \gamma_\mu P_L u^e_s(\mathbf{p}_e) \,,$$

- In the **non-relativistic limit**

$$\sum_s \bar{u}^e_s \gamma_\mu \gamma_5 u^e_s \propto (0, \vec{s}) \,, \qquad \sum_s \bar{u}^e_s \gamma_\mu u^e_s \propto (n_e, \vec{0}) \,.$$

- Since **electrons are not polarized** in usual material:

$$V_{\beta\alpha} \bar{u}_\alpha \gamma_0 P_L u_\beta \,, \qquad -V^*_{\beta\alpha} \bar{v}_\beta \gamma_0 P_L v_\alpha \,,$$

where **only the time-component can survive**.

Modified Equation of Motion

- **Kinetic Terms**

$$\begin{aligned}\bar{\nu}_\beta(i\partial\!\!\!/ + M_{\beta\alpha})\nu_\alpha &= \bar{u}_\beta e^{+ip\cdot x}(i\partial\!\!\!/ + M_{\beta\alpha})u_\alpha e^{-ip\cdot x}(a^\dagger a)\\ &- \bar{v}_\alpha e^{-ip\cdot x}(i\partial\!\!\!/ + M_{\alpha\beta})v_\beta e^{+ip\cdot x}(b^\dagger b)\end{aligned}$$

- **Vacuum**

$$\begin{aligned}\bar{u}_\beta(p\!\!\!/ + M_{\beta\alpha})u_\alpha &= 0\,,\\ \bar{v}_\alpha\,(p\!\!\!/ - M_{\alpha\beta})v_\beta &= 0\,,\end{aligned}$$

- **Matter Effect**

$$\begin{aligned}\bar{u}_\beta(p\!\!\!/ + V_{\beta\alpha}\gamma_0 + M_{\beta\alpha})u_\alpha &= 0\,,\\ \bar{v}_\alpha(p\!\!\!/ - V_{\alpha\beta}\gamma_0 - M_{\alpha\beta})v_\beta &= 0\,.\end{aligned}$$

Dispersion Relation & Effective Hamiltonian

- **Dispersion Relation**

$$(E \pm \mathbf{V})^2 = \vec{p}^2 + \mathbf{M}\mathbf{M}^\dagger$$

- **Effective Hamiltonian**

$$\mathcal{H} = \sqrt{\vec{p}^2 + \mathbf{M}\mathbf{M}^\dagger} \pm \mathbf{V} \approx |\vec{p}| + \frac{\mathbf{M}\mathbf{M}^\dagger}{2E} \pm \mathbf{V}$$

Since the **leading term is universal**, it would not affect neutrino oscillation and hence can be omitted. The neutrino oscillation is determined by the **effective Hamiltonian**

$$\mathcal{H}_{\rm eff} = \frac{\mathbf{M}\mathbf{M}^\dagger}{2E} \pm \mathbf{V}$$

Note that neutrino oscillation is described by $\mathcal{H}_{\rm eff}$ but the anti-neutrino one by $\mathcal{H}^*_{\rm eff}$. Since the neutrino energy E is a constant, it is equivalent to use $\mathbf{2E}\mathcal{H}$ for describing neutrino oscillation.

MSW Effect

- Take **2-neutrino oscillation** as an example

$$\frac{1}{2E}\begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}m_1^2 & \\ & m_2^2\end{pmatrix}\begin{pmatrix}\cos\theta & -\sin\theta \\ \sin\theta & \cos\theta\end{pmatrix}+\begin{pmatrix}\mathbf{V}_{\rm cc} & 0 \\ 0 & 0\end{pmatrix}$$

- The lagrangian can be described by effective matter term

$$\mathcal{H}_{\rm eff}^{\rm vac}=\frac{1}{2E}\begin{pmatrix}\cos\widetilde{\theta} & \sin\widetilde{\theta} \\ -\sin\widetilde{\theta} & \cos\widetilde{\theta}\end{pmatrix}\begin{pmatrix}\widetilde{m}_1^2 & \\ & \widetilde{m}_2^2\end{pmatrix}\begin{pmatrix}\cos\widetilde{\theta} & -\sin\widetilde{\theta} \\ \sin\widetilde{\theta} & \cos\widetilde{\theta}\end{pmatrix}$$

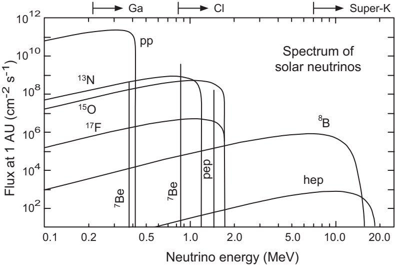
- **Resonance** if $\boxed{V_{\rm cc}\Delta m^2 > 0}$

