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

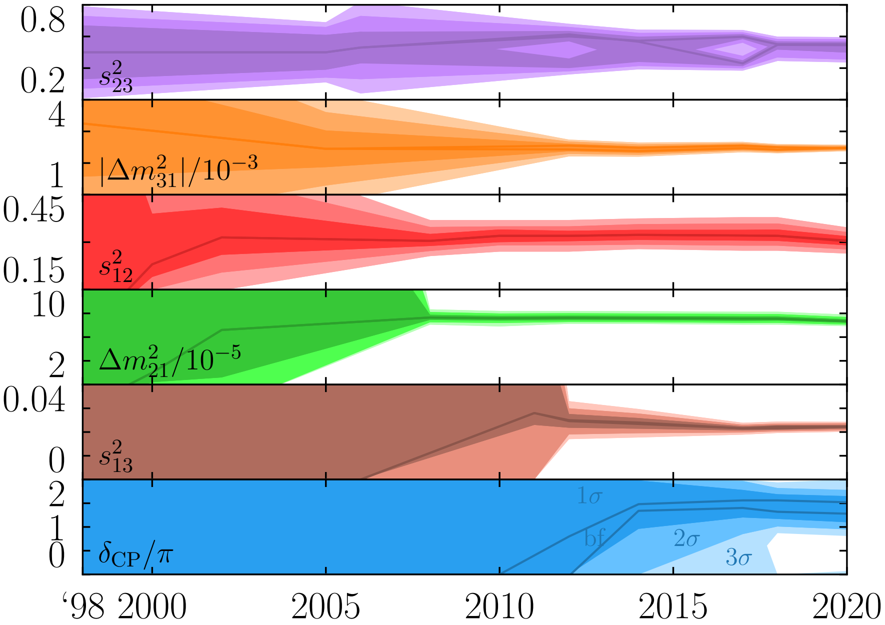
BNL HET Friday Lunch Discussion

March 15, 2024

Brookhaven National Laboratory

Brookhaven NDI
Neutrino Discovery Initiative

Speaking from Setauket land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δ_{CP}/π
