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

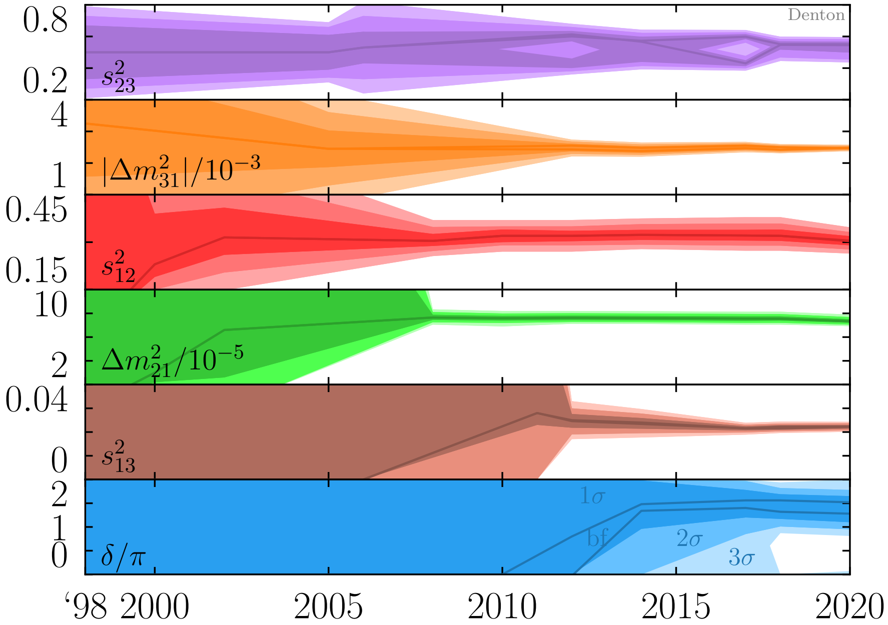
Colorado State University

March 19, 2024

Brookhaven National Laboratory

Brookhaven NDI
Neutrino Discovery Initiative

Speaking from Cheyenne land


Denton
0.8
0.2
s^2_{23}
4
1
$|\Delta m^2_{31}|/10^{-3}$
0.45
0.15
s^2_{12}
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$\Delta m^2_{21}/10^{-5}$
0.04
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δ/π
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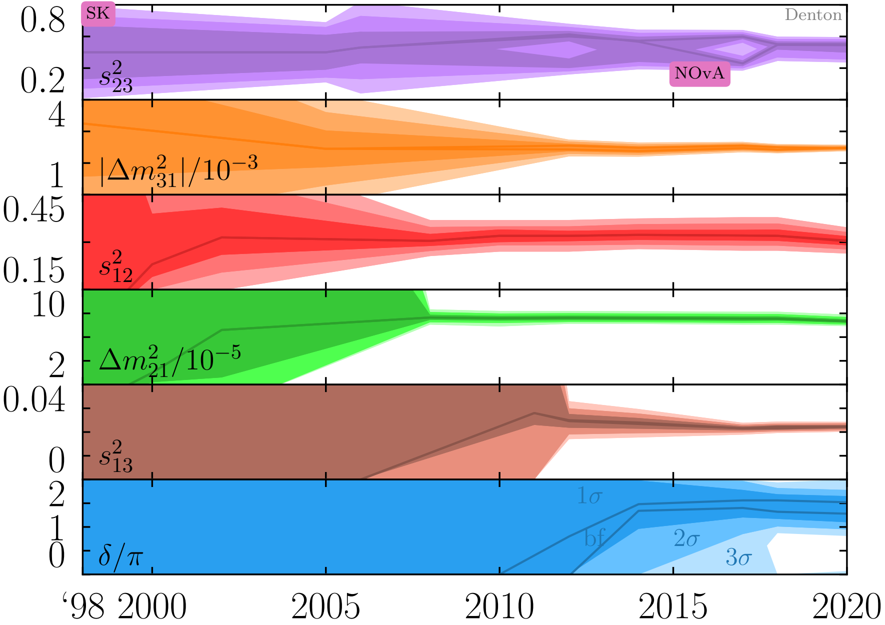
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NOvA
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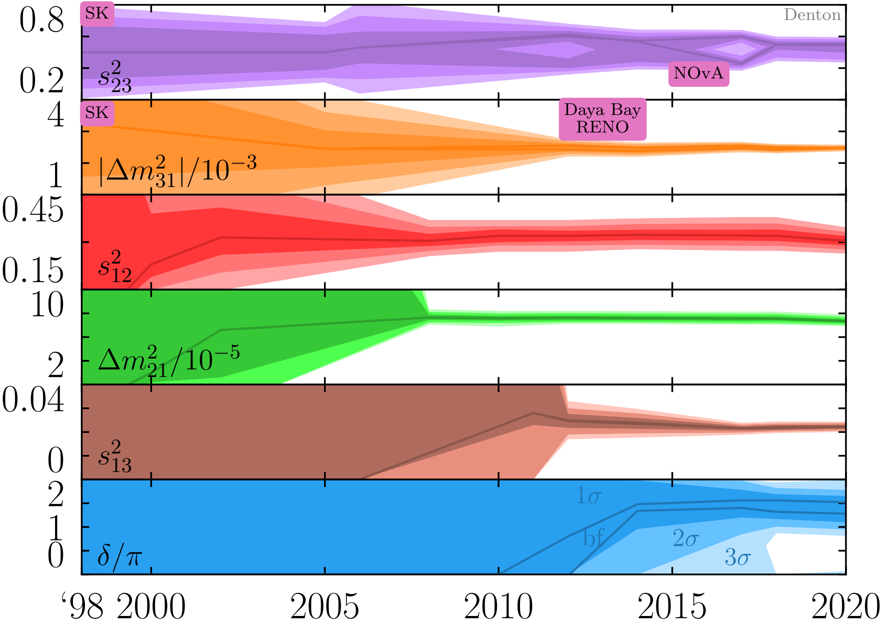