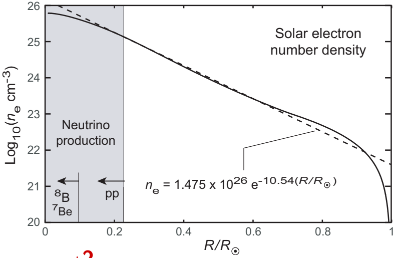
$$\sin 2\widetilde{\theta} = \frac{\sin 2\theta}{\sqrt{\sin^2 2\theta + (\cos 2\theta - 2E\mathbf{V}/\boldsymbol{\Delta}\mathbf{m}^2)^2}}$$

$$\boldsymbol{\Delta}\widetilde{\mathbf{m}}^2 = \Delta m^2\sqrt{\sin^2 2\theta + (\cos 2\theta - 2E\mathbf{V}/\boldsymbol{\Delta}\mathbf{m}^2)^2}$$

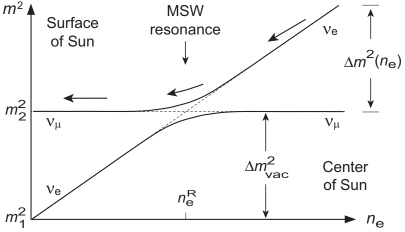
- Energy modulation: $\boxed{\mathcal{H} \to 2\mathbf{E}\mathcal{H}}$

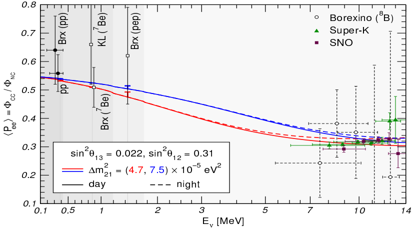
Adiabatic Evolution of Solar Neutrinos





$$\mathbf{P}_{\mathbf{ee}}^{\mathrm{sun}} = \left| \mathbf{U}_{\mathbf{ei}}^{\mathrm{prod}} (\mathbf{U}_{\mathbf{ei}}^{\mathrm{vac}})^* \right|^2$$

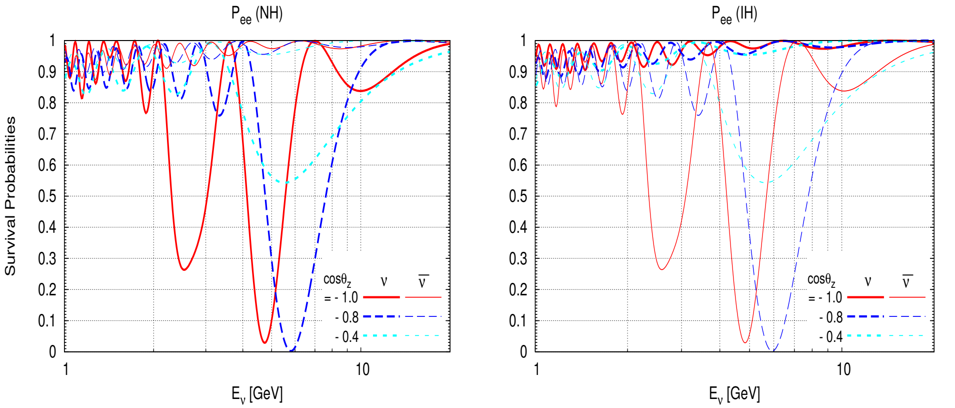




Guidry & Billings [arXiv:1812.00035]; Maltoni & Smirnov [arXiv:1507.05287]

Parametric Resonance of Atmospheric Neutrinos

$$\sin 2\widetilde{\theta} = \frac{\sin 2\theta}{\sqrt{\sin^2 2\theta + (\cos 2\theta - 2EV/\Delta m^2)^2}}.$$



(Semi)-Analytical Way? SFG, Kaoru Hagiwara, Carsten Rott, **JHEP 1406 (2014) 150** [arXiv:1309.3176]

Sizable Matter Effect of Reactor Neutrinos

Chinese Physics C Vol. 40, No. 9 (2016) 091001

Terrestrial matter effects on reactor antineutrino oscillations at JUNO or RENO-50: how small is small? *