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3σ
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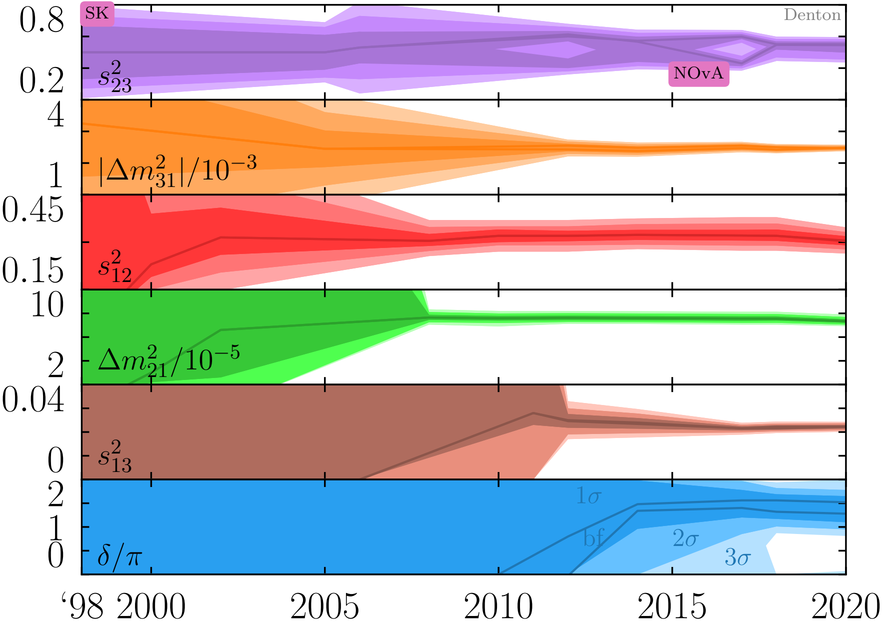
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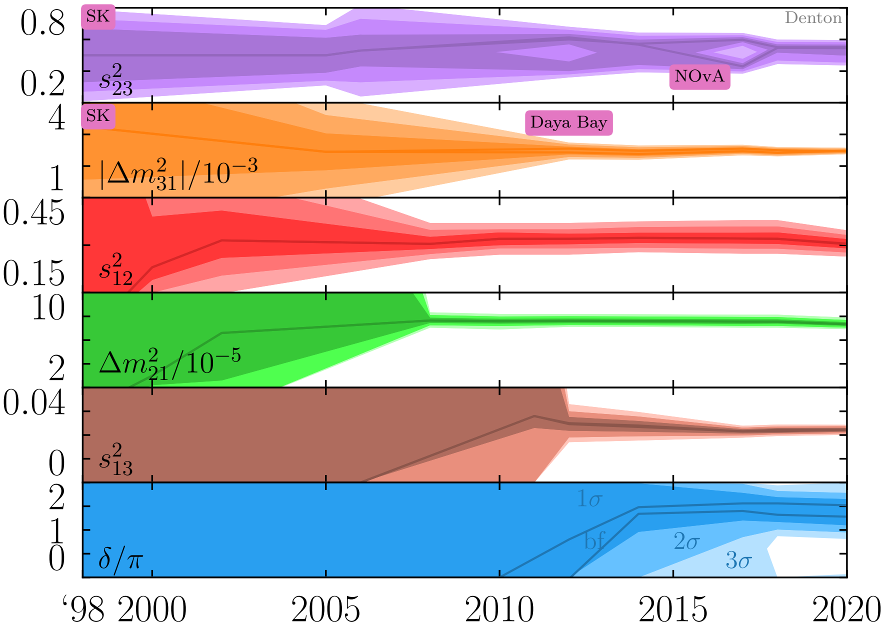
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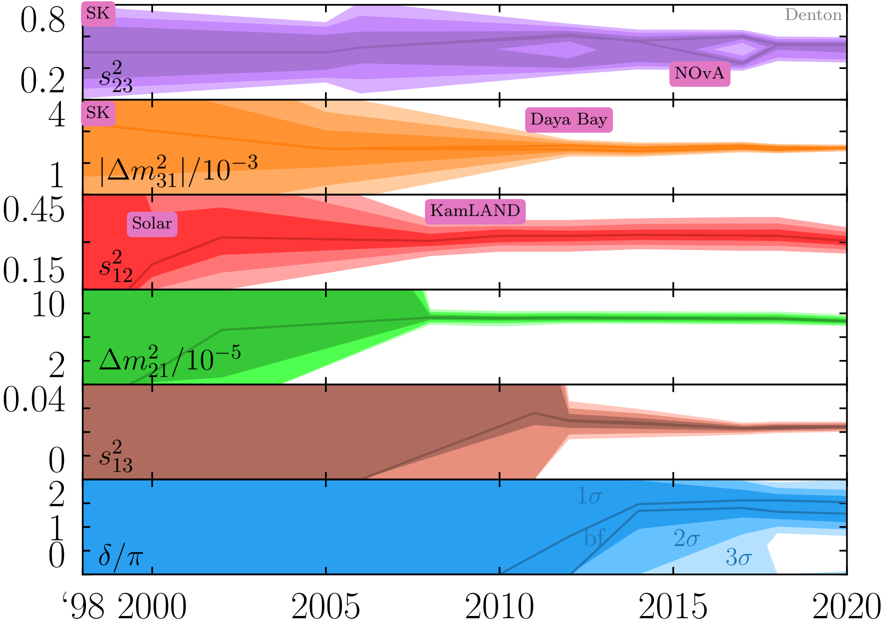
