Overview of knowns and unknowns in the standard 3ν framework

EPS-HEP, Venice, July 2017

Eligio Lisi
INFN, Bari, Italy

Mainly based on:

F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, A. Melchiorri, A. Palazzo,

"Global constraints on absolute neutrino masses and their ordering"

arXiv:1703.04471 [PRD 95, 096014 (2017)]

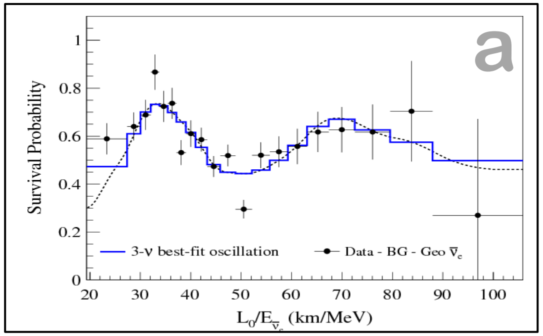
[For an independent analysis of recent oscillation data, see I. Esteban *et al.*, 1611.01514]

OUTLINE:

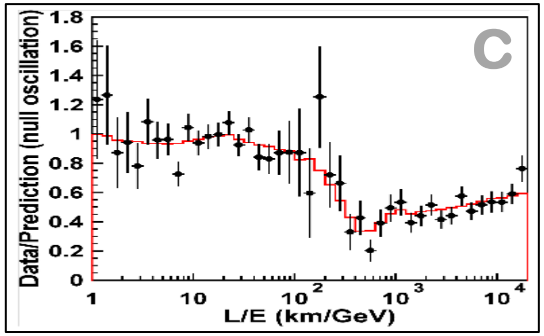
- Knowns and unknowns from 3ν oscillations
- Nonoscillation constraints from $0\nu\beta\beta$ & Cosmology
- Global analysis of oscillation + nonoscillation data
- Summary and prospects

Last two decades: oscillations → "standard" 3ν framework

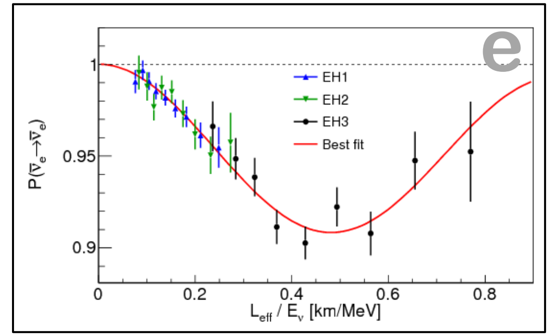
e→e (δm^2 , θ_{12})



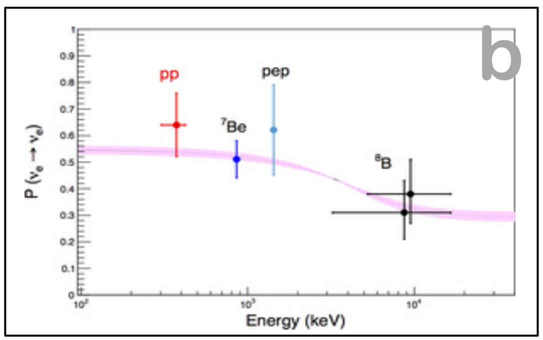
μ→μ (Δm^2 , θ_{23})



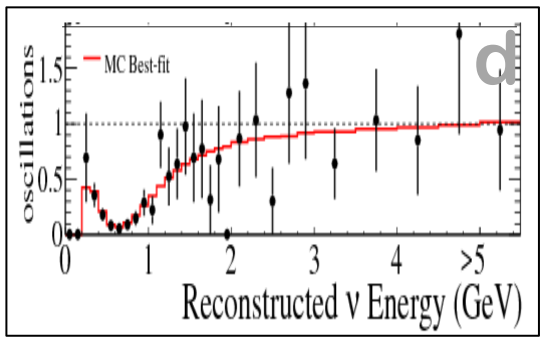
e→e (Δm^2 , θ_{13})



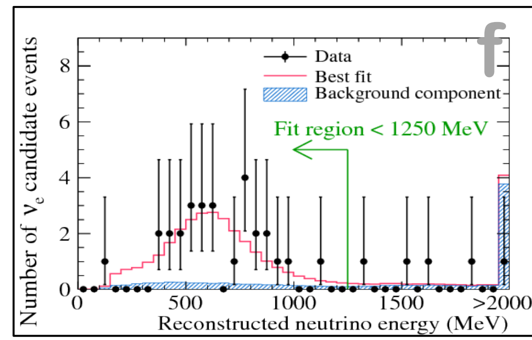
e→e (δm^2 , θ_{12})



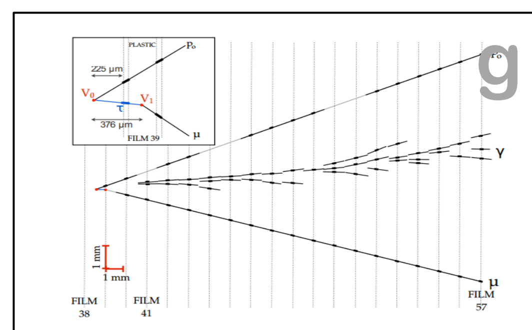
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



μ→τ (Δm^2 , θ_{23})



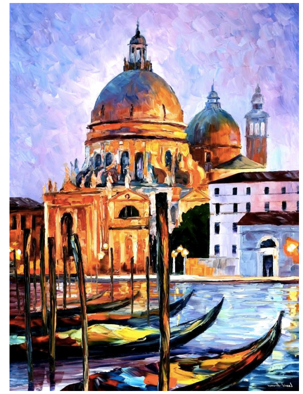
Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline accelerator, (e) short-baseline reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS, NOvA; (g) OPERA [plot], Super-K atmospheric.

"Broad-brush" picture (with 1-digit accuracy)

