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

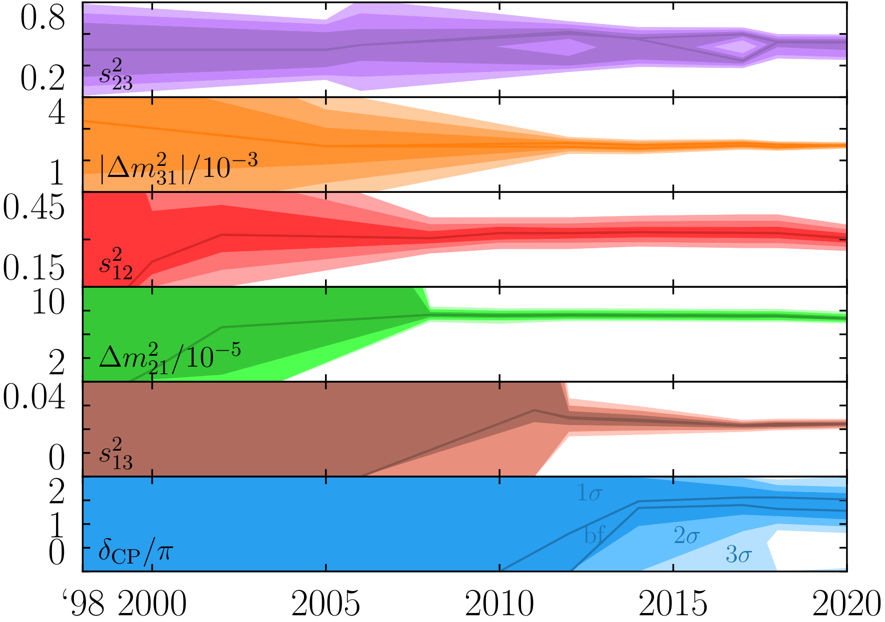
DUNE LBL WG

March 4, 2024

Brookhaven National Laboratory

Brookhaven NDI
Neutrino Discovery Initiative

Speaking from Setauket land


0.8
0.2
s^2_{23}
4
1
$|\Delta m^2_{31}|/10^{-3}$
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_{CP}/π
1σ
bf
2σ
3σ
'98 2000
2005
2010
2015
2020

Four known unknown in particle physics: all neutrinos

Atmospheric mass ordering

θ_{23} octant

Complex phase

Absolute mass scale

Four known unknown in particle physics: all neutrinos

Atmospheric mass ordering

θ_{23} octant

Complex phase

Absolute mass scale

Outline

1. Why CPV is interesting
2. Relationship between appearance, disappearance, CP, T, CPT
3. Three ways to see why there is CPV information in disappearance
   - 3.1 Degrees of freedom
   - 3.2 Direct analytic calculation
   - 3.3 Numerical test
4. Recommendation

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

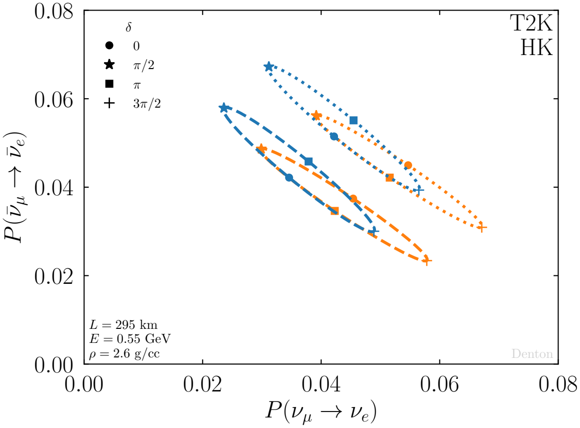
3. Lepton mass matrix: **?**

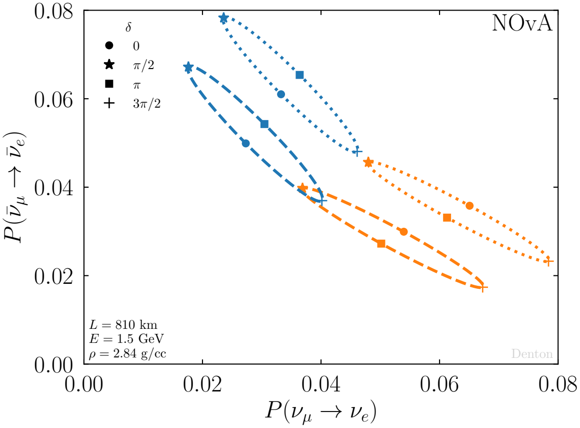
$$\frac{|J_{\rm PMNS}|}{J_{\rm max}} < 0.34$$

PBD, J. Gehrlein, R. Pestes 2008.01110

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

δ: what is it really?





