Here comes the Sun: Solar parameters in long-baseline accelerator neutrino oscillations

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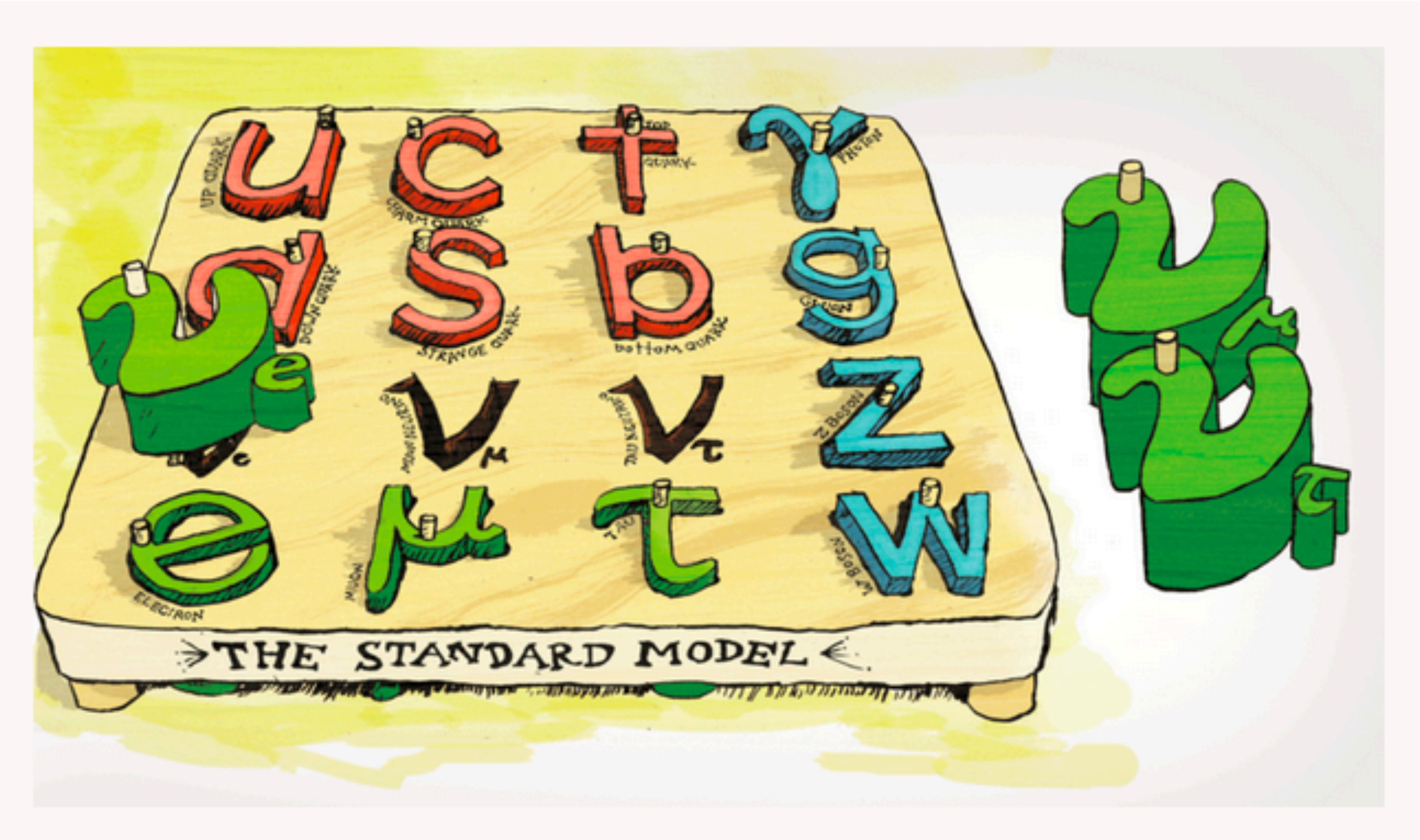
Neutrino oscillations

Observation of neutrino oscillations:

→ Strong evidence of physics beyond the SM

Discovery of neutrino flavor change
by SuperKamiokande and SNO
awarded Nobel Prize in 2015



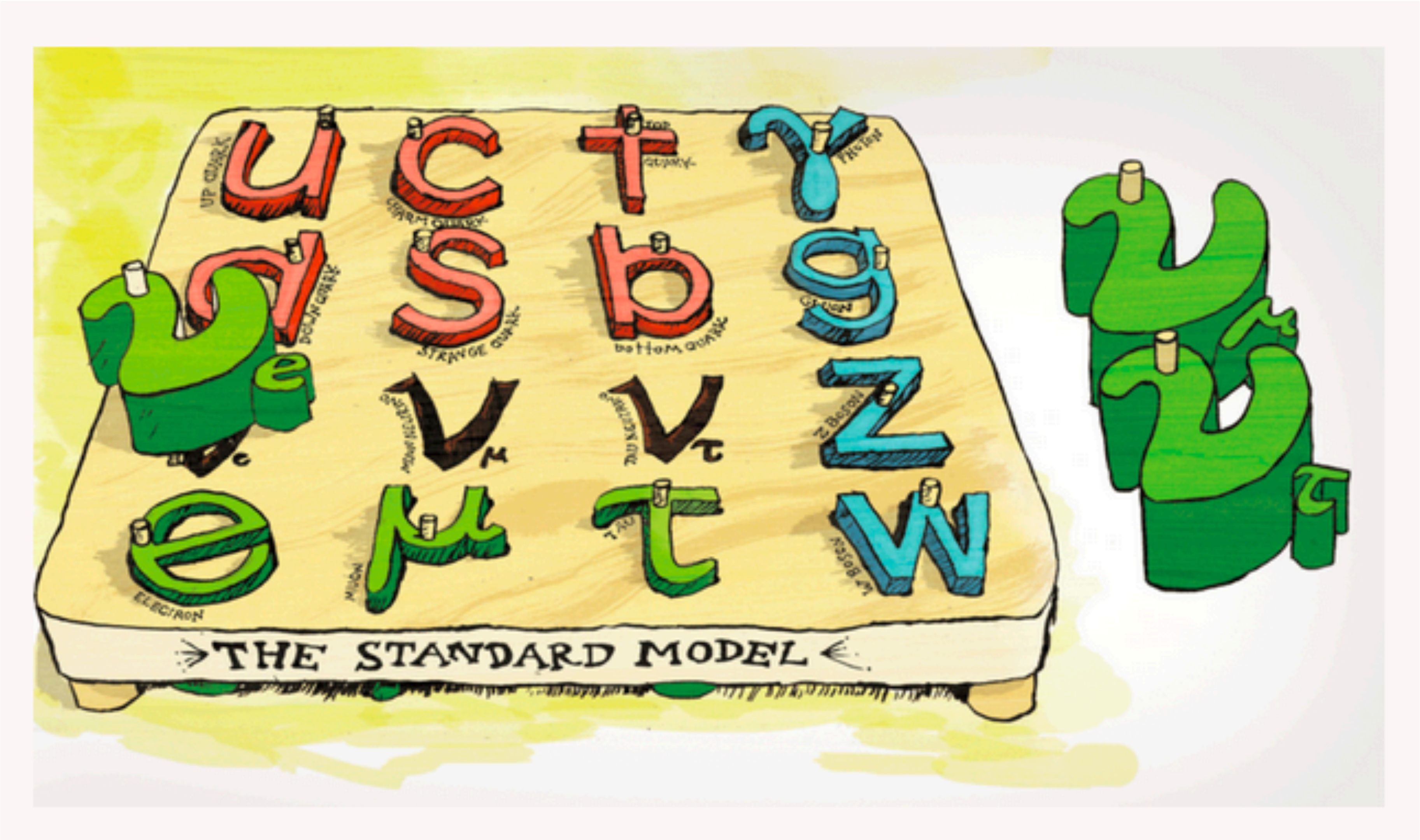
Neutrino oscillations

Observation of neutrino oscillations:

→ Strong evidence of physics beyond the SM

→ introduced more parameters to the model (3 angles, at least one phase, 3 masses)

⇒ want to measure them



Neutrino oscillations

flavor eigenstates (of weak interaction) and mass eigenstates (of free particle Hamiltonian)
not aligned for neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U_{PMNS}: relates flavor and mass states

Parametrized by four parameters (3 angles and at least one phase)

$$U_{\text{PMNS}} = U_{23}(\theta_{23})U_{13}(\theta_{13},\delta)U_{12}(\theta_{12})\,\text{diag}(\mathrm{e}^{\mathrm{i}\alpha_1/2},\, \mathrm{e}^{\mathrm{i}\alpha_2/2},\, 1)$$

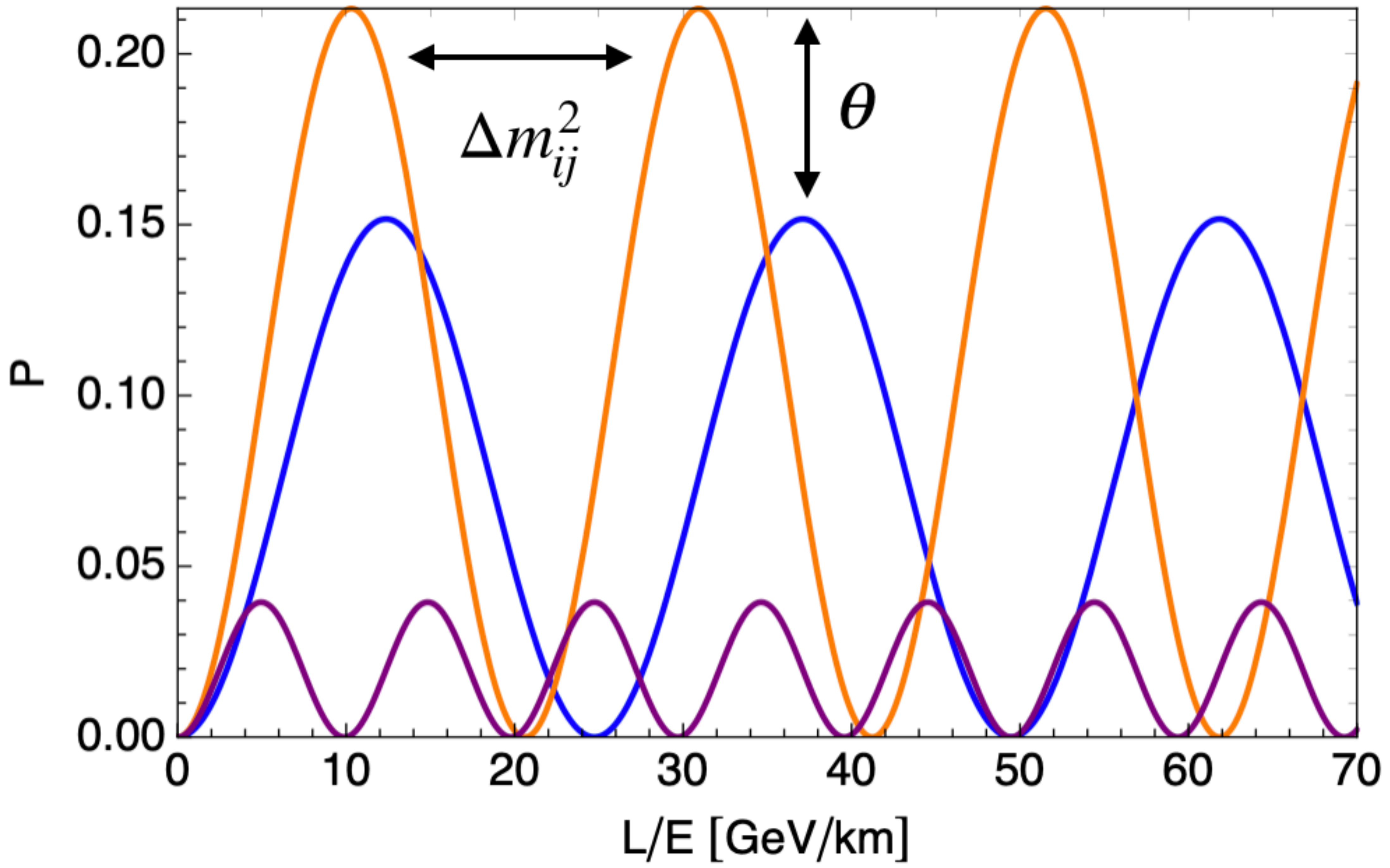
Majorana phases: only physical for Majorana neutrinos,
oscillation experiments not sensitive to them
$\rightarrow$ not going to talk about them further

Neutrino oscillations

produce neutrino of flavor α with energy E, probability to detect neutrino with flavor β at distance L is

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2(\Delta m_{ij}^2 L/4E), \ \Delta m_{ij}^2 = m_i^2 - m_j^2$$

In a 2-flavor approximation



Neutrino oscillation parameters

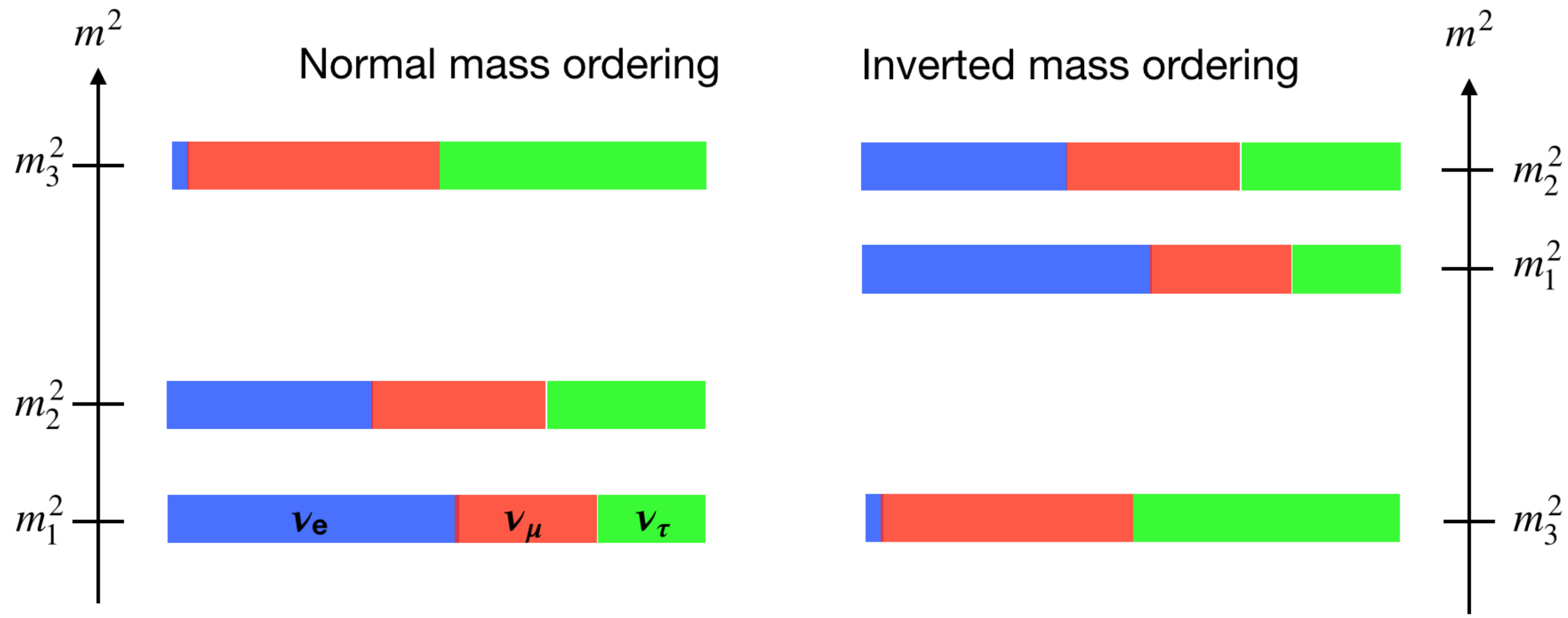
Global fits to oscillation data:

Information on mixing angles, mass splittings

mass splittings: $|\Delta m^2_{32}| = 2.5 \cdot 10^{-3}\ \mathrm{eV}^2,\ \Delta \mathrm{m}^2_{21} = 7.4 \cdot 10^{-5}\ \mathrm{eV}^2$

[nufit v5.1]

mass ordering unknown



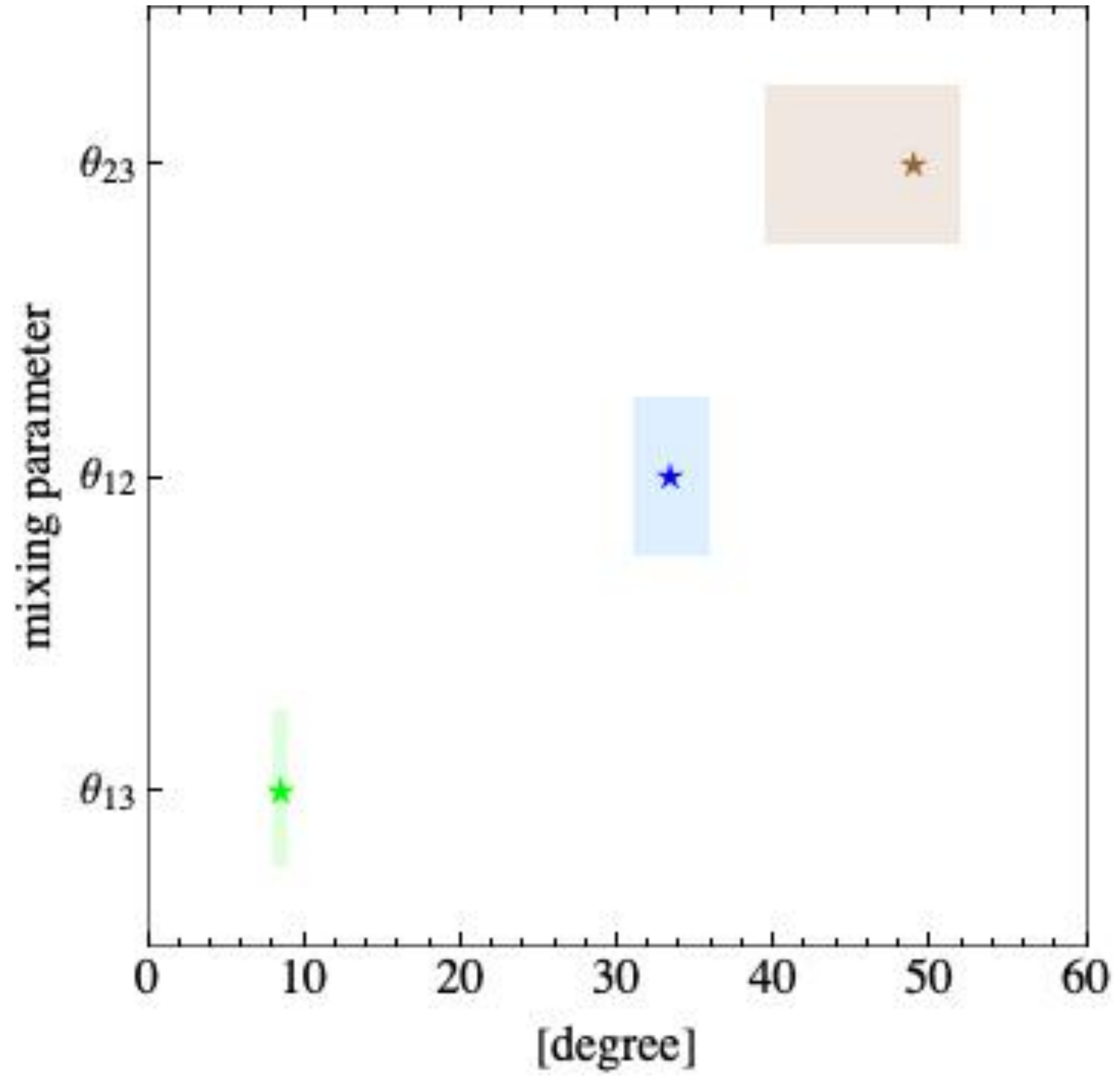
Neutrino oscillation parameters

Global fits to oscillation data:

Information on mixing angles, mass splittings

[nufit v5.1]

Measurement of angles from several experiments
all three angles non-zero
mixing angles are large!



