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

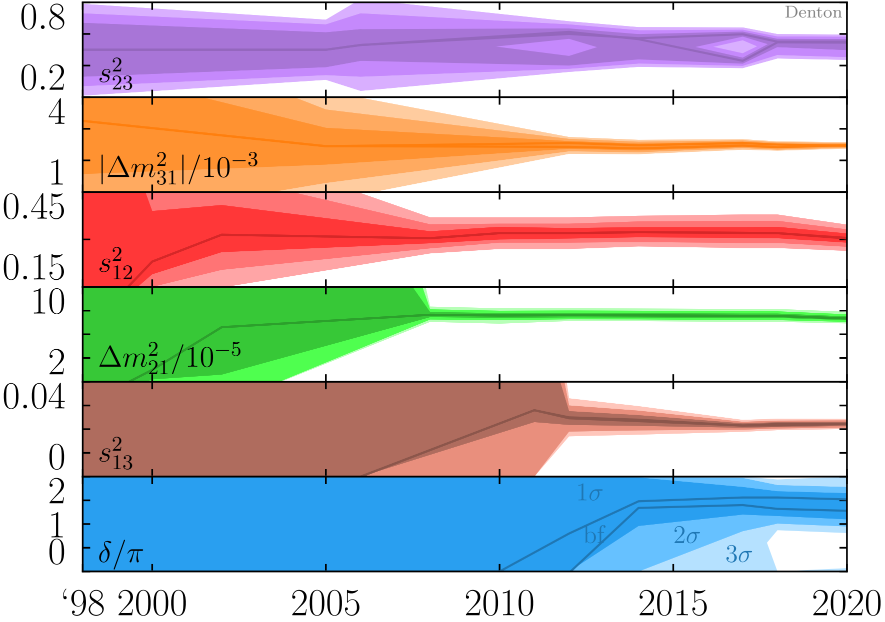
University of Virginia

May 8, 2024

2309.03262

Brookhaven National Laboratory

Brookhaven NDI Neutrino Discovery Initiative


Denton
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}
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δ/π
1σ
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2σ
3σ
'98
2000
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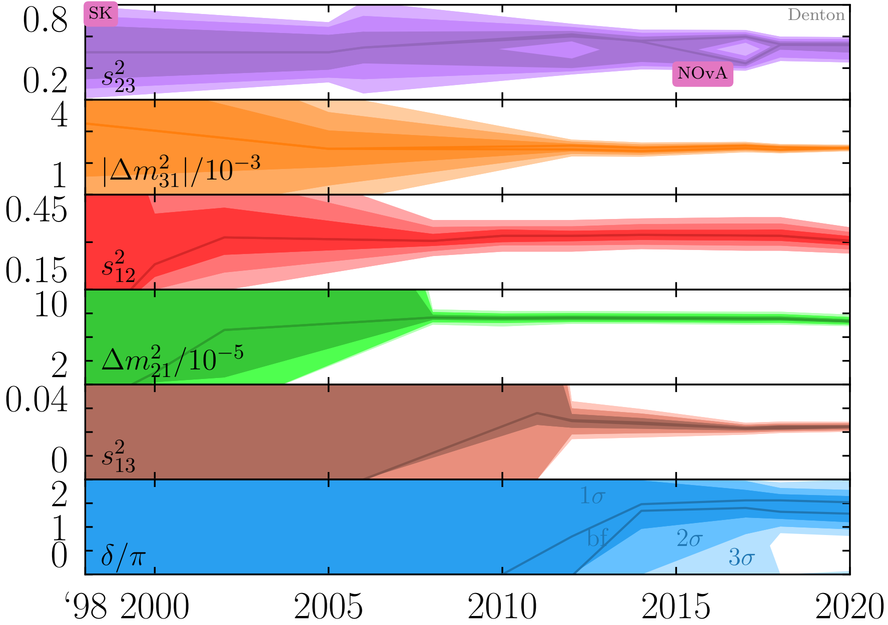
2020



SK
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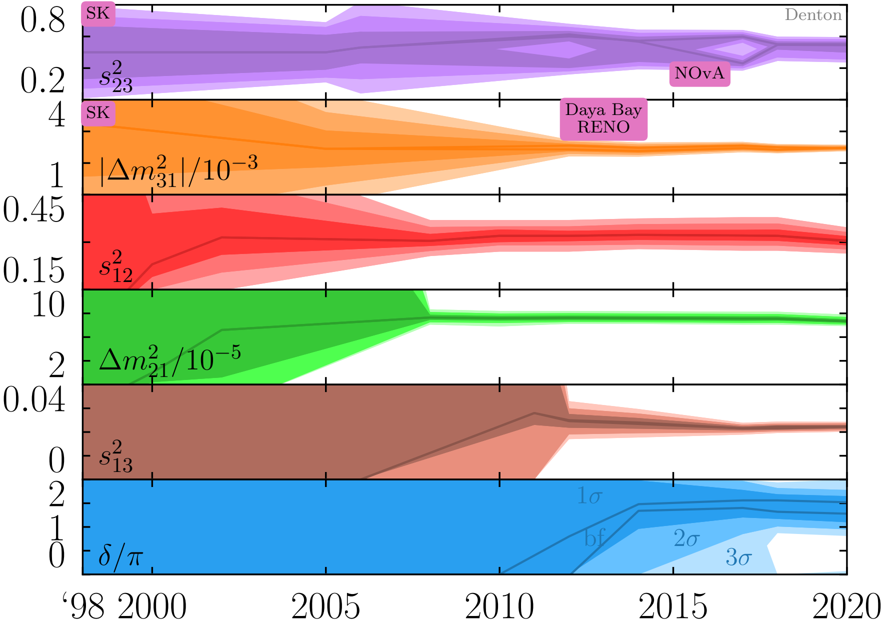