δ: what is it not?

$$\delta \not\Rightarrow \text{Baryogenesis}$$

The amount of leptogenesis is a function of:

1. the heavy mass scale
2. δ
3. α, β (Majorana phases)
4. CP phases in the RH neutrinos
5. …

C. Hagedorn, et al. 1711.02866

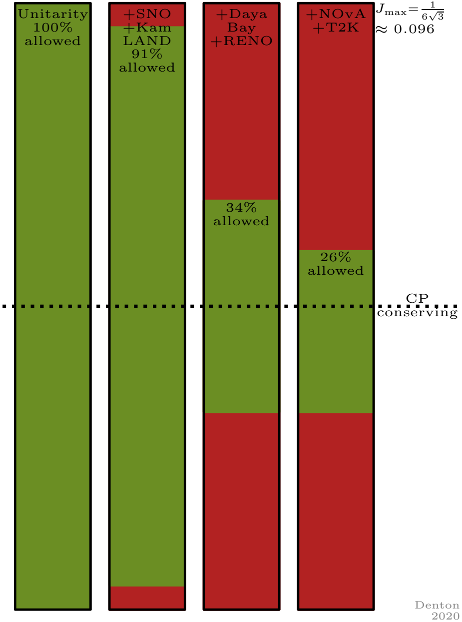
K. Moffat, et al. 1809.08251

$$\begin{array}{lcl} \text{Measuring } \delta = 0, \pi & \not\Rightarrow & \text{no leptogenesis} \\ \text{Measuring } \delta \neq 0, \pi & \not\Rightarrow & \text{leptogenesis} \end{array}$$

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, disappearance, and CP

Appearance vs. Disappearance

Some oscillation experiments can do appearance or disappearance experiments

Disappearance

MINOS, NOνA, T2K

KamLAND, Daya Bay, RENO, Double CHOOZ

(Sort of) SNO, Borexino, SK-solar

Appearance

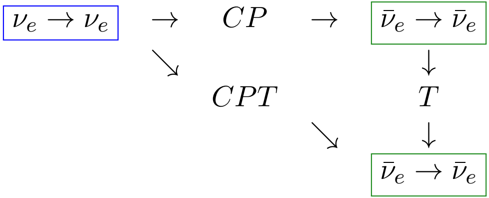
T2K, NOνA

OPERA

Neither appearance nor disappearance

SK-atm, IceCube

CP, T: Disappearance



Disappearance measurements are even eigenstates of CP

$$P(\nu_e \to \nu_e) = P(\bar{\nu}_e \to \bar{\nu}_e)$$

Assume that CPT is a good symmetry

CP, T: Appearance

$$\boxed{\nu_\mu \to \nu_e} \quad \to \quad CP \quad \to \quad \boxed{\bar\nu_\mu \to \bar\nu_e}$$

$$\searrow \; CPT \; \searrow \qquad \downarrow \; T \; \downarrow$$

$$\boxed{\bar\nu_e \to \bar\nu_\mu}$$

Appearance measurements are not eigenstates of CP

Appearance and Disappearance, CPC and CPV

Disappearance:

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

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

Appearance and Disappearance, CPC and CPV

Disappearance:

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

Appearance:

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

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

Sign depends on α, β

Conventional Wisdom

1. Appearance is sensitive to CPV [True]
2. Disappearance has no CPV sensitivity [False]
3. Any δ dependence in disappearance doesn't exist in 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)

Degrees of Freedom

1. Four DOFs in the PMNS matrix

Majorana phases are irrelevant

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   - ν_e: Daya Bay/RENO measured 1, KamLAND measured a different 1, JUNO will measure all 3
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   - Since one row can always be "simple" ($c_{12}c_{13}$, $s_{12}c_{13}$, s_{13}) no one row is ever enough
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   - 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 $\cos\delta \neq +1, -1 \quad \Rightarrow \quad$ CP is violated!