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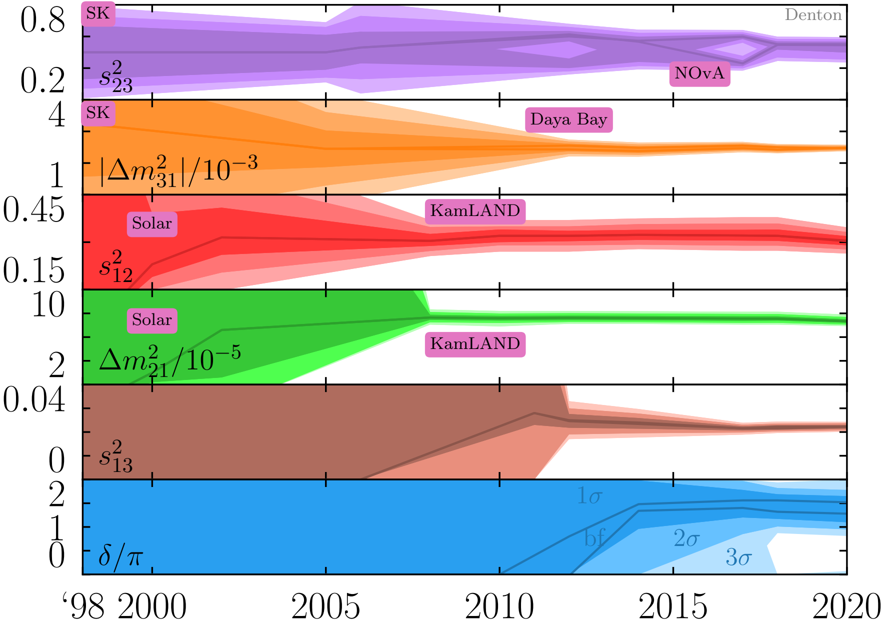
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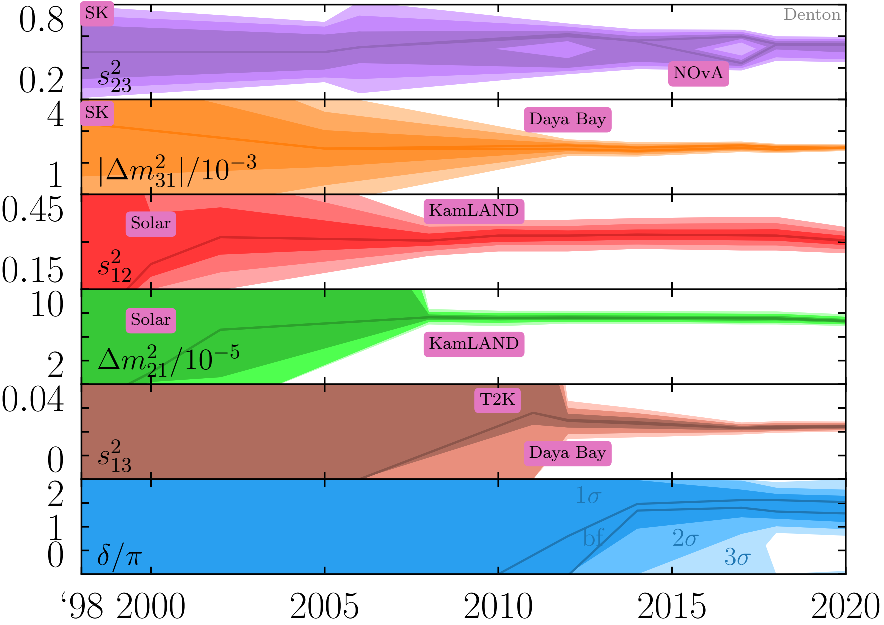
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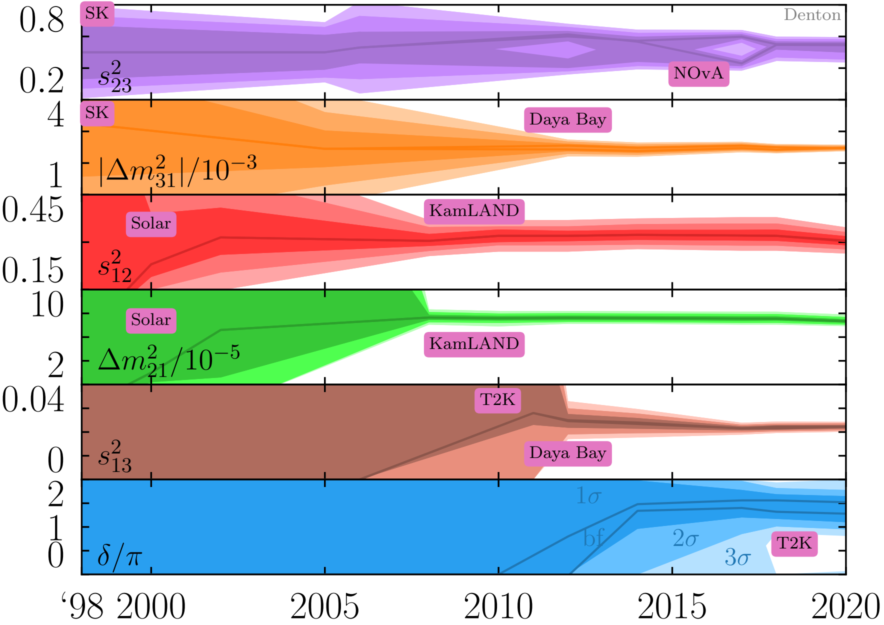

