Neutrino Fits

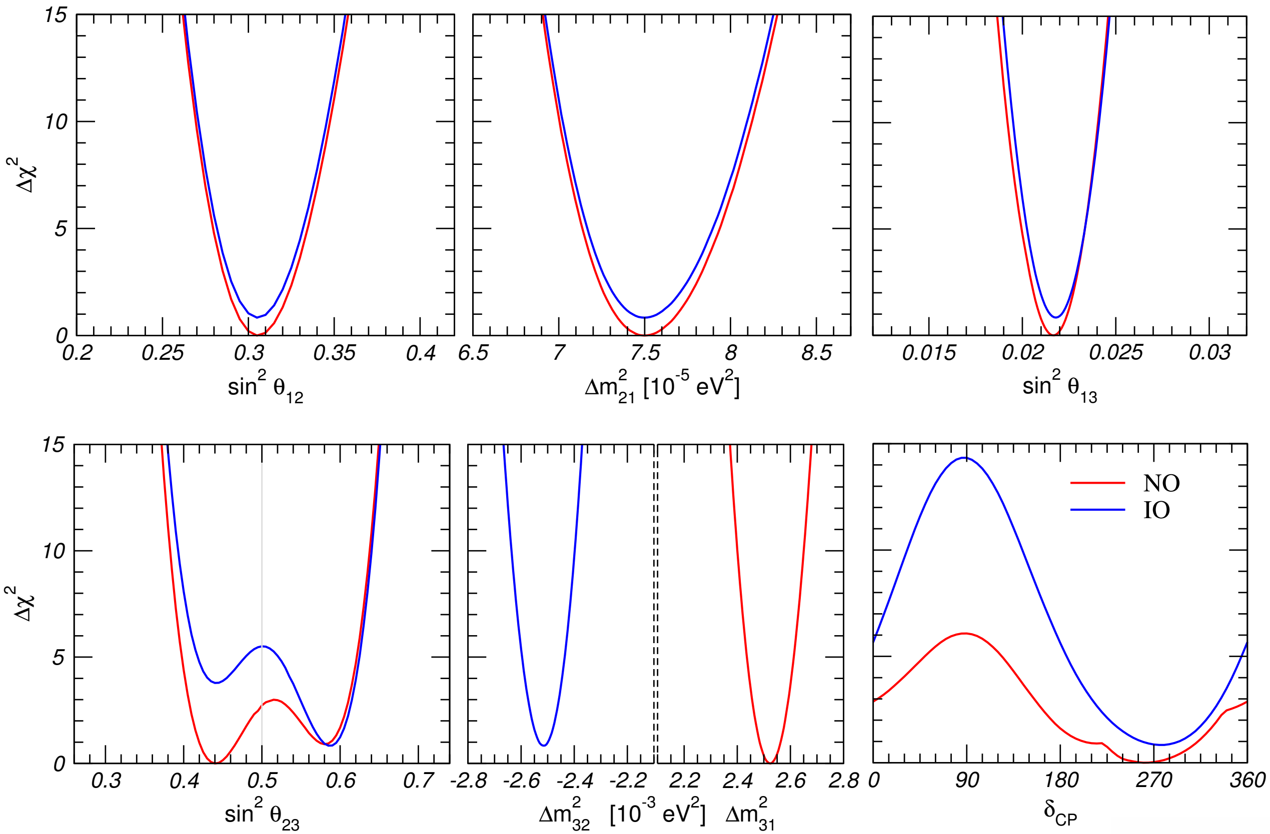
Thomas Schwetz-Mangold

Moriond EW, March 18-25, 2017

Karlsruher Institut für Technologie

elusives
neutrinos, dark matter &

3-flavour mixing - global fit as of fall 2016



- well determined parameters

  $\theta_{12}\ \theta_{13}\ \Delta m^2_{21}\ |\Delta m^2_{31}|$

open issues:

- θ_{23}: octant/maximality
- mass ordering
- δ_{CP} : preference for $180° < \delta_{CP} < 360°$

NuFIT 3.0, Esteban et al., 1611.01514 www.nu-fit.org

www.nu-fit.org

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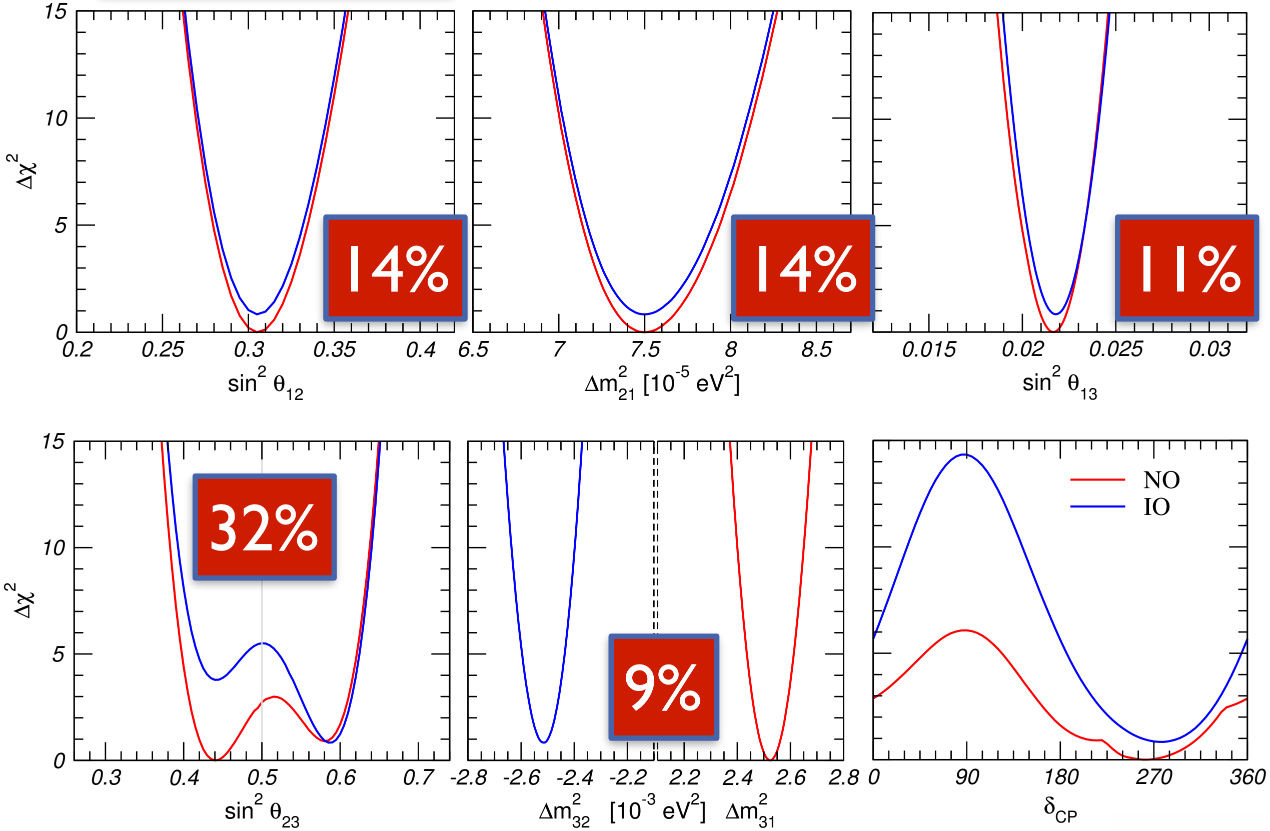
3-flavour mixing - global fit as of fall 2016

precision at 3σ:



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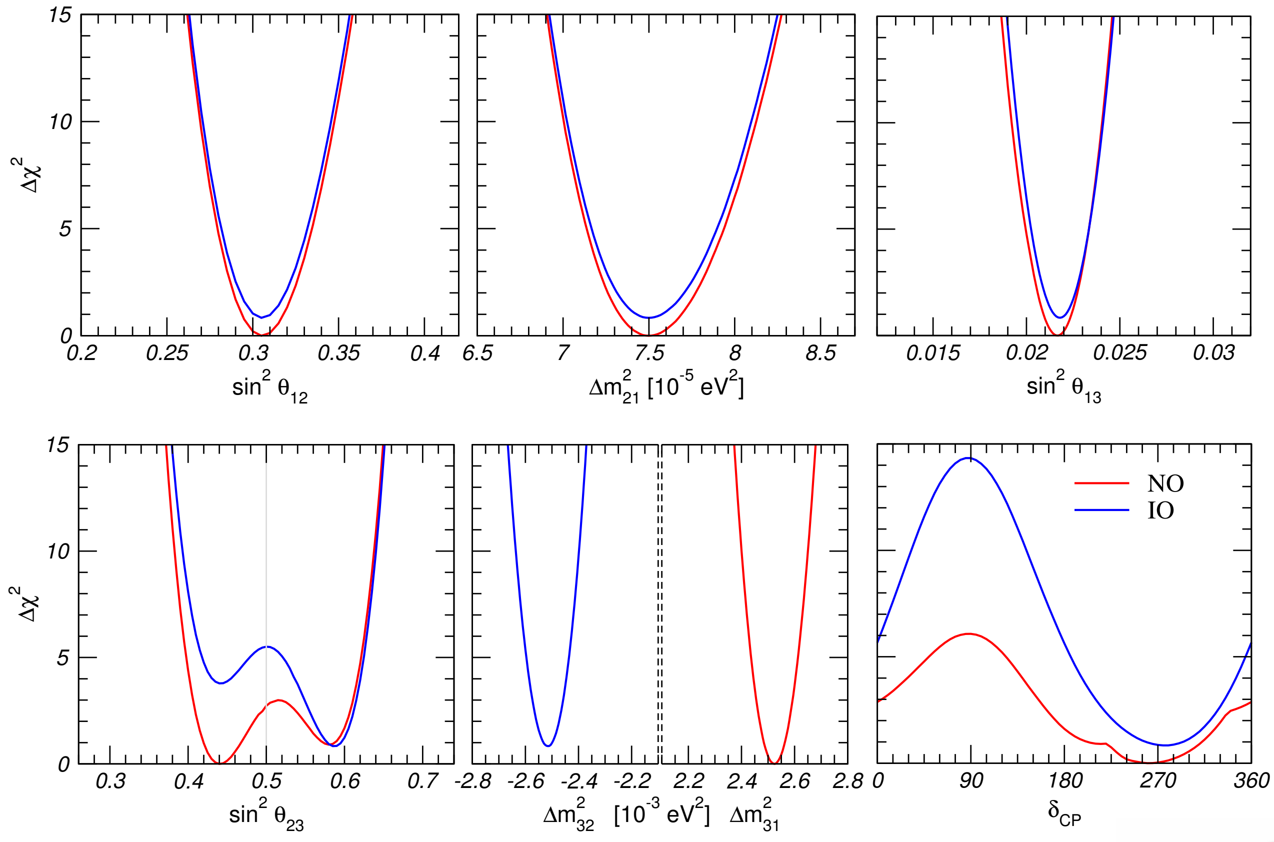

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This talk

- determination of the CP phase
- status of the mass ordering and θ_{23}
- non-standard neutrino interactions

Leptonic CP violation

Leptonic CP violation will manifest itself in a difference of the vacuum oscillation probabilities for neutrinos and anti-neutrinos

Cabibbo, 1977; Bilenky, Hosek, Petcov, 1980, Barger, Whisnant, Phillips, 1980

$$P_{\nu_\alpha \to \nu_\beta} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta} \propto J \,, \qquad J = |\mathrm{Im}(U_{\alpha 1} U^*_{\alpha 2} U^*_{\beta 1} U_{\beta 2})|$$

J: leptonic analogue to Jarlskog-invariant Jarlskog, 1985

standard parameterization: $J = s_{12} c_{12} s_{23} c_{23} s_{13} c_{13}^2 \sin\delta \equiv J^{\max} \sin\delta$

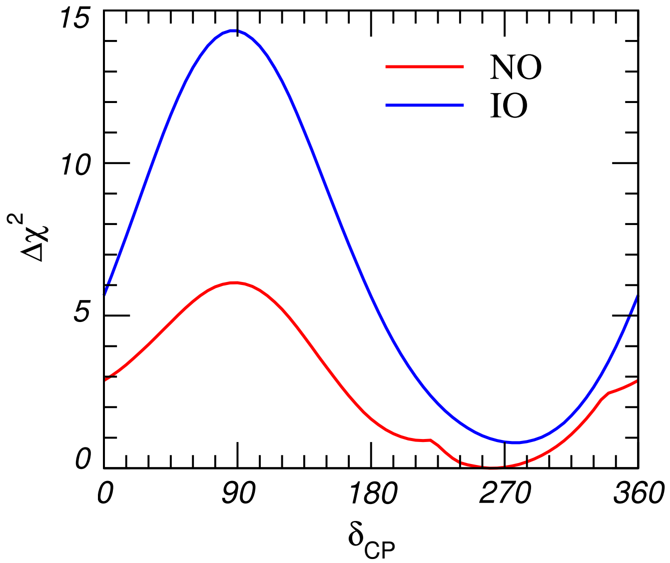
NuFit 3.0: $J_{\rm CP}^{\rm max} = 0.0329 \pm 0.0007$

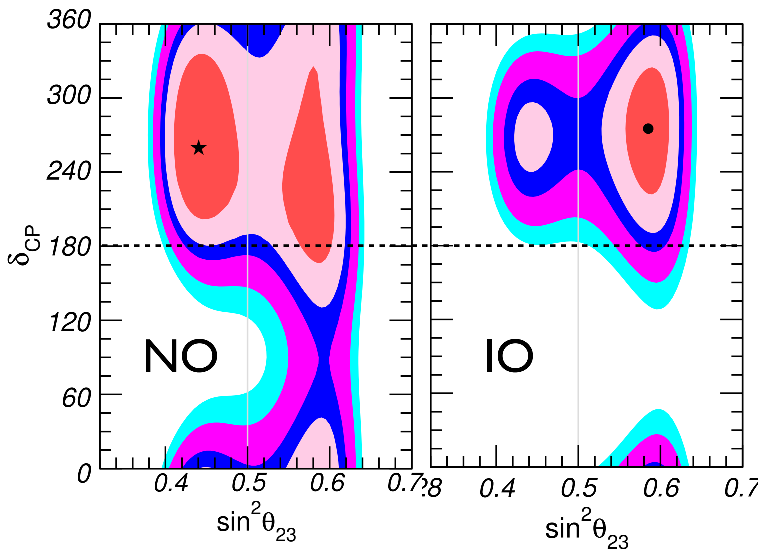
compare with Jarlskog invariant in the quark sector:

$$J_{\rm CKM} = (3.06^{+0.21}_{-0.20}) \times 10^{-5}$$

- CPV for leptons might be a factor 1000 larger than for quarks
- OBS: for quarks we know J, for leptons only $J^{\max}$ (do not know δ!)

