Neutrino Factory

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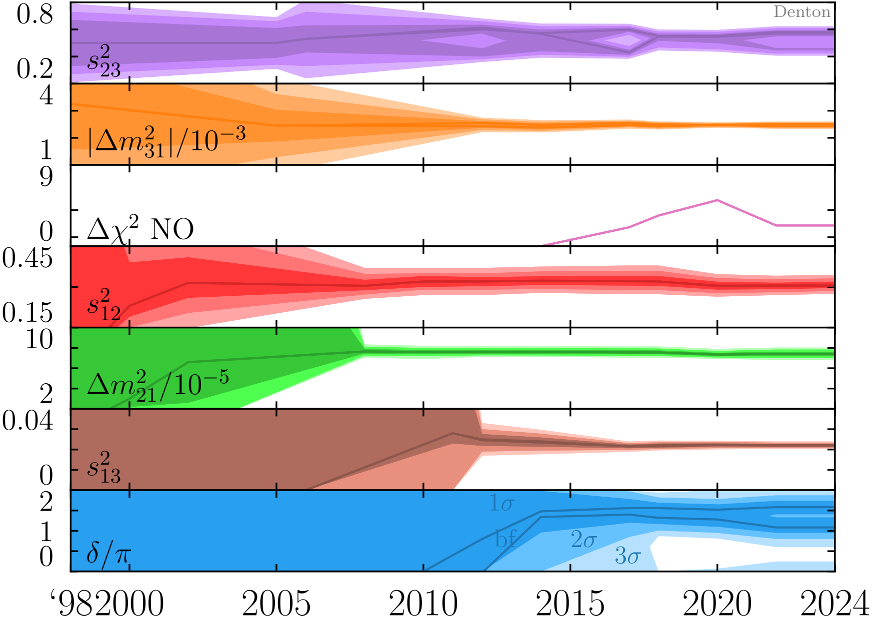
Universidad Católica del Norte

April 3, 2025

2407.02572 with J. Gehrlein
2502.14027 with J. Gehrlein and C-F. Kong

Neutrino oscillations add ≥ 7 new parameters:

Measure them!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$|\Delta m^2_{31}|/10^{-3}$
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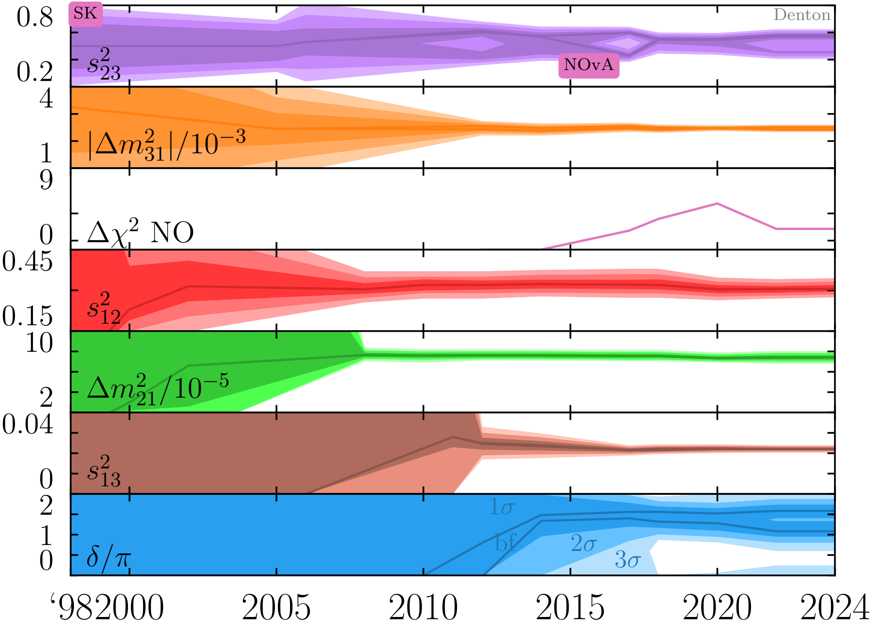
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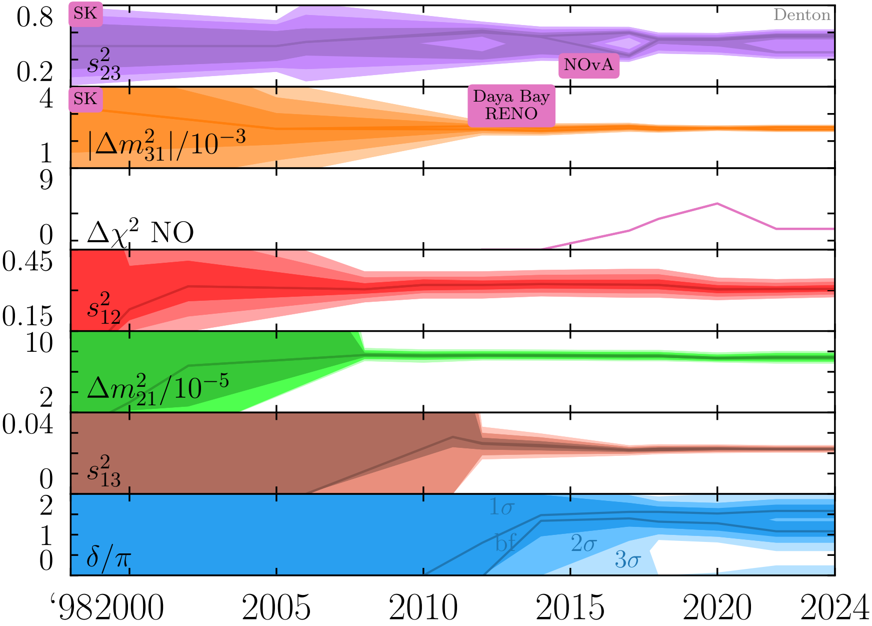