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Four known unknown in particle physics: all neutrinos

Atmospheric mass ordering

θ_{23} octant

Complex phase

Absolute mass scale

Four known unknown in particle physics: all neutrinos

Atmospheric mass ordering

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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. 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

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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

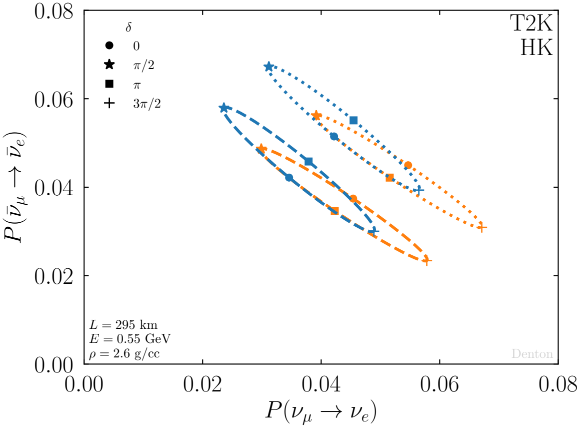
3. Lepton mass matrix: **?**

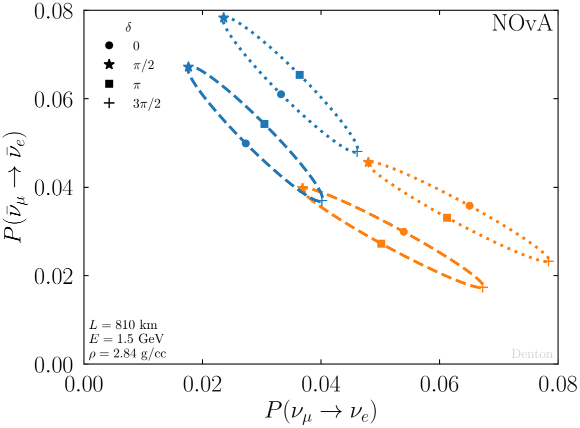
$$\frac{|J_{\rm PMNS}|}{J_{\rm max}} < 0.34$$

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

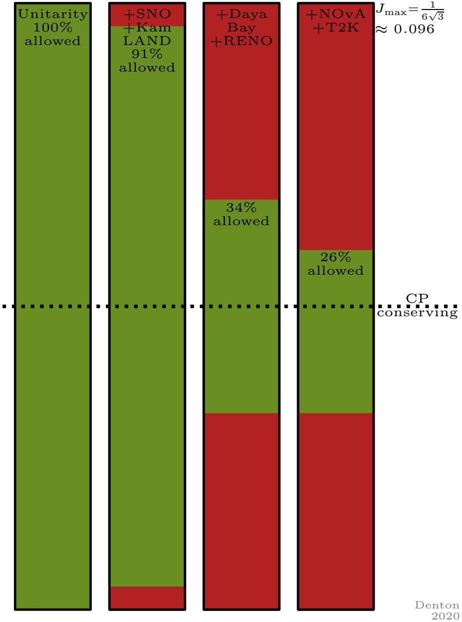
K. Moffat, et al. 1809.08251

$$\text{Measuring } \delta = 0, \pi \quad \not\Rightarrow \quad \text{no leptogenesis}$$
$$\text{Measuring } \delta \neq 0, \pi \quad \not\Rightarrow \quad \text{leptogenesis}$$

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 $\cos\delta$

Other non-standard CPV probes

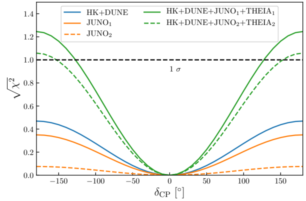
1. Some information in solar due to loops in elastic scattering

V. Brdar, X-J. Xu 2306.03160

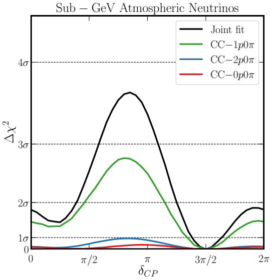
2. Sub-GeV atmospherics

K. Kelly, et al. 1904.02751

See also e.g. A. Suliga, J. Beacom 2306.11090



Solar (no systematics): $\sim 0.5\sigma$



Atmospherics at DUNE: $< 2\sigma$

Appearance, disappearance, and CP

Appearance vs. Disappearance

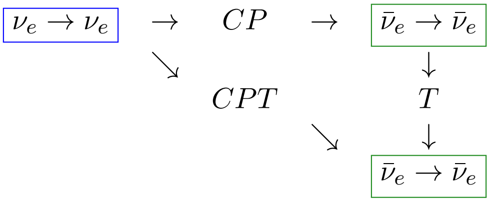
Some oscillation experiments can do appearance or disappearance experiments

