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Leptonic CP Violation in Neutrino Oscillations

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Based on T. Ohlsson, H. Zhang & S.Zhou,
Phys. Rev. D 87 (2013) 013012;
Phys. Rev. D 87 (2013) 053006;
Phys. Rev. D (to be published), arXiv:1303.6130

Outline

- Introduction
- RG running of Dirac CP-violating phase
- Leptonic CP violation in ν oscillations
- NSI effects @ IceCube (DeepCore & PINGU)
- Summary

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Open Questions in ν Physics

- **Are neutrinos Dirac or Majorana particles?**

  Lepton number violation, neutrinoless double beta decays

- **What is the neutrino mass ordering?**

  Normal ($m_1 < m_2 < m_3$) or inverted ($m_3 < m_1 < m_2$)?

- **What is the absolute neutrino mass scale?**

  Is the lightest ν massless? Hierarchical or degenerate?

- **What is the origin of neutrino masses and flavor mixing?**

  Seesaw mechanisms, flavor symmetries, …

- **Is there CP violation in the lepton sector?**

  What is the value of the Dirac CP-violating phase δ?

Current Status

Precision measurements of neutrino parameters:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric / Accelerator — Reactor / Accelerator — Solar / Reactor

Global-fit analyses:

Forero *et al.*, Phys. Rev. D 86 (2012) 073012

Fogli *et al.*, Phys. Rev. D 86 (2012) 013012

Gonzalez-Garcia *et al.*, JHEP 1212 (2012) 123

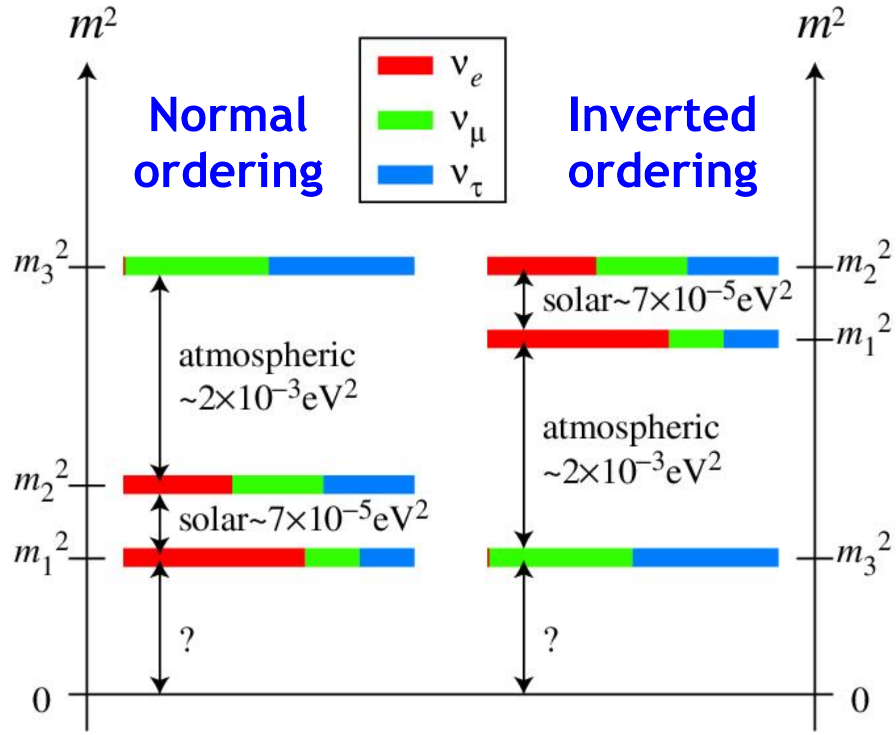
	bfp ± 1σ	3σ range
$\sin^2\theta_{12}$	0.30 ± 0.013	$0.27 \to 0.34$
$\theta_{12}/^\circ$	33.3 ± 0.8	$31 \to 36$
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.34 \to 0.67$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.2}_{-1.3}$	$36 \to 55$
$\sin^2\theta_{13}$	0.023 ± 0.0023	$0.016 \to 0.030$
$\theta_{13}/^\circ$	$8.6^{+0.44}_{-0.46}$	$7.2 \to 9.5$
$\delta/^\circ$	300^{+66}_{-138}	$0 \to 360$
$\Delta m^2_{21}/10^{-5}$ eV^2	7.50 ± 0.185	$7.00 \to 8.09$
$\Delta m^2_{31}/10^{-3}$ eV^2 (NH)	$2.47^{+0.069}_{-0.067}$	$2.27 \to 2.69$
$\Delta m^2_{32}/10^{-3}$ eV^2 (IH)	$-2.43^{+0.042}_{-0.065}$	$-2.65 \to -2.24$

Pascoli & Schwetz, Adv. HEP (2013) 503401

Leptonic CP violation?

Neutrino mass ordering?

Neutrino Mass Ordering



- Medium-baseline reactor experiments:
  Daya Bay-II, RENO-II
- Long-baseline accelerator experiments:
  T2K, NOνA, LBNO, LBNE
- Huge neutrino telescopes:
  PINGU, ORCA

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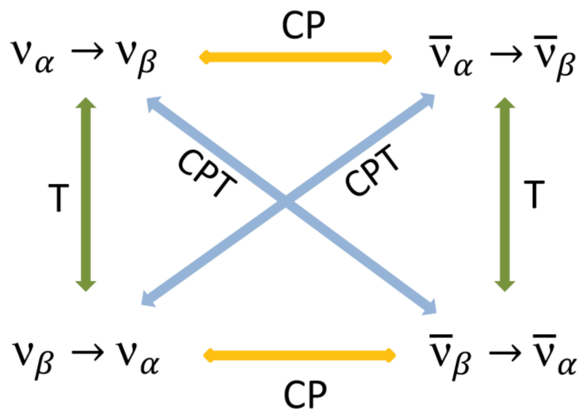
Leptonic CP Violation

Neutrino oscillations in vacuum:

Branco *et al.*, Rev. Mod. Phys. 84 (2012) 515

$$A^{CP}_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

$$= 16 \underbrace{s_{12} c_{12} s_{23} c_{23} s_{13} c_{13}^2 \sin\delta}_{J\,:\,\text{Jarlskog Invariant}} \sin\frac{\Delta m_{21}^2 L}{4E} \sin\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E}$$



Parameter	Fogli *et al.*	Gonzalez-Garcia *et al.*	Forero *et al.*
$\sin^2\theta_{12}$	0.307 0.291–0.325	0.300 0.287–0.313	0.320 0.303–0.336
$\sin^2\theta_{13}$	0.0241 0.0216–0.0266	0.0230 0.0207–0.0253	0.0246 0.0218–0.0275
$\sin^2\theta_{23}$	0.386 0.365–0.410	0.410 0.385–0.447	0.427 0.400–0.461
$\Delta m^2_{21}/10^{-5}$ eV^2	7.54 7.32–7.80	7.50 7.32–7.69	7.62 7.43–7.81
$\Delta m^2_{31}/10^{-3}$ eV^2	2.51 2.41–2.57	2.47 2.40–2.54	2.55 2.46–2.61
$\boxed{\delta/\pi}$	1.08 0.77–1.36	1.67 0.90–2.03	0.8 0–2.0

- First hint from global fits?
- Predictions from theories?
- Compare between theory & exp. observation of δ: Radiative corrections
- Optimize the exp. setup: CP measures, ν-oscillogram
- E.g., NSI effects in the ice

RG Running of Neutrino Parameters

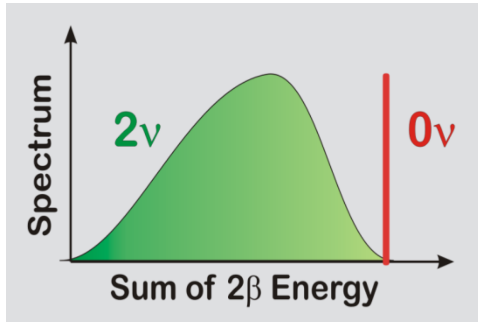
Why is RG running important?