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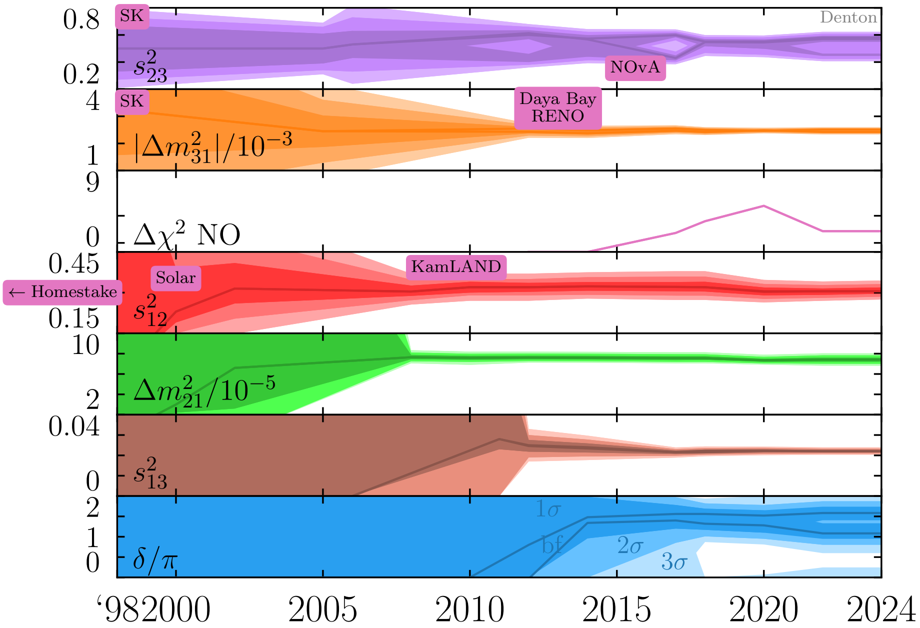
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KamLAND
Solar
← Homestake
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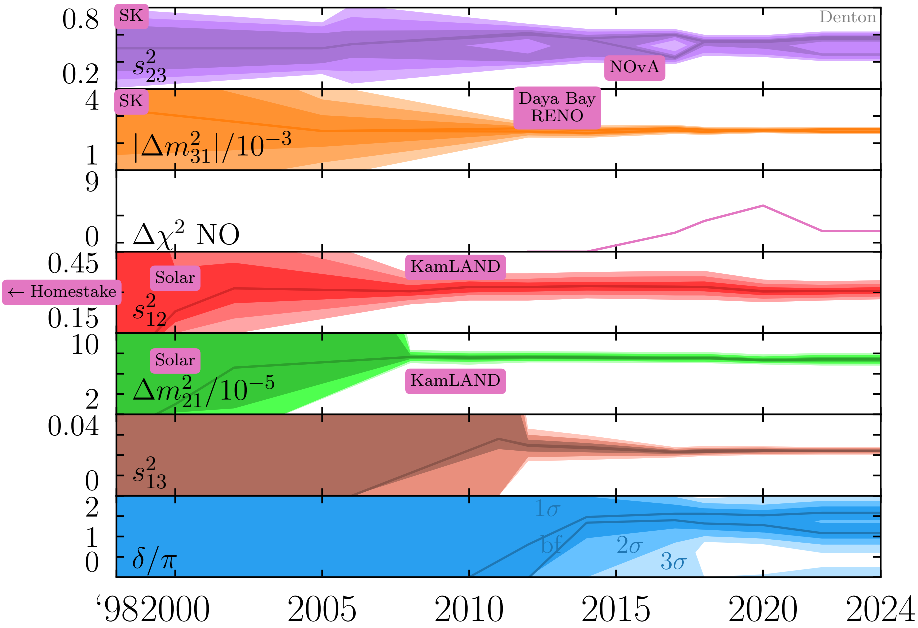
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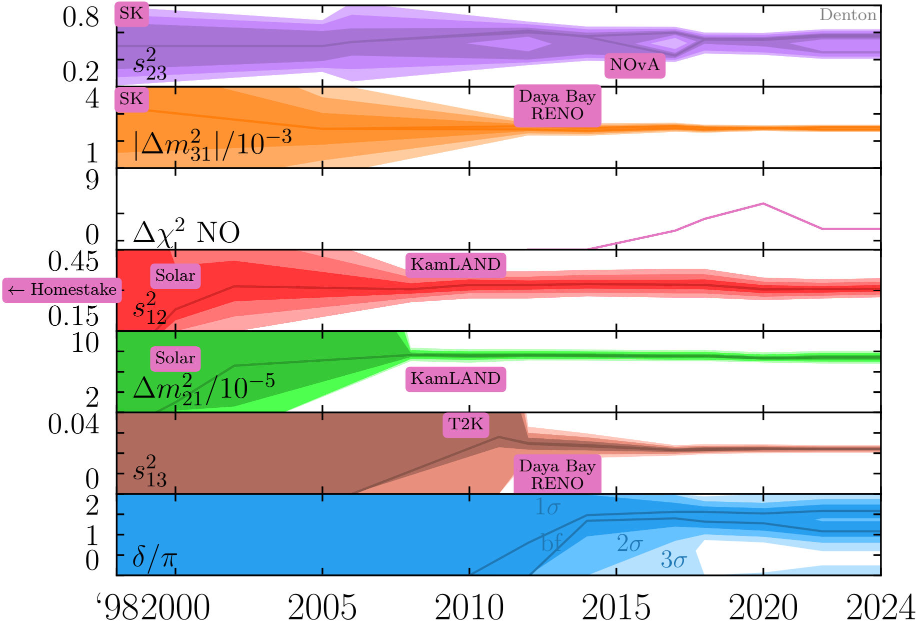
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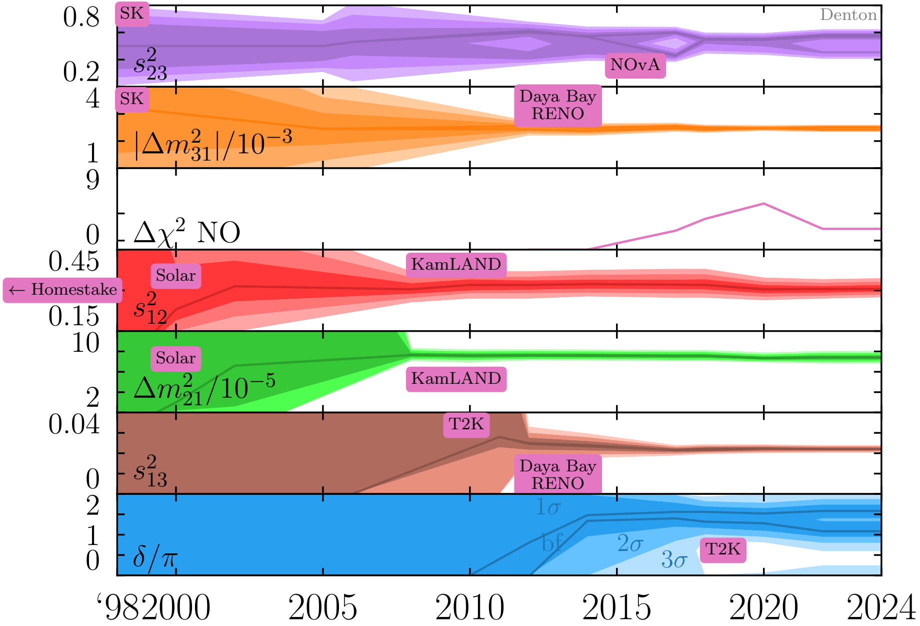

