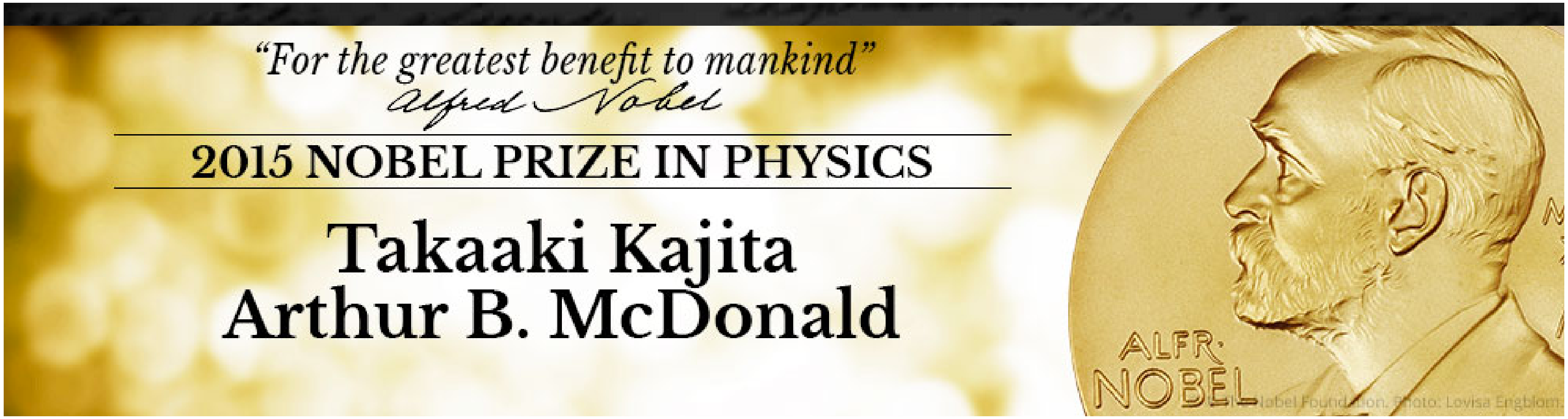
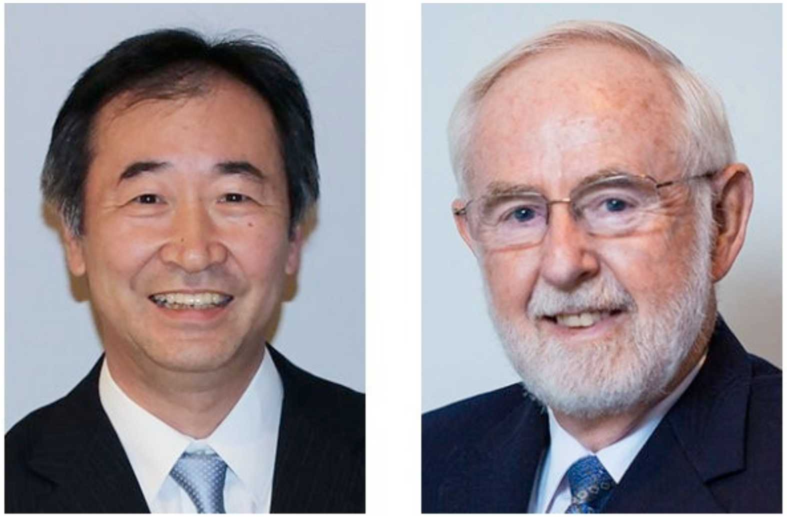
Neutrino mass and implications for the Standard Model of particle physics

Thomas Schwetz-Mangold

Institutsseminar, TU Dresden, Inst. für Kern- und Teilchenphysik, 18.4.2019





„…for the discovery of neutrino oscillations, which shows that neutrinos have mass“

Outline

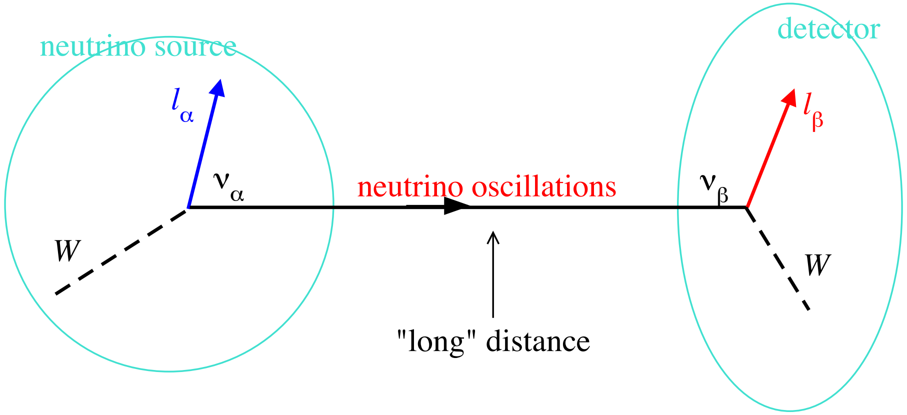
- Neutrino oscillations
  - basic introduction
  - present status of 3-flavour oscillations from global data
- Beyond oscillations
  - absolute mass observables
  - implications for the Standard Model of particle physics
  - how to identify the mechanism behind neutrino mass? comments on lepton number and lepton flavour violation
- Summary

Neutrino oscillations - basics

- Flavour neutrinos ν_α are superpositions of massive neutrinos ν_i:

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_i \qquad (\alpha = e, \mu, \tau)$$

- $U_{\alpha i}$: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix
  → mismatch between mass and interaction basis



$$|\nu_\alpha\rangle = U^*_{\alpha i} |\nu_i\rangle \qquad e^{-i(E_i t - p_i x)} \qquad |\nu_\beta\rangle = U^*_{\beta i} |\nu_i\rangle$$

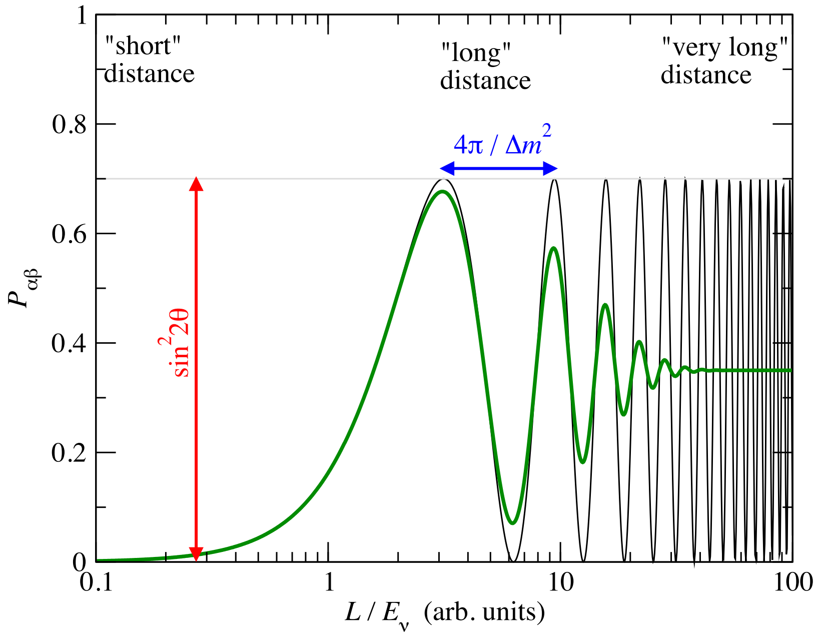
$$\mathcal{A}_{\nu_\alpha \to \nu_\beta} = \sum_i U_{\beta i} U^*_{\alpha i} e^{-i(E_i t - p_i x)} , \qquad P_{\nu_\alpha \to \nu_\beta} = \left| \mathcal{A}_{\nu_\alpha \to \nu_\beta} \right|^2$$

Neutrino oscillations - basics

2-flavour limit:

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \qquad P = \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

$\Delta m^2 = m_2^2 - m_1^2$ → oscillations are sensitive to mass differences



$$\frac{\Delta m^2 L}{4E_\nu} = 1.27 \frac{\Delta m^2[\mathrm{eV}^2]\, L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}$$

Neutrino oscillations - basics

Evolution of flavour state can be described by effective Schrödinger equ.:

$$i\frac{d}{dt}\begin{pmatrix} a_e \\ a_\mu \\ a_\tau \end{pmatrix} = H \begin{pmatrix} a_e \\ a_\mu \\ a_\tau \end{pmatrix}$$

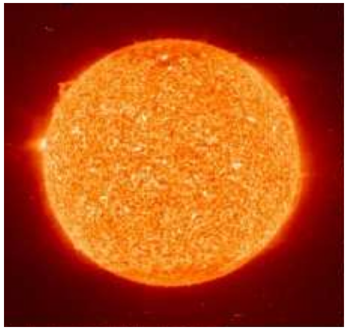
where

$$H = U \mathrm{diag}\left(0, \frac{\Delta m^2_{21}}{2E_\nu}, \frac{\Delta m^2_{31}}{2E_\nu}\right) U^\dagger$$

Global data on neutrino oscillations

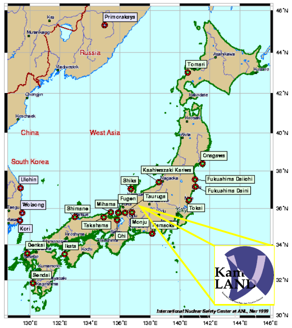
from various neutrino sources and
vastly different energy and distance scales:

sun



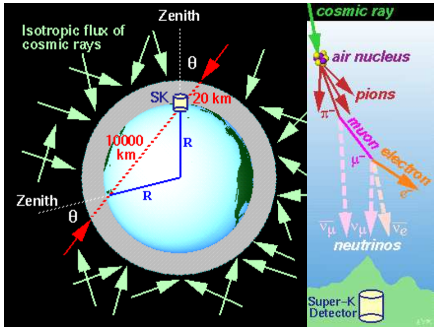
Homestake,SAGE,GALLEX
SuperK, SNO, Borexino

reactors



KamLAND, CHOOZ

atmosphere



SuperKamiokande

accelerators

K2K, MINOS, T2K

- global data fits nicely with the 3 neutrinos from the SM
- a few "anomalies" at 2-3 σ: LSND, MiniBooNE, reactor anomaly, no LMA MSW up-turn of solar neutrino spectrum

The 3-flavour paradigm

- 3 masses: Δm^2_{21} , Δm^2_{31}, m_0
- 3 mixing angles θ_{12} θ_{13} θ_{23}
- 3 phases (1 Dirac, 2 Majorana)

$$U = \underset{\text{atm+LBL(dis)}}{\overset{\Delta m^2_{31}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}} \underset{\text{react+LBL(app)}}{\begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix}} \underset{\text{solar+KamLAND}}{\overset{\Delta m^2_{21}}{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}}$$

The 3-flavour paradigm

- 3 masses: Δm^2_{21} , Δm^2_{31}, m_0
- 3 mixing angles θ_{12} θ_{13} θ_{23} ← neutrino oscillations
- 3 phases (1 Dirac, 2 Majorana)

$$U = \underset{\text{atm+LBL(dis)}}{\overset{\Delta m^2_{31}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}} \underset{\text{react+LBL(app)}}{\begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix}} \underset{\text{solar+KamLAND}}{\overset{\Delta m^2_{21}}{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}}$$

The 3-flavour paradigm

- 3 masses: Δm^2_{21} , Δm^2_{31}, m_0
- 3 mixing angles θ_{12} θ_{13} θ_{23} ← neutrino oscillations
- 3 phases (1 Dirac, 2 Majorana)

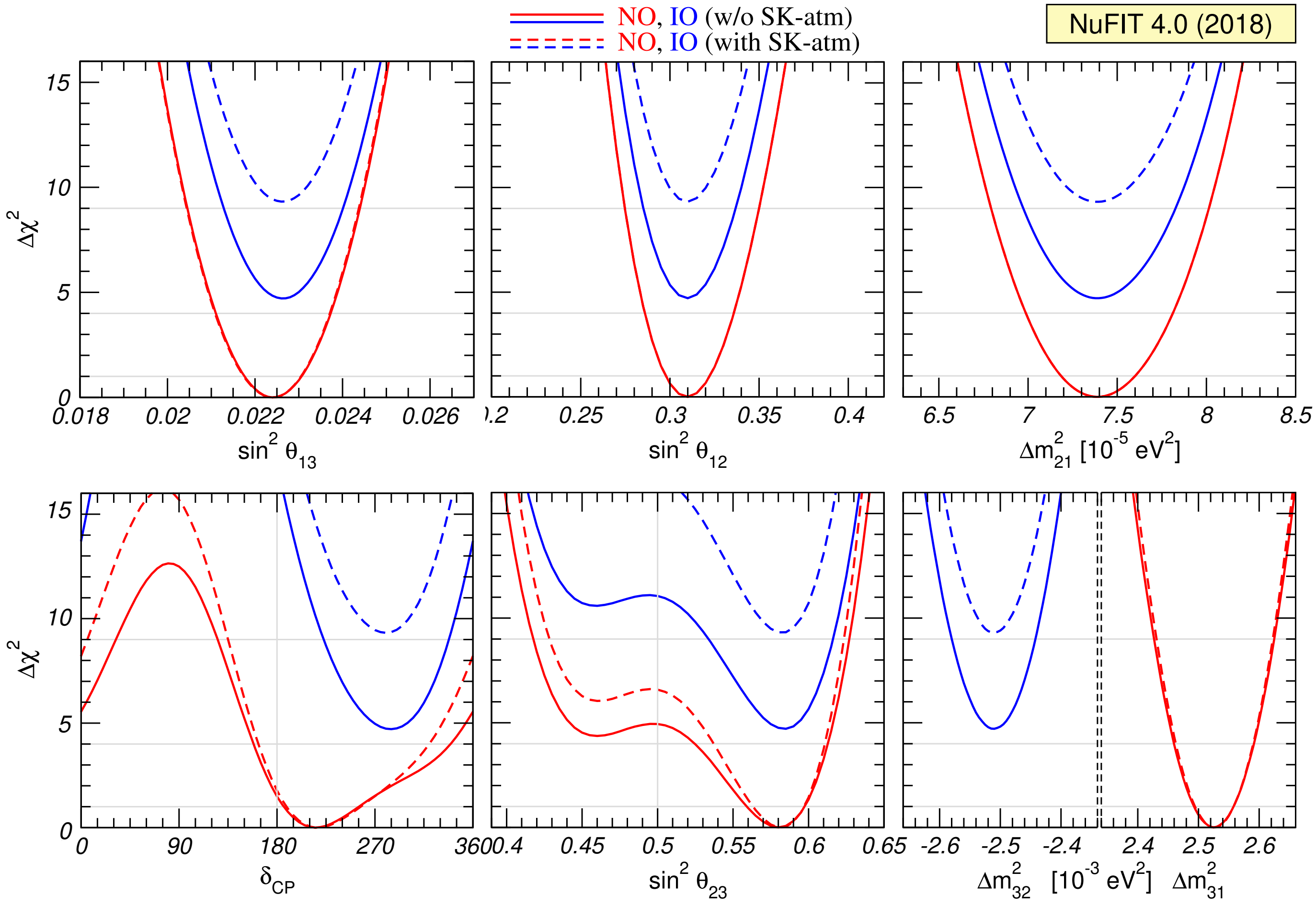
- each parameter determined by several (classes of) experiments
- especially true for not-so-well determined parameters (θ_{23}, MO, Dirac-phase)
- interplay of different data sets → global analyses

NuFit 4.0 (2018)

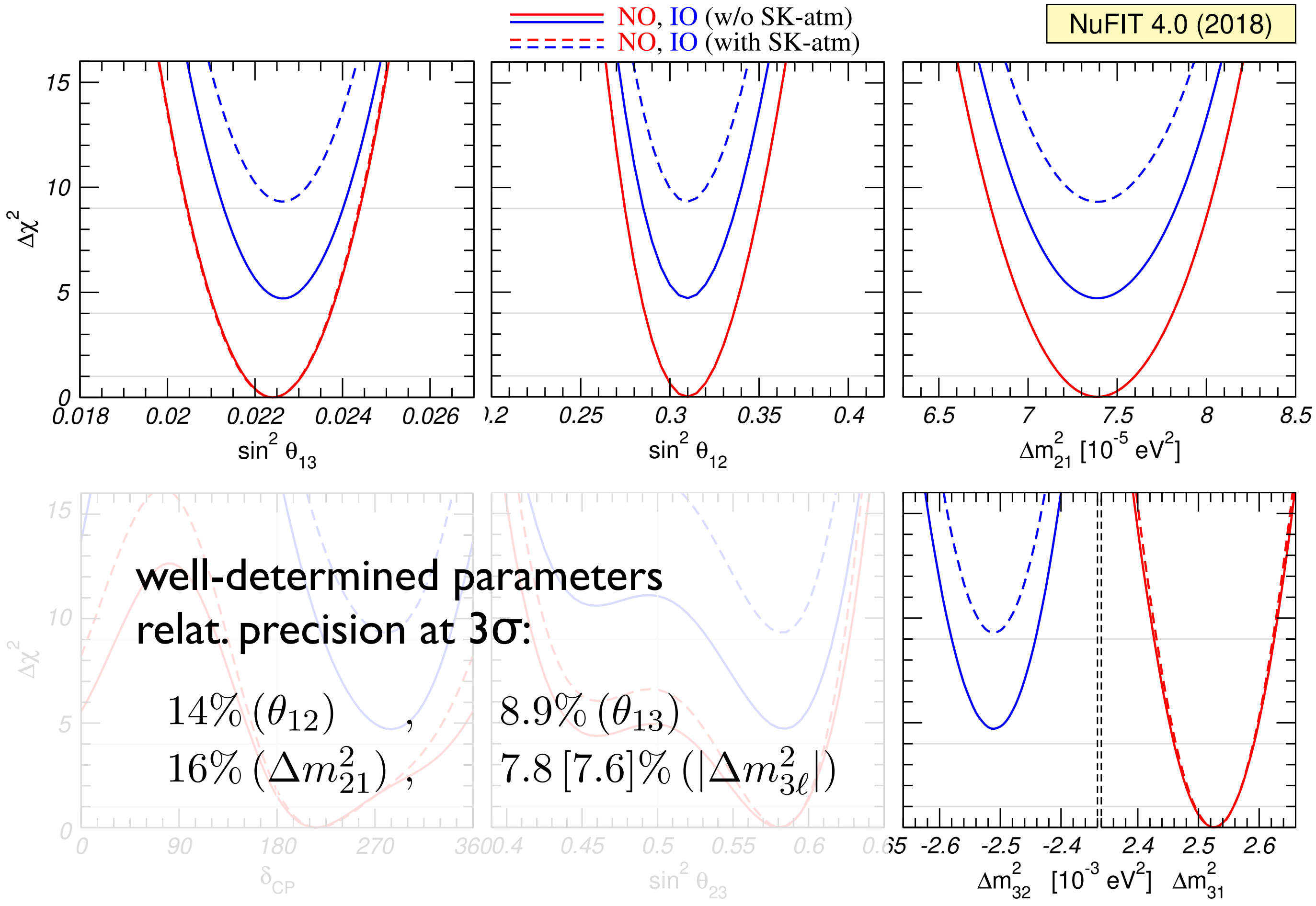
I. Esteban, C. Gonzalez-Garcia, A. Hernandez, M. Maltoni, T. Schwetz, JHEP 19, [arXiv:1811.05487]

- data available till Oct 2018 (incl. Neutrino 2018 releases)
- updated results, full list of data, χ^2 tables
  http://www.nu-fit.org

NuFit 4.0 (2018)



NuFit 4.0 (2018)