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

$$CP[P(\nu_e \to \nu_e)] = P(\bar\nu_e \to \bar\nu_e) \overset{CPT}{=} P(\nu_e \to \nu_e)$$

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

Appearance and Disappearance, CP even and CP odd terms

Disappearance:

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

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

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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:

$$\begin{aligned}P(\nu_\alpha\to\nu_\beta)=&-4\Re[U_{\alpha1}U_{\beta1}^*U_{\alpha2}^*U_{\beta2}]\sin^2\Delta_{21}\\&-4\Re[U_{\alpha1}U_{\beta1}^*U_{\alpha3}^*U_{\beta3}]\sin^2\Delta_{31}\\&-4\Re[U_{\alpha3}U_{\beta3}^*U_{\alpha2}^*U_{\beta2}]\sin^2\Delta_{32}\\&\pm8J_{CP}\sin\Delta_{21}\sin\Delta_{31}\sin\Delta_{32}\\=P_{\alpha\beta}^{CP+}+P_{\alpha\beta}^{CP-}\end{aligned}$$

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

Sign depends on α,β

Conventional Wisdom

1. Appearance is sensitive to CPV [True]

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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

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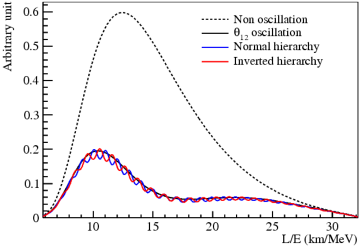
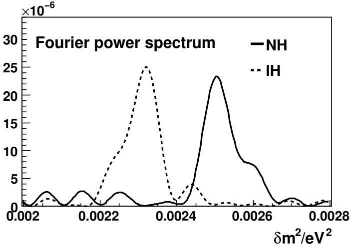


JUNO 1507.05613



L. Zhan, et al. 0807.3203

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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 $\cos\delta \neq \pm 1 \quad \Rightarrow \quad$ CP is violated!