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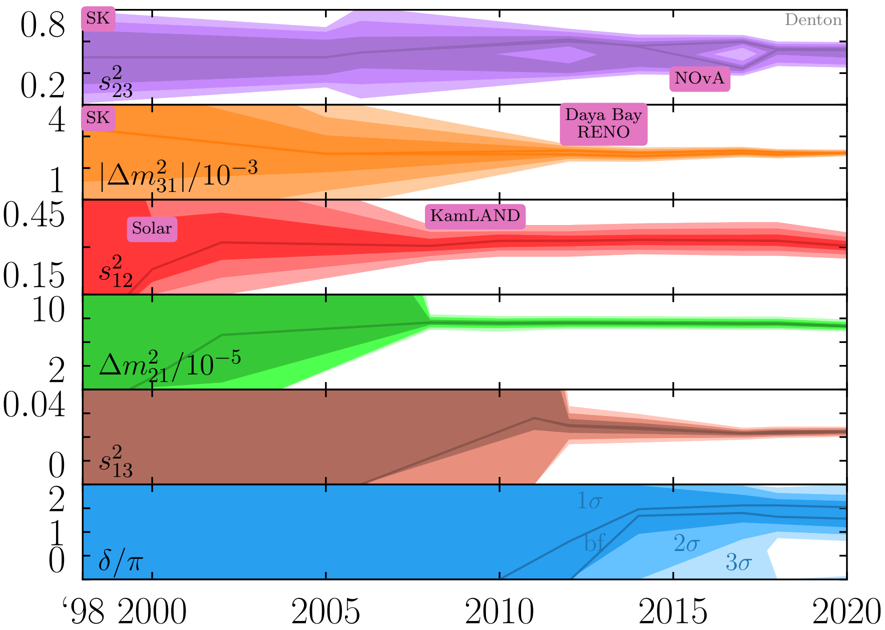
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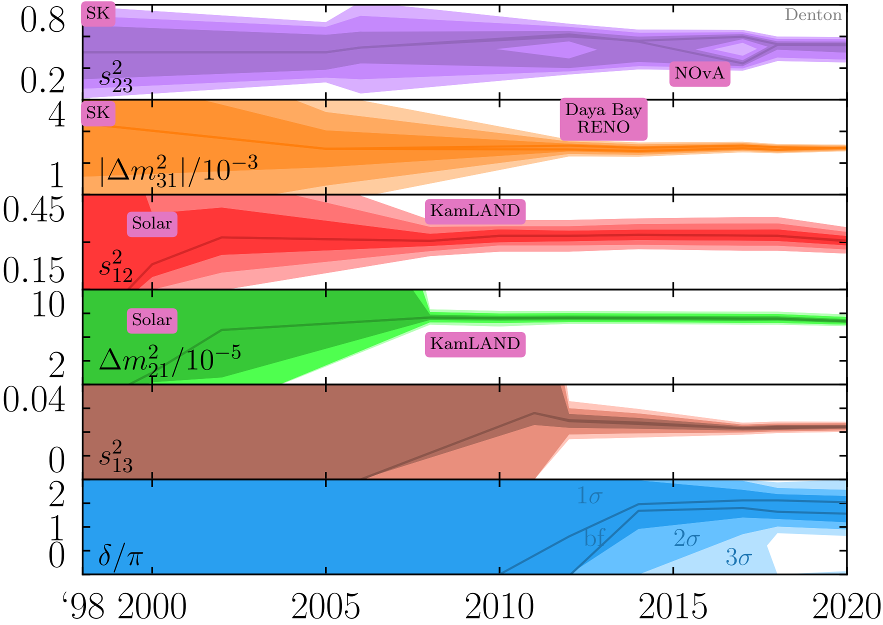