Direct Analytic Calculation

Disappearance experiments measure various $|U_{\alpha i}|^2$ terms

Suppose 4 are measured: $|U_{e2}|^2$, $|U_{e3}|^2$, $|U_{\mu 2}|^2$, $|U_{\mu 3}|^2$

Actually this gives all 9 magnitudes by unitarity

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Actually this gives all 9 magnitudes by unitarity

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

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

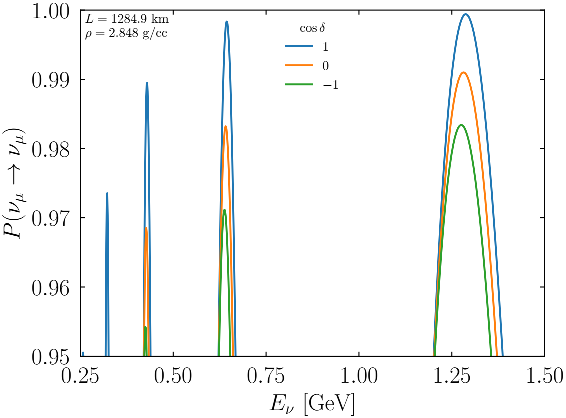
Numerical Studies

Inputs are *only*:

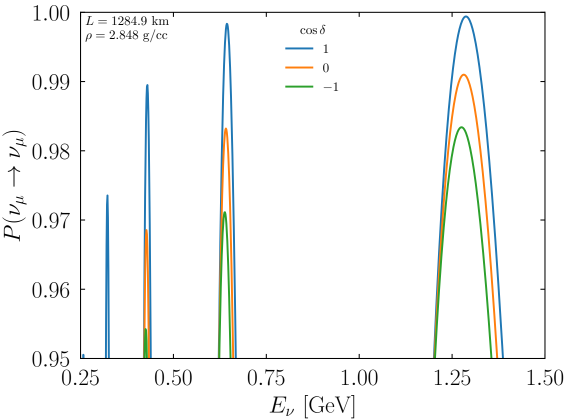
- Daya Bay for θ_{13} 1809.02261
- JUNO 6 yrs precision on θ_{12}, Δm^2_{21}, Δm^2_{31} 2204.13249
- DUNE 6.5+6.5 yrs disappearance channels only 2103.04797

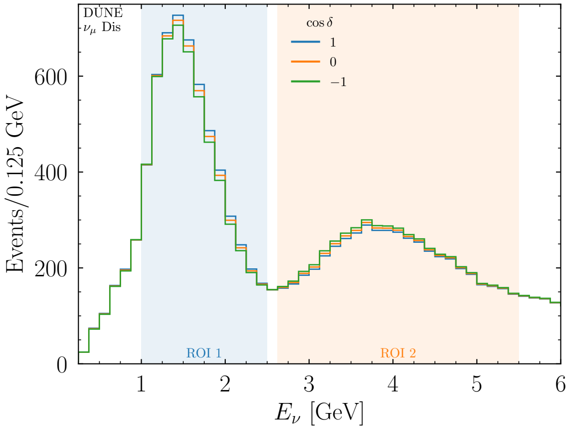
Also looked at varying JUNO's and DUNE's runtime, and at HK

Where is $|U_{\mu2}|^2$?