Direct Analytic Calculation

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

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

Actually this gives all 9 magnitudes by unitarity

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

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

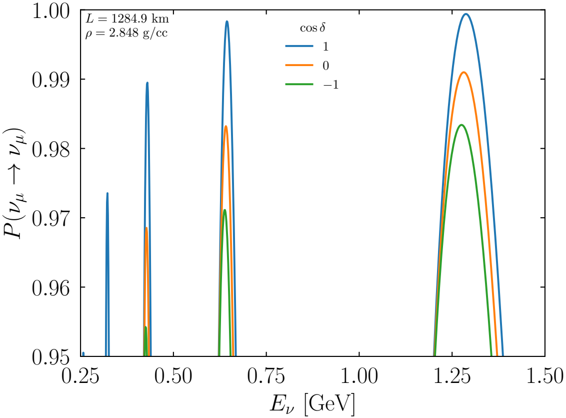
Numerical Studies

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



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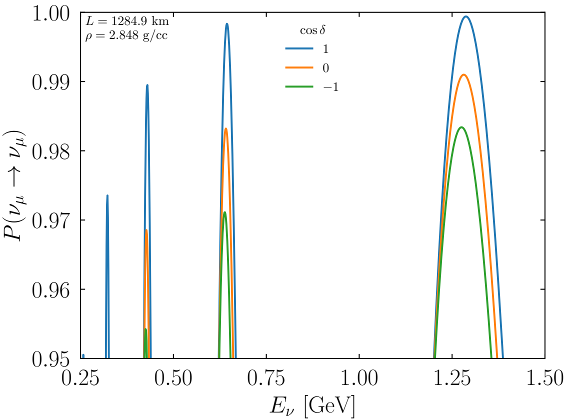
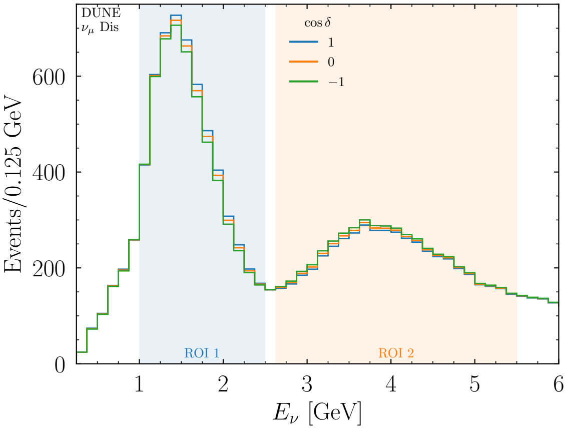
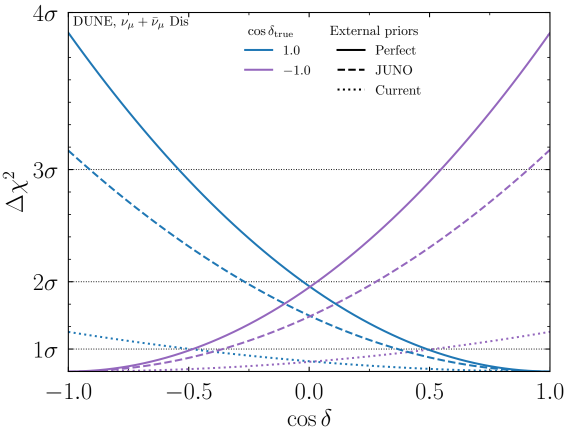


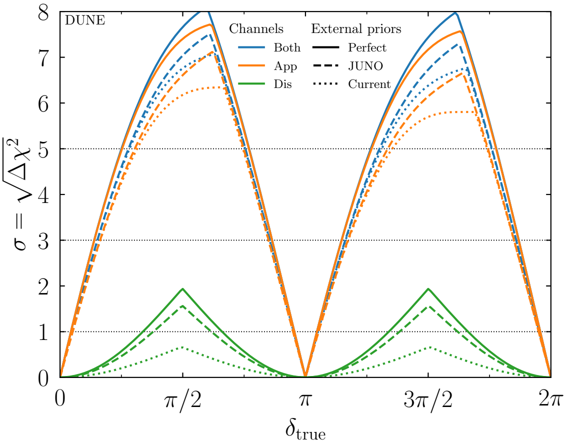


6.5 yrs ν_μ rates

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

Final Sensitivities





Approximate size of $|U_{\mu2}|^2$ signal

- There is no δ information in $|U_{\mu1}|^2 + |U_{\mu2}|^2$

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

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- This term is

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

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

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

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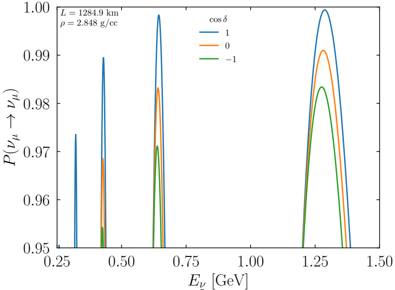
$$\approx -2 \quad (0.21 \quad + \quad 0.03\cos\delta)\left(\frac{\pi}{33}\right)^2$$

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

- 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



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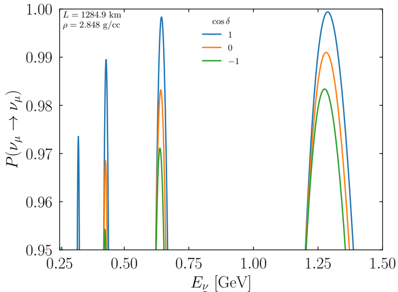
$$\approx -4c_{23}^2\left(s_{12}^2c_{12}^2 + s_{23}c_{23}s_{13}\sin 2\theta_{12}\cos 2\theta_{12}\cos\delta\right)\sin^2\Delta_{21}$$

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

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

- 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



- 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

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

- This term is

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

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

- So the probability is large for $\cos\delta = -1$? — Sign is wrong
- So the effect is $\sim -0.0005\cos\delta$? — Magnitude is ~ 15 too small

Matter effects matter

- Let's start again at

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

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- Solar splitting modified by

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

$$\mathcal{S}_\odot \approx \sqrt{(\cos 2\theta_{12}-c_{13}^2 a/\Delta m_{21}^2)^2+\sin^2 2\theta_{12}} \approx 3.6$$

at $E = 1.3$ GeV

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$$\sin 2\theta_{12}\cos 2\theta_{12} = 0.37 \to -0.25$$