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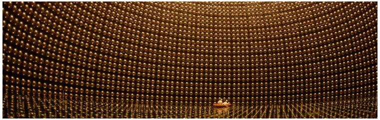
Experimental Oscillation Landscape Today

Three-flavor oscillation focused:

NOvA

LBL-acc: $\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_\mu$, and $\bar{\nu}_\mu \to \bar{\nu}_e$

T2K/SK



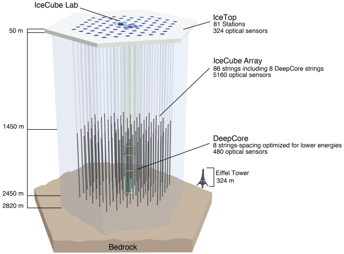
LBL-acc: $\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_\mu$, and $\bar{\nu}_\mu \to \bar{\nu}_e$

Atm: + $\nu_e \to \nu_\mu$, $\nu_e \to \nu_e$, $\bar{\nu}_e \to \bar{\nu}_e$, $\bar{\nu}_e \to \bar{\nu}_\mu$,

$\nu_\mu \to \nu_\tau$, $\bar{\nu}_\mu \to \bar{\nu}_\tau$, $\nu_e \to \nu_\tau$, $\bar{\nu}_e \to \bar{\nu}_\tau$

Solar: $\nu_e \to \nu_e$

IceCube



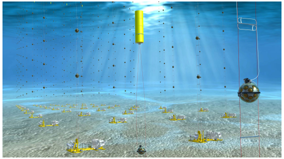
Atm: $\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_\mu$, $\bar{\nu}_\mu \to \bar{\nu}_e$,

$\nu_e \to \nu_\mu$, $\nu_e \to \nu_e$, $\bar{\nu}_e \to \bar{\nu}_e$, $\bar{\nu}_e \to \bar{\nu}_\mu$,

$\nu_\mu \to \nu_\tau$, $\bar{\nu}_\mu \to \bar{\nu}_\tau$, $\nu_e \to \nu_\tau$, $\bar{\nu}_e \to \bar{\nu}_\tau$

Experimental Landscape Tomorrow

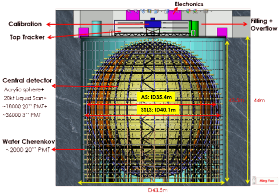
KM3NeT-ORCA



Atmospherics
Partially constructed

Has preliminary results

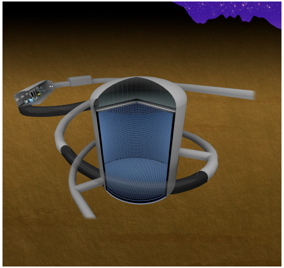
JUNO



LBL-reactor
Partially constructed

Data taking in 1-2(?) years

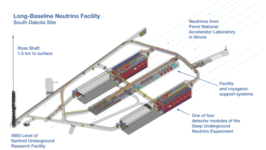
HK



LBL-accelerator,
atmospherics, solar
Under construction

Data taking in several(?) years

DUNE



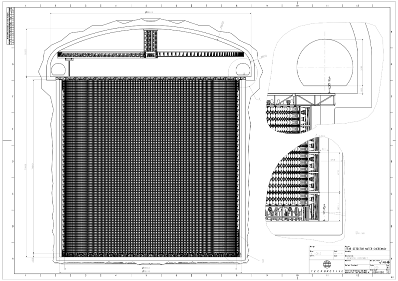
LBL-accelerator,
atmospherics, solar
Under construction

Data taking in 5(?) years

Plus IceCube upgrade

Possible Experimental Landscape of the Future

ESSnuSB

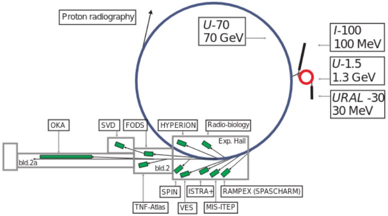


LBL-accelerator
Requires upgrades to ESS
Targets the second maximum

Also discussing a nuSTORM option

2303.17356

P2O

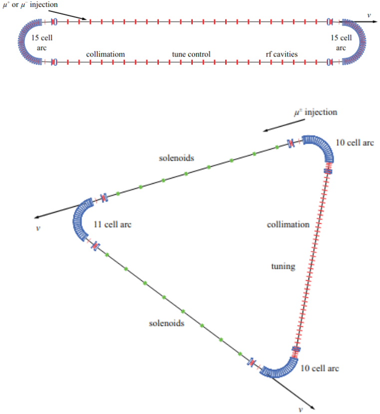


LBL-accelerator
Targets the second maximum

Tagged neutrinos?

1902.06083

Neutrino Facotry



Muon storage ring

Clean sources of ν_μ and ν_e

Plus astro/cosmo/mass experiments...

DUNE and HK will measure remaining oscillation parameters at some level

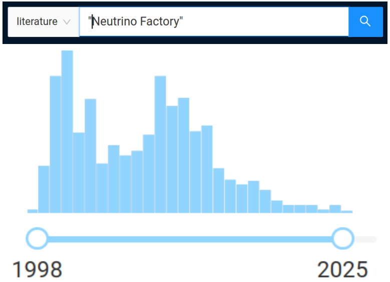
Should we have another oscillation experiment after that?

What does it look like?

What level of precision will it reach?

What new physics searches will it enable?

Neutrino Factory History



- Many designs considered for each stage
- A lot of oscillation theory work done
- Detectors assumed to be very simple, e.g. iron
- R&D on accelerators broadly useful for muon program

2014 P5 Report

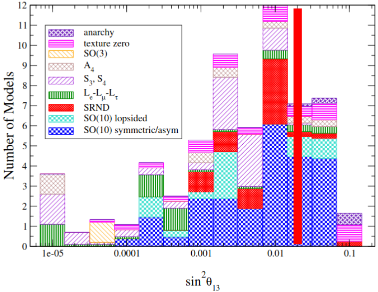
"The large value of $\sin^2 2(2\theta_{13})$ *enables the next generation of oscillation experiments to use conventional neutrino beams, pushing the time frame when neutrino factories might be needed further into the future."*

"The construction of PIP-II and the beamline for LBNF will bring major advances in accelerator technology in the areas of SCRF and targetry and lay the foundation for a possible future neutrino factory."

usparticlephysics.org/2014-p5-report

What Happened?