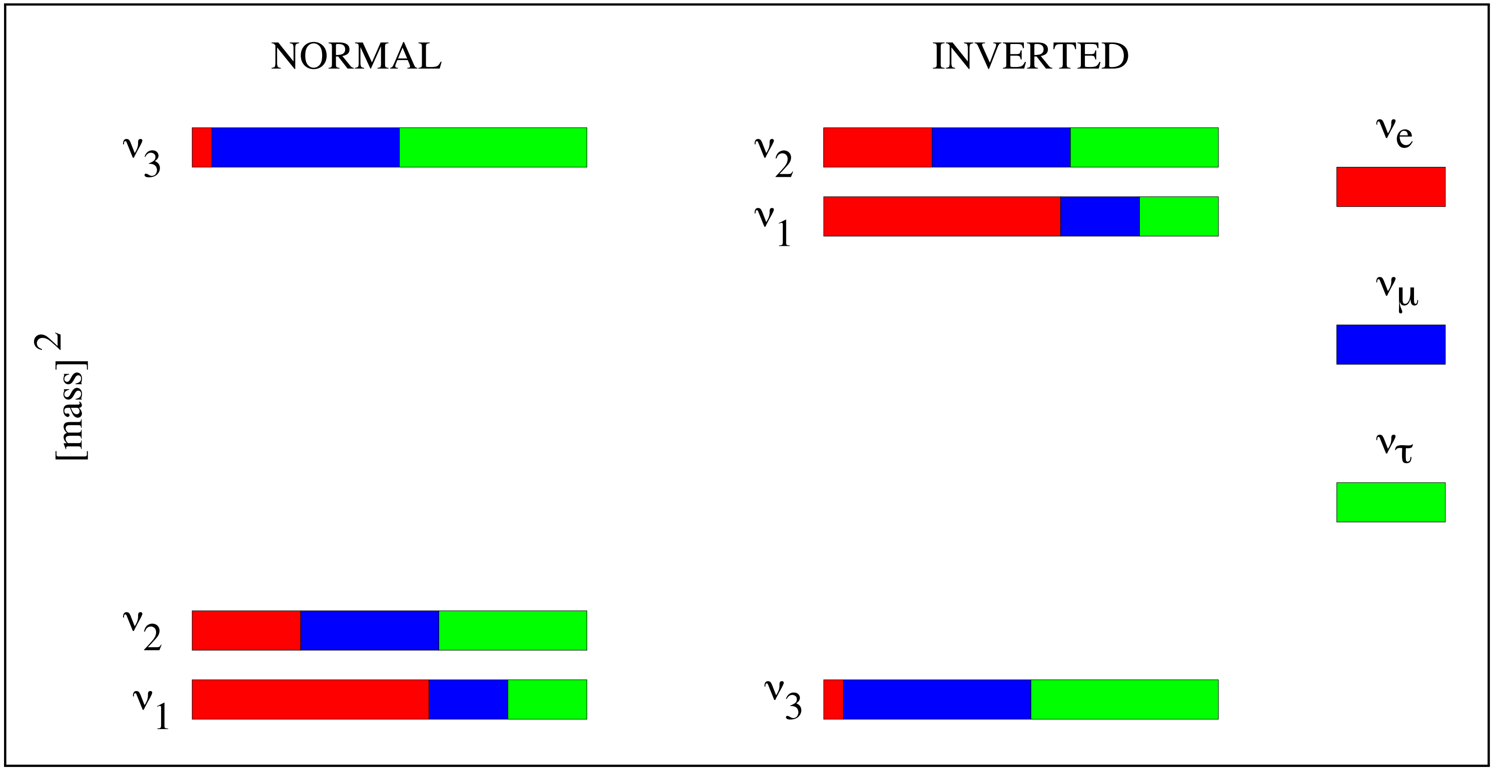


well-determined parameters
relat. precision at 3σ:

$14\%\ (\theta_{12})$, $8.9\%\ (\theta_{13})$

$16\%\ (\Delta m^2_{21})$, $7.8\,[7.6]\%\ (|\Delta m^2_{3\ell}|)$

3-flavour mixing



The SM flavour puzzle

Lepton mixing:

$$\theta_{12} \approx 33^\circ \qquad \theta_{23} \approx 45^\circ \qquad \theta_{13} \approx 9^\circ$$

$$U_{PMNS} = \frac{1}{\sqrt{3}} \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(1) & \epsilon \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix}$$

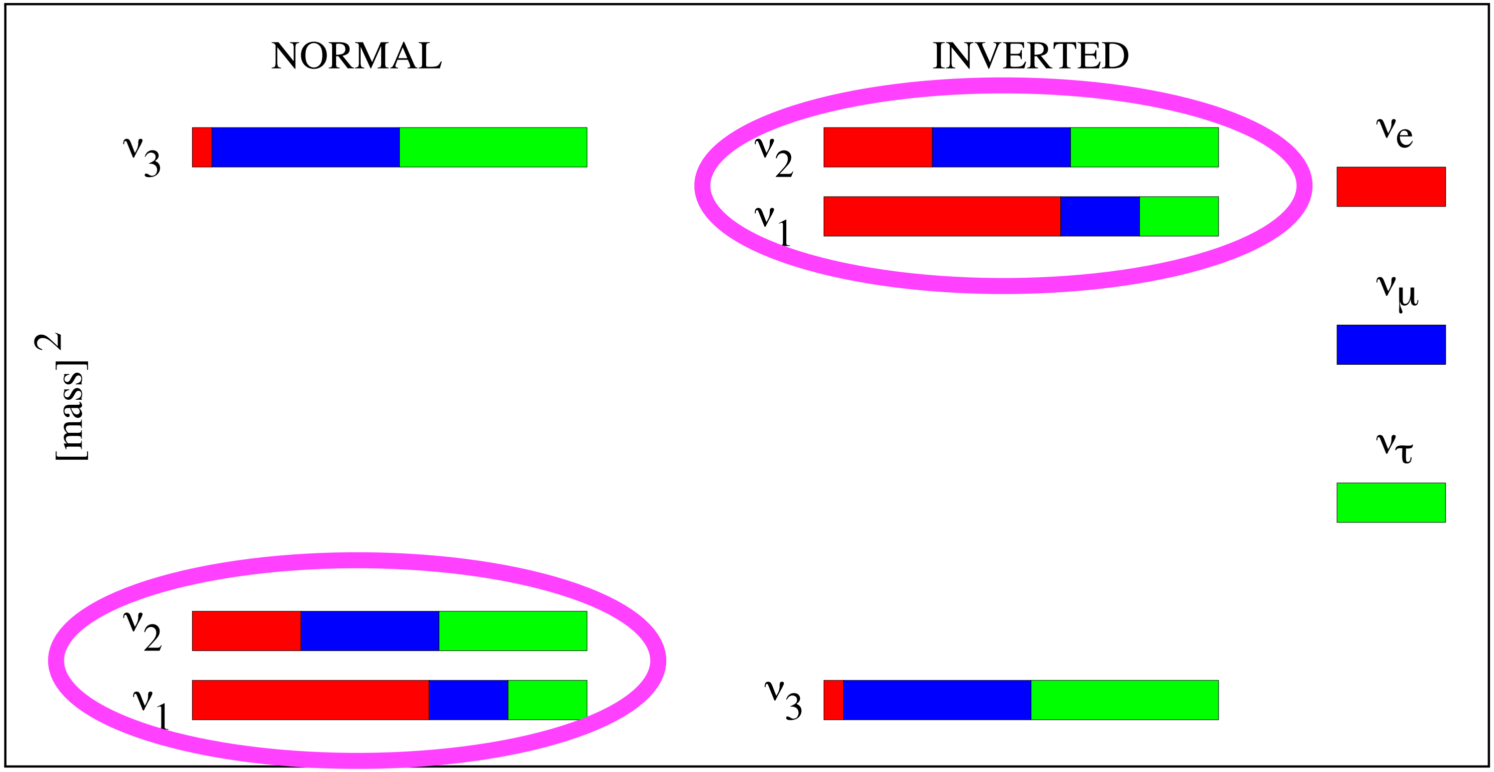
Quark mixing:

$$\theta_{12} \approx 13^\circ \qquad \theta_{23} \approx 2^\circ \qquad \theta_{13} \approx 0.2^\circ$$

$$U_{CKM} = \begin{pmatrix} 1 & \epsilon & {\scriptstyle\epsilon} \\ \epsilon & 1 & {\scriptstyle\epsilon} \\ {\scriptstyle\epsilon} & {\scriptstyle\epsilon} & 1 \end{pmatrix}$$

The dominant oscillation modes

1-2 sector: θ_{12} and Δm^2_{21}



Matter effect

When neutrinos pass through matter the interactions with the particles in the background induce an effective potential for the neutrinos

Effective 4-point interaction Hamiltonian

$$H_{\rm int}^{\nu_\alpha} = \frac{G_F}{\sqrt{2}} \bar{\nu}_\alpha \gamma_\mu (1-\gamma_5)\nu_\alpha \underbrace{\sum_f \bar{f}\gamma^\mu (g_V^{\alpha,f} - g_A^{\alpha,f}\gamma_5) f}_{J^\mu_{\rm mat}}$$

coherent forward scattering amplitude leads to an "index of refraction"

L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978); *ibid.* D **20**, 2634 (1979)

Matter effect

effective Schrödinger eq. in matter:

$$i\frac{d}{dt}\begin{pmatrix} a_e \\ a_\mu \\ a_\tau \end{pmatrix} = H \begin{pmatrix} a_e \\ a_\mu \\ a_\tau \end{pmatrix}$$

with

$$H = \underbrace{U \mathrm{diag}\left(0, \frac{\Delta m^2_{21}}{2E_\nu}, \frac{\Delta m^2_{31}}{2E_\nu}\right) U^\dagger}_{\text{vaccum}} + \underbrace{\mathrm{diag}(\sqrt{2} G_F N_e, 0, 0)}_{\text{matter}}$$

$N_e(x)$: electron density along the neutrino path

for non-constant matter: $H(t) \rightarrow$ time-dependent Schrödinger eq.

"MSW resonance" Mikheev, Smirnov, Sov. J. Nucl. Phys. 42, 913 (1985)

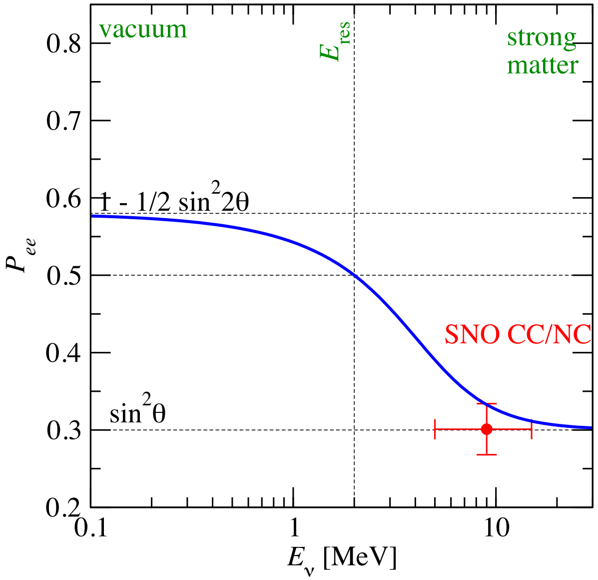
1-2 sector: θ_{12} and Δm^2_{21}

MSW conversion in the Sun

2002: SNO: CC to NC ratio of solar neutrino flux

CC: $\nu_e + d \to p + p + e^-$
NC: $\nu_x + d \to p + n + \nu_x$

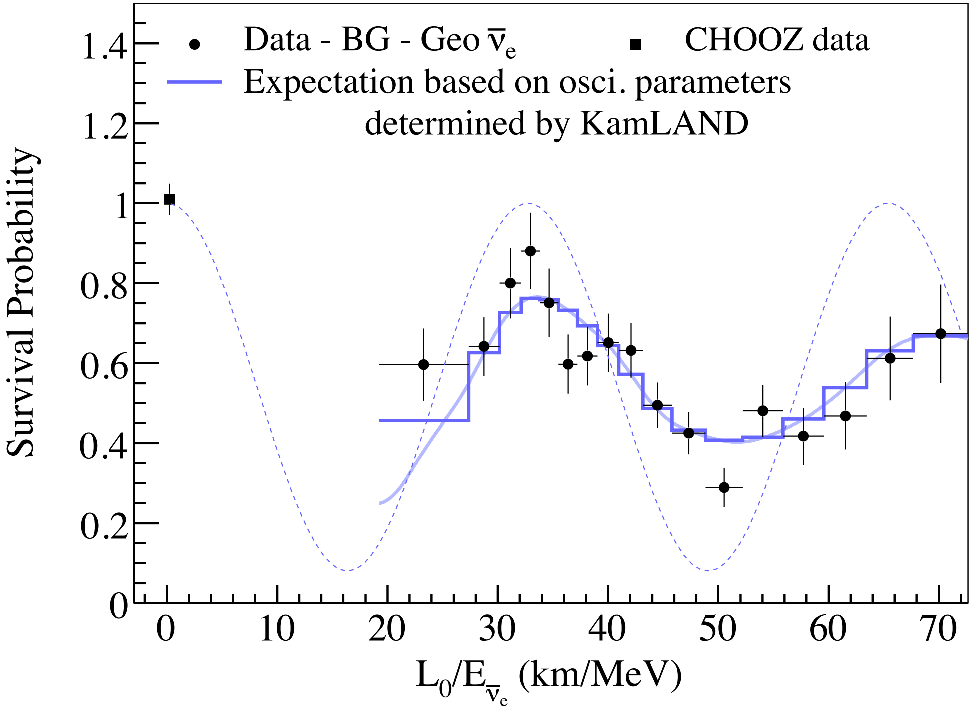
- evidence for $\nu_e \to \nu_\mu, \nu_\tau$ conversion
- MSW effect inside the sun adiabatic conversion through resonance
- fixes ordering of the 1-2 mass states

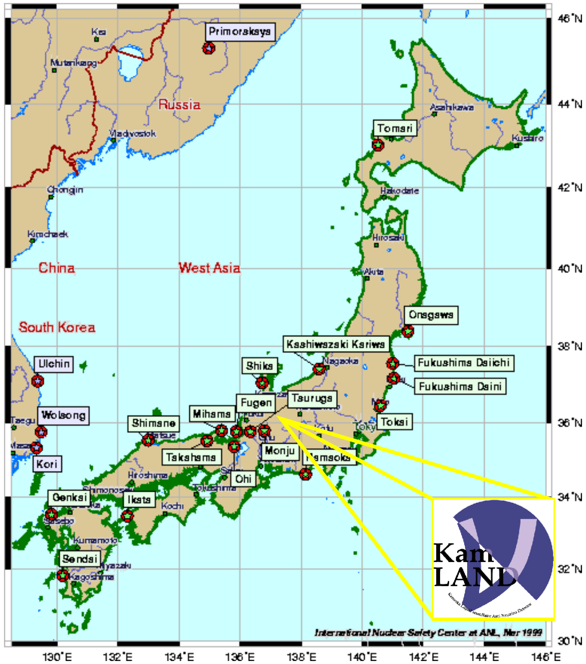


$$P_{ee} = \frac{\phi_e}{\phi_e + \phi_\mu + \phi_\tau} = \frac{\phi_{\rm CC}}{\phi_{\rm NC}}$$

1-2 sector: θ_{12} and Δm^2_{21}

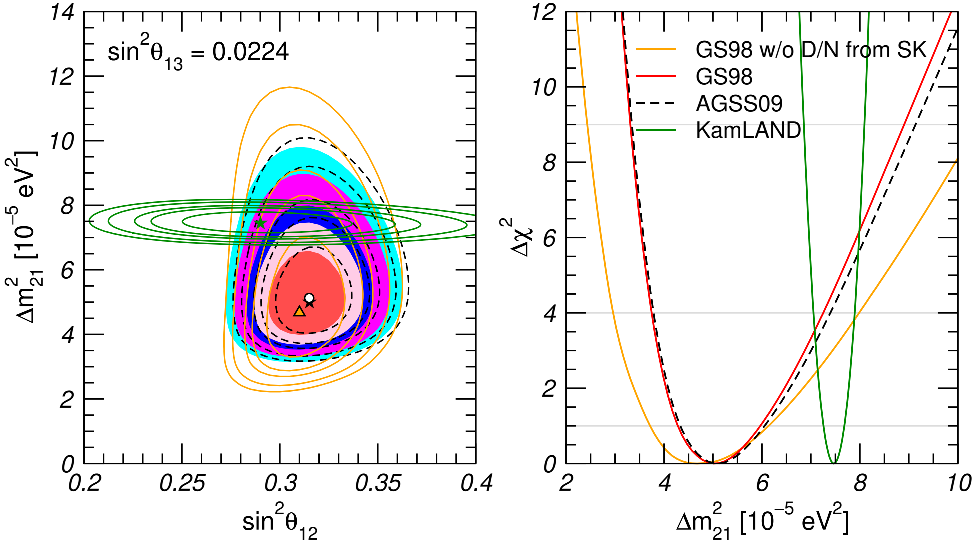
Evidence for spectral distortion: KamLAND 2004



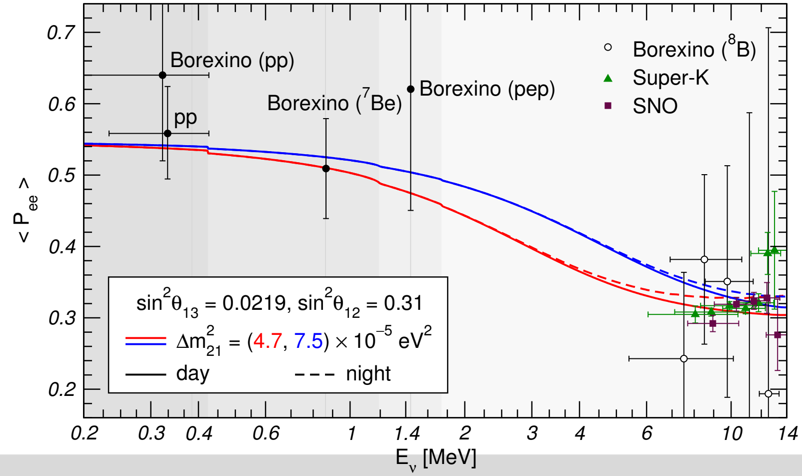


Solar parameters

NuFIT 4.0 (2018)