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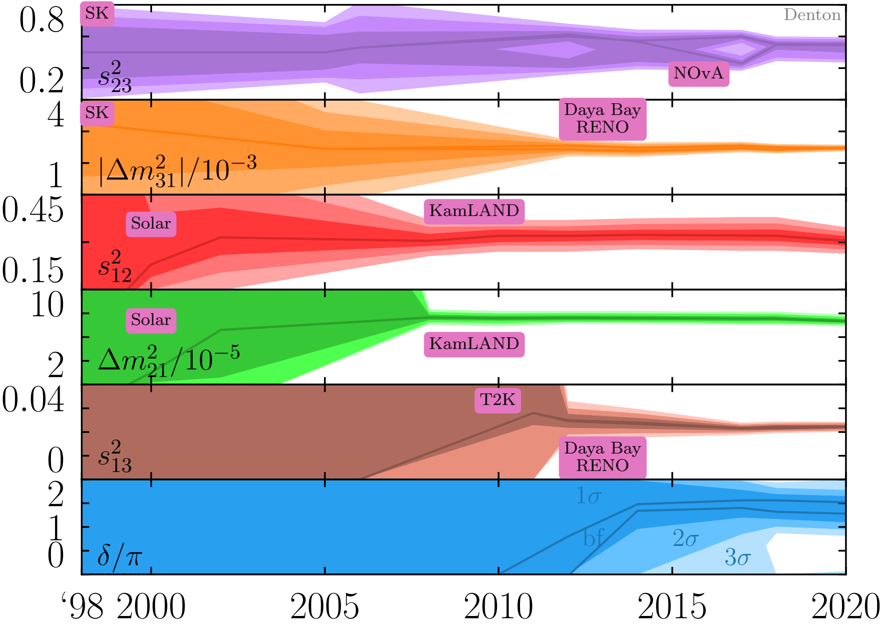
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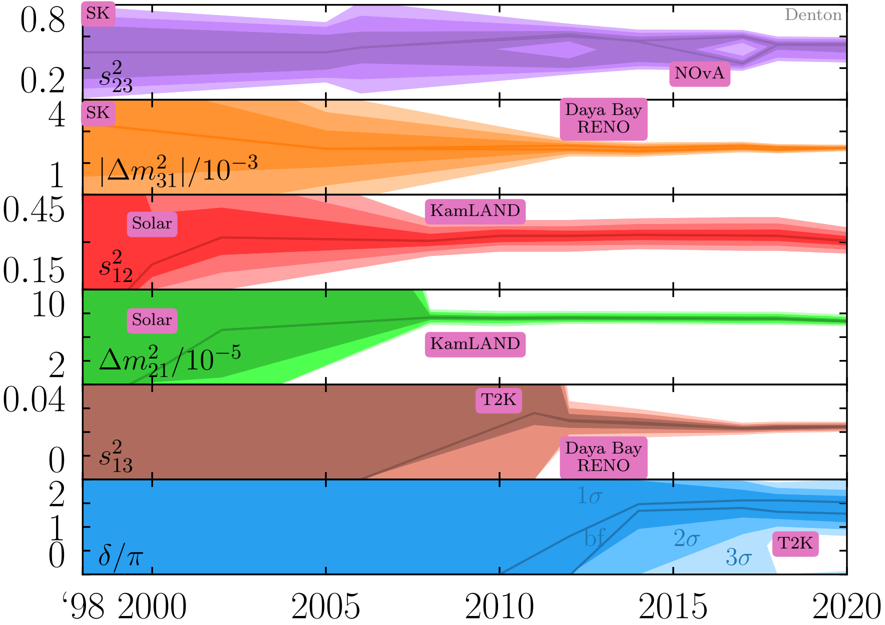