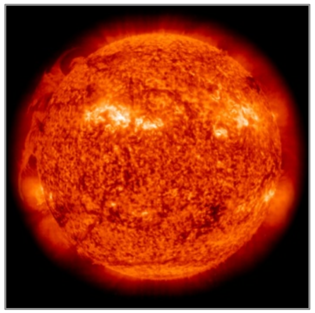
Predictions from high-energy theories

RG running

Measurements in low-energy experiments

- Grand Unified Theories: SU(5), SO(10), …
- Extra-dimensional models: ADD, UED, …
- Flavor symmetry models: A_4, S_4, …





RG Running of Neutrino Parameters

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The SM as an effective theory: dimension-5 operator

Weinberg, Phys. Rev. Lett. 43 (1979) 1566

$$\mathcal{L}_\nu = \frac{1}{2}(\overline{\ell} H) \cdot \underline{\kappa} \cdot (H^T \ell^C)$$

$[\Lambda]^{-1}$: high energy scale Λ

Majorana neutrino mass matrix:

$$M_\nu = \kappa v^2$$

Masses, mixing angles, and leptonic CP-violating phases

Renormalization Group Equation:

Antusch *et al.*, Phys. Lett. B 519 (2001) 238

$$16\pi^2 \frac{\mathrm{d}\kappa}{\mathrm{d}t} = \alpha_\kappa + C_\kappa[(Y_l Y_l^\dagger)\kappa + \kappa(Y_l Y_l^\dagger)^T]$$

$$t = \ln\left(\frac{\mu}{\Lambda_{\mathrm{EW}}}\right) \qquad C_\kappa = -\frac{3}{2}$$

$$\alpha_\kappa = -3g_2^2 + \lambda + 2\mathrm{tr}\left[3\left(Y_{\mathrm{u}}Y_{\mathrm{u}}^+\right) + 3\left(Y_{\mathrm{d}}Y_{\mathrm{d}}^+\right) + \left(Y_l Y_l^+\right)\right]$$

- Realized in various seesaw models

- Running of masses is dominated by the flavor-diagonal term (gauge, quark Yuk.)

- RG running of mixing angles and CP-violating phases is dominated by charged-lepton Yukawa couplings

MSSM and 5D-UED

Extensions of the SM: supersymmetry and extra dimensions

$$L_\nu = \frac{1}{2} LH_u \cdot \kappa \cdot LH_u$$

ν mass matrix:

$$M_\nu = \kappa (v \sin\beta)^2$$

RGE coefficients:

$$C_\kappa^{\mathrm{MSSM}} = 1$$

Tau Yukawa coupling dominated:

$$y_\tau^2 = m_\tau^2 (1 + \tan^2\beta) / v^2$$

$$L_\nu = \frac{1}{2} LH \cdot \hat{\kappa} \cdot LH$$

ν mass matrix:

$$M_\nu = \hat{\kappa} v^2 / (\pi R)$$

radius of the extra spatial dimension

RGE coefficients:

$$C_\kappa^{\mathrm{UED}} = C_\kappa^{\mathrm{SM}} (1 + s)$$

number of excited KK modes

Coefficient becomes larger at higher-energy scales:

$$s \equiv \left\lfloor \ln\left(\frac{\mu}{\mu_0}\right) \right\rfloor$$

RG Running of Dirac CP-violating Phase

In the standard parametrization:

$$\dot{\delta} \approx -\frac{C_\kappa y_\tau^2}{8\pi^2} \boxed{\frac{m_1^2}{\Delta m_{21}^2}} \left\{ s_{23}^2 s_{2(\rho-\sigma)} + \frac{2 s_{23} c_{23}}{s_{12} c_{12} s_{13}} \left[s_{13}^2 c_{(\delta+\rho-\sigma)} + \frac{\Delta m_{21}^2}{\Delta m_{31}^2} s_{12}^2 c_{12}^2 c_{(\delta+\rho+\sigma)} s_{(\rho-\sigma)} \right] \right\}$$

enhanced if neutrino masses are nearly degenerate

the same order of magnitude according to the latest global-fit results

- Keep all contributions of the same order.
- RG running depends crucially on the Majorana CP-violating phases; insignificant running for ρ=σ.
- RG running is in the opposite direction for the MSSM, compared to the SM and 5D-UED.

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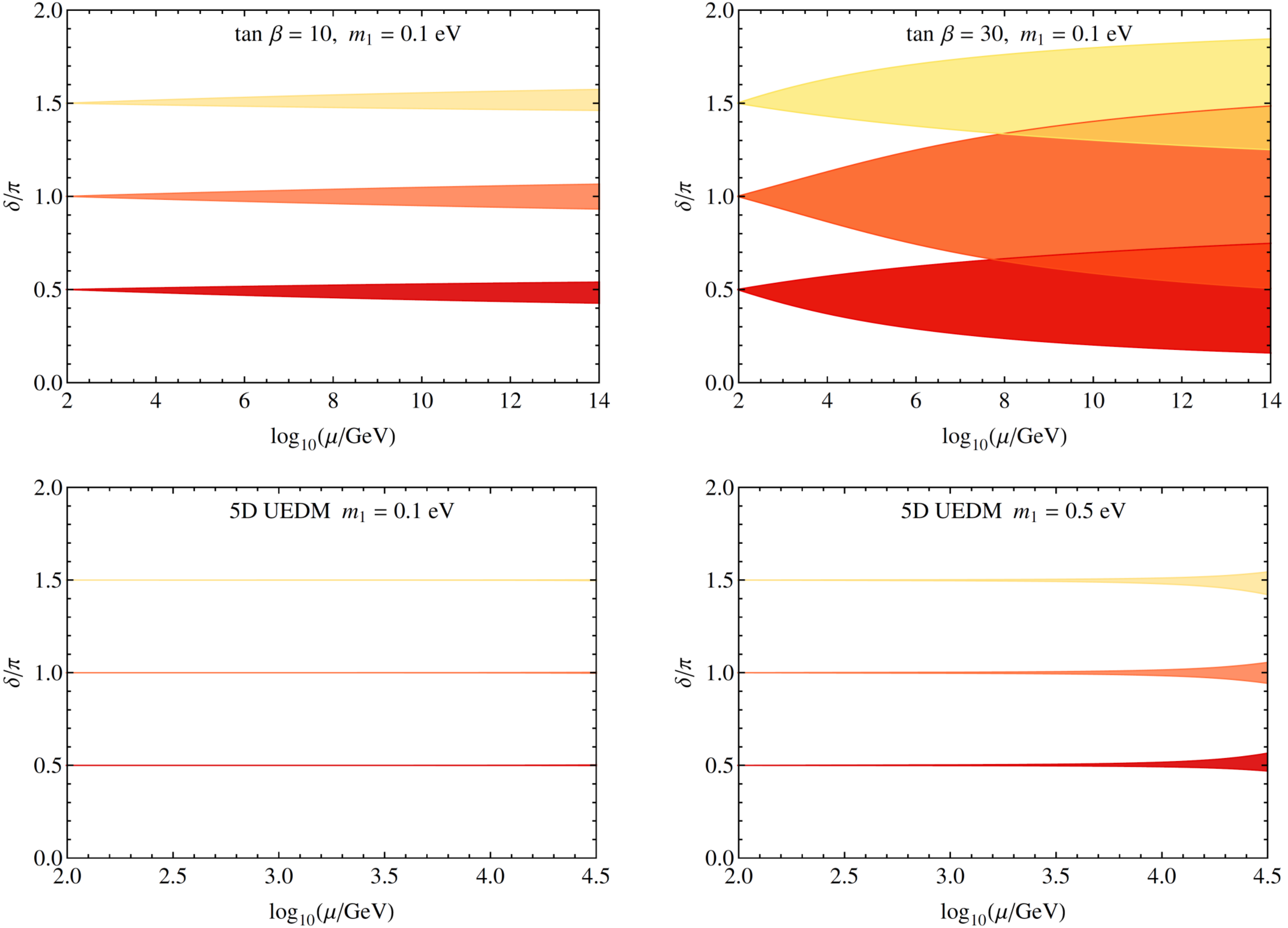
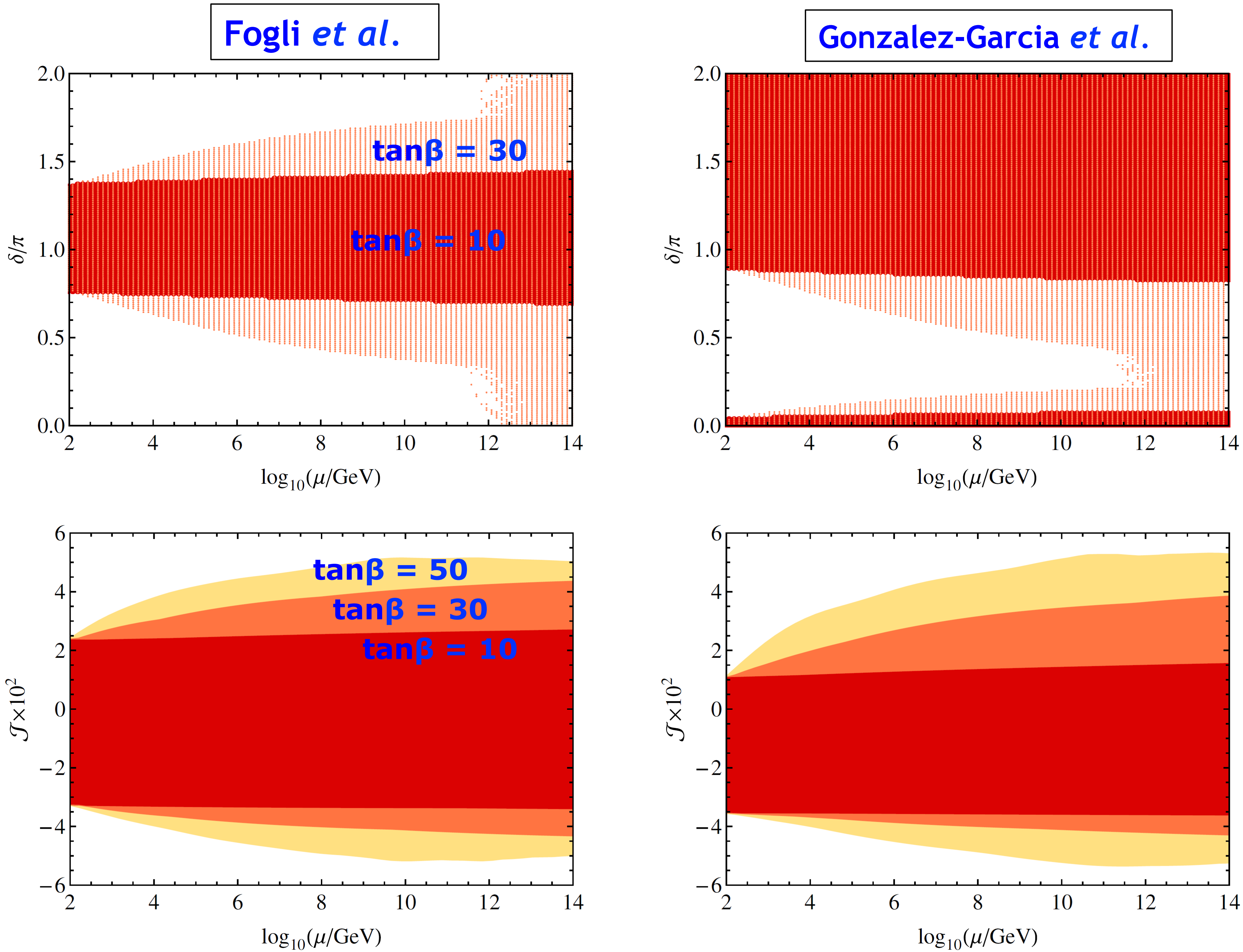
significant running for large tanβ