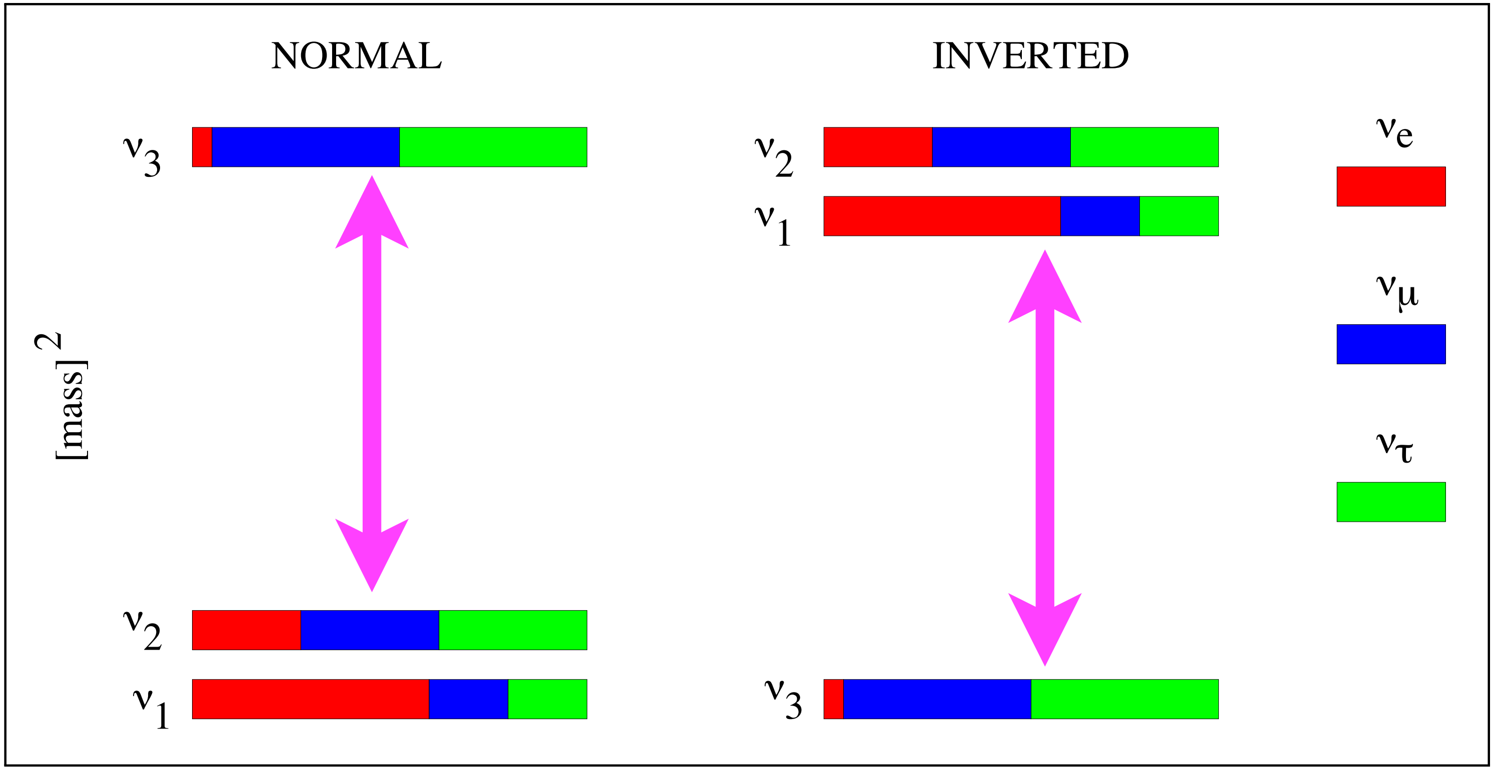


NuFIT 2.0 (2014)

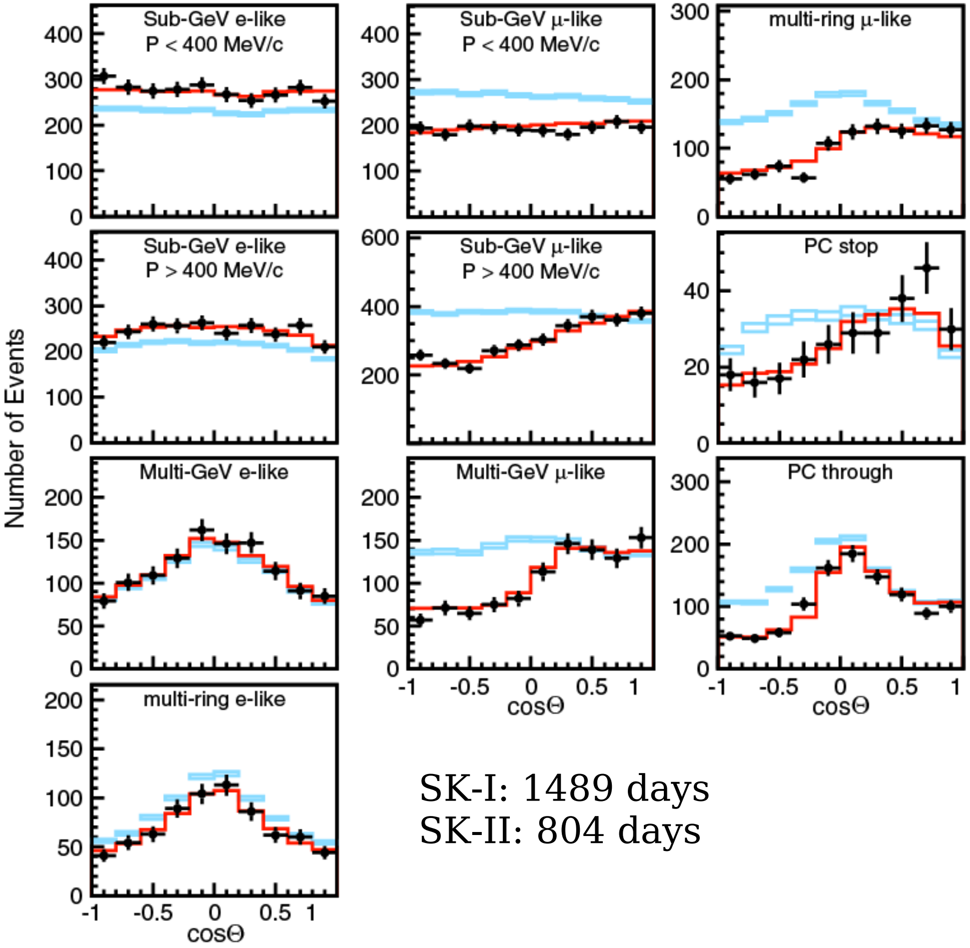


- using reconstructed fluxes from Daya-Bay in KamLAND analysis
- tension between solar and KamLAND at ~2σ
- robust wrt to solar models (abundances)
- driven by spectrum upturn and day/night data from SK

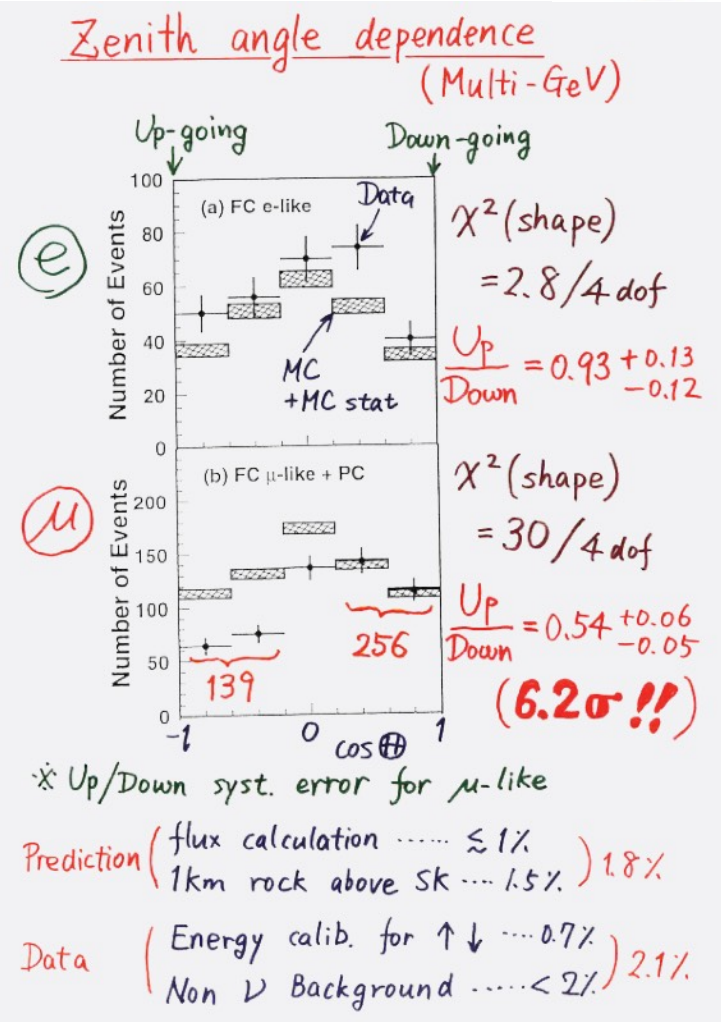
i-3 sector: θ_{i3} and Δm^2_{3i} (i=1,2)



i-3 sector: θ_{i3} and Δm^2_{3i} (i=1,2)



SK-I: 1489 days
SK-II: 804 days



Zenith angle dependence (Multi-GeV)

e: χ²(shape) = 2.8/4 dof

$\frac{Up}{Down} = 0.93^{+0.13}_{-0.12}$

μ: χ²(shape) = 30/4 dof

$\frac{Up}{Down} = 0.54^{+0.06}_{-0.05}$

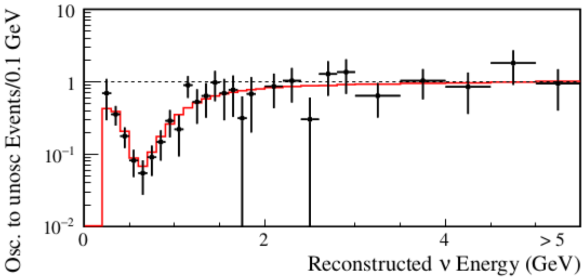
(6.2σ!!)

※ Up/Down syst. error for μ-like

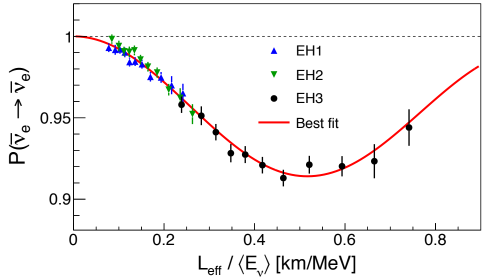
Prediction (flux calculation ······ ≲ 1% ; 1km rock above SK ···· 1.5%) 1.8%

Data (Energy calib. for ↑ ↓ ···· 0.7% ; Non ν Background ·····< 2%) 2.1%

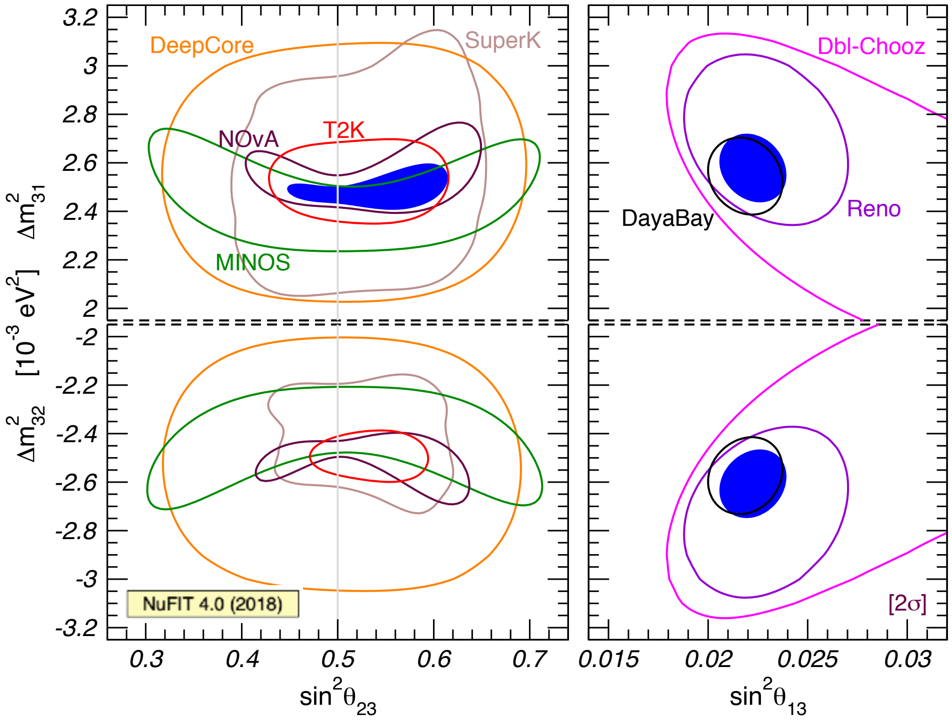
i-3 sector: θ_{i3} and Δm^2_{3i} (i=1,2)



T2K, 2015 $\nu_\mu \to \nu_\mu$

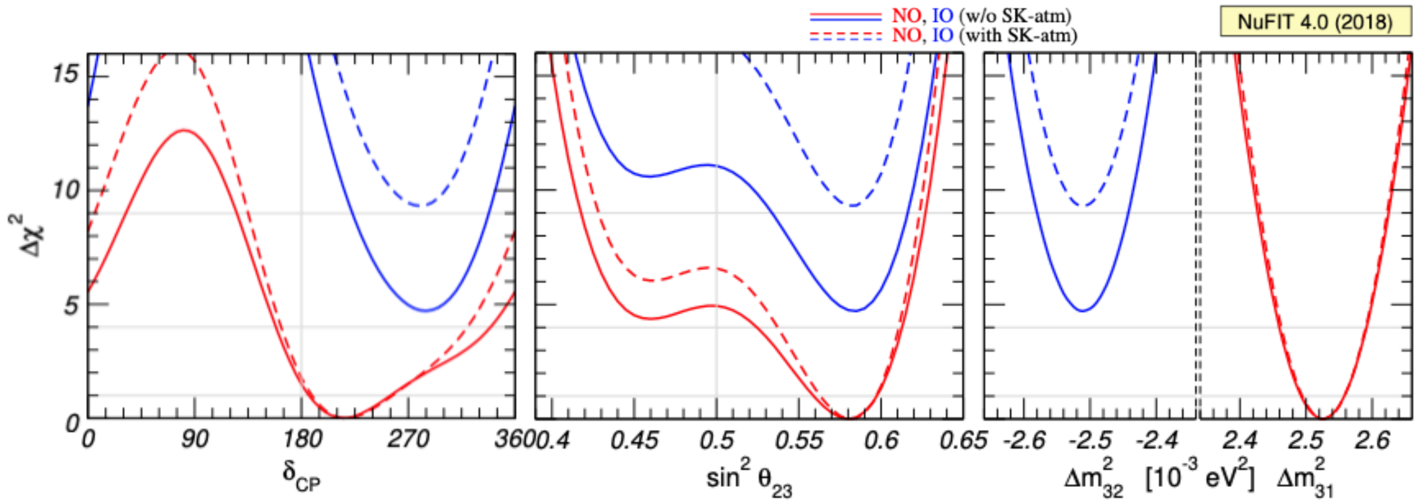


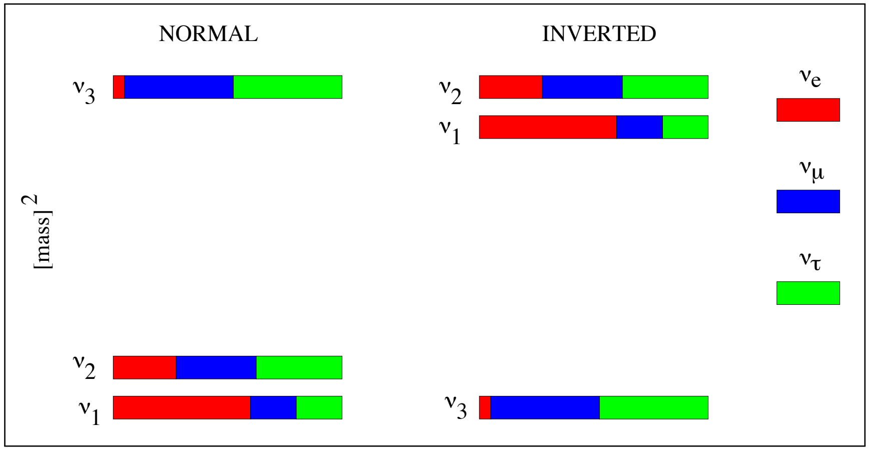
DayaBay, 2016 $\bar{\nu}_e \to \bar{\nu}_e$