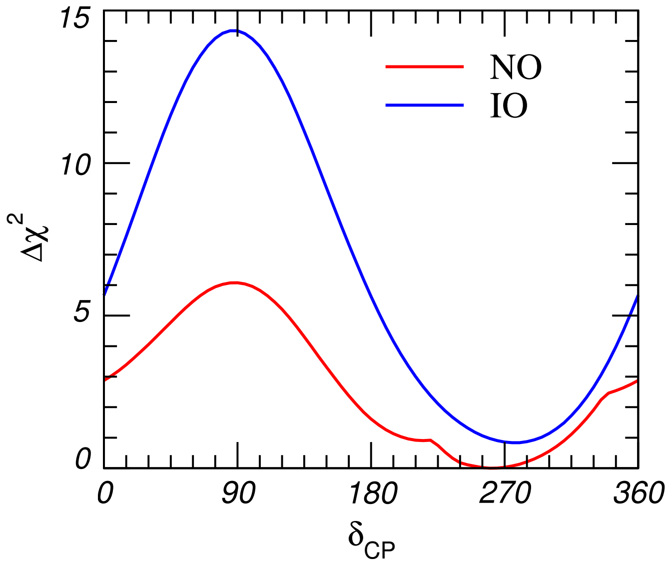
CP phase from present data



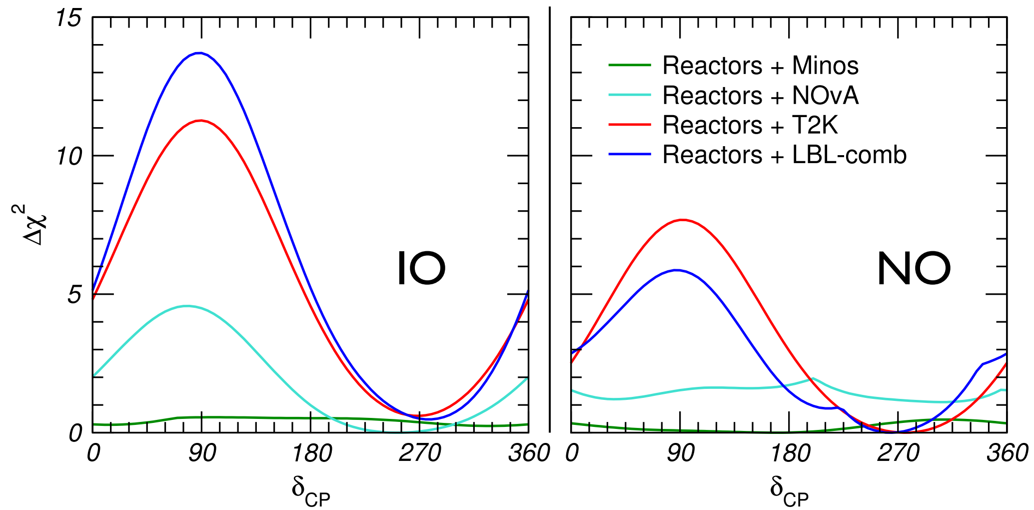


- best fit at $\delta_{CP} \approx 270°$
- correlations with θ_{23}
- CP conservation allowed at 70% CL (NO), 97% CL (IO)
- $\delta_{CP} \approx 90°$ disfavoured with $\Delta\chi^2 \approx 6$ (14) for NO (IO)

CP phase from present data



contribution of different experiments



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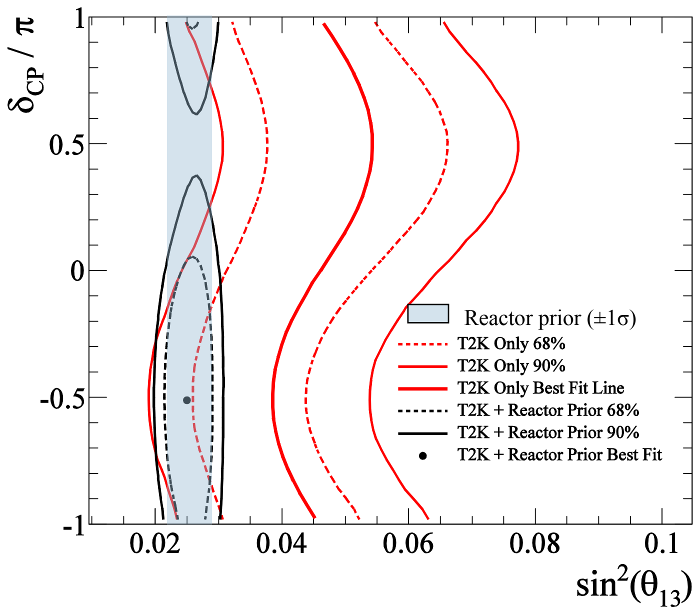
Sensitivity from reactor - accelerator complementarity



	ν_e		$\bar{\nu}_e$	
Mass hierarchy	Normal	Inverted	Normal	Inverted
$\delta_{CP} = -\pi/2$	28.8	25.5	6.0	6.5
$\delta_{CP} = 0$	24.2	21.2	6.9	7.4
$\delta_{CP} = \pi/2$	19.7	17.2	7.7	8.4
$\delta_{CP} = \pm\pi$	24.2	21.6	6.8	7.4
Data	32		4	

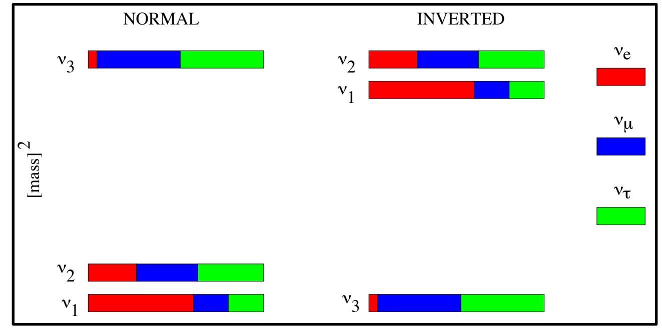
T2K coll., K. Duffy, NuPhys2016, London

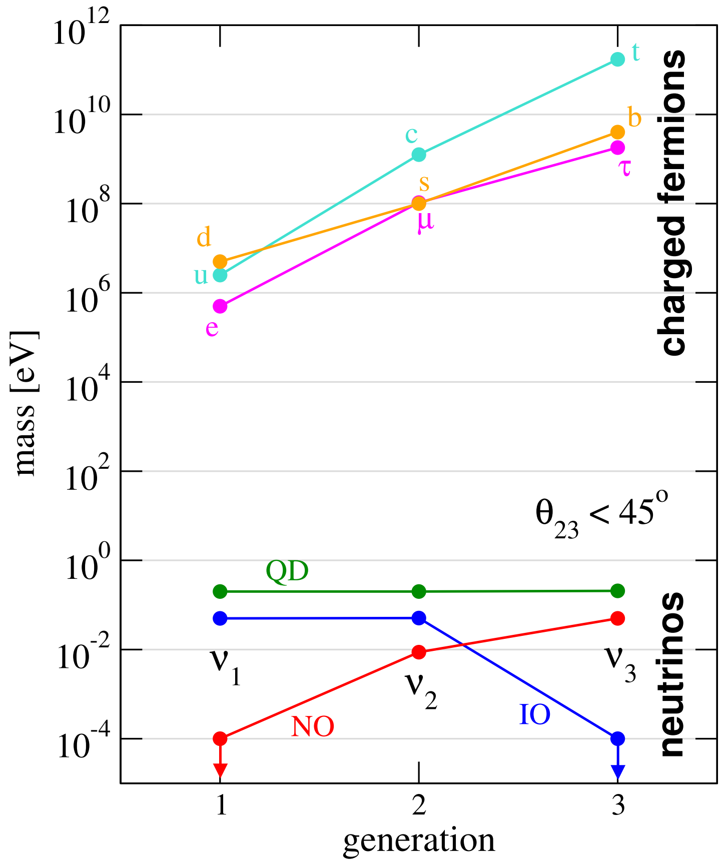
- „lucky“ fluctuation in T2K?
- significance may grow slower than sqrt-N
- significant progress on CP expected in the long term (DUNE, T2HK)

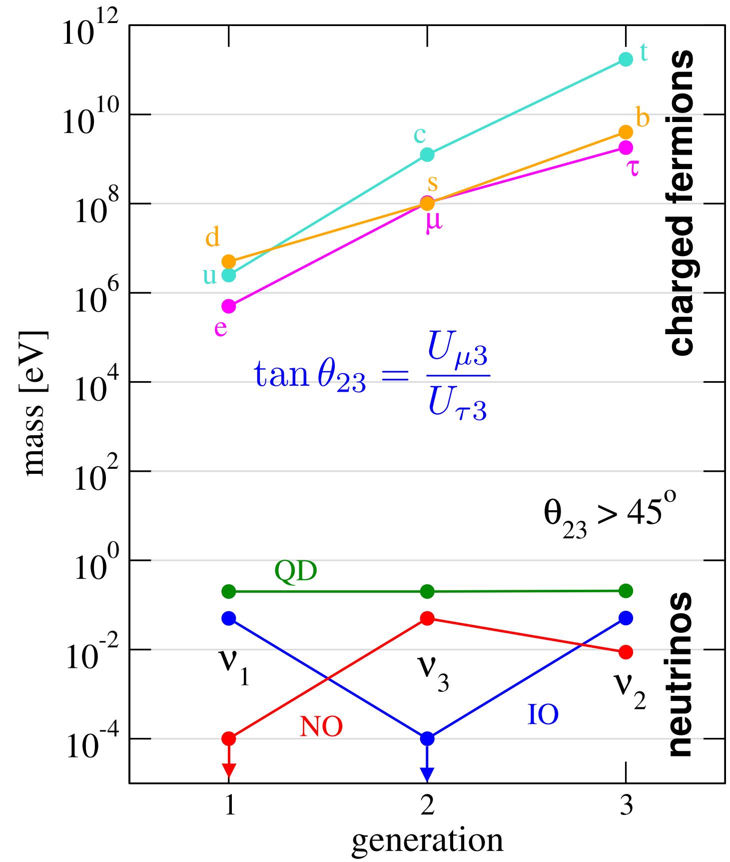
Mass ordering and θ_{23}

Neutrino mass spectrum

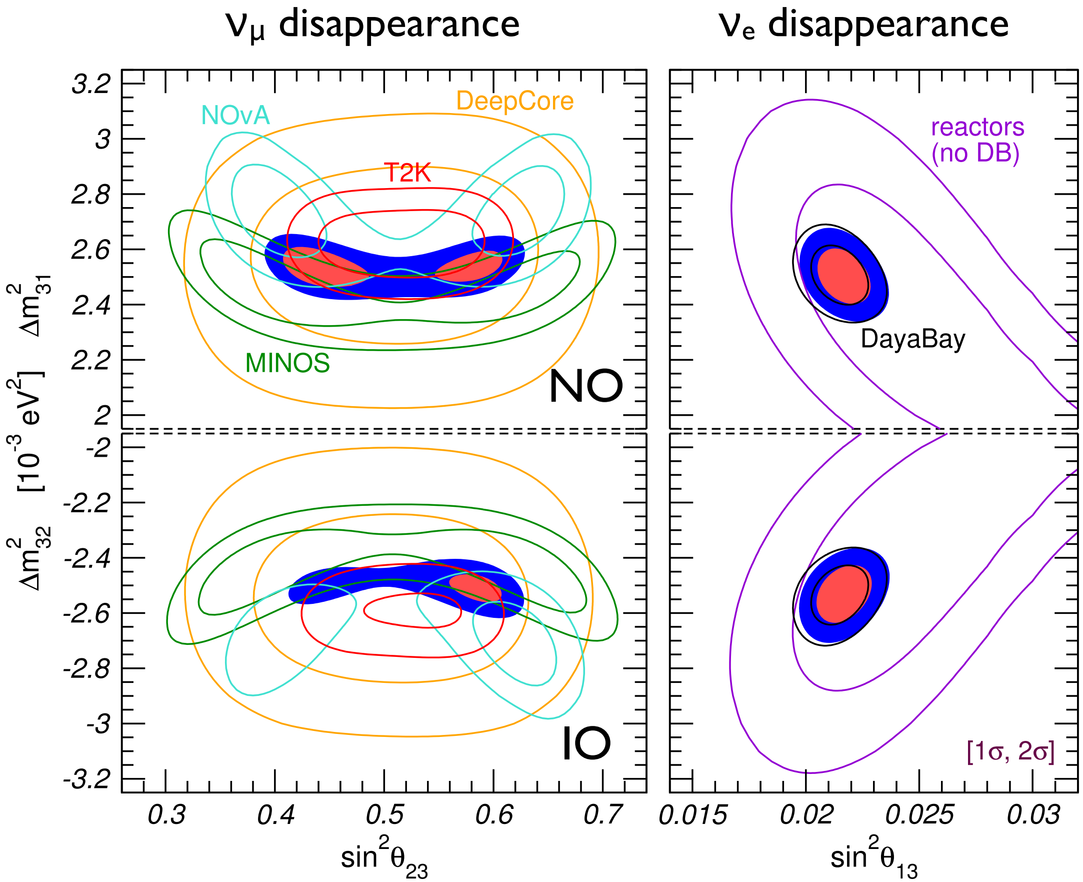
for inverted ordering and/or $\theta_{23} > 45°$
lepton mixing is very different from quarks





