The best way to probe CP violation in the lepton sector is with long-baseline accelerator neutrino experiments in the appearance mode: the appearance of ν_e in predominantly ν_μ beams. Here we show that it is possible to discover CP violation with disappearance experiments only, by combining JUNO for electron neutrinos and DUNE or Hyper-Kamiokande for muon neutrinos. While the maximum sensitivity to discover CP is quite modest (1.6σ with 6 years of JUNO and 13 years of DUNE), some values of δ may be disfavored by $> 3\sigma$ depending on the true value of δ.

CP-Violation with Neutrino Disappearance

Peter B. Denton

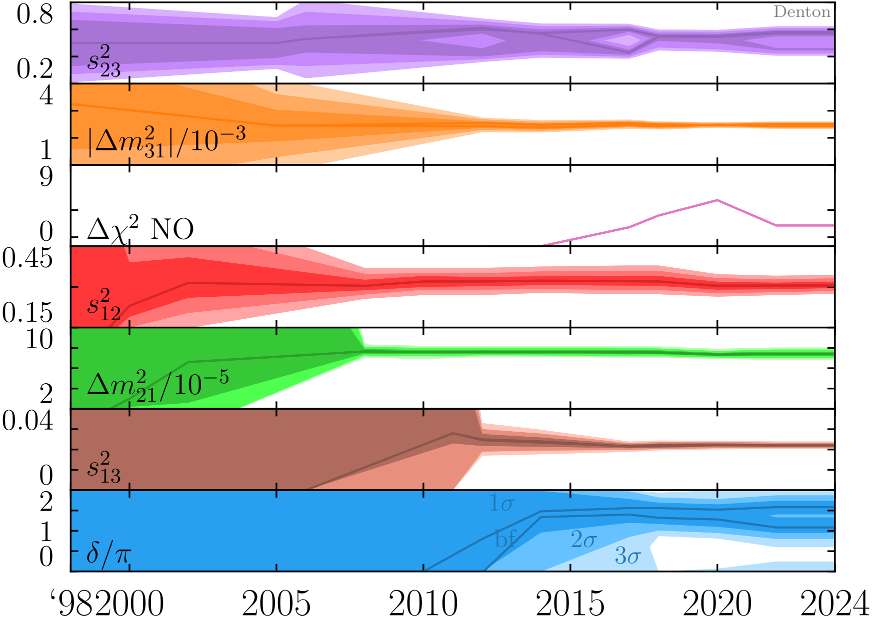
CERN Neutrino Platform

February 18, 2025

2309.03262 PRL

Brookhaven National Laboratory

Brookhaven NDI Neutrino Discovery Initiative


Denton
0.8
0.2
s^2_{23}
4
1
$|\Delta m^2_{31}|/10^{-3}$
9
0
$\Delta\chi^2$ NO
0.45
0.15
s^2_{12}
10
2
$\Delta m^2_{21}/10^{-5}$
0.04
0
s^2_{13}
2
1
0
δ/π
1σ
bf
2σ
3σ
'98
2000
2005
2010
2015
2020
2024

Outline

1. Why CPV is interesting
2. Other non-standard probes of CPV
3. Relationship between appearance, disappearance, CP, T, CPT
4. Three ways to see why there is CPV information in disappearance
   4.1 Parameter counting
   4.2 Direct analytic calculation
   4.3 Numerical test
5. Role of the matter effect
6. Sensitivities

Why is CPV interesting?

δ and CP Violation

$$J_{CP} = s_{12}c_{12}s_{13}c_{13}^2s_{23}c_{23}\sin\delta$$

C. Jarlskog PRL 55, 1039 (1985)

δ and CP Violation

$$J_{CP} = s_{12}c_{12}s_{13}c_{13}^2s_{23}c_{23}\sin\delta$$

C. Jarlskog PRL 55, 1039 (1985)

1. Strong interaction: no observed EDM $\Rightarrow$ CP (nearly) **conserved**

$$\frac{\bar\theta}{2\pi} < 10^{-11}$$

J. Pendlebury, et al. 1509.04411

2. Quark mass matrix: non-zero but **small** CP violation

$$\frac{|J_{\rm CKM}|}{J_{\rm max}} = 3\times10^{-4}$$

CKMfitter 1501.05013

3. Lepton mass matrix: **?**

$$\frac{|J_{\rm PMNS}|}{J_{\rm max}} < 0.34$$

PBD, J. Gehrlein, R. Pestes 2008.01110

$J_{\rm max} = \frac{1}{6\sqrt{3}} \approx 0.096$

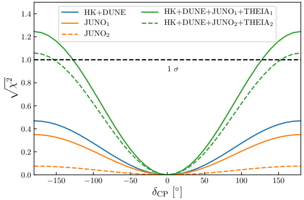
Other Non-standard CPV Probes

1. Some information in solar due to loops in elastic scattering

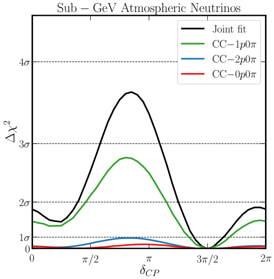
V. Brdar, X-J. Xu 2306.03160
K. Kelly, et al. 2407.03174 requires 3k Borexinos

2. Sub-GeV → sub-100 MeV atmospherics

K. Kelly, et al. 1904.02751
See also e.g. A. Suliga, J. Beacom 2306.11090



Solar (no systematics)