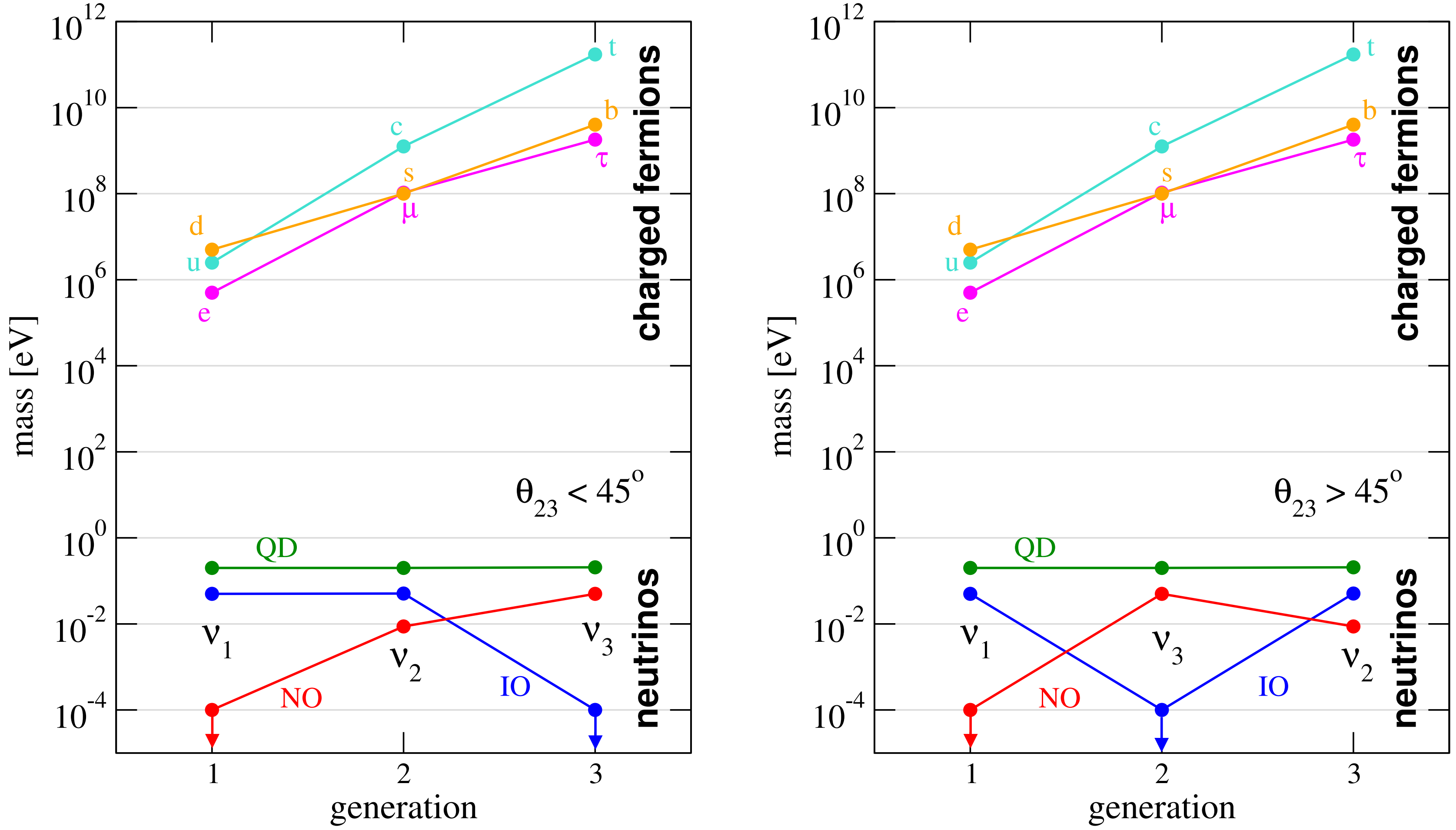
not-so-well determined parameters

CP phase, θ_{23}, mass ordering



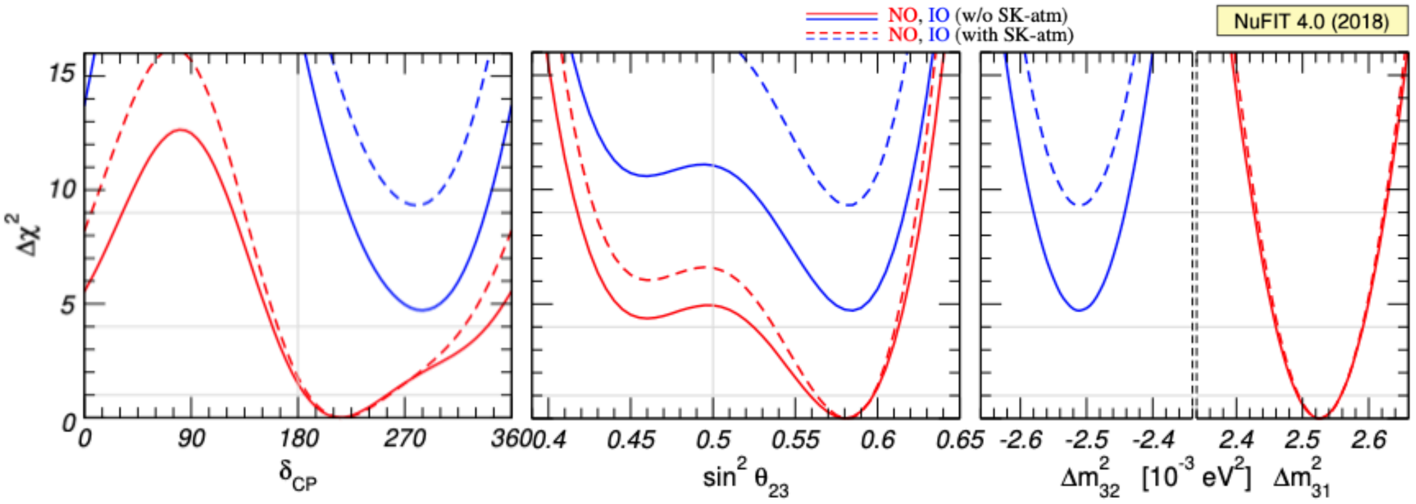


The SM fermion mass puzzle



CP phase, θ_{23}, mass ordering

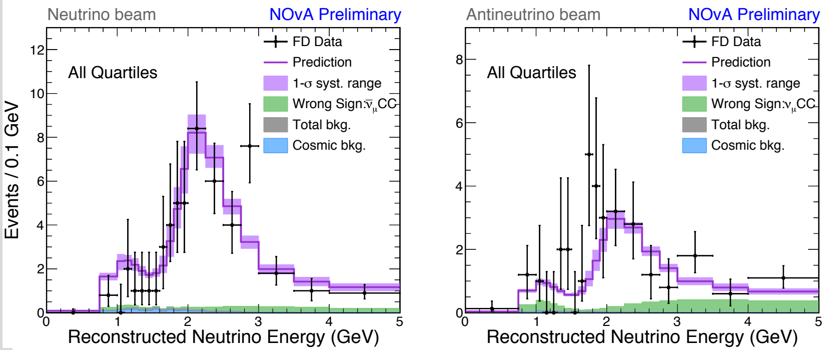
- CP conservation allowed at $\Delta\chi^2 = 1.8$, bf at $\delta = 217°$
- preference for second octant of θ_{23}, bf at $\sin^2\theta_{23} = 0.58$
  $\sin^2\theta_{23} < 0.5$ disfavoured with $\Delta\chi^2 \approx 4.4$ (6.0) without (with) SK atm
- NO preferred over IO by $\Delta\chi^2 = 4.7$ (9.3) without (with) SK atm



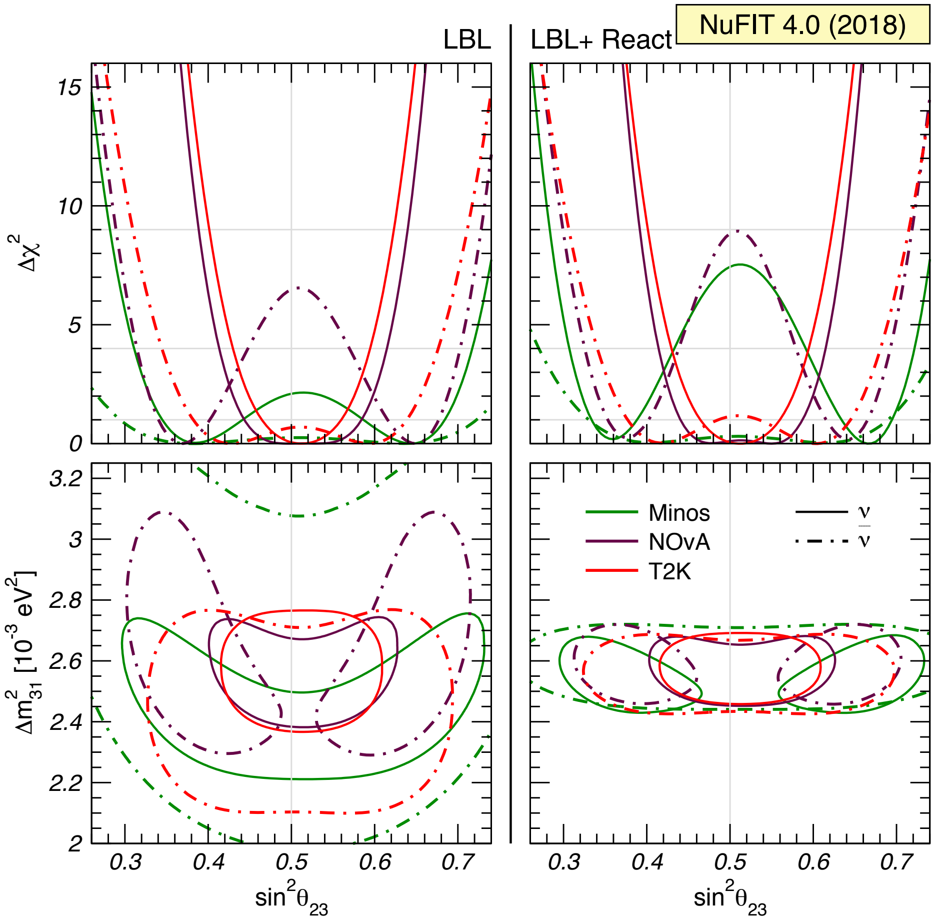
θ_{23} from LBL disappearance results

$$P_{\mu\mu} \approx 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{\mu\mu} L}{4E_\nu}$$

$$\begin{aligned} \sin^2\theta_{\mu\mu} &= \cos^2\theta_{13}\sin^2\theta_{23}\,, \\ \Delta m^2_{\mu\mu} &= \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} \\ &\quad + \cos\delta_{\rm CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21} \end{aligned}$$



M. Sanchez, Neutrino18



2σ contours, normal ordering, prior on θ_{13} imposed

LBL $\nu_\mu \to \nu_e$ appearance data

following Elevant, Schwetz, 15

$$C' \approx 0.28$$

$$o \equiv \mathrm{sgn}(\Delta m^2_{3\ell})$$

$$A \equiv \left|\frac{2EV}{\Delta m^2_{3\ell}}\right| \approx \begin{cases} 0.05 & \text{T2K} \\ 0.1 & \text{NOvA} \end{cases}$$

$$N_{\nu_e} \approx \mathcal{N}_\nu \left[2 s^2_{23}(1+2oA) - C' \sin\delta_{\rm CP}(1+oA)\right]$$

$$N_{\bar\nu_e} \approx \mathcal{N}_{\bar\nu} \left[2 s^2_{23}(1-2oA) + C' \sin\delta_{\rm CP}(1-oA)\right]$$

	T2K CCQE (ν)	T2K CC1π (ν)	T2K CCQE ($\bar\nu$)	NOvA (ν)	NOvA ($\bar\nu$)
$\mathcal{N}$	40	3.8	11	34	11
$N_{\rm obs} - N_{\rm bck}$	61.4	13.6	6.1	43.6	13.8

- Both neutrino and anti-neutrino events are enhanced by increasing s^2_{23}.
- Values of $\sin\delta_{\rm CP} \simeq +1\,(-1)$ suppress (increase) neutrino events, and have the opposite effect for anti-neutrino events.
- For NO (IO) neutrino events are enhanced (suppressed) due to the matter effect, whereas anti-neutrino events are suppressed (enhanced).
- For NO (IO) the matter effect increases (decreases) the impact of $\delta_{\rm CP}$ for neutrinos, while the opposite happens for anti-neutrinos.

θ_{23} octant

$$N_{\nu_e} \approx \mathcal{N}_\nu \left[2s_{23}^2(1+2oA) - C' \sin\delta_{\rm CP}(1+oA)\right]$$
$$N_{\bar\nu_e} \approx \mathcal{N}_{\bar\nu} \left[2s_{23}^2(1-2oA) + C' \sin\delta_{\rm CP}(1-oA)\right]$$

$$C' \approx 0.28$$
$$o \equiv \mathrm{sgn}(\Delta m^2_{3\ell})$$
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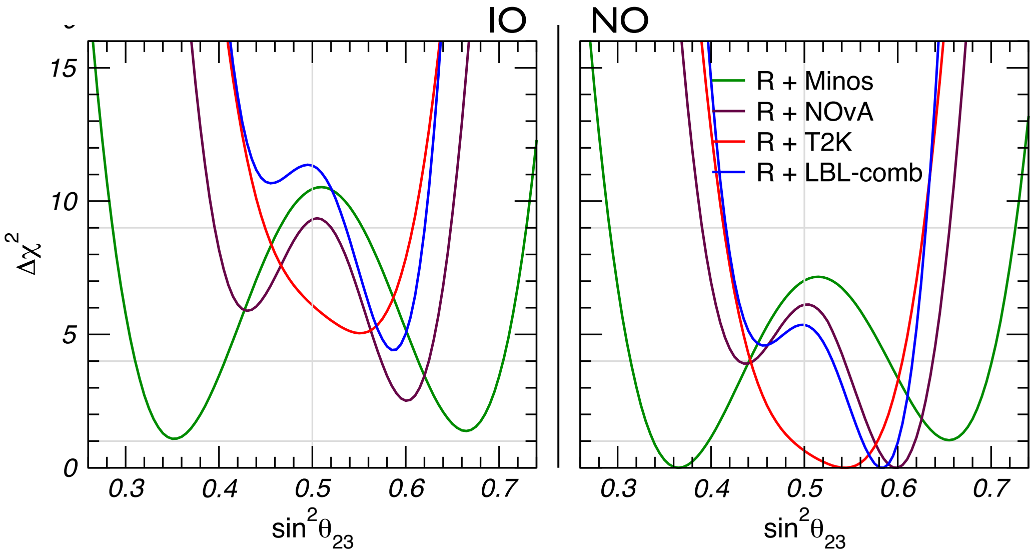

CP phase

$$N_{\nu_e} \approx \mathcal{N}_\nu \left[2s_{23}^2(1+2oA) - C' \sin\delta_{\rm CP}(1+oA)\right]$$
$$N_{\bar\nu_e} \approx \mathcal{N}_{\bar\nu} \left[2s_{23}^2(1-2oA) + C' \sin\delta_{\rm CP}(1-oA)\right]$$

$$C' \approx 0.28$$
$$o \equiv \mathrm{sgn}(\Delta m_{3\ell}^2)$$
$$A \equiv \left|\frac{2EV}{\Delta m_{3\ell}^2}\right| \approx \begin{cases} 0.05 & \text{T2K} \\ 0.1 & \text{NOvA} \end{cases}$$

	T2K CCQE (ν)	T2K CC1π (ν)	T2K CCQE ($\bar\nu$)	NOvA (ν)	NOvA ($\bar\nu$)
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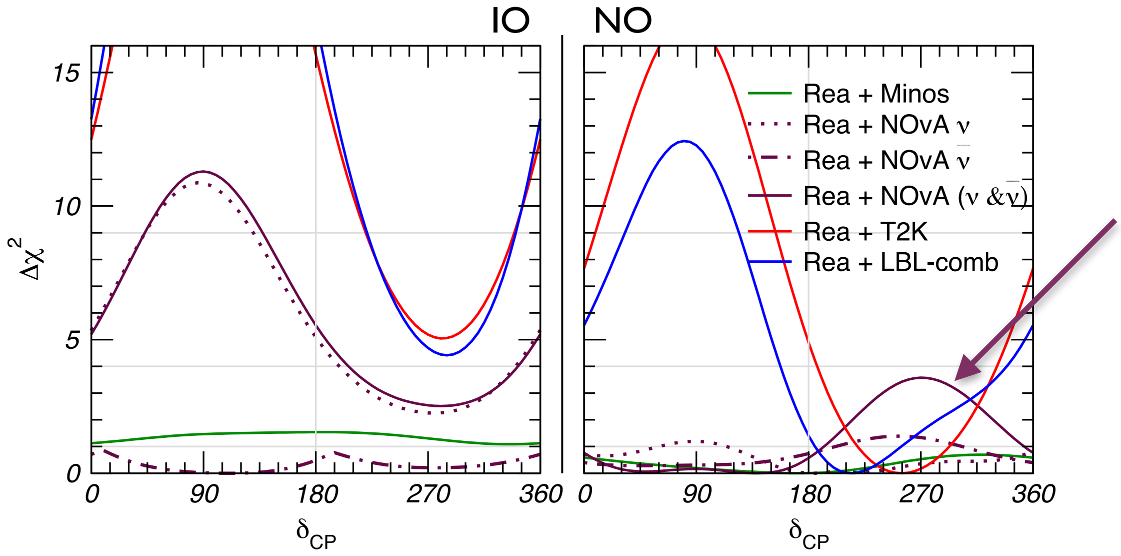
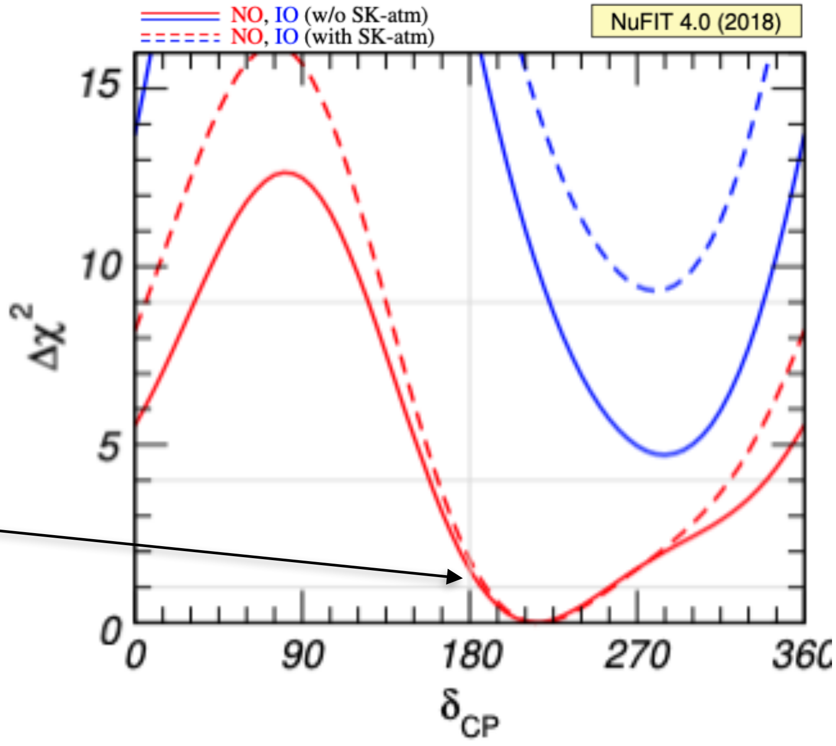


NOvA: non-max θ_{23} from antineut. + matter enhancement predict too many neutrino events for $\delta \approx 270°$

CP phase



CP conservation
at $\Delta\chi^2 = 1.8$

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.3$)	
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\delta_{\mathrm{CP}}/^\circ$	217^{+40}_{-28}	$135 \to 366$	280^{+25}_{-28}	$196 \to 351$

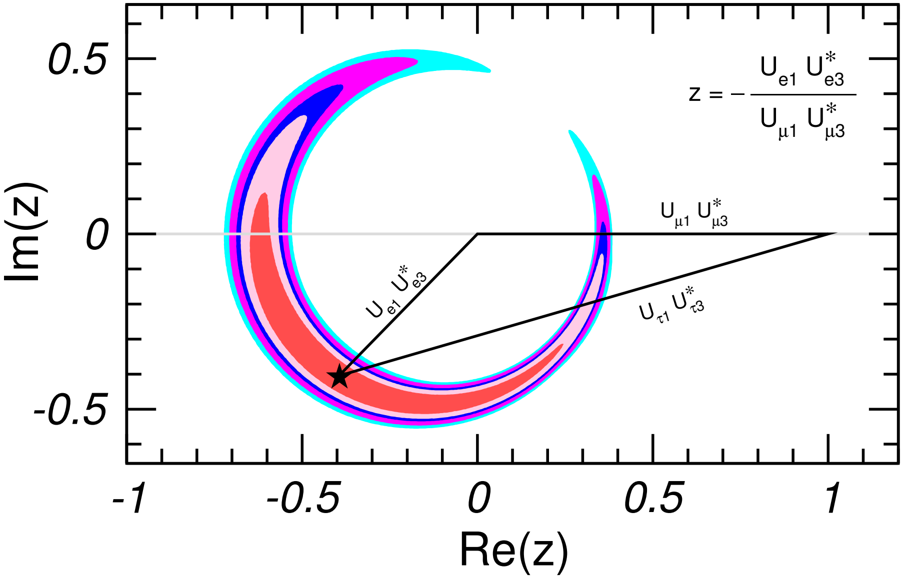
Leptonic CP violation

Jarlskog invariant:

$$J = |\mathrm{Im}(U_{\alpha 1} U^*_{\alpha 2} U^*_{\beta 1} U_{\beta 2})| \; = s_{12} c_{12} s_{23} c_{23} s_{13} c^2_{13} \sin\delta \equiv J^{\max} \sin\delta$$

$$\boxed{J^{\max}_{\rm CP} = 0.0333 \pm 0.0006 \, (\pm 0.0019) \;\text{ at } 1\sigma \; (3\sigma)}$$

NuFIT 4.0 (2018)



Leptonic CP violation

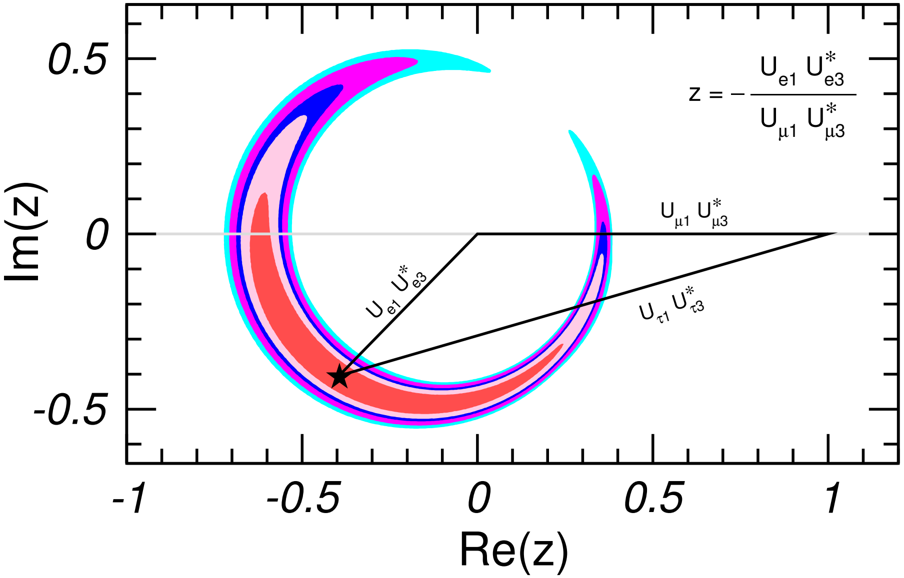
Jarlskog invariant:

$$J = \left|\mathrm{Im}(U_{\alpha 1} U^*_{\alpha 2} U^*_{\beta 1} U_{\beta 2})\right| \; = s_{12} c_{12} s_{23} c_{23} s_{13} c_{13}^2 \sin\delta \equiv J^{\max} \sin\delta$$