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Four known unknown in particle physics: all neutrinos

Atmospheric mass ordering

θ_{23} octant

Complex phase

Absolute mass scale

Four known unknown in particle physics: all neutrinos

Atmospheric mass ordering

θ_{23} octant

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Outline

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

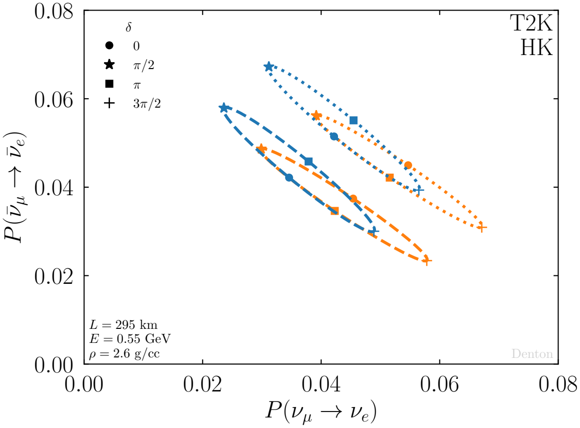
3. Lepton mass matrix: **?**

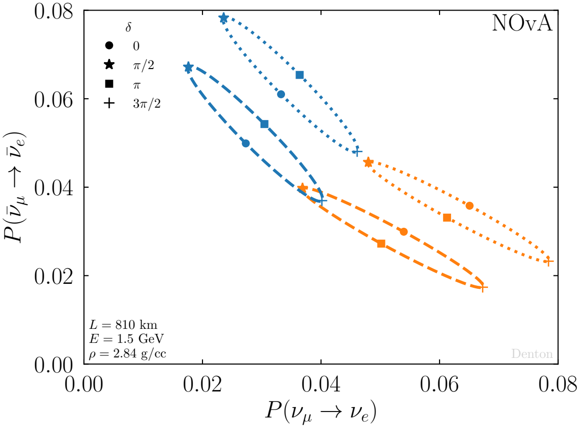
$$\frac{|J_{\rm PMNS}|}{J_{\max}} < 0.34$$

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

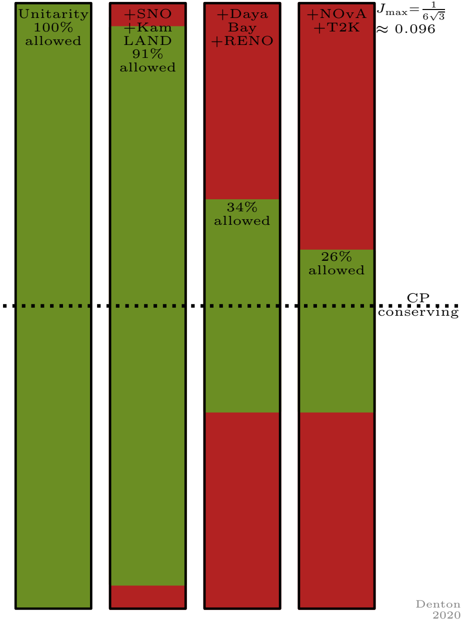
K. Moffat, et al. 1809.08251

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

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

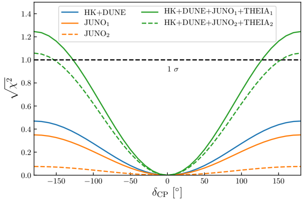
1. Some information in solar due to loops in elastic scattering