Denton
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Daya Bay RENO
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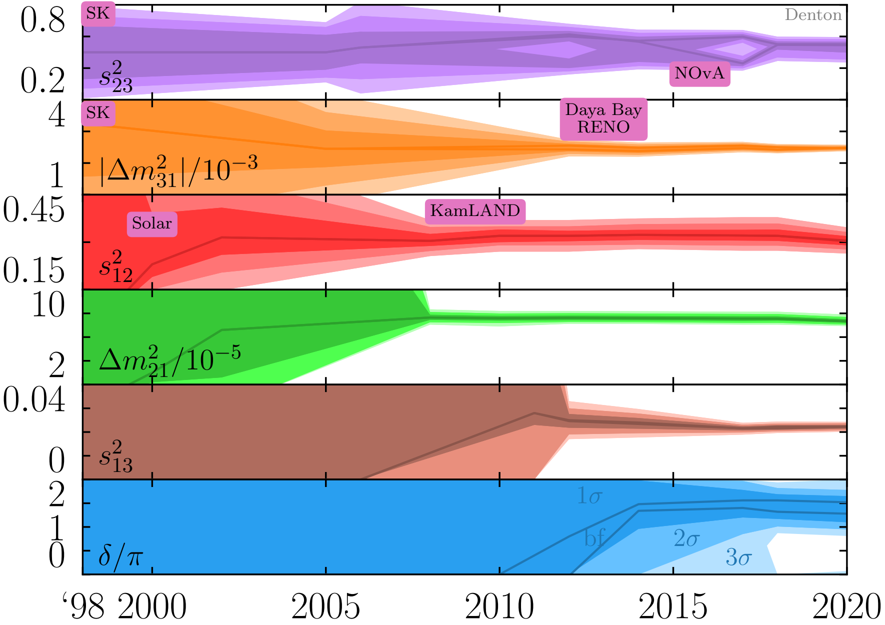

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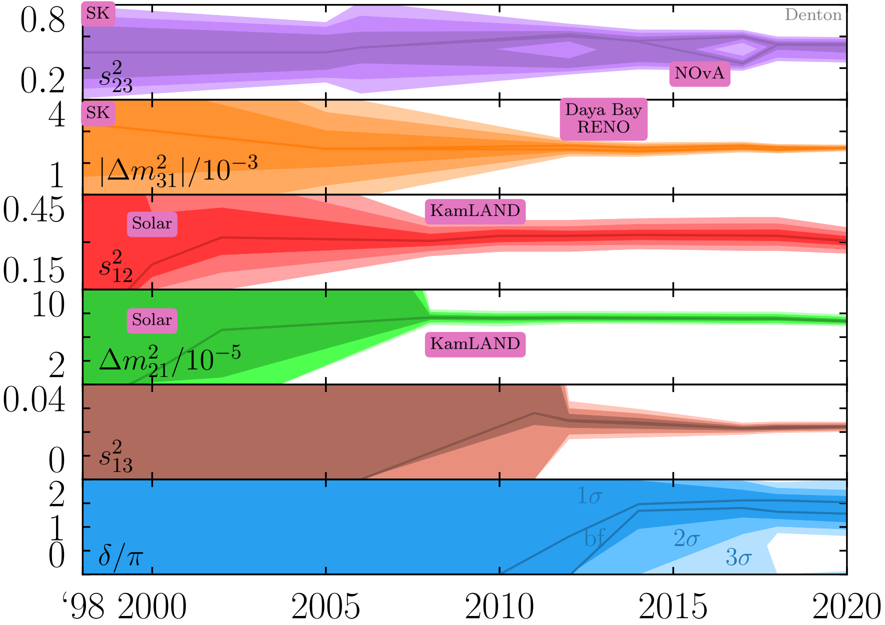