Atmospherics at DUNE

Appearance, Disappearance, and CP

Appearance and Disappearance, CP Even and CP Odd Terms

Disappearance:

$$\begin{aligned} P(\nu_\alpha \to \nu_\alpha) = 1 &- 4|U_{\alpha 1}|^2|U_{\alpha 2}|^2 \sin^2 \Delta_{21} \\ &- 4|U_{\alpha 1}|^2|U_{\alpha 3}|^2 \sin^2 \Delta_{31} \\ &- 4|U_{\alpha 2}|^2|U_{\alpha 3}|^2 \sin^2 \Delta_{32} \\ = P_{\alpha\alpha}^{CP+} & \end{aligned}$$

$$\Delta_{ij} \equiv \Delta m_{ij}^2 L/4E$$

Appearance and Disappearance, CP Even and CP Odd Terms

Disappearance:

$$\begin{aligned} P(\nu_\alpha \to \nu_\alpha) = 1 &- 4|U_{\alpha1}|^2|U_{\alpha2}|^2 \sin^2\Delta_{21} \\ &- 4|U_{\alpha1}|^2|U_{\alpha3}|^2 \sin^2\Delta_{31} \\ &- 4|U_{\alpha2}|^2|U_{\alpha3}|^2 \sin^2\Delta_{32} \\ = P_{\alpha\alpha}^{CP+} \end{aligned}$$

Appearance:

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) = &- 4\Re[U_{\alpha1}U_{\beta1}^*U_{\alpha2}^*U_{\beta2}] \sin^2\Delta_{21} \\ &- 4\Re[U_{\alpha1}U_{\beta1}^*U_{\alpha3}^*U_{\beta3}] \sin^2\Delta_{31} \\ &- 4\Re[U_{\alpha3}U_{\beta3}^*U_{\alpha2}^*U_{\beta2}] \sin^2\Delta_{32} \\ &\pm 8J_{CP} \sin\Delta_{21} \sin\Delta_{31} \sin\Delta_{32} \\ = P_{\alpha\beta}^{CP+} + P_{\alpha\beta}^{CP-} \end{aligned}$$

$\Delta_{ij} \equiv \Delta m_{ij}^2 L/4E$

Sign depends on α, β

Conventional Wisdom

1. Appearance is sensitive to CPV [True]

Conventional Wisdom

1. Appearance is sensitive to CPV [True]
2. Disappearance has no CPV sensitivity [False]

Conventional Wisdom

1. Appearance is sensitive to CPV [True]
2. Disappearance has no CPV sensitivity [False]
3. Any δ dependence in disappearance is in ν_μ not ν_e [Confusing/False]

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

Correct Statements

- Appearance is the best way to measure δ and CPV

  …given known oscillation parameters, systematics, and realistic experiments

  - Probes mostly $\sin\delta$ not $\cos\delta$
  - Don't need both ν and $\bar{\nu}$ (but systematics)
- **Disappearance can measure δ**
  - CPV can be discovered with only disappearance measurements
  - Probes mostly $\cos\delta$ not $\sin\delta$
  - Requires measurements of two flavors
  - "Works through unitarity" (as do nearly all oscillation measurements)

Parameter Counting

1. Four parameters in the PMNS matrix

Majorana phases are irrelevant in oscillations

Parameter Counting

1. Four parameters in the PMNS matrix

   Majorana phases are irrelevant in oscillations

2. Disappearance experiments of one flavor can measure up to three amplitudes
   - Electron neutrino row:
     - KamLAND measured one
     - Daya Bay/RENO measured a different one
     - JUNO will measure all three
   - Muon neutrino row:
     - MINOS/T2K/NOνA measured one

Parameter Counting

1. Four parameters in the PMNS matrix

   Majorana phases are irrelevant in oscillations

2. Disappearance experiments of one flavor can measure up to three amplitudes
   - Electron neutrino row:
     - KamLAND measured one
     - Daya Bay/RENO measured a different one
     - JUNO will measure all three
   - Muon neutrino row:
     - MINOS/T2K/NOνA measured one

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4\sum_{i>j} C^\alpha_{ij} \sin^2\Delta_{ij}$$

$$C^\alpha_{ij} = |U_{\alpha i}|^2 |U_{\alpha j}|^2$$

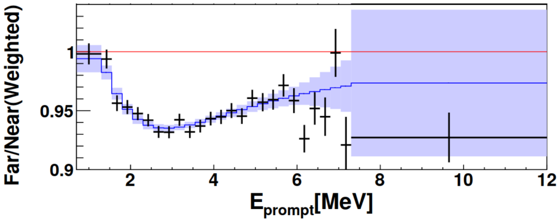
$$|U_{\alpha i}| = \left(\frac{C^\alpha_{ij} C^\alpha_{ik}}{C^\alpha_{jk}}\right)^{1/4}$$

Parameter Counting

1. Four parameters in the PMNS matrix

Majorana phases are irrelevant in oscillations

2. Disappearance experiments of one flavor can measure up to three amplitudes
   - Electron neutrino row:
     - KamLAND measured one
     - Daya Bay/RENO measured a different one
     - JUNO will measure all three
   - Muon neutrino row:
     - MINOS/T2K/NOνA measured one