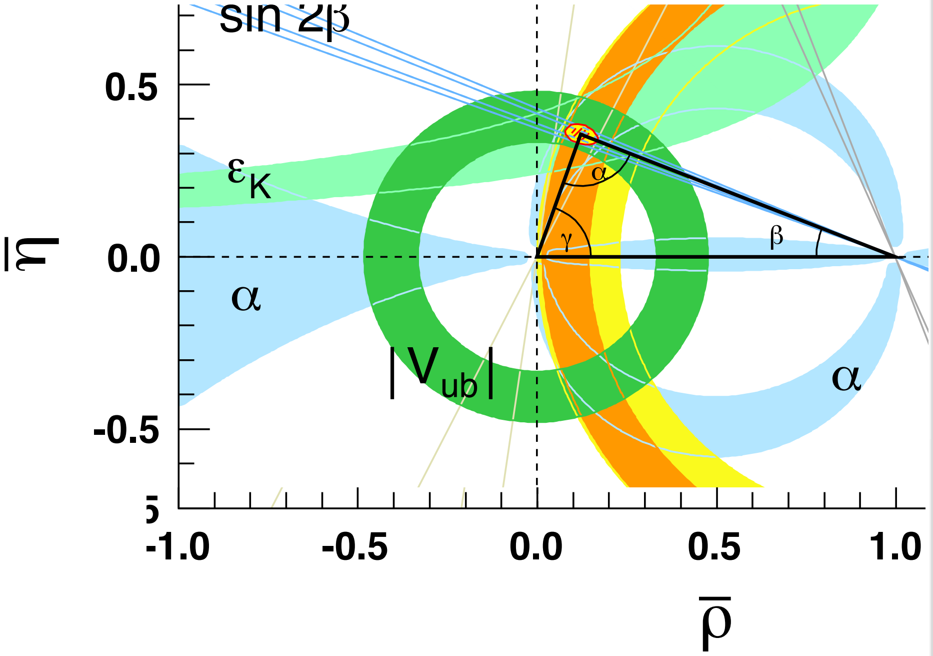
$$\boxed{J_{\mathrm{CP}}^{\max} = 0.0333 \pm 0.0006 \, (\pm 0.0019) \;\; \text{at } 1\sigma \; (3\sigma)}$$

$$J_{\mathrm{CP}}^{\mathrm{quarks}} = (3.18 \pm 0.15) \times 10^{-5}$$

NuFIT 4.0 (2018)



PDG 2018



Mass ordering

$$N_{\nu_e} \approx \mathcal{N}_\nu \left[2s_{23}^2(1+2oA) - C'\sin\delta_{\rm CP}(1+oA)\right]$$

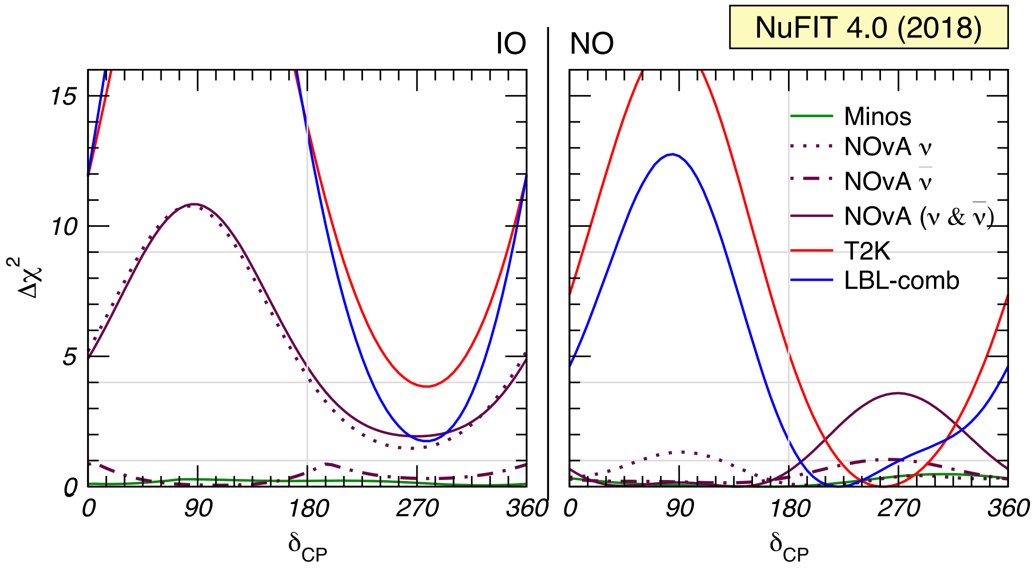
$$N_{\bar\nu_e} \approx \mathcal{N}_{\bar\nu} \left[2s_{23}^2(1-2oA) + C'\sin\delta_{\rm CP}(1-oA)\right]$$

$$C' \approx 0.28$$

$$o \equiv \mathrm{sgn}(\Delta m_{3\ell}^2)$$

$$A \equiv \left|\frac{2EV}{\Delta m_{3\ell}^2}\right| \approx \begin{cases} 0.05 & \text{T2K} \\ 0.1 & \text{NOvA} \end{cases}$$

	T2K CCQE (ν)	T2K CC1π (ν)	T2K CCQE ($\bar\nu$)	NOvA (ν)	NOvA ($\bar\nu$)
$\mathcal{N}$	40	3.8	11	34	11
$N_{\rm obs} - N_{\rm bck}$	61.4	13.6	6.1	43.6	13.8

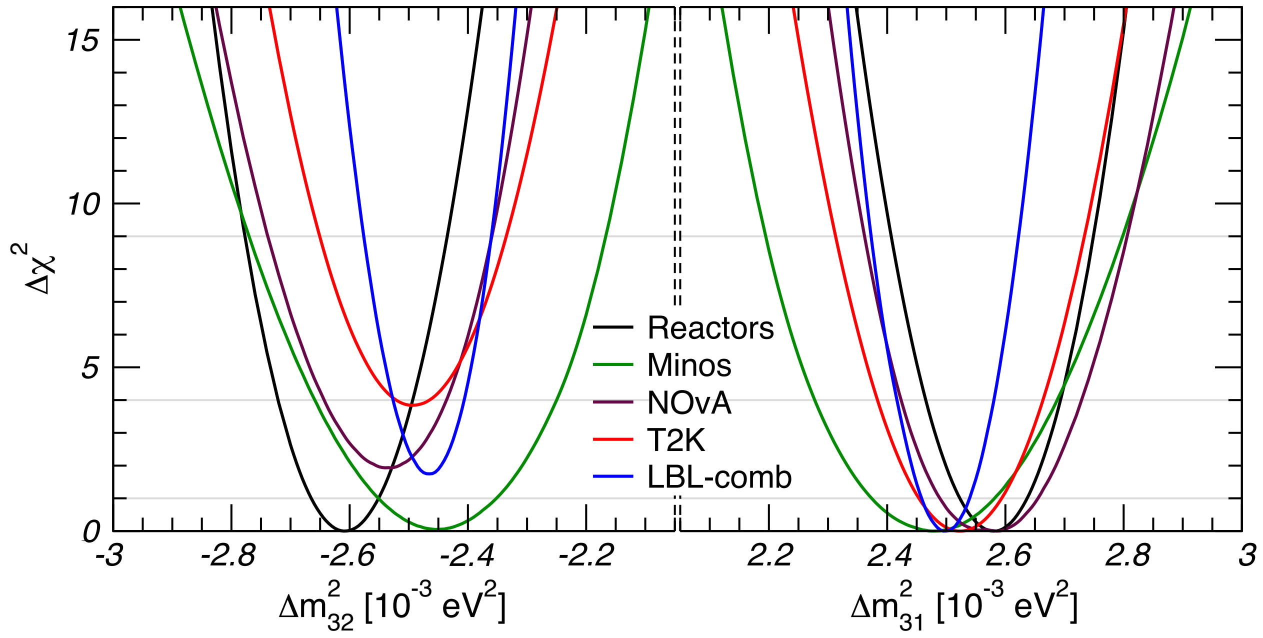


no reactor data, but θ_{13} prior added

T2K: $\Delta\chi^2$(IO) ≈ 4

adding NOvA: $\Delta\chi^2$(IO) ≈ 2

Mass ordering



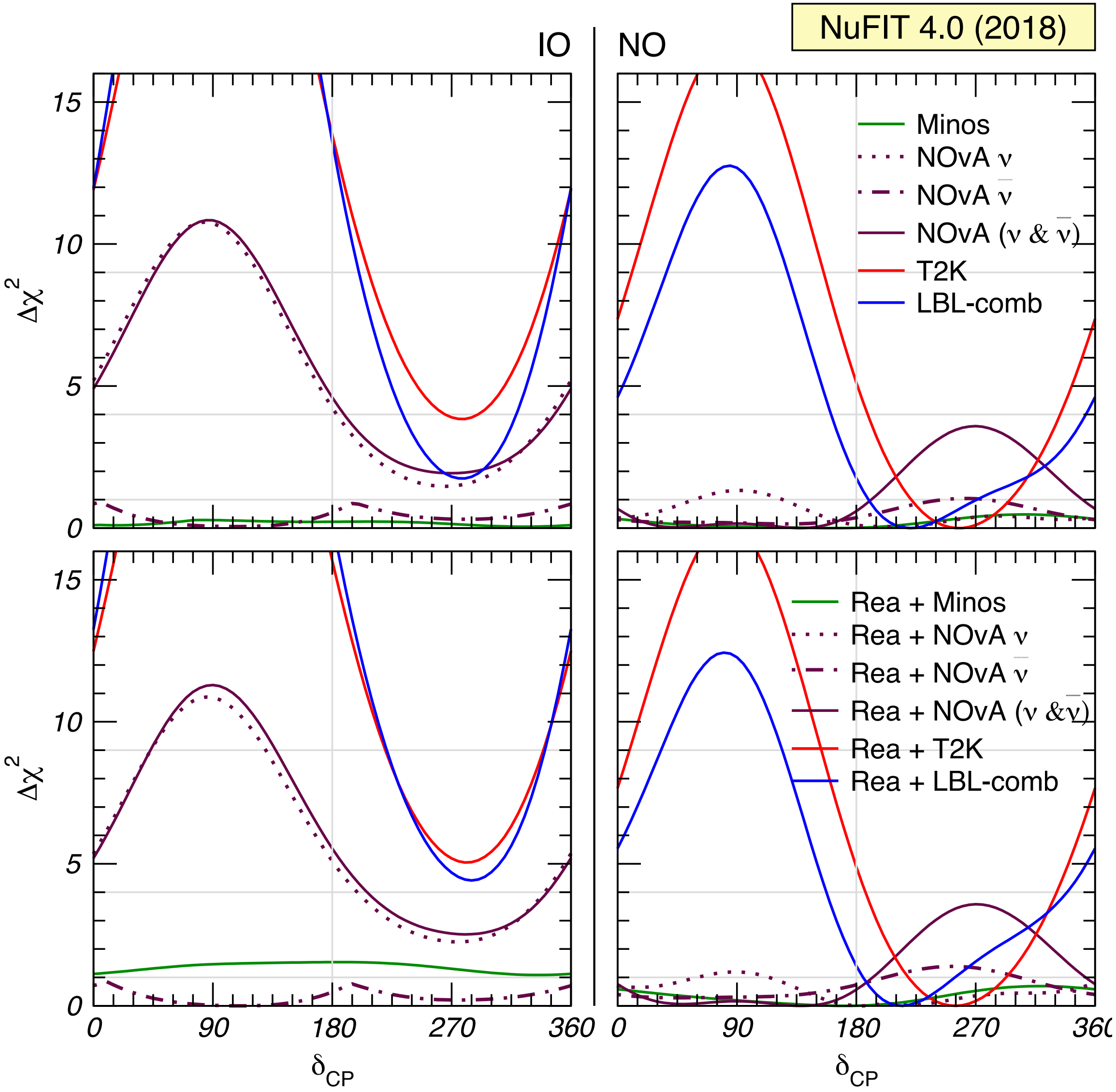
ν_e and ν_μ disappearance depend on slightly different effective mass-squared differences

$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

$$\Delta m^2_{\mu\mu} = \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} + \cos\delta_{\rm CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21}$$

Nunokawa, Parke, Zukanovich, 05, 06

Mass ordering



no reactor data, but
θ_{13} prior added

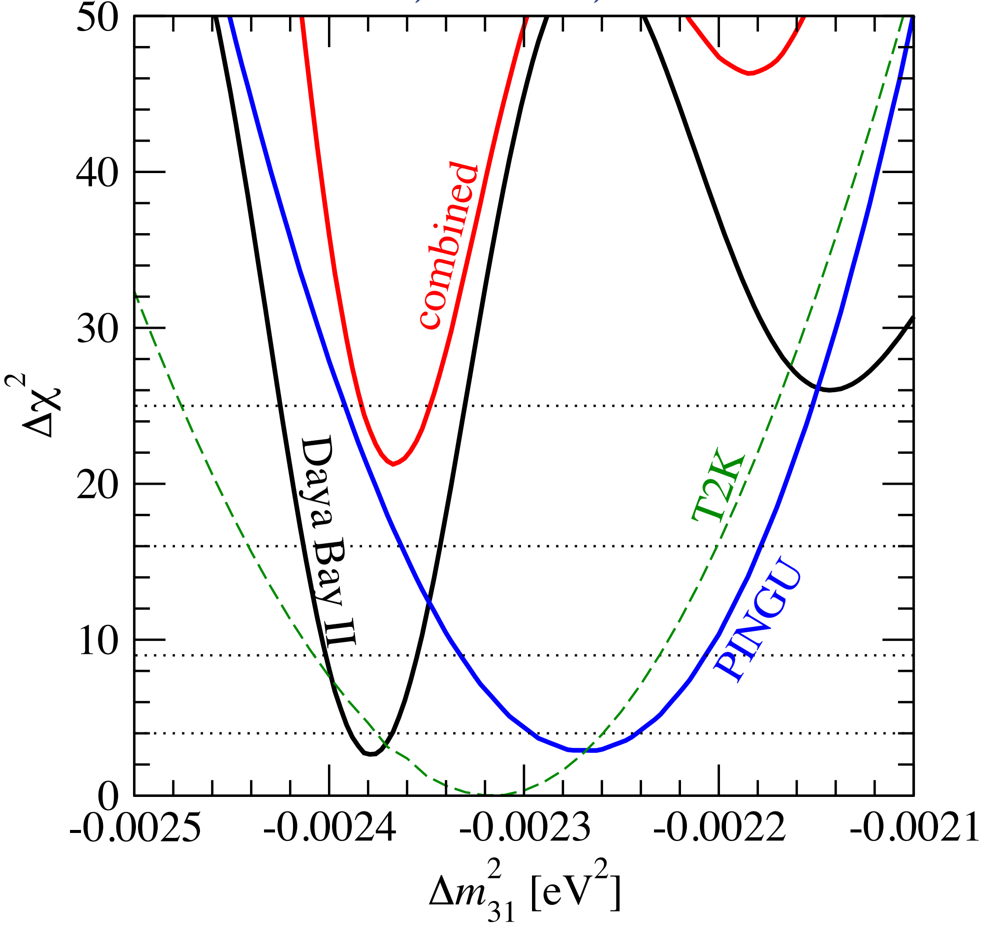
T2K: $\Delta\chi^2(\mathrm{IO}) \approx 4$

adding NOvA: $\Delta\chi^2(\mathrm{IO}) \approx 2$

adding reactors: $\Delta\chi^2(\mathrm{IO}) \approx 4$

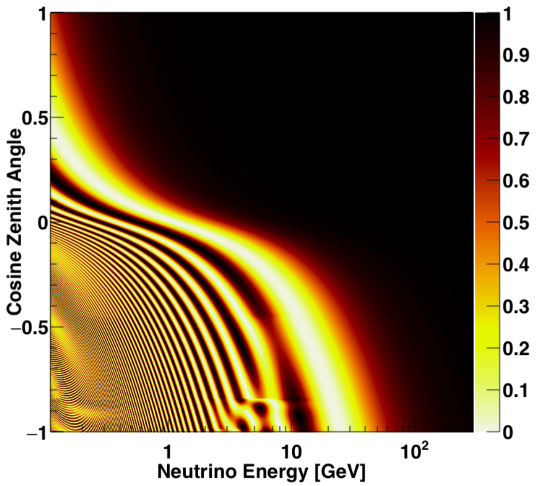
ν_e and ν_μ disapp. complementarity in future