- $P_{\mu e}(\delta=3\pi/2) - P_{\mu e}(\delta=\pi/2) \propto \sin 2\theta_{13}$
- Theorists had largely predicted a small value



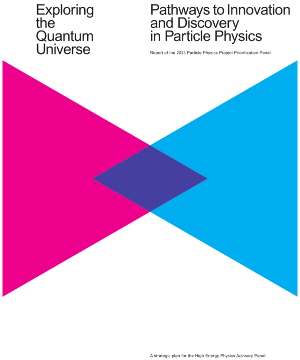
Review: C. Albright, M-C. Chen hep-ph/0608137

- Daya Bay and RENO determined θ_{13} to be $\sim 8.5^\circ$ in 2012

Daya Bay 1203.1669
RENO 1204.0626

- Funding, etc.

2023 P5 Report



"Such a [10 TeV muon collider] demonstrator might produce intense muon and neutrino beams"

"The upgraded facility would also generate bright, well-characterized neutrino beams bringing natural synergies with studies of neutrinos beyond DUNE."

"20-Year Vision: ... could entail the deployment of a low-energy muon storage ring, as exemplified by the Neutrinos from Stored Muons (nuSTORM) experiment"

⋮

usparticlephysics.org/2023-p5-report

A Neutrino Factory Today

My perspectives:

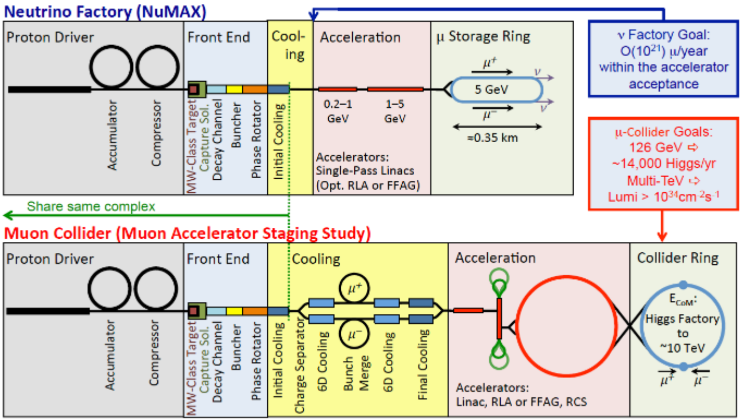
- Likely in the US connected to the development of a high energy muon collider
- Accelerator likely based at FNAL, could be BNL?
- Likely leverage DUNE LArTPC far detectors under construction now

The importance of a new study:

- Interest fell off immediately after $\theta_{13} > 0$ was first determined
- It has now been well measured
- $|\Delta m^2_{31}|$ has improved by a factor of ~ 2 in the last 10-15 years

  Provides a clear indication of the correct E_μ
- The US landscape is much more clear (DUNE, interest in muon collider)
- The global neutrino oscillation landscape has progressed considerably (HK, JUNO, IceCube, KM3NeT)

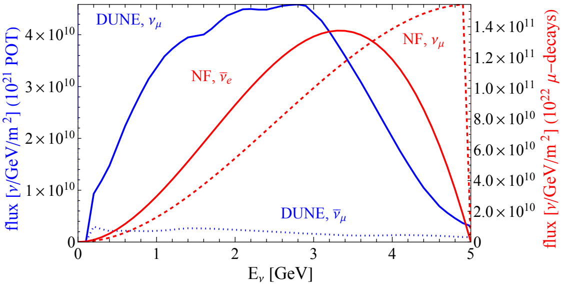
Possible Design



A. Bogacz, et al 2203.08094

The Big Advantage

A neutrino factory provides well-characterized beams of ν_μ and ν_e



Charge Identification

CID allows for separation of ν_μ from $\bar{\nu}_e$

$$N_{\nu_{\rm f,obs}} = \frac{\epsilon_f}{2}\left[(1+\epsilon_{CID})N_{\nu_f} + (1-\epsilon_{CID})N_{\bar{\nu}_f}\right]$$
$$N_{\bar{\nu}_{\rm f,obs}} = \frac{\epsilon_f}{2}\left[(1+\epsilon_{CID})N_{\bar{\nu}_f} + (1-\epsilon_{CID})N_{\nu_f}\right]$$

Older studies typically assume perfect CID

See e.g. A. Rujula, B. Gavela, P. Hernandez hep-ph/9811390
E. Fernandez-Martinez, T. Li, O. Mena, S. Pascoli 0911.3776

Realistic:

- DUNE may be able to achieve $\epsilon_{CID,\nu_\mu} = 72\%$ from muon capture on Ar

C. Ternes, et al 1905.03589

- Some ν_e CID can be achieved in a LArTPC and some can happen statistically

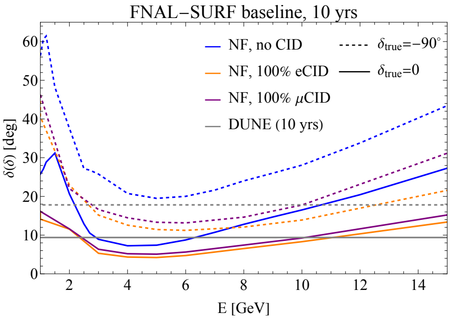
A. Rubbia 0908.1286
P. Huber, T. Schwetz 0805.2019

Neutrino Factory Configurations

FNAL-SURF:

$L = 1284.9$ km

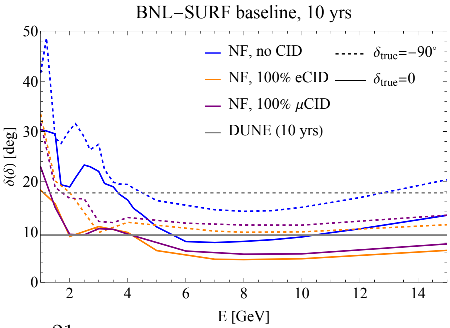
$E_\mu = 5$ GeV



BNL-SURF:

$L = 2542.3$ km

$E_\mu = 8$ GeV

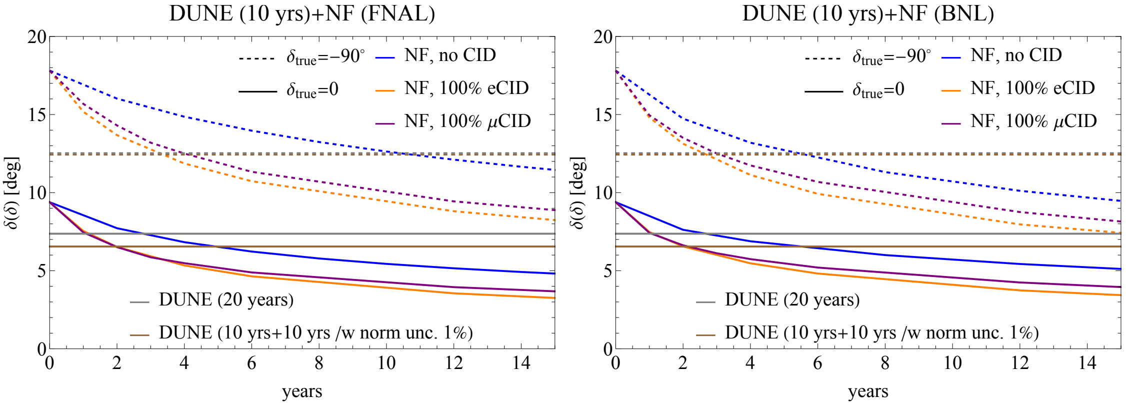


5 years of μ^+ and 5 years of μ^- and 10^{21} μ decays per year

Interim Deisgn Report NF 1112.2853

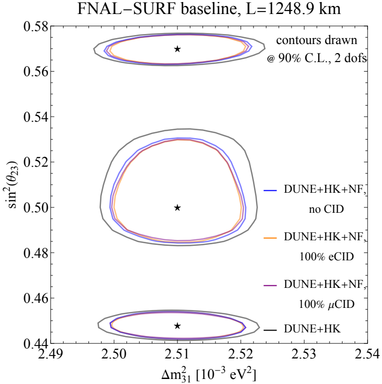
Three-flavor oscillation sensitivities

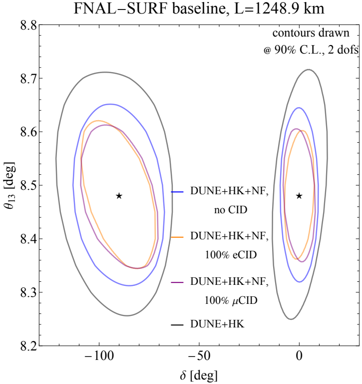
CPV Phase δ



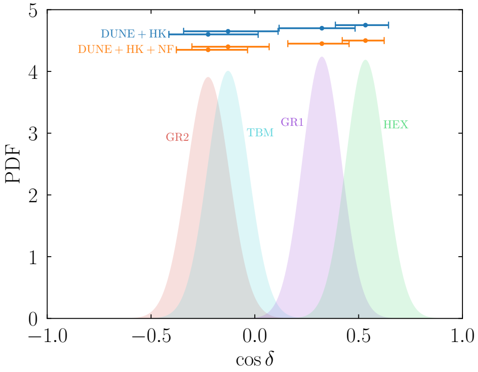
More Precision

Need improvement in all oscillation parameters





Neutrino Factory and Oscillations



Enhanced sensitivity to $\delta \Rightarrow$ flavor model discrimination

New physics at a neutrino factory

New Physics at a Near Detector

- Precision in Cross Section Measurements
- Standard Candles
- Precision in $\sin^2\theta_W$ Measurement
- Light Sterile Neutrinos
- Lepton Number Violation
- NSI and New Physics at the Multi-TeV scale
- Light Dark Sectors, Dark Matter
- Decay in flight of new particles

A. Bogacz, et al 2203.08094

New Oscillation Physics at a Neutrino Factory

Many new physics cases that affect oscillations,
which to focus on?

- Steriles: interesting Δm^2 regions are not easy to probe in a neutrino factory
- Neutrino decay: stronger constraints from solar, astro, cosmo
- Scalar NSI: stronger constraints from solar
- **Vector NSI**: matter effect, controlled beams, multiple channels: yes!
- **CPT violation**: can over constrain the oscillation picture: yes!

Vector NSI

NSI at the Lagrangian Level

EFT Lagrangian:

$$\mathscr{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon_{\alpha,\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$

with $\Lambda = \frac{1}{\sqrt{2\sqrt{2}\epsilon G_F}}$.

Simplified model Lagrangian:

$$\mathscr{L}_{\rm NSI} = g_\nu Z'_\mu \bar{\nu}\gamma^\mu \nu + g_f Z'_\mu \bar{f}\gamma^\mu f$$

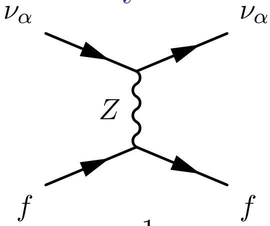
which gives a potential

$$V_{\rm NSI} \propto \frac{g_\nu g_f}{q^2 + m_{Z'}^2}$$

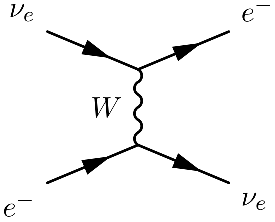
Models with large NSIs consistent with CLFV:

Y. Farzan, I. Shoemaker 1512.09147 Y. Farzan, J. Heeck 1607.07616 D. Forero and W. Huang 1608.04719
K. Babu, A. Friedland, P. Machado, I. Mocioiu 1705.01822 PBD, Y. Farzan, I. Shoemaker 1804.03660
U. Dey, N. Nath, S. Sadhukhan 1804.05808 Y. Farzan 1912.09408

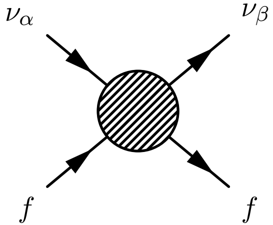
Matter Effects in Feynman Diagrams



$$V_{\mathrm{NC}} = \mp\frac{1}{2}\sqrt{2}G_F n_n$$

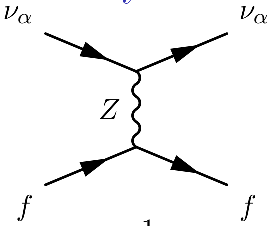


$$V_{\mathrm{CC}} = \pm\sqrt{2}G_F n_e$$

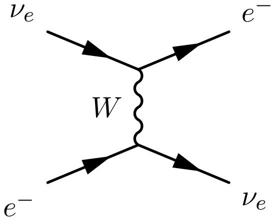


$$V_{\mathrm{NSI}} = \pm\epsilon_{\alpha\beta}^{f,X}\sqrt{2}G_F n_f$$

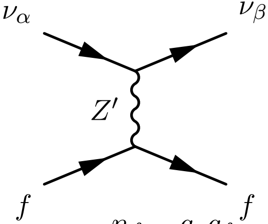
Matter Effects in Feynman Diagrams



$$V_{\rm NC} = \mp\frac{1}{2}\sqrt{2}G_F n_n$$



$$V_{\rm CC} = \pm\sqrt{2}G_F n_e$$



$$V_{\rm NSI} = \frac{n_f}{2}\frac{g_\nu g_f}{q^2 + m_{Z'}^2}$$

NSI at the Hamiltonian Level

$$H^{\text{vac}} = \frac{1}{2E} U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger$$