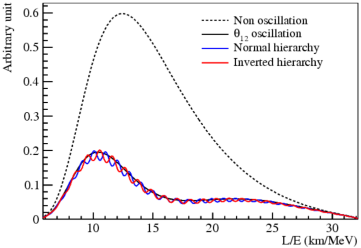
Daya Bay 1809.02261

Parameter Counting

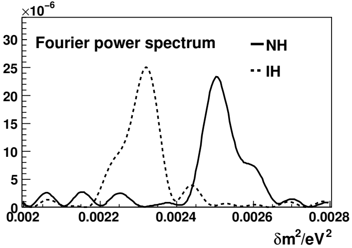
1. Four parameters in the PMNS matrix

   Majorana phases are irrelevant in oscillations

2. Disappearance experiments of one flavor can measure up to three amplitudes
   - Electron neutrino row:
     - KamLAND measured one
     - Daya Bay/RENO measured a different one
     - JUNO will measure all three
   - Muon neutrino row:
     - MINOS/T2K/NOνA measured one



JUNO 1507.05613



L. Zhan, et al. 0807.3203

Parameter Counting

1. Four parameters in the PMNS matrix

   Majorana phases are irrelevant in oscillations

2. Disappearance experiments of one flavor can measure up to three amplitudes
   - Electron neutrino row:
     - KamLAND measured one
     - Daya Bay/RENO measured a different one
     - JUNO will measure all three
   - Muon neutrino row:
     - MINOS/T2K/NOνA measured one
3. Only two parameters for one flavor are independent

Parameter Counting

1. Four parameters in the PMNS matrix

   Majorana phases are irrelevant in oscillations

2. Disappearance experiments of one flavor can measure up to three amplitudes
   - Electron neutrino row:
     - KamLAND measured one
     - Daya Bay/RENO measured a different one
     - JUNO will measure all three
   - Muon neutrino row:
     - MINOS/T2K/NOνA measured one
3. Only two parameters for one flavor are independent
4. Given good measurements of the ν_e and ν_μ disappearance, 4 independent parameters will be measured
   - Any row can be "simple" (e.g. $c_{12}c_{13}$, $s_{12}c_{13}$, ...) $\Rightarrow$ no one row is ever enough
   - That is, CPV is physical and cannot depend on parameterization

Parameter Counting

1. Four parameters in the PMNS matrix

   Majorana phases are irrelevant in oscillations

2. Disappearance experiments of one flavor can measure up to three amplitudes
   - Electron neutrino row:
     - KamLAND measured one
     - Daya Bay/RENO measured a different one
     - JUNO will measure all three
   - Muon neutrino row:
     - MINOS/T2K/NOνA measured one
3. Only two parameters for one flavor are independent
4. Given good measurements of the ν_e and ν_μ disappearance, 4 independent parameters will be measured
   - Any row can be "simple" (e.g. $c_{12}c_{13}$, $s_{12}c_{13}$, ...) $\Rightarrow$ no one row is ever enough
   - That is, CPV is physical and cannot depend on parameterization
5. This is sufficient to constrain $\cos\delta$ and three mixing angles

Parameter Counting

1. Four parameters in the PMNS matrix

   Majorana phases are irrelevant in oscillations
2. Disappearance experiments of one flavor can measure up to three amplitudes
   - Electron neutrino row:
     - KamLAND measured one
     - Daya Bay/RENO measured a different one
     - JUNO will measure all three
   - Muon neutrino row:
     - MINOS/T2K/NOνA measured one
3. Only two parameters for one flavor are independent
4. Given good measurements of the ν_e and ν_μ disappearance, 4 independent parameters will be measured
   - Any row can be "simple" (e.g. $c_{12}c_{13}$, $s_{12}c_{13}$, ...) $\Rightarrow$ no one row is ever enough
   - That is, CPV is physical and cannot depend on parameterization
5. This is sufficient to constrain $\cos\delta$ and three mixing angles
6. If we determine $\cos\delta \neq \pm 1 \quad \Rightarrow \quad$ CP is violated!

Direct Analytic Calculation

Disappearance experiments measure various $|U_{\alpha i}|^2$ terms
Suppose 4 are measured: $|U_{e2}|^2$, $|U_{e3}|^2$, $|U_{\mu2}|^2$, $|U_{\mu3}|^2$

Actually this gives all 9 magnitudes by unitarity

Direct Analytic Calculation

Disappearance experiments measure various $|U_{\alpha i}|^2$ terms
Suppose 4 are measured: $|U_{e2}|^2$, $|U_{e3}|^2$, $|U_{\mu 2}|^2$, $|U_{\mu 3}|^2$

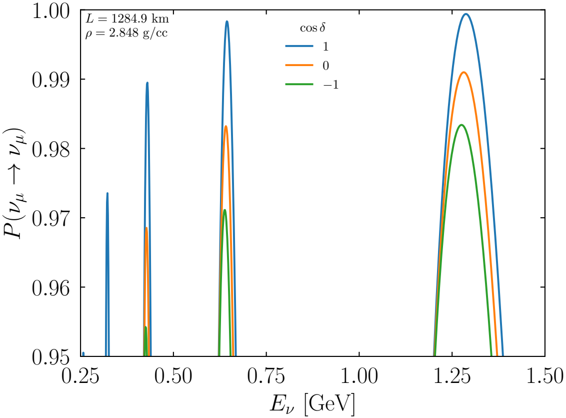
Actually this gives all 9 magnitudes by unitarity

$$J_{CP}^2 = |U_{e2}|^2|U_{\mu 2}|^2|U_{e3}|^2|U_{\mu 3}|^2 - \frac{1}{4}\left(1 - |U_{e2}|^2 - |U_{\mu 2}|^2 - |U_{e3}|^2 - |U_{\mu 3}|^2 + |U_{e2}|^2|U_{\mu 3}|^2 + |U_{e3}|^2|U_{\mu 2}|^2\right)^2$$