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Matter effects matter

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- So the sign is swapped

$$\sin 2\theta_{12}\cos 2\theta_{12} = 0.37 \to -0.25$$

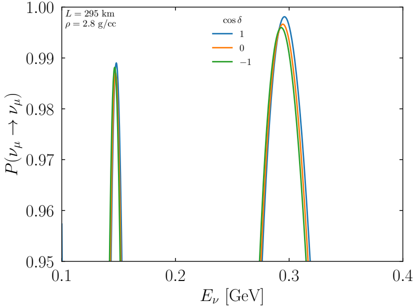
- Also s_{13} increases in matter $\sim 15\%$
- This gets us most of the effect, and the correct sign

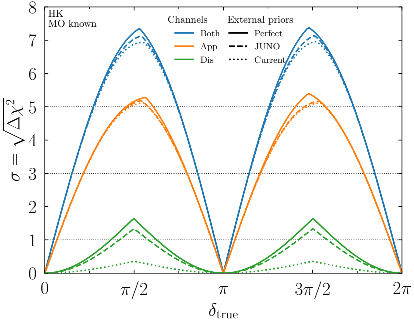
Matter effects at HK

- At HK $\mathcal{S}_\odot = 1.04$, so no enhancement in Δ_{21}

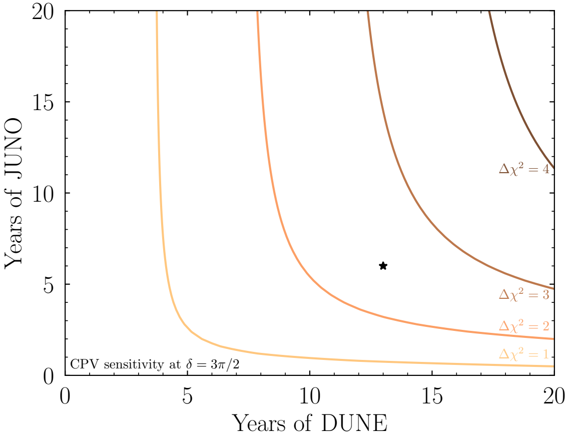
$E = 0.3$ GeV

- Slight enhancement in the θ_{12} impact relative to DUNE: $0.37 \to -0.42$ instead of -0.25
- Slight decrease in the θ_{13} impact relative to DUNE: $0.141 \to 0.145$ instead of 0.16





Varying Runtime/Power

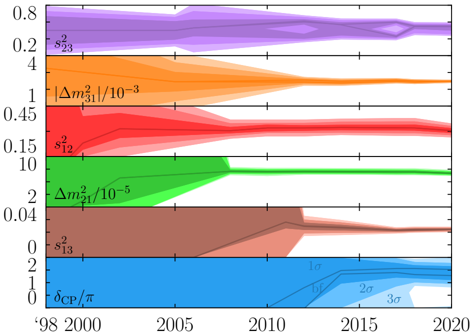


Discussion

- **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

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

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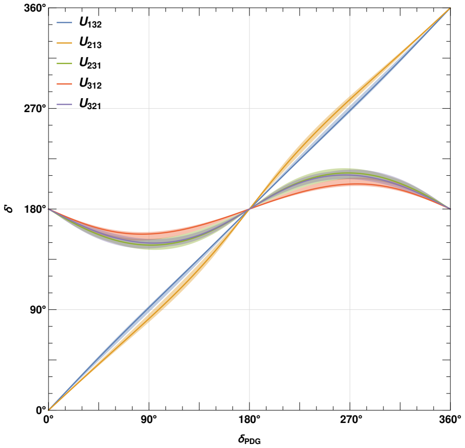
P. de Salas, et al. 1708.01186