Neutrino oscillation parameters

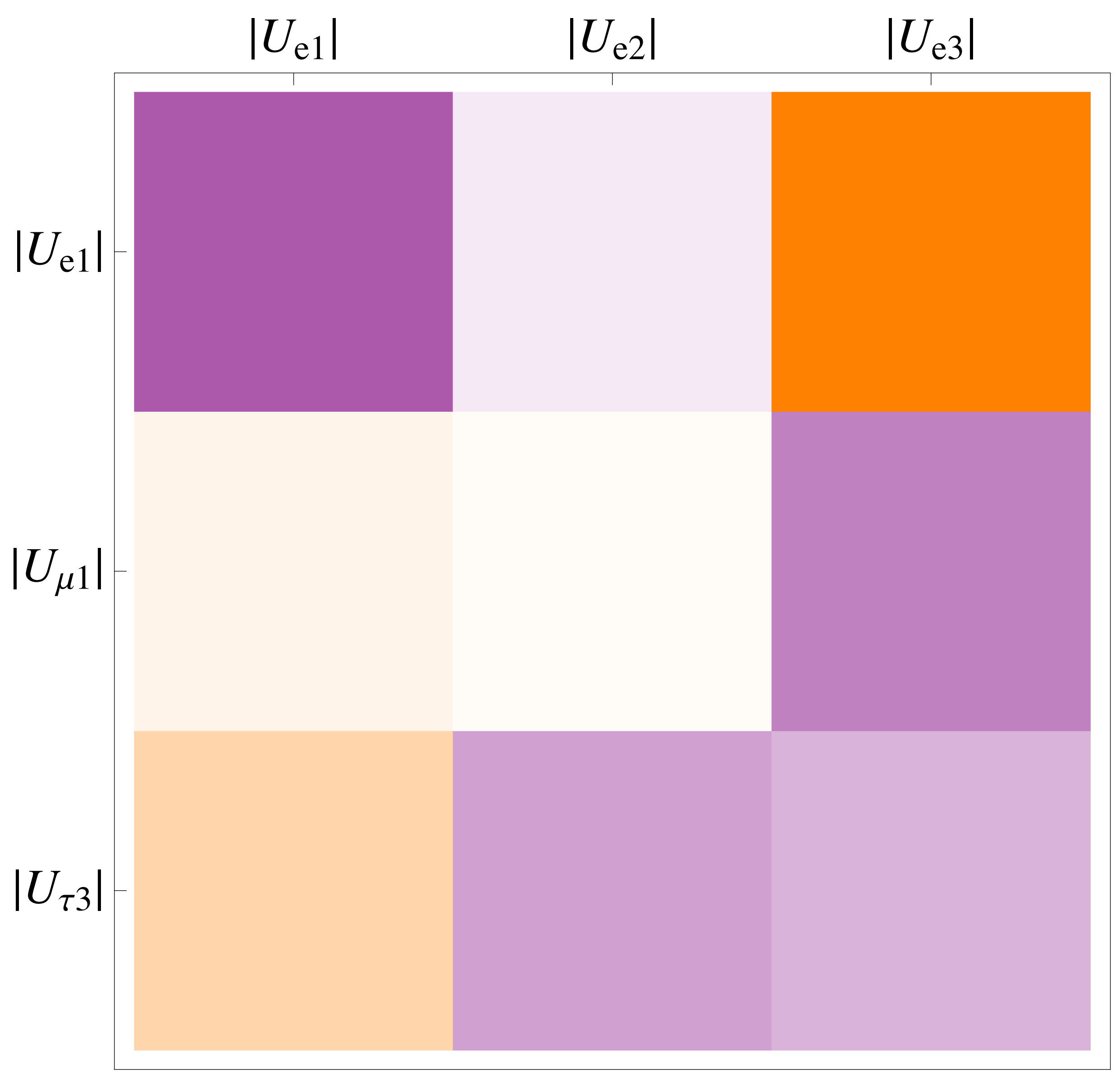
Global fits to oscillation data:

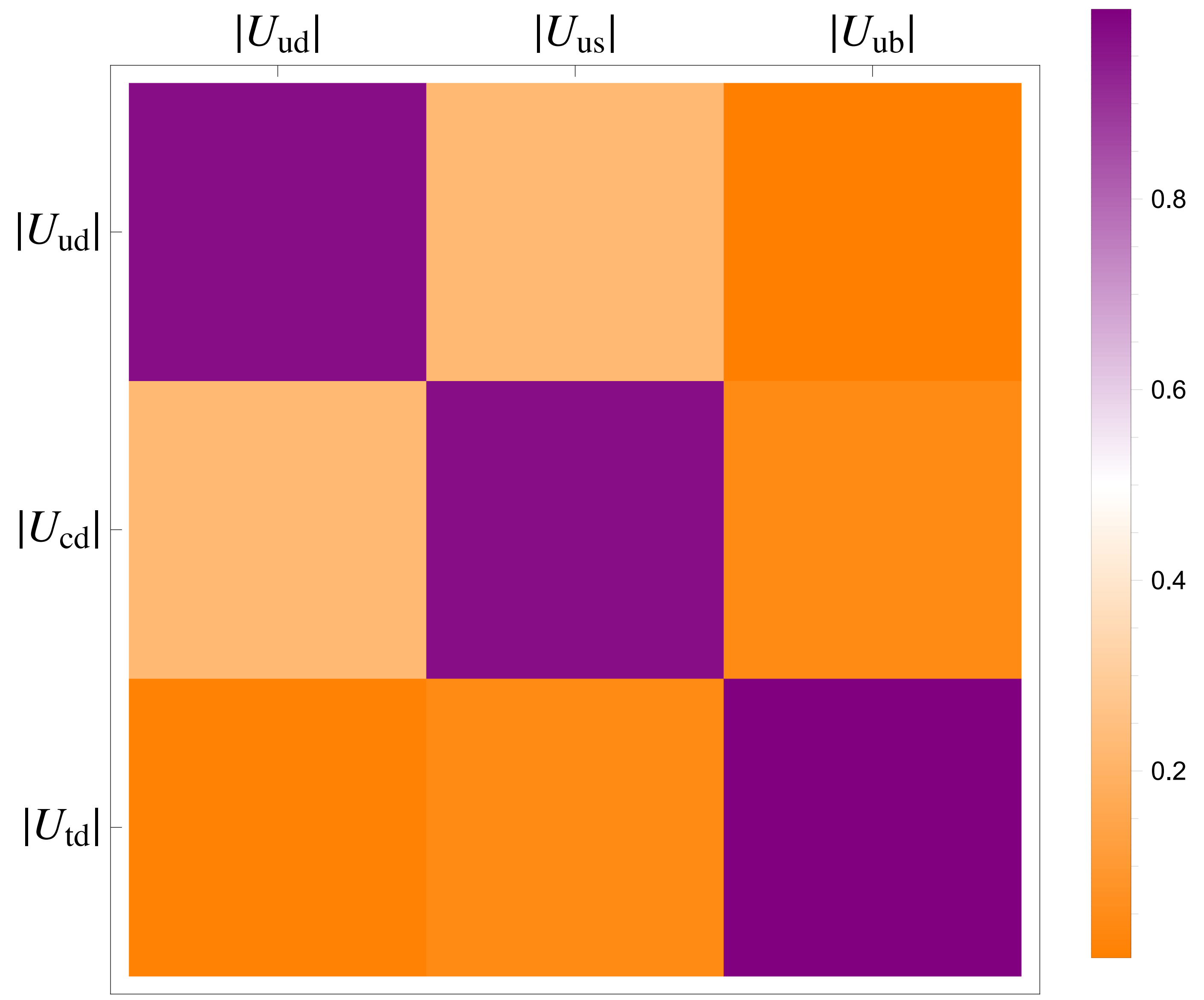
Information on mixing angles, mass splittings

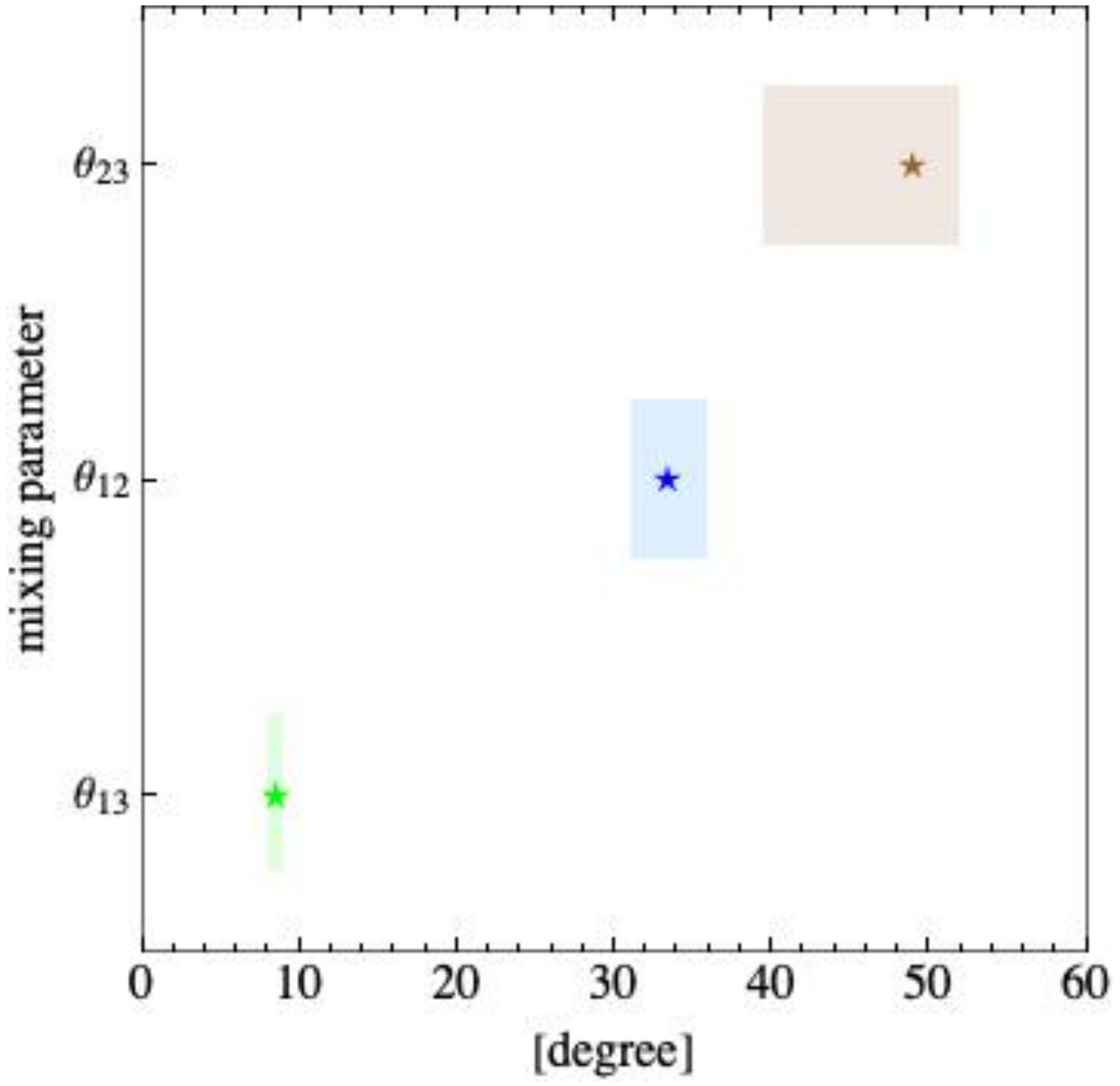
[nufit v5.1]

all three angles non-zero
mixing angles are large!

surprising if compared to small quark mixing







Neutrino oscillation parameters

Global fits to oscillation data:
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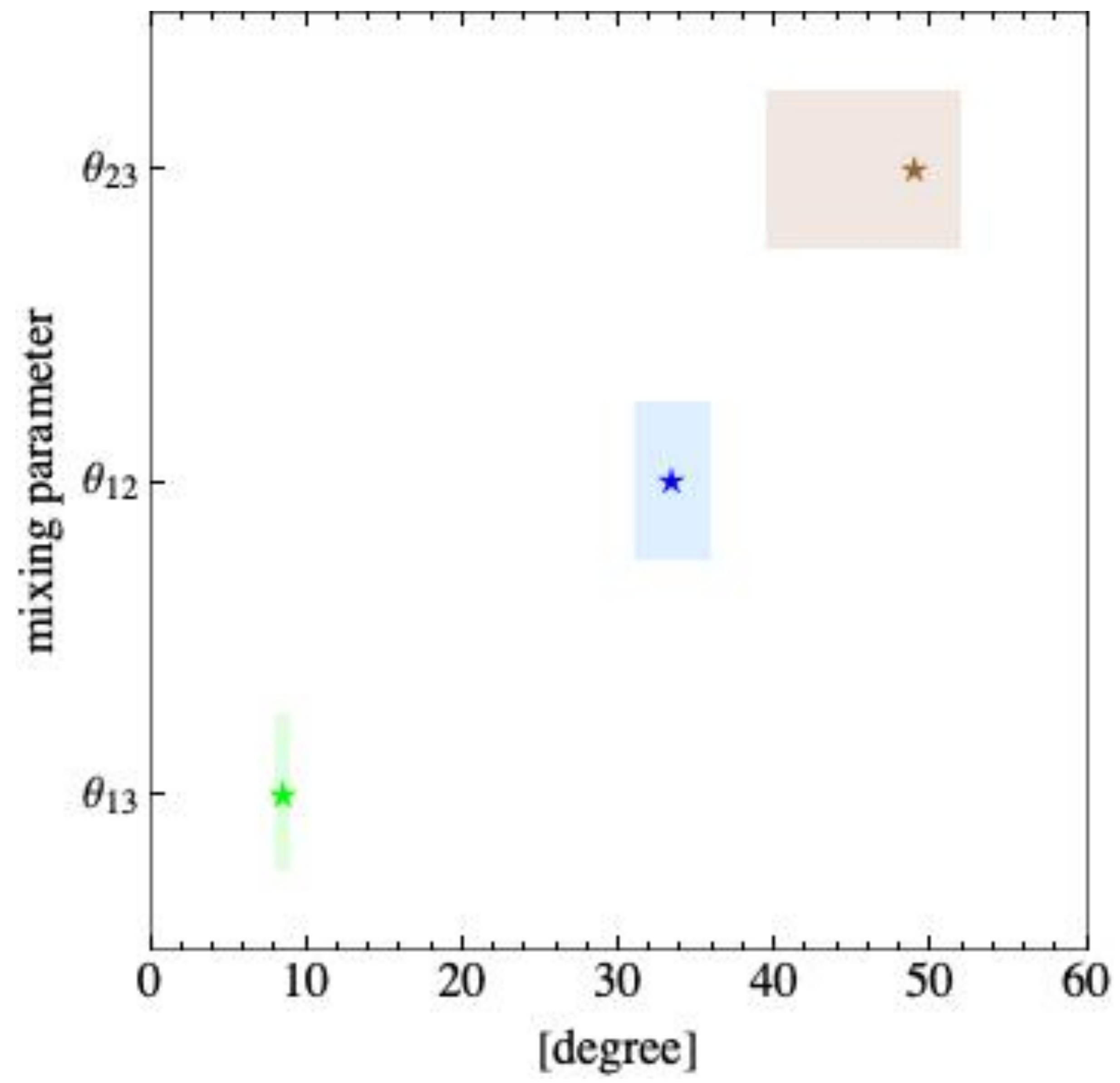
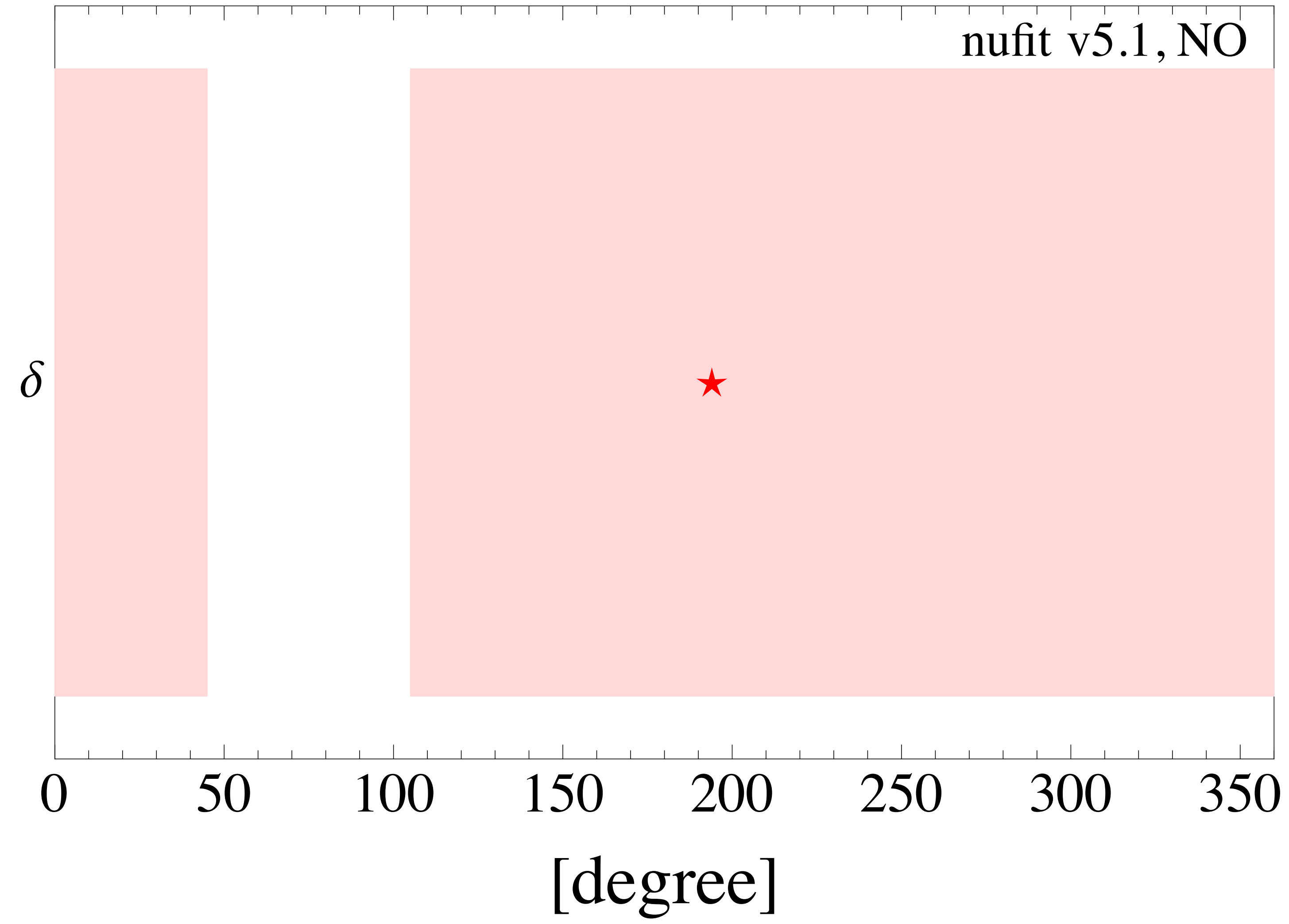


all three mixing angles are non-zero
→ possibility for CPV in lepton sector

currently least known parameter is δ which governs CPV in lepton sector

⇒ Want to measure δ!