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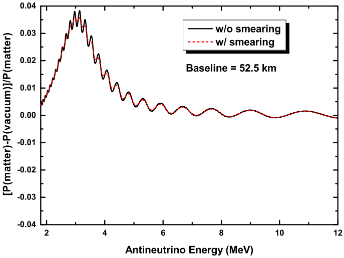
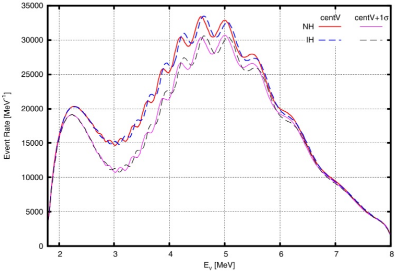
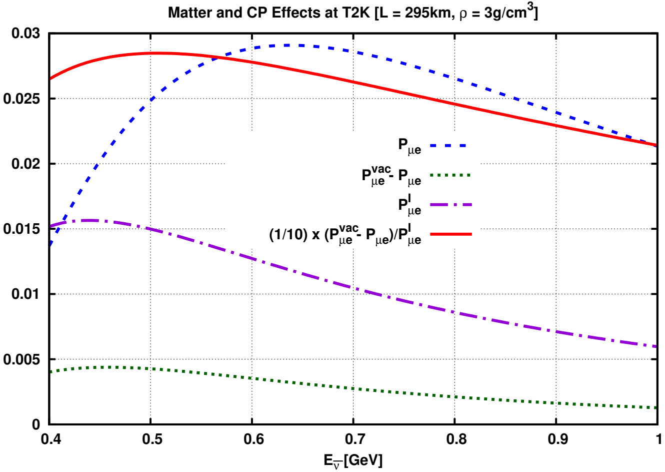




$$\frac{A}{\Delta_{21}} \simeq 1.05 \times \mathbf{10^{-2}} \times \frac{E}{4\ \mathrm{MeV}} \times \frac{7.5 \times 10^{-5}\ \mathrm{eV}^2}{\Delta_{21}}$$

see also SFG & Werner Rodejohann, PRD2015 [arXiv:1507.05514]

Matter Effect @ Accelerator



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

Standard & Non-Standard Interactions

- **Effective Hamiltonian**

$$\mathcal{H}_{\text{eff}} = \frac{\mathbf{M}\mathbf{M}^\dagger}{2E} \pm \mathbf{V} = \frac{\mathbf{M}\mathbf{M}^\dagger}{2E} \pm \mathbf{V}_{\text{SI}} \pm \mathbf{V}_{\text{NSI}}$$

- **Standard Interactions**

$$\mathbf{V}_{\text{SI}} = \mathbf{V}_{\text{cc}} \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix} + \mathbf{V}_{\text{nc}} \mathbb{I}_{3\times 3}$$

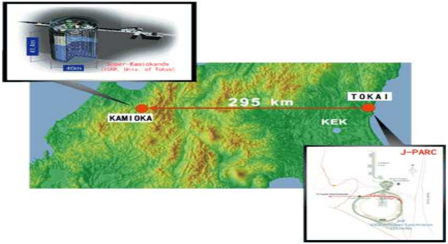
- **Non-Standard Interactions**

$$\mathbf{V}_{\text{NSI}} = \mathbf{V}_{\text{cc}} \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

In the same way as Standard Interactions through **vector boson mediation**.

CP Measurement @ Accelerator Exps

- T2K



- NOνA

- DUNE/T2KII/T2HK/T2HKK/T2KO; MOMENT/ADS-CI/DAEδALUS; 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. $[\phi_{ij} \equiv \frac{\delta m^2_{ij} L}{4 E_\nu}]$

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

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

Non-Standard Interaction

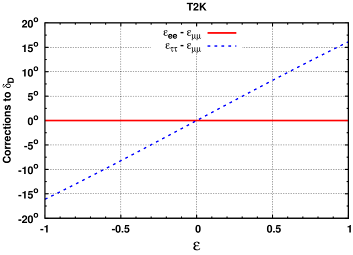
SFG & Alexei Smirnov [arXiv:1607.08513]

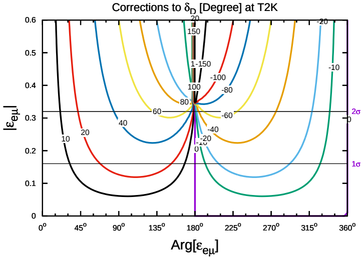
$$\mathcal{H} \equiv \frac{1}{2\mathbf{E}_\nu} U \begin{pmatrix} 0 & & \\ & \Delta m_s^2 & \\ & & \Delta m_a^2 \end{pmatrix} U^\dagger + V_{cc} \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^*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

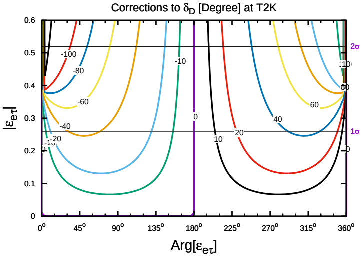
- Standard Interaction – V_{cc} (also V_{nc})
- Non-Standard Interaction – $\epsilon_{\alpha\beta}$
  - Diagonal $\epsilon_{\alpha\alpha}$ are real
  - Off-diagonal $\epsilon_{\alpha\neq\beta}$ are complex
  - Both can fake CP
- Z' in LMA-Dark model with $L_\mu - L_\tau$ gauged as $U(1)$
  - $M_{Z'}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