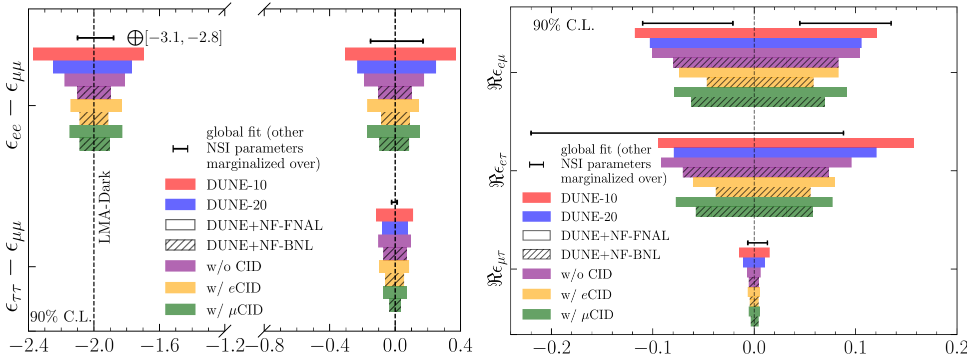
$$H^{\text{mat,SM}} = \frac{a}{2E} \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix}$$ (NC subtracted out)

$$H^{\text{mat,NSI}} = \frac{a}{2E} \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

$$\epsilon_{\alpha\beta} = \sum_{f\in\{e,u,d\}} \epsilon^{f,V}_{\alpha\beta} \frac{N_f}{N_e}$$

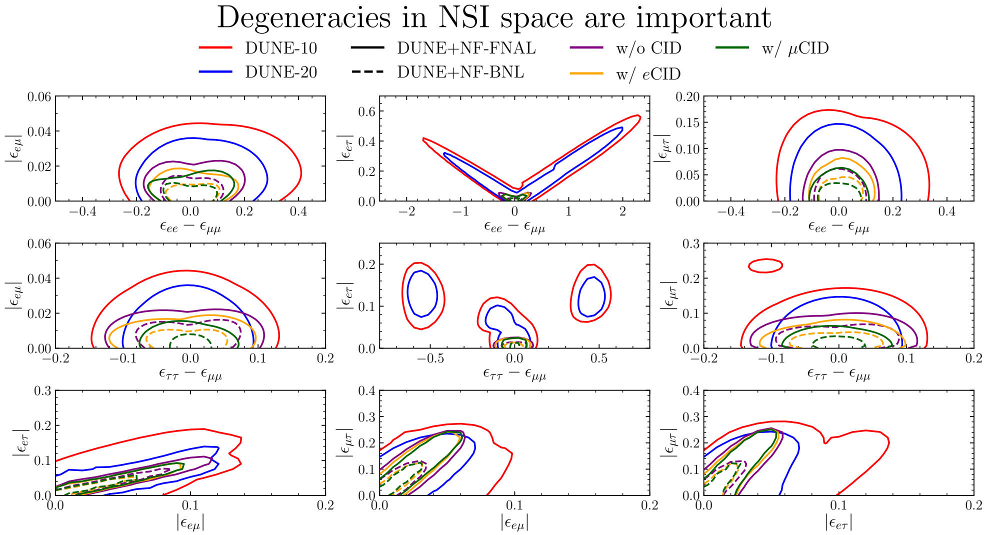
$$H = H^{\text{vac}} + H^{\text{mat,SM}} + H^{\text{mat,NSI}}$$

Vector NSI Sensitivities



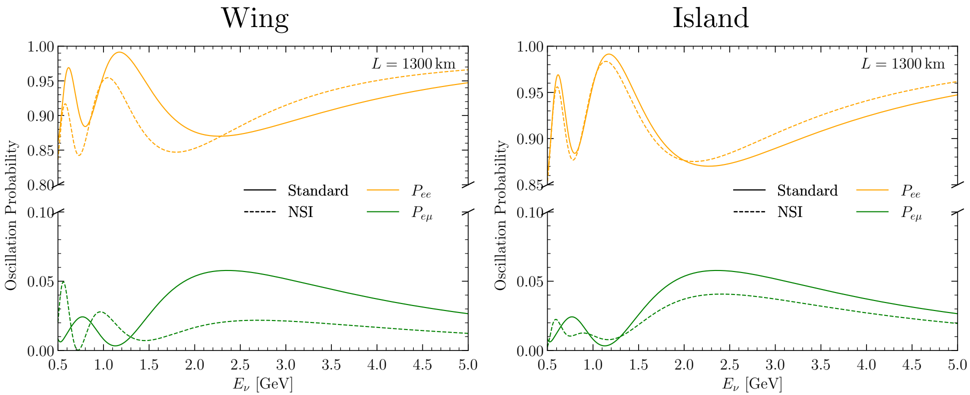
Global fit from:
P. Coloma, et al 2305.07698

Vector NSI Degeneracies



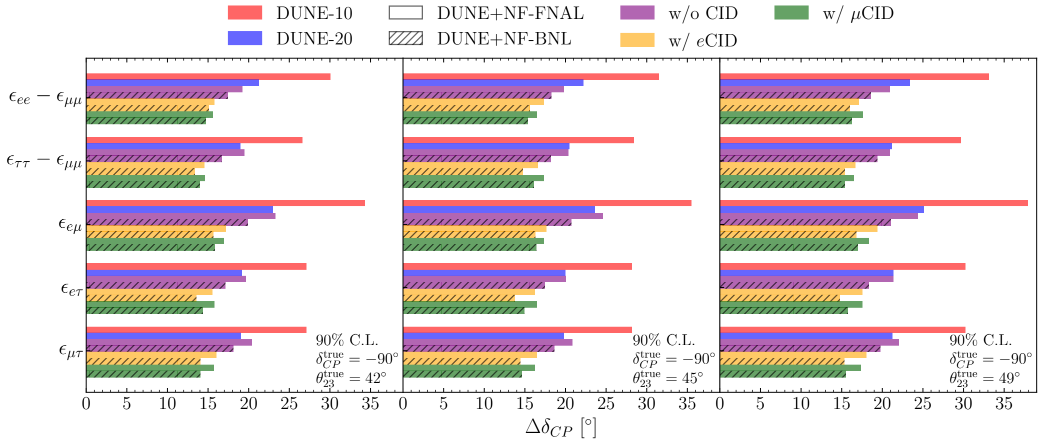
Marginalized over δ and the relevant $\phi_{\alpha\beta}$