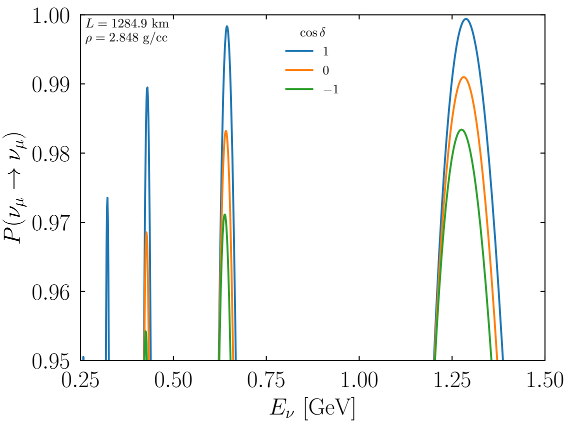
Can show that if any one $|U_{\alpha i}|^2 = 0 \Rightarrow J = 0$

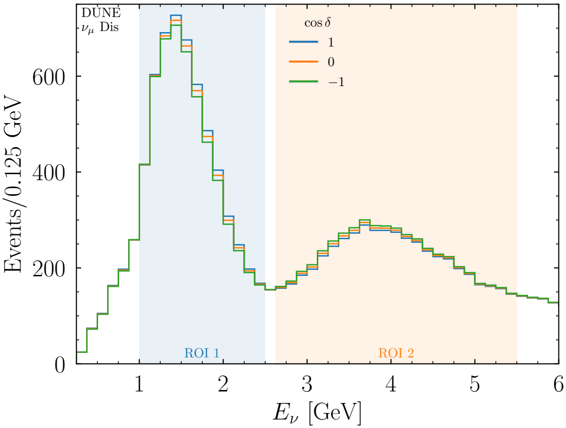
Disappearance can tell us if CP is violated,
but not if Nature prefers ν's or $\bar{\nu}$'s

Where is $|U_{\mu 2}|^2$?



Where is $|U_{\mu 2}|^2$?





6.5 yrs ν_μ rates

$\cos\delta$	ROI 1	ROI 2
1	5506	5038
0	5418	5115
-1	5334	5193

Matter Effects Matter: (21) Sector

- Let's start at

$$\approx -4c_{23}^2\left(s_{12}^2c_{12}^2+s_{23}c_{23}s_{13}\sin 2\theta_{12}\cos 2\theta_{12}\cos\delta\right)\sin^2\Delta_{21}$$

Matter Effects Matter: (21) Sector

- Let's start at

$$\approx -4c_{23}^2\left(s_{12}^2c_{12}^2 + s_{23}c_{23}s_{13}\sin 2\theta_{12}\cos 2\theta_{12}\cos\delta\right)\sin^2\Delta_{21}$$

- Solar splitting modified by

$$\Delta m_{21}^2 \to \Delta m_{21}^2\mathcal{S}_\odot$$

$$\mathcal{S}_\odot \approx \sqrt{(\cos 2\theta_{12} - c_{13}^2 a/\Delta m_{21}^2)^2 + \sin^2 2\theta_{12}} \approx 3.4$$

at $E = 1.3$ GeV
PBD, S. Parke 1902.07185

Matter Effects Matter: (21) Sector

- Let's start at

$$\approx -4c_{23}^2\left(s_{12}^2c_{12}^2+s_{23}c_{23}s_{13}\sin 2\theta_{12}\cos 2\theta_{12}\cos\delta\right)\sin^2\Delta_{21}$$

- Solar splitting modified by

$$\Delta m_{21}^2 \to \Delta m_{21}^2\mathcal{S}_\odot$$

$$\mathcal{S}_\odot \approx \sqrt{(\cos 2\theta_{12}-c_{13}^2a/\Delta m_{21}^2)^2+\sin^2 2\theta_{12}} \approx 3.4$$

at $E = 1.3$ GeV

PBD, S. Parke 1902.07185

- Mixing angle is modified

$$\cos 2\theta_{12} = 0.37 \to \frac{\cos 2\theta_{12}-c_{13}^2a/\Delta m_{21}^2}{\mathcal{S}_\odot} \approx -0.96 < 0$$

$a \propto \rho E$

Matter Effects Matter: (21) Sector

- Let's start at

$$\approx -4c_{23}^2\left(s_{12}^2c_{12}^2 + s_{23}c_{23}s_{13}\sin 2\theta_{12}\cos 2\theta_{12}\cos\delta\right)\sin^2\Delta_{21}$$

- Solar splitting modified by

$$\Delta m_{21}^2 \to \Delta m_{21}^2 \mathcal{S}_\odot$$

$$\mathcal{S}_\odot \approx \sqrt{(\cos 2\theta_{12} - c_{13}^2 a/\Delta m_{21}^2)^2 + \sin^2 2\theta_{12}} \approx 3.4$$

at $E = 1.3$ GeV

PBD, S. Parke 1902.07185

- Mixing angle is modified

$$\cos 2\theta_{12} = 0.37 \to \frac{\cos 2\theta_{12} - c_{13}^2 a/\Delta m_{21}^2}{\mathcal{S}_\odot} \approx -0.96 < 0$$

- So the sign is swapped

$a \propto \rho E$

$$\sin 2\theta_{12}\cos 2\theta_{12} = 0.35 \to -0.26$$

Matter Effects Matter: (21) Sector

- Let's start at

$$\approx -4c_{23}^2\left(s_{12}^2c_{12}^2 + s_{23}c_{23}s_{13}\sin 2\theta_{12}\cos 2\theta_{12}\cos\delta\right)\sin^2\Delta_{21}$$