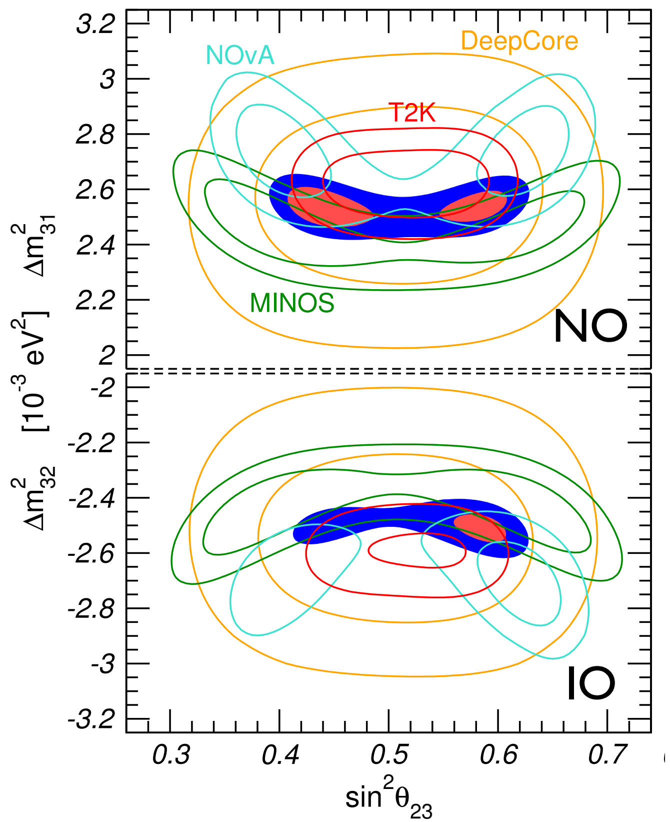


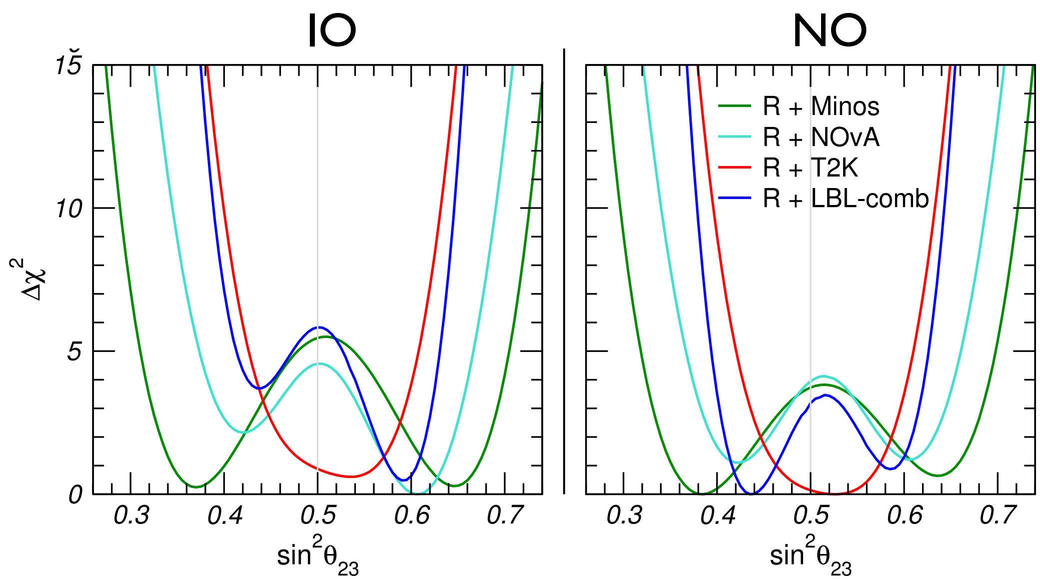
Entering the era of redundancy



- consistent results in ν_e and ν_μ disappearance searches
- several consistent results in ν_μ disappearance

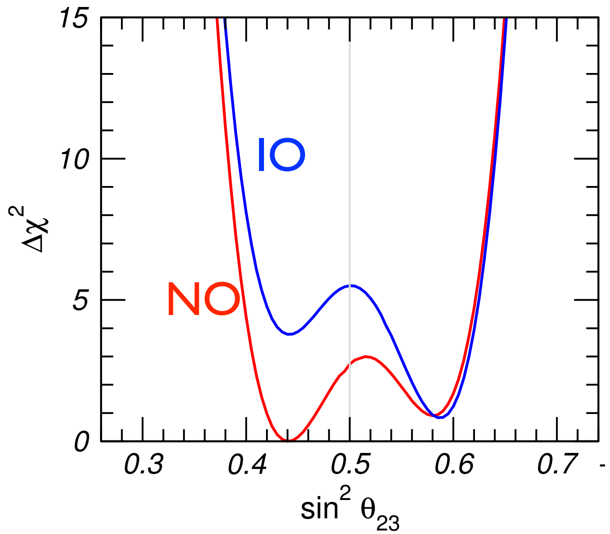
Mass ordering and θ_{23}





- hint for non-maximal θ_{23} driven by NOvA/MINOS
- between 91% and 98% CL

Mass ordering and θ_{23}

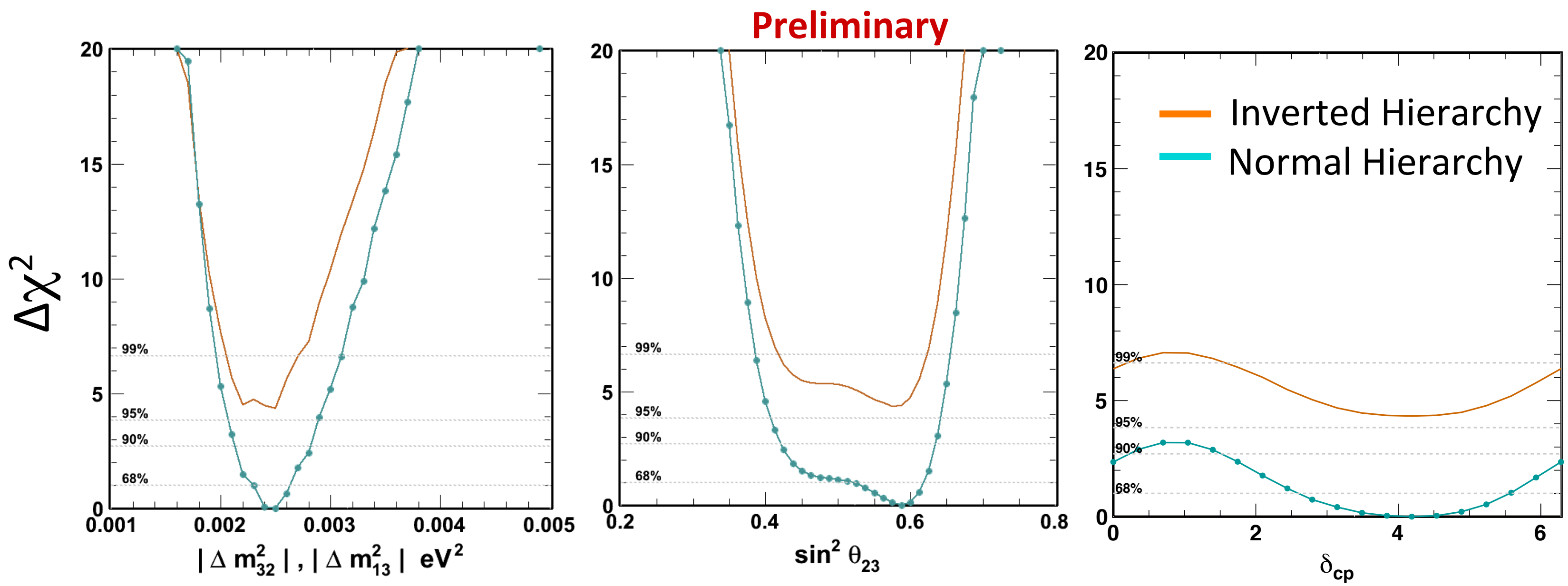


CL from MC study of LBL and reactor data:

$\delta_{CP,true}$	NO/2nd Oct.	IO/1st Oct.	IO/2nd Oct.
0°	62%	91%	28%
180°	56%	89%	32%
270°	70%	83%	27%
Gaussian	72%	94%	46%

- preferred octant depends on MO, poor sensitivity to octant
- results from global fit for normal vs inverted: $\Delta\chi^2 \approx 1$

Three flavor ν oscillation analysis Super-K atm.ν only



Fit (517 d.o.f.)	χ2	δ_{cp}	θ_{23}	Δm_{23} ($\times 10^{-3}$)
Normal Hierarchy	571.74	4.189	0.587	2.5
Inverted Hierarchy	576.08	4.19	0.575	2.5

- $\chi^2_{NH} - \chi^2_{IH}$ = **-4.3 (-3.1 expected)**
- The probability to obtain Δχ2 of -4.3 or less for IH is 0.03 ($\sin^2\theta_{23}$=0.6), 0.007 ($\sin^2\theta_{23}$=0.4). NH hypothesis : 0.45 ($\sin^2\theta_{23}$=0.6)
- θ_{13} fixed to PDG average and its uncertainty is included as a systematic error.

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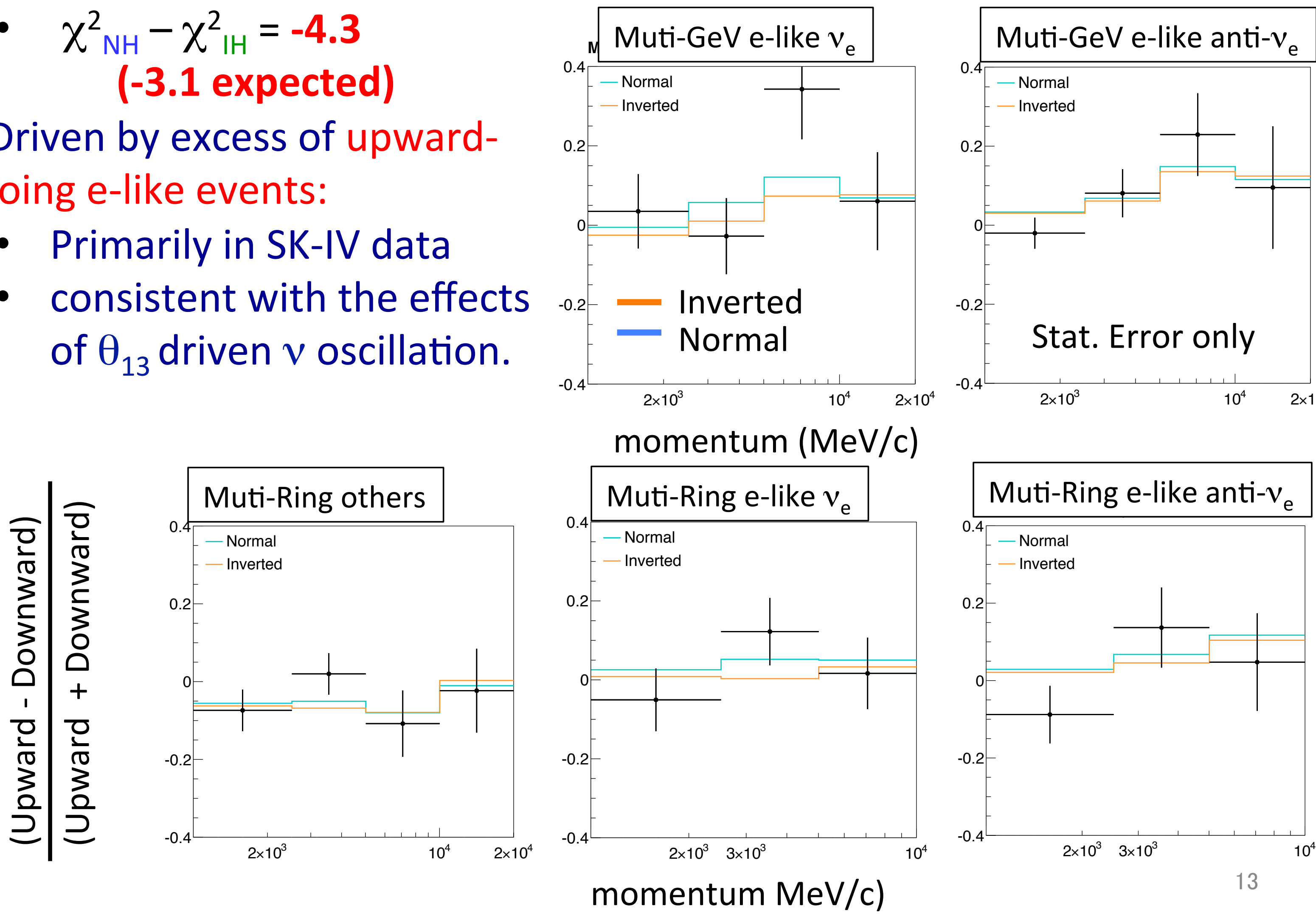
SK coll., talk by J. Kameda, NuFact 2016, Vietnam

- **Normal** hierarchy favored at:
  - $\chi^2_{NH} - \chi^2_{IH}$ = **-4.3** **(-3.1 expected)**
- Driven by excess of upward-going e-like events:
  - Primarily in SK-IV data
  - consistent with the effects of θ_{13} driven ν oscillation.