Vector NSI Degeneracies



Comparison between the degenerate points
and the standard cases in the new channels

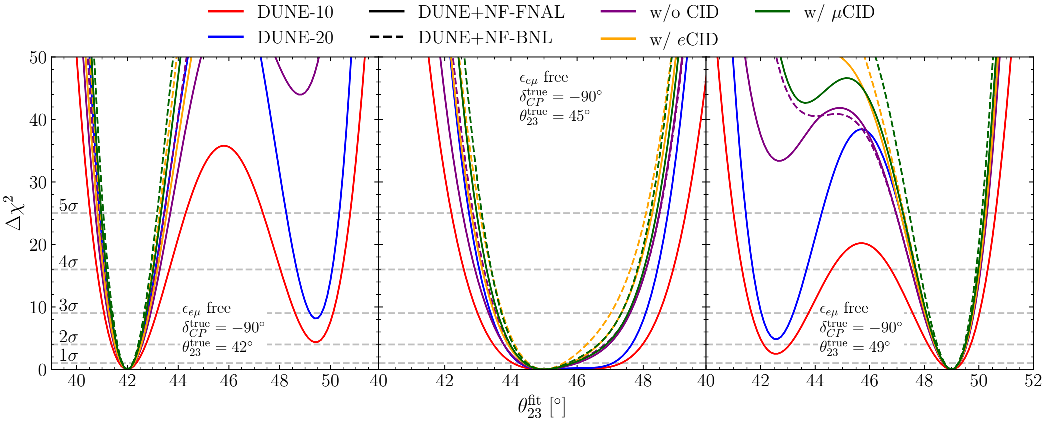
Impact of Vector NSI on Regular Oscillation Parameters



When considering new physics, DUNE alone has poor sensitivity to δ

DUNE+NF has excellent sensitivity

Impact of Vector NSI on Regular Oscillation Parameters



Marginalized over $|\epsilon_{e\mu}|$ and $\phi_{e\mu}$

Neutrino factory is required to identify the octant

Same for other NSI parameters

Impact of Vector NSI on Regular Oscillation Parameters

A neutrino factory significantly increases the robustness of the oscillation picture under new physics

If there are tensions in DUNE/HK, a neutrino factory will likely be able to identify them

CPT violation

CPT Violation

- CPT violation appears in many UV complete theories

V. Kostelecky, S. Samuel PRD 1989
V. Kostelecky, S. Samuel PRL 1989
V. Kostelecky, S. Samuel PRD 1989
S. Carroll, et al hep-th/0105082
O. Greenberg hep-ph/0201258

- Neutrinos may be the first place CPT violation appears

G. Barenboim, J. Lykken hep-ph/0210411
A. de Gouvea hep-ph/0204077
S. Ge, H. Murayama 1904.02518

- The low energy implementation in neutrinos is usually parameterized as:

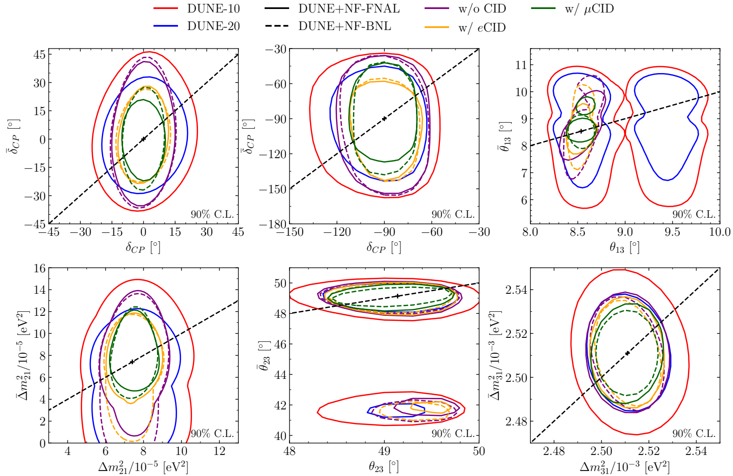
$$\theta_{ij} \to (\theta_{ij}, \bar{\theta}_{ij}), \quad \delta \to (\delta, \bar{\delta}), \quad \Delta m^2_{ij} \to (\Delta m^2_{ij}, \Delta \bar{m}^2_{ij})$$

- Two curious anomalies in θ_{13} and Δm^2_{21}

$$\sin^2 \theta_{13} = 0.032, \quad \sin^2 \bar{\theta}_{13} = 0.022$$

$$\Delta m^2_{21} = 5.4 \times 10^{-5} \text{ eV}^2, \quad \Delta \bar{m}^2_{21} = 7.5 \times 10^{-5} \text{ eV}^2$$

CPT Violation Sensitivities

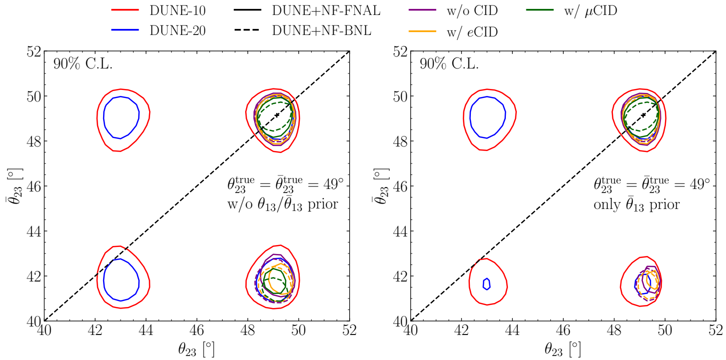


More degeneracies appear: θ_{13}, θ_{23}

Neutrino factory lifts the θ_{13} degeneracy

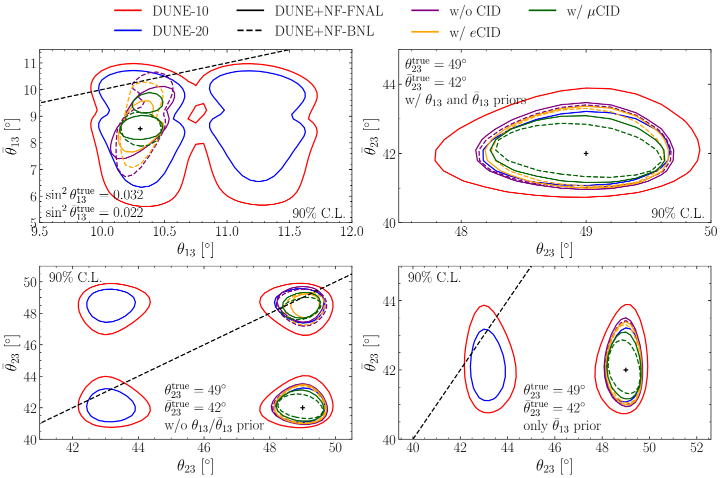
CPT Violation Sensitivities θ_{23} Degeneracies