- Solar splitting modified by

$$\Delta m_{21}^2 \to \Delta m_{21}^2 \mathcal{S}_\odot$$

$$\mathcal{S}_\odot \approx \sqrt{(\cos 2\theta_{12} - c_{13}^2 a/\Delta m_{21}^2)^2 + \sin^2 2\theta_{12}} \approx 3.4$$

at $E = 1.3$ GeV
PBD, S. Parke 1902.07185

- Mixing angle is modified

$$\cos 2\theta_{12} = 0.37 \to \frac{\cos 2\theta_{12} - c_{13}^2 a/\Delta m_{21}^2}{\mathcal{S}_\odot} \approx -0.96 < 0$$

- So the sign is swapped

$a \propto \rho E$

$$\sin 2\theta_{12}\cos 2\theta_{12} = 0.35 \to -0.26$$

- Also s_{13} increases in matter $\sim 15\%$: total effect is $0.004\cos\delta$

Matter Effects Matter: (21) Sector

- Let's start at

$$\approx -4c_{23}^2\left(s_{12}^2c_{12}^2 + s_{23}c_{23}s_{13}\sin 2\theta_{12}\cos 2\theta_{12}\cos\delta\right)\sin^2\Delta_{21}$$

- Solar splitting modified by

$$\Delta m_{21}^2 \to \Delta m_{21}^2 \mathcal{S}_\odot$$

$$\mathcal{S}_\odot \approx \sqrt{(\cos 2\theta_{12} - c_{13}^2 a/\Delta m_{21}^2)^2 + \sin^2 2\theta_{12}} \approx 3.4$$

at $E = 1.3$ GeV

PBD, S. Parke 1902.07185

- Mixing angle is modified

$$\cos 2\theta_{12} = 0.37 \to \frac{\cos 2\theta_{12} - c_{13}^2 a/\Delta m_{21}^2}{\mathcal{S}_\odot} \approx -0.96 < 0$$

- So the sign is swapped

$a \propto \rho E$

$$\sin 2\theta_{12}\cos 2\theta_{12} = 0.35 \to -0.26$$

- Also s_{13} increases in matter $\sim 15\%$: total effect is $0.004\cos\delta$
- This gets us **half** of the effect, and the correct sign

Matter Effects Matter: (32) Sector

- $\frac{\Delta m^2_{\mu\mu} L}{4E}$ in matter at the maximum is $\sim \pi$

H. Nunokawa, S. Parke, R. Funchal hep-ph/0503283
PBD, S. Parke 2401.10326

Matter Effects Matter: (32) Sector

- $\frac{\Delta m^2_{\mu\mu} L}{4E}$ in matter at the maximum is $\sim \pi$

H. Nunokawa, S. Parke, R. Funchal hep-ph/0503283
PBD, S. Parke 2401.10326

- The Δm^2_{32} component is a bit off π at max

Matter Effects Matter: (32) Sector

- $\frac{\Delta m^2_{\mu\mu} L}{4E}$ in matter at the maximum is $\sim \pi$

H. Nunokawa, S. Parke, R. Funchal hep-ph/0503283
PBD, S. Parke 2401.10326

- The Δm^2_{32} component is a bit off π at max
- Leading order in s_{13}:

$$\approx -4 s_{23}^2 (c_{12}^2 c_{23}^2 - 2 s_{13} s_{12} c_{12} s_{23} c_{23} \cos\delta) \sin^2\Delta_{32}$$
$$\approx -2 \quad (0.0094 \qquad - 0.023 \cos\delta) 0.1 \qquad \text{(matter)}$$

Matter Effects Matter: (32) Sector

- $\frac{\Delta m^2_{\mu\mu} L}{4E}$ in matter at the maximum is $\sim \pi$

H. Nunokawa, S. Parke, R. Funchal hep-ph/0503283
PBD, S. Parke 2401.10326

- The Δm^2_{32} component is a bit off π at max
- Leading order in s_{13}:

$$\approx -4 s^2_{23} (c^2_{12} c^2_{23} - 2 s_{13} s_{12} c_{12} s_{23} c_{23} \cos\delta) \sin^2 \Delta_{32}$$
$$\approx -2 \quad (0.0094 \qquad -0.023 \cos\delta) 0.1 \qquad \text{(matter)}$$

- Adds in another $\approx 0.004 \cos\delta$ effect

Matter Effects Matter: (32) Sector

- $\frac{\Delta m^2_{\mu\mu} L}{4E}$ in matter at the maximum is $\sim \pi$

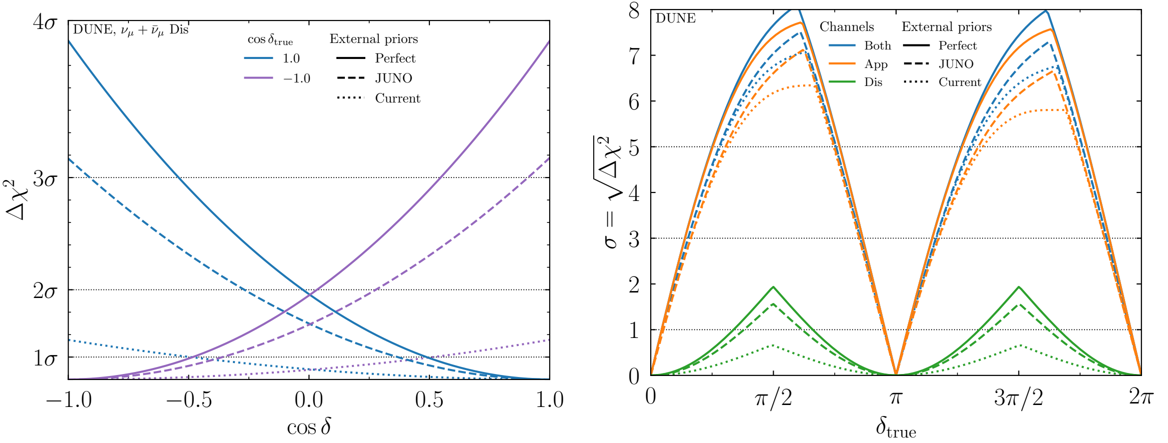
H. Nunokawa, S. Parke, R. Funchal hep-ph/0503283
PBD, S. Parke 2401.10326