Blennow, Schwetz, 1306.3988

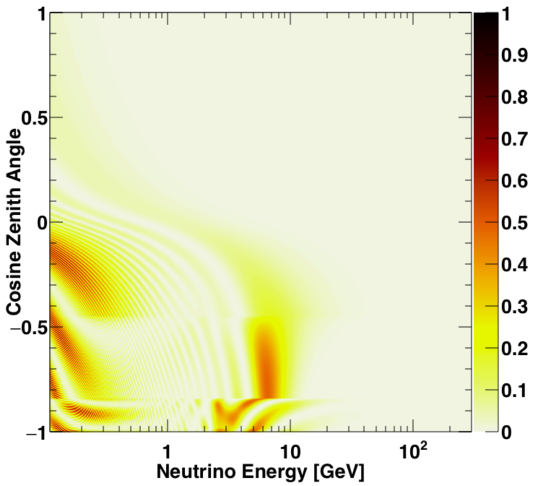


joint IceCube & JUNO paper
is in preparation

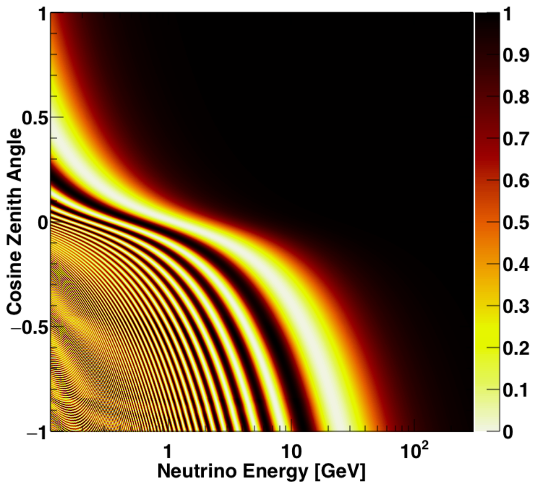
Mass ordering - atmospheric neutrinos



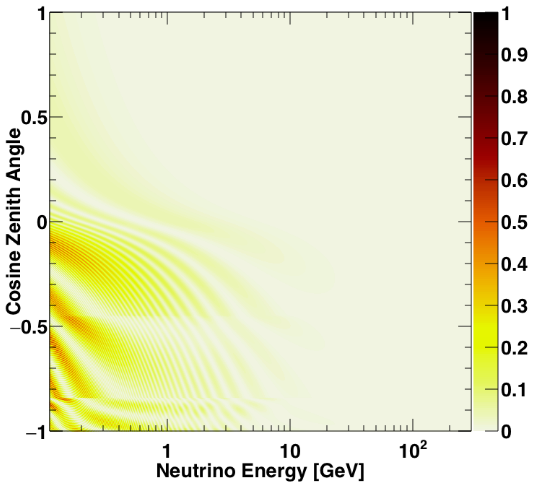
(a) $P(\nu_\mu \to \nu_\mu)$



(b) $P(\nu_\mu \to \nu_e)$



(c) $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$

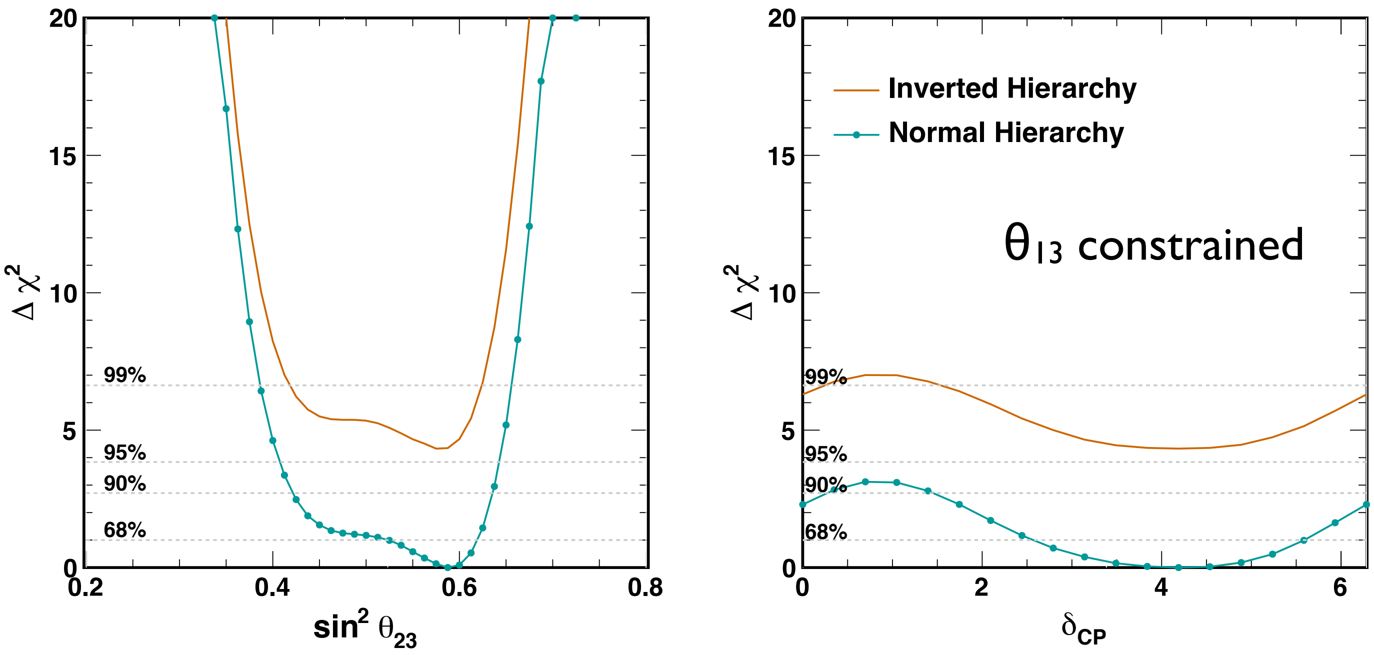


(d) $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

1710.09126

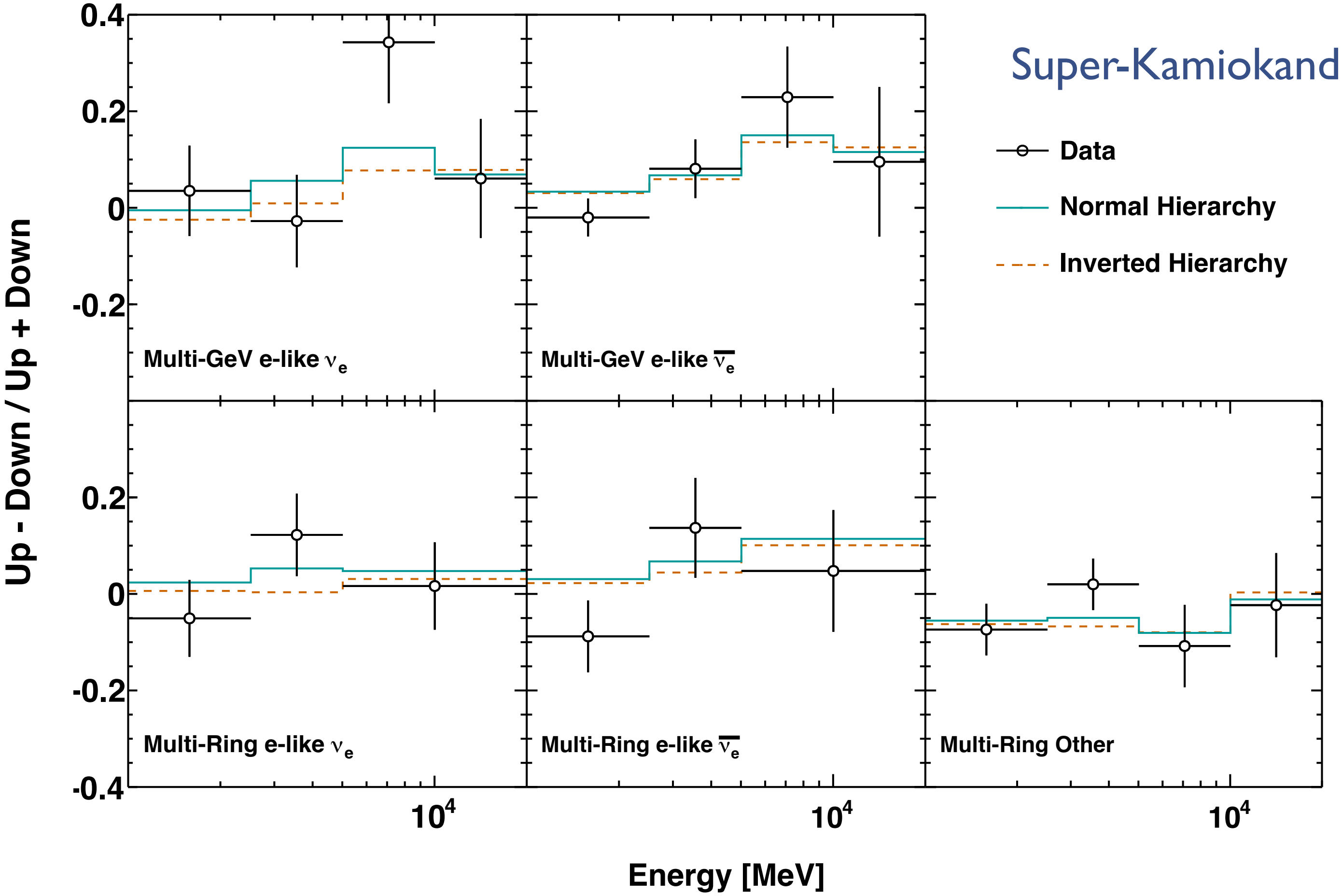
Mass ordering - atmospheric neutrinos

Super-Kamiokande I-IV, 1710.09126



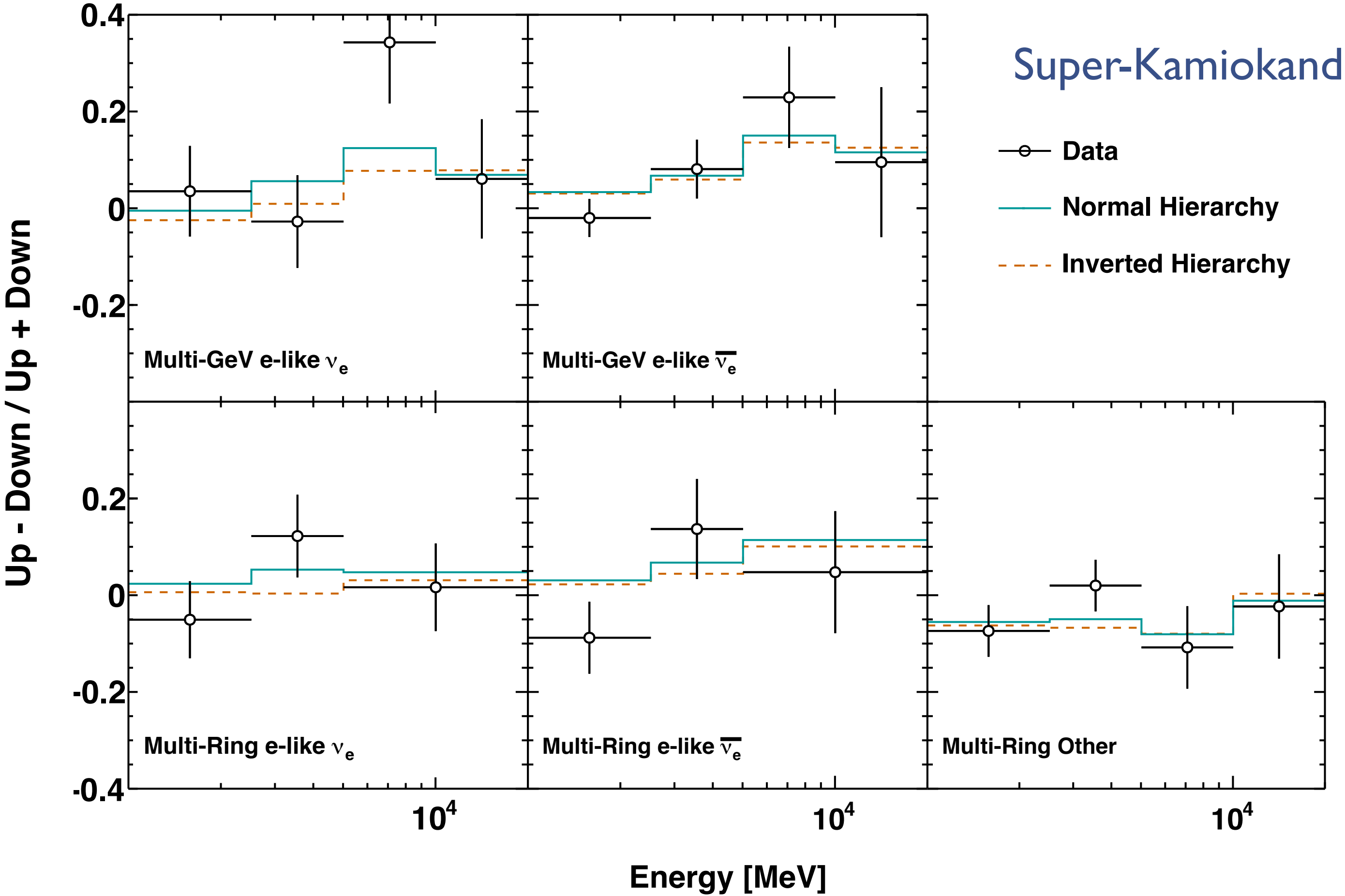
- prefers 2nd θ_{23} octant and $\pi < \delta < 2\pi$
- $\chi^2(\mathrm{IO}) - \chi^2(\mathrm{NO}) = 4.3$

Mass ordering - atmospheric neutrinos



- analysis not reproducable outside SK
- add χ^2 table to global fit („black box“)

Mass ordering - atmospheric neutrinos

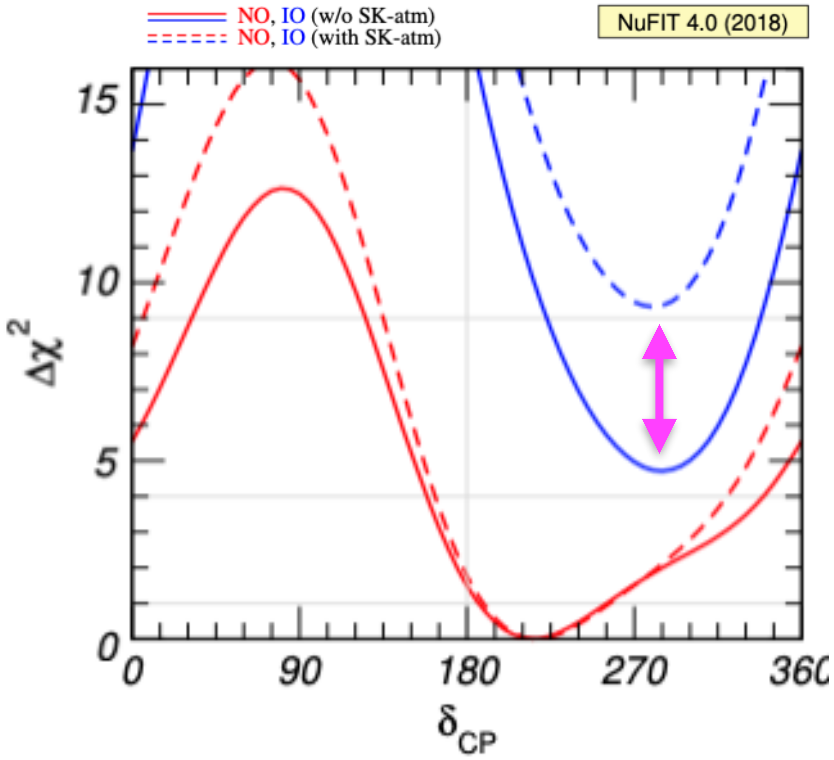


Super-Kamiokande I-IV, 1710.09126

Where are 4.3 units in χ^2?

- analysis not reproducable outside SK
- add χ^2 table to global fit („black box“)

Mass ordering incl. atmospherics



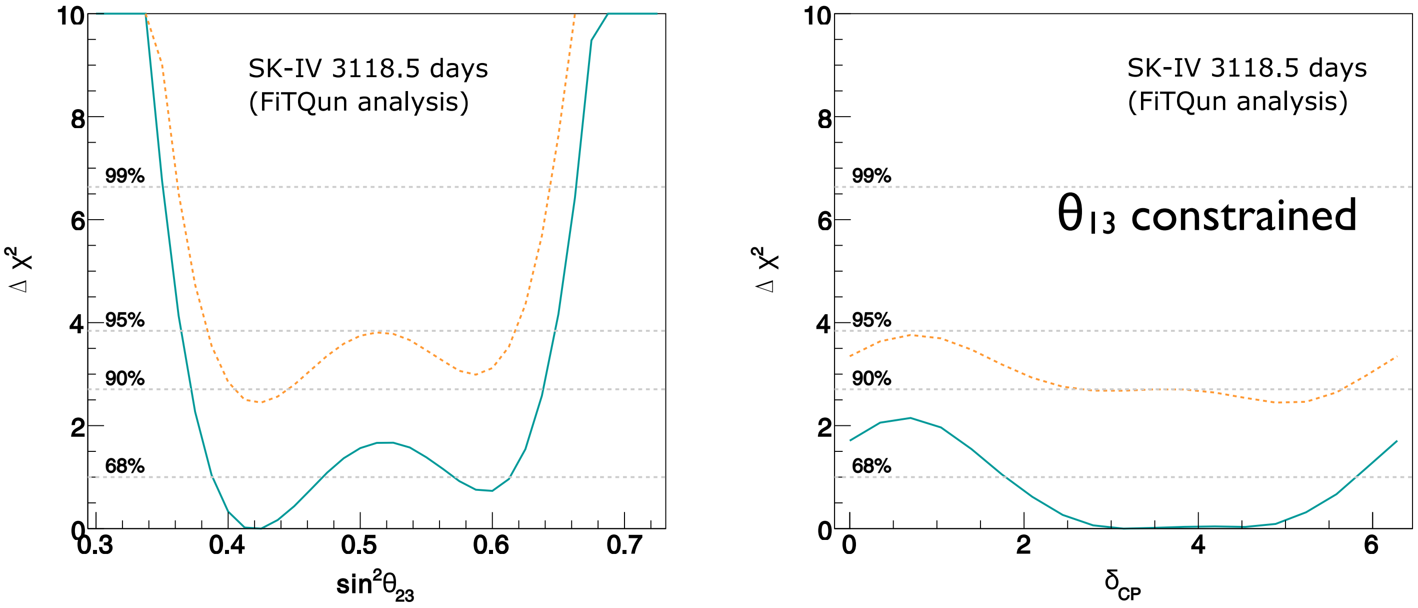
adding SuperK I-IV atm χ^2 table to the global fit → inverted ordering becomes disfavoured at 3σ

(contribution of IceCube to MO still very small)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.3$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\delta_{CP}/^\circ$	217^{+40}_{-28}	$135 \to 366$	280^{+25}_{-28}	$196 \to 351$

Mass ordering - atmospheric neutrinos

Atmospheric Neutrino Oscillation Analysis With Improved Event Reconstruction in Super-Kamiokande IV, 1901.03230



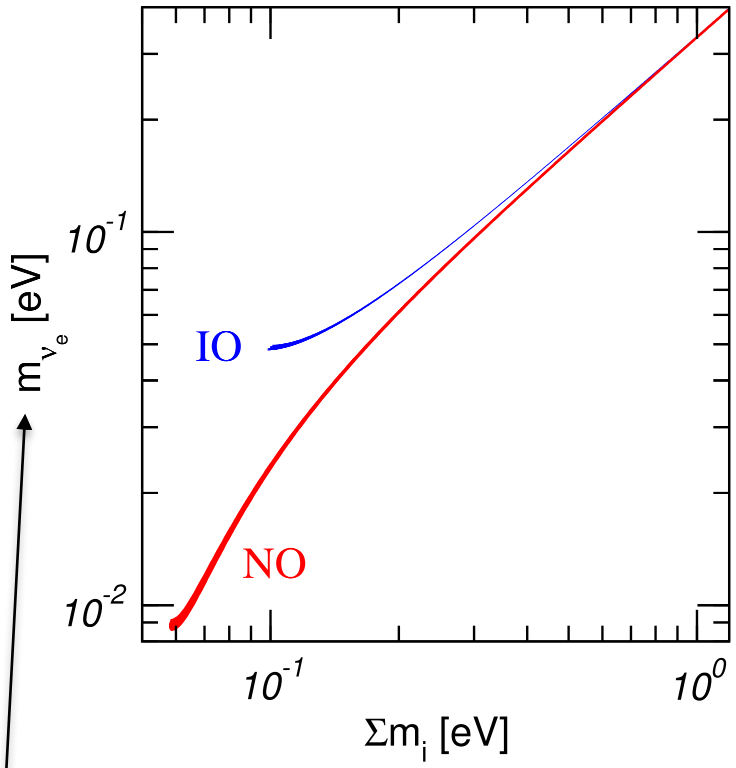
θ_{13} constrained

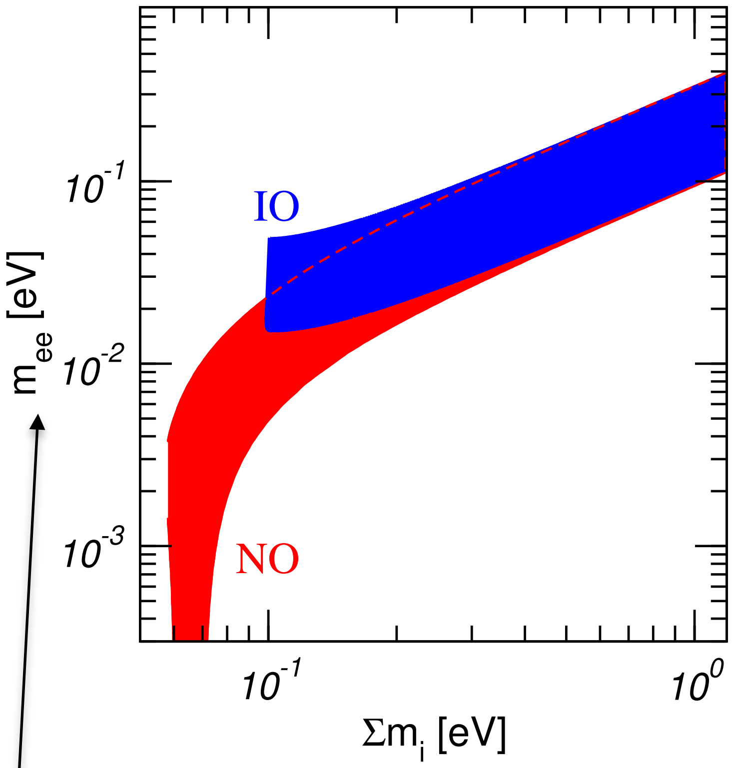
- χ^2(IO) - χ^2(NO) = 2.45 (compared to 4.3 from SK I-IV 2017)
- effective exposure 254 kt yr only 23% smaller (32% larger fiducial volume) (compared to 328 kt yr of SK I-IV 2017)