Upward/Downward asymmetry in energetic electron samples (νe/anti-νe enriched)



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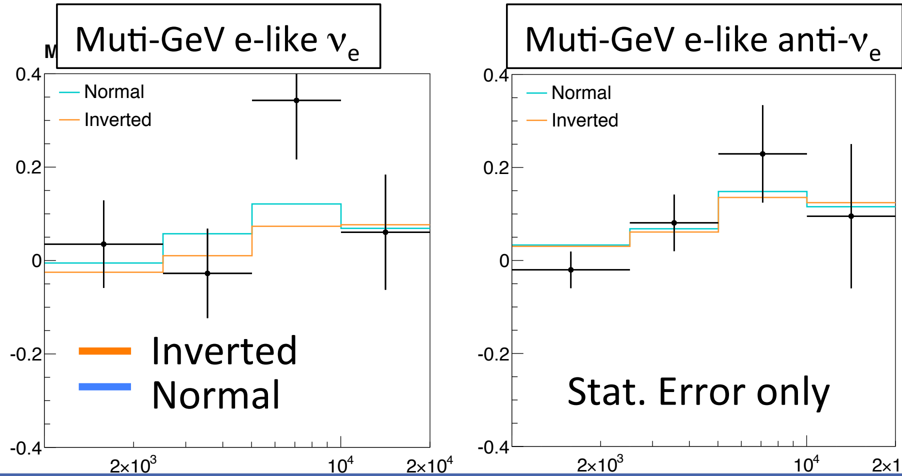
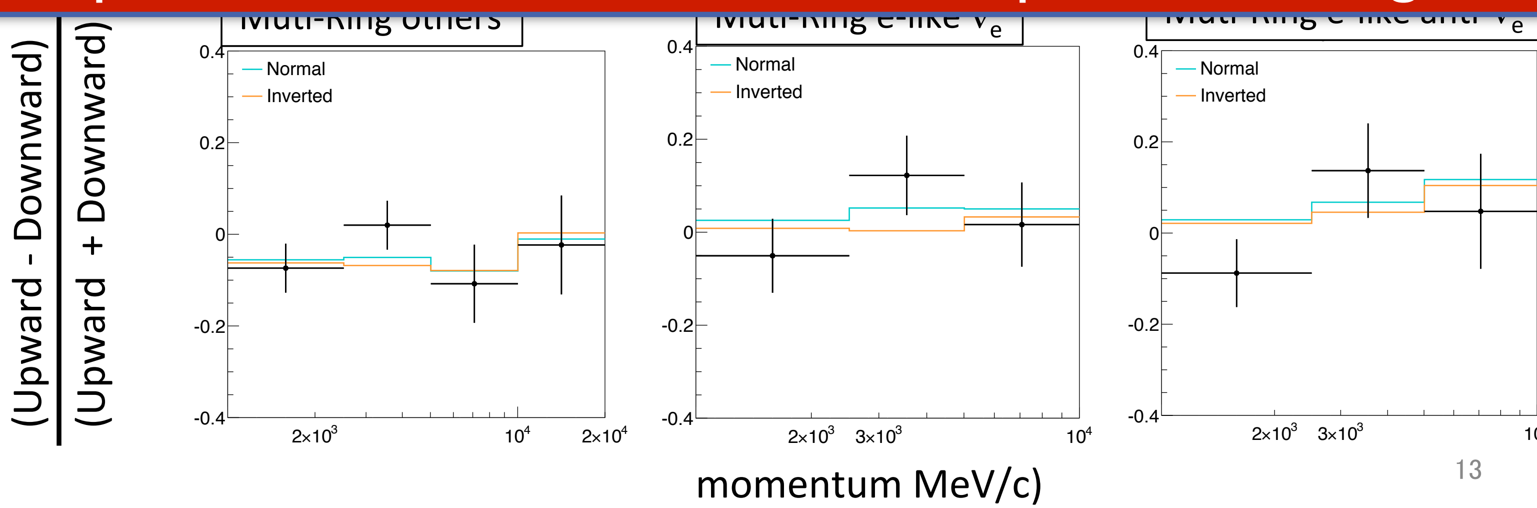


please publish data in a format useful for phenomenologists!



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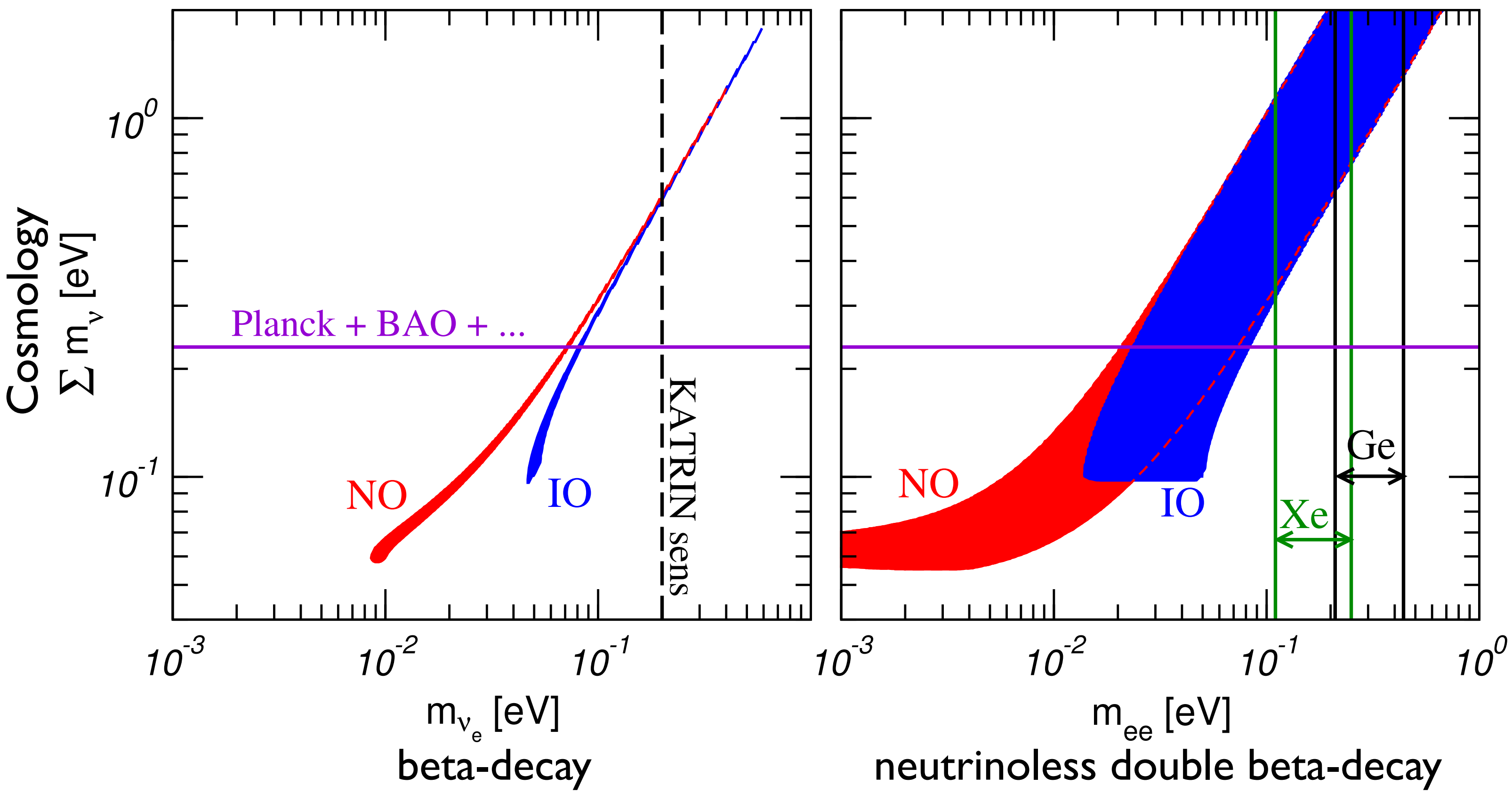
MO from absolute mass measurements?



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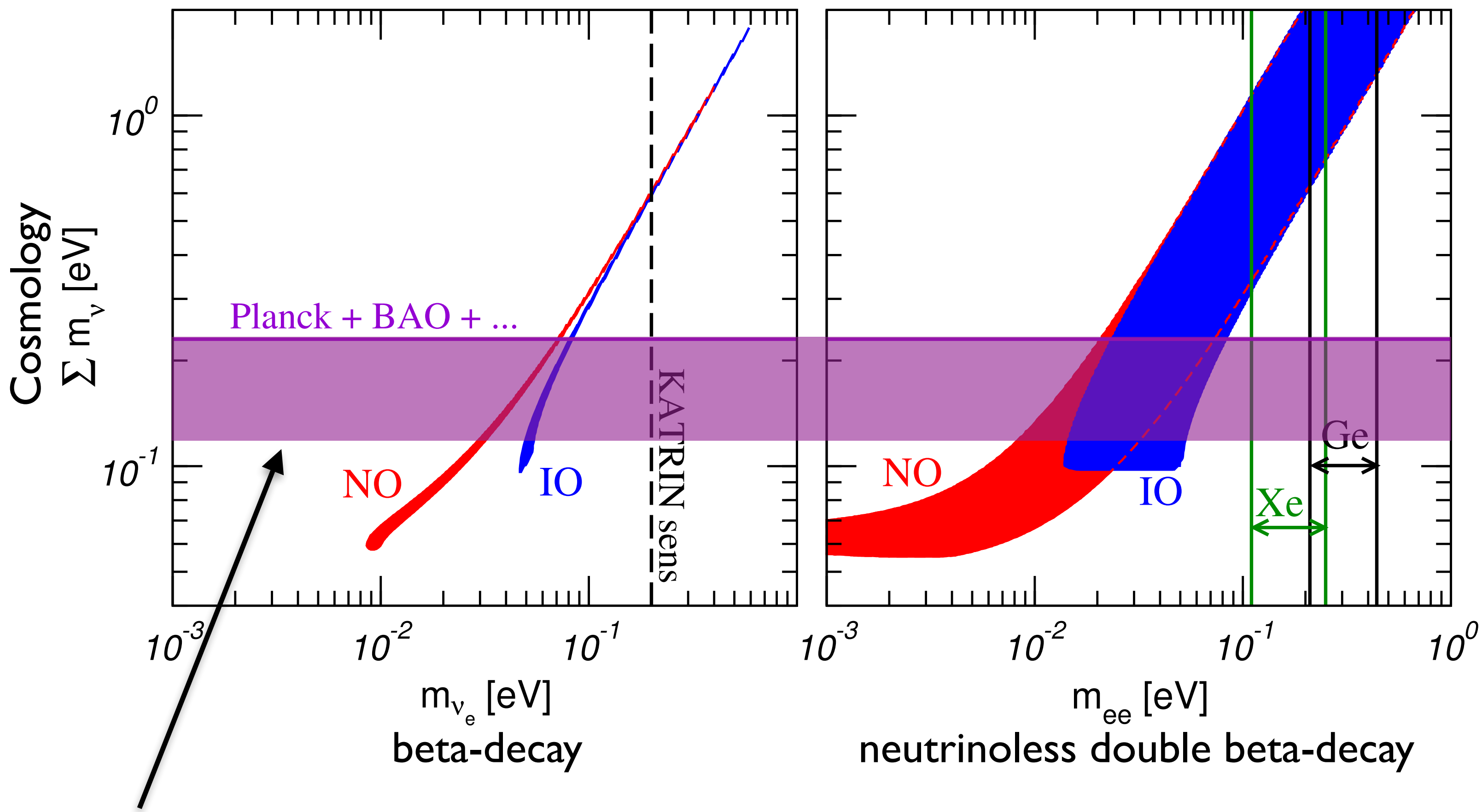