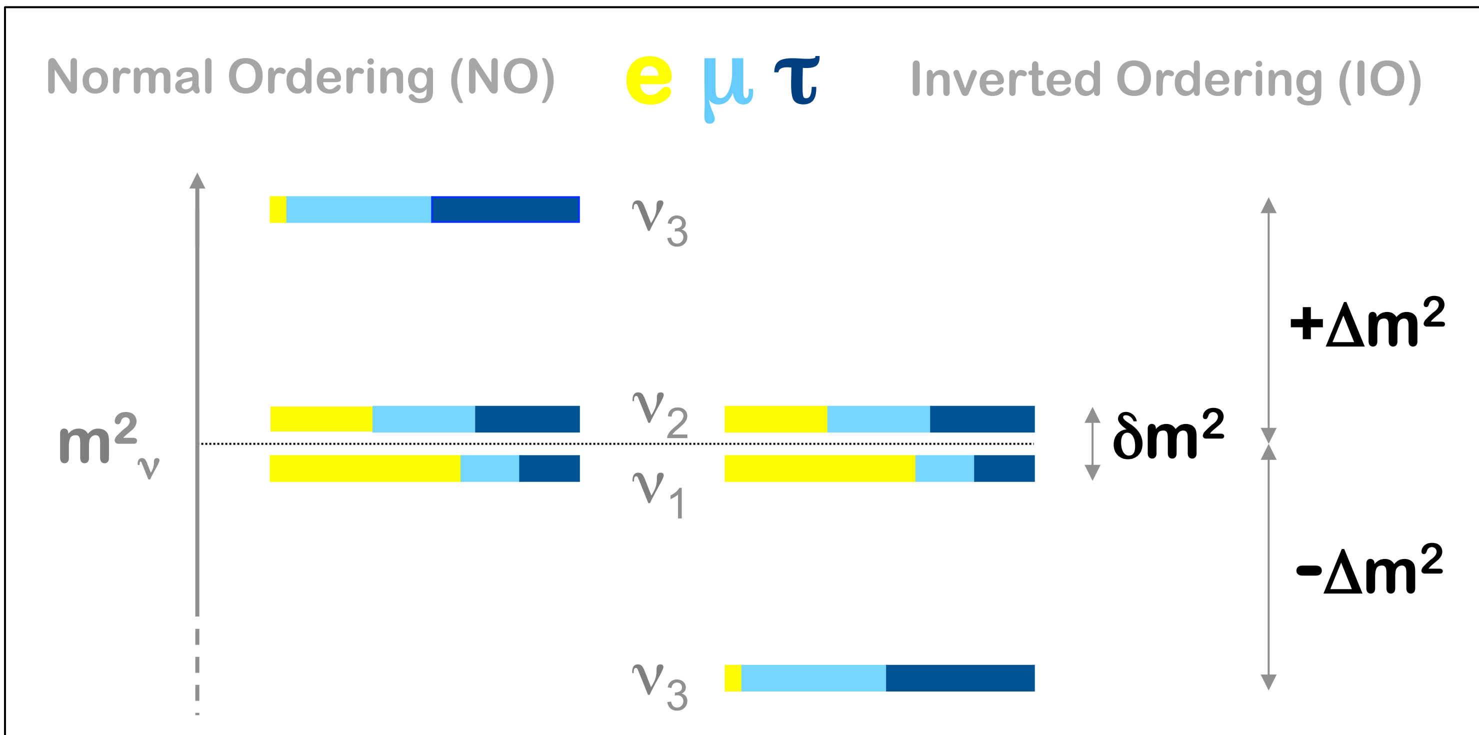
Knowns:

$\delta m^2 \sim 7 \times 10^{-5}$ eV^2
$\Delta m^2 \sim 2 \times 10^{-3}$ eV^2
$\sin^2\theta_{12} \sim 0.3$
$\sin^2\theta_{23} \sim 0.5$
$\sin^2\theta_{13} \sim 0.02$



Unknowns:

δ(CP)
sign(Δm^2) = ordering
octant(θ_{23})
absolute mass scale
Dirac/Majorana nature



Hi-res and broader picture → Global analysis of ν oscill. data

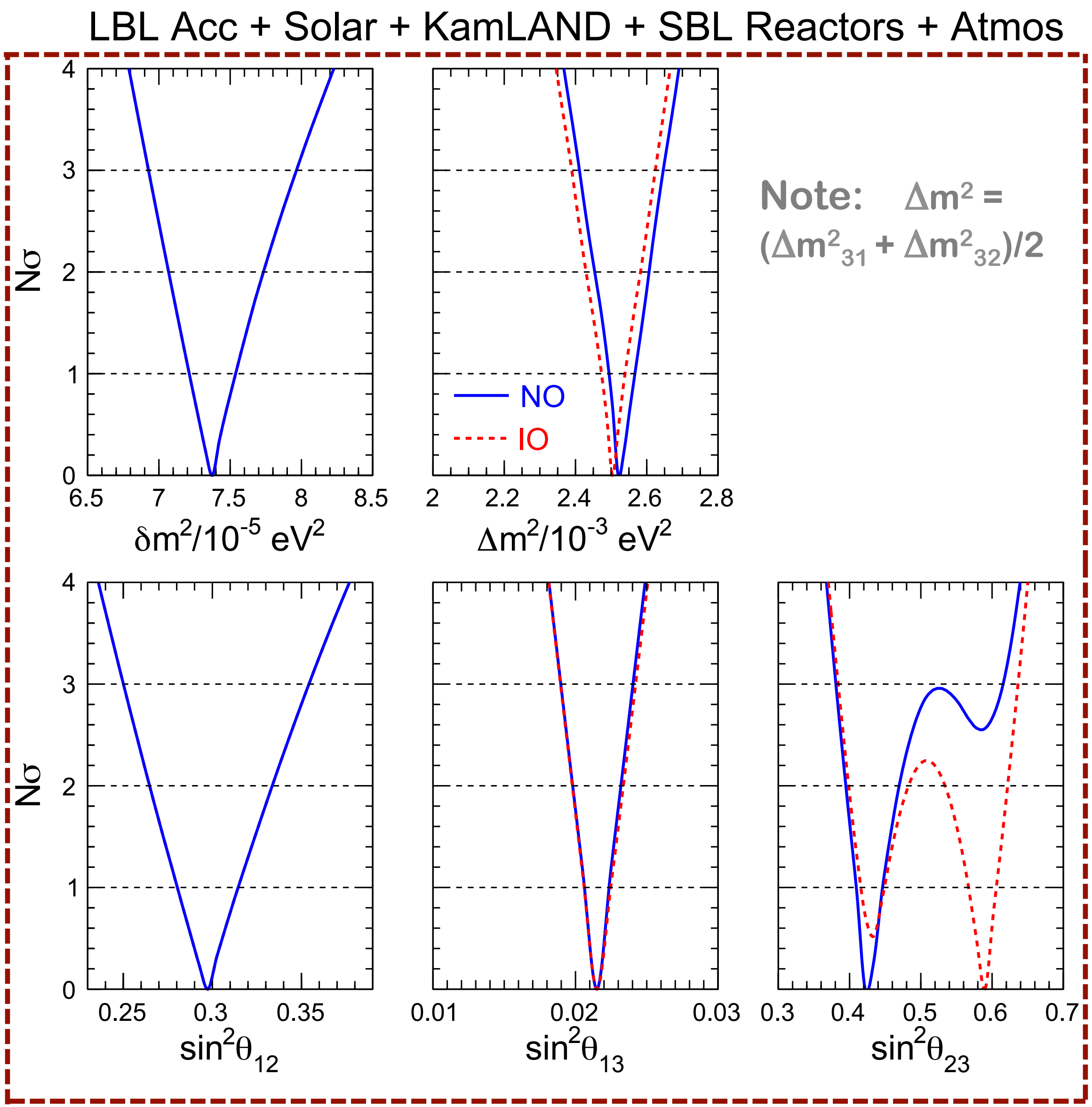
Analysis includes increasingly rich oscillation data sets:

LBL Acc + Solar + KL
LBL Acc + Solar + KL + SBL Reactor
LBL Acc + Solar + KL + SBL Reactor + Atmosph.