Beyond oscillations — absolute neutrino mass

Absolute neutrino mass observables

NuFIT 4.0 (2018)





cosmology

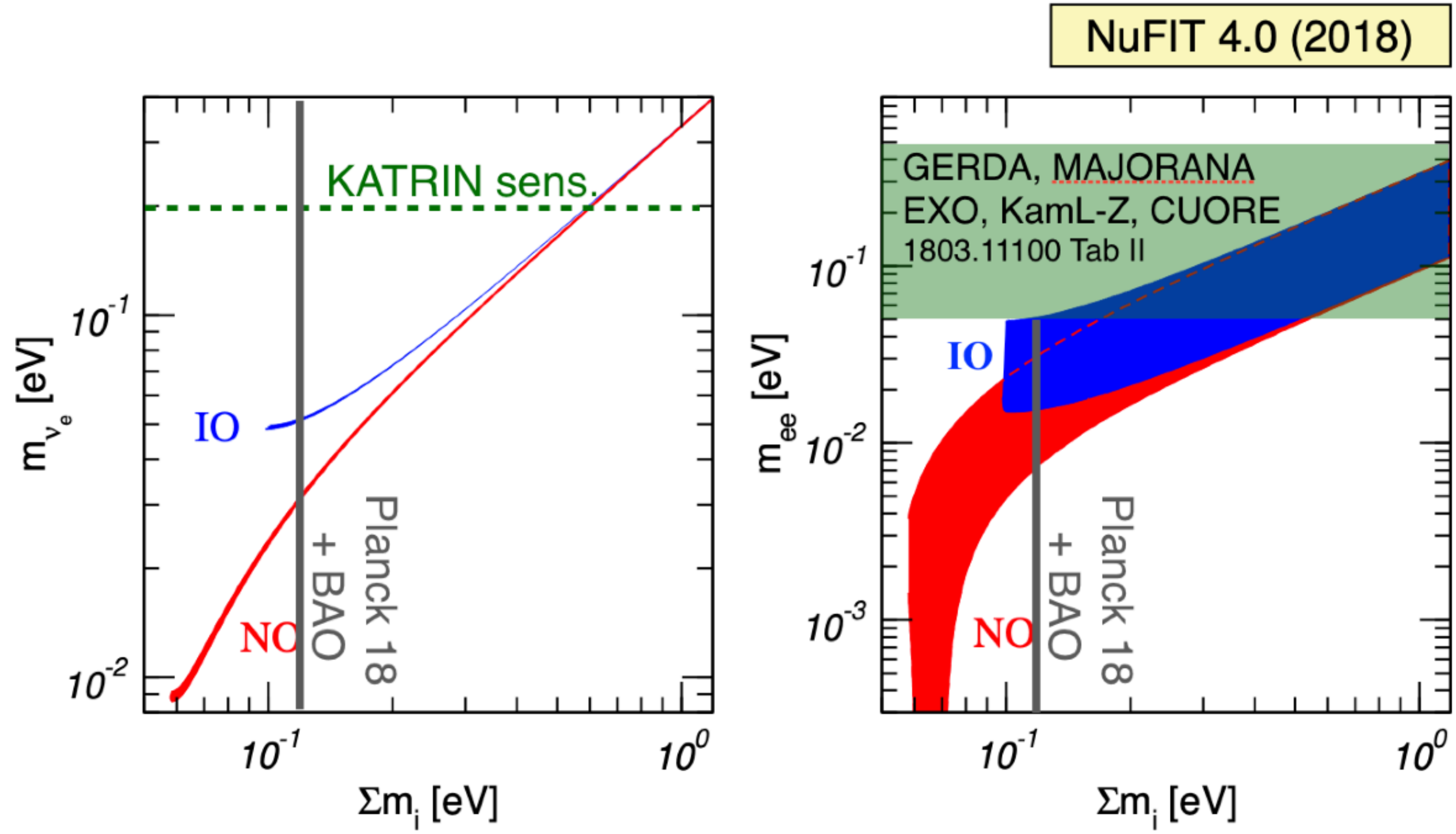
beta-decay endpoint

$$m_\beta^2 = \sum_i |U_{ei}^2| m_i^2$$

neutrinoless double-beta decay

$$m_{ee} = |\sum_i U_{ei}^2 m_i|$$

Absolute neutrino mass observables

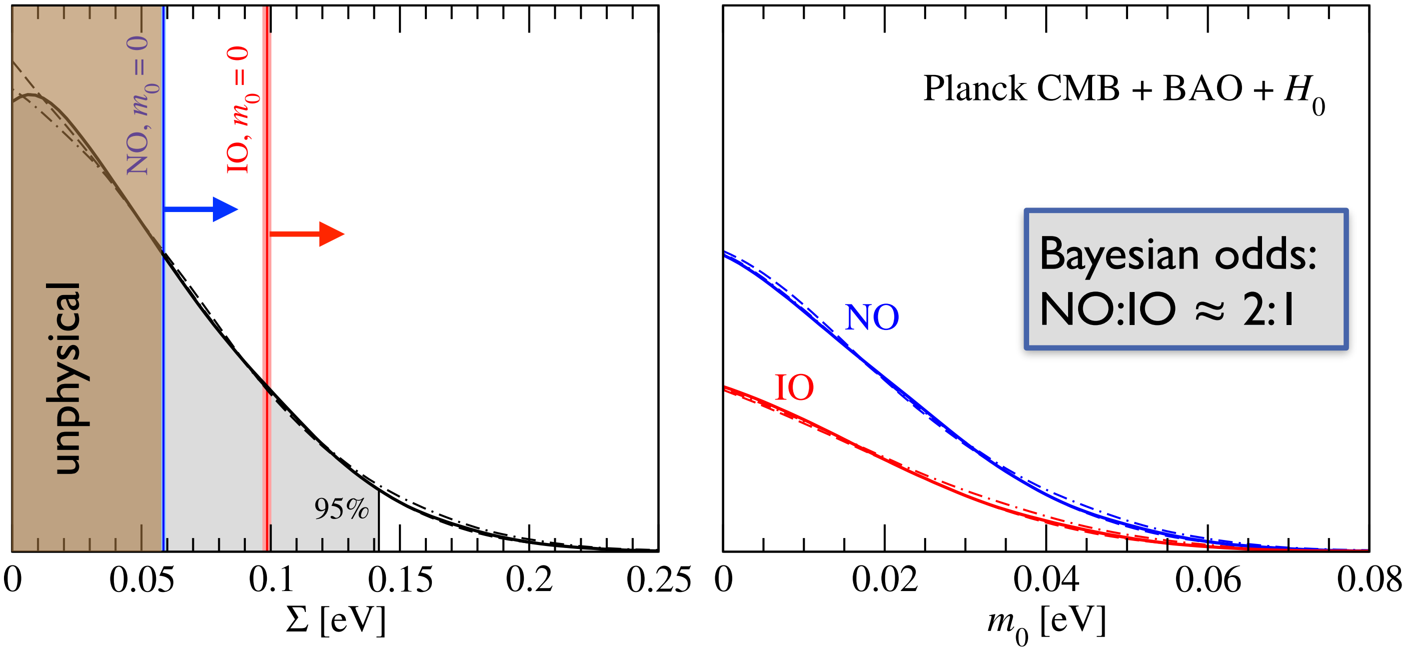


assumes standard 3-flavour & standard cosmology & Majorana neutrinos

Excluding inverted ordering with cosmology?

Hannestad, Schwetz, 1606.04691

minimal values: $$\Sigma = \begin{cases} 58.5 \pm 0.48\,\mathrm{meV} & \text{(NO)} \\ 98.6 \pm 0.85\,\mathrm{meV} & \text{(IO)} \end{cases} \qquad (m_0 = 0)\,.$$



Bayesian odds:
NO:IO ≈ 2:1

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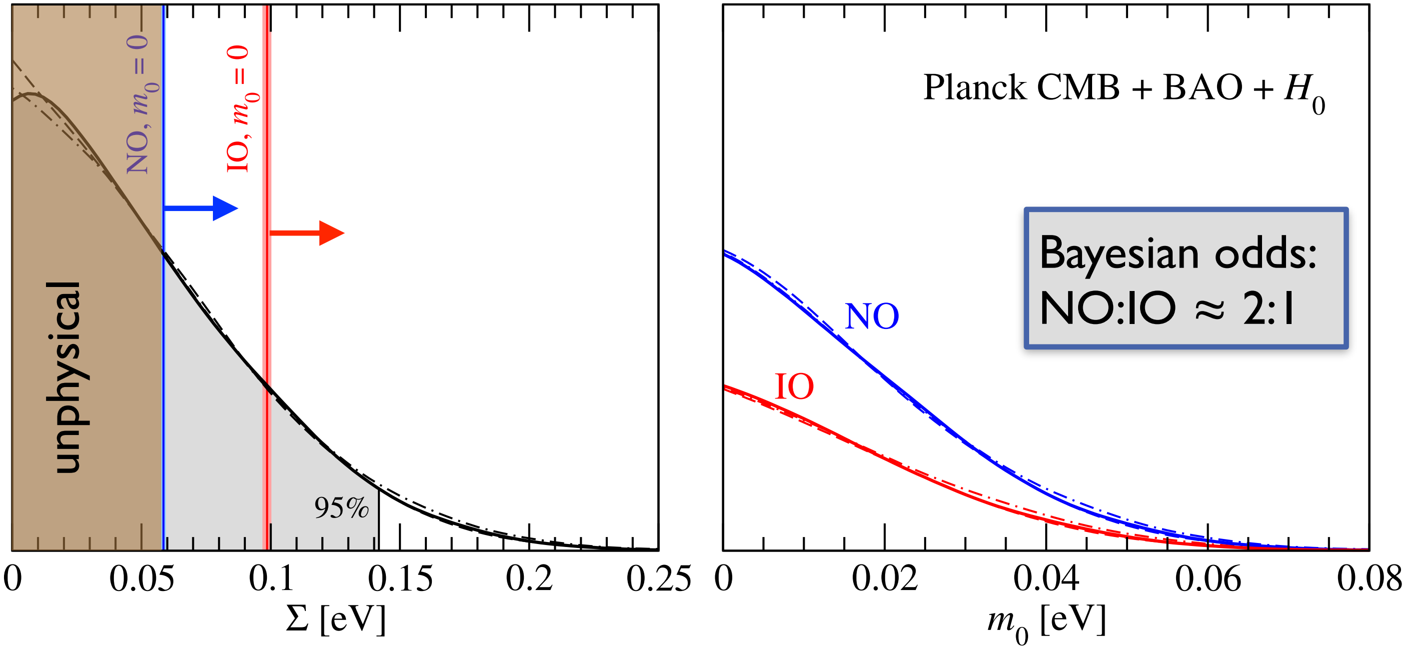

Bayesian odds:
NO:IO ≈ 2:1

„Strong evidence“ for NO claimed in Simpson et al. 1703.03425
→ be aware of Bayesian priors [TS et al. 1703.04585]

Excluding inverted ordering with cosmology?

Hannestad, Schwetz, 1606.04691

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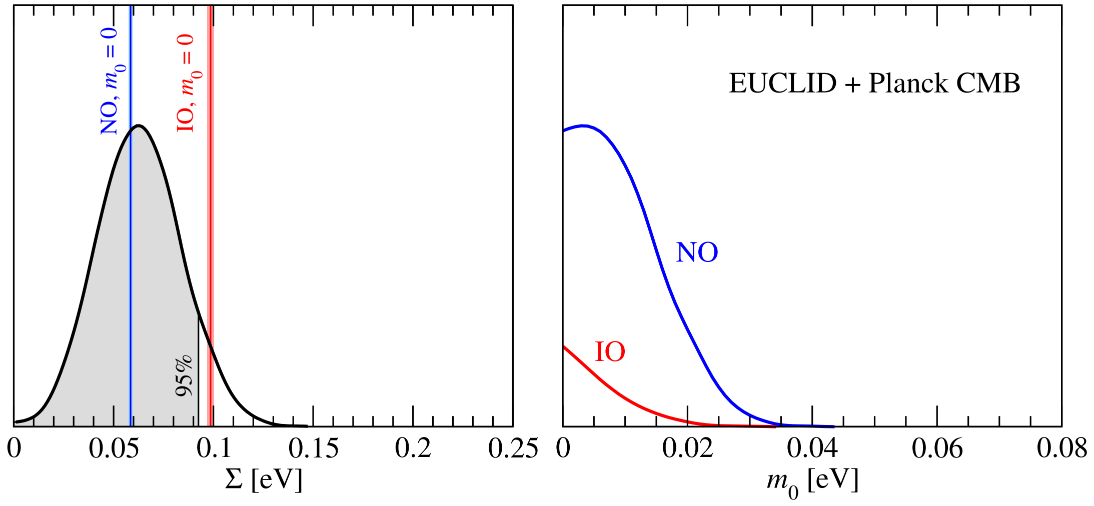
simulated future data:
2 yrs of EUCLID data, available ~2023-24



- need accuracy better than 0.02 eV to exclude 0.1 eV against 0.06 eV at 2σ
- this would imply a 3σ evidence for non-zero neutrino mass (for Sum = 0.06 eV)

How to give mass to neutrinos?

Masses in the Standard Model

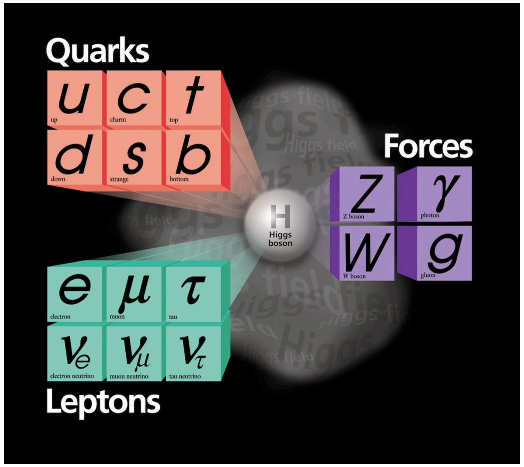
- The Standard Model has only one dimension full parameter: the vacuum expectation value of the Higgs:

$$\langle H \rangle \approx 174 \text{ GeV}$$

- All masses in the Standard Model are set by this single scale:

$$m_i = y_i \langle H \rangle$$

top quark: $y_t \approx 1$
electron: $y_e \approx 10^{-6}$



Neutrino masses in the Standard Model

- fermion mass terms require left- and right-handed fields
- right-handed neutrinos are complete singlets under the SM gauge group → not part of the original formulation of the SM

➡ no Dirac mass term for neutrinos!

Neutrino masses in the Standard Model

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- right-handed neutrinos are complete singlets under the SM gauge group → not part of the original formulation of the SM

➡ no Dirac mass term for neutrinos!

- for electrically neutral fermions a mass term can be built only from left-handed fields (Majorana mass term)
- cannot assign conserved quantum number → Lepton number would be violated
- BUT: in the SM Lepton number is an accidental symmetry → cannot break L at renormalizable level

➡ no Majorana mass term for neutrinos!

Neutrino mass requires physics beyond the SM

- which type of new physics?
- at which energy scale?

The Weinberg operator

Assume there is new physics at a high scale Λ. It will manifest itself by non-renormalizable operators suppressed by powers of Λ.

Weinberg 1979: there is only one dim-5 operator consistent with the gauge symmetry of the SM, and this operator will lead to a Majorana mass term for neutrinos after EWSB:

$$Y^2 \frac{L^T \tilde{H}^* \tilde{H}^\dagger L}{\Lambda} \quad \longrightarrow \quad m_\nu \sim Y^2 \frac{\langle H \rangle^2}{\Lambda}$$

at dim-5 lepton number can be broken
($L \to e^{i\alpha} L$ forbidden by above operator)

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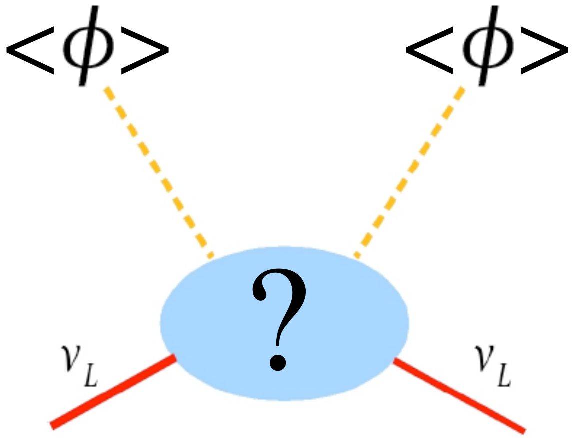
Seesaw: neutrinos are light because of the presence of the large energy scale Λ

The Weinberg operator

$$Y^2 \frac{L^T \tilde{H}^* \tilde{H}^\dagger L}{\Lambda}$$



What is the new physics responsible for neutrino mass?

many realisations (too many?) are known:

- right-handed neutrinos
- extended Higgs sector
- realisations due to quantum effects (loop-induced neutrino mass)
- …

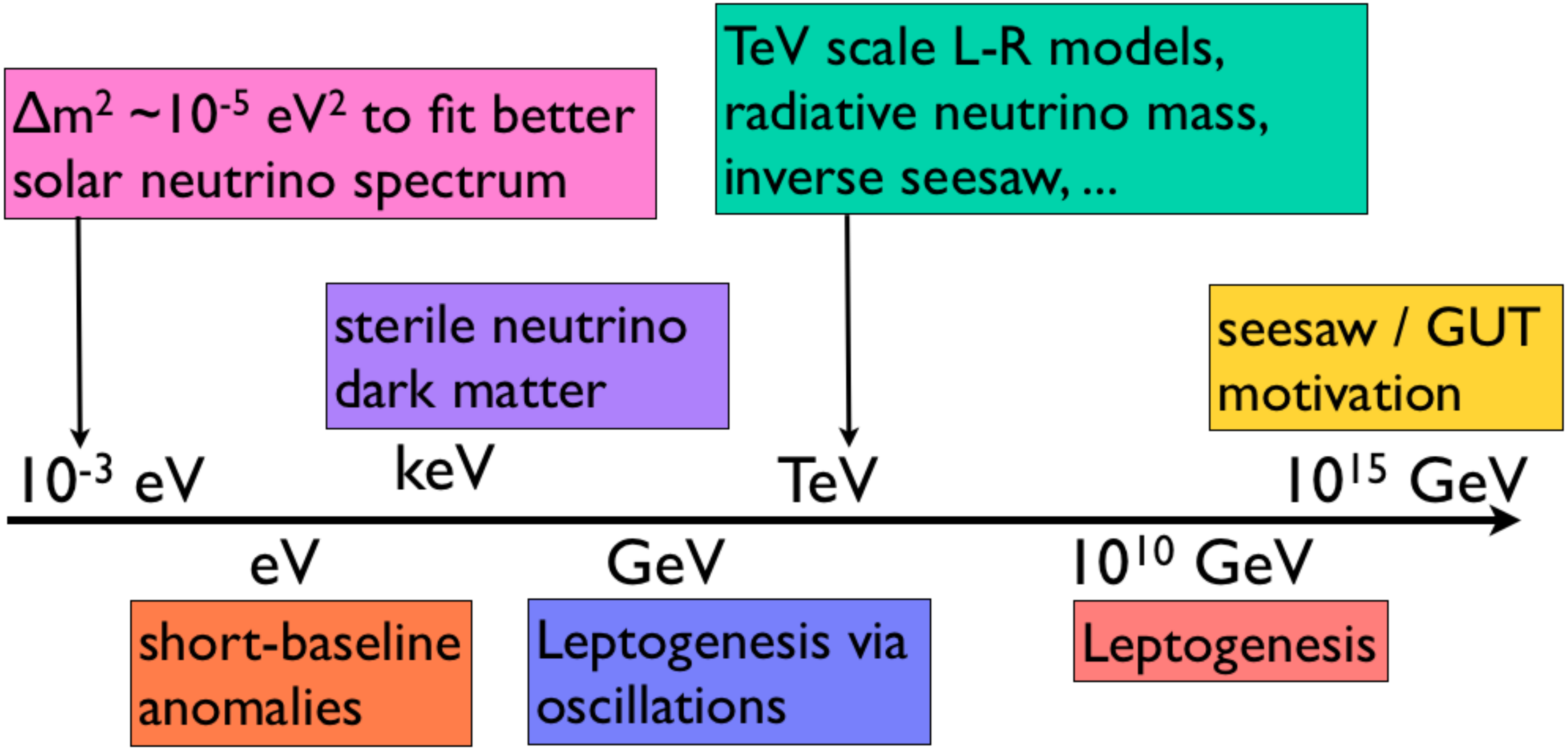
What is the energy scale responsible for neutrino mass?