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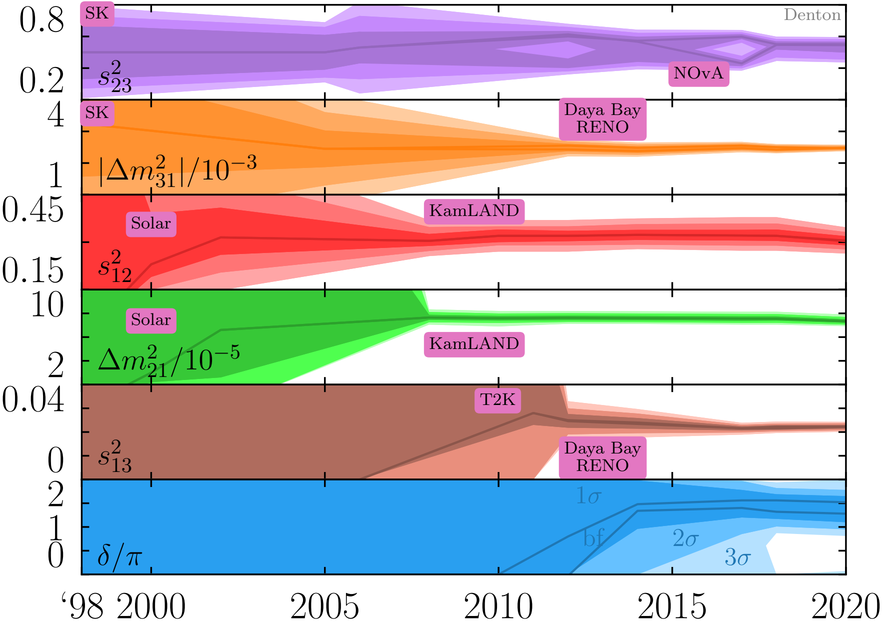

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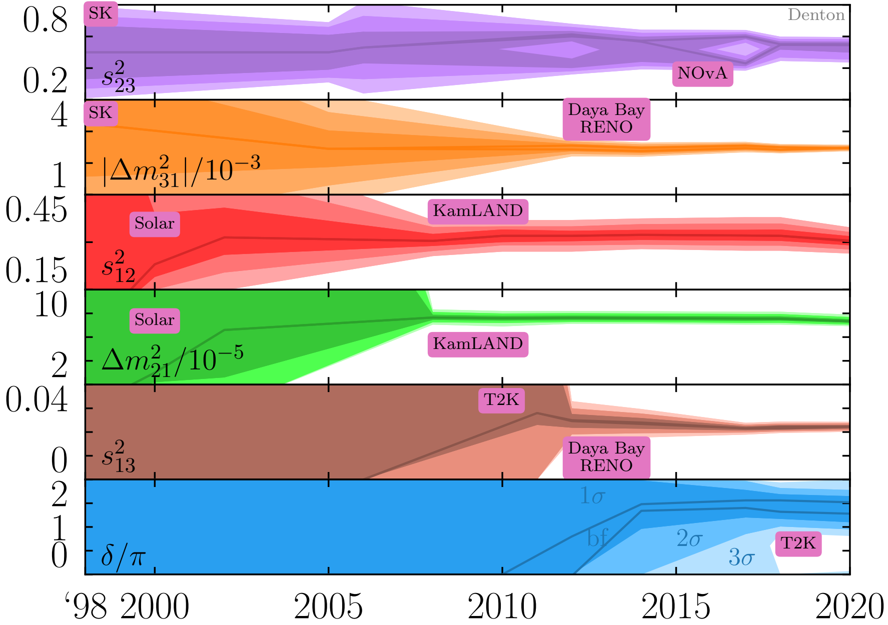

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Four known unknown in particle physics: all neutrinos

Atmospheric mass ordering

θ_{23} octant

Complex phase

Absolute mass scale

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Atmospheric mass ordering

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Absolute mass scale

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
7. New paper and code out last week! `NuFast`
8. 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

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

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

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

CKMfitter 1501.05013

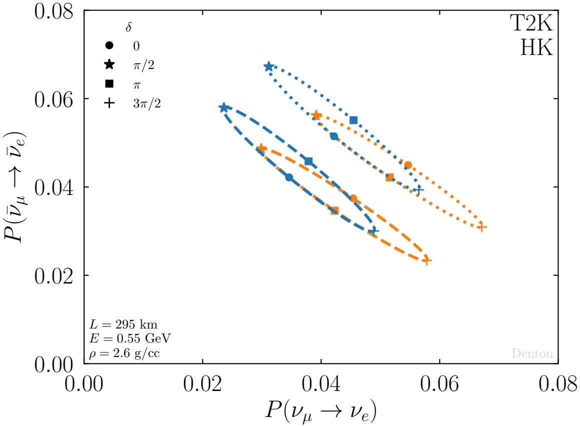
3. Lepton mass matrix: **?**

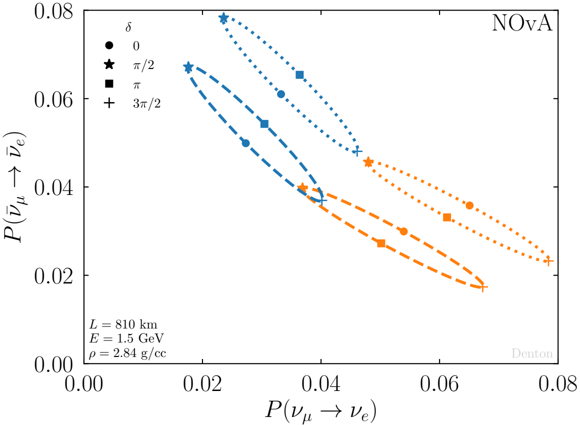
$$\frac{|J_{\rm PMNS}|}{J_{\max}} < 0.34$$