χ^2 metric adopted. Parameters not shown are marginalized away:

C.L.'s refer to $N\sigma = \sqrt{\Delta\chi^2} = 1, 2, 3, \ldots$

Five known oscillation parameters:



Current 1σ errors
(1/6 of ±3σ range):

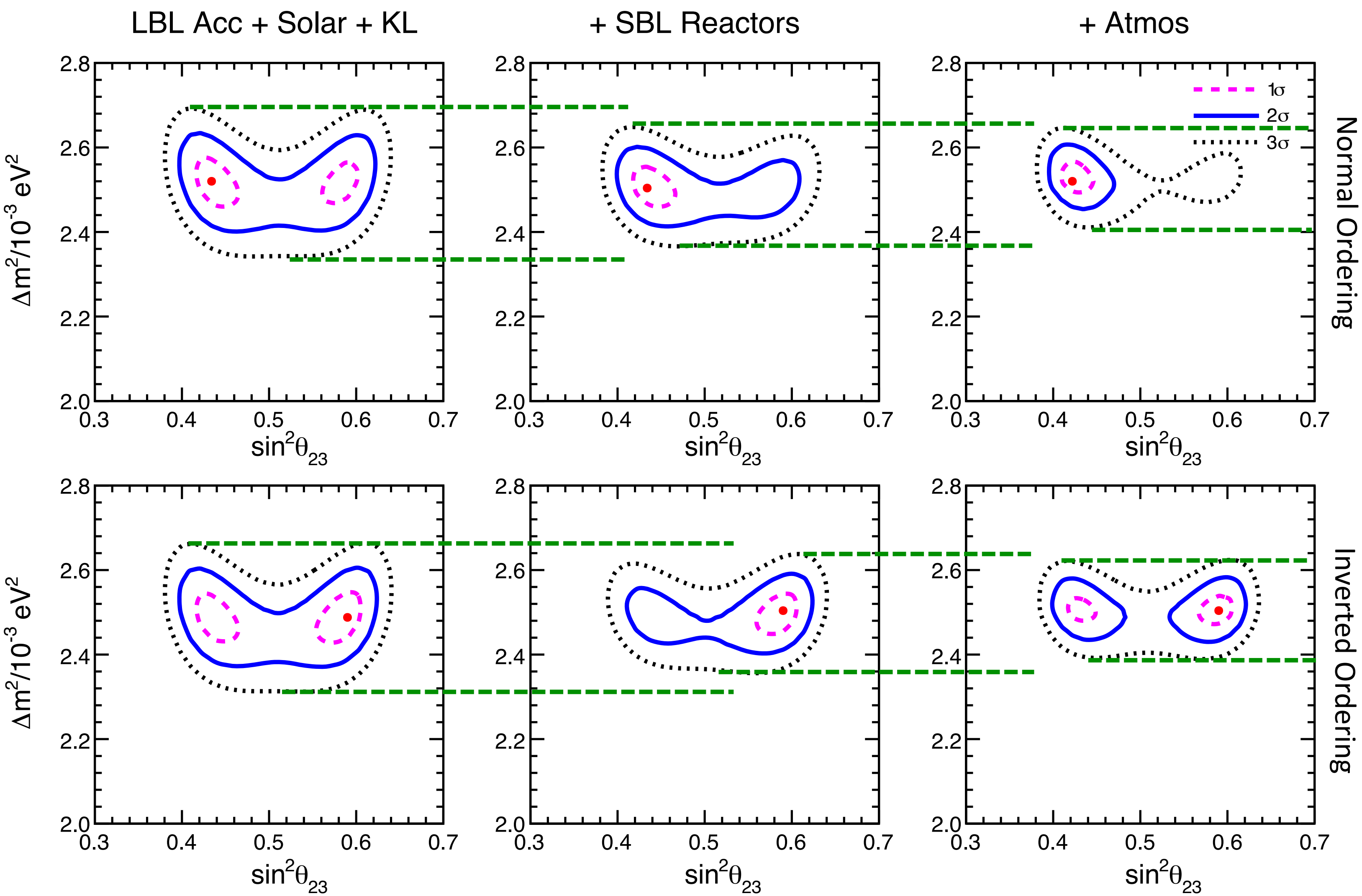
δm^2	2.3 %
Δm^2	1.6 %
$\sin^2\theta_{12}$	5.8 %
$\sin^2\theta_{13}$	4.0 %
$\sin^2\theta_{23}$	~ 9 %

all < 10%...

Precision Era!

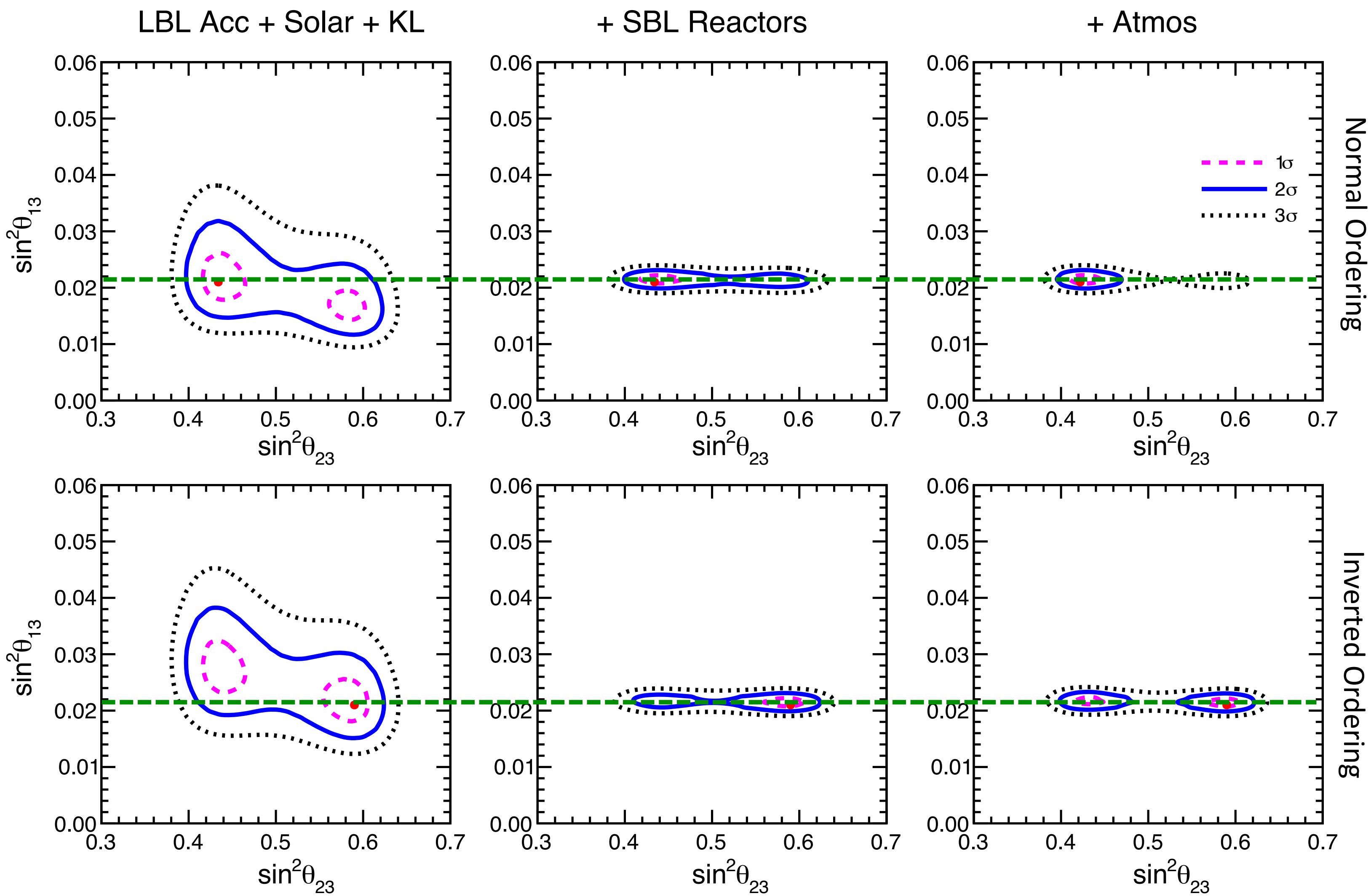
[but PMNS still very far from CKM accuracy]