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

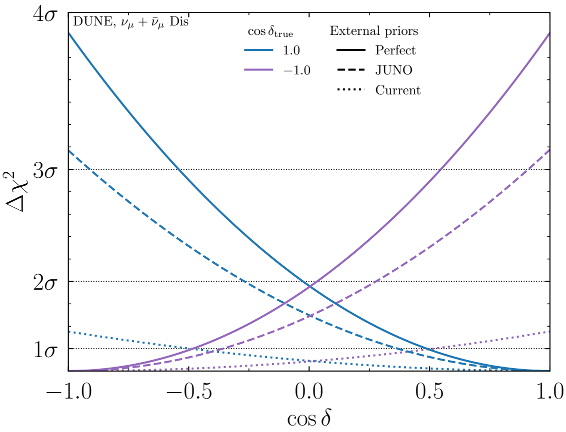


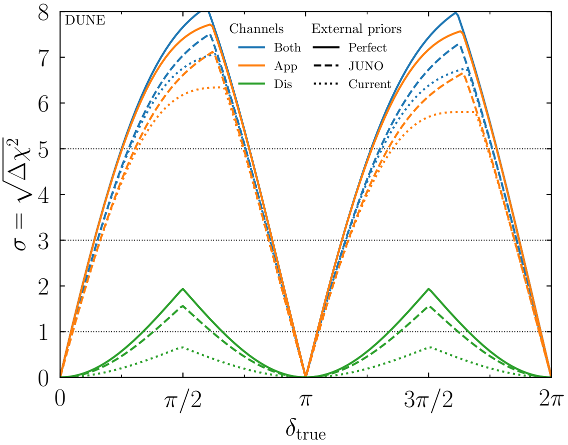


6.5 yrs ν_μ rates

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

Final Sensitivities



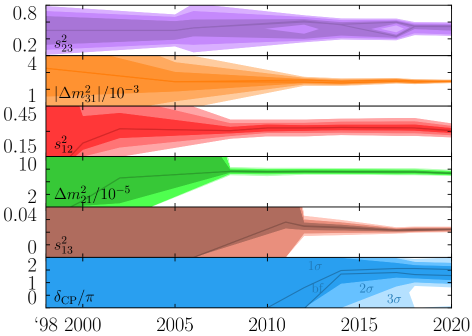


Discussion

- **Disappearance can discover CPV**
- Requires two good measurements: JUNO and DUNE/HK
- Can rule out some values of δ at $> 3\sigma$
- Analyses already exist but…
- **LBL Experiments should break down δ analyses into app vs. dis**
- Since systematics are different, provides a good cross check
- Subject to BSM degeneracies, as are most other oscillation measurements
- Works in vacuum or matter; matter slightly minimizes HK's effect

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

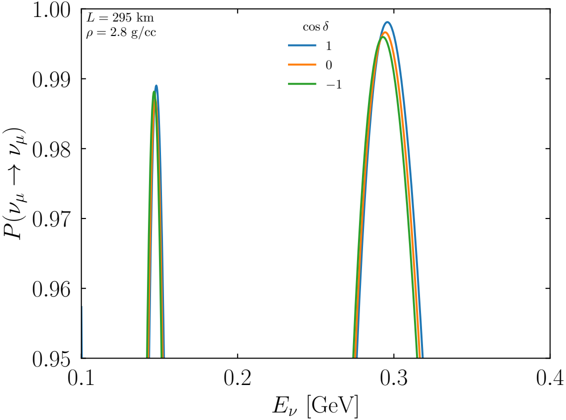
D. Forero, M. Tortola, J. Valle 1205.4018

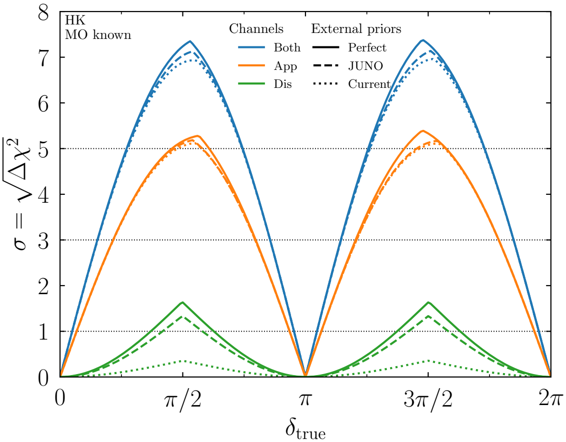
D. Forero, M. Tortola, J. Valle 1405.7540