PBD, J. Gehrlein, R. Pestes 2008.01110

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

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

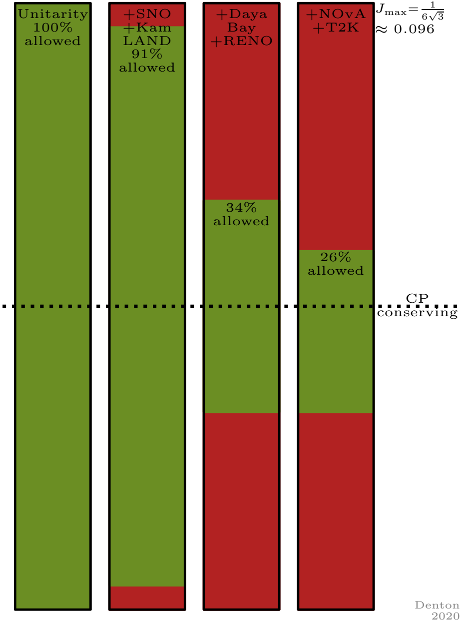
K. Moffat, et al. 1809.08251

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

δ, J: current status

Maximal CP violation is already ruled out:

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

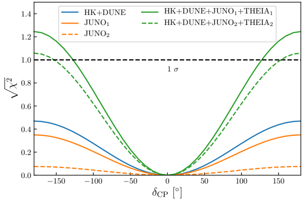
1. Some information in solar due to loops in elastic scattering

V. Brdar, X-J. Xu 2306.03160

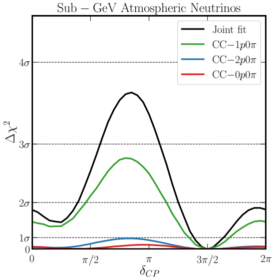
2. Sub-GeV atmospherics

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

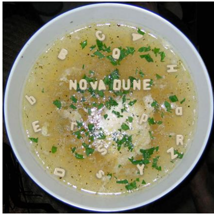
Appearance vs. Disappearance

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

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

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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Appearance:

$$\begin{aligned}P(\nu_\alpha \to \nu_\beta) = &- 4\Re[U_{\alpha 1}U_{\beta 1}^*U_{\alpha 2}^*U_{\beta 2}] \sin^2 \Delta_{21}\\ &- 4\Re[U_{\alpha 1}U_{\beta 1}^*U_{\alpha 3}^*U_{\beta 3}] \sin^2 \Delta_{31}\\ &- 4\Re[U_{\alpha 3}U_{\beta 3}^*U_{\alpha 2}^*U_{\beta 2}] \sin^2 \Delta_{32}\\ &\pm 8J_{CP} \sin \Delta_{21} \sin \Delta_{31} \sin \Delta_{32}\\ &= P_{\alpha\beta}^{CP+} + P_{\alpha\beta}^{CP-}\end{aligned}$$

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

Sign depends on α, β

Conventional Wisdom

1. Appearance is sensitive to CPV [True]

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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 in oscillations

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2. Disappearance experiments of one flavor can measure up to three amplitudes
   - Electron neutrino row:
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$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4 \sum_{i>j} C_{ij}^\alpha \sin^2 \Delta_{ij}$$

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

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

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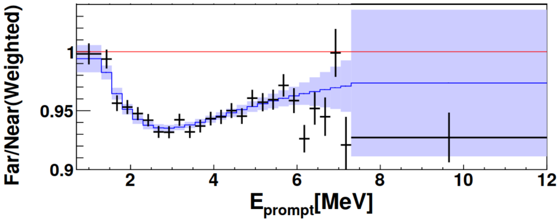

Daya Bay 1809.02261

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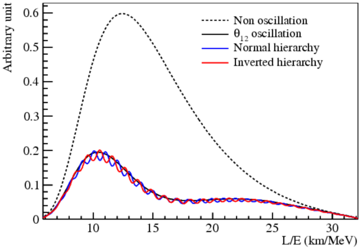
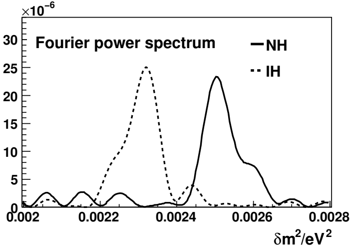