[nufit v5.1]

Neutrino oscillation parameters

Global fits to oscillation data:
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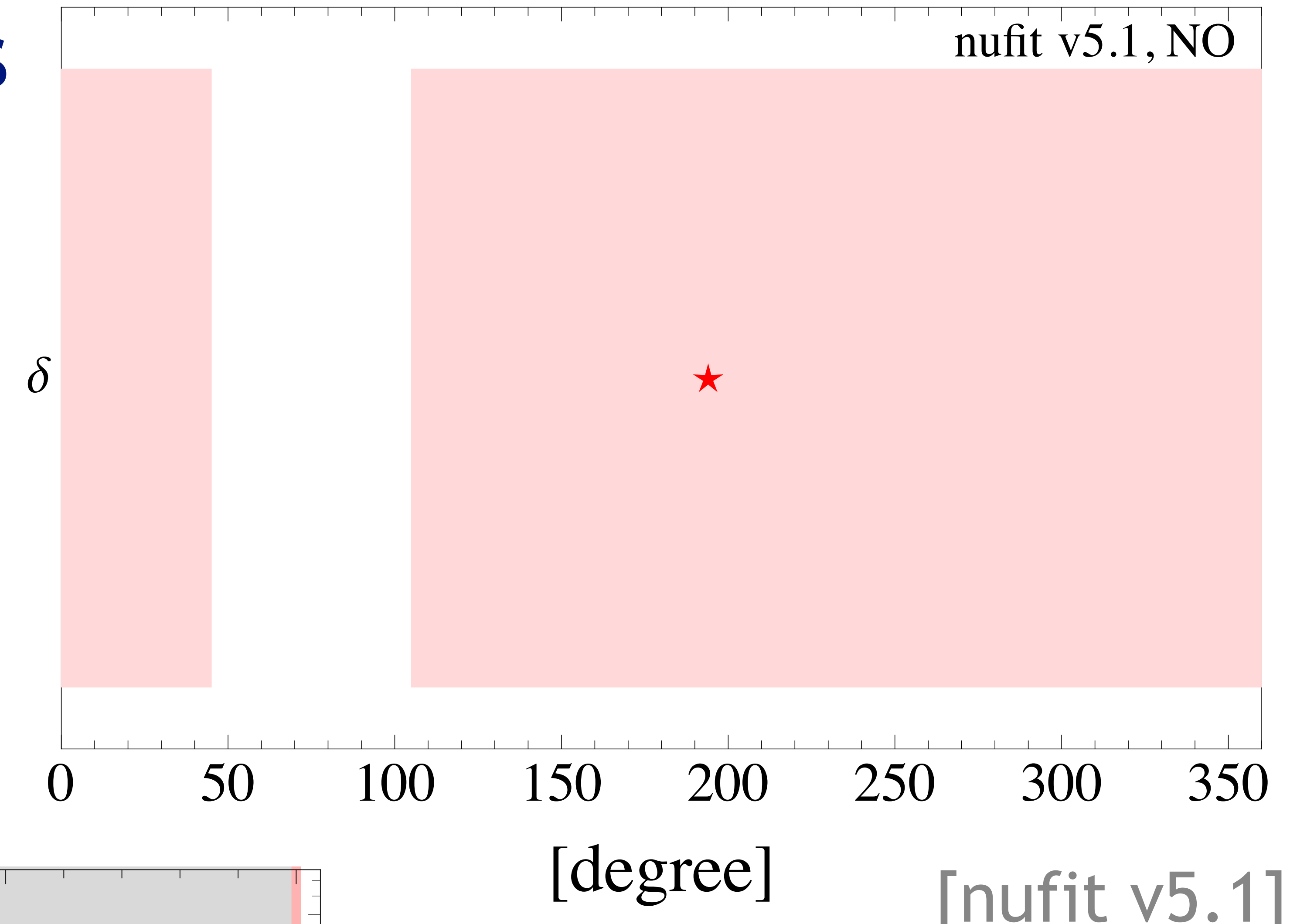

[nufit v5.1]

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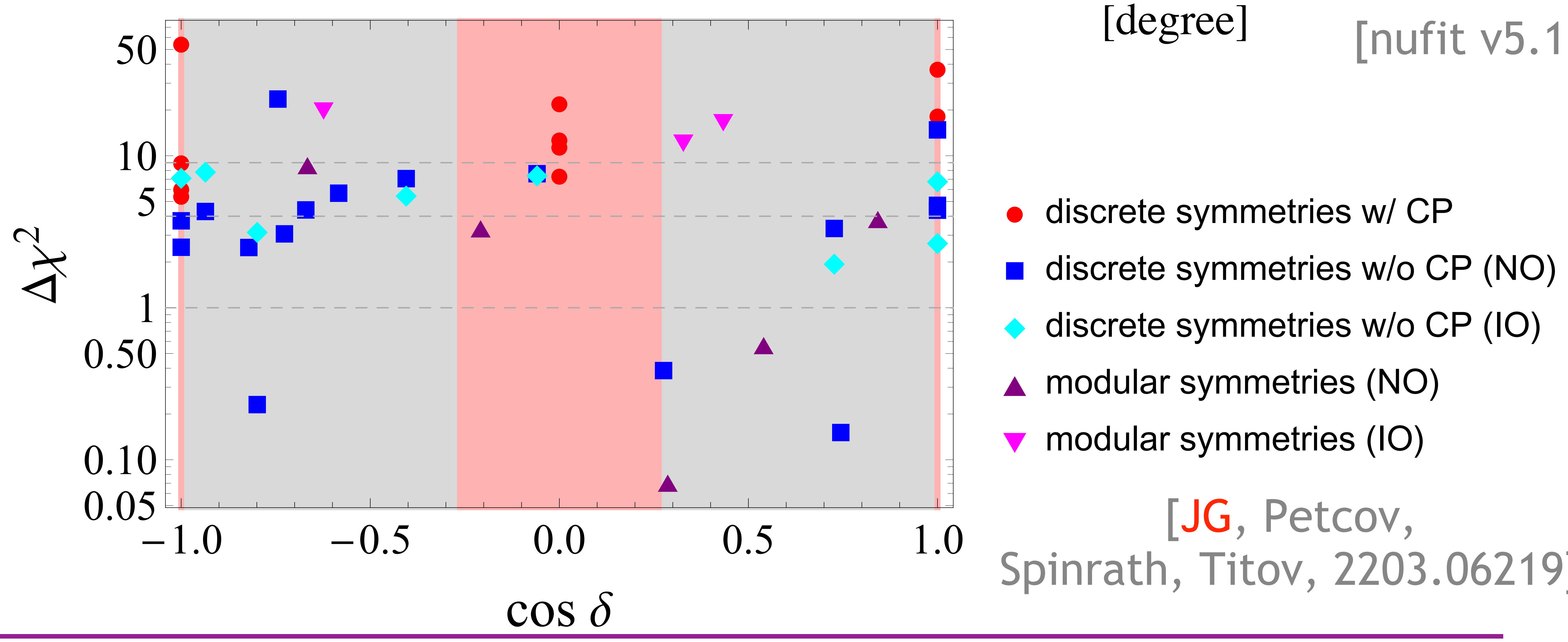
⇒ Want to measure δ!

Is CP violated in the lepton sector?

Distinguish different flavor models

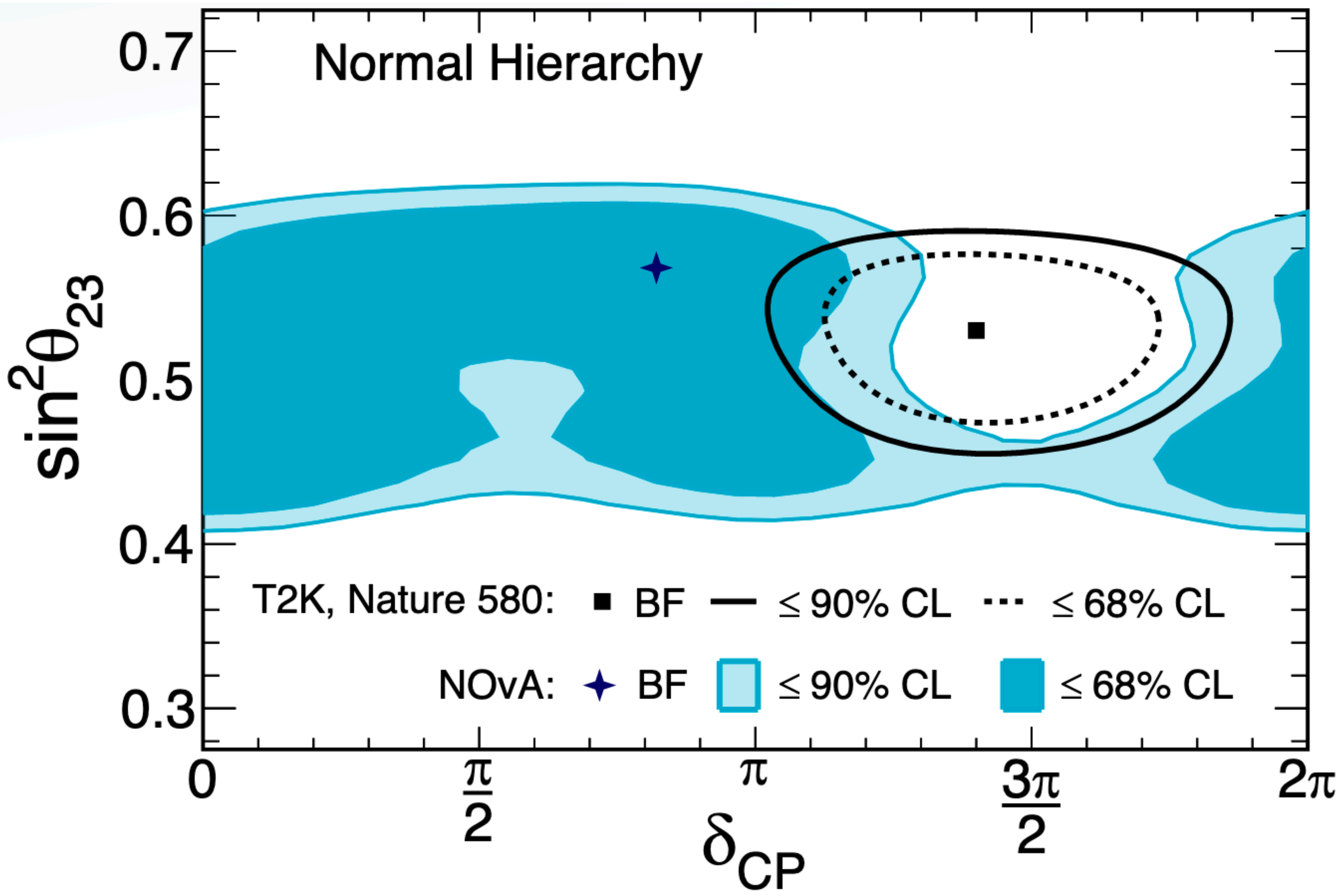


[JG, Petcov, Spinrath, Titov, 2203.06219]

Neutrino oscillation parameters

Current status of CPV search

[Himmel '20]



NOvA, T2K experiments prefer NO

no strong preference for NOvA, generally around $\delta \approx \pi$,

T2K prefers $\delta \approx 3\pi/2$

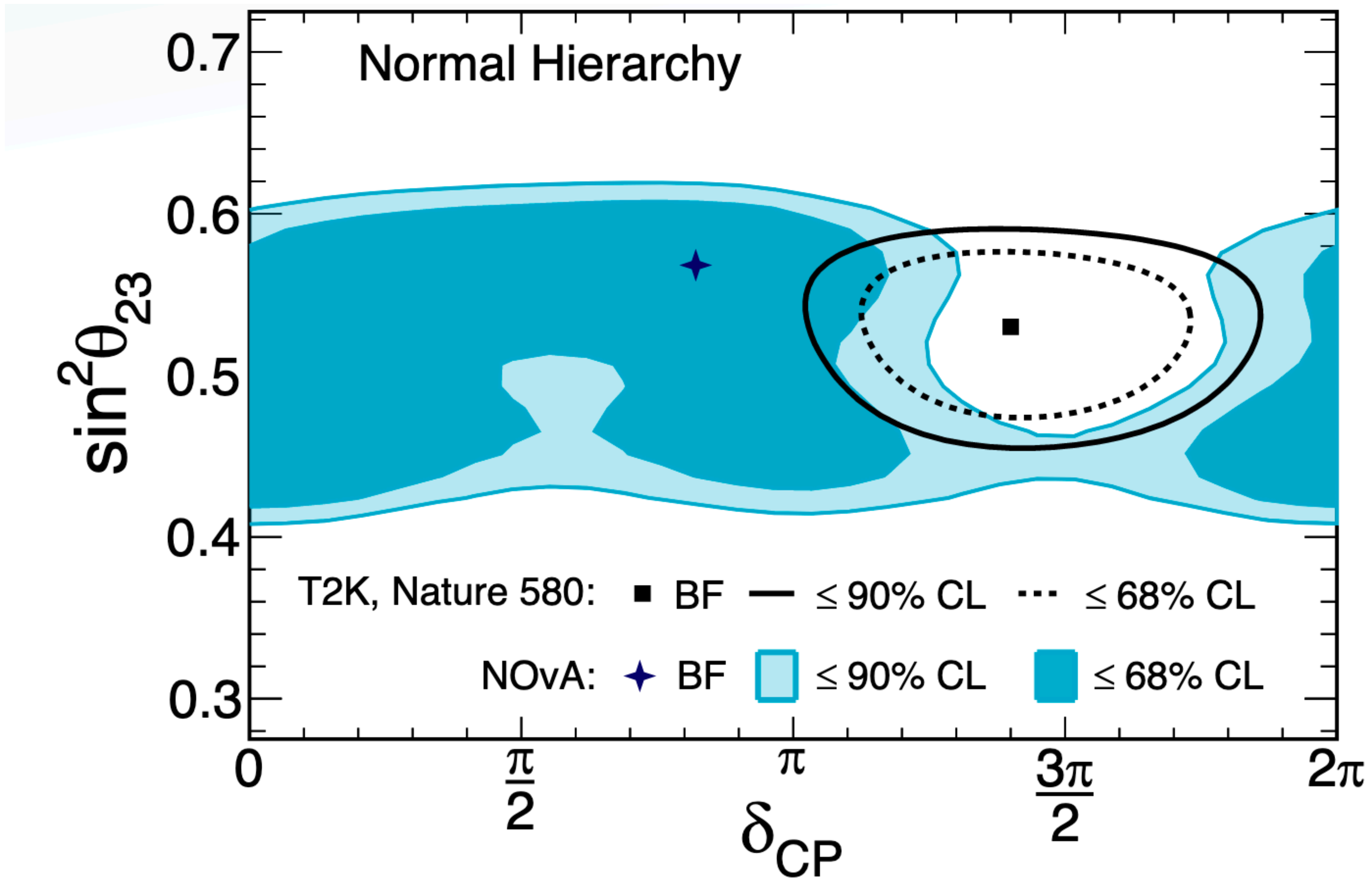
⇒ slight disagreement!

Neutrino 2022 update:
similar results of T2K and NOvA using different statistical framework

Neutrino oscillation parameters

Current status of CPV search

[Himmel ’20]



Introduction of new neutrino interactions can fully resolve the tension

Complex neutrino non-standard interactions with $|\epsilon| \approx 0.2,\ \phi \approx 3\pi/2,\ \delta \approx 3\pi/2$, NO required

[Denton, JG, Pestes, 2008.01110, See also Chatterjee, Palazzo, 2008.04161]

NOvA, T2K experiments prefer NO

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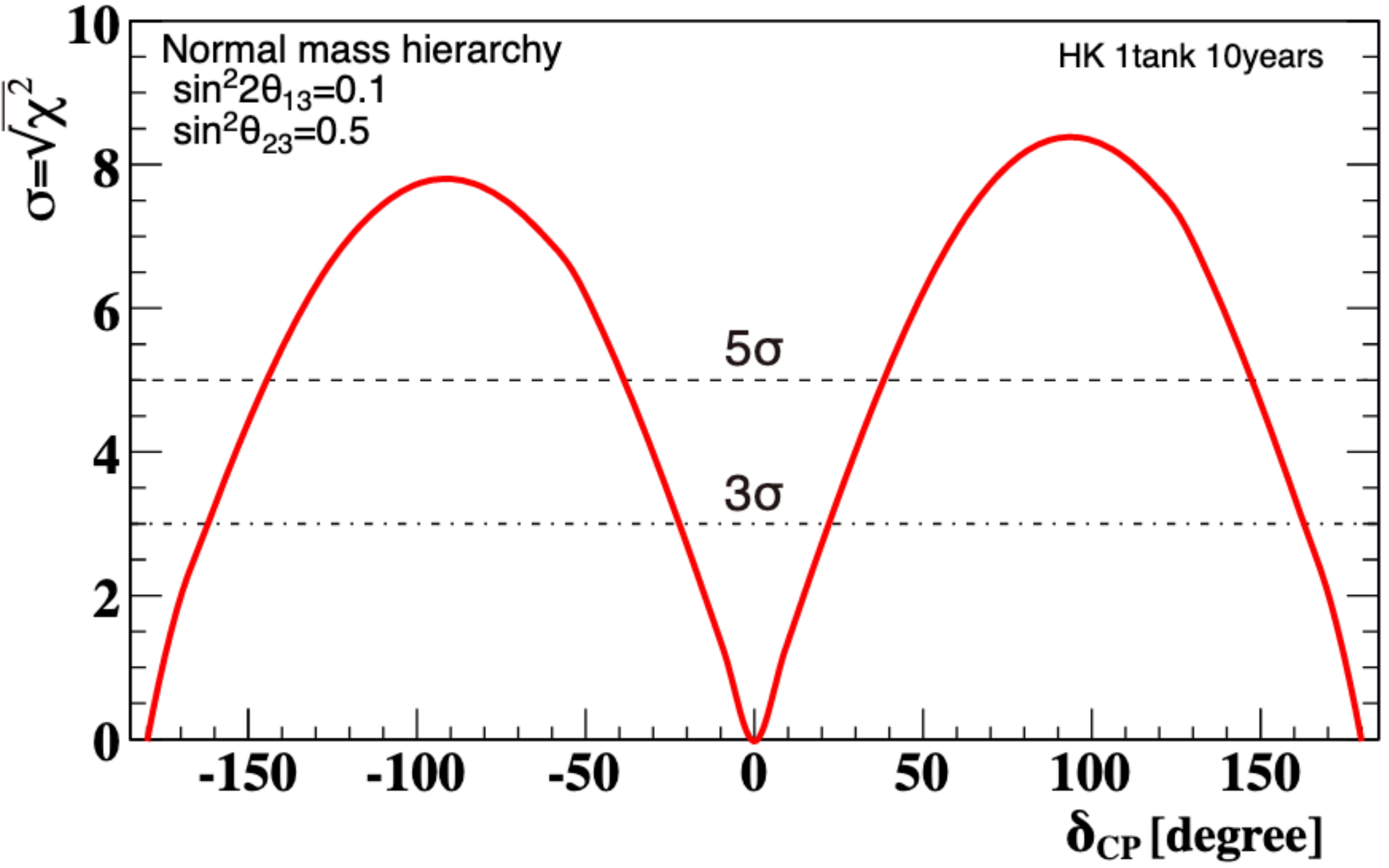
Neutrino 2022 update: similar results of T2K and NOvA using different statistical framework

Measurement of neutrino CPV

Upcoming experiments HK and DUNE will measure δ!