MSSM

5D-UED




Fogli et al.
Gonzalez-Garcia et al.
tanβ = 30
tanβ = 10
δ/π
log10(μ/GeV)
tanβ = 50
tanβ = 30
tanβ = 10
J×10²

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Summary for RG Running of δ

- The RGE of the leptonic Dirac CP-violating phase is derived, and small contributions of the same order are included.
- Very tiny RG running effects in the SM, even for nearly-degenerate neutrino masses
- No significant RG running also in the MSSM and 5D-UED, except for a very large $\tan\beta$ in the former case; however, note the dependence on the Majorana phases
- Non-zero δ can be radiatively generated at the low-energy scale even if $\delta = 0$ holds at a high-energy scale.
- For Dirac neutrinos, RG running is even smaller because of the absence of Majorana CP-violating phases.
- Constraints on δ from neutrino oscillation experiments can be directly applied to theory at a superhigh-energy scale.

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CP Violation and Matter Effects

Neutrino oscillations in matter:

$$H_{\text{eff}} = \frac{1}{2E}\left[U\begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 & \\ & & \Delta m_{31}^2 \end{pmatrix}U^{+} + 2\sqrt{2}G_{\text{F}}N_e E\begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix}\right]$$

Oscillation probabilities:

$$\left.\begin{aligned} P_{\mu e}(\delta) &\equiv P(\nu_\mu \to \nu_e) = a\cos\delta + b\sin\delta + c \\ \overline{P}_{\mu e}(\delta) &\equiv P(\overline{\nu}_\mu \to \overline{\nu}_e) = \overline{a}\cos\delta + \overline{b}\sin\delta + \overline{c} \end{aligned}\right\} \Rightarrow A_{\mu e}^{\text{CP}}(\delta) = \Delta a\cos\delta + \Delta b\sin\delta + \Delta c$$

- **Fake CP violation is induced by matter effects:**
  - obscuring the intrinsic CP-violating effects by *δ*
- **How to describe leptonic CP violation?**
  - working observables based on oscillation probabilities

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Working Observables

Series expansions of the probabilities in terms of $\alpha = \Delta m^2_{21} / \Delta m^2_{31}$ and s_{13}:

$$a \approx +8\alpha J_r \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \cos\Delta$$

$$b \approx -8\alpha J_r \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \sin\Delta$$

$$c \approx 4 s_{13}^2 s_{23}^2 \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$J_r \equiv s_{12} c_{12} s_{23} c_{23} s_{13} c_{13}^2$$

$$\Delta a \approx +8\alpha J_r \Theta_- \frac{\sin A\Delta}{A} \cos\Delta$$

$$\Delta b \approx -8\alpha J_r \Theta_+ \frac{\sin A\Delta}{A} \sin\Delta$$

$$\Delta c \approx 4 s_{13}^2 s_{23}^2 \Theta_+ \Theta_-$$

$$\Theta_\pm \equiv \frac{\sin(A-1)\Delta}{A-1} \pm \frac{\sin(A+1)\Delta}{A+1}$$

Here $\Delta = \Delta m^2_{31} L/4E$ and $A = VL/2\Delta$, with V being the matter potential, Δ the oscillation phase, and L the distance between the source and the detector.

$$\underline{\Delta P^{\mathrm{CP}}_{\mu e}(\delta) \;\&\; \Delta P^{\mathrm{m}}_{\mu e}}$$

Definitions:

$$\Delta P^{\mathrm{CP}}_{\mu e}(\delta) \equiv P_{\mu e}(\delta) - P_{\mu e}(\delta = 0)$$

$$\Delta P^{\mathrm{m}}_{\mu e} \equiv \max\left[P_{\mu e}(\delta)\right] - \min\left[P_{\mu e}(\delta)\right]$$

$$\underline{\Delta A^{\mathrm{CP}}_{\mu e}(\delta) \;\&\; \Delta A^{\mathrm{m}}_{\mu e}}$$

Definitions:

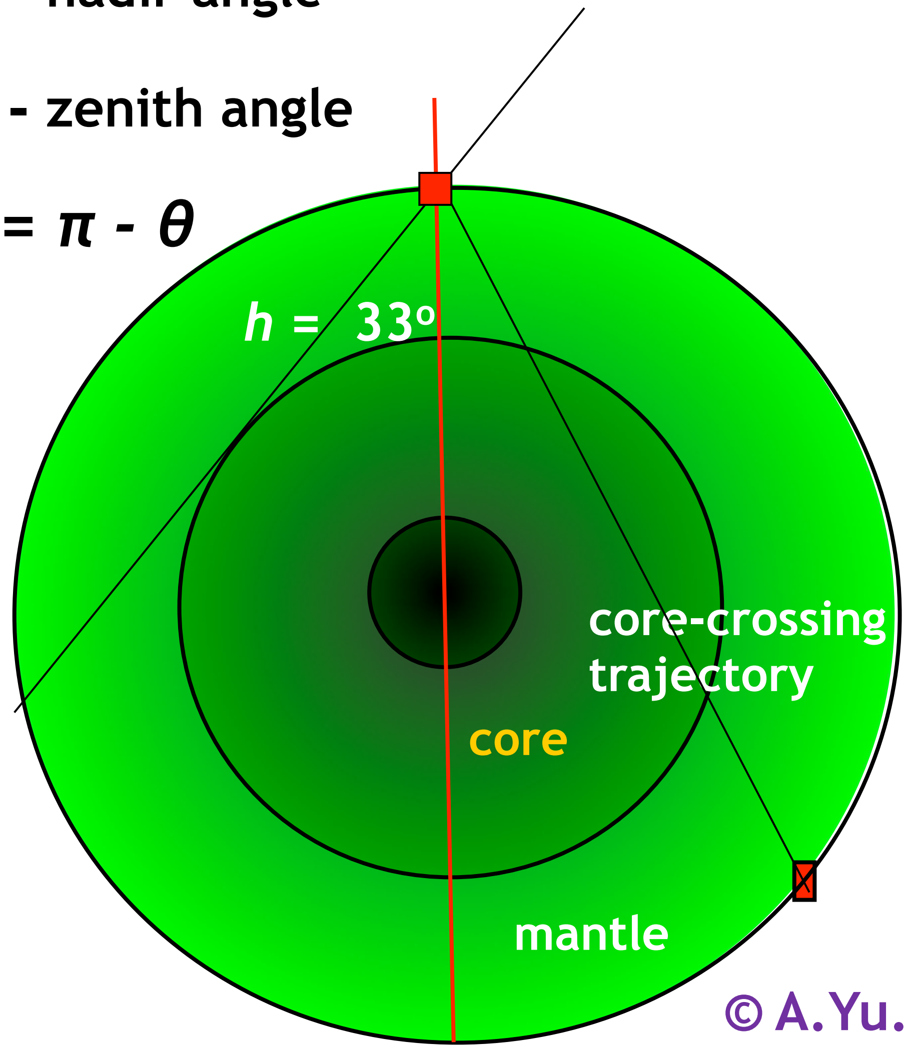
$$\boxed{\begin{aligned}\Delta A^{\mathrm{CP}}_{\mu e}(\delta) &\equiv A^{\mathrm{CP}}_{\mu e}(\delta) - A^{\mathrm{CP}}_{\mu e}(\delta = 0)\\ \Delta A^{\mathrm{m}}_{\mu e} &\equiv \max\left[A^{\mathrm{CP}}_{\mu e}(\delta)\right] - \min\left[A^{\mathrm{CP}}_{\mu e}(\delta)\right]\end{aligned}}$$

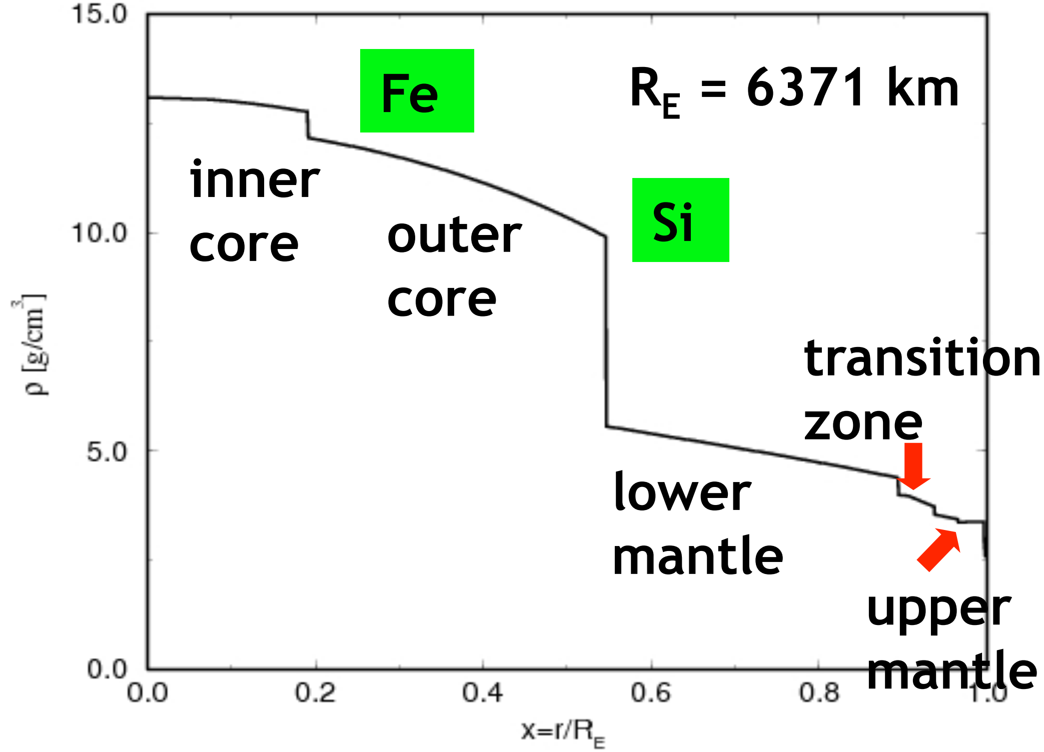
Neutrino Oscillograms of the Earth

h **- nadir angle**

θ **- zenith angle**

$h = \pi - \theta$





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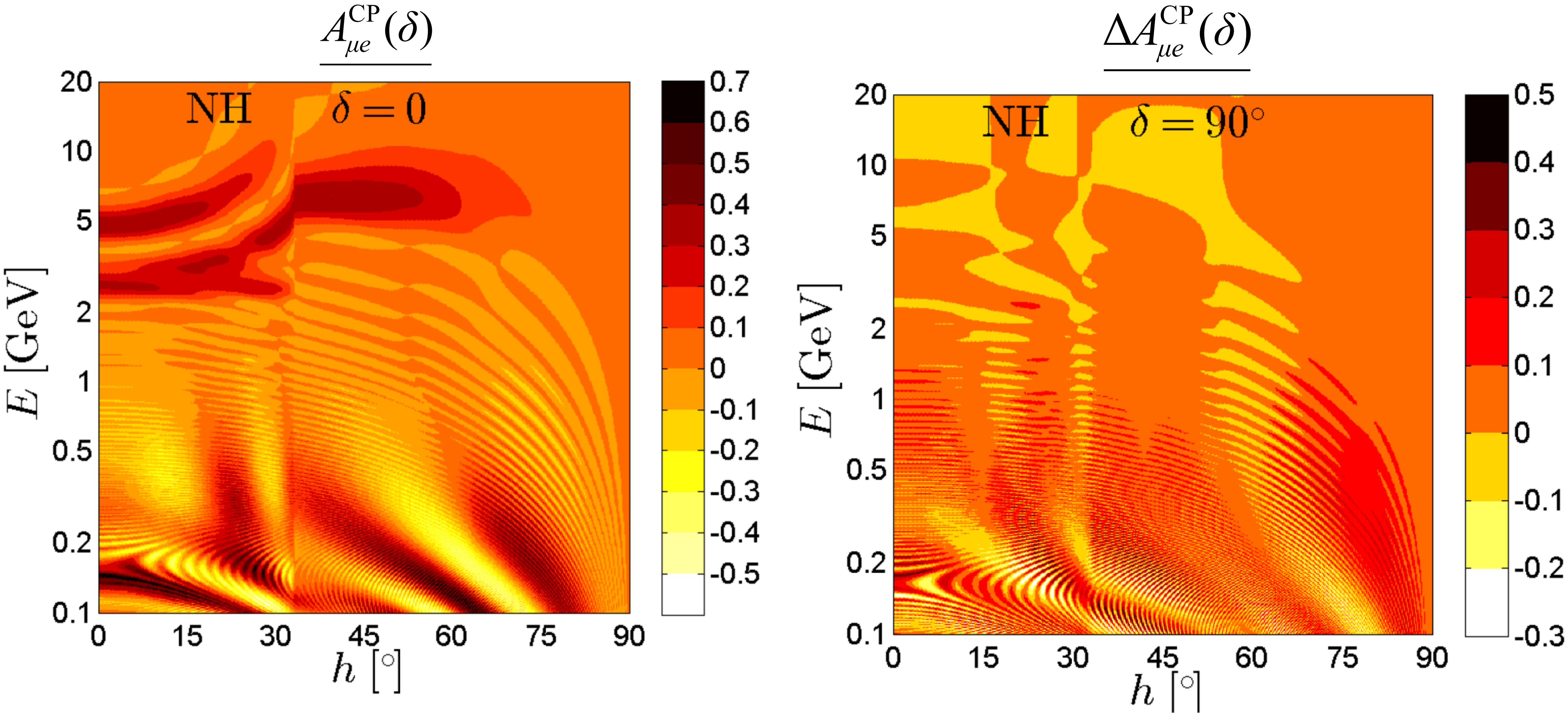
Oscillograms for CP Violation