- The Δm^2_{32} component is a bit off π at max
- Leading order in s_{13}:

$$\approx -4 s^2_{23} (c^2_{12} c^2_{23} - 2 s_{13} s_{12} c_{12} s_{23} c_{23} \cos\delta) \sin^2 \Delta_{32}$$
$$\approx -2 \quad (0.0094 \qquad -0.023 \cos\delta) 0.1 \qquad \text{(matter)}$$

- Adds in another $\approx 0.004 \cos\delta$ effect
- Total is $\approx 0.008 \cos\delta$ which agrees with numerical calculation

JUNO and DUNE Disappearance Sensitivities



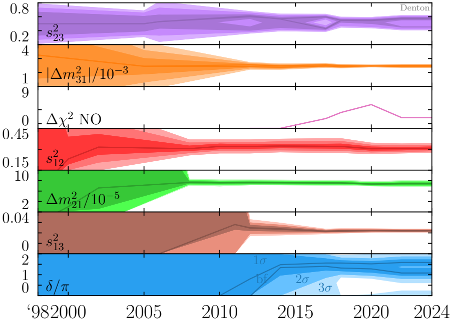
Discussion and Conclusions

- **Disappearance can discover CPV**
- Requires two good measurements: JUNO and DUNE/HK
- Can rule out some values of δ at $> 3\sigma$
- Works in vacuum or matter; matter slightly minimizes HK's effect
- Subject to BSM degeneracies, as are most other oscillation measurements
- Analyses already exist but…

- **LBL Experiments should break down δ analyses into app vs. dis**
- Since systematics are different, provides a good cross check

Backups

References



SK hep-ex/9807003

M. Gonzalez-Garcia, et al. hep-ph/0009350

M. Maltoni, et al. hep-ph/0207227

SK hep-ex/0501064

SK hep-ex/0604011

T. Schwetz, M. Tortola, J. Valle 0808.2016

M. Gonzalez-Garcia, M. Maltoni, J. Salvado 1001.4524

T2K 1106.2822

D. Forero, M. Tortola, J. Valle 1205.4018

D. Forero, M. Tortola, J. Valle 1405.7540

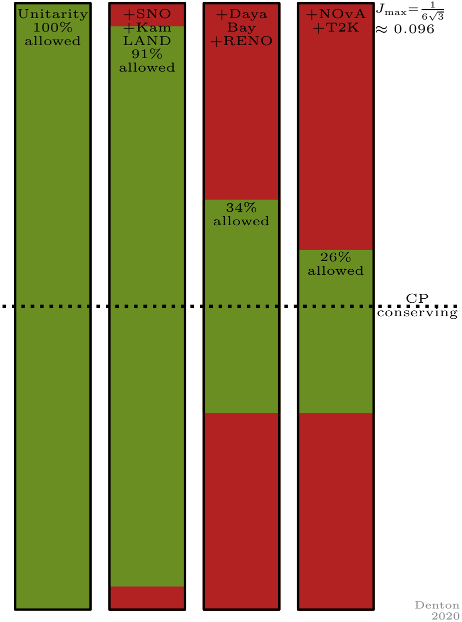
P. de Salas, et al. 1708.01186

F. Capozzi et al. 2003.08511

δ, J: Current Status

Maximal CP violation is already ruled out:

1. $\theta_{12} \neq 45^\circ$ at $\sim 15\sigma$
2. $\theta_{13} \neq \tan^{-1}\frac{1}{\sqrt{2}} \approx 35^\circ$ at many (100) σ
3. $\theta_{23} = 45^\circ$ allowed at $\sim 1\sigma$
4. $|\sin\delta| = 1$ allowed



When δ and When J?

If the goal is **CP violation** the Jarlskog invariant should be used

however

If the goal is **measuring the parameters** one must use δ

Given θ_{12}, θ_{13}, θ_{23}, and J, I can't determine the sign of $\cos\delta$ which is physical

e.g. $P(\nu_\mu \to \nu_\mu)$ depends on $\cos\delta$

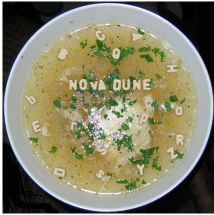
Appearance vs. Disappearance

Oscillation experiments can do
appearance or disappearance experiments:

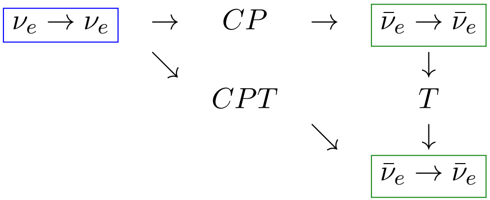
Disappearance
K2K, MINOS, T2K, NOνA
KamLAND, Daya Bay, RENO, Double CHOOZ
(Sort of) SNO, Borexino, SK-solar
JUNO, DUNE, HK