$m_\nu \sim Y^2 \frac{\langle H \rangle^2}{\Lambda}$ small neutrino mass by making Λ large or Y small or both

- High scale seesaw: $Y \sim 1$ (top Yukawa) $\rightarrow \Lambda \sim 10^{14}$ GeV
  - "natural" explanation of small neutrino masses
  - Λ close to GUT scale $\rightarrow$ SO(10) models
  - Leptogenesis
  - very hard to test experimentally

- Low scale seesaw: $Y \sim 10^{-6}$ (electron Yukawa) $\rightarrow \Lambda \sim 1$ TeV
  - link neutrino mass generation to TeV scale physics
  - potentially testable at colliders
  - observable signatures in searches for LFV
    $\mu \rightarrow e\gamma, \tau \rightarrow \mu\gamma, \mu \rightarrow eee, \ldots$

What is the energy scale responsible for neutrino mass?



$\Delta m^2 \sim 10^{-5}$ eV^2 to fit better solar neutrino spectrum

TeV scale L-R models, radiative neutrino mass, inverse seesaw, ...

sterile neutrino dark matter

seesaw / GUT motivation

10^{-3} eV

keV

TeV

10^{15} GeV

eV

GeV

10^{10} GeV

short-baseline anomalies

Leptogenesis via oscillations

Leptogenesis

Testing the Majorana nature

Weinberg operator breaks lepton number ($L \to e^{i\alpha} L$ forbidden)

$$Y^2 \frac{L^T \tilde{H}^* \, \tilde{H}^\dagger L}{\Lambda}$$

→ predicts Majorana neutrinos!

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$$Y^2 \frac{L^T \tilde{H}^* \, \tilde{H}^\dagger L}{\Lambda}$$

$\rightarrow$ predicts Majorana neutrinos!

Neutrinoless double-beta decay: $(A, Z) \to (A, Z+2) + 2e^-$

- observation of this process would prove that lepton number is violated
- in a "natural theory" neutrinos will get a Majorana mass term
  Schechter, Valle, 1982; Takasugi, 1984
- lot's of experimental activity
  GERDA, Majorana, EXO, XMASS, KamLAND-Zen, CUORE, NEMO, SNO+, ...

What if lepton number is conserved?

➡ neutrinos have to be Dirac particles
(like all other fermions of the SM)

What if lepton number is conserved?

➡ neutrinos have to be Dirac particles
(like all other fermions of the SM)

- need to add right-handed neutrinos N
- need tiny Yukawa couplings $y_\nu \lesssim 10^{-11}$
  (compare: top quark: $y_t \sim 1$, electron: $y_e \sim 10^{-6}$)
- Majorana mass term for N is allowed by gauge symmetry
  there is "no reason" why lepton number is conserved
  there is no longer an accidental symmetry of the theory
  $\rightarrow$ impose "by hand"
- $m_{\mathrm{Maj}} = 0$ is "technically natural" (stable under quantum corrections)

How to identify the neutrino mass mechanism?

- theory provides little guidance towards the physics beyond the SM responsible for neutrino mass

- hope of additional signatures:
    - lepton number violation
      neutrinoless double-beta decay / at LHC
    - search for „unexpected“ neutrino properties
      (exotic interactions, sterile neutrinos, non-unitarity, neutrino decay,…)
    - lepton flavour violation in charged leptons

Charged lepton flavour violation

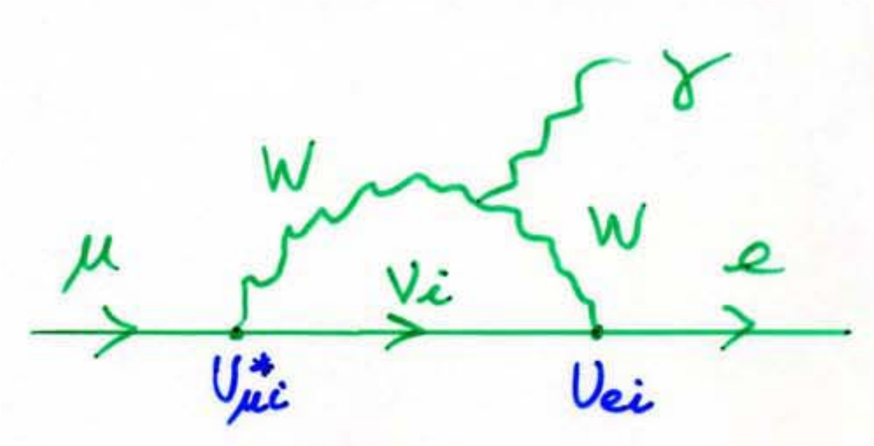
- Neutrino oscillations imply violation of lepton flavour, e.g.: $\nu_\mu \rightarrow \nu_e$
- Can we see also LFV in charged leptons?

$$\begin{aligned} &\mu^\pm \rightarrow e^\pm \gamma \\ &\tau^\pm \rightarrow \mu^\pm \gamma \\ &\mu^+ \rightarrow e^+ e^+ e^- \\ &\mu^- + N \rightarrow e^- + N \end{aligned}$$

rich experimental programme with
sensitivities in the 10^{-13} to 10^{-18} range!

Can we see LFV in charged leptons?

Yes, BUT: $\mu^\pm \to e^\pm\gamma$ in the SM + ν mass:



$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{m^2_W}\right|^2 \lesssim 10^{-54}$$

- unobservably small (present limits: $\sim 10^{-13}$)
- observation of $\mu \to e\gamma$ implies new physics beyond neutrino mass

Charged lepton flavour violation

generically: $\mathrm{Br}(\mu \to e\gamma) \sim 10^{-10} \left(\frac{\mathrm{TeV}}{\Lambda_{\mathrm{LFV}}}\right)^4 \left(\frac{\theta_{e\mu}}{10^{-2}}\right)^2$

- sensitive to new physics at 1-1000 TeV
  (TeV-scale SUSY, TeV-scale neutrino mass models,…)
- cLFV does not (directly) probe Majorana mass
  LFV is lepton number conserving; LNV: dim-5, LFV: dim-6

$$\mathcal{L}_{\mathrm{LFV}} = \frac{1}{\Lambda^2_{\mathrm{LFV1}}}(\overline{\mu}e)(\overline{e}e) + \frac{1}{\Lambda^2_{\mathrm{LFV2}}}(\overline{\mu}e)(\overline{q}q) + \ldots$$

- cLFV probes new physics which may or may not be related to neutrino mass → extremely viable information!

Summary

- 3-flavour oscillation paradigm well established
- first hints on open issues emerging (θ_{23}, mass ordering, CPV) → main goal of upcoming oscillation programme (JUNO, IceCube-g2, ORCA, T2HK, DUNE)
- entering the era of precision / over-constraining the neutrino sector / search for unexpected neutrino properties

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- neutrino mass requires physics beyond the SM
- identifying the mechanism responsible for neutrino mass is challenging
- urgent need of complementary information:
  - lepton number violation (neutrinoless double-beta decay)
  - charged lepton flavour viol.
  - leptonic signals at LHC

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Thank you for your attention!

supplementary slides

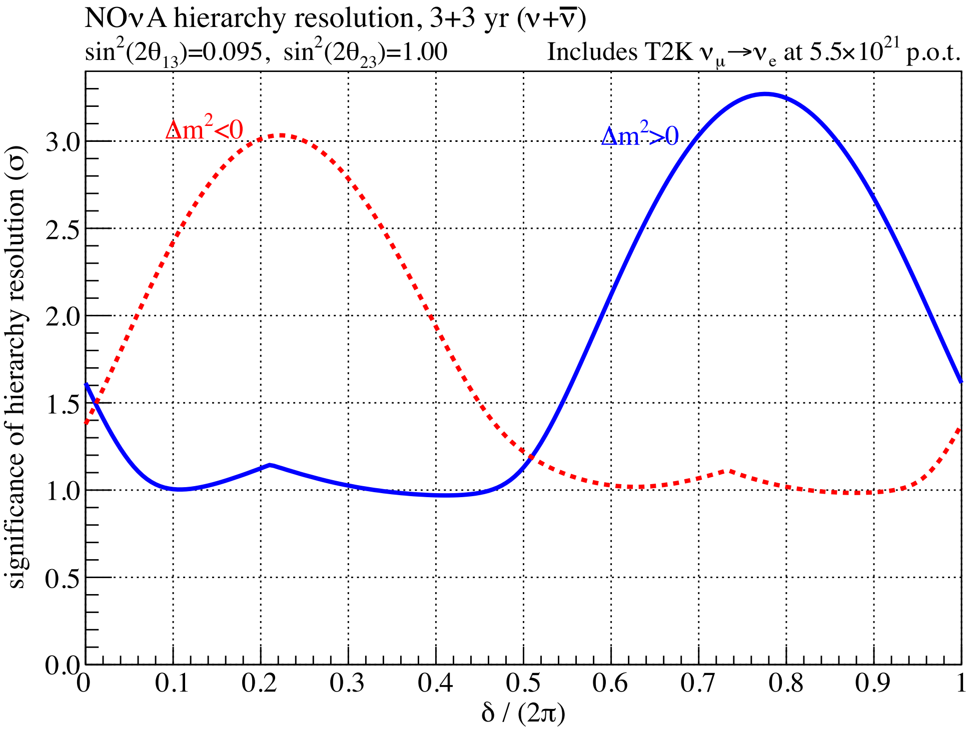
NuFit 4.0 (2018)

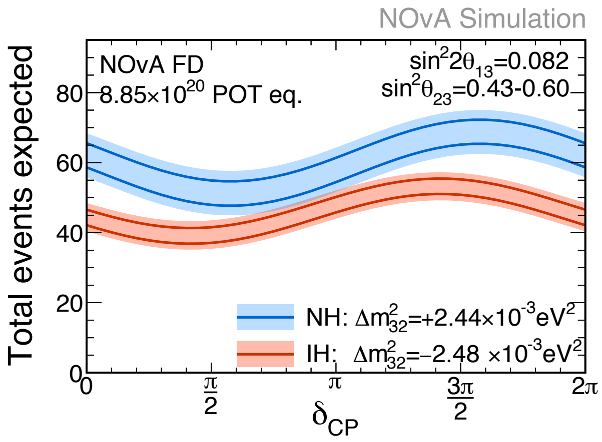
www.nu-fit.org

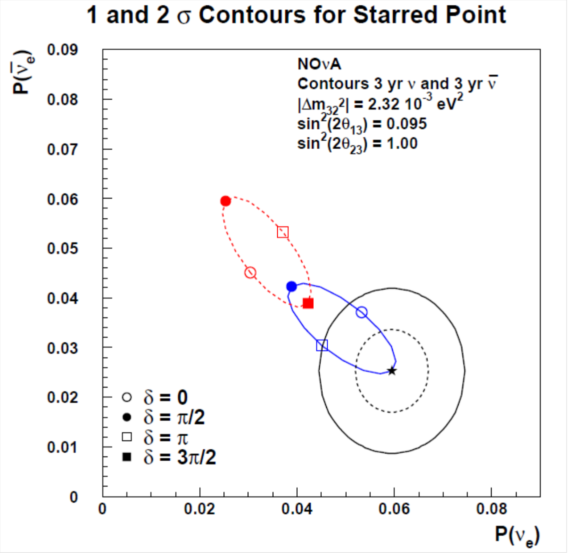
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK-atm	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$	$0.584^{+0.016}_{-0.020}$	$0.423 \to 0.629$
	$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$	$49.8^{+1.0}_{-1.1}$	$40.6 \to 52.5$
	$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$	$0.02264^{+0.00066}_{-0.00066}$	$0.02068 \to 0.02463$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{\rm CP}/^\circ$	215^{+40}_{-29}	$125 \to 392$	284^{+27}_{-29}	$196 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$	$-2.512^{+0.034}_{-0.032}$	$-2.611 \to -2.412$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK-atm	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.62 \to 36.27$
	$\sin^2\theta_{23}$	$0.582^{+0.015}_{-0.019}$	$0.428 \to 0.624$	$0.582^{+0.015}_{-0.018}$	$0.433 \to 0.623$
	$\theta_{23}/^\circ$	$49.7^{+0.9}_{-1.1}$	$40.9 \to 52.2$	$49.7^{+0.9}_{-1.0}$	$41.2 \to 52.1$
	$\sin^2\theta_{13}$	$0.02240^{+0.00065}_{-0.00066}$	$0.02044 \to 0.02437$	$0.02263^{+0.00065}_{-0.00066}$	$0.02067 \to 0.02461$
	$\theta_{13}/^\circ$	$8.61^{+0.12}_{-0.13}$	$8.22 \to 8.98$	$8.65^{+0.12}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{\rm CP}/^\circ$	217^{+40}_{-28}	$135 \to 366$	280^{+25}_{-28}	$196 \to 351$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.525^{+0.033}_{-0.031}$	$+2.431 \to +2.622$	$-2.512^{+0.034}_{-0.031}$	$-2.606 \to -2.413$

MO sensitivity of existing experiments

- strong dependence on true ordering and δ_{CP}
- 3σ possible for the most favourable combinations



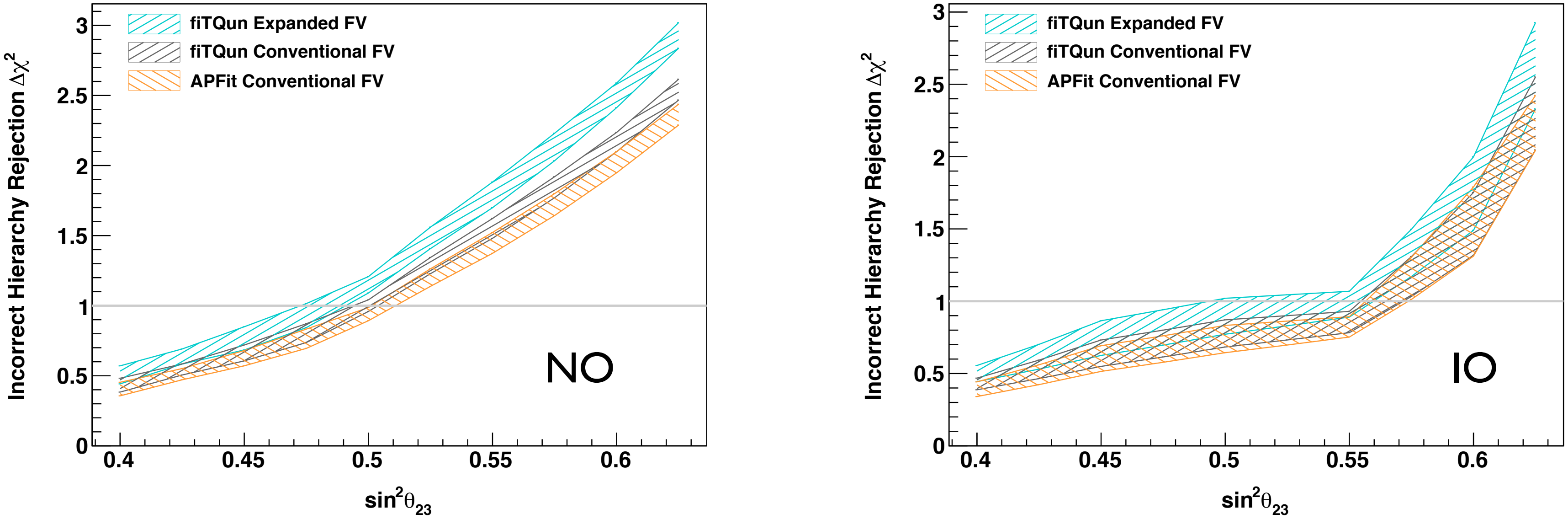




http://www-nova.fnal.gov/plots_and_figures/plots_and_figures.html

Mass ordering - atmospheric neutrinos

Atmospheric Neutrino Oscillation Analysis With Improved Event Reconstruction in Super-Kamiokande IV, 1901.03230

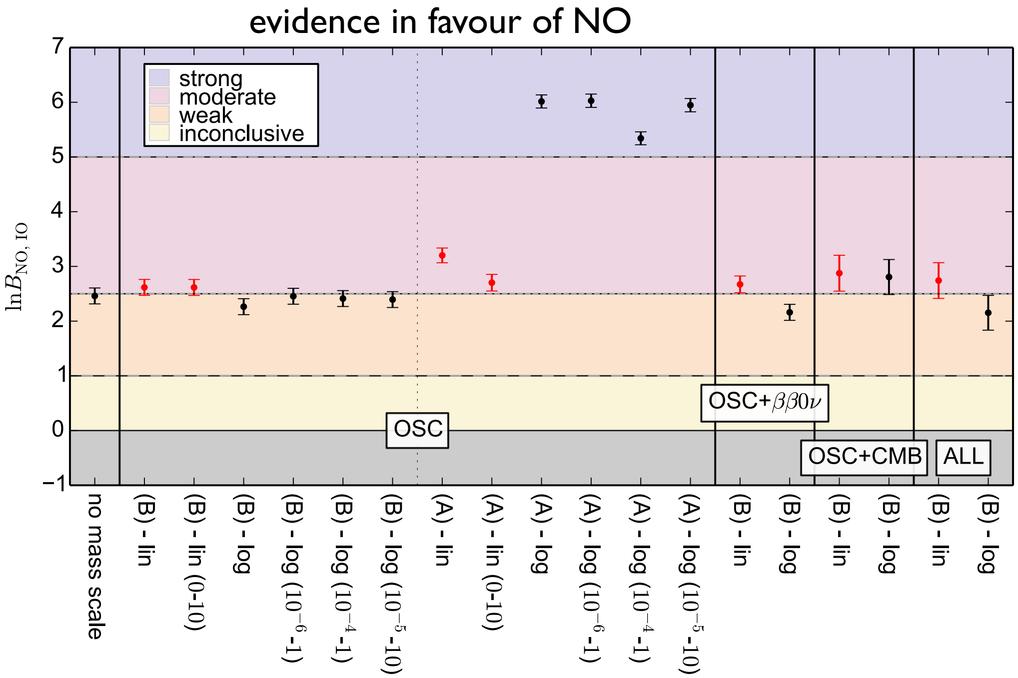


θ_{13} constrained — expected sensitivity

Excluding inverted ordering with cosmology?

Model A			Model B		
Parameter	Prior	Range	Parameter	Prior	Range
m_1/eV	linear log	$0 - 1$ $10^{-5} - 1$	$m_{\mathrm{lightest}}/\mathrm{eV}$	linear log	$0 - 1$ $10^{-5} - 1$
m_2/eV	linear log	$0 - 1$ $10^{-5} - 1$	$\Delta m^2_{21}/\mathrm{eV}^2$	linear	$5 \times 10^{-5} - 10^{-4}$
m_3/eV	linear log	$0 - 1$ $10^{-5} - 1$	$\lvert\Delta m^2_{31}\rvert/\mathrm{eV}^2$	linear	$1.5 \times 10^{-3} - 3.5 \times 10^{-3}$

Archidiacono, de Salas, Gariazzo, Mena, Ternes, Tortola, 1801.04946



- assuming a log prior in the 3 masses prefers strongly NO (just from oscillation data!)