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

Peter B. Denton

HET Lunch Discussion

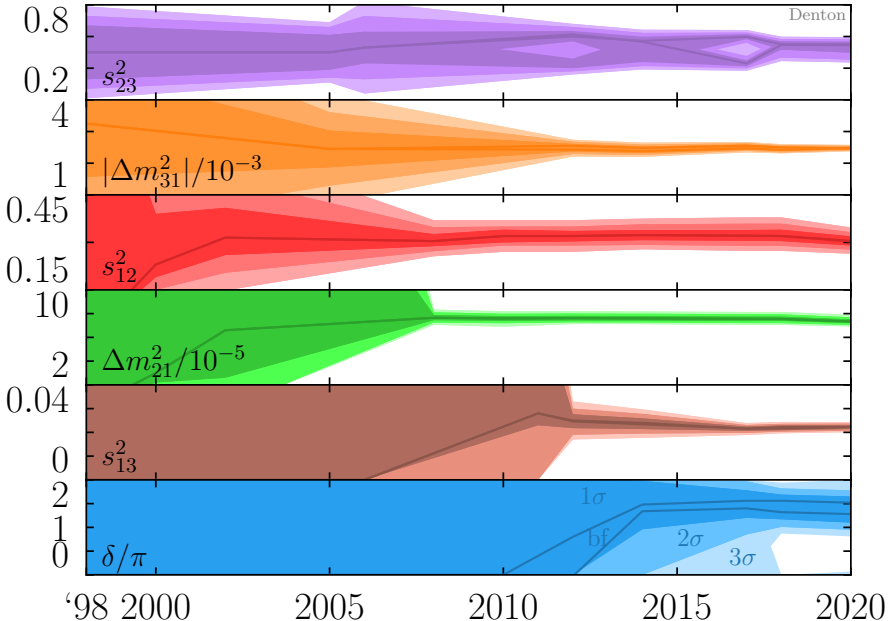
July 28, 2023

2302.08513

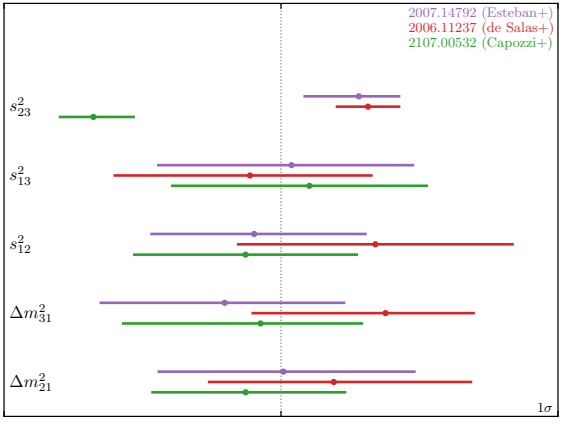
with Julia Gehrlein

Brookhaven National Laboratory

Speaking from Setauket land

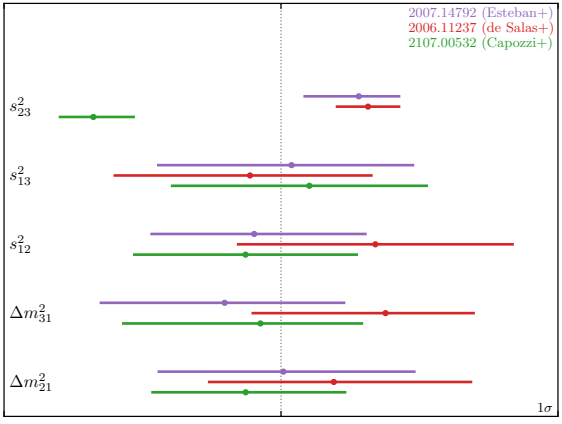

Denton
0.8
0.2
s^2_{23}
4
1
$|\Delta m^2_{31}|/10^{-3}$
0.45
0.15
s^2_{12}
10
2
$\Delta m^2_{21}/10^{-5}$
0.04
0
s^2_{13}
2
1
0
δ/π
1σ
bf
2σ
3σ
'98
2000
2005
2010
2015
2020

Global fit comparison



Esteban+ 2007.14792
de Salas+ 2006.11237
Capozzi+ 2107.00532

Global fit comparison



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Global fit uncertainty $\Rightarrow \sim 1\sigma$ extra uncertainty