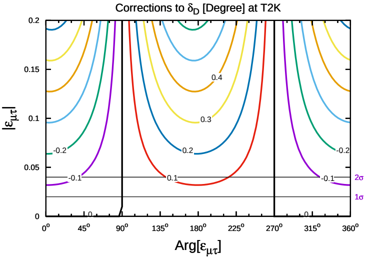
Faked CP with NSI

SFG & Alexei Smirnov [arXiv:1607.08513]



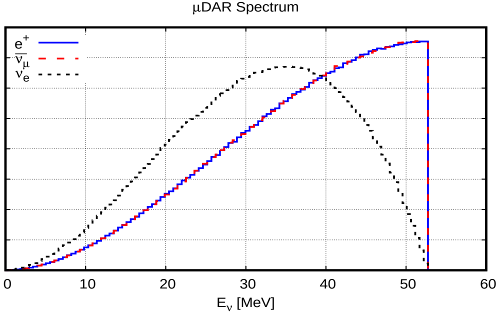






μDAR $\bar{\nu}$ Oscillation Experiments

- 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: $\boldsymbol{\mu^+ \to e^+ + \overline{\nu}_\mu + \nu_e}$.

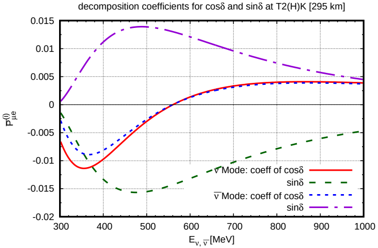


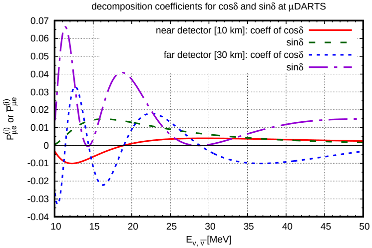
- $\overline{\nu}_\mu$ travel in all directions, oscillating as they go.
- A detector measures the $\overline{\nu}_e$ from $\boldsymbol{\overline{\nu}_\mu \to \overline{\nu}_e}$ **oscillation**.

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])

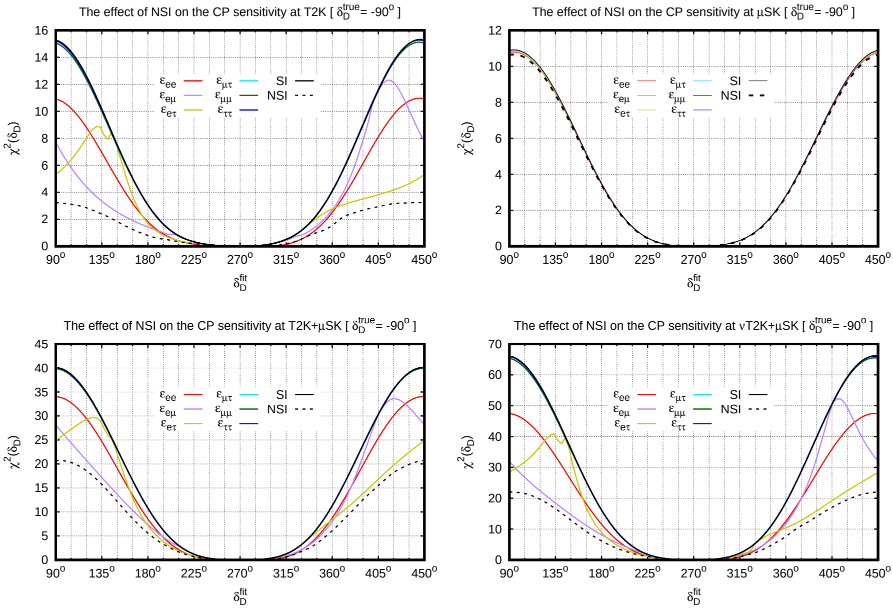




J. Evslin, SFG, K. Hagiwara, JHEP 1602 (2016) 137 [arXiv:1506.05023]; SFG [arXiv:1704.08518]

CP Sensitivity at T2K & μSK

SFG & Alexei Smirnov [arXiv:1607.08513]

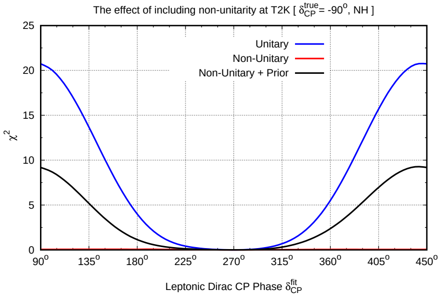


Non-Unitarity Mixing (NUM)