More on known oscillation parameters: sinergy on Δm^2



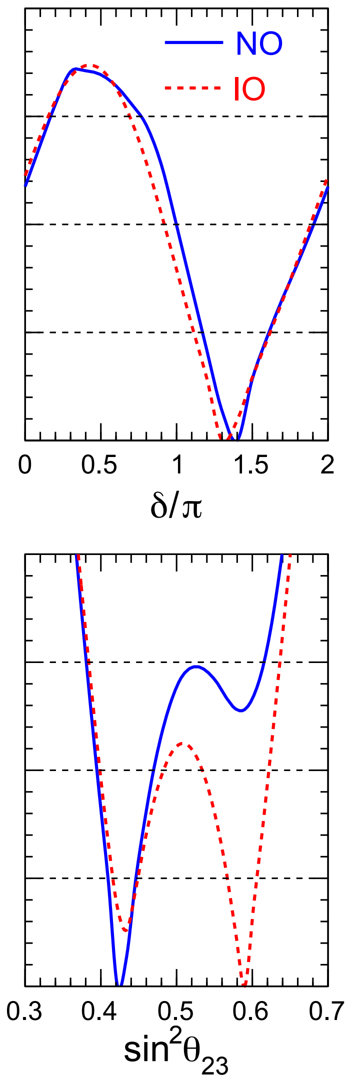
All data sets contribute to Δm^2

More on known oscillation parameters: sinergy on θ_{13}



LBL + solar + KL prefer the same θ_{13} as reactors (within large uncertainties)

Three unknown oscillation parameters



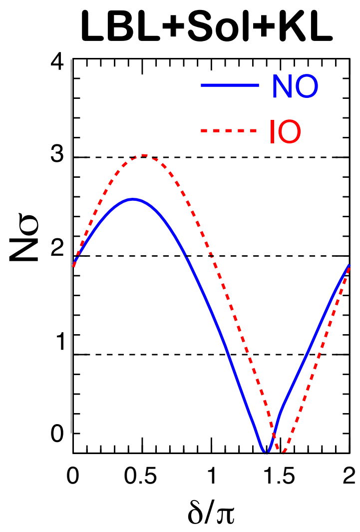
δ_{CP}

θ_{23} octant

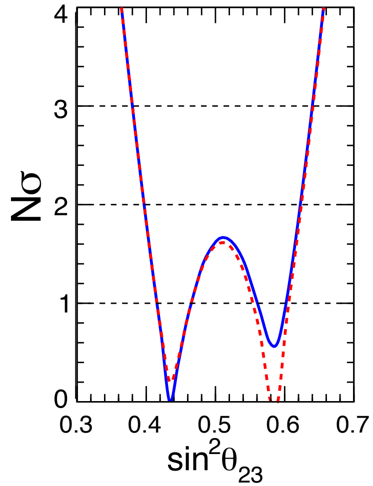
NO or IO

More on unknown oscillation parameters:

δ_{CP}



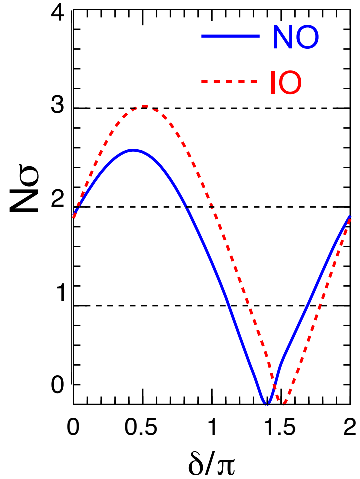
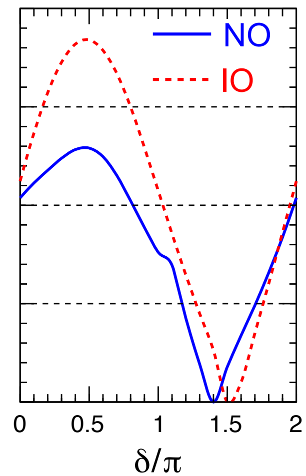
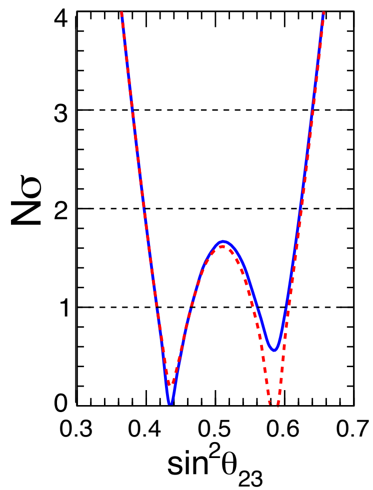
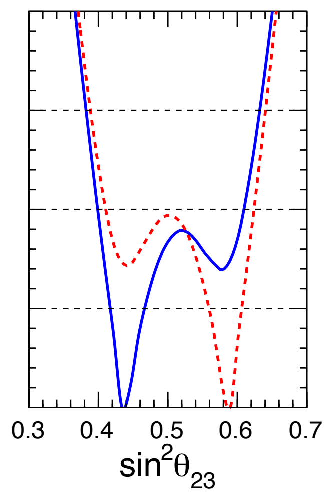
θ_{23} octant



$\Delta\chi^2$ (IO-NO)