Solar parameter status

Data	Δm^2_{21} [10^{-5} eV^2]	$\sin^2\theta_{12}$	Ref.
SK+SNO	+6.10	0.305	SK Neutrino 2022
KamLAND	±7.54	0.316	1303.4667
			SK Neutrino 2022
SK+SNO+KamLAND	**7.49**	**0.305**	SK Neutrino 2022
Global fit	7.42	0.304	Esteban+ 2007.14792
	7.5	0.318	de Salas+ 2006.11237
	7.36	0.303	Capozzi+ 2107.00532

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		$\delta x/x$		
Generation	Data	Δm^2_{21}	$\sin^2\theta_{12}$	Ref.
Current	SK+SNO	15%	4.6%	SK Neutrino 2022
	KamLAND	2.5%	9.5%	1303.4667
				SK Neutrino 2022
	SK+SNO+KamLAND	**2.4%**	**4.3%**	SK Neutrino 2022
	Global fit	2.8%	4.3%	Esteban+ 2007.14792
		2.9%	5.0%	de Salas+ 2006.11237
		2.2%	4.3%	Capozzi+ 2107.00532
Future	DUNE-solar	5.9%	3.0%	Capozzi+ 1808.08232
	JUNO	0.3%	0.5%	JUNO 2204.13249

Neutrino mass eigenstate definition: aside

The mass eigenstates can be numbered in a number of different ways

1. $|U_{e1}| > |U_{e2}| > |U_{e3}|$
2. $m_1 < m_2 < m_3$
3. $m_1 < m_2$ and $|U_{e3}| < |U_{e1}|$ and $|U_{e3}| < |U_{e2}|$
4. $\vdots$

PBD 2003.04319
PBD, R. Pestes 2006.09384
PBD, S. Parke 2106.12436

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- We know that in the solar sector all three are equivalent
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Thus $\theta_{12} \in [0, 45^\circ]$ by definition
Only solar data tells us that $\Delta m^2_{21} > 0$

PBD 2003.04319
PBD, R. Pestes 2006.09384
PBD, S. Parke 2106.12436

Four ways of determining sign of Δm^2_{31}

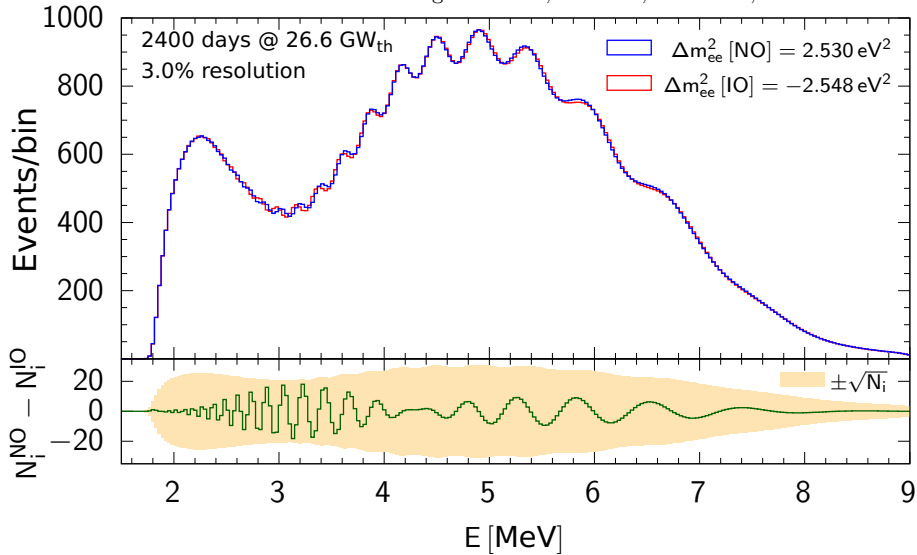
1. Matter effect in appearance (DUNE)
2. Comparison of ν_μ disappearance (IceCube, KM3NeT, DUNE, HK) and ν_e disappearance (Daya Bay, JUNO)

   H. Nunokawa, R. Funchal, S. Parke hep-ph/0503283
3. Measure all three Δm^2_{ij} at once (JUNO)
4. $\sum m_{\nu_i}$, $m_{\beta\beta}$: Cosmology/$0\nu\beta\beta$