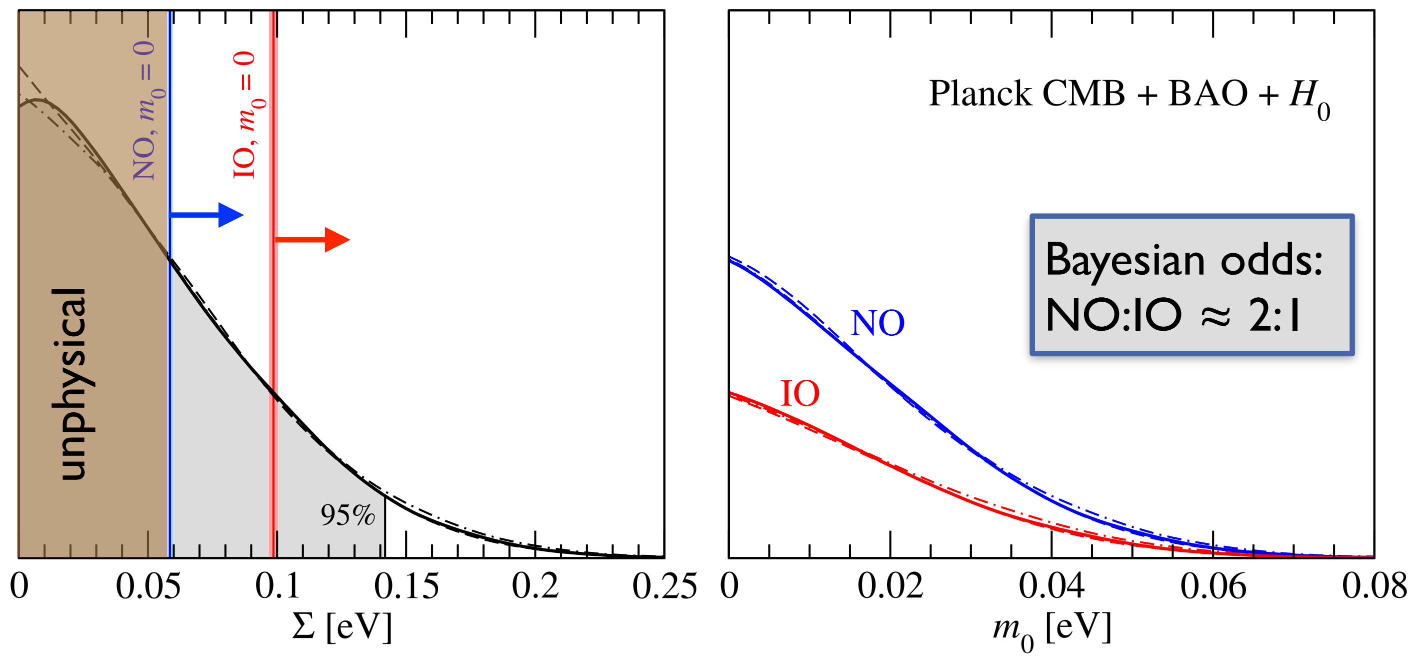
incl. Lyman-α

Baur et al., 1506.05976

Excluding inverted ordering with cosmology?

Hannestad, Schwetz, 1606.04691

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



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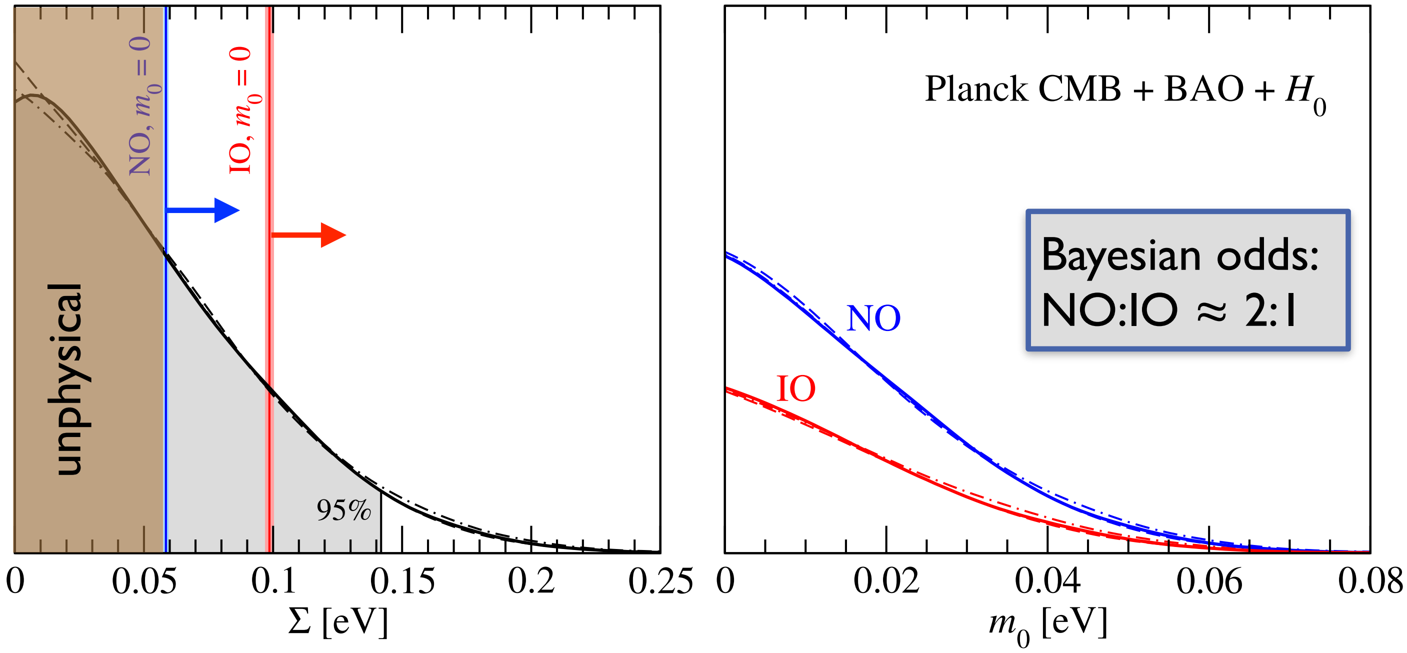

„Strong evidence" for NO claimed in Simpson et al. 1703.03425

→ be aware of Bayesian priors [TS et al. 1703.04585]

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Hannestad, Schwetz, 1606.04691

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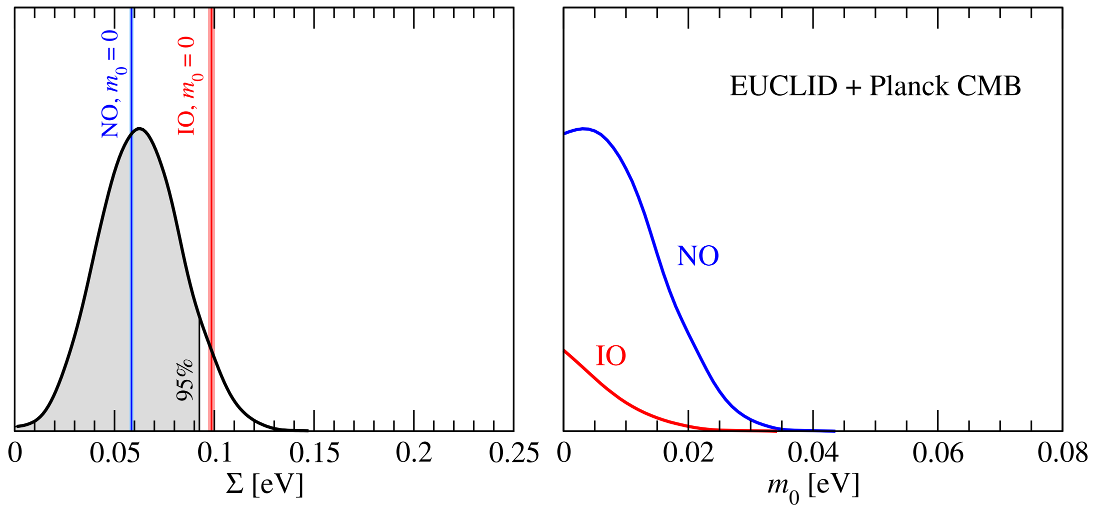
simulated future data:
2 yrs of EUCLID data, available ~2023-24



- 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)

Beyond three-flavour oscillations?

Beyond three-flavour oscillations?

- three-flavour scenario very robust

- most extensions lead to sub-leading perturbations
  ex.: non-unitarity, eV-scale sterile neutrinos
  talk by C. Giunti

- counter example: non-standard interactions

Non-standard neutrino interactions

assume presence of NC-like dim-6 effective operators:

$$H_{\rm NSI} = \frac{G_F}{\sqrt{2}} \bar{\nu}_\alpha \gamma_\mu (1-\gamma_5) \nu_\beta \sum_f \bar{f} \gamma^\mu \epsilon^f_{\alpha\beta} f$$

- $\epsilon^f_{\alpha\beta}$ parametrizes strength of NSI relative to G_F
- restrict to vector-type interactions (matter potential)
- NSI can be non-universal ($\alpha = \beta$) or flavour-changing ($\alpha \neq \beta$)
- in general not directly related to neutrino mass (dim-6) but generically expected at some level

NSI constraints from oscillation data

Gonzalez-Garcia, Maltoni, 1307.3092

		90% CL	
Param.	best-fit	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$+0.298$	$[+0.00, +0.51]$	$\oplus [-1.19, -0.81]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.03, +0.03]$
$\varepsilon^u_{e\mu}$	-0.021	$[-0.09, +0.04]$	$[-0.09, +0.10]$
$\varepsilon^u_{e\tau}$	$+0.021$	$[-0.14, +0.14]$	$[-0.15, +0.14]$
$\varepsilon^u_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$+0.310$	$[+0.02, +0.51]$	$\oplus [-1.17, -1.03]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.01, +0.03]$
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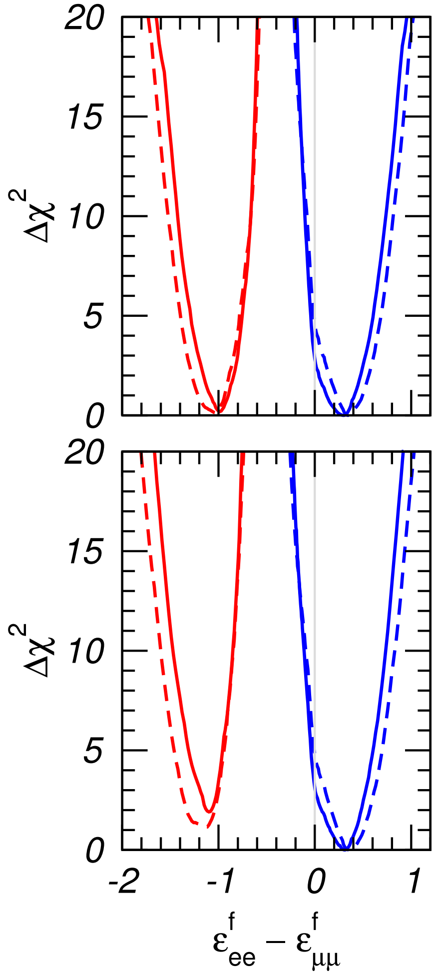

- limits of few %,
- exceptions: $\varepsilon_{e\tau}$, ε_{ee}-$\varepsilon_{\mu\mu}$

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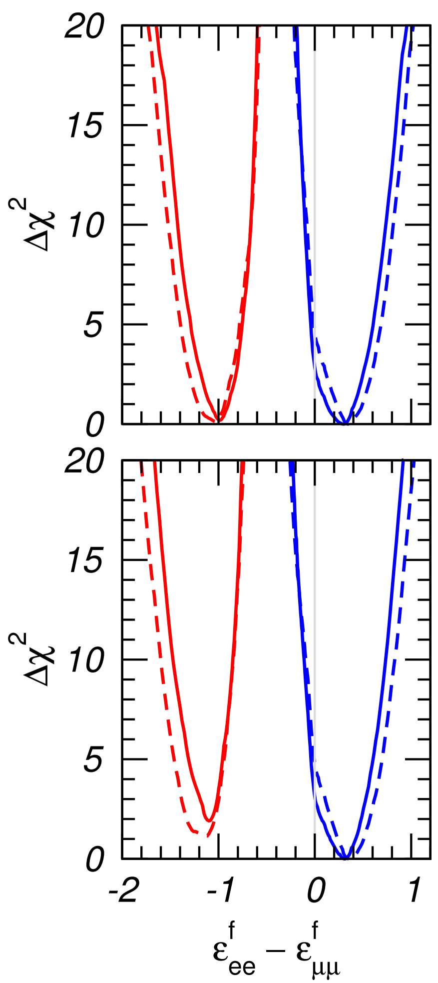