+1.1

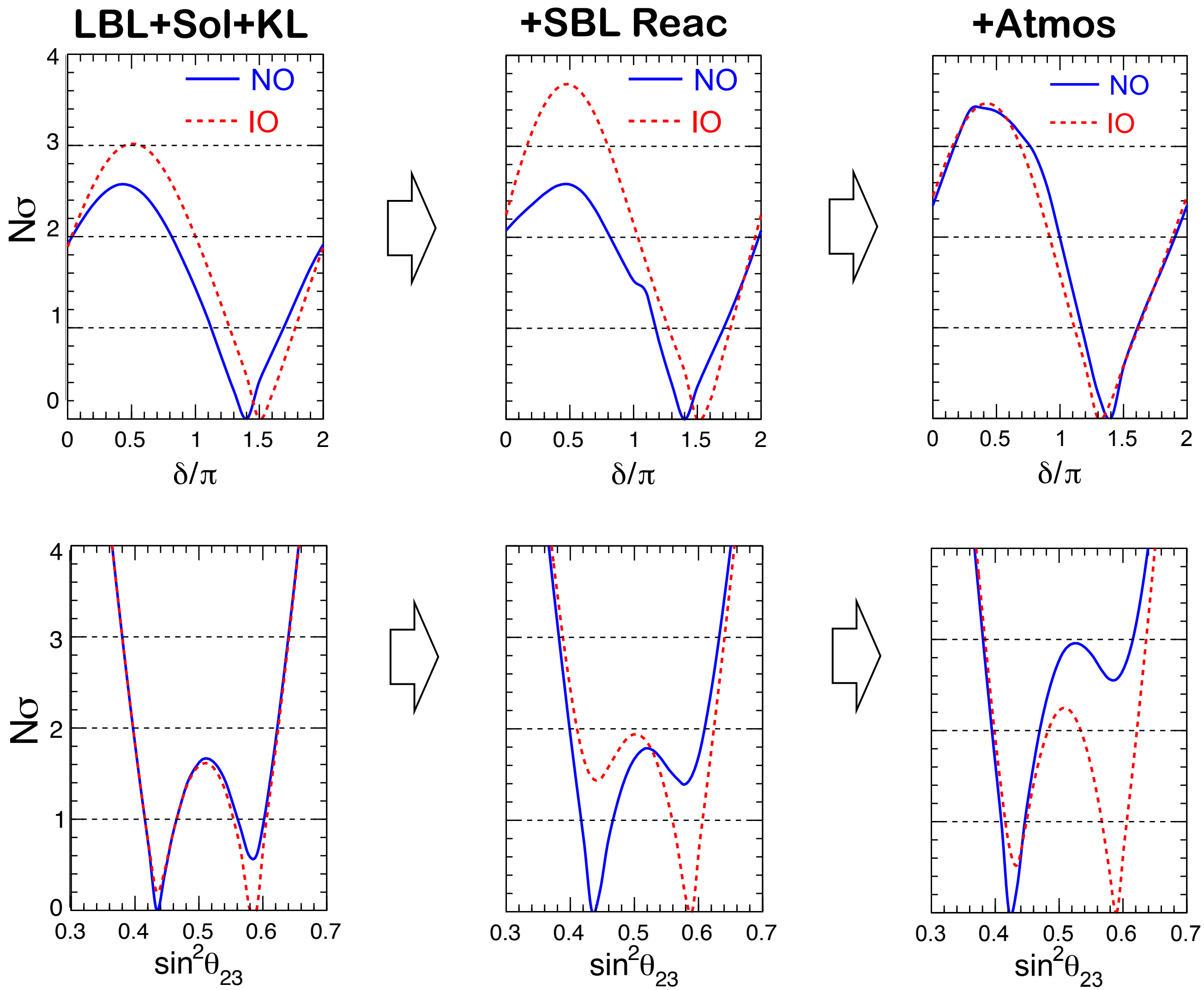
More on unknown oscillation parameters:

	LBL+Sol+KL		+SBL Reac
δ_{CP}		⇨	
θ_{23} octant		⇨	
$\Delta\chi^2$ (IO-NO)	+1.1	⇨	+1.1

More on unknown oscillation parameters:

δ_{CP}

θ_{23} octant



sin δ ~ -1
(or sin δ < 0)
favored;
sin δ ~ +1
excluded

Max-mixing disfavored;
octant flips with NO/IO

$\Delta\chi^2$ (IO-NO)

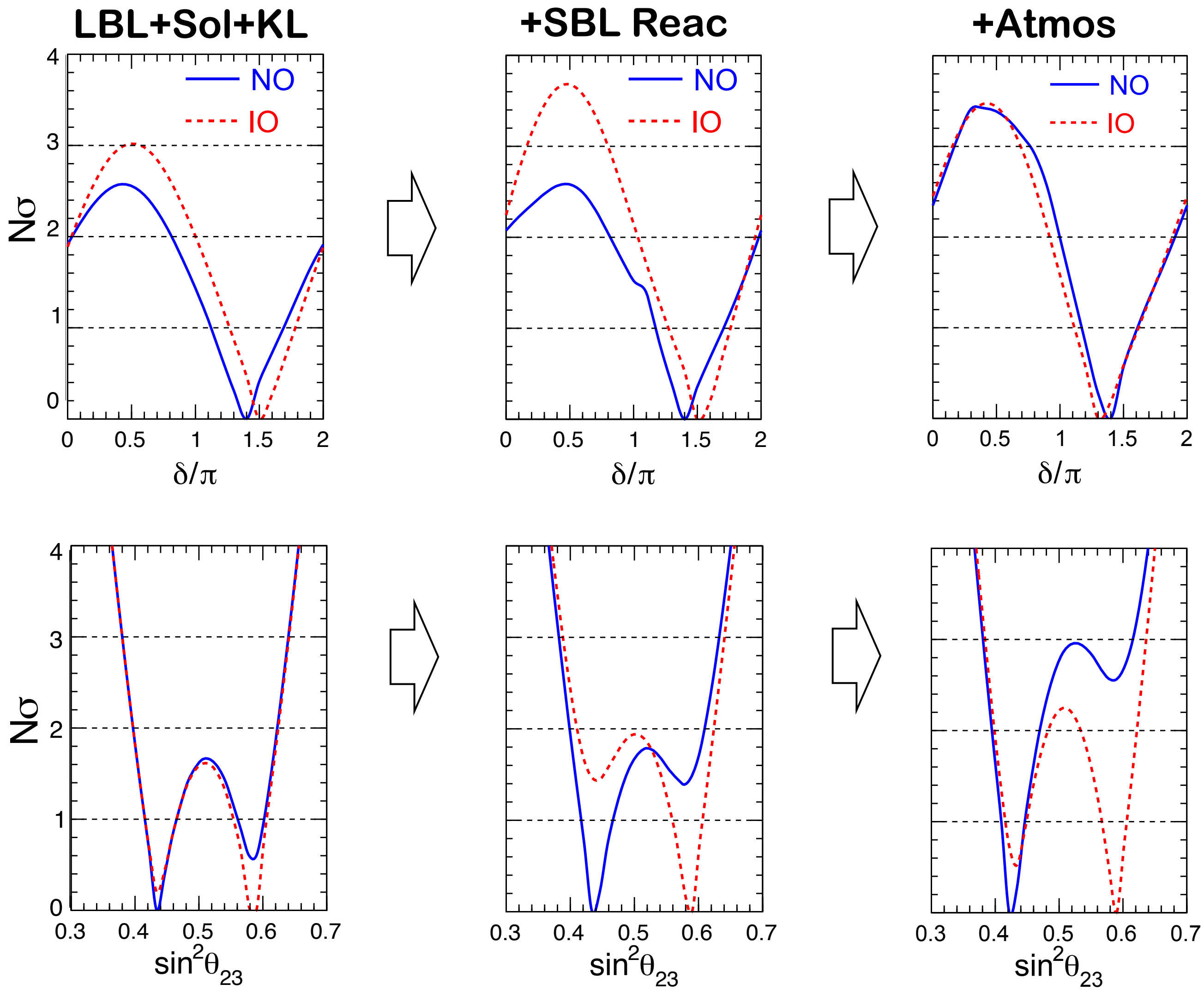
+1.1 → **+1.1** → **+3.6**

Intriguing!
NO favored

Compare the current results (circa 2017) with...