Ge, Pasquini, Tortola & Valle [1605.01670]

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

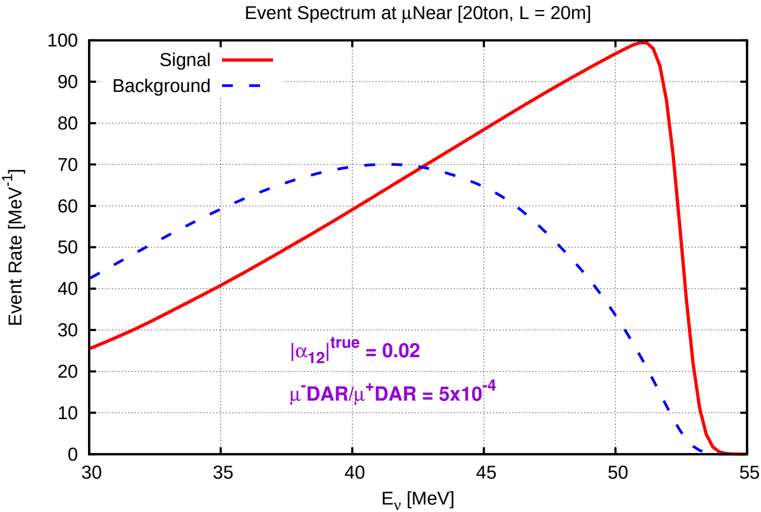
$$P^{NP}_{\mu e} = \alpha^2_{11} \left\{ \alpha^2_{22} \left[c^2_a |S'_{12}|^2 + s^2_a |S'_{13}|^2 + 2 c_a s_a (\cos \delta_D \mathbb{R} - \sin \delta_D \mathbb{I})(S'_{12} S'^*_{13}) \right] + |\alpha_{21}|^2 P_{ee} \right.$$
$$\left. + 2 \alpha_{22} |\alpha_{21}| \left[c_a \left(c_\phi \mathbb{R} -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



μNear at μDAR

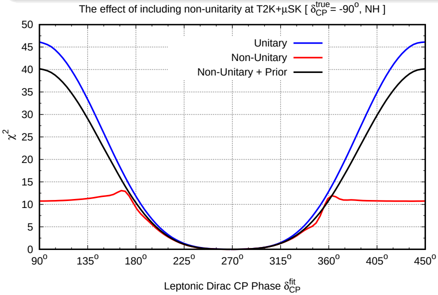
Ge, Pasquini, Tortola & Valle [1605.01670]

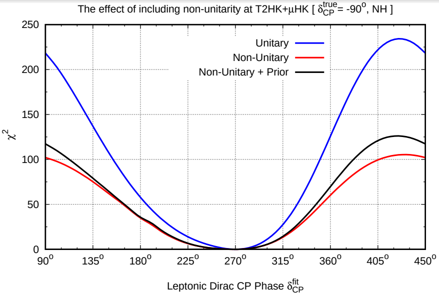
$$P^{NP}_{\mu e}(L \to 0) = \alpha^2_{11}|\alpha_{21}|^2 P_{ee} \approx \alpha^2_{11}|\alpha_{21}|^2 \approx |\alpha_{21}|^2$$

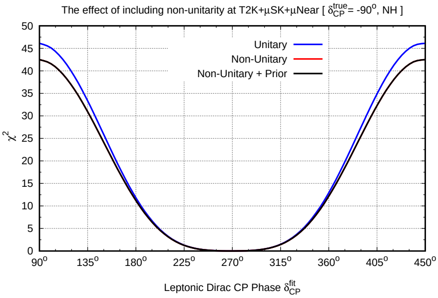


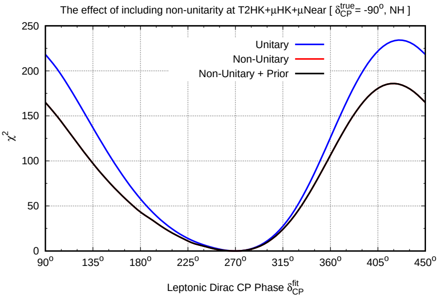
TNT2K+μNear

Ge, Pasquini, Tortola & Valle [1605.01670]









Extra New Physics from Scalar NSI

- **Vector NSI**

$$\mathcal{L}_{\rm cc}^{\rm eff} = \frac{g_{\alpha\rho} g^*_{\beta\sigma}}{2} \frac{1}{-m_V^2} \left(\overline{\nu_\alpha} \gamma_\mu P_L \nu_\beta\right) \left(\overline{\ell}_\sigma \gamma^\mu P_L \ell_\rho\right) ,$$

which is **vector-vector type vertex**.