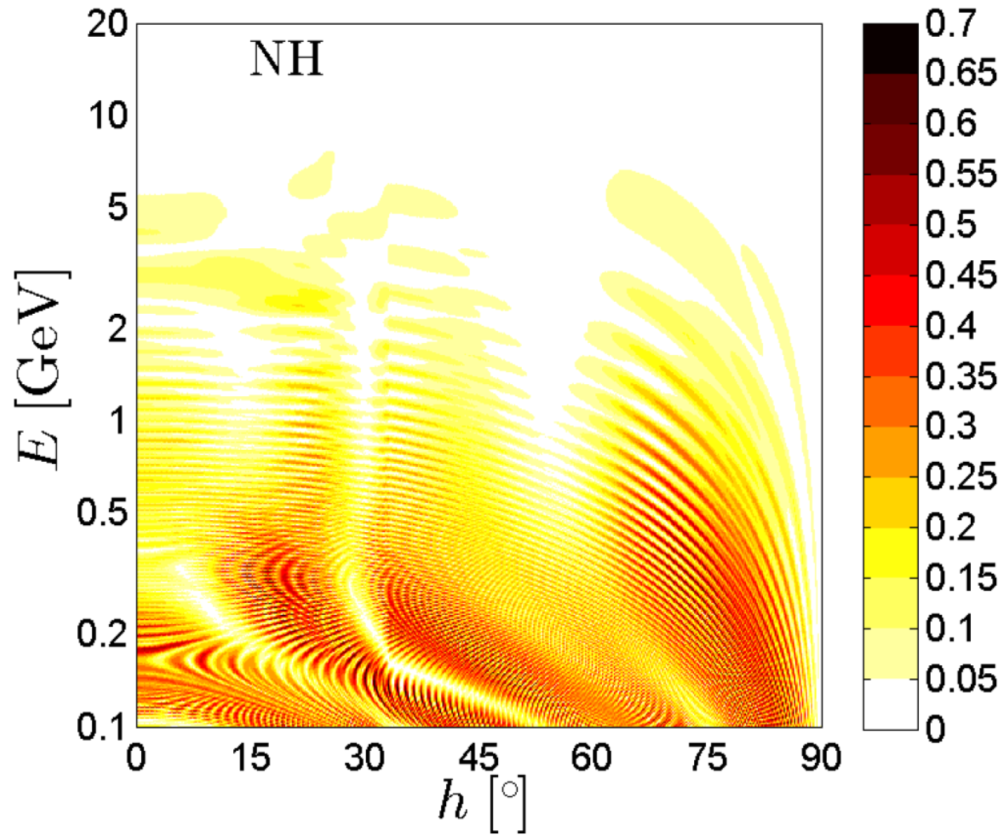
Conventional CP asymmetry | **Working observable**



Oscillograms for CP Violation

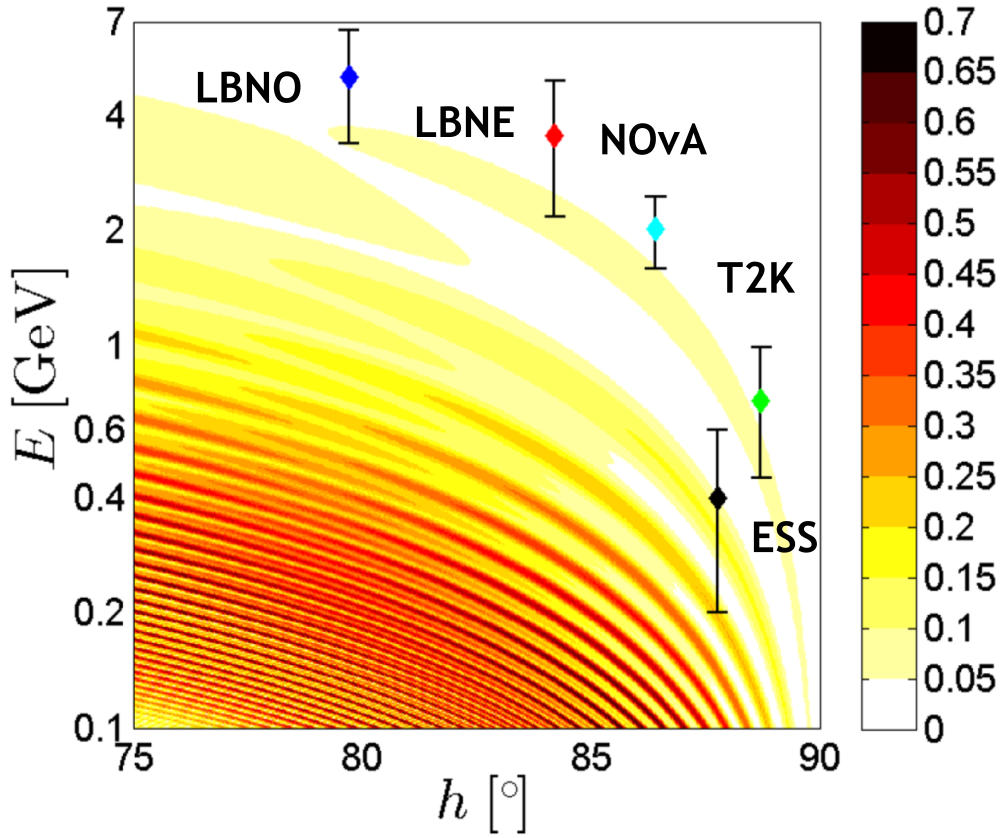
Working observable

$\underline{\Delta A_{\mu e}^{\mathrm{m}}}$



Locating future experiments

$\underline{\Delta A_{\mu e}^{\mathrm{m}}}$: Zoom-in Plot



Non-Standard Neutrino Interactions

Neutrino oscillations in matter with NSIs:

$$H_{\text{eff}} = \frac{1}{2E}\left\{U\begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 & \\ & & \Delta m_{31}^2 \end{pmatrix}U^+ + 2\sqrt{2}G_{\text{F}}N_e E\left[\begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix} + \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}\right]\right\}$$

Oscillation probability with NSIs:

$$\begin{aligned} P_{\mu\mu}^{\text{NSI}} \simeq P_{\mu\mu}^{\text{SD}} \; & - \; |\varepsilon_{\mu\tau}| c_{\phi_{\mu\tau}} \left(s_{2\times 23}^3 A\Delta \sin\Delta + 4 s_{2\times 23} c_{2\times 23}^2 A \sin^2\frac{\Delta}{2} \right) \\ & + \; \left(|\varepsilon_{\mu\mu}| - |\varepsilon_{\tau\tau}) \right| s_{2\times 23}^2 c_{2\times 23} \left(\frac{A\Delta}{2} \sin\Delta - 2A\sin^2\frac{\Delta}{2} \right) \end{aligned}$$

- **Deviation from the std. probability; only mu-tau flavors are involved**
- **Not suppressed by mixing angle θ_{13} or the mass ratio Δm^2_{21} / Δm^2_{31}**

Neutrino Parameter Mappings

Leptonic mixing matrix elements in matter:

$$U^{\rm m}_{e3} = \sin\hat\theta_{13} + \frac{\cos\hat\theta_{13}}{2\hat C}\left\{\sin 2\hat\theta_{13}\left[\alpha s^2_{12} + A(\varepsilon_{ee} - \tilde\varepsilon_{\tau\tau})\right] + 2A\left[\cos 2\hat\theta_{13}{\rm Re}(\tilde\varepsilon_{e\tau}) + {\rm i}{\rm Im}(\tilde\varepsilon_{e\tau})\right]\right\}$$

$$U^{\rm m}_{e2} = -\frac{c_{13}}{2A}\alpha\sin 2\theta_{12} - \tilde\varepsilon_{e\mu} + \frac{\tan\theta_{13}}{A}\tilde\varepsilon^*_{\mu\tau} ,$$

$$U^{\rm m}_{\mu 3} = s_{23}\cos\hat\theta_{13}e^{{\rm i}\delta}\left\{1 - \frac{A\tan\hat\theta_{13}}{\hat C}\left[\cos 2\hat\theta_{13}{\rm Re}(\tilde\varepsilon_{e\tau}) + {\rm i}{\rm Im}(\tilde\varepsilon_{e\tau})\right]\right\} + \frac{\alpha c_{23}\sin 2\theta_{12}\sin\hat\theta_{13}}{1 + A + \hat C} ,$$