δ_{CP}

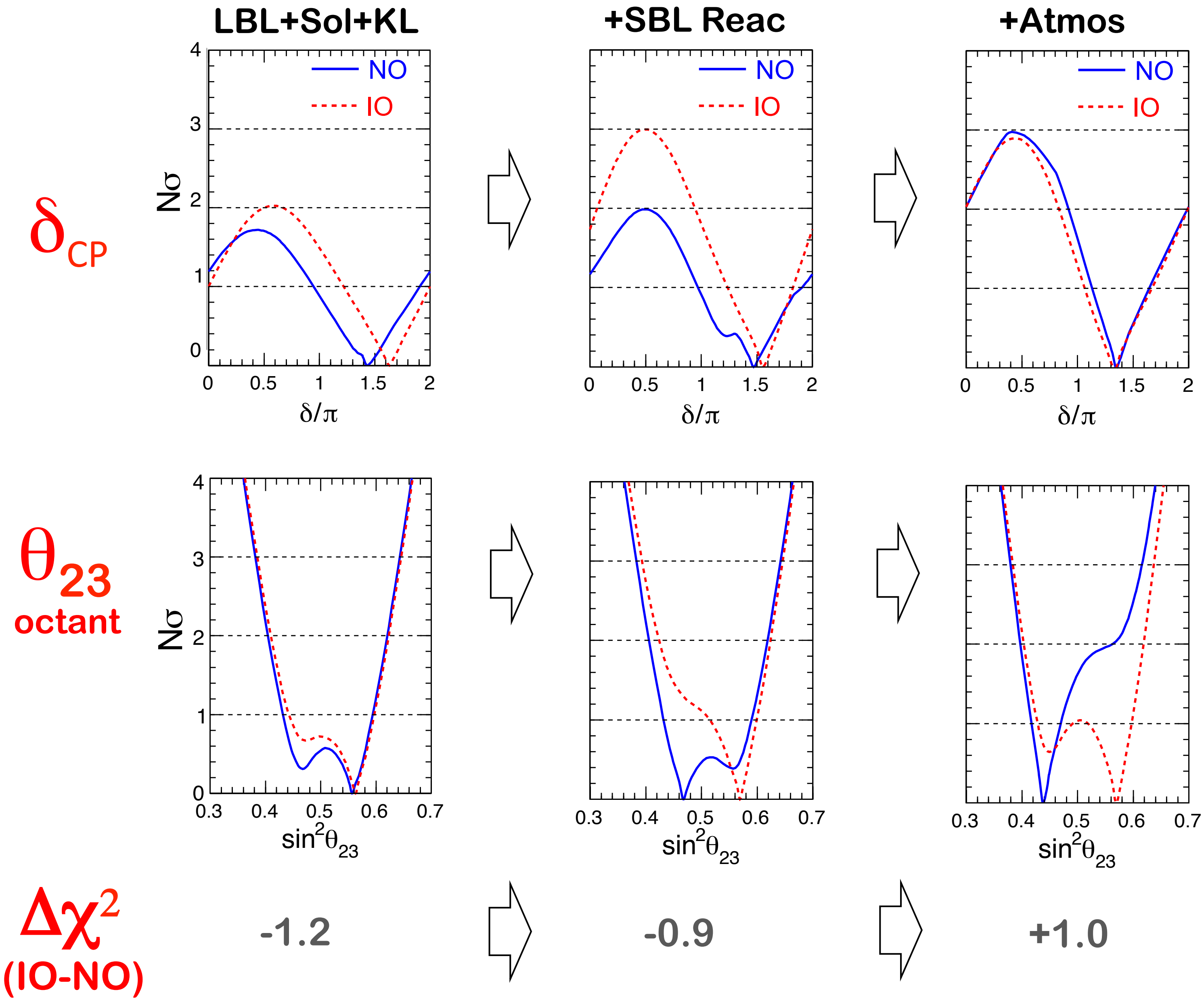
θ_{23} octant



$\Delta\chi^2$ (IO-NO)

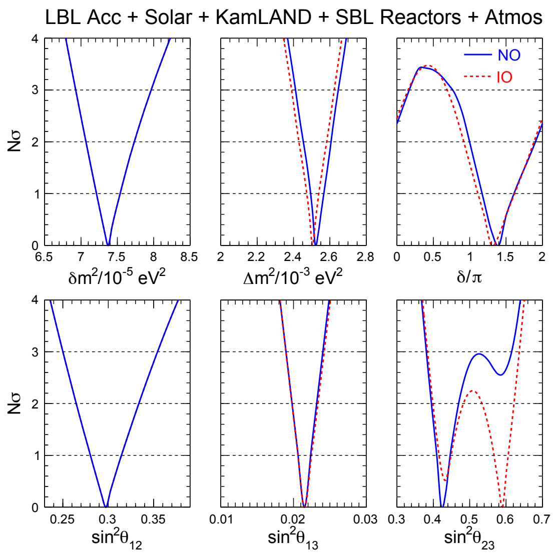
	LBL+Sol+KL	+SBL Reac	+Atmos
$\Delta\chi^2$ (IO-NO)	+1.1	+1.1	+3.6

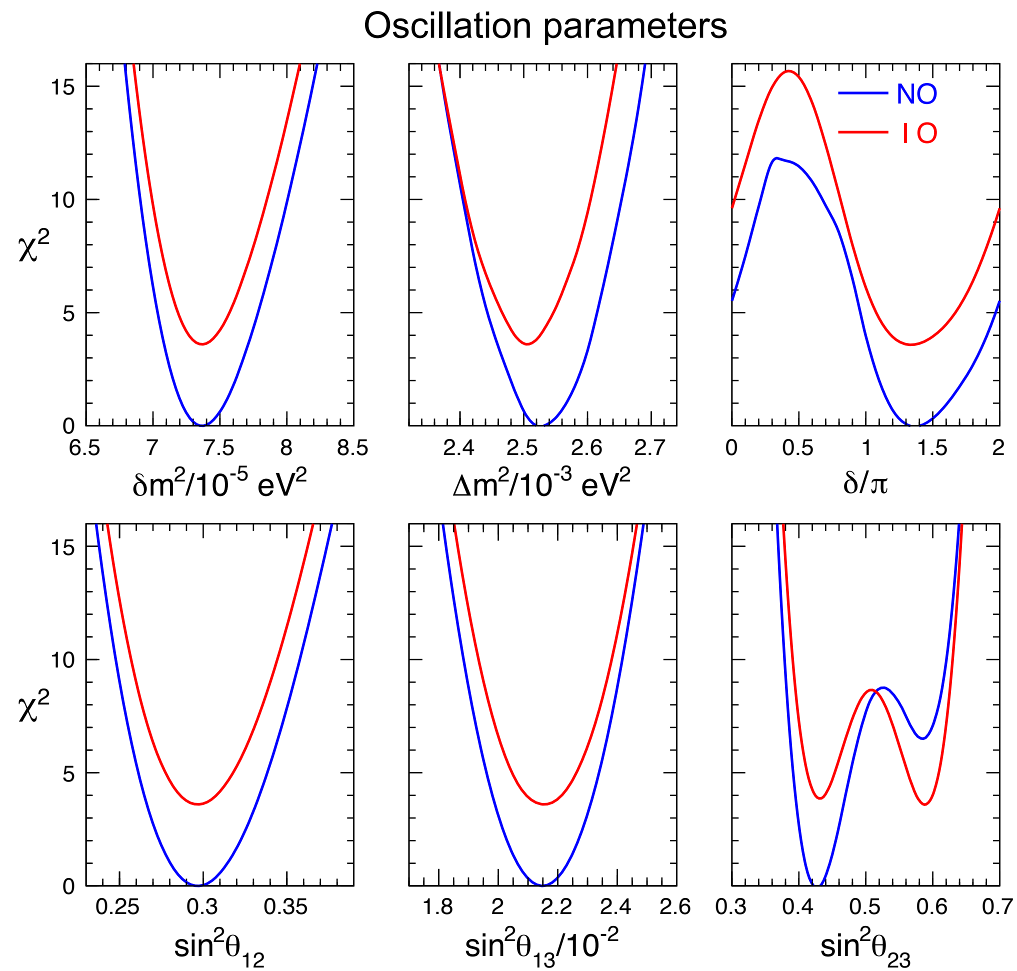
… 1yr ago, 2016: trends were somewhat weaker



Current indication $\Delta\chi^2_{IO-NO} = 3.6$ from oscill. data starts to be interesting.