P. de Salas, et al. 1708.01186

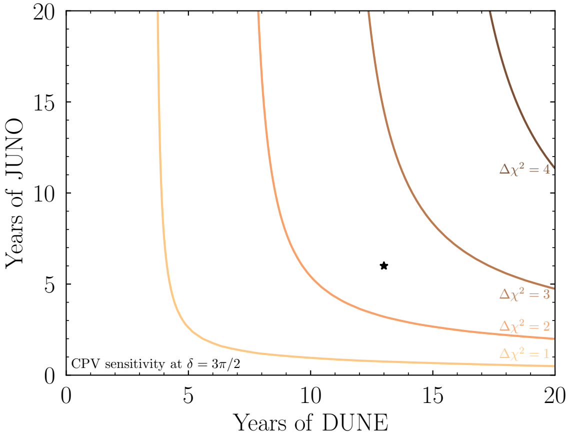
F. Capozzi et al. 2003.08511

CPV Sensitivity at HK





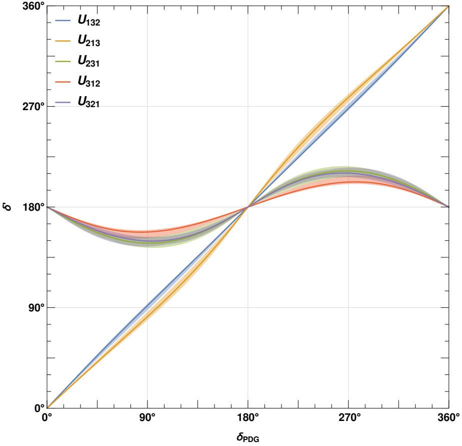
Varying Runtime/Power



Complex phase in different parameterizations

- Can relate the complex phase in one parameterization to that in another
- U_{132} and U_{213} similar to U_{123}
- δ constrained to $\sim [150°, 210°]$ in U_{231}, U_{312}, U_{321}
- Bands indicate 3σ uncertainty on θ_{12}, θ_{13}, θ_{23}
- "50% of possible values of δ"
  $\Rightarrow$ parameterization dependent

DUNE TDR II 2002.03005



Quark mixing

From the PDG, $V_{\rm CKM}$ in the V_{123} parameterization is

$$\theta_{12}=13.09^\circ \quad \theta_{13}=0.2068^\circ \quad \theta_{23}=2.323^\circ \quad \delta_{\rm PDG}=68.53^\circ$$

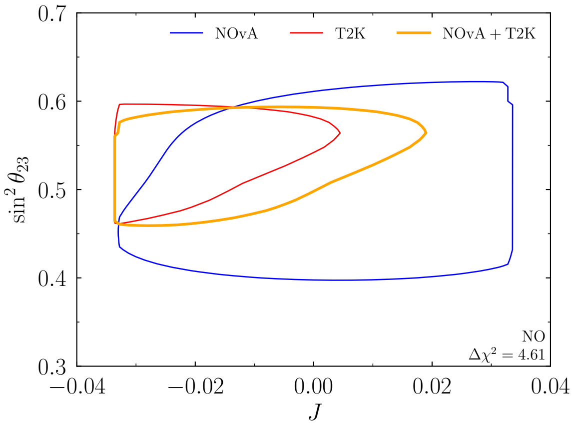
Looks like "large" CPV:

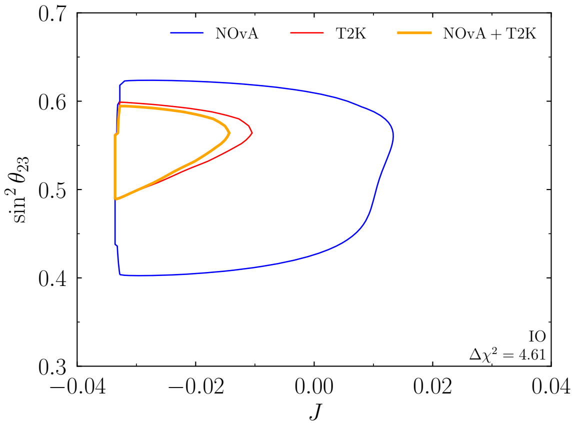
$$\sin\delta_{\rm PDG}=0.93\sim 1$$

yet $J_{\rm CKM}/J_{\rm max}=3\times 10^{-4}$.

Switch to V_{212} parameterization, $\Rightarrow \delta'=1^\circ$ and $\sin\delta'=0.02$.