- **Scalar Mediator**

$$-\mathcal{L} = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} M_{\alpha\beta} \bar{\nu}_\alpha \nu_\beta + y_{\alpha\beta} \phi \bar{\nu}_\alpha \nu_\beta + Y_{\alpha\beta} \phi \bar{f}_\alpha f_\beta + h.c. ,$$

Due to **forward scattering**, the **effective Lagrangian** is

$$\mathcal{L}_{\rm eff}^s \propto y_{\alpha\beta} Y_{ee} \left[\bar{\nu}_\alpha(p_3) \nu_\beta(p_2)\right] \left[\overline{e}(p_1) e(p_4)\right] ,$$

which is a **scalar-scalar type vertex** $\Rightarrow$ **significant phenomenological consequences**.

EOM & Effective Hamiltonian with Scalar NSI

- **Two-Point Correlation Function**

$$\delta\Gamma_S = \frac{y_{\alpha'\beta'} y_{ee}}{m_\phi^2} \langle \nu_\alpha | \bar{\nu}_{\alpha'} \nu_{\beta'} | \nu_\beta \rangle \langle e | \bar{e} e | e \rangle \,,$$

$$\delta\bar{\Gamma}_S = \frac{y_{\beta'\alpha'} y_{ee}}{m_\phi^2} \langle \bar{\nu}_\alpha | \bar{\nu}_{\alpha'} \nu_{\beta'} | \bar{\nu}_\beta \rangle \langle e | \bar{e} e | e \rangle \,.$$

- **Equation of Motion**

$$\bar{\nu}_\beta \left[i\partial_\mu \gamma^\mu + \left(M_{\beta\alpha} + \frac{n_e y_e Y_{\alpha\beta}}{m_\phi^2} \right) \right] \nu_\alpha = 0 \,,$$

- **Effective Hamiltonian**

$$\mathcal{H} \approx E_\nu + \frac{(M + M_S)(M + M_S)^\dagger}{2E_\nu} \pm V_{\rm SI} \,,$$

Mass Scale & Unphysical CP Phases in Oscillation

- The **effective mass term** is a combination

$$\mathbf{M}\mathbf{M}^\dagger \to (\mathbf{M} + \mathbf{M_S})(\mathbf{M} + \mathbf{M_S})^\dagger = \mathbf{M}\mathbf{M}^\dagger + \mathbf{M}\mathbf{M_S}^\dagger + \mathbf{M_S}\mathbf{M}^\dagger + \mathbf{M_S}\mathbf{M_S}^\dagger$$

- The **absolute neutrino mass** can enter neutrino oscillation!

$$\mathbf{M}\mathbf{M_S}^\dagger + \mathbf{M_S}\mathbf{M}^\dagger$$

- The **unphysical CP phases** can also enter neutrino oscillation!

$$M \equiv R_\nu D_\nu R_\nu^\dagger \quad \& \quad R_\nu \equiv P_\nu U_\nu Q_\nu$$

The **Majorana rephasing matrice** $Q_\nu = \{e^{i\delta_{\mathrm{M1}}/2}, 1, e^{i\delta_{\mathrm{M3}}/2}\}$ can be absorbed, $Q_\nu D_\nu Q_\nu^\dagger = D_\nu$ while the **unphysical rephasing matrix** $P_\nu \equiv \{e^{i\alpha}, e^{i\beta}, e^{i\gamma}\}$ can not be simply rotated away now:

$$M \to \widetilde{\mathbf{M}} = \mathbf{U}_\nu \mathbf{D}_\nu \mathbf{U}_\nu^\dagger\,, \qquad M_S \to \widetilde{\mathbf{M}}_\mathbf{S} = \mathbf{P}_\nu^\dagger \mathbf{M_S} \mathbf{P}_\nu$$

Parametrization & Constant Density Subtraction

- Use **characteristic scale** $\mathbf{\Delta m_a^2}$ to parametrize scalar NSI

$$\widetilde{\mathbf{M}}_{\mathbf{S}} \equiv \sqrt{\mathbf{\Delta m_a^2}} \begin{pmatrix} \eta_{ee} & \eta_{\mu e}^* & \eta_{\tau e}^* \\ \eta_{\mu e} & \eta_{\mu\mu} & \eta_{\tau\mu}^* \\ \eta_{\tau e} & \eta_{\tau\mu} & \eta_{\tau\tau} \end{pmatrix},$$

where $\mathbf{\Delta m_a^2} \equiv \Delta m_{31}^2 = 2.7 \times 10^{-3}\,\mathrm{eV}^2$.

- We first need **input** for $\widetilde{\mathbf{M}}$ which is not directly measured.