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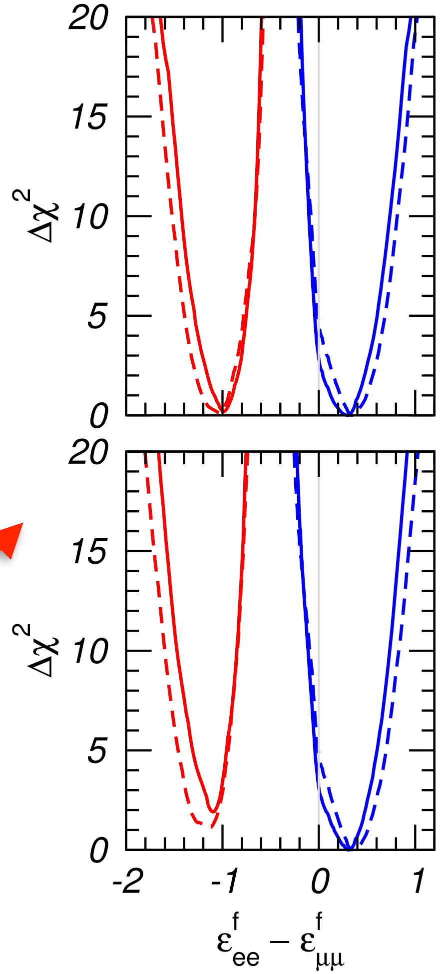

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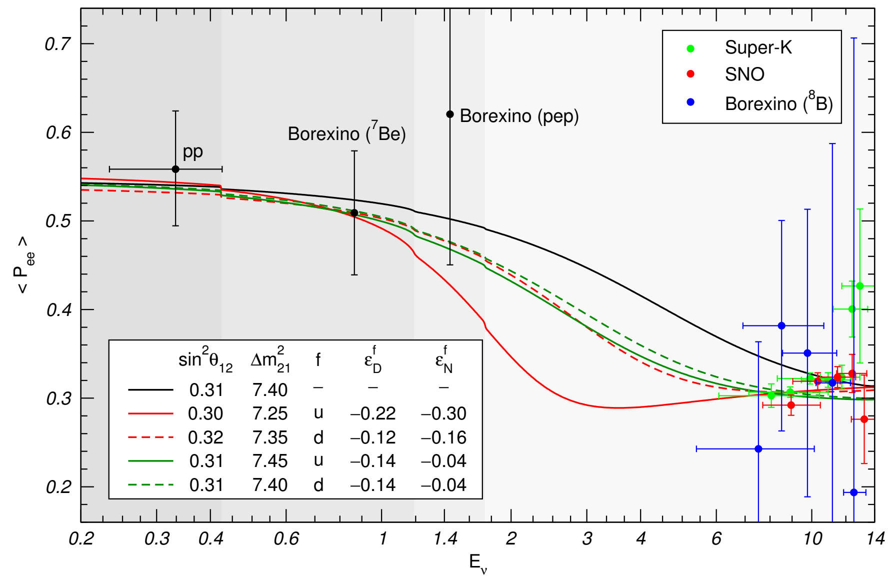
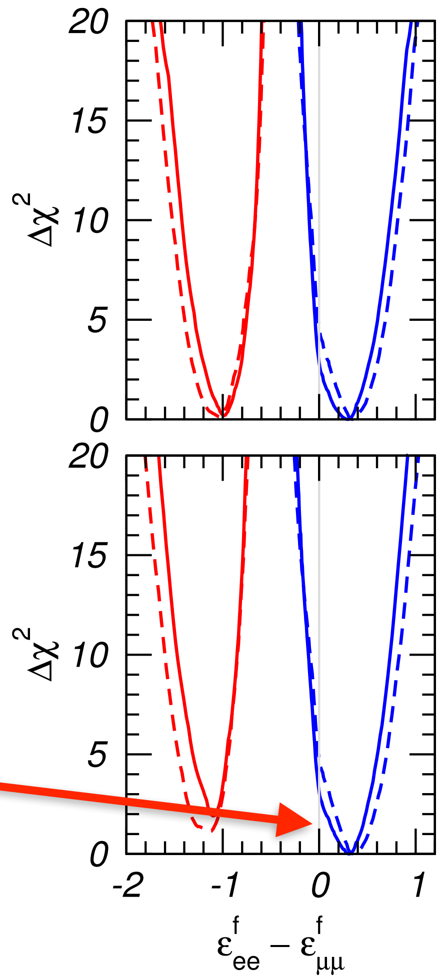
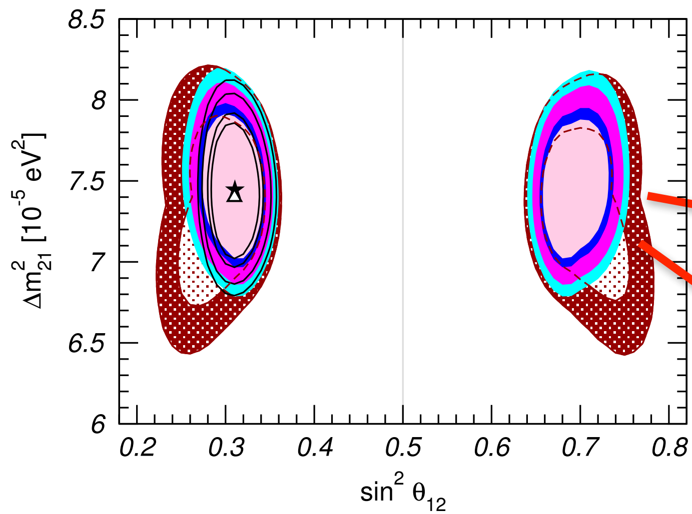


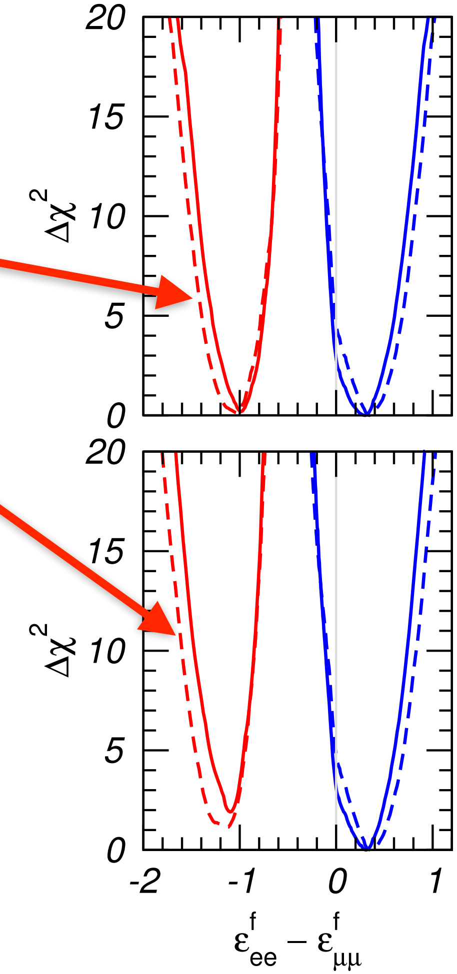


- slightly improved fit to solar neutrino data

NSI constraints from oscillation data

Gonzalez-Garcia, Maltoni, 1307.3092





- degenerate solution with θ_{12} in the second octant: „LMA-dark“

Miranda, Tortola, Valle, hep-ph/0406280

Gonzalez-Garcia, Maltoni, 13; Bakhti, Farzan, 14, Coloma, Schwetz, 16

- LMA-dark is a manifestation of a general symmetry of neutrino evolution related to CPT symmetry:

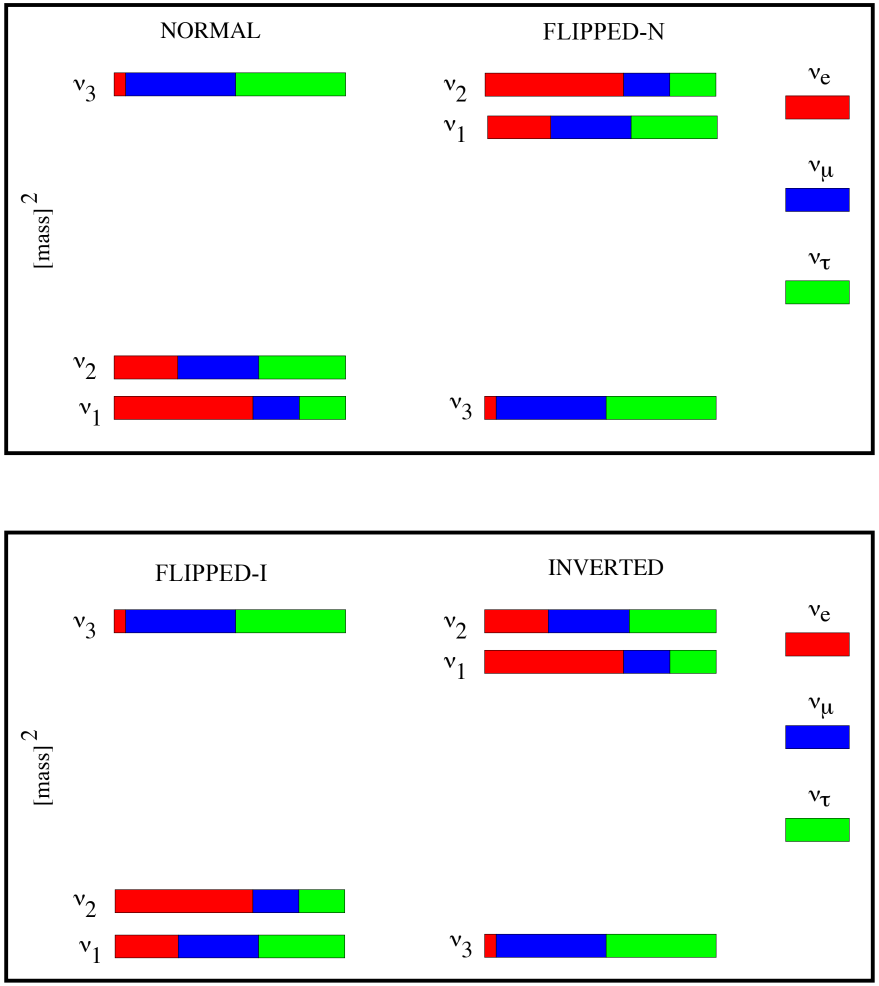
$$H \to -H^*$$

- broken by SM matter effect but can be restored in presence of NSI:

$$\begin{aligned} \Delta m^2_{31} &\to -\Delta m^2_{32} \\ \sin\theta_{12} &\leftrightarrow \cos\theta_{12} \\ \delta &\to \pi - \delta \end{aligned} \qquad \begin{aligned} &(\epsilon_{ee} - \epsilon_{\mu\mu}) \to -(\epsilon_{ee} - \epsilon_{\mu\mu}) - 2\,, \\ &(\epsilon_{\tau\tau} - \epsilon_{\mu\mu}) \to -(\epsilon_{\tau\tau} - \epsilon_{\mu\mu})\,, \\ &\epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta} \qquad (\alpha \neq \beta)\,, \end{aligned}$$

Generalized mass ordering degeneracy

Coloma, Schwetz, 16



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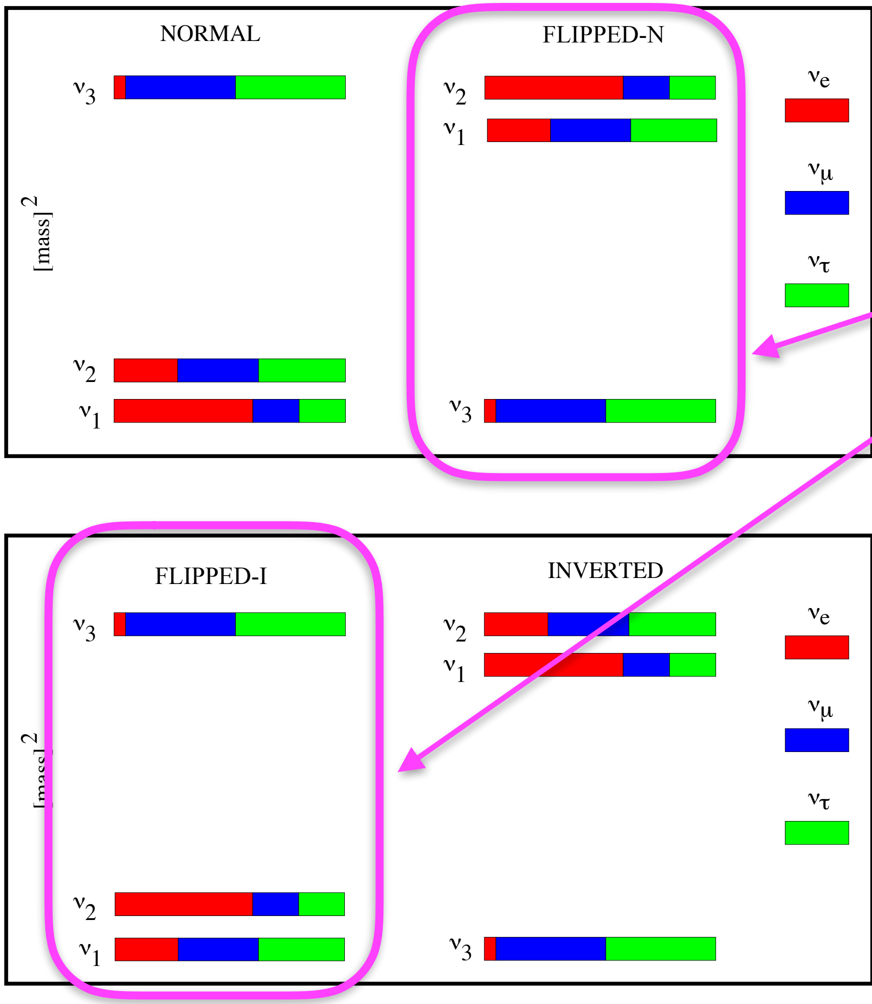