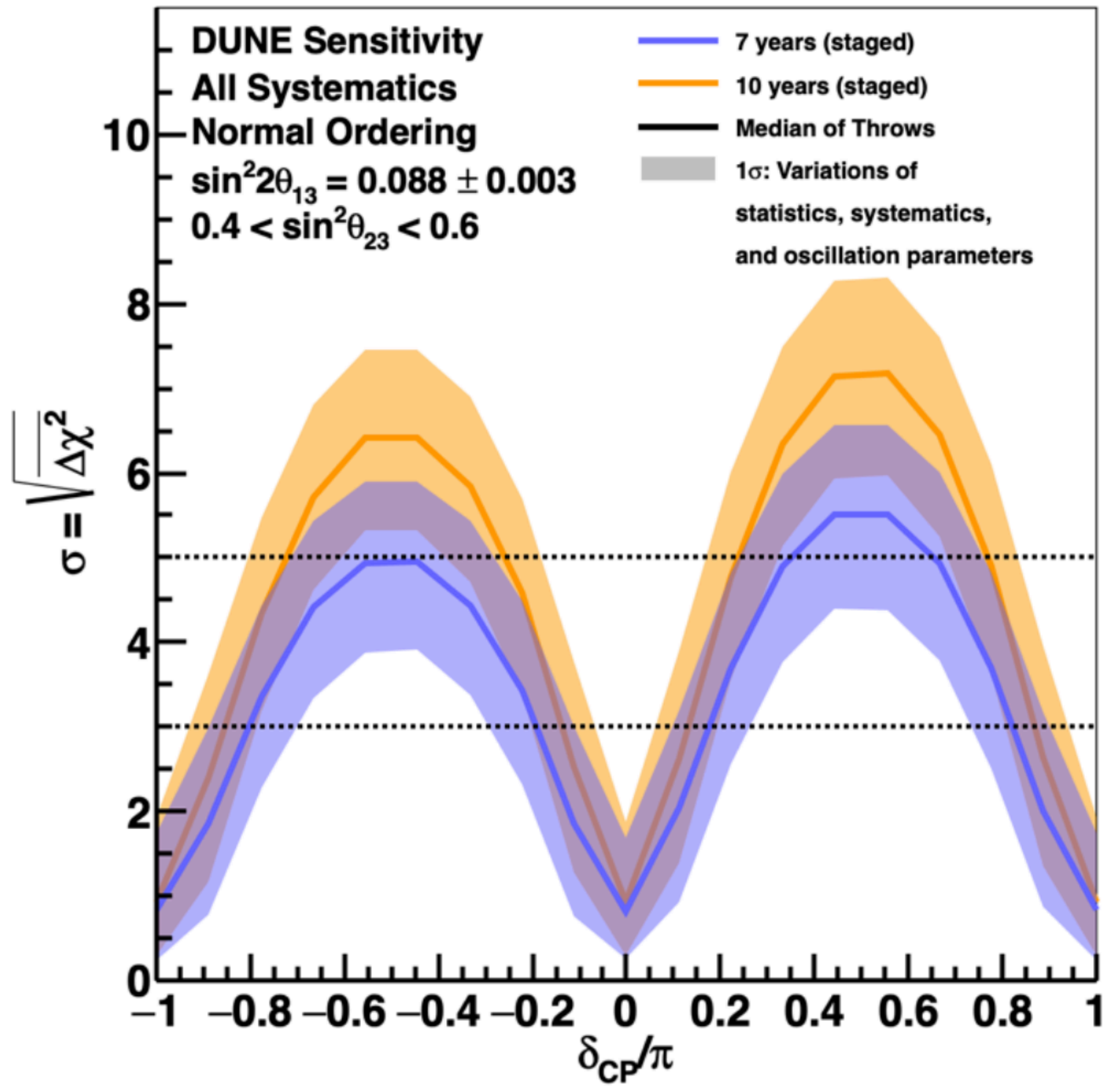
Hyper-Kamiokande sensitivity

[HK DR '18]



DUNE sensitivity

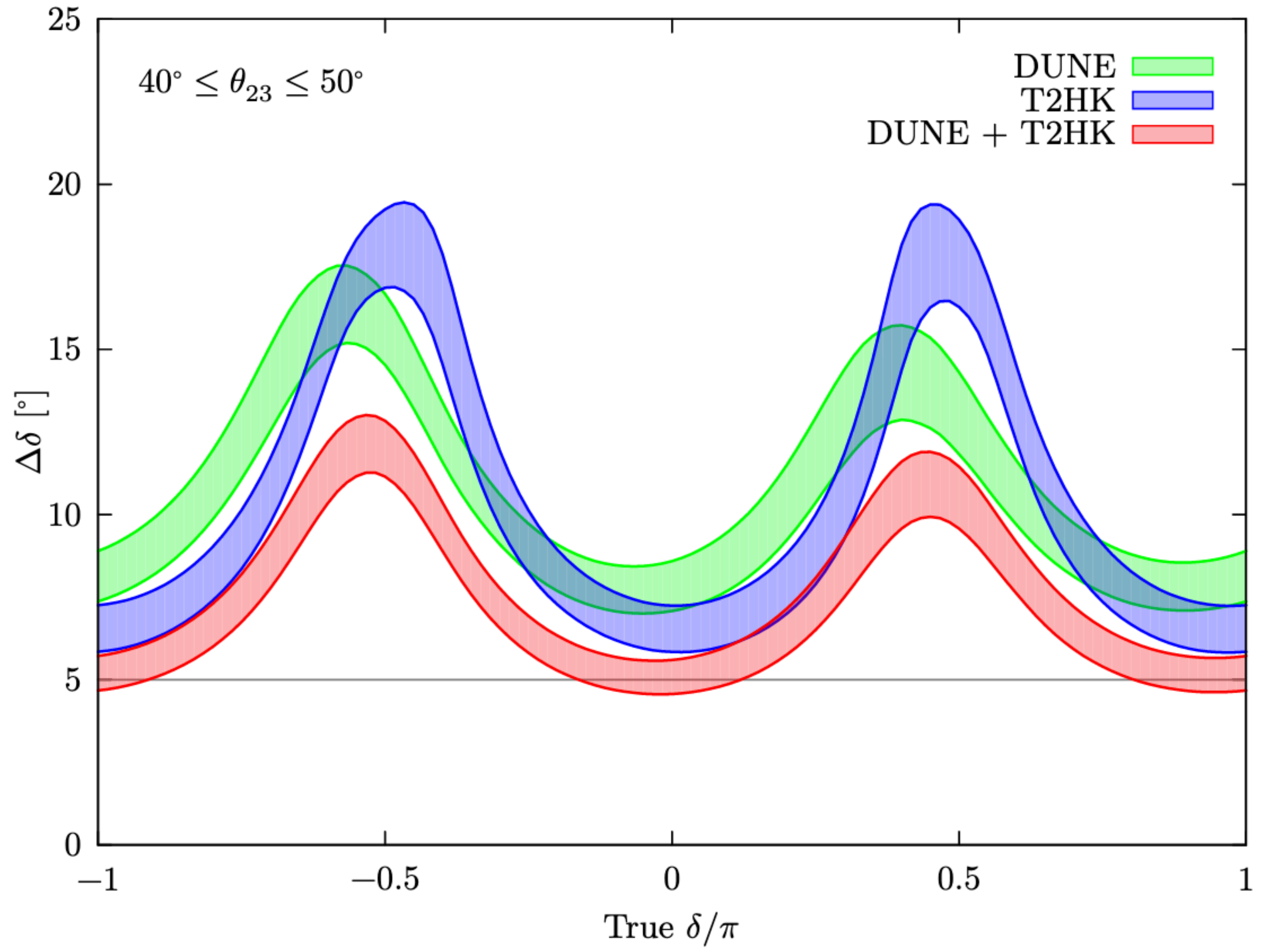
[DUNE TDR '20]



DUNE FD at SURF!

DUNE & HK combination for precision on δ

[Ballett et al, 1612.07275]



Future experiments can also test new physics solution NOvA-T2K tension!

Measurement of neutrino CPV

Upcoming experiments HK and DUNE will measure δ!

Sensitivity to CPV >7σ

Experiments rely on inputs:

- Neutrino cross sections
- Initial neutrino flux
- Priors on oscillation parameters (CPV=3-flavor-effect!)

Measurement of neutrino CPV

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Sensitivity to CPV >7σ

In vacuum near first oscillation maximum

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16J \sin\left(\frac{\Delta m^2_{31} L}{4E}\right) \sin\left(\frac{\Delta m^2_{32} L}{4E}\right) \sin\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

$$\approx -8\pi J \frac{\Delta m^2_{21}}{\Delta m^2_{32}}, \qquad J = s_{12} c_{12} s_{13} c^2_{13} s_{23} c_{23} \sin\delta$$

[Jarlskog '85]

Degeneracy between $\sin\delta$ and oscillation parameters

However matter effects, neutrino vs antineutrino measurements,
information around second oscillation maximum complicates simple analytical understanding

Measurement of neutrino CPV

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Experiments rely on inputs:

- Neutrino cross sections
- Initial neutrino flux

} $\Rightarrow$ Near Detector (DUNE-PRISM) [JG, Kopp, ongoing]

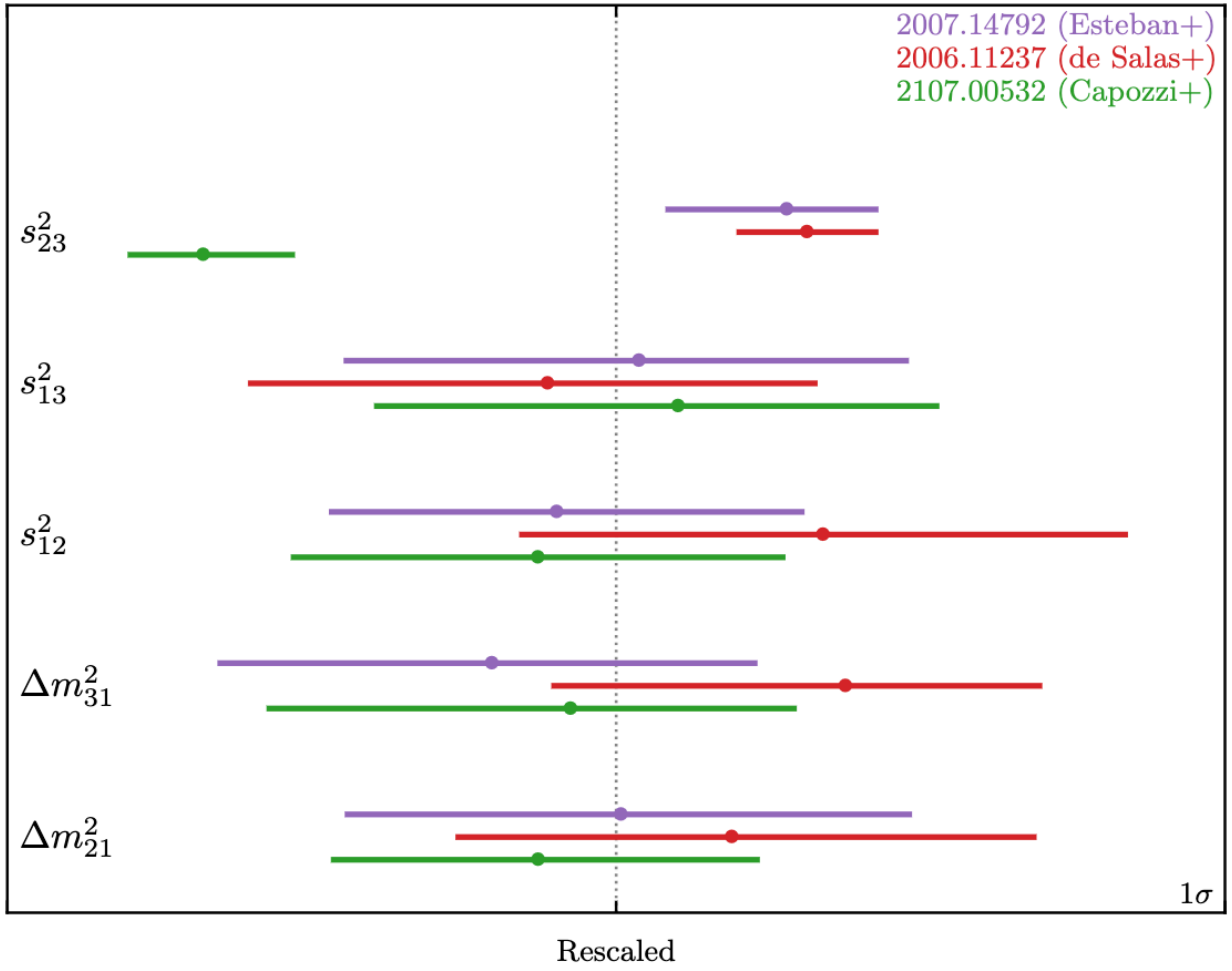
- Priors on oscillation parameters (CPV=3-flavor-effect)

$\Rightarrow$ rely on results from other experiments/global fits

Measurement of neutrino CPV

Global fit knowledge of oscillation parameters

[Denton, JG 2302.08513}



General agreement

Slight disagreement on $\sin^2\theta_{12}$, Δm^2_{31}

Previous disagreement between Δm^2_{21} from KamLand and SK shrunk to $< 2\sigma$

Neutrino'22

"Solar parameters": θ_{12}, Δm^2_{21}
First measured with solar neutrinos
Now also measured with reactor neutrinos

Measurement of neutrino CPV

Upcoming experiments HK and DUNE will measure δ!

Sensitivity to CPV >7σ

Experiments rely on inputs:

- cross sections
- Initial neutrino flux

} $\Rightarrow$ Near Detector (DUNE-PRISM)

- Priors on oscillation parameters (3-flavor-effect)

$\Rightarrow$ rely on results from other experiments/global fits

How large is the impact of other oscillation parameters on the sensitivity/precision of δ?

Here Comes the Sun:
Solar Parameters in Long-Baseline Accelerator Neutrino Oscillations

Peter B. Denton[1] and Julia Gehrlein[2,1]

[Denton, JG 2302.08513}

Measurement of neutrino CPV

How large is the impact of other oscillation parameters on the sensitivity/precision of δ?

Degeneracy between $\sin\delta$ and oscillation parameters

However matter effects, neutrino vs antineutrino measurements, information around second oscillation maximum complicates analytical understanding

$\Rightarrow$ Numerically analyse impact of oscillation prior on LBL data using GLoBES software

[Huber, Lindner, Winter, 0407333}

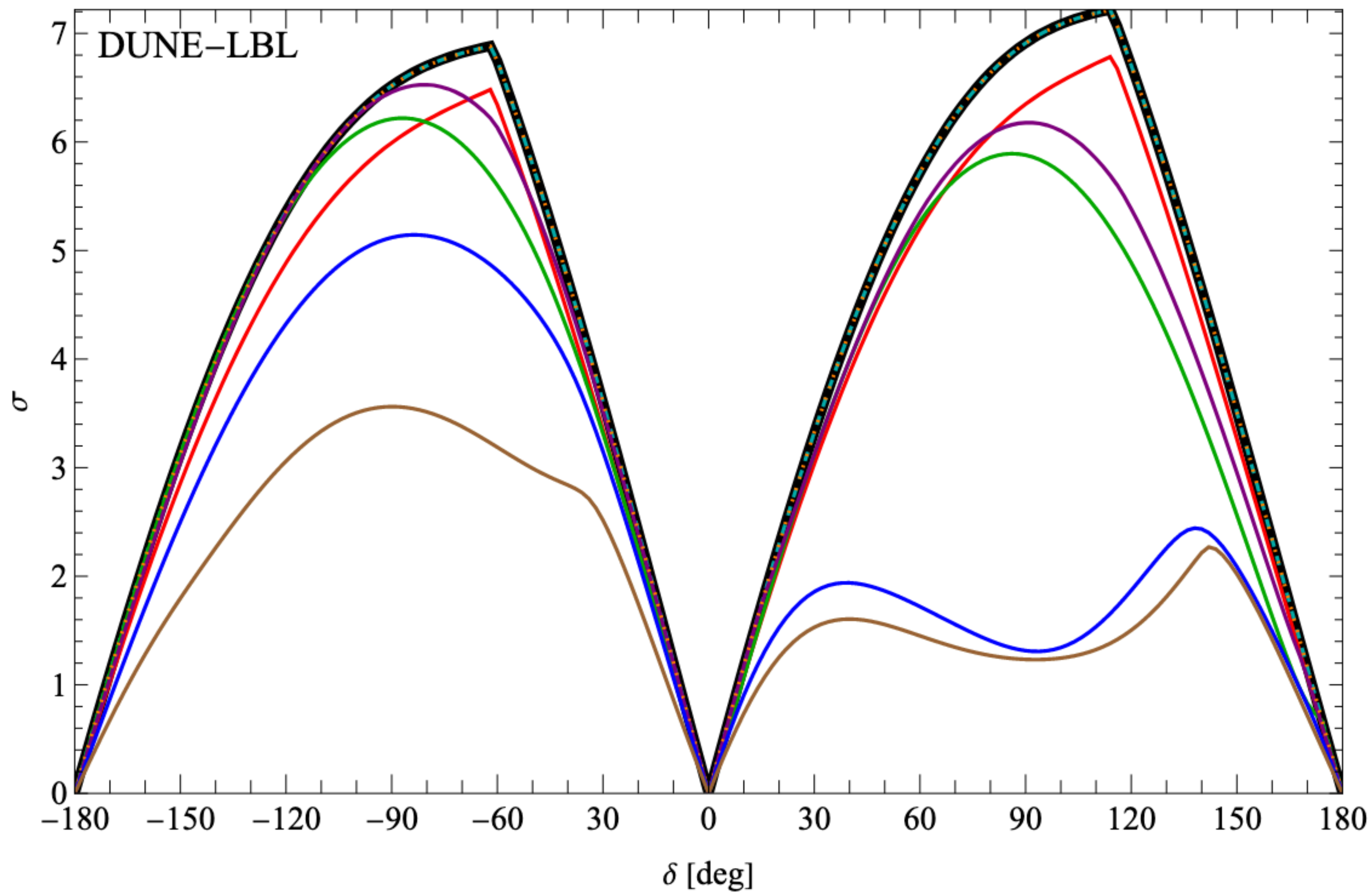
Results for

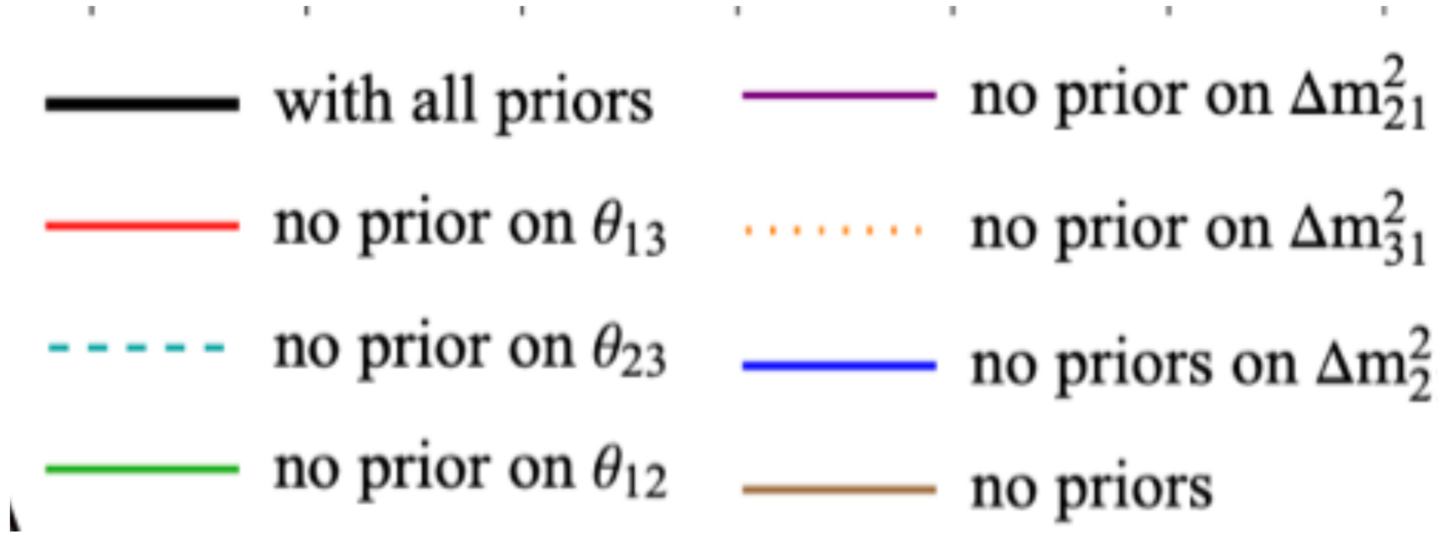
- Future experiments: DUNE, HK
- Current experiments: T2K, NOvA
- Using ν, $\bar{\nu}$
- ν_e appearance+ ν_μ disappearance