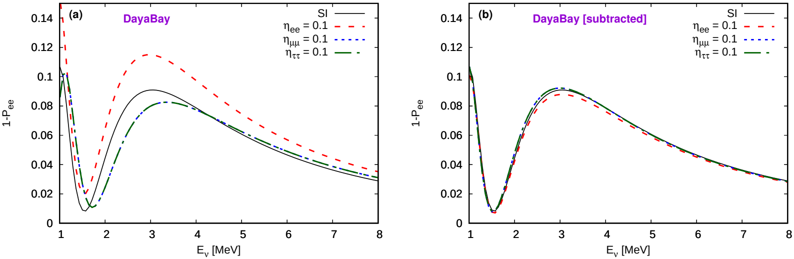
- However, the directly measured from terrestial experiments is always a combination, $\widetilde{\mathbf{M}} + \widetilde{\mathbf{M}}_{\mathbf{S}}(\rho_{\mathbf{s}} \approx \mathbf{3}\mathrm{g/cm}^{\mathbf{3}})$. It is then necessary to first substract a constant term:

$$\widetilde{M} \to \widetilde{M} + \widetilde{\mathbf{M}}_{\mathbf{S}} \frac{\rho - \rho_{\mathbf{s}}}{\rho_{\mathbf{s}}}$$

where $\widetilde{\mathbf{M}} = \mathbf{U}_\nu \mathbf{D}_\nu \mathbf{U}_\nu^\dagger$ is **reconstructed** in terms of the measured mixing matrix while $\widetilde{M}_S$ is the scalar NSI @ typical constant **subtraction density** $\rho_{\mathbf{s}}$.

Density Subtraction for Reactor Anti-Neutrinos

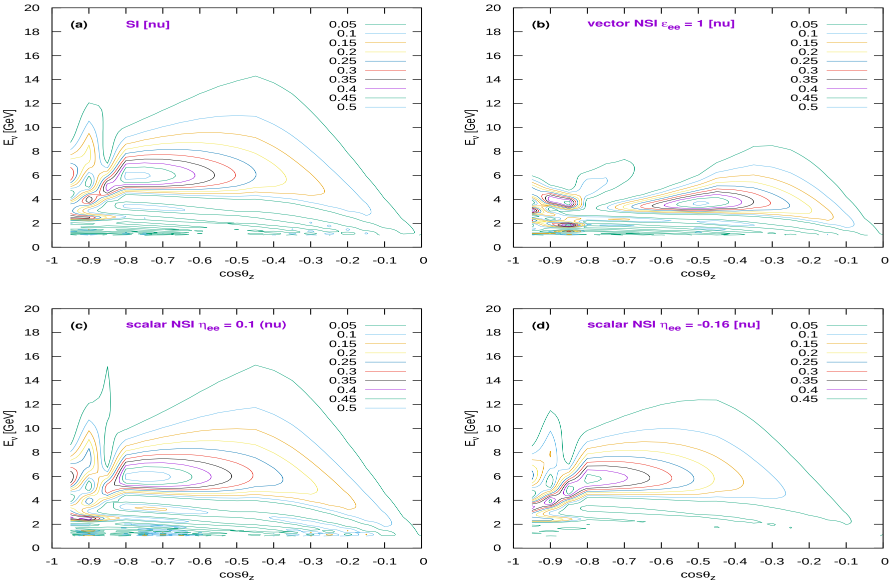
- Since the reactor anti-neutrino experiments (**Daya Bay** & **JUNO**) are the most precise ones, we do substraction according to them:



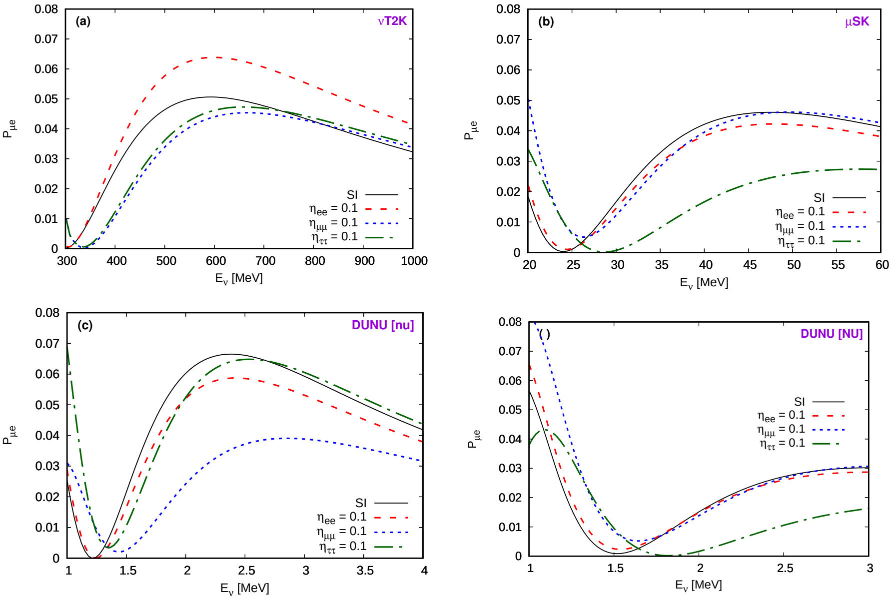
$$\widetilde{M} \to \widetilde{M} + \widetilde{\mathbf{M}}_{\mathbf{S}} \frac{\rho - \rho_{\mathbf{s}}}{\rho_{\mathbf{s}}}$$