- excluded by SM matter effect, but allowed in presence of NSI

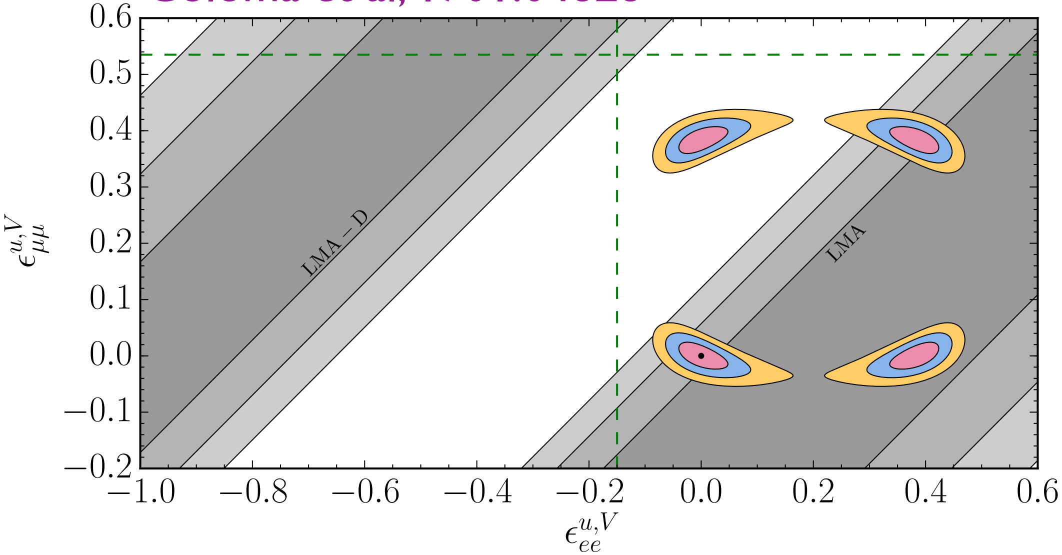
generalized degeneracy makes determination of mass ordering impossible!

Generalized mass ordering degeneracy

- cannot be resolved by any oscillation experiment

- NC neutrino scattering experiments are needed (at low energy, e.g. coherent scattering)

Coloma et al, 1701.04828



sensitivity estimate for the COHERENT proposal 1509.08702

Generalized mass ordering degeneracy

- cannot be resolved by any oscillation experiment
- NC neutrino scattering experiments are needed (at low energy, e.g. coherent scattering)
  Coloma et al, 1701.04828
- requires NSI of order G_F
  points towards „light mediators“ (below EW)
  Farzan, 15; Farzan, Shoemaker, 15

Summary

- CP phase:
  values of $\pi < \delta < 2\pi$ preferred over $0 < \delta < \pi$
  CP conservation allowed at 70% CL → be patient!

- mass ordering: no significant preference
  (hints for normal ordering from atmospheric neutrinos and maybe cosmology)
  upcoming experiments: JUNO, PINGU, ORCA

- non-standard neutrino interactions: NSI ~ G_F
  introduce degeneracy which makes determination of mass ordering by oscillations impossible

supplementary slides

3-flavour mixing - global fit as of fall 2016

www.nu-fit.org

NuFIT 3.0, Esteban et al., 1611.01514

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

3-flavour mixing - global fit as of fall 2016

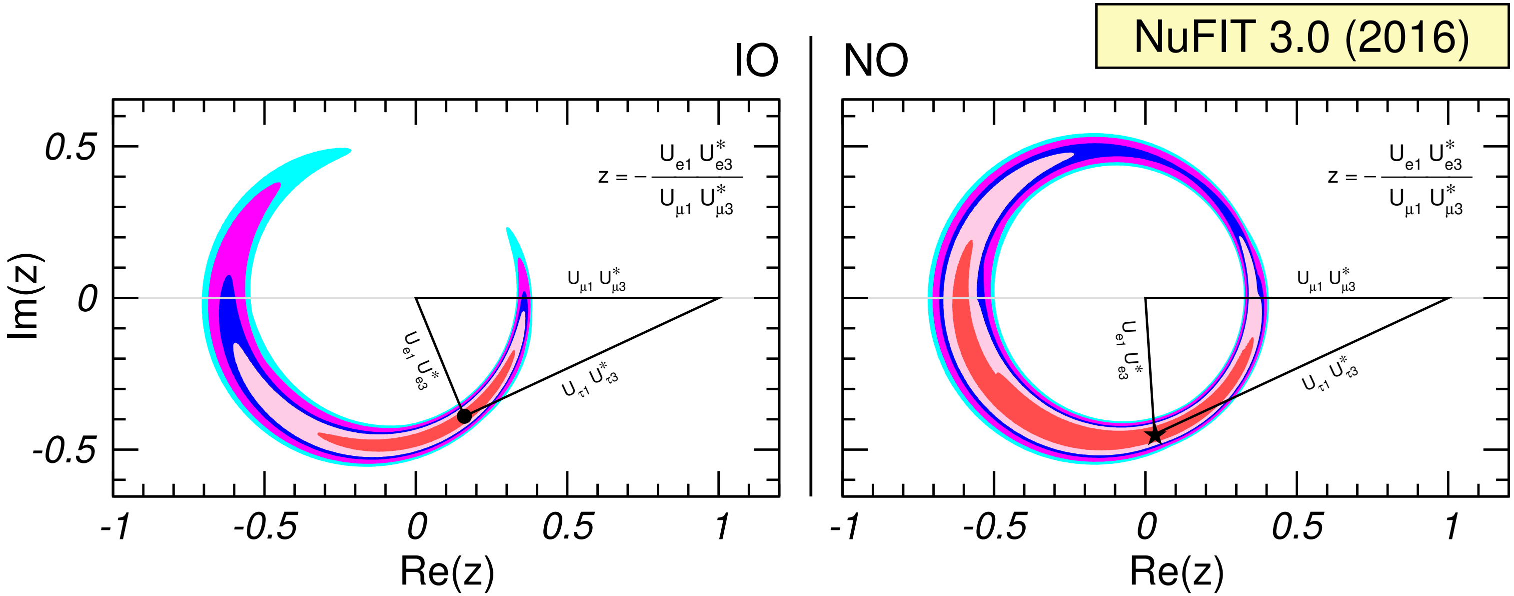
www.nu-fit.org

NuFIT 3.0, Esteban et al., 1611.01514

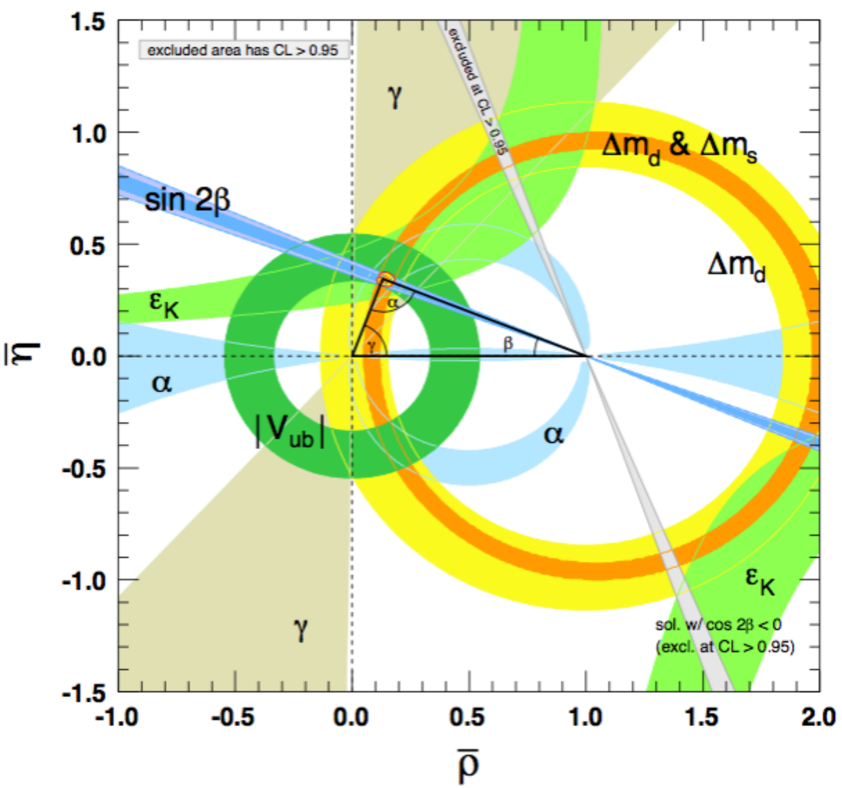
precision at 3σ: $2\frac{x^{up} - x^{low}}{x^{up} + x^{low}}$

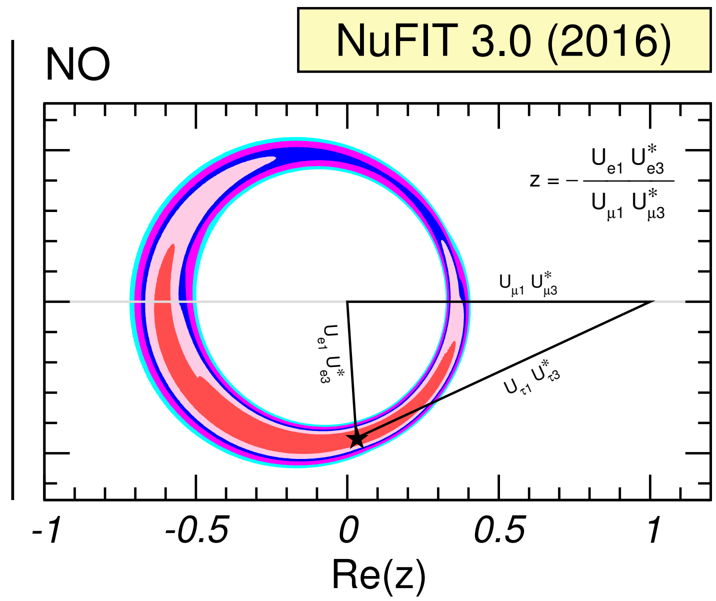
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range	precision at 3σ
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$	14%
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$	
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$	32%
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$	
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$	11%
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$	
$\delta_{CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$	
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$	14%
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix}+2.407 \to +2.643 \\ -2.629 \to -2.405\end{bmatrix}$	9%

Leptonic unitarity triangle



Leptonic unitarity triangle

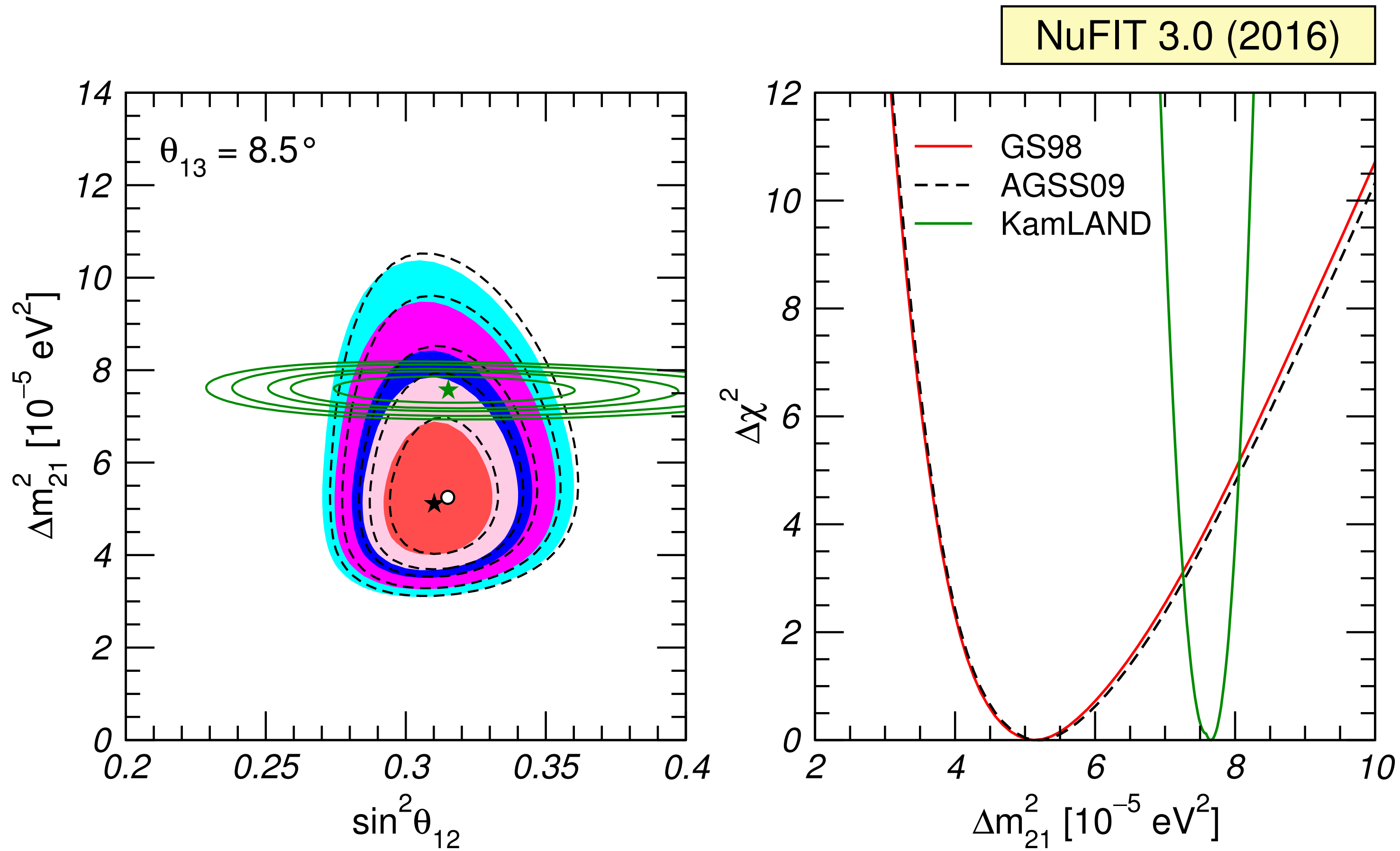




very far from CKM precision!