Measurement of neutrino CPV

Impact of oscillation parameter priors

[Denton, JG 2302.08513}





Drastic reduction of sensitivity without using priors on both solar parameters!

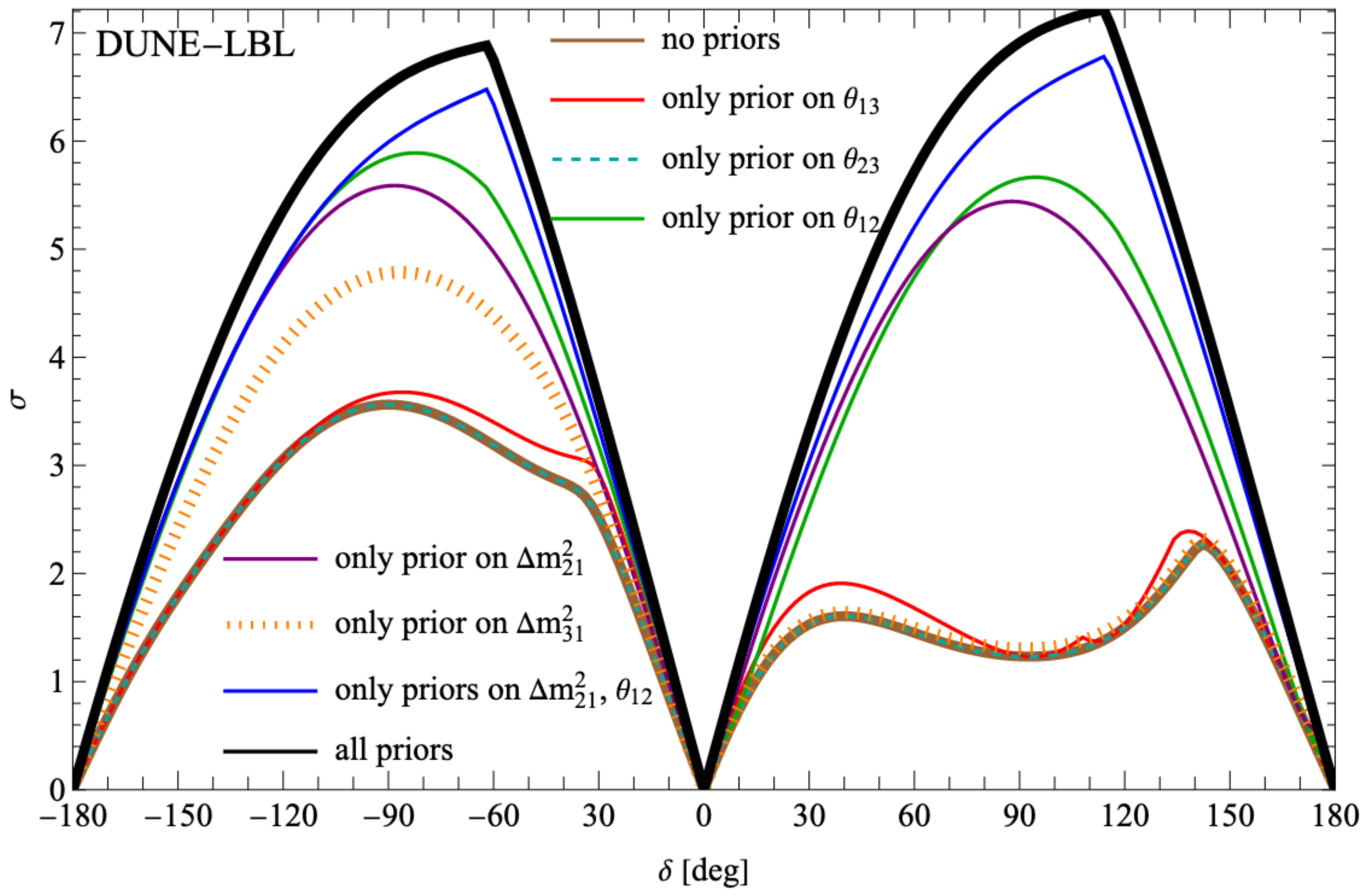
Without any priors: sensitivity $\lesssim 3\sigma$ for DUNE

In general qualitative similar results for HK (focus on DUNE in following)

Measurement of neutrino CPV

Impact of oscillation parameter priors

[Denton, JG 2302.08513}

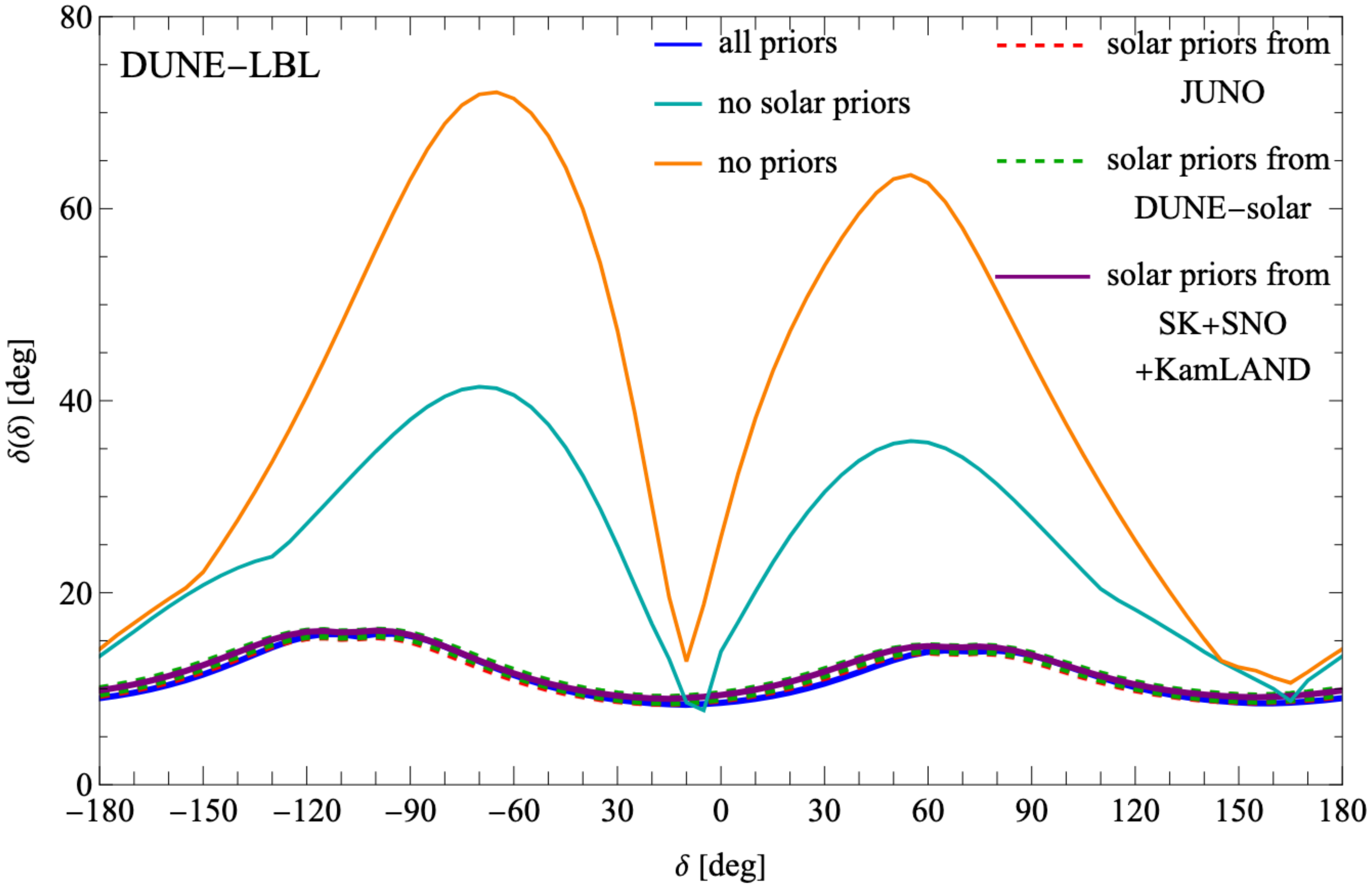


⇒ Priors on solar parameters important to reach expected sensitivity

Measurement of neutrino CPV

Impact of oscillation parameter priors

[Denton, JG 2302.08513]

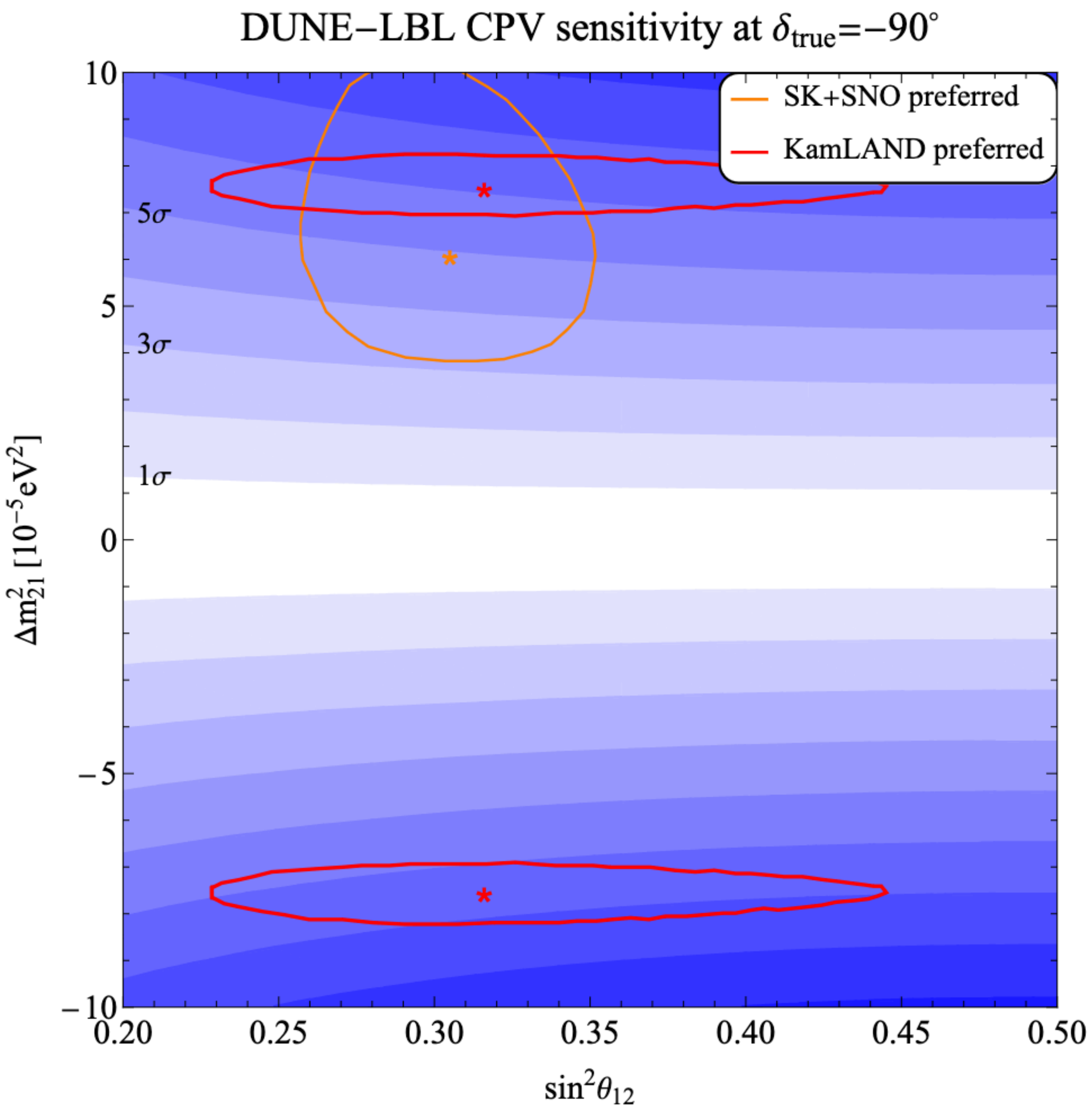


⇒ Drastic reduction of precision on δ without priors on both solar parameters!

Measurement of neutrino CPV

Impact of oscillation parameter priors

[Denton, JG 2302.08513}

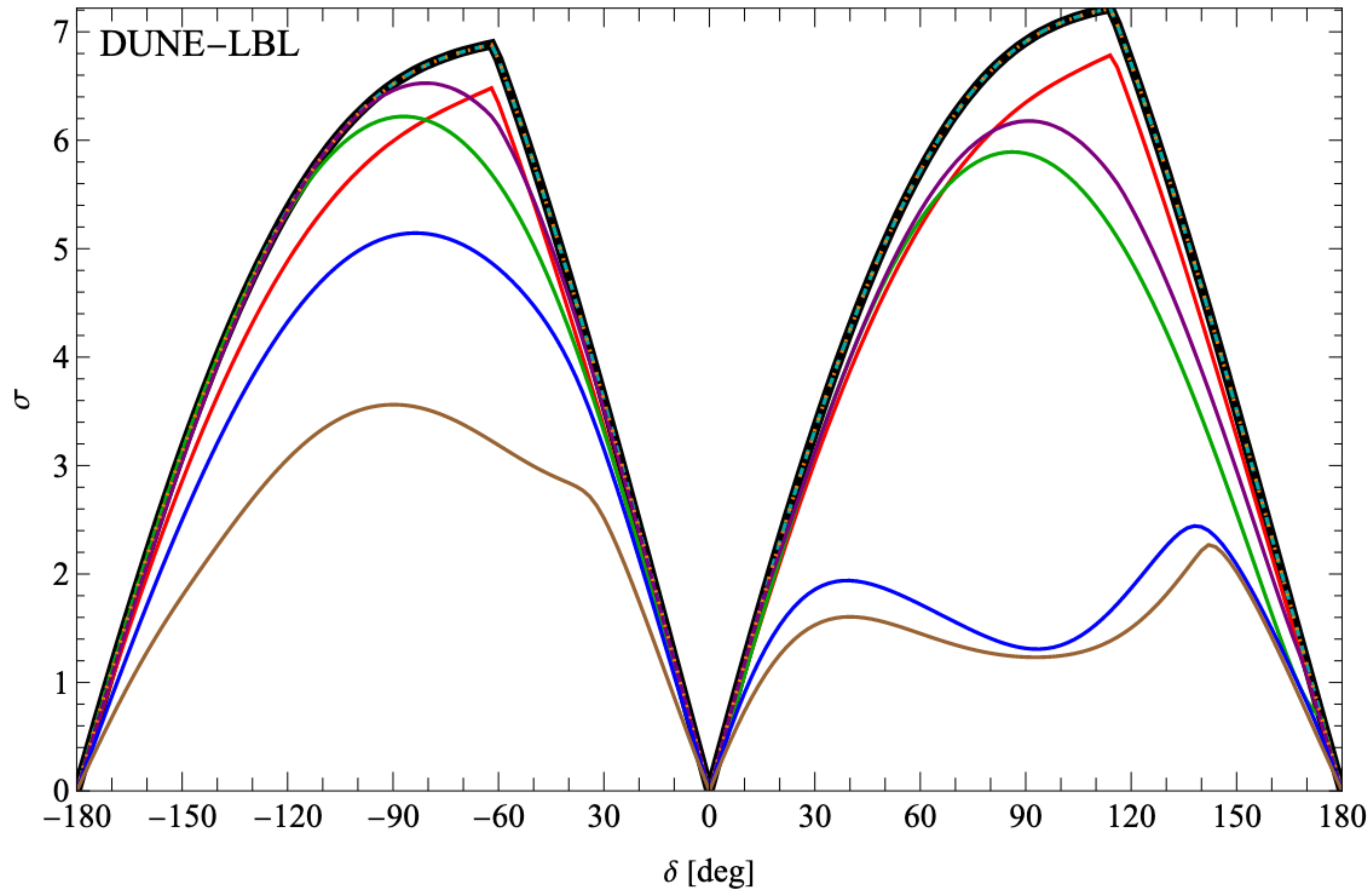


Sensitivity to discover $\delta = -90^\circ$ varying best fit values of solar parameters while keeping their uncertainty fixed

Depending on best fit values from KamLand to solar reduces sensitivity by $> 1\sigma$!