- Then **no constraint** on **scalar NSI** from reactor experiments!

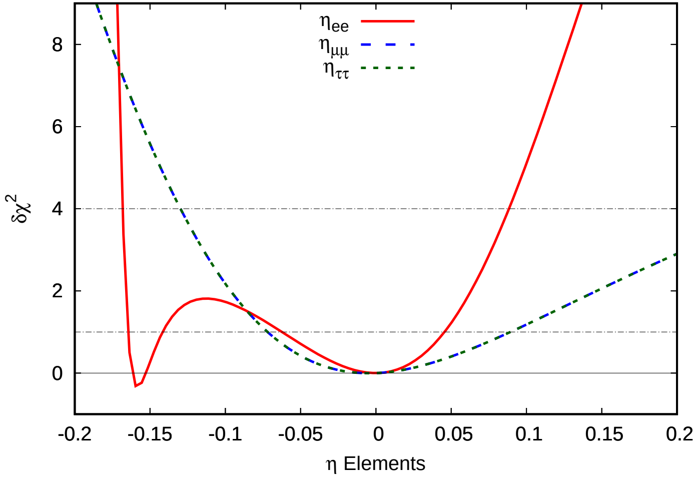
Scalar NSI @ Atmospheric Neutrino Oscillation



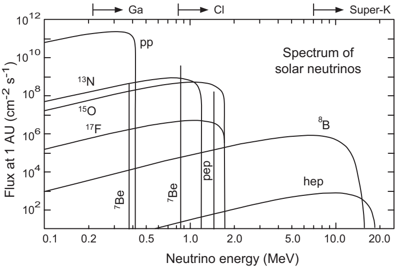
Scalar NSI @ Accelerator Neutrino Oscillation

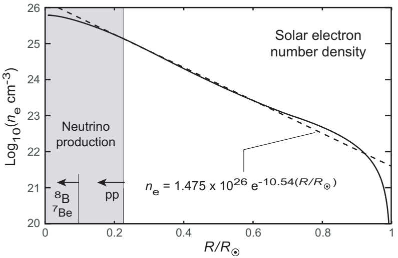


Fitting the Borexino 2017 Data

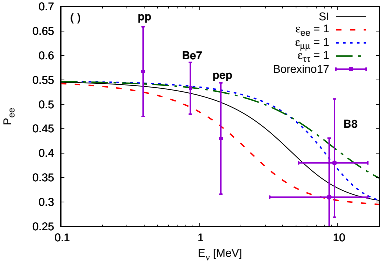


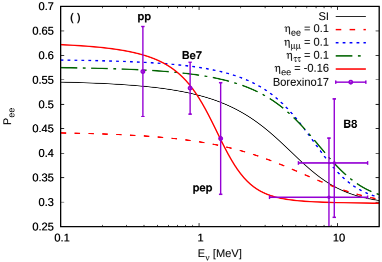
Solar Neutrino Flux





$$P_{ee}^{sun} = \left| U_{ei}^{prod} (U_{ei}^{vac})^* \right|^2$$





Summary

- **Neutrino oscillation** $=$ **Mass** $+$ **Interaction**
  - **Mass** $\to$ **vacuum mixing & oscillation**
  - **Interaction** $\to$ **matter effect**
- **Both are important**
  - **Yukawa** coupling $\to$ **Mass**
  - **Gauge** coupling $\to$ **Interaction**
- **Crossing & Hybrid** of the two $\to$ scalar NSI
- **Unique features** of scalar NSI
  - Directly related to **Yukawa** coupling & **mass generation** of ν's.
  - Appears as **NSI**, but contribute as **mass term correction**.
  - The effect of scalar NSI is **not suppressed by neutrino energy**.
  - Can completely **disguise the original oscillation parameters**.
  - Neutrino **mass scale** & **unphysical CP phases** can enter oscillation.
  - **Matter density variation** can help to identify scalar NSI;
  - **Solar neutrinos** are of great importance due to large matter density variation.

Thank You!