V. Brdar, X-J. Xu 2306.03160

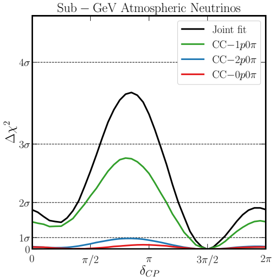
2. Sub-GeV atmospherics

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

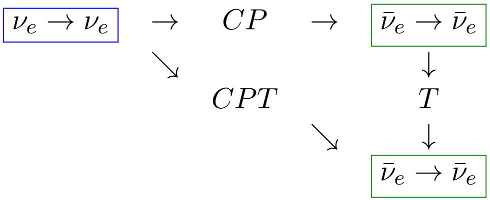
Some oscillation experiments can do appearance or disappearance experiments

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

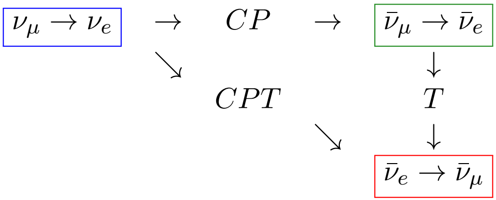


Disappearance measurements are even eigenstates of CP

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

Assume that CPT is a good symmetry

CP, T: Appearance



Appearance measurements are not eigenstates of CP

Appearance and Disappearance, CP even and CP odd terms

Disappearance:

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

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

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Disappearance:

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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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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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   - Electron neutrino row:
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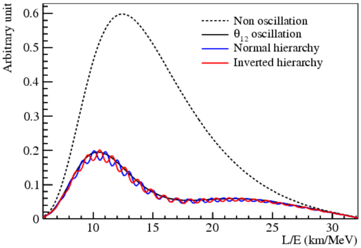
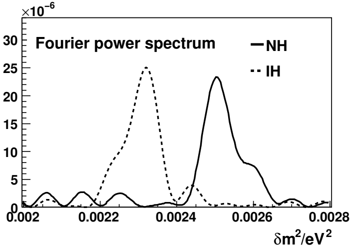


JUNO 1507.05613



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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   - 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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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