Measurement of neutrino CPV

[Denton, JG 2302.08513}

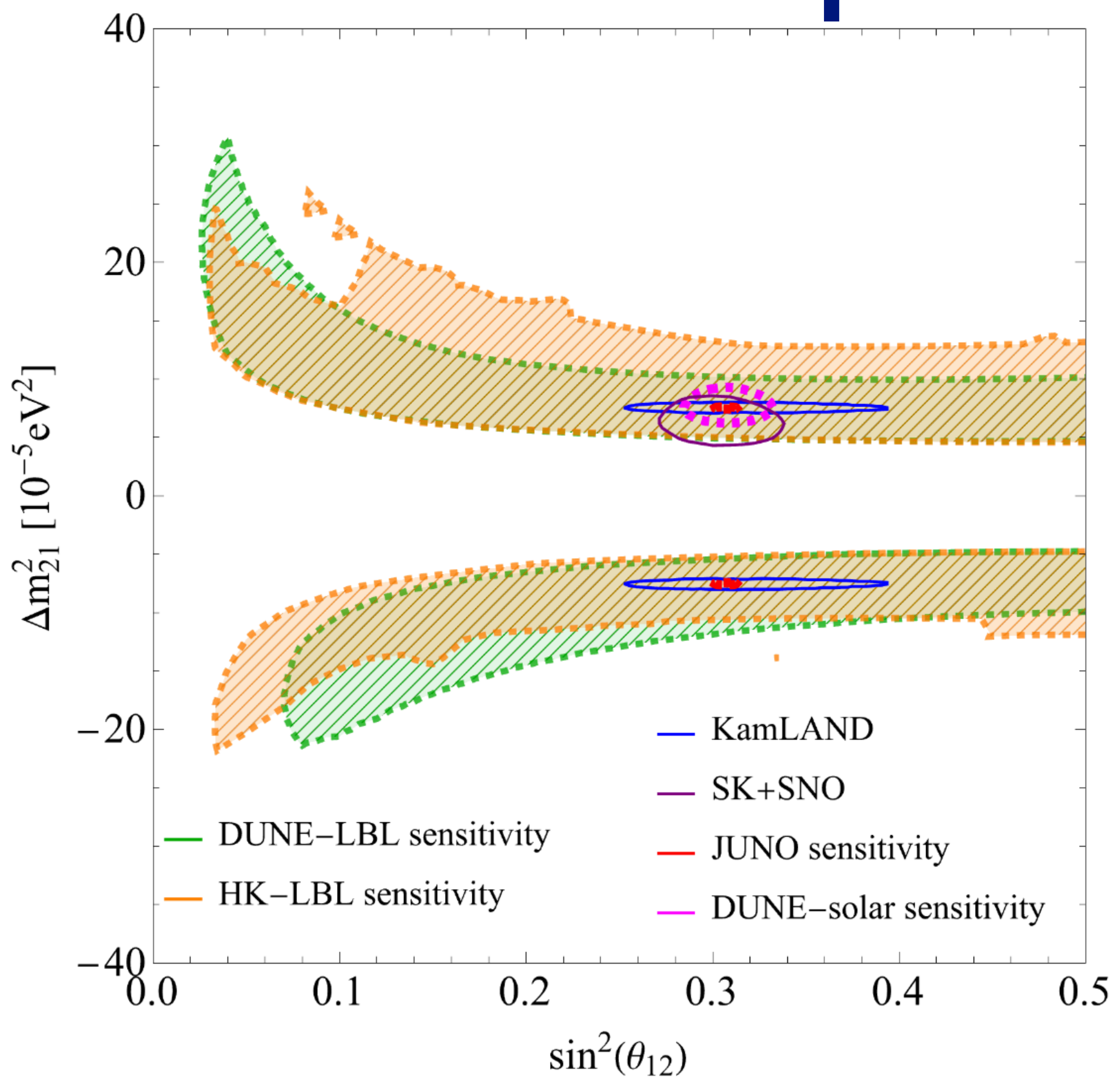


Without solar priors the sensitivity does not reduce to zero

→ DUNE-LBL is sensitive to solar parameters

DUNE-LBL sensitivity to solar parameters

[Denton, JG 2302.08513}



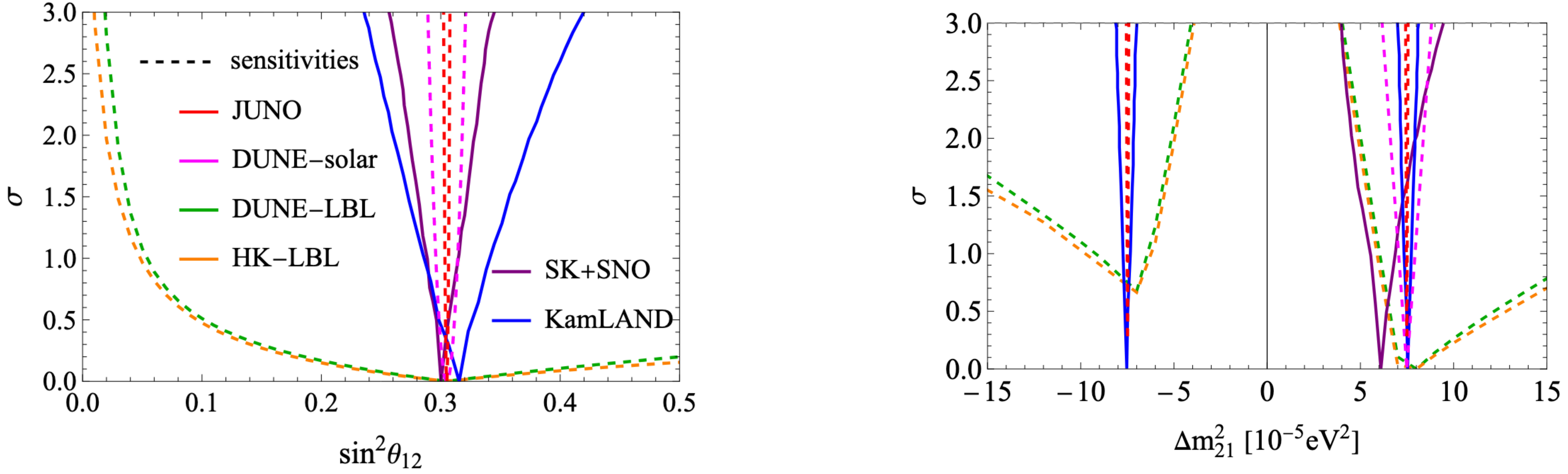
Some sensitivity to solar parameters at future LBL experiments

Not competitive with JUNO or DUNE-solar (Comparable sensitivity to solar mass splitting as solar experiments)

However allows LBL experiments to cross check three flavor paradigm!

DUNE-LBL sensitivity to solar parameters

[Denton, JG 2302.08513}



Some sensitivity to solar parameters at future LBL experiments

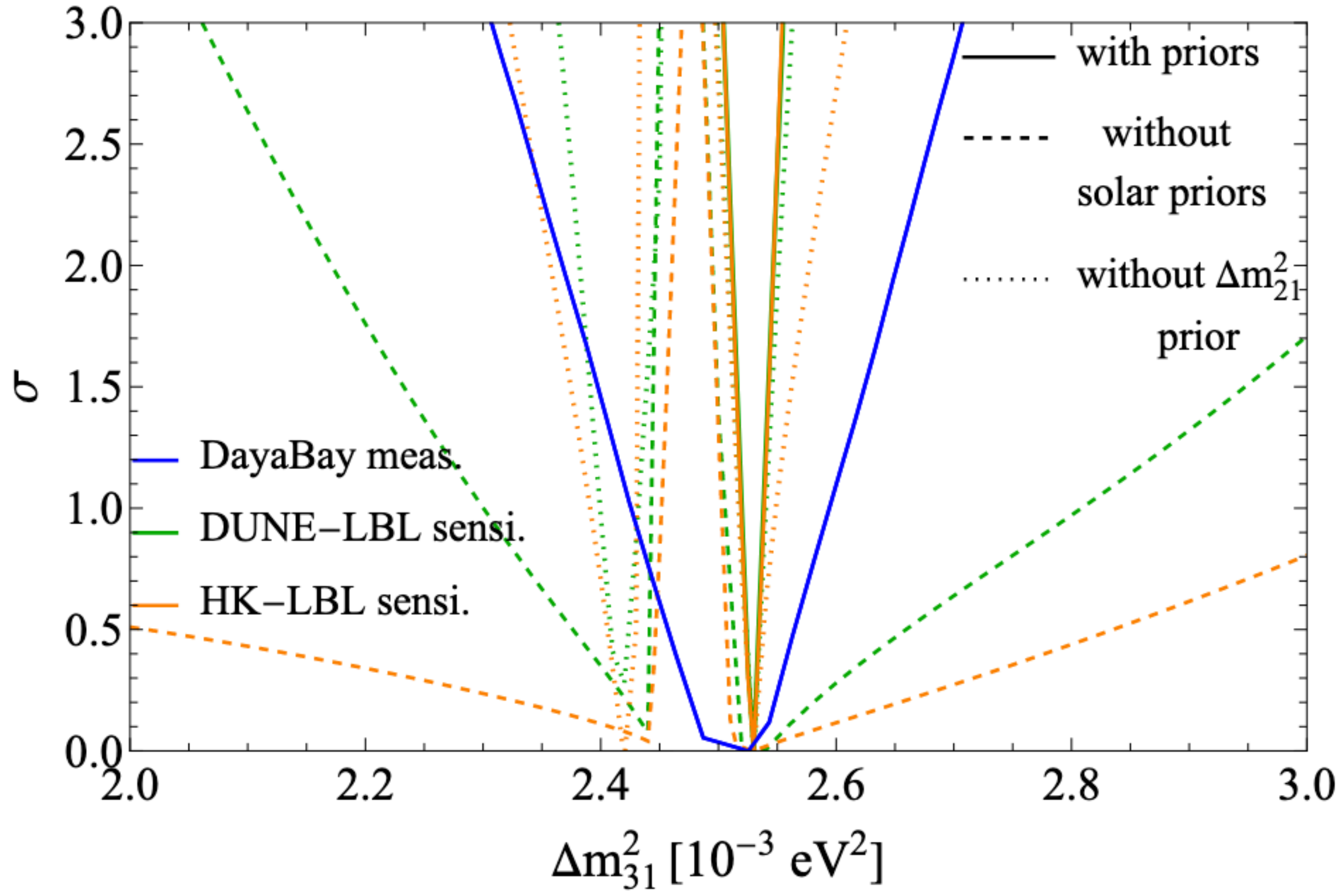
Can rule out vanishing solar parameters at 7σ sigma

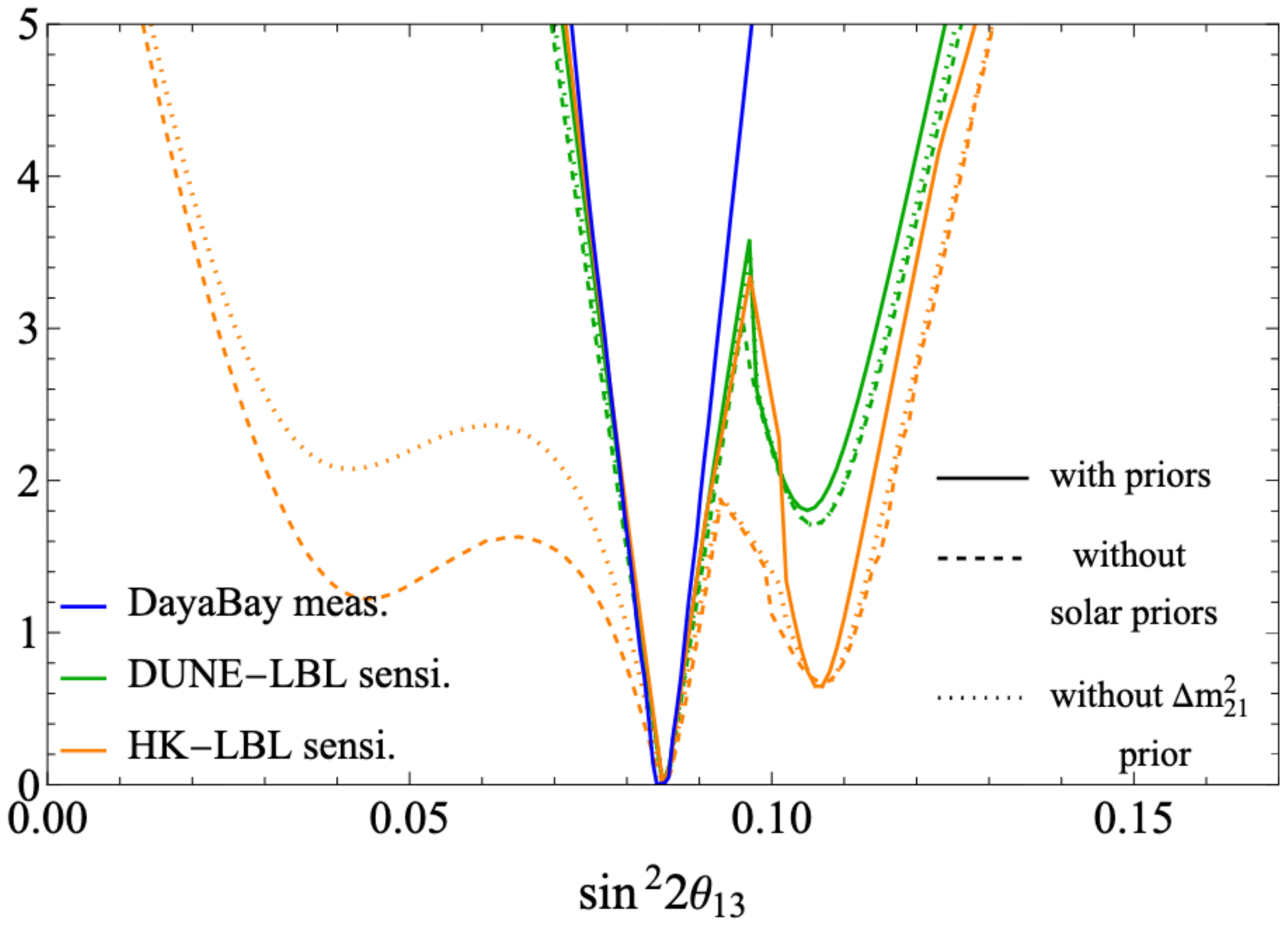
Determine sign(Δm^2_{21}) at $\sim 1\sigma$

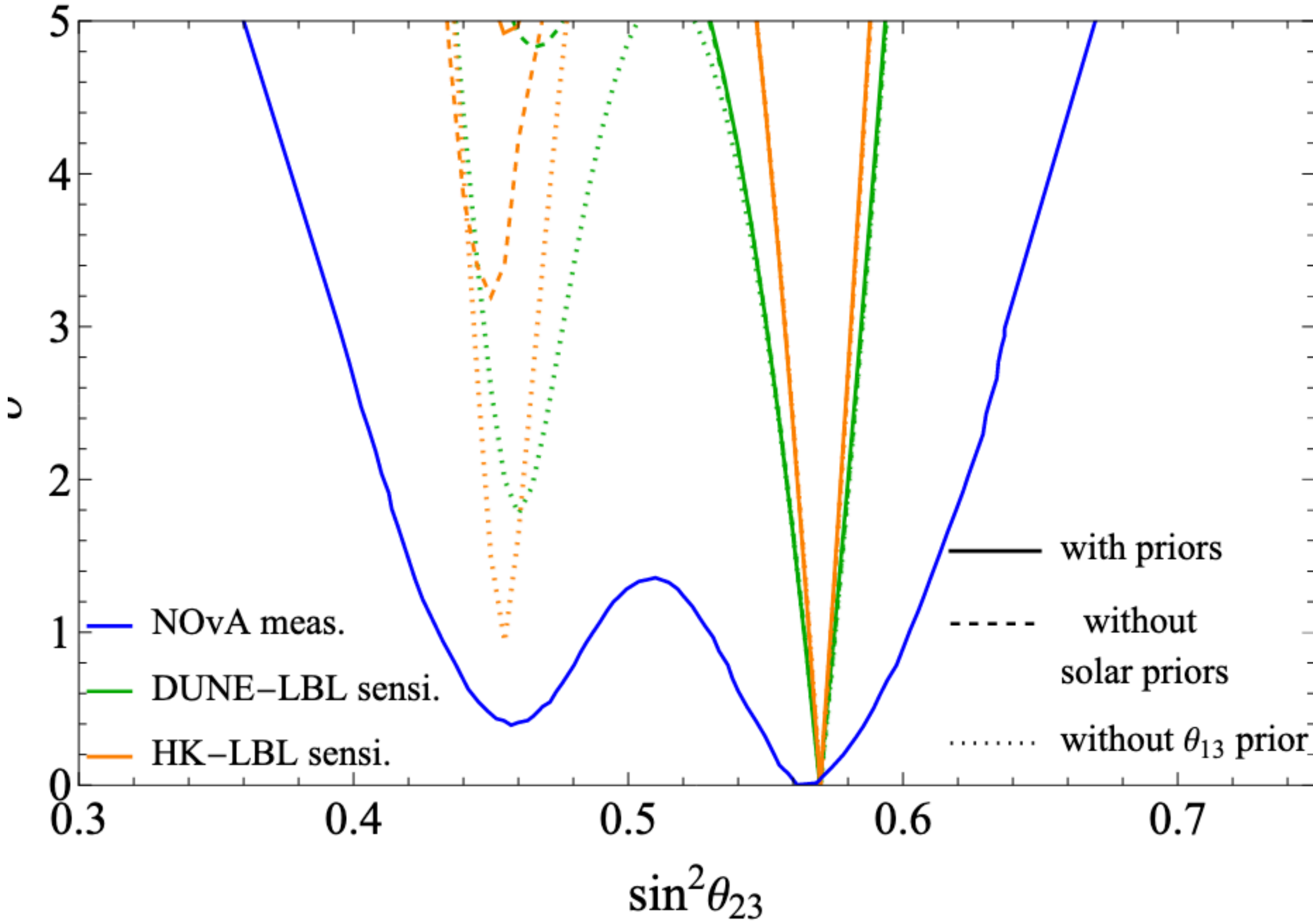
Impact of solar parameters On other quantities