Standard oscillation parameters





Can see that the combination doesn't like the NO while it does like the IO

IO preferred over NO at $\Delta\chi^2 = 2.3$

CP violation in oscillations

In vacuum at first maximum:

$$P_{\mu e} - \bar{P}_{\mu e} \approx 8\pi J \frac{\Delta m^2_{21}}{\Delta m^2_{32}}$$

$$J \equiv s_{12}c_{12}s_{13}c^2_{13}s_{23}c_{23}\sin\delta$$

C. Jarlskog PRL 55, 1039 (1985)

- Extracting δ from data requires every other oscillation parameter
- J requires only Δm^2_{21} (up to matter effects)

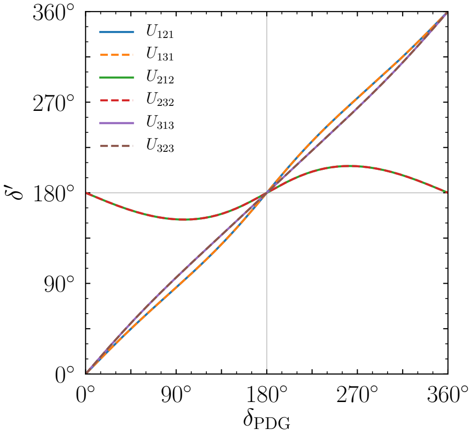
Matter effects are easily accounted for

$$\hat{J} \simeq \frac{J}{\sqrt{(c_{212} - c^2_{13}a/\Delta m^2_{21})^2 + s^2_{212}}\sqrt{(c_{213} - a/\Delta m^2_{ee})^2 + s^2_{213}}}$$

PBD, S. Parke 1902.07185

PBD, H. Minakata, S. Parke 1604.08167

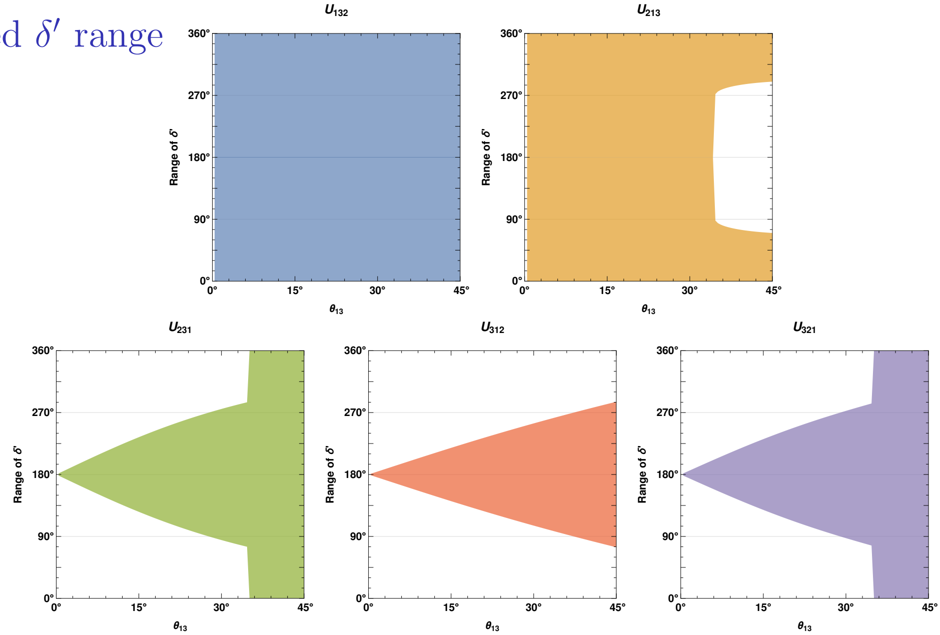
Repeated rotations



	U_{121}	U_{131}	U_{212}	U_{232}	U_{313}	U_{323}
$\lvert U_{e2}\rvert$	✓	✓	✓	✓	✗	✗
$\lvert U_{e3}\rvert$	✓	✓	✗	✗	✓	✓
$\lvert U_{\mu3}\rvert$	✗	✗	✓	✓	✓	✓

Note that $e^{i\delta}$ must be on first or third rotation

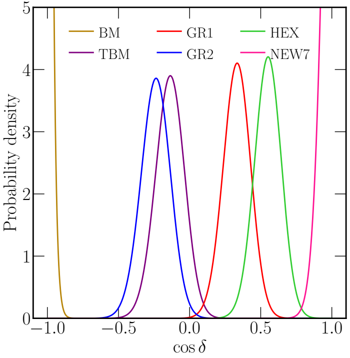
Allowed δ' range



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