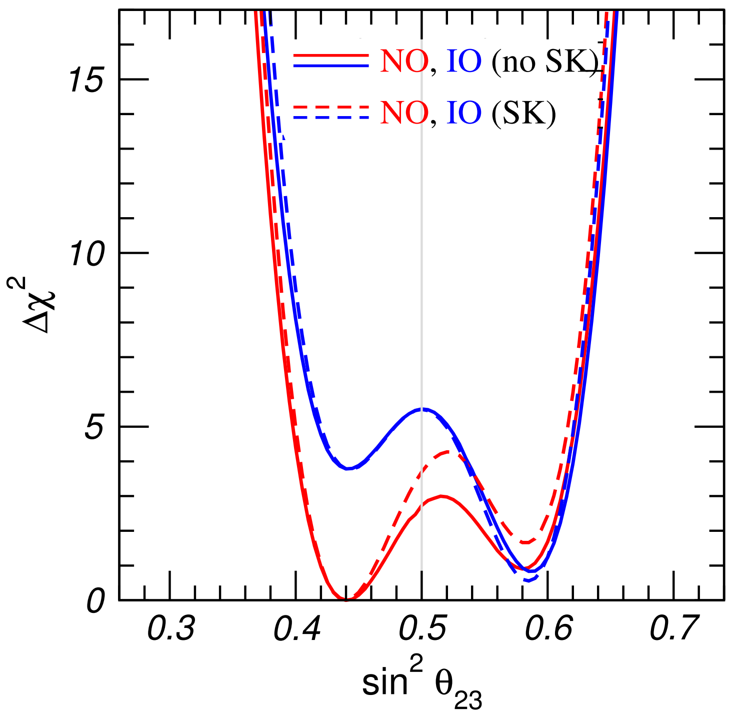
need subsequent generation of experiments (T2HK, DUNE) to say something meaningful on CP phase

Minor tension between solar neutrinos and KamLAND

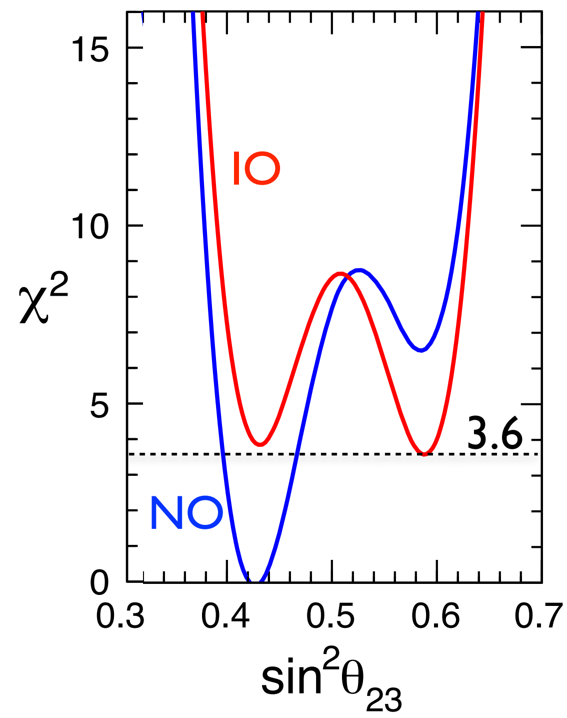


Comparison with Bari group

NuFIT 3.0, Esteban et al., 1611.01514



Cappozzi et al., 1703.04471



differences mostly due to atmospheric neutrino analysis

Comparison with Bari group

Cappozzi et al., 1703.04471

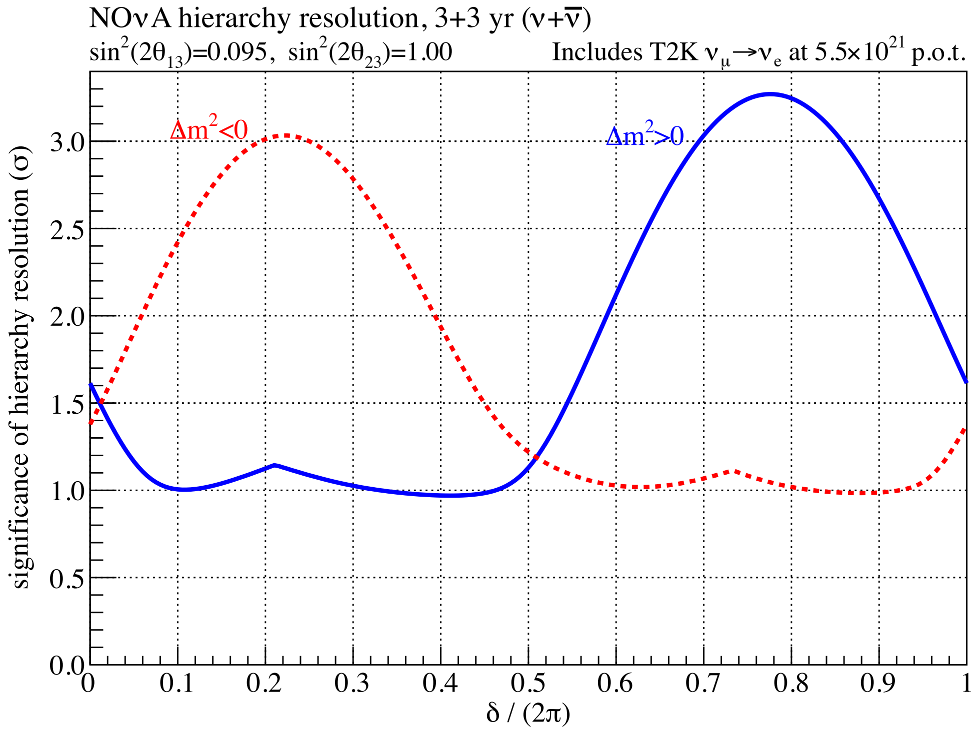
TABLE III: Values of $\Delta\chi^2_{\rm IO-NO}$ from the global analysis of oscillation and non oscillation data (numbered according to the adopted cosmological datasets as in Table II), to be compared with the value 3.6 from oscillation data only [Eq. (9)]. An overall preference emerges for NO, at the level of 1.9–2.1σ.

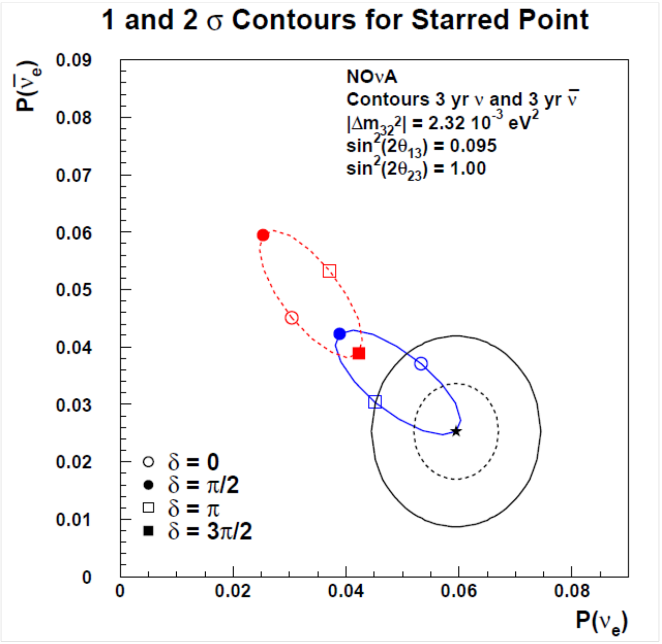
#	1	2	3	4	5	6	7	8	9	10	11	12
$\Delta\chi^2_{\rm IO-NO}$	4.3	3.8	4.4	4.2	3.9	4.4	3.6	3.7	3.8	3.7	3.8	3.9

- preference for NO at 1.9 to 2.1σ
- driven by atmospheric neutrino analisys $\Delta\chi^2 = 3.6$
- contribution from cosmology for all considered data sets $\Delta\chi^2 < 1$

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

MO - compilation of upcoming experiments

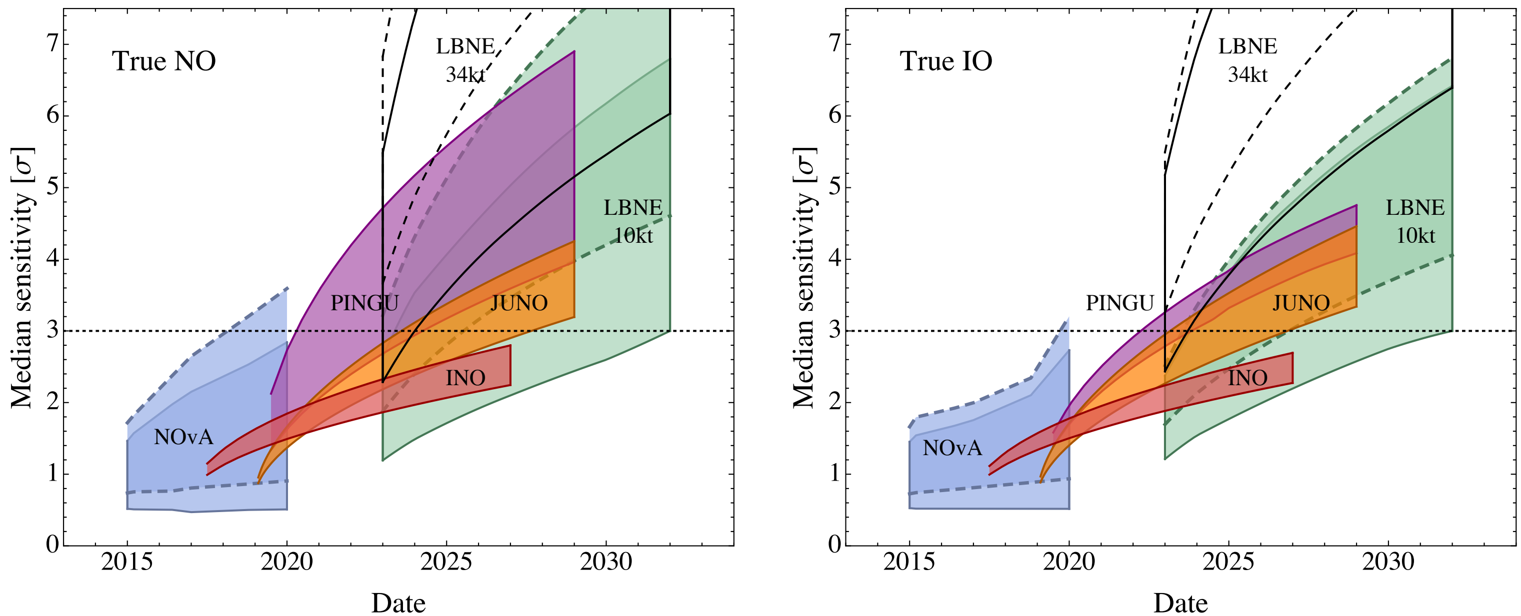


FIG. 12: The left (right) panel shows the median sensitivity in number of sigmas for rejecting the IO (NO) if the NO (IO) is true for different facilities as a function of the date. The width of the bands correspond to different true values of the CP phase δ for NOνA and LBNE, different true values of θ_{23} between 40° and 50° for INO and PINGU, and energy resolution between $3\%\sqrt{1\ \mathrm{MeV}/E}$ and $3.5\%\sqrt{1\ \mathrm{MeV}/E}$ for JUNO. For the long baseline experiments, the bands with solid (dashed) contours correspond to a true value for θ_{23} of 40° (50°). In all cases, octant degeneracies are fully searched for.

[not shown: ORCA and HyperK (atm)]

Blennow, Coloma, Huber, TS, 1311.1822