Appearance
T2K, NOνA
OPERA
Atm ν_τ hints @ SK & IceCube
DUNE, HK

Neither appearance nor disappearance
SK-atm, IceCube



CP, T: Disappearance



Disappearance measurements are even eigenstates of CP

$$CP[P(\nu_e \to \nu_e)] = P(\bar{\nu}_e \to \bar{\nu}_e) \stackrel{CPT}{=} P(\nu_e \to \nu_e)$$

Assume that CPT is a good symmetry

CP, T: Appearance

$$\begin{array}{ccccc} \boxed{\nu_\mu \to \nu_e} & \to & CP & \to & \boxed{\bar\nu_\mu \to \bar\nu_e} \\ & \searrow & & & \downarrow \\ & & CPT & & T \\ & & & \searrow & \downarrow \\ & & & & \boxed{\bar\nu_e \to \bar\nu_\mu} \end{array}$$

Appearance measurements are not eigenstates of CP

Approximate Size of $|U_{\mu 2}|^2$ Signal: (21) Sector

- There is no δ information in $|U_{\mu 1}|^2 + |U_{\mu 2}|^2$ (sum of Δ_{31} and Δ_{32} terms)

Approximate Size of $|U_{\mu 2}|^2$ Signal: (21) Sector

- There is no δ information in $|U_{\mu 1}|^2 + |U_{\mu 2}|^2$ (sum of Δ_{31} and Δ_{32} terms)
- There is δ information in $|U_{\mu 1}|^2 |U_{\mu 2}|^2$

Approximate Size of $|U_{\mu2}|^2$ Signal: (21) Sector

- There is no δ information in $|U_{\mu1}|^2 + |U_{\mu2}|^2$ (sum of Δ_{31} and Δ_{32} terms)
- There is δ information in $|U_{\mu1}|^2|U_{\mu2}|^2$
- This comes from the Δm^2_{21} term

DUNE and HK can measure Δm^2_{21} somewhat
PBD, J. Gehrlein 2302.08513

Approximate Size of $|U_{\mu 2}|^2$ Signal: (21) Sector

- There is no δ information in $|U_{\mu 1}|^2 + |U_{\mu 2}|^2$ (sum of Δ_{31} and Δ_{32} terms)
- There is δ information in $|U_{\mu 1}|^2 |U_{\mu 2}|^2$
- This comes from the Δm^2_{21} term

DUNE and HK can measure Δm^2_{21} somewhat
PBD, J. Gehrlein 2302.08513

- This term is

$$\approx -4c^2_{23}\left(s^2_{12}c^2_{12} + s_{23}c_{23}s_{13}\sin 2\theta_{12}\cos 2\theta_{12}\cos\delta\right)\sin^2\Delta_{21}$$

$$\approx -2 \quad (0.21 \quad + \quad 0.03\cos\delta)\left(\frac{\pi}{33}\right)^2$$

$\Delta m^2_{21}/|\Delta m^2_{31}| \approx 33$

Approximate Size of $|U_{\mu 2}|^2$ Signal: (21) Sector

- There is no δ information in $|U_{\mu 1}|^2 + |U_{\mu 2}|^2$ (sum of Δ_{31} and Δ_{32} terms)
- There is δ information in $|U_{\mu 1}|^2 |U_{\mu 2}|^2$
- This comes from the Δm^2_{21} term

DUNE and HK can measure Δm^2_{21} somewhat
PBD, J. Gehrlein 2302.08513

- This term is

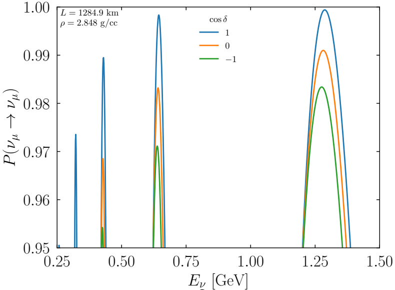
$$\approx -4c_{23}^2 \left(s_{12}^2 c_{12}^2 + s_{23} c_{23} s_{13} \sin 2\theta_{12} \cos 2\theta_{12} \cos\delta \right) \sin^2 \Delta_{21}$$

$$\approx -2 \quad (0.21 \quad + \quad 0.03 \cos\delta) \left(\frac{\pi}{33}\right)^2$$

$\Delta m^2_{21} / |\Delta m^2_{31}| \approx 33$

- So the probability is large for $\cos\delta = -1$?
- So the effect is $\sim -0.0005 \cos\delta$?

Approximate Size of $|U_{\mu2}|^2$ Signal: (21) Sector



DUNE and HK can measure Δm^2_{21} somewhat
PBD, J. Gehrlein 2302.08513

- There is no δ information in $|U_{\mu1}|^2 + |U_{\mu2}|^2$
- There is δ information in $|U_{\mu1}|^2|U_{\mu2}|^2$
- This comes from the Δm^2_{21} term

- This term is

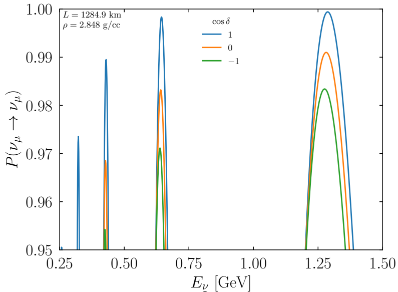
$$\approx -4c^2_{23}\left(s^2_{12}c^2_{12} + s_{23}c_{23}s_{13}\sin 2\theta_{12}\cos 2\theta_{12}\cos\delta\right)\sin^2\Delta_{21}$$

$$\approx -2 \quad (0.21 \quad + \qquad 0.03\cos\delta)\left(\frac{\pi}{33}\right)^2$$

$\Delta m^2_{21}/|\Delta m^2_{31}| \approx 33$

- So the probability is large for $\cos\delta = -1$?
- So the effect is $\sim -0.0005\cos\delta$?