JUNO 1507.05613



L. Zhan, et al. 0807.3203

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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

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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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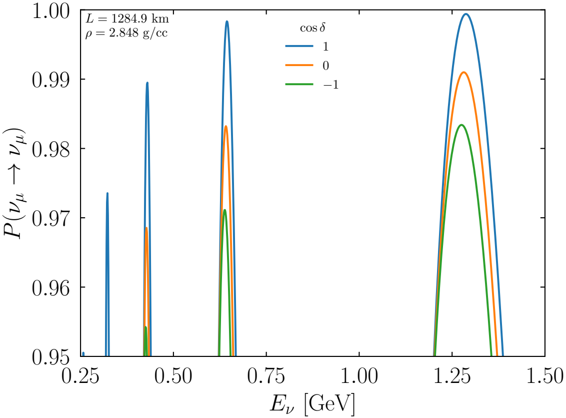
Suppose 4 are measured: $|U_{e2}|^2$, $|U_{e3}|^2$, $|U_{\mu2}|^2$, $|U_{\mu3}|^2$

Actually this gives all 9 magnitudes by unitarity

$$J_{CP}^2 = |U_{e2}|^2|U_{\mu2}|^2|U_{e3}|^2|U_{\mu3}|^2 - \frac{1}{4}\left(1 - |U_{e2}|^2 - |U_{\mu2}|^2 - |U_{e3}|^2 - |U_{\mu3}|^2 + |U_{e2}|^2|U_{\mu3}|^2 + |U_{e3}|^2|U_{\mu2}|^2\right)^2$$

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

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



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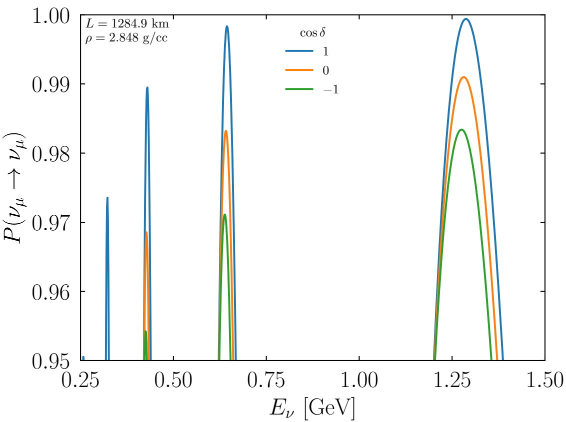

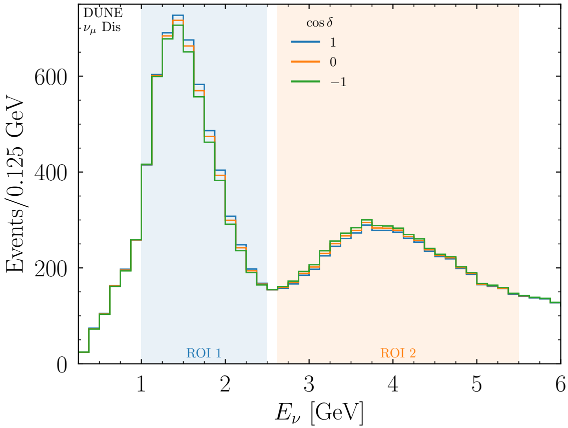

6.5 yrs ν_μ rates

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

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)

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- This comes from the Δm^2_{21} term

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

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- This term is

$$
\begin{aligned}
&\approx -4c_{23}^2 \left(s_{12}^2 c_{12}^2 + s_{23} c_{23} s_{13} \sin 2\theta_{12} \cos 2\theta_{12} \cos\delta\right) \sin^2 \Delta_{21} \\
&\approx -2 \quad (0.21 \quad + \qquad 0.03 \cos\delta) \left(\frac{\pi}{33}\right)^2
\end{aligned}
$$

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

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

- This term is

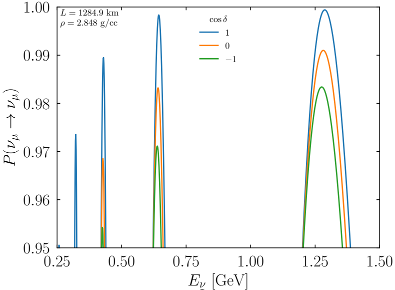
$$\approx -4c_{23}^2 \left(s_{12}^2 c_{12}^2 + s_{23} c_{23} s_{13} \sin 2\theta_{12} \cos 2\theta_{12} \cos\delta \right) \sin^2 \Delta_{21}$$

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

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

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

Approximate size of $|U_{\mu 2}|^2$ signal: (21) sector



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PBD, J. Gehrlein 2302.08513

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- There is δ information in $|U_{\mu 1}|^2 |U_{\mu 2}|^2$
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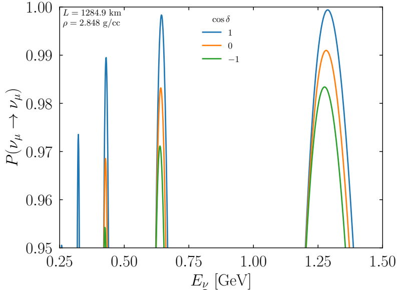