[Denton, JG 2302.08513}

Future experiments will also measure Δm^2_{31}, θ_{13}, θ_{23}







Solar parameters also play an important role there

Conclusions

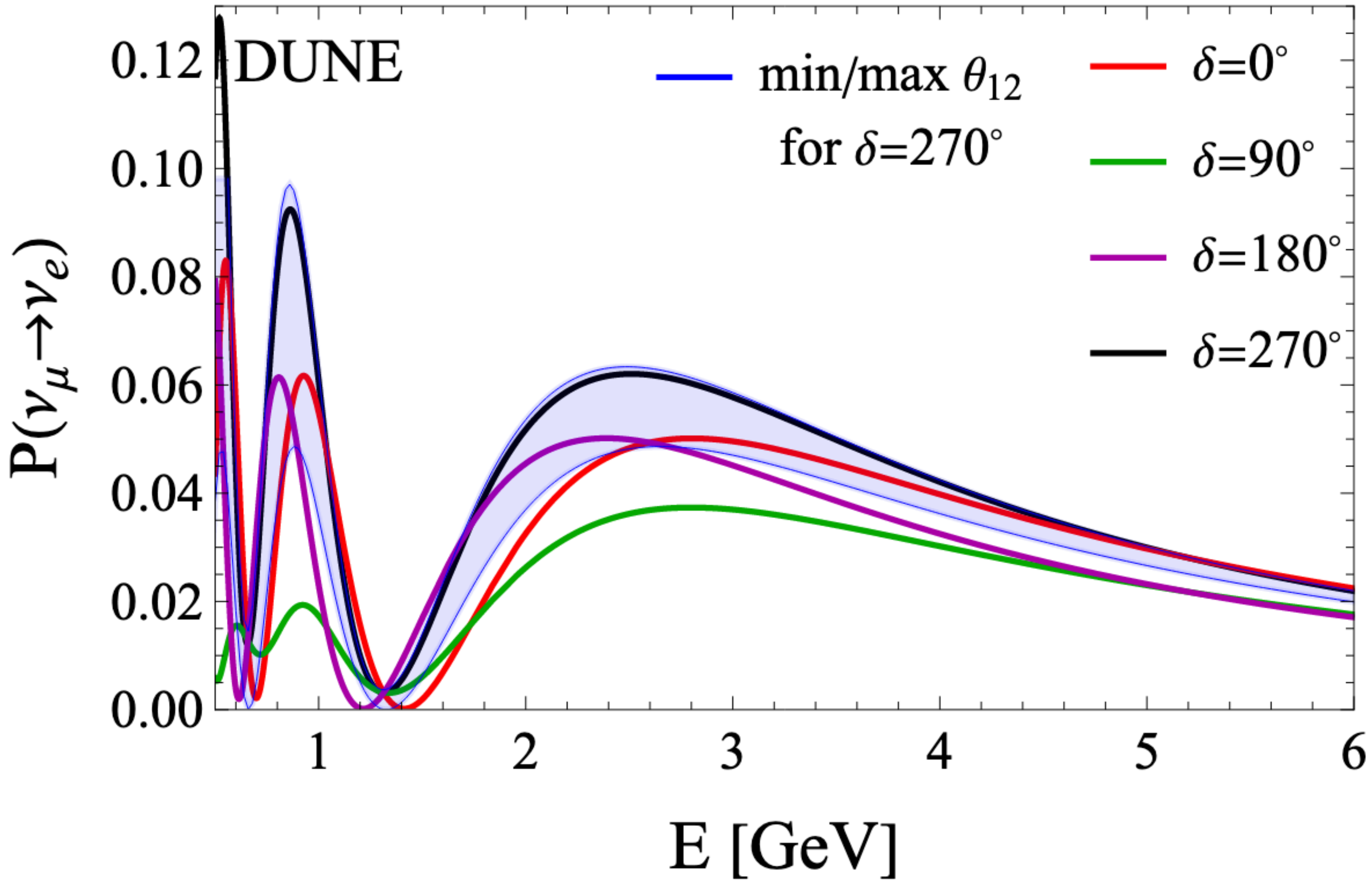
- Next generation LBL experiments will measure δ
- First study of solar parameters at LBL experiments
- To achieve envisioned sensitivity and precision: Priors on solar parameters required!
- Some sensitivity to solar parameters at LBL → important cross check of 3- flavor-paradigm
- Solar parameters are important for measurement of remaining parameters $(\Delta m^2_{31},\ \sin^2\theta_{13})$
- Current LBL experiments: similar results but sensitivity worse even with priors

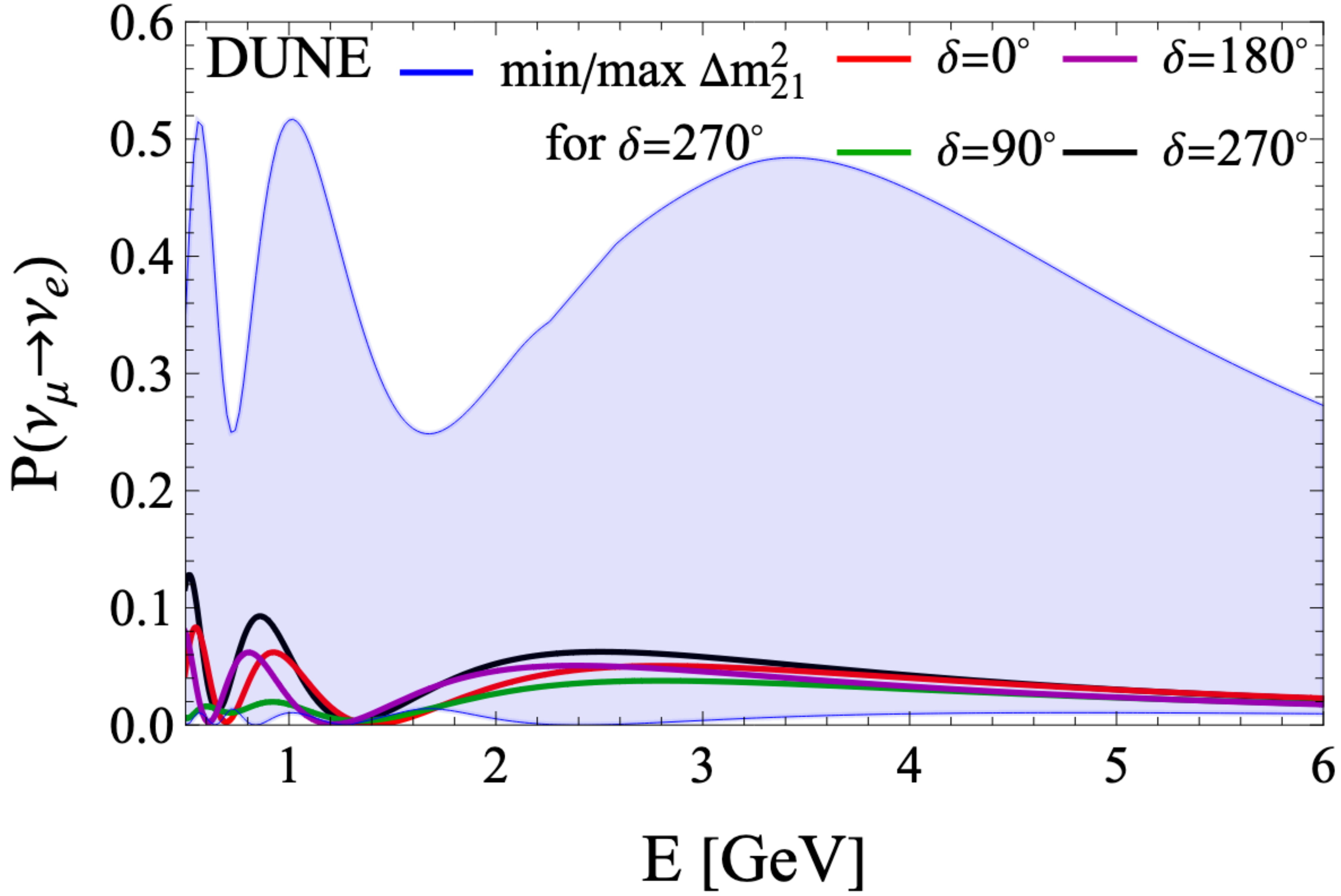
Thanks for your attention!

Backup: analysis details

[Denton, JG 2302.08513}

Extreme values of probability assuming $\delta = -90°$ varying θ_{12} or Δm^2_{21}





Backup: analysis details

[Denton, JG 2302.08513}

Experiments studied

Experiment	Technology	Fiducial Volume	Total POT ($\nu+\bar{\nu}$)	$\nu:\bar{\nu}$
NOvA	Scintillator	25 kT	7.2×10^{21}	1:1
T2K	Water Cherenkov	22.5 kT	10×10^{21}	1:1
DUNE-LBL	LArTPC	40 kT	14×10^{21}	1:1
HK-LBL	Water Cherenkov	190 kT	27×10^{21}	1:3

Current best fit values

Data	Δm^2_{21} [10^{-5} eV^2]	$\sin^2\theta_{12}$
SK+SNO	6.10	0.305
KamLAND	±7.54	0.316
SK+SNO+KamLAND	**7.49**	**0.305**
Global fit	7.42	0.304
	7.5	0.318
	7.36	0.303

Uncertainties

Generation	Data	$\delta x/x$: Δm^2_{21}	$\delta x/x$: $\sin^2\theta_{12}$
Current	SK+SNO	15%	4.6%
	KamLAND	2.5%	9.5%
	SK+SNO+KamLAND	**2.4%**	**4.3%**
	Global fit	2.8%	4.3%
		2.9%	5.0%
		2.2%	4.3%
Future	DUNE-solar	5.9%	3.0%
	JUNO	0.3%	0.5%

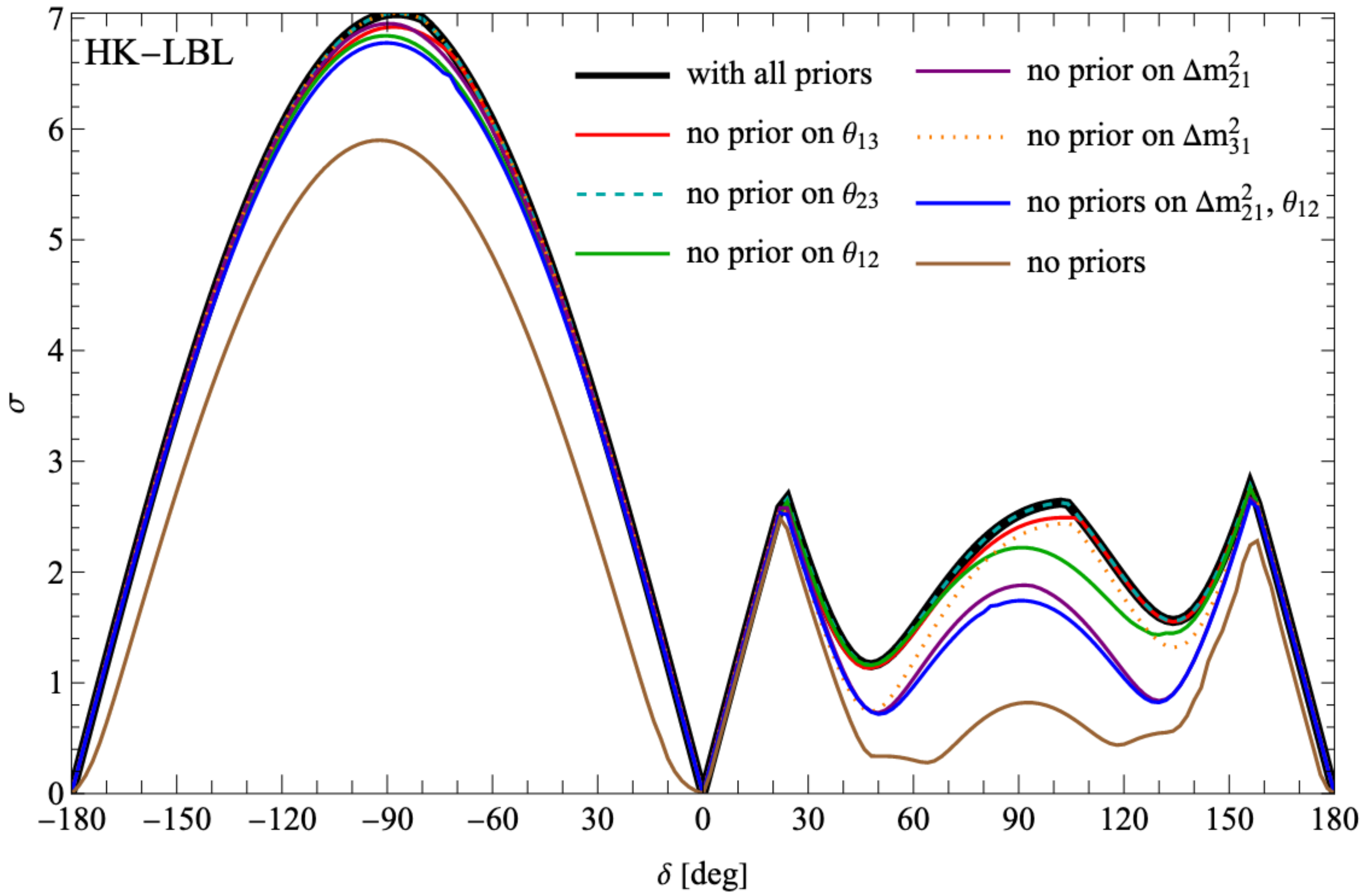
$\sin^2 2\theta_{13} = 0.0853$ ($\pm 2.8\%$) from [77],

$\Delta m^2_{32} = 2.454 \times 10^{-3}$ eV^2 ($\pm 2.3\%$) from [77]

$\sin^2\theta_{23} = 0.57$ ($\pm 7.0\%$) from [78]