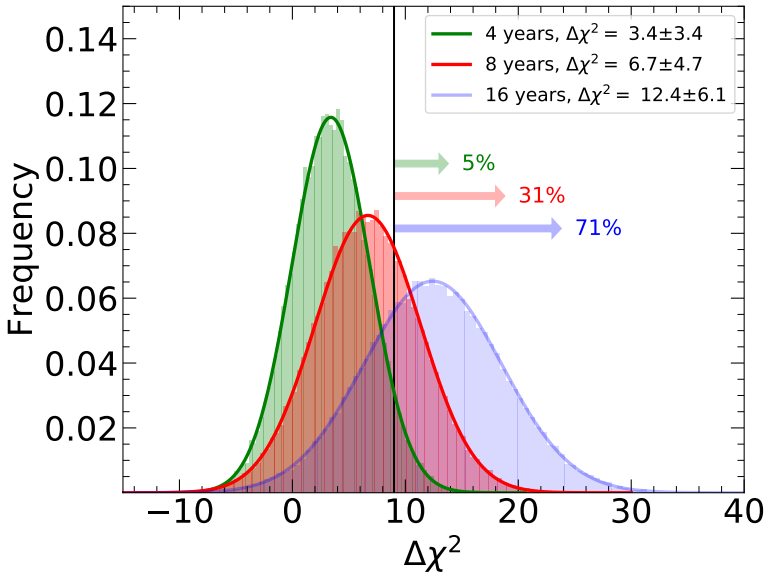
   Mostly only works to rule out the IO

JUNO's mass ordering measurement

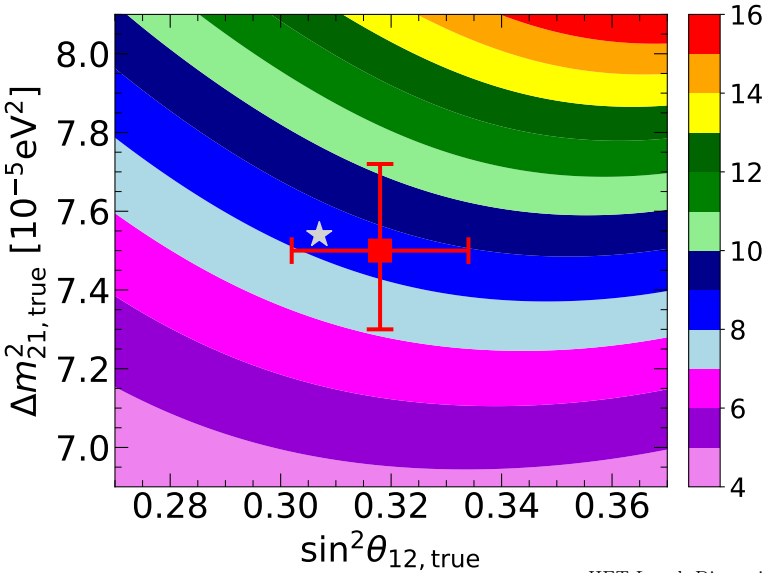
Following D. Forero, S. Parke, C. Ternes, R. Funchal 2107.12410



JUNO's mass ordering sensitivity



JUNO's mass ordering sensitivity dependence



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)

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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

$$\frac{|J_{\rm CKM}|}{J_{\rm max}} = 3\times 10^{-4}$$

CKMfitter 1501.05013

3. Lepton mass matrix: **?**

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

PBD, J. Gehrlein, R. Pestes 2008.01110

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

CP violation in neutrinos

$$P_{\mu e} - \bar{P}_{\mu e} \simeq 8\pi s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \qquad \text{(in vacuum)}$$

- Need appearance to measure it

  One could do ultra-long-baseline ν_μ disappearance

- Appearance has only been clearly seen in long-baseline accelerator neutrinos at NOvA and T2K

  T2K 1502.01550

  NOvA 1601.05022

  But see also solar, astrophysical, and atmospheric

- Appearance probabilities depend on all six parameters

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Can't determine CP violation and δ
without knowing all five other parameters!

True in two ways

Which parameters are important?

DUNE-LBL and HK-LBL will have world-leading measurements of:

1. $|\Delta m^2_{31}|$ (see also JUNO, HK-Atm, & IceCube)

   The sign of Δm^2_{31} will be determined in multiple ways

2. θ_{23} (see also HK-Atm & IceCube)
3. δ
4. θ_{13} (Daya Bay & RENO)