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- So the probability is large for $\cos\delta = -1$? — Sign is wrong
- So the effect is $\sim -0.0005\cos\delta$? — Magnitude is ~ 16 too small

Matter effects matter: (21) sector

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at $E = 1.3$ GeV

PBD, S. Parke 1902.07185

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$$\sin 2\theta_{12}\cos 2\theta_{12} = 0.37 \to -0.26$$

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$$\sin 2\theta_{12}\cos 2\theta_{12} = 0.37 \to -0.26$$

- 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

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H. Nunokawa, S. Parke, R. Funchal hep-ph/0503283
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\end{aligned}$$

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

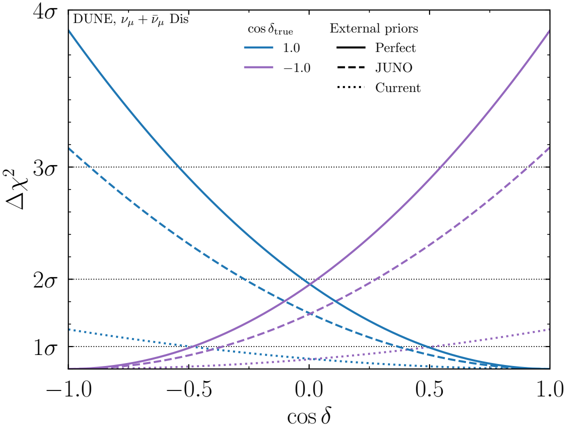
Numerical Studies

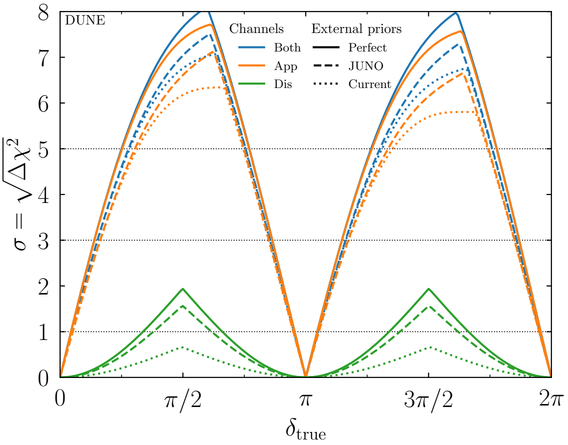
Inputs are *only*:

- 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

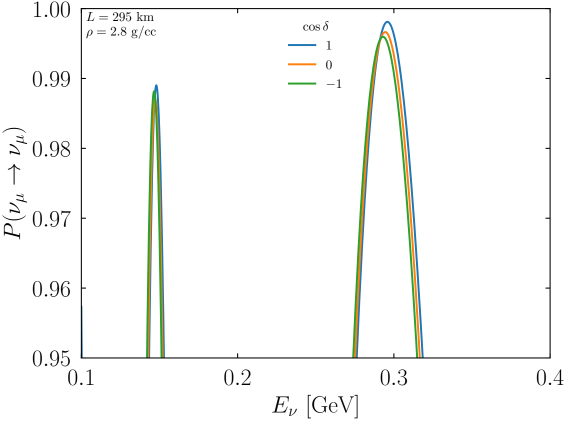
Also looked at varying JUNO's and DUNE's runtime, and at HK

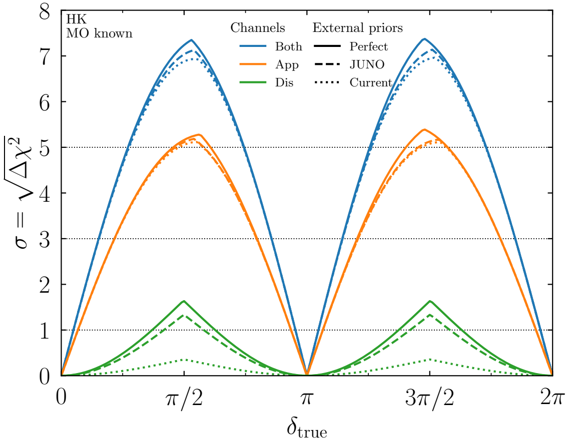
JUNO and DUNE disappearance Sensitivities





JUNO and HK disappearance Sensitivities





NuFast: Fast Neutrino Oscillation Probabilities

Quick advertisement:

- "nearly 35 million core-hours were consumed by NOvA in the 54-hour period"

  FNAL Article

- Most of the time spent was computing probabilities

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Quick advertisement:

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FNAL Article

- Most of the time spent was computing probabilities
- With S. Parke, presented a new algorithm, optimized for LBL:
  - NOvA, T2K, DUNE, HK, and JUNO
- Leverages past results