Modified NSI parameters:

$$\tilde\varepsilon_{e\mu} = \varepsilon_{e\mu}c_{23} - \varepsilon_{e\tau}s_{23} ,$$

$$\tilde\varepsilon_{e\tau} = (\varepsilon_{e\mu}s_{23} + \varepsilon_{e\tau}c_{23})e^{{\rm i}\delta} ,$$

$$\tilde\varepsilon_{\mu\mu} = (\varepsilon_{\mu\mu}c^2_{23} + \varepsilon_{\tau\tau}s^2_{23}) - 2s_{23}c_{23}{\rm Re}[\varepsilon_{\mu\tau}] ,$$

$$\tilde\varepsilon_{\tau\tau} = (\varepsilon_{\mu\mu}s^2_{23} + \varepsilon_{\tau\tau}c^2_{23}) + 2s_{23}c_{23}{\rm Re}[\varepsilon_{\mu\tau}] ,$$

$$\tilde\varepsilon_{\mu\tau} = \left[(\varepsilon_{\mu\tau}c^2_{23} - \varepsilon^*_{\mu\tau}s^2_{23}) + (\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau})s_{23}c_{23}\right]e^{{\rm i}\delta}$$

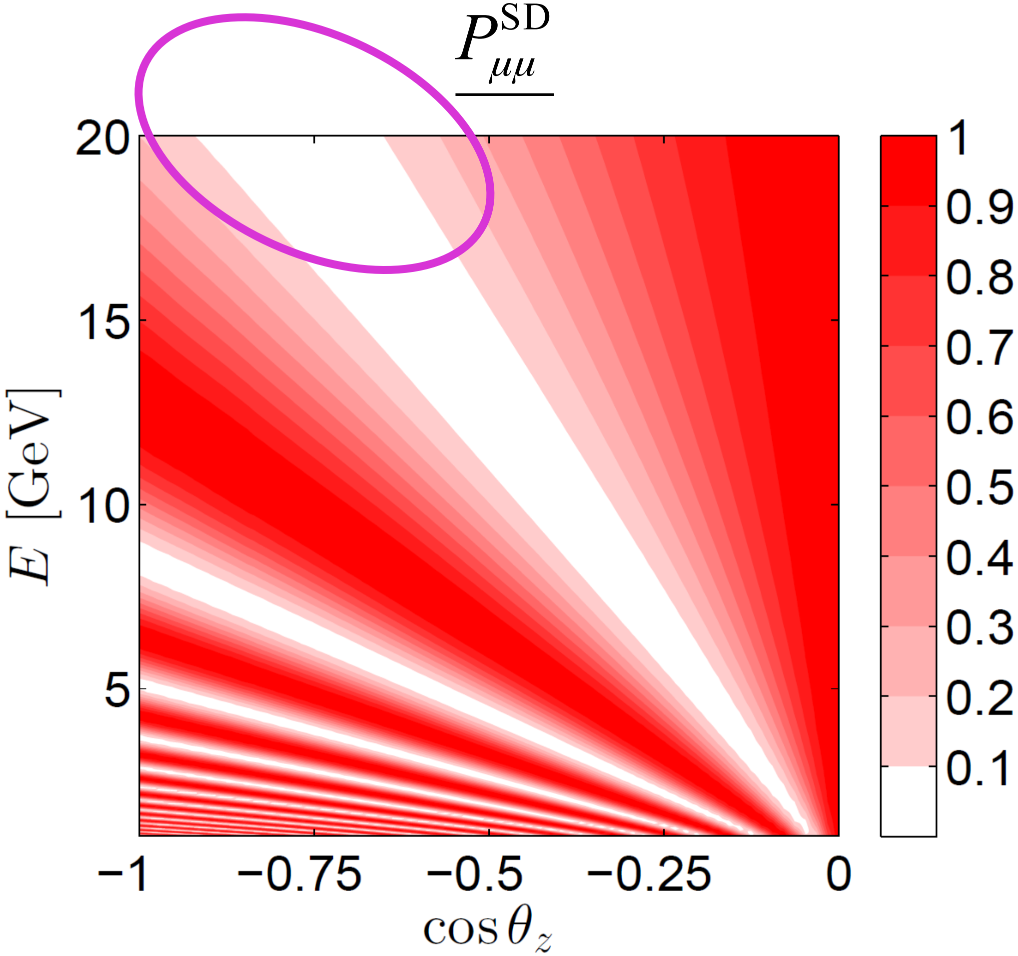
Modified mixing angle:

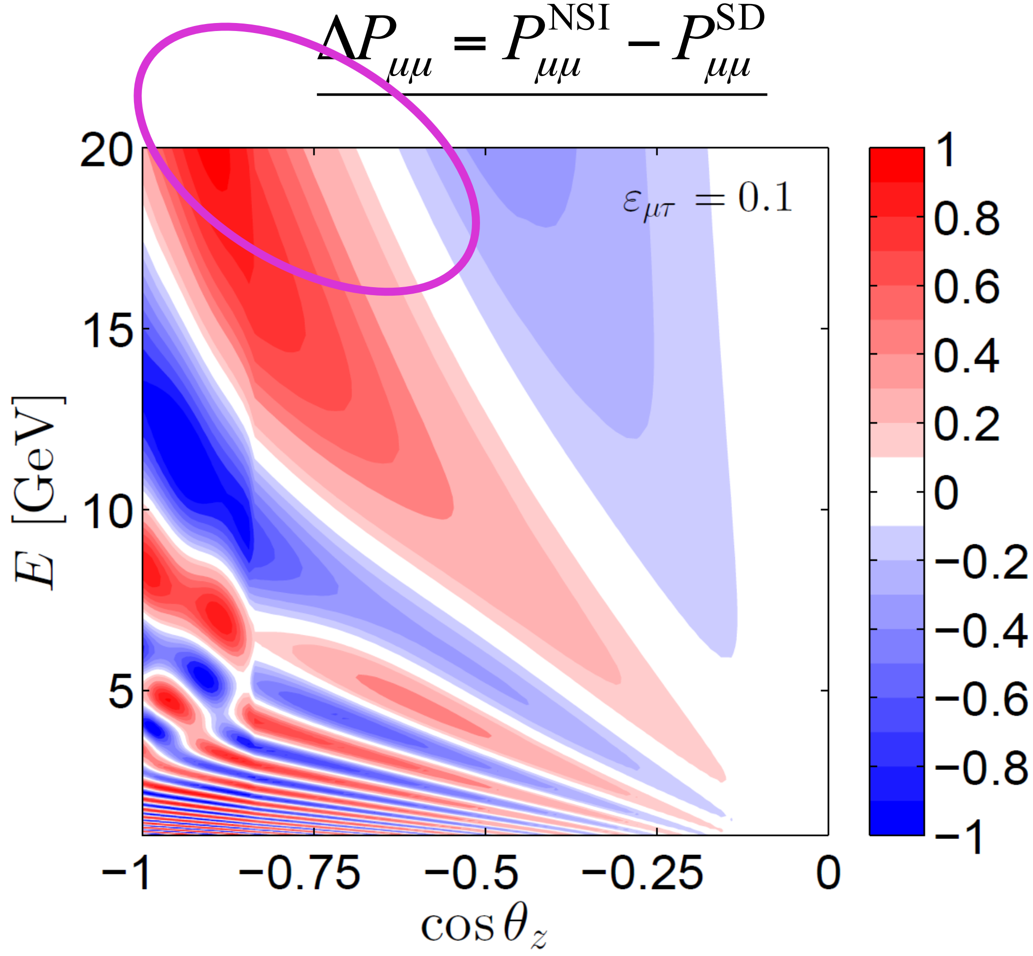
$$\sin^2\theta_{13} = \frac{\hat C - \cos 2\theta_{13} + A}{2\hat C}$$