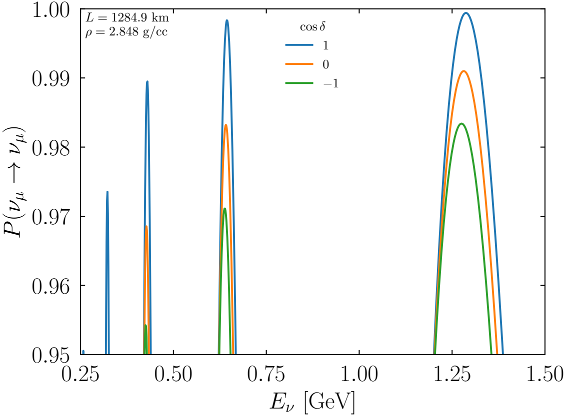
Numerical Studies

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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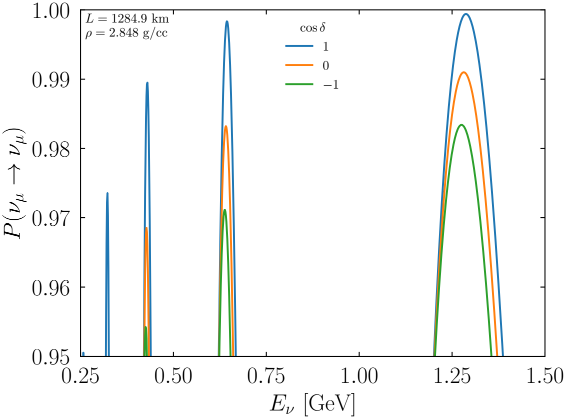
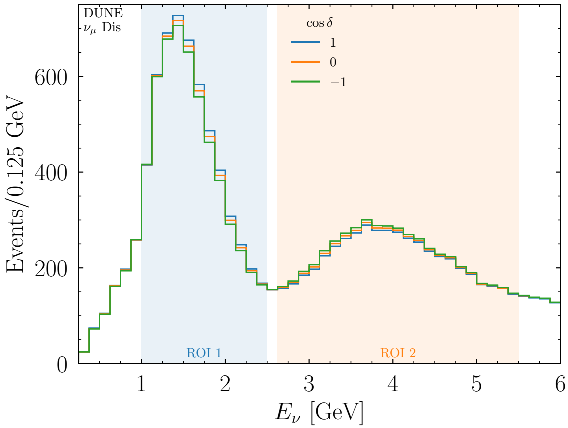
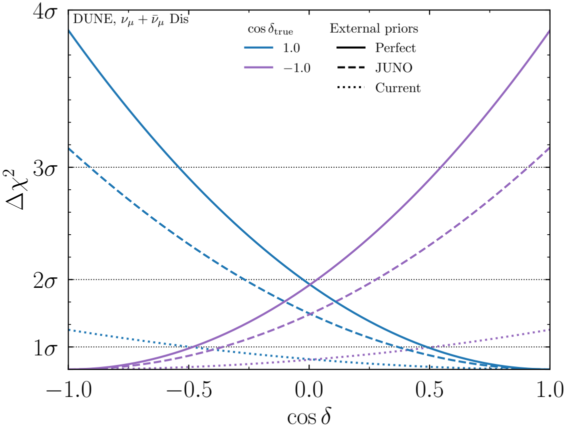


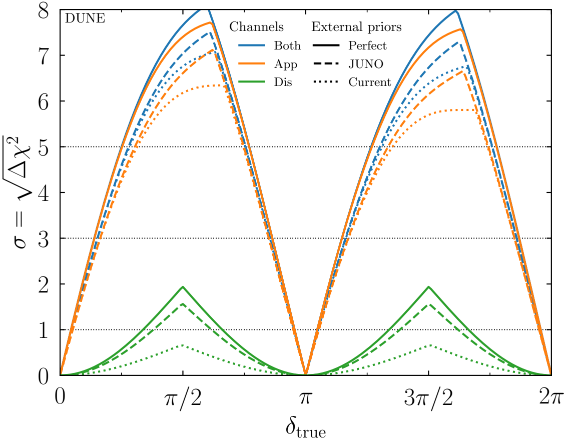


6.5 yrs ν_μ rates

$\cos\delta$	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 $|U_{\mu1}|^2 + |U_{\mu2}|^2$

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

- 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

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

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- This term is

$$\approx -4c_{23}^2\left(s_{12}^2c_{12}^2+s_{23}c_{23}s_{13}\sin2\theta_{12}\cos2\theta_{12}\cos\delta\right)\sin^2\Delta_{21}$$

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

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

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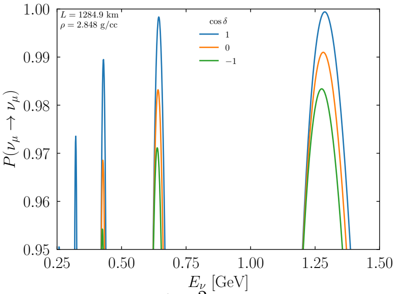
$$\approx -2 \quad (0.21 \quad + \quad 0.03\cos\delta)\left(\frac{\pi}{33}\right)^2$$

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

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

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



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PBD, J. Gehrlein 2302.08513

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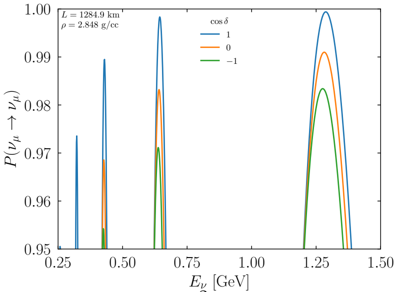
- So the effect is $\sim -0.0005\cos\delta$?