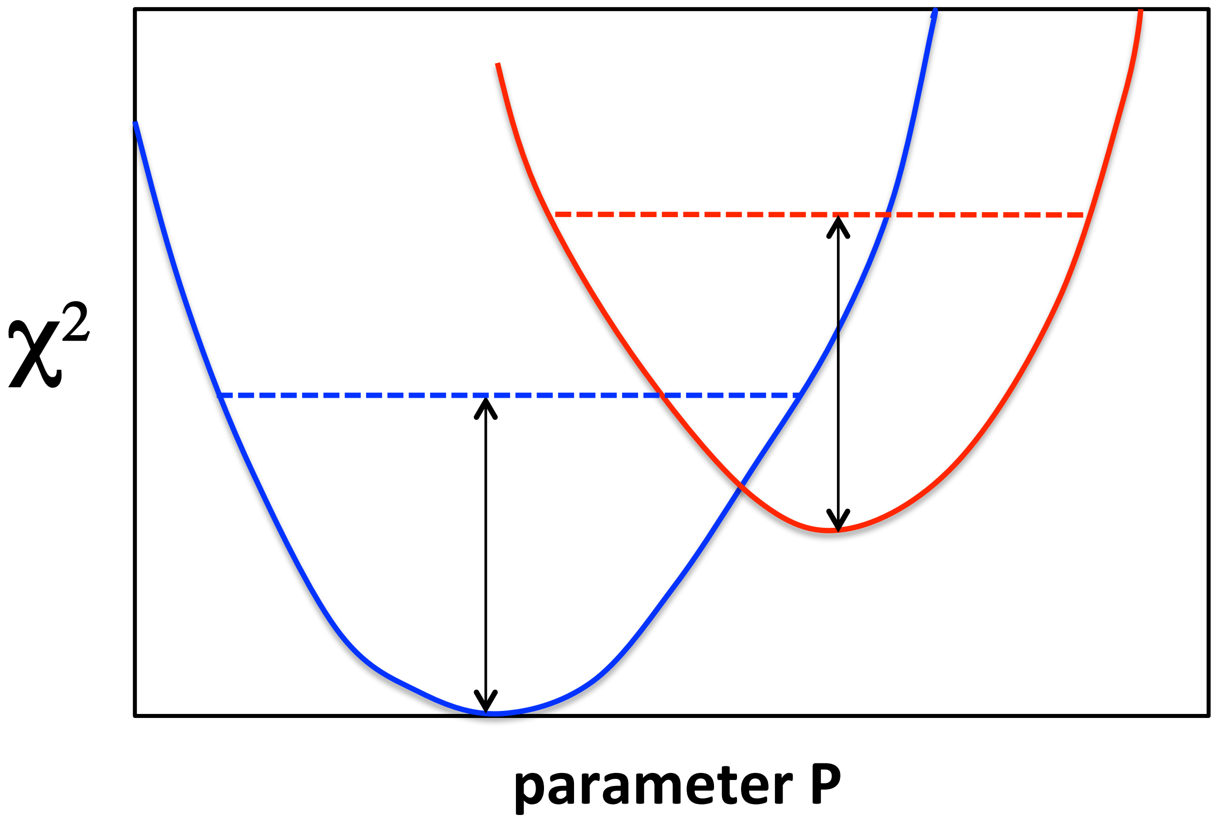
Useful to see the effect of excluding/including this offset in the analysis:





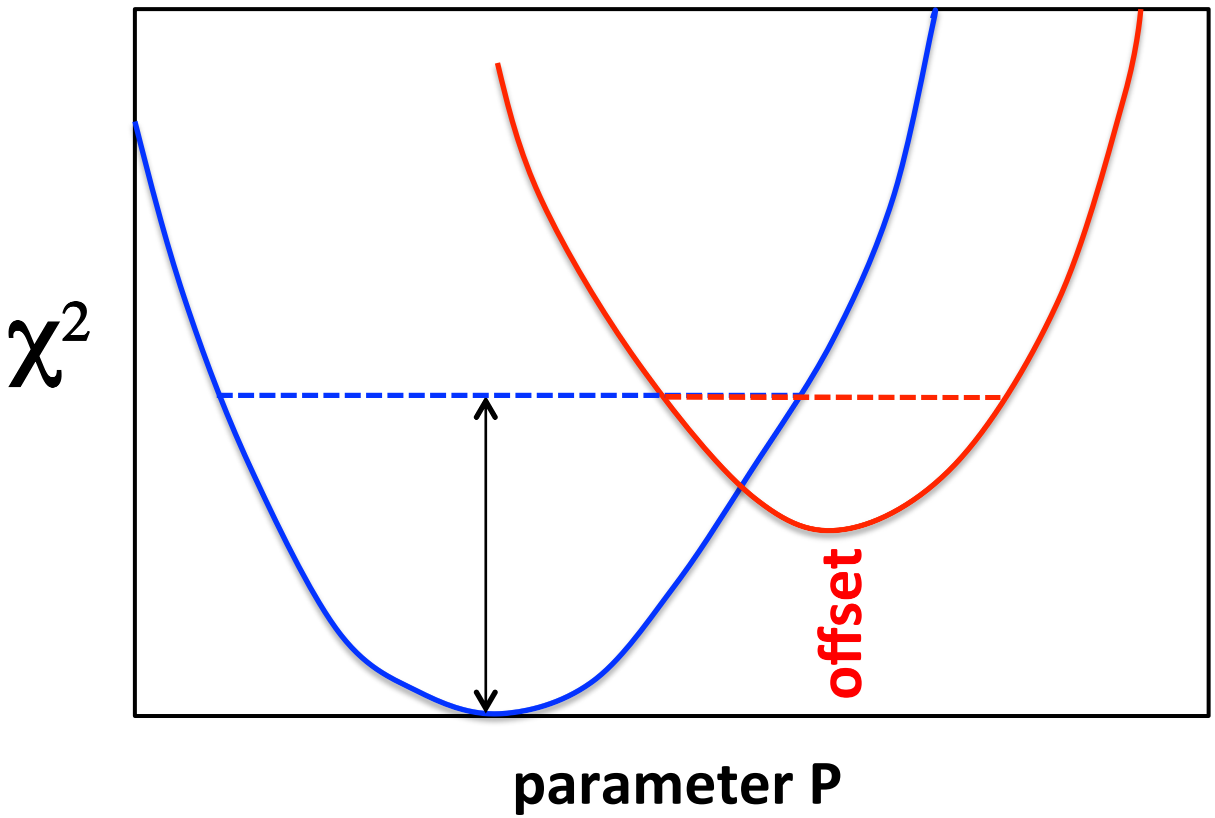
Two different ways of marginalizing over mass ordering(s) →

Apply a "$\Delta\chi^2$ cut" to **SEPARATE** minima in **NO**, **IO**....