$$\hat C = \sqrt{\left(\cos 2\theta_{13} - A\right)^2 + \sin^2 2\theta_{13}}$$

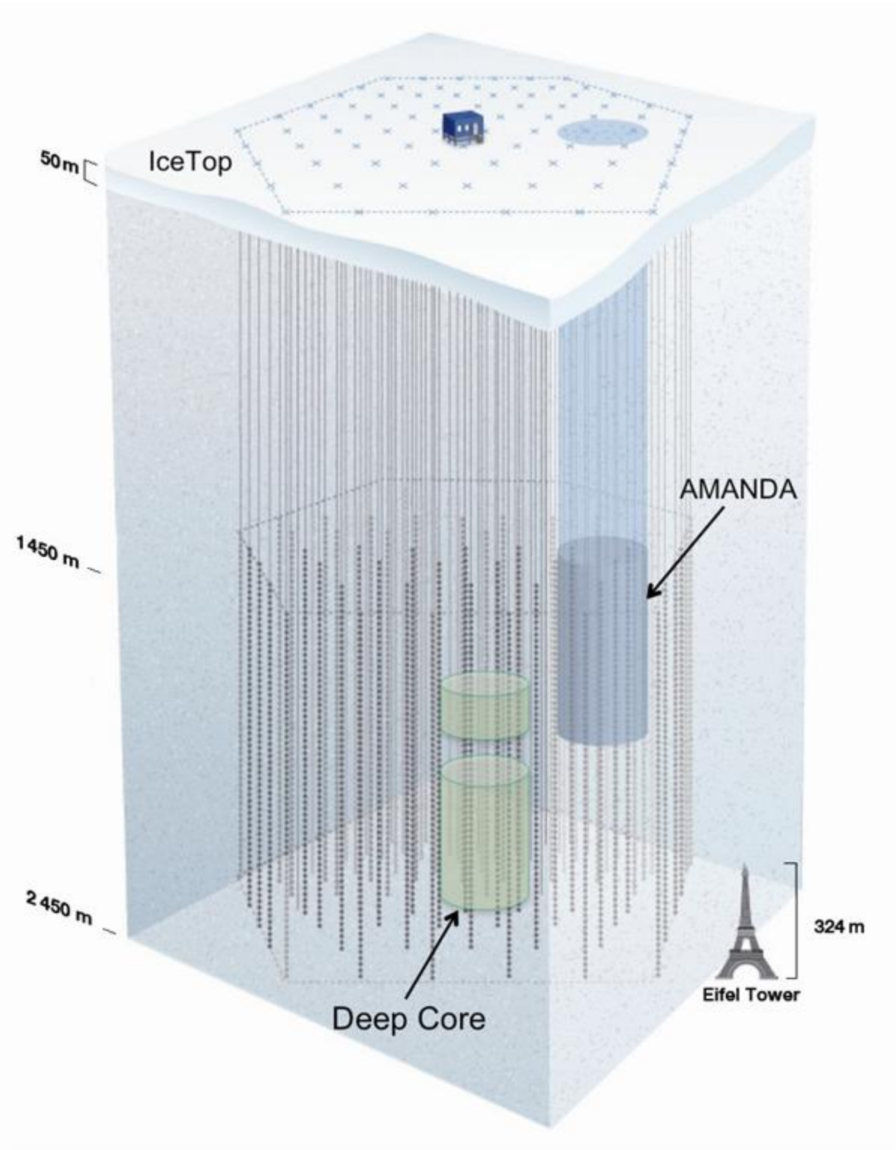
Oscillation Probabilities with NSIs

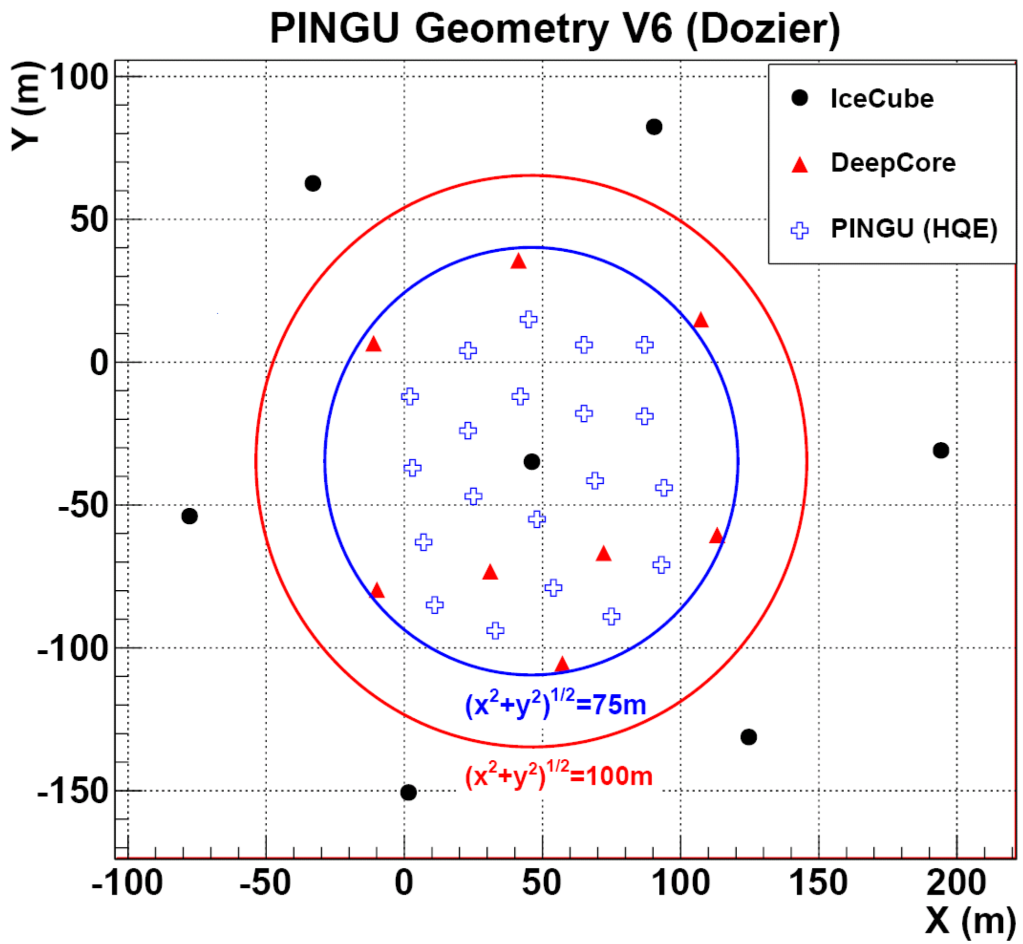
Significant deviation in the high-energy range:





IceCube (DeepCore and PINGU)





(PINGU, 12/2012)