PBD, H. Minakata, S. Parke 1604.08167
PBD, S. Parke, X. Zhang 1907.02534
A. Abdulahi, S. Parke 2212.12565

- Including the Eigenvector-Eigenvalue Identity:

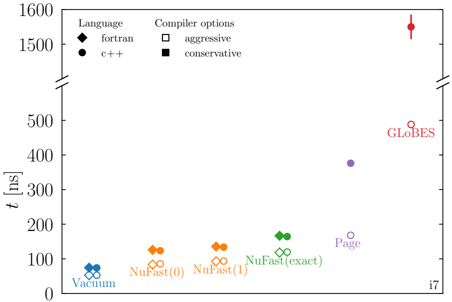
$$|\hat{U}_{\alpha i}|^2 = \frac{\prod_{j=1}^{n-1}(\lambda_i - \xi_\alpha^j)}{\prod_{j=1,j\neq i}^{n}(\lambda_i - \lambda_j)}$$

PBD, S. Parke, T. Tao, X. Zhang 1908.03795

NuFast: Fast Neutrino Oscillation Probabilities

- Code is designed to be fast:
  - c++
  - f90

```
// NuFast.cpp
// Calculate the probabilities:
Probability_Matter_LBL(s12sq, s13sq, s23sq, delta,
    Dmsq21, Dmsq31, L, E, rho, Ye, N_Newton,
    &probs_returned);
// Print out the probabilities to terminal
for (int alpha = 0; alpha < 3; alpha++)
{
    for (int beta = 0; beta < 3; beta++)
    {
        printf("%d %d %g\n", alpha, beta,
            probs_returned[alpha][beta]);
    } // beta, 3
} // alpha, 3
```



- Faster than existing in the literature
- Far more precise that HK, DUNE, or JUNO will need
- Publicly available: github.com/PeterDenton/NuFast
- Atmospherics and nighttime solar in the works!

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…

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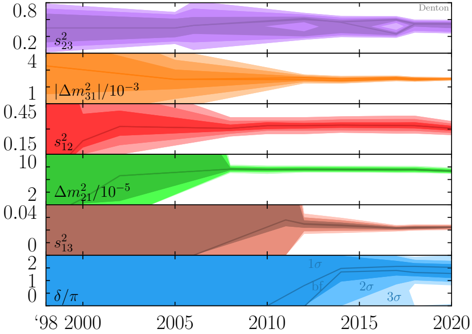
- **LBL Experiments should break down δ analyses into app vs. dis**
- Since systematics are different, provides a good cross check

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

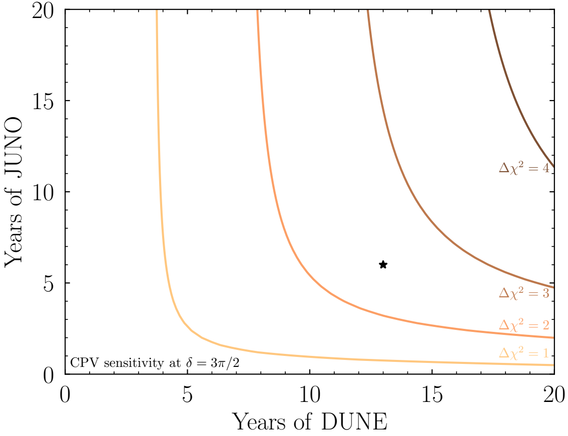
D. Forero, M. Tortola, J. Valle 1205.4018

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

P. de Salas, et al. 1708.01186

F. Capozzi et al. 2003.08511

Varying Runtime/Power

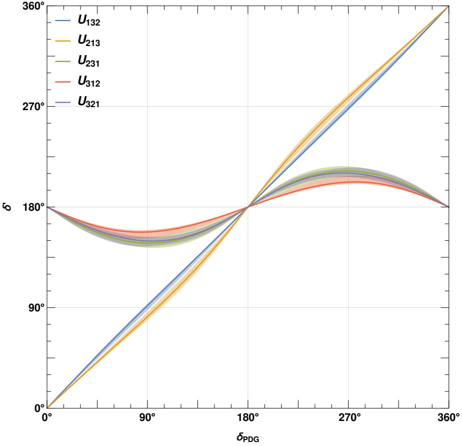


Improvement requires **both** experiments!