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



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

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

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

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

- 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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$$\cos 2\theta_{12} \to \frac{\cos 2\theta_{12} - c_{13}^2 a/\Delta m_{21}^2}{\mathcal{S}_\odot} \approx -0.97 < 0$$

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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

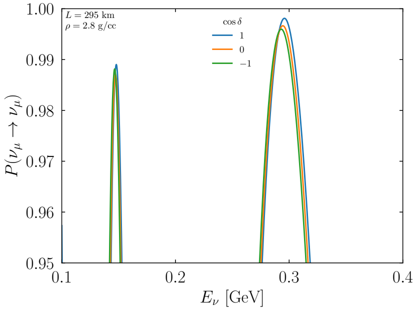
$$\sin 2\theta_{12}\cos 2\theta_{12} = 0.37 \to -0.25$$

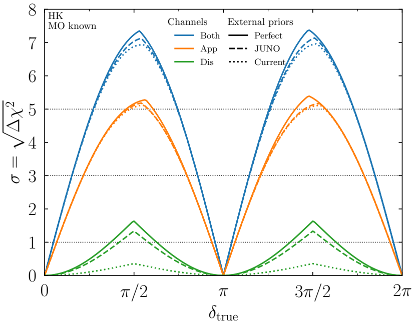
- Also s_{13} increases in matter $\sim 15\%$
- This gets us most of the effect, and the correct sign

Matter effects at HK

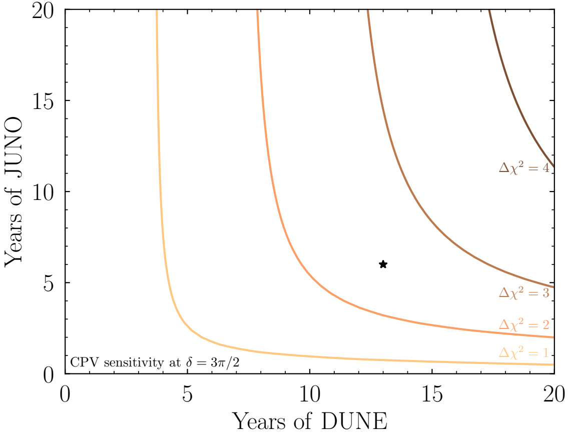
Leading order approximations

	$\mathcal{S}_\odot$	$\sin 2\theta_{12} \cos 2\theta_{12}$	s_{13}
Vacuum	1	0.37	0.141
HK	1.04	-0.42	0.145
DUNE	3.6	-0.25	0.16





Varying Runtime/Power



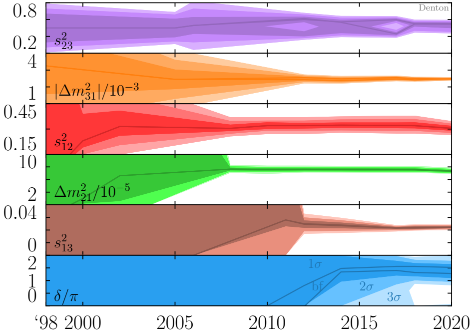
Improvement requires **both** experiments!

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

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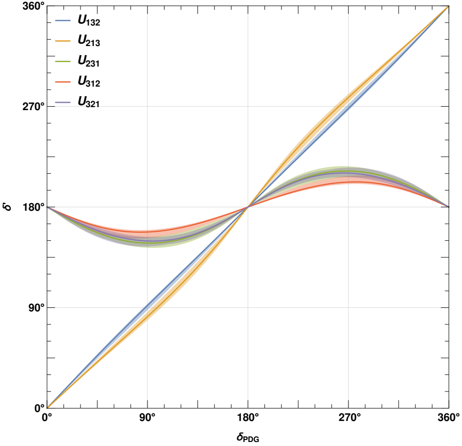
P. de Salas, et al. 1708.01186