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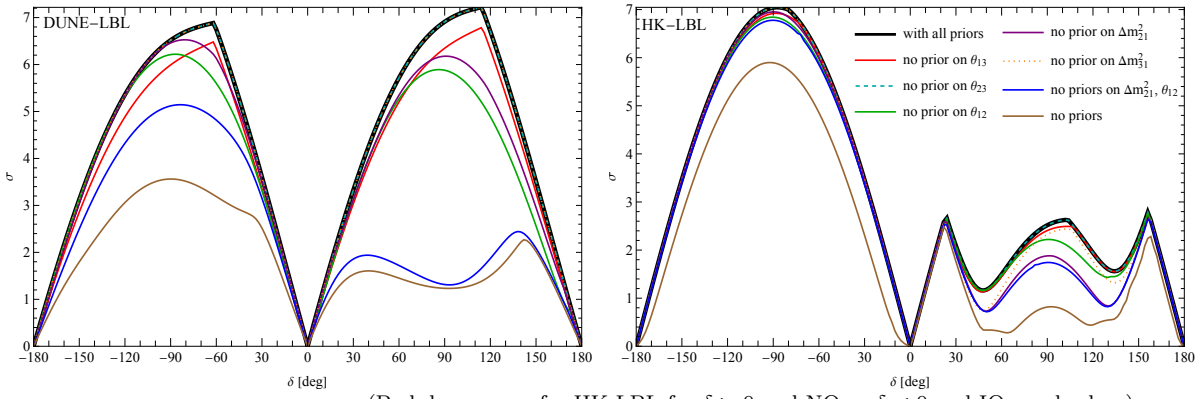
What about Δm^2_{21} and θ_{12}?

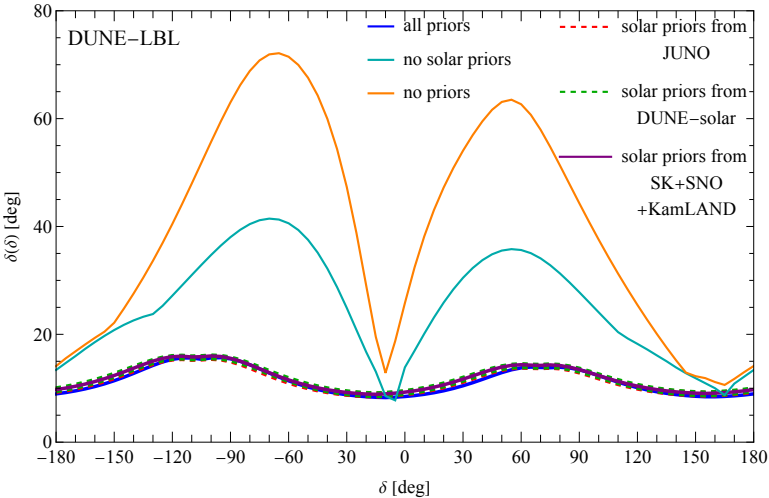
Impact of current priors

How much does removing one prior change the McDonald's plot?



(Bad degeneracy for HK-LBL for $\delta > 0$ and NO or $\delta < 0$ and IO, see backup)

Precision on δ



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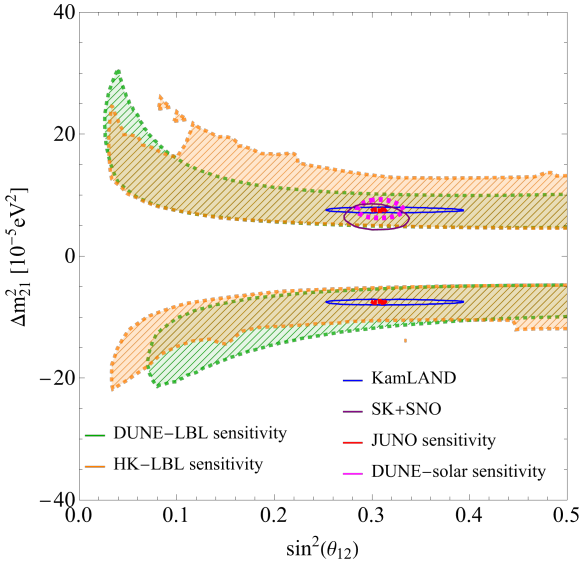
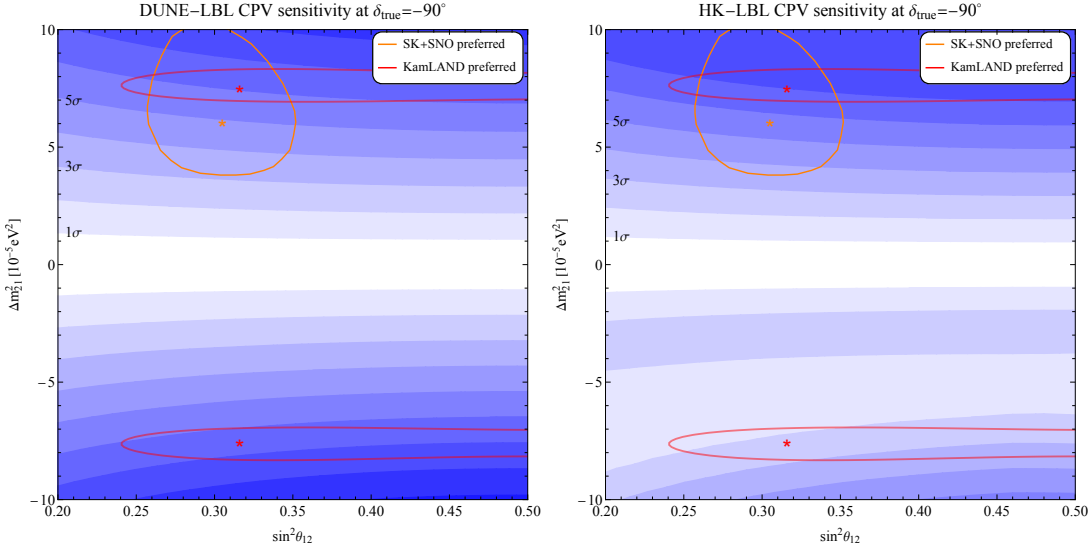
Some sensitivity to CP violation with no solar information?