With information from Daya Bay and μCID at NF, all degenerate regions are lifted



$$P_{\mu e} \sim 4\sin^2\theta_{23}\sin^2\theta_{13}\cos^2\theta_{13}\sin^2\Delta_{31}$$

CPT Violation Discovery Potential

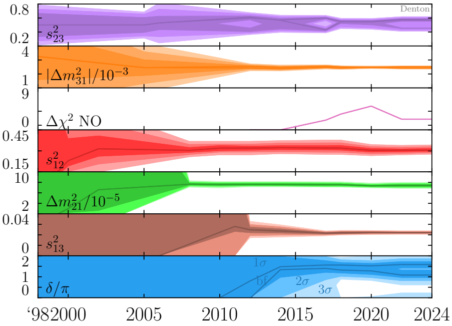


Neutrino Factory Summary

- A Neutrino Factory may be a stepping stone to a muon collider
- Previous studies ended when θ_{13} was measured
- Since then: DUNE FD design completed, $|\Delta m^2_{31}|$ precision improved, more clear global picture
- Improved precision on δ and other parameters
- Improved flavor model differentiation capabilities
- Breaks degeneracies and improves constraints on new physics

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

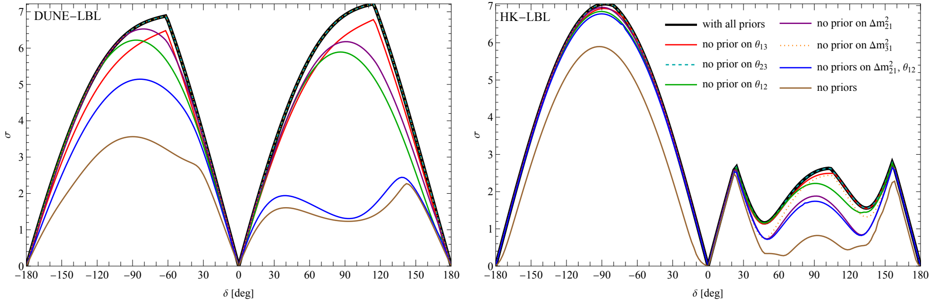
F. Capozzi et al. 2003.08511

I. Esteban et al. 2007.14792

δ: Future Sensitivities

DUNE and HK will make great measurements via appearance $\nu_\mu \to \nu_e$

$\nu+\bar{\nu}$ helps systematics but isn't strictly necessary



PBD, J. Gehrlein 2302.08513

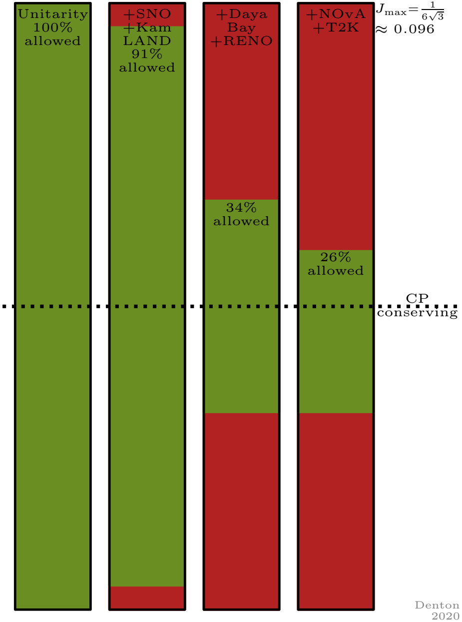
Need to know solar parameters to measure δ!

Current solar knowledge: okay
Future (JUNO): excellent

δ, J: Current Status

Maximal CP violation is already ruled out:

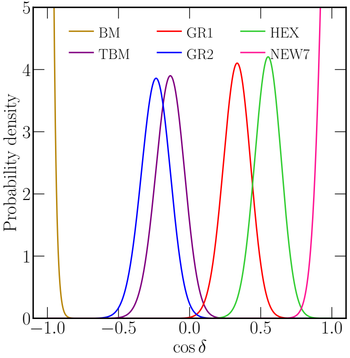
1. $\theta_{12} \neq 45^\circ$ at $\sim 15\sigma$
2. $\theta_{13} \neq \tan^{-1}\frac{1}{\sqrt{2}} \approx 35^\circ$ at many (100) σ
3. $\theta_{23} = 45^\circ$ allowed at $\sim 1\sigma$
4. $|\sin\delta| = 1$ allowed



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 $\cos\delta$

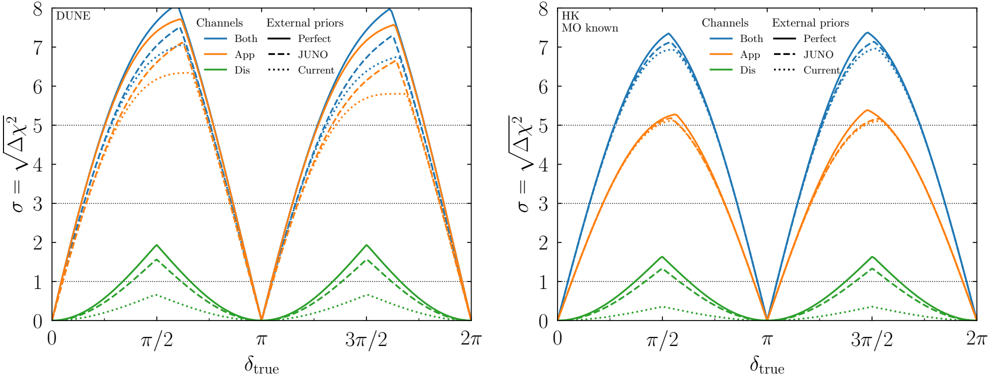
J. Gehrlein, et al. 2203.06219



L. Everett, et al. 1912.10139

CP Violation Discovery with Disappearance

Need JUNO and DUNE or HK



PBD 2309.03262

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been added to receive it.
If you rerun the document (without altering it) this surplus page will go away,
because LaTeX now knows how many pages to expect for this document.