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

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

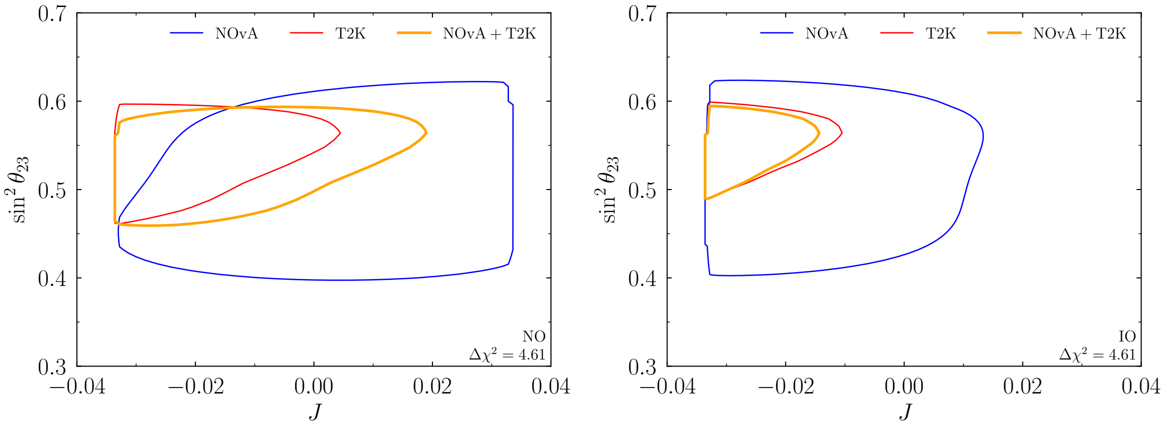
Looks like "large" CPV:

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

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

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)

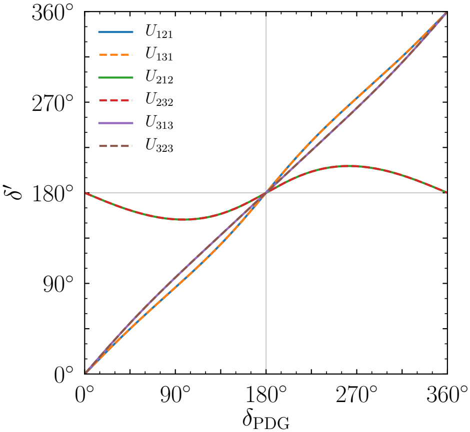
Matter effects are easily accounted for

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

PBD, S. Parke 1902.07185

PBD, H. Minakata, S. Parke 1604.08167

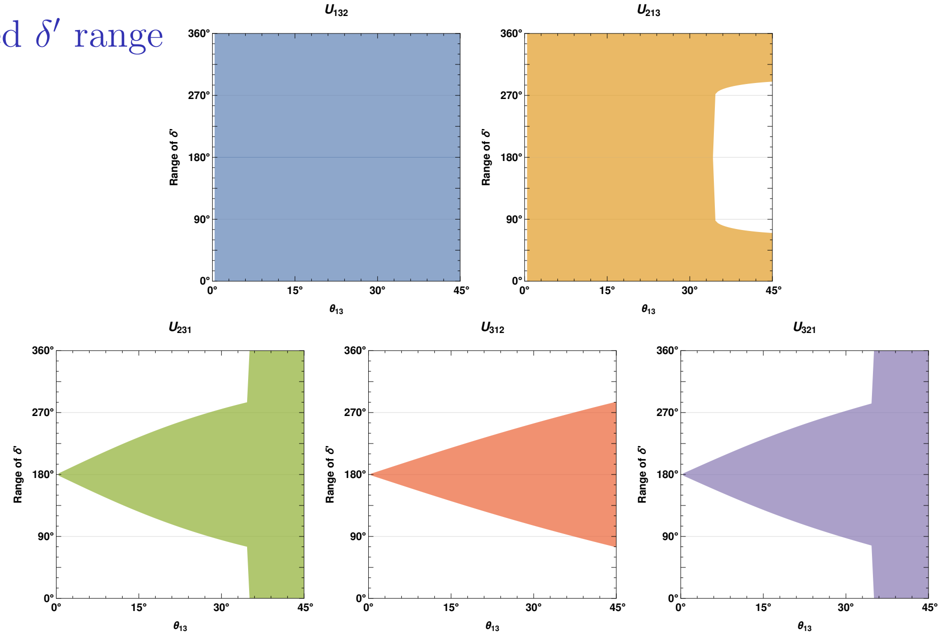
Repeated rotations



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

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

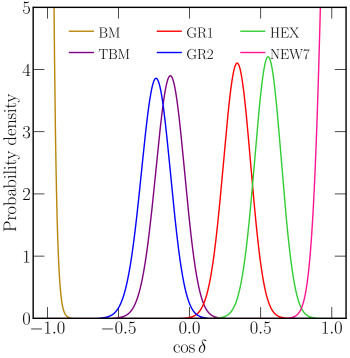
Allowed δ' range



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