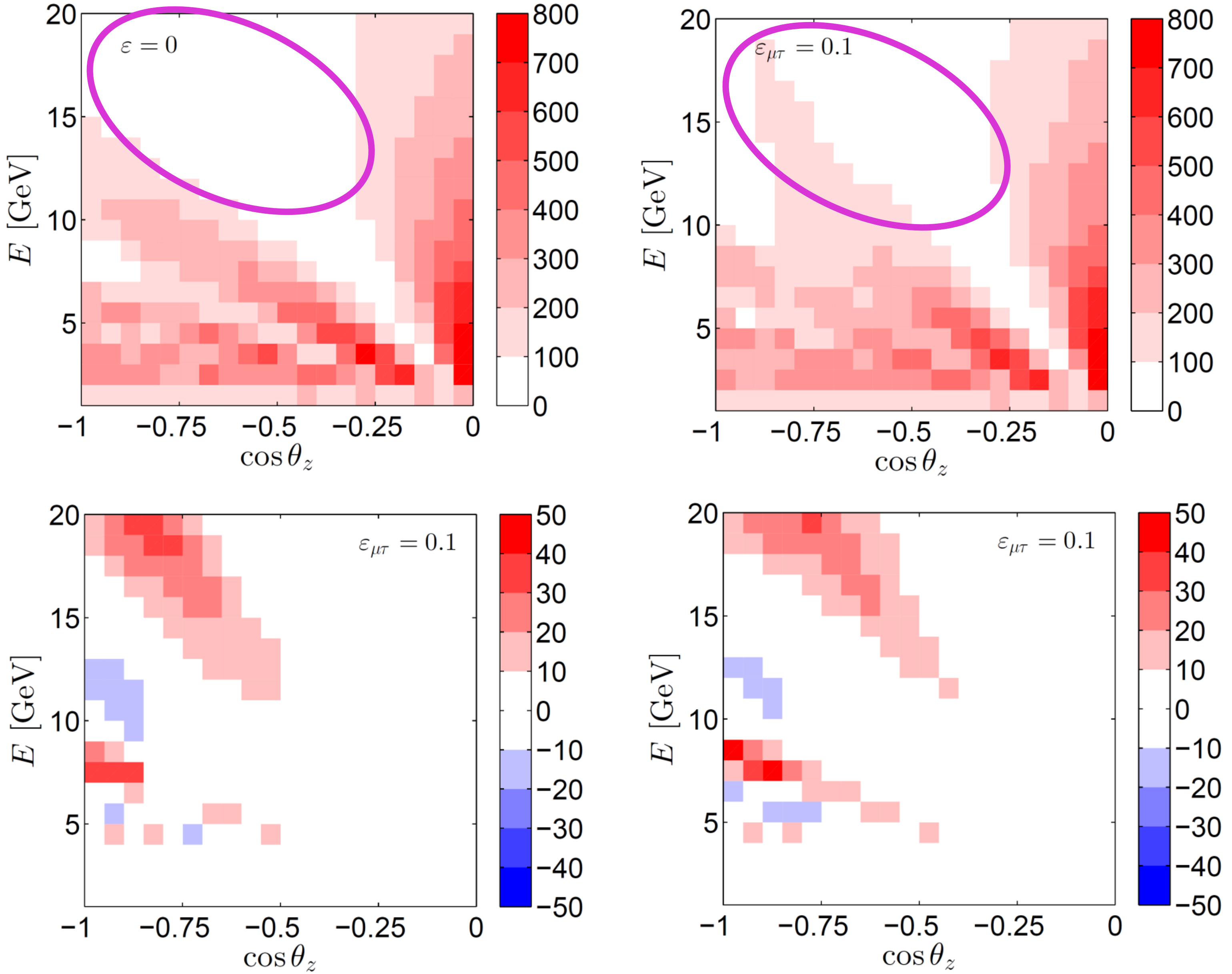
Number of Events @ PINGU

Compare between standard and NSIs

Normal ordering (NO)

$$A \equiv \frac{N_\mu^{\mathrm{SD}} - N_\mu^{\mathrm{NSI}}}{\sqrt{N_\mu^{\mathrm{SD}}}}$$

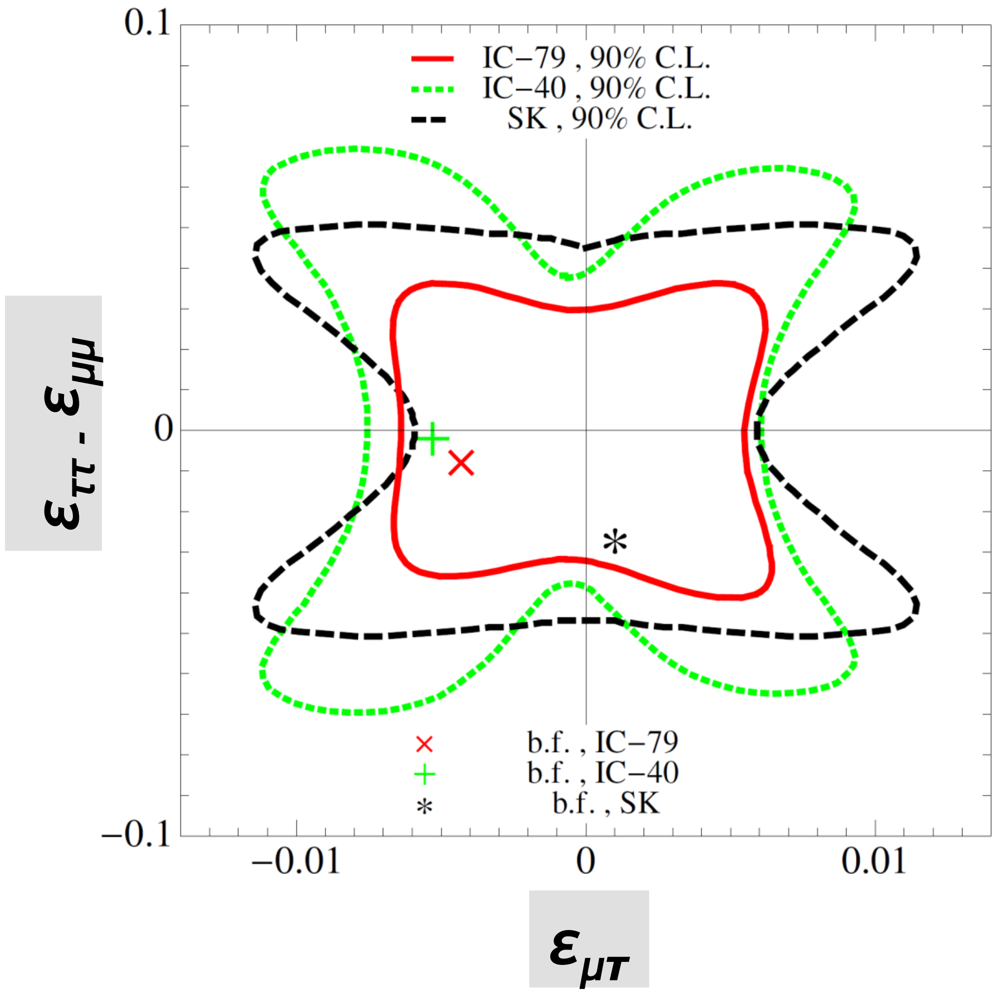
NO (left) IO (right)

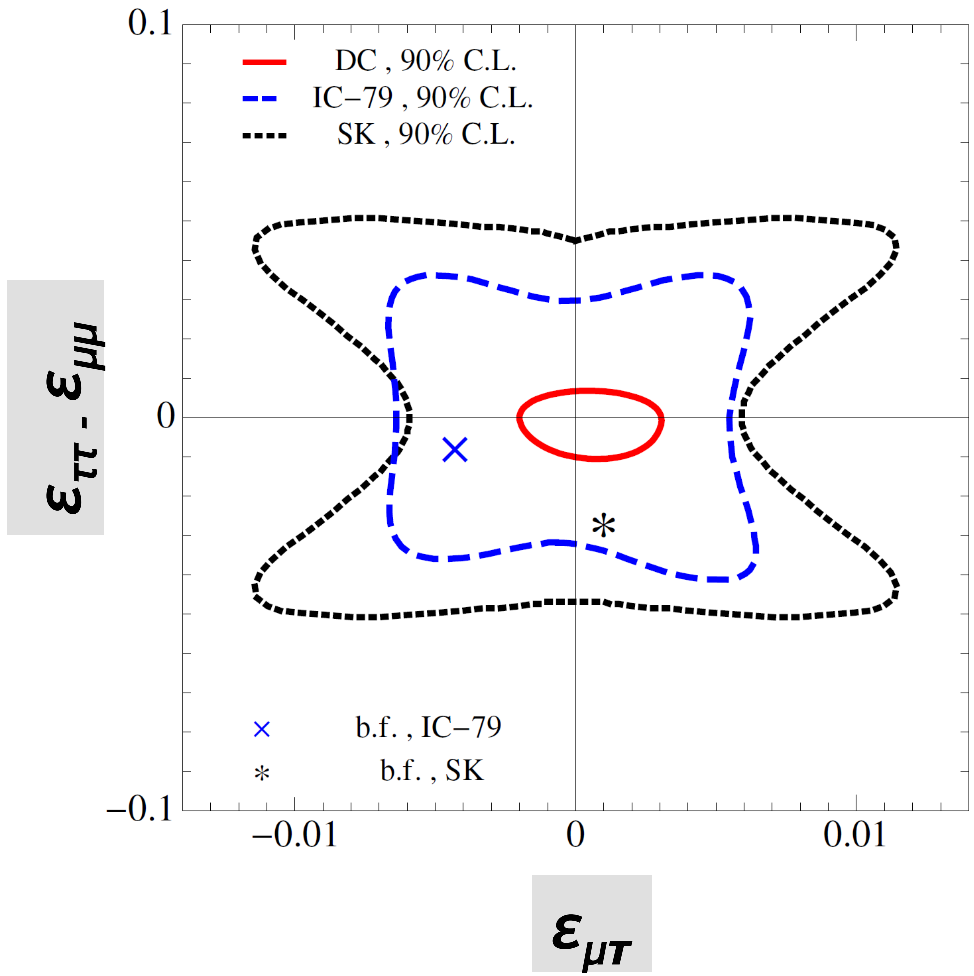


Sensitivity @ IceCube (DeepCore)

Higher resonance energy for smaller $\varepsilon_{\alpha\beta}$

Esmaili & Smirnov, JHEP 1306 (2013) 026





Summary

- Future neutrino oscillation experiments aim to determine the neutrino mass ordering and measure the Dirac CP-violating phase.

- Usually theoretical prediction for the CP phase is given at a super-high energy scale, which should be compared with low-energy measurements. So, RG running has to be taken into account.

- Two new working observables have been introduced to describe intrinsic leptonic CP violation, disentangle the fake CP-violating effects, and optimize the experimental setup.

- The possibility to constrain NSIs has been investigated at IceCube (DeepCore and PINGU).