Approximate Size of $|U_{\mu 2}|^2$ Signal: (21) Sector



DUNE and HK can measure Δm^2_{21} somewhat
PBD, J. Gehrlein 2302.08513

- There is no δ information in $|U_{\mu 1}|^2 + |U_{\mu 2}|^2$
- There is δ information in $|U_{\mu 1}|^2 |U_{\mu 2}|^2$
- This comes from the Δm^2_{21} term

- This term is

$$\approx -4c_{23}^2 \left(s_{12}^2 c_{12}^2 + s_{23}c_{23}s_{13}\sin 2\theta_{12}\cos 2\theta_{12}\cos\delta\right)\sin^2\Delta_{21}$$

$$\approx -2 \quad (0.21 \quad + \quad 0.03\cos\delta)\left(\frac{\pi}{33}\right)^2$$

$\Delta m^2_{21}/|\Delta m^2_{31}| \approx 33$

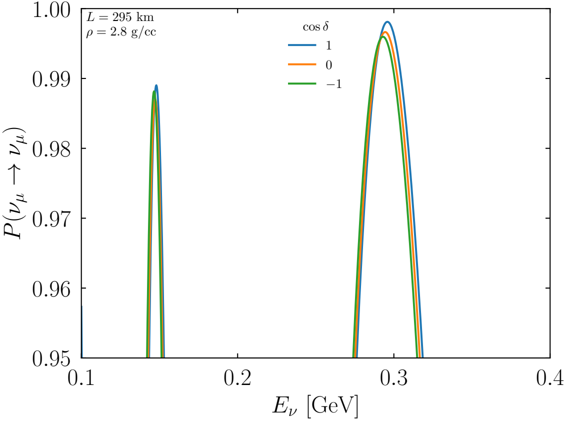
- So the probability is large for $\cos\delta = -1$? — Sign is wrong
- So the effect is $\sim -0.0005\cos\delta$? — Magnitude is ~ 16 too small

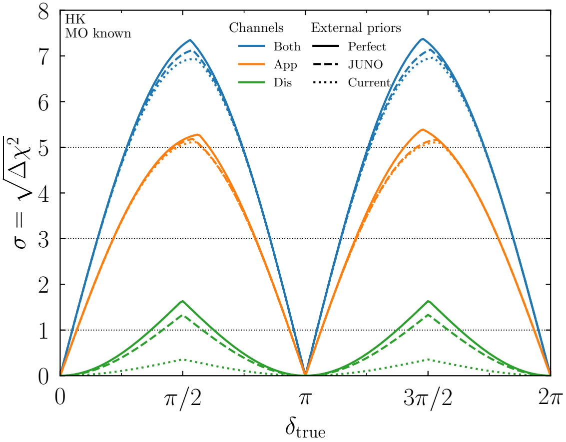
Numerical Studies

Inputs are *only*:

- Daya Bay data for θ_{13} 1809.02261
- KamLAND data for θ_{12} and Δm^2_{21} 1303.4667
- JUNO 6 yrs precision sensitivity on θ_{12}, Δm^2_{21}, Δm^2_{31} 2204.13249
- DUNE 6.5+6.5 yrs disappearance channels sensitivity only 2103.04797

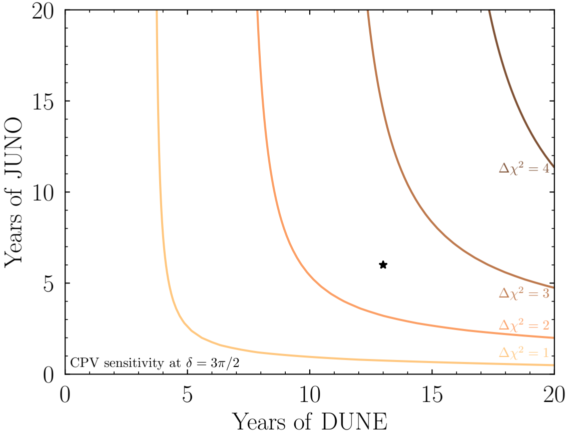
JUNO and HK Disappearance Sensitivities





Varying Runtime/Power

Significance to disfavor $|\cos\delta| = 1$ at $\cos\delta = 0$

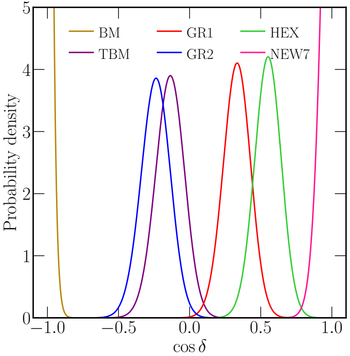


Improvement requires **both** experiments!

The Importance of $\cos\delta$

- If only $\sin\delta$ is measured $\Rightarrow$ sign degeneracy: $\cos\delta = \pm\sqrt{1-\sin^2\delta}$
- Most flavor models predict $\cos\delta$

J. Gehrlein, et al. 2203.06219



L. Everett, et al. 1912.10139

δ: What is it Really?