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_{CKM} in the V_{123} parameterization is

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

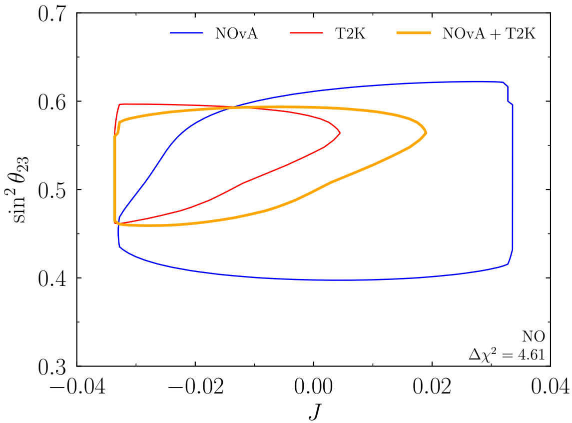
Looks like "large" CPV:

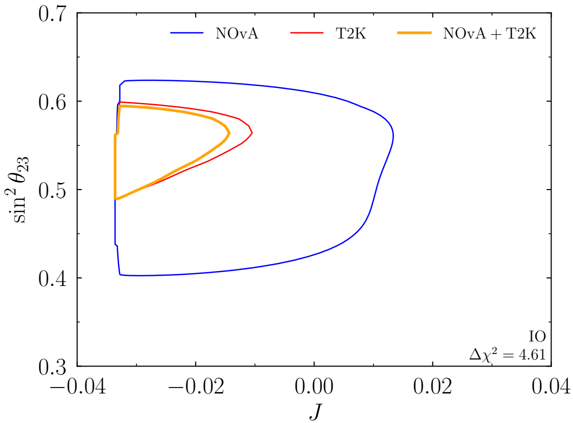
$$\sin\delta_{\mathrm{PDG}} = 0.93 \sim 1$$

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

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)

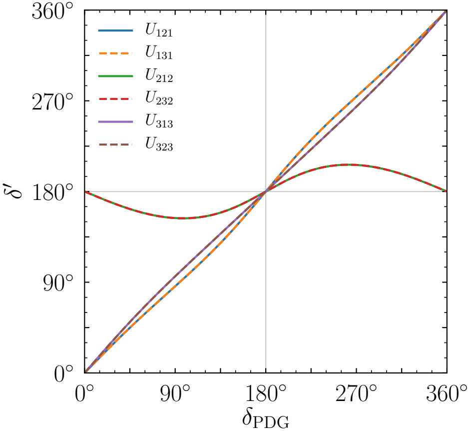
Matter effects are easily accounted for

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

PBD, S. Parke 1902.07185

PBD, H. Minakata, S. Parke 1604.08167

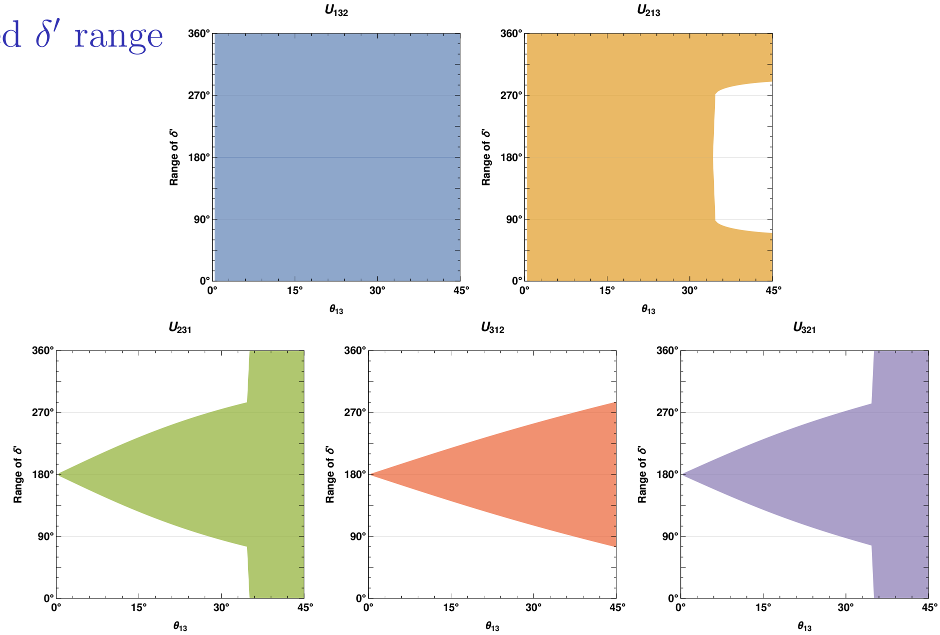
Repeated rotations



	U_{121}	U_{131}	U_{212}	U_{232}	U_{313}	U_{323}
$\lvert U_{e2}\rvert$	✓	✓	✓	✓	✗	✗
$\lvert U_{e3}\rvert$	✓	✓	✗	✗	✓	✓
$\lvert U_{\mu 3}\rvert$	✗	✗	✓	✓	✓	✓

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

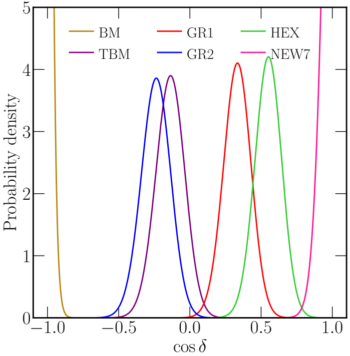
Allowed δ' range



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