F. Capozzi et al. 2003.08511

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

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

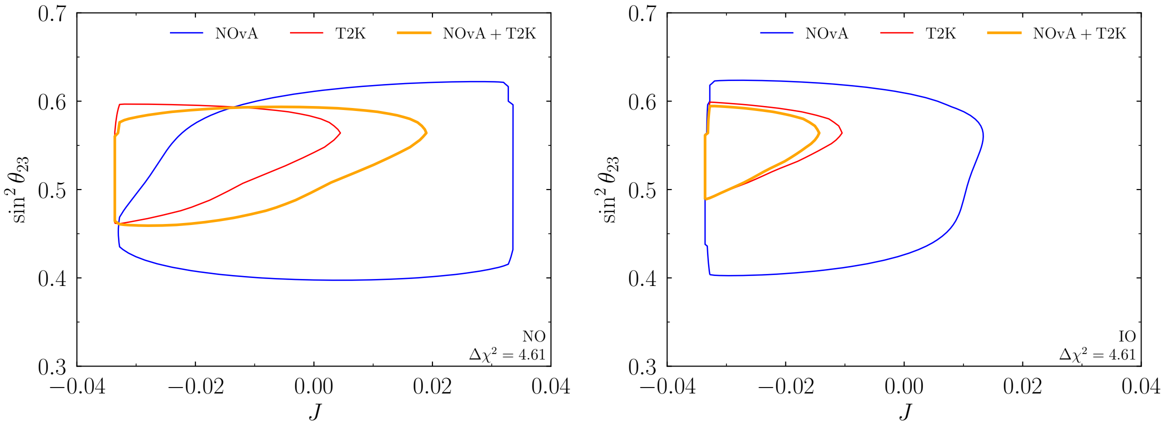
Looks like "large" CPV:

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

yet $J_{\rm CKM}/J_{\max}=3\times10^{-4}$.

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)

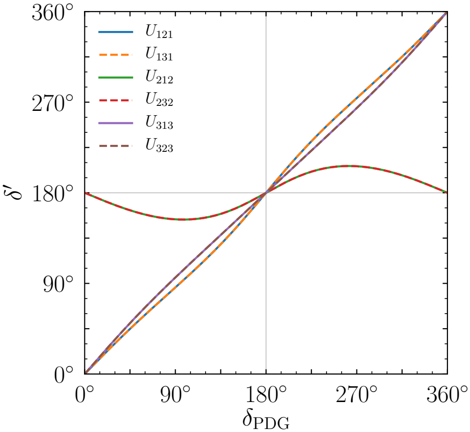
Matter effects are easily accounted for

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

PBD, S. Parke 1902.07185

PBD, H. Minakata, S. Parke 1604.08167

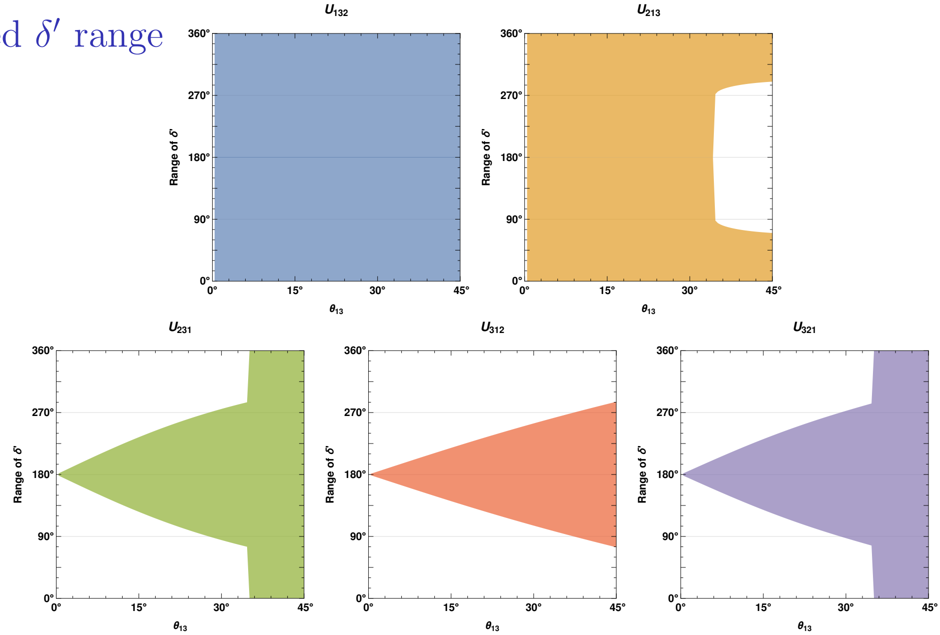
Repeated rotations



	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

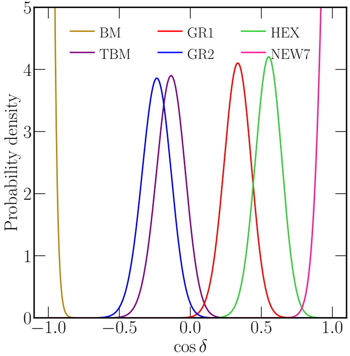
Allowed δ' range



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