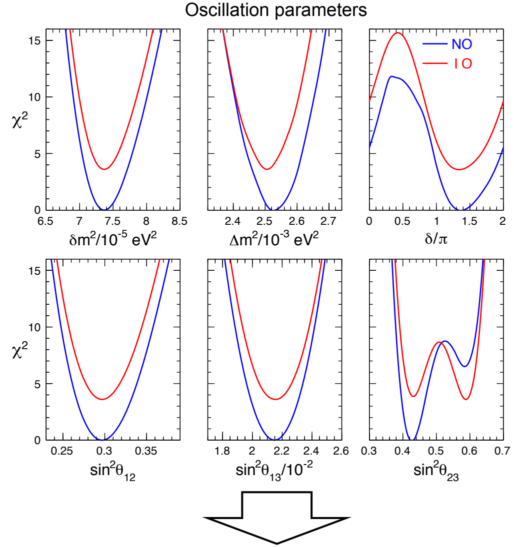


(does **not** include **IO-NO offset** information)

...or minimize and expand over **ANY ORDERING**



(includes **IO-NO offset** information)



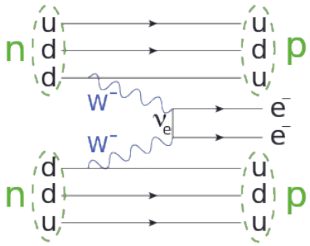
Oscillation parameter ranges

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values for the mass-mixing parameters and associated $n\sigma$ ranges ($n = 1, 2, 3$), defined by $\chi^2 - \chi^2_{\rm min} = n^2$ with respect to the separate minima in each mass ordering (NO, IO) and to the absolute minimum in any ordering. (Note that the fit to the δm^2 and $\sin^2\theta_{12}$ parameters is basically insensitive to the mass ordering.) We recall that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, and that δ is taken in the (cyclic) interval $\delta/\pi \in [0, 2]$.

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2	NO, IO, Any	7.37	7.21 – 7.54	7.07 – 7.73	6.93 – 7.96
$\sin^2\theta_{12}/10^{-1}$	NO, IO, Any	2.97	2.81 – 3.14	2.65 – 3.34	2.50 – 3.54
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.525	2.495 – 2.567	2.454 – 2.606	2.411 – 2.646
	IO	2.505	2.473 – 2.539	2.430 – 2.582	2.390 – 2.624
	Any	2.525	2.495 – 2.567	2.454 – 2.606	2.411 – 2.646
$\sin^2\theta_{13}/10^{-2}$	NO	2.15	2.08 – 2.22	1.99 – 2.31	1.90 – 2.40
	IO	2.16	2.07 – 2.24	1.98 – 2.33	1.90 – 2.42
	Any	2.15	2.08 – 2.22	1.99 – 2.31	1.90 – 2.40
$\sin^2\theta_{23}/10^{-1}$	NO	4.25	4.10 – 4.46	3.95 – 4.70	3.81 – 6.15
	IO	5.89	4.17 – 4.48 $\oplus$ 5.67 – 6.05	3.99 – 4.83 $\oplus$ 5.33 – 6.21	3.84 – 6.36
	Any	4.25	4.10 – 4.46	3.95 – 4.70 $\oplus$ 5.75 – 6.00	3.81 – 6.26
δ/π	NO	1.38	1.18 – 1.61	1.00 – 1.90	0 – 0.17 $\oplus$ 0.76 – 2
	IO	1.31	1.12 – 1.62	0.92 – 1.88	0 – 0.15 $\oplus$ 0.69 – 2
	Any	1.38	1.18 – 1.61	1.00 – 1.90	0 – 0.17 $\oplus$ 0.76 – 2

Absolute neutrino mass observables

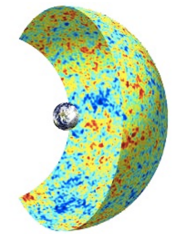
$0\nu\beta\beta$



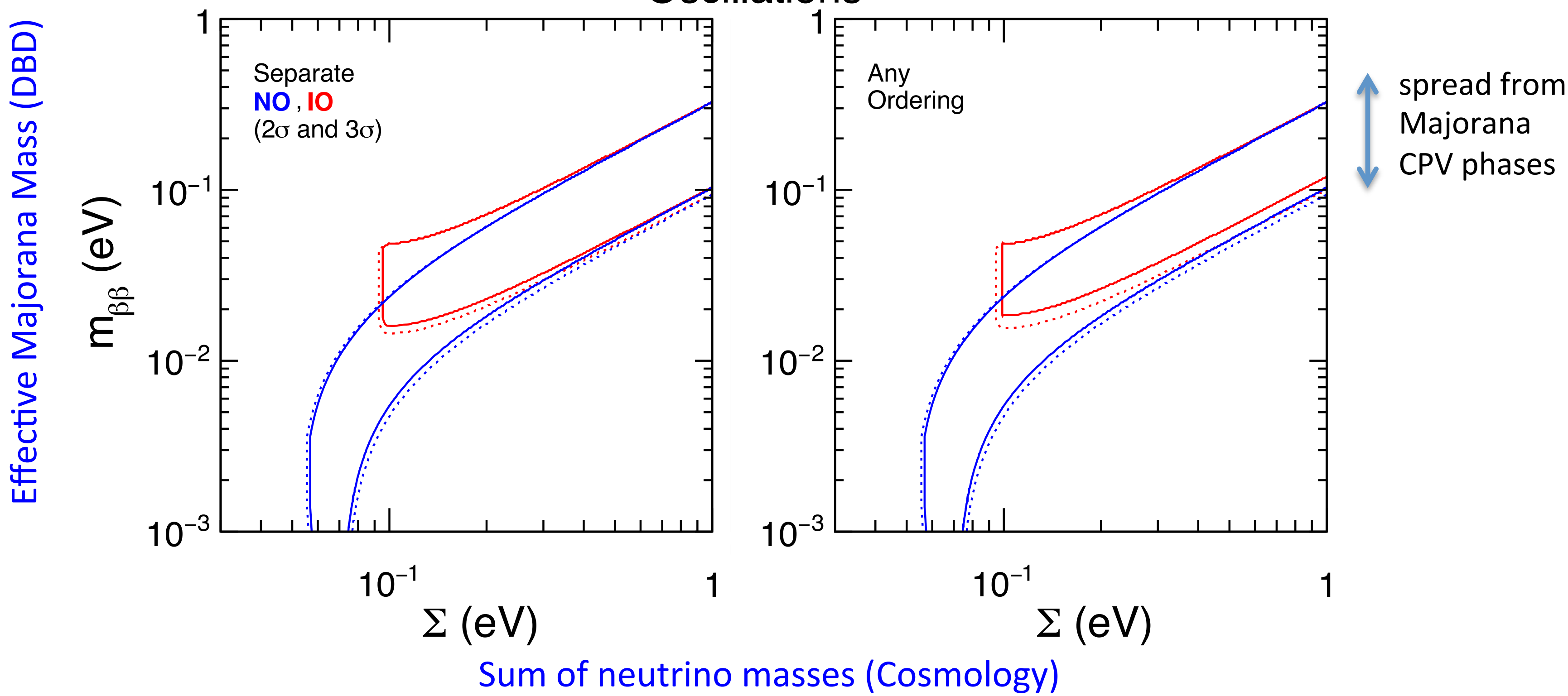
$$m_{\beta\beta} = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

$$\Sigma = m_1 + m_2 + m_3$$

Cosmo