LBL can measure solar parameters!



True values matter



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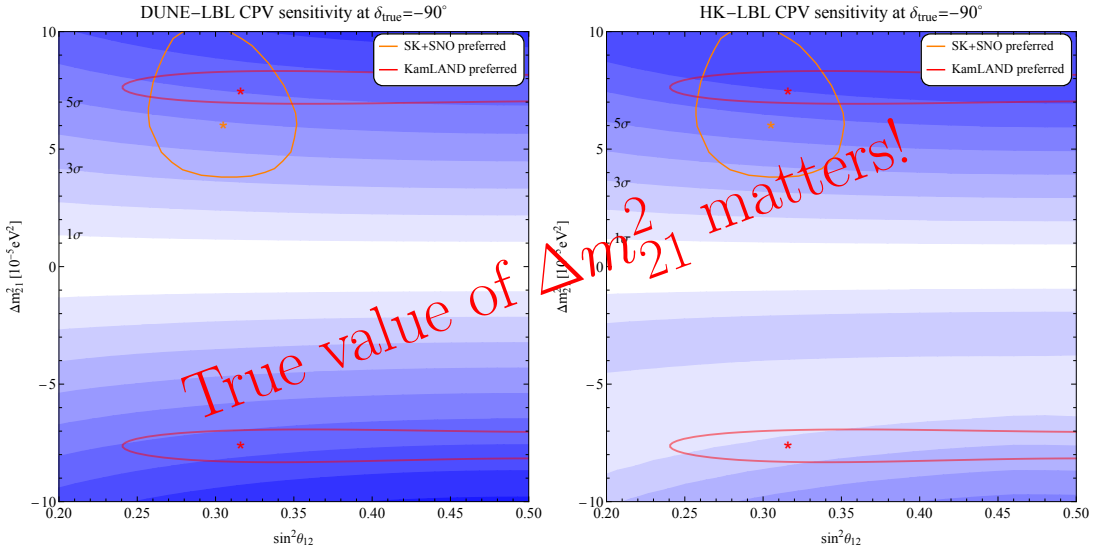

Long-baseline solar parameter summary

- To reach δ goals, DUNE & HK *need* external input on Δm^2_{21} and θ_{12}
- DUNE & HK can provide a very orthogonal cross check of solar parameters
- Pay attention to the exact value of Δm^2_{21} that JUNO measures

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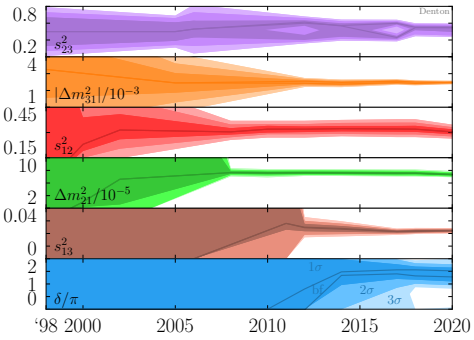
Thanks!

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

δ: what is it really?