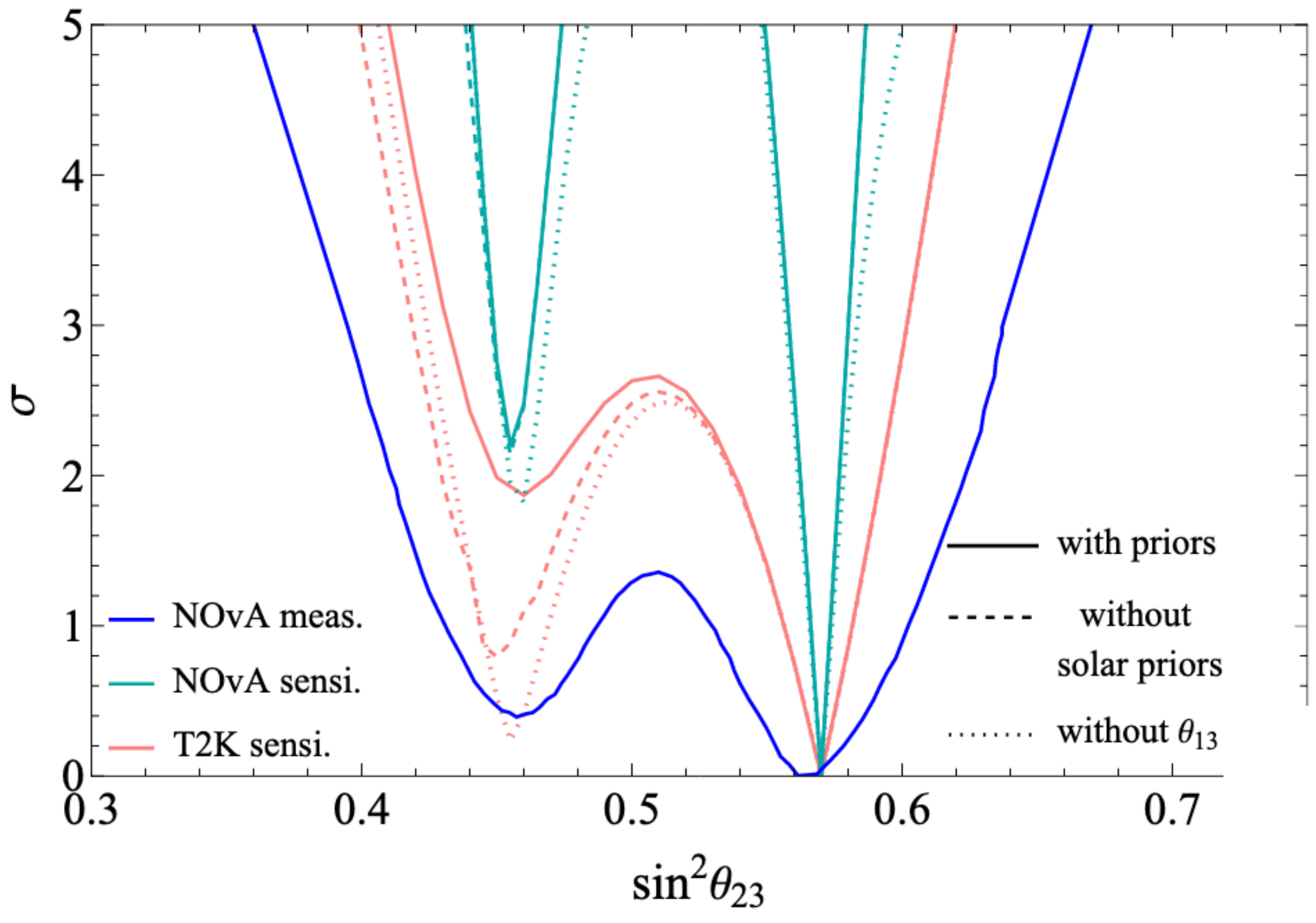
Backup: HK

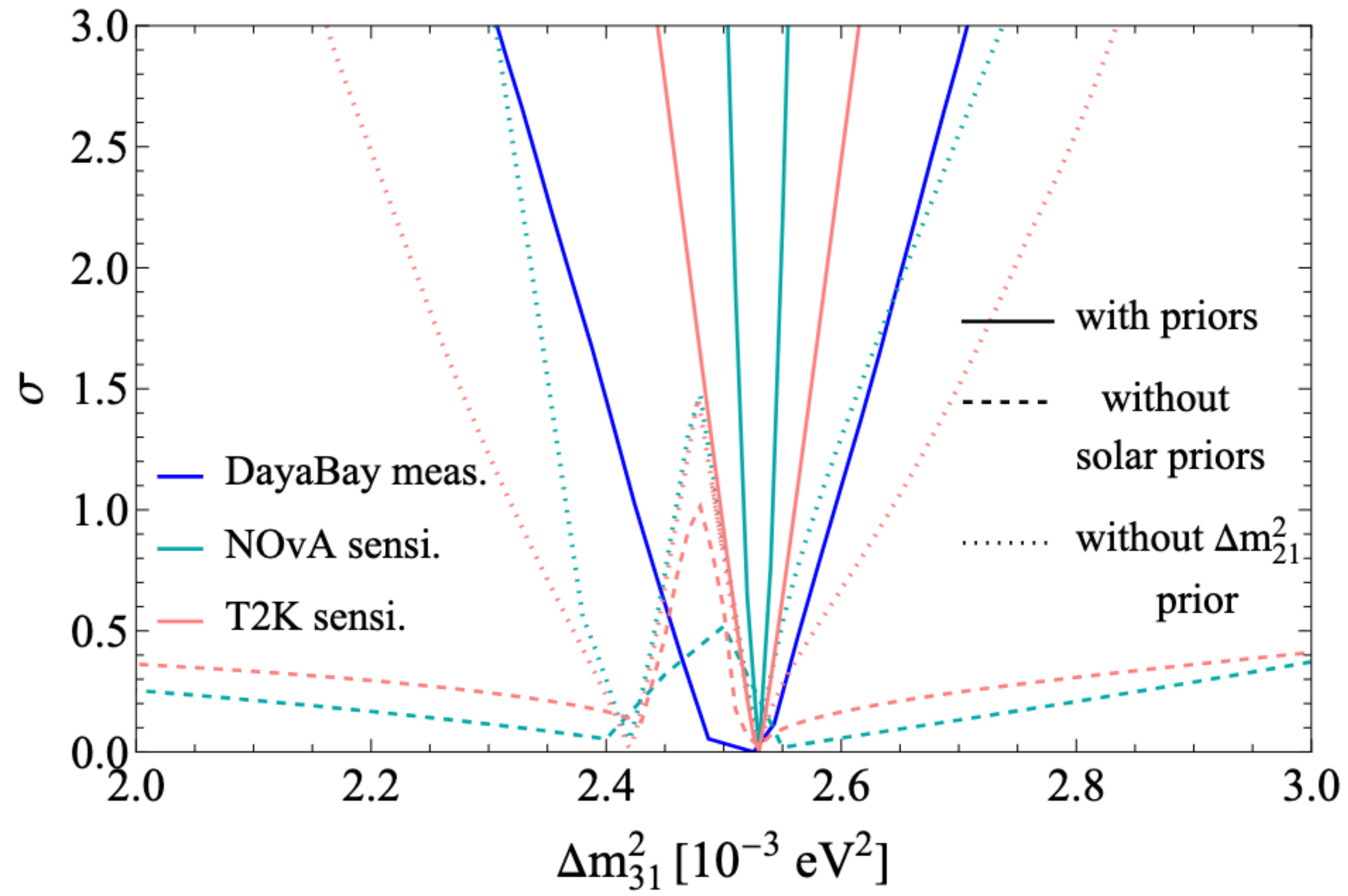
[Denton, JG 2302.08513}

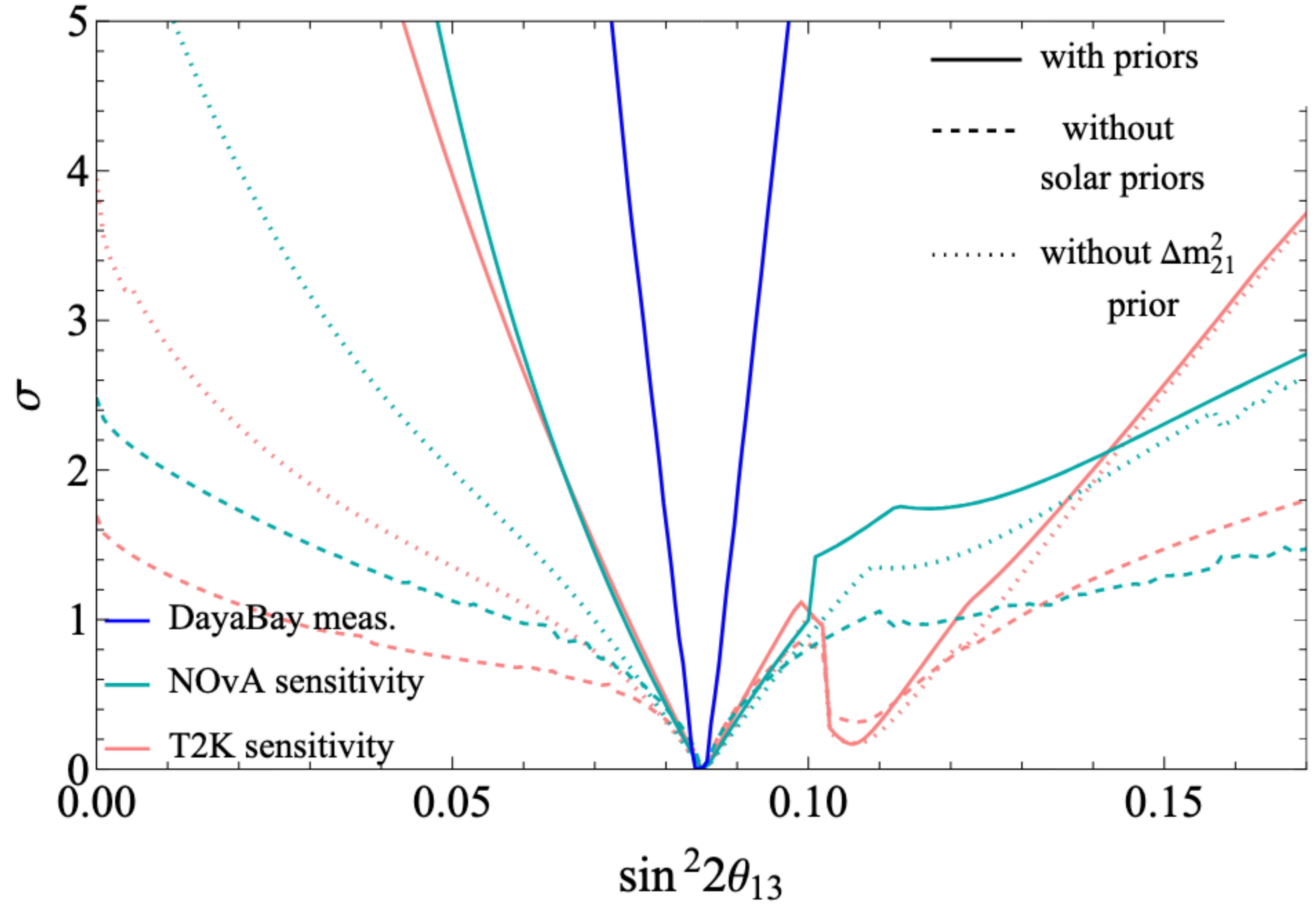


Backup: Other parameters

[Denton, JG 2302.08513}







Backup: Results

[Denton, JG 2302.08513]

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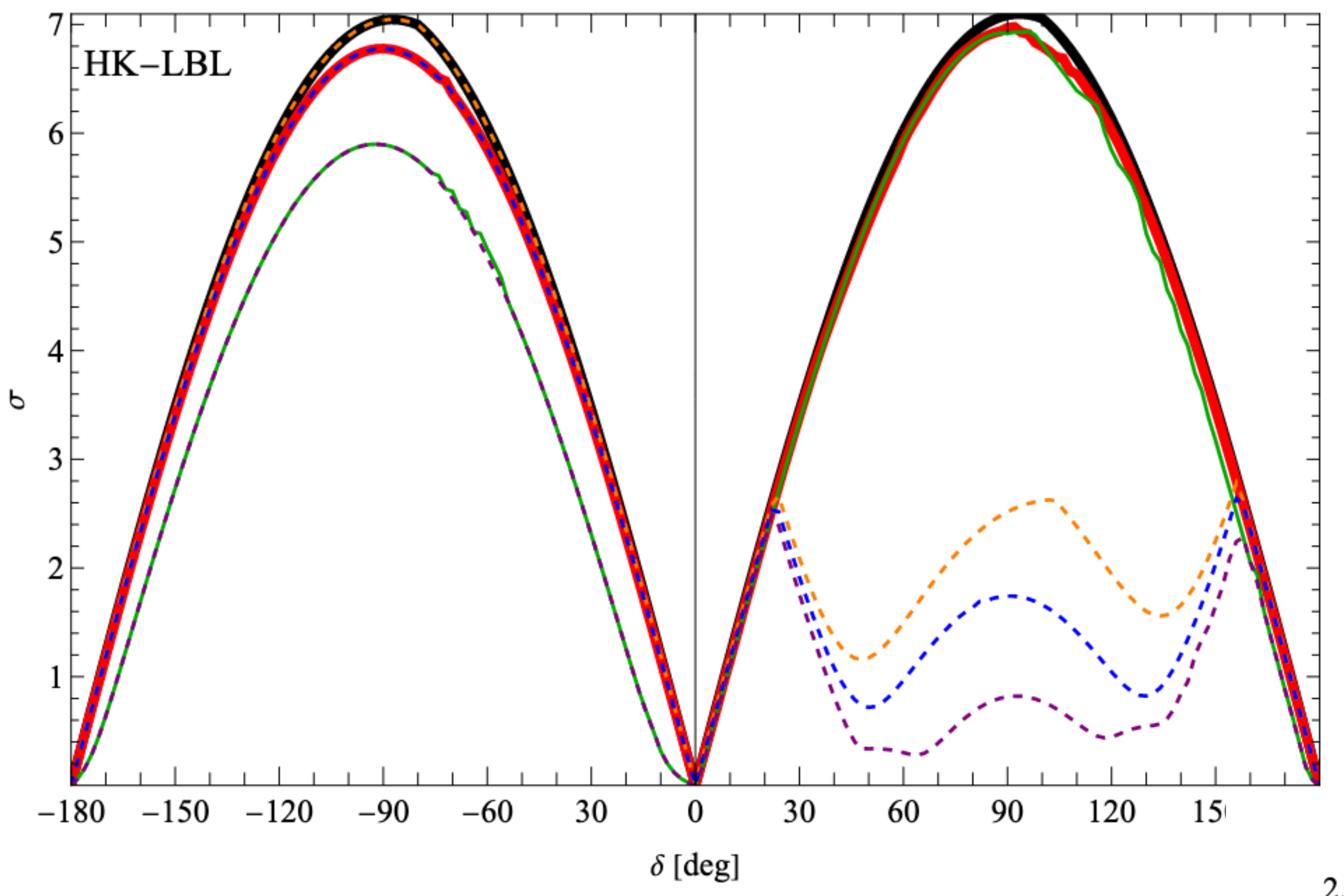
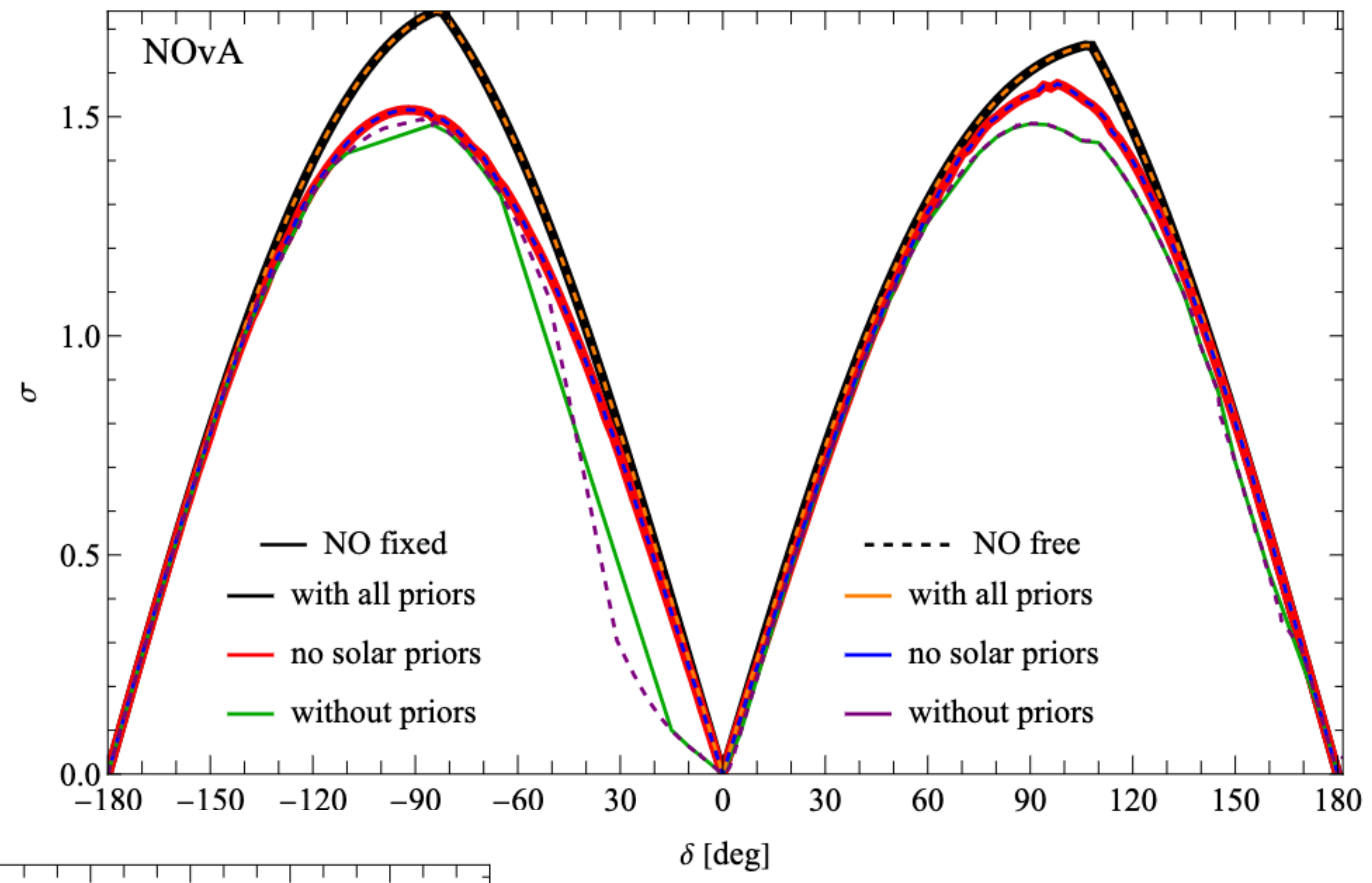
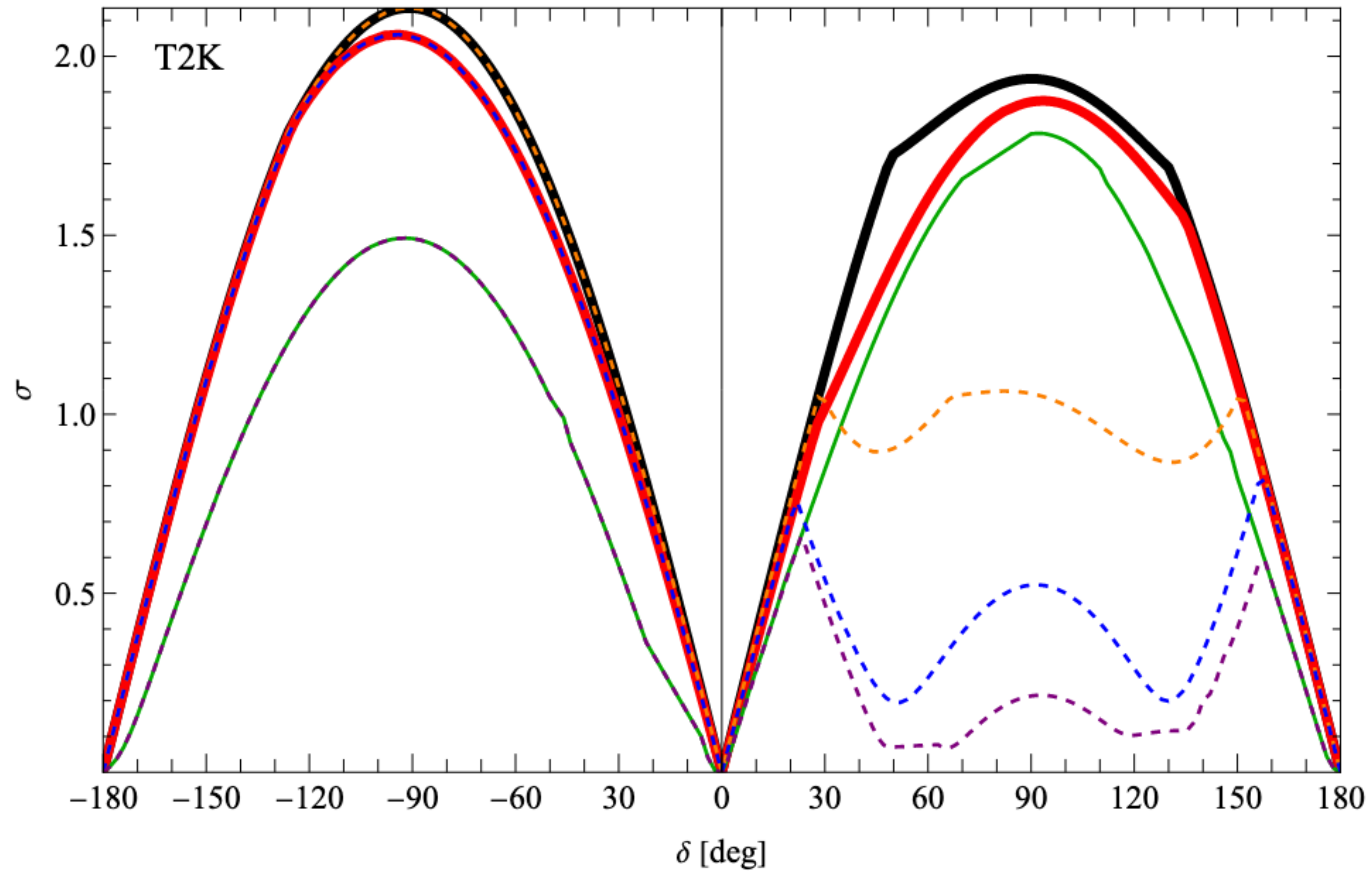
[Denton, JG 2302.08513}



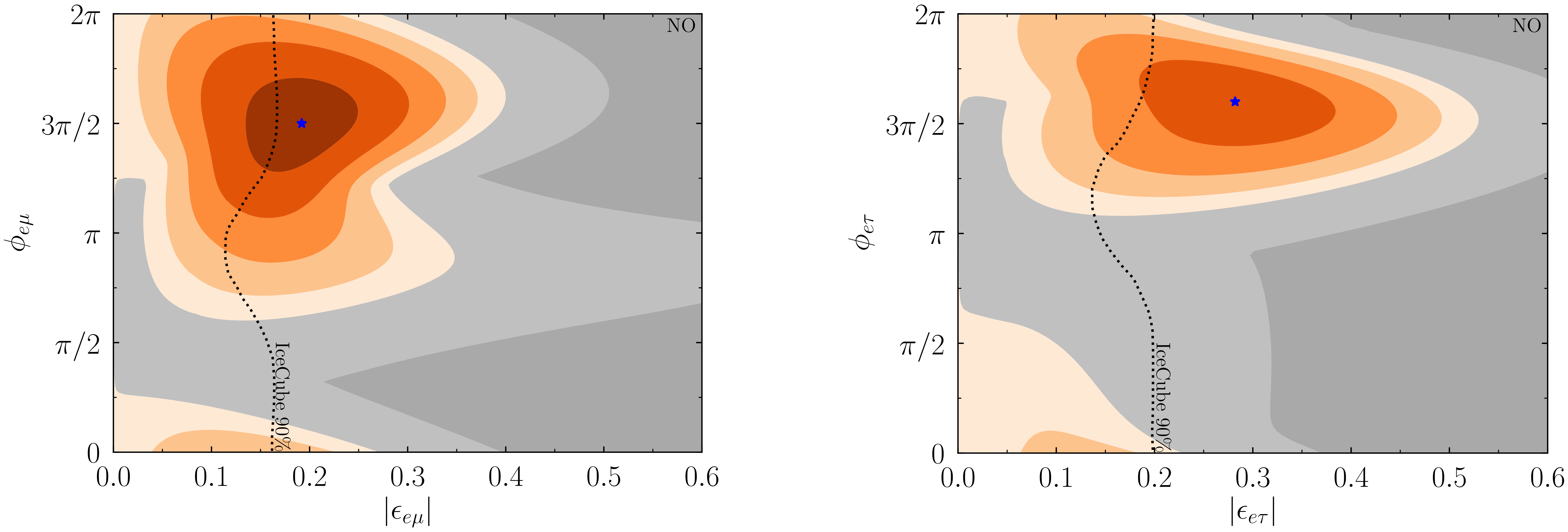




Backup: Current status of CPV in lepton sector

[Denton, JG, Pestes, 2008.01110, See also Chatterjee, Palazzo, 2008.04161]

Complex NSI with $|\epsilon| \approx 0.2,\ \phi \approx 3\pi/2,\ \delta \approx 3\pi/2,$ NO can fully resolve the tension



orange preferred over SM at integer values of $\Delta\chi^2$, dark gray disfavored at $\Delta\chi^2 = 4.61$

Allowed region evades constraints from atmospheric neutrinos at IceCube and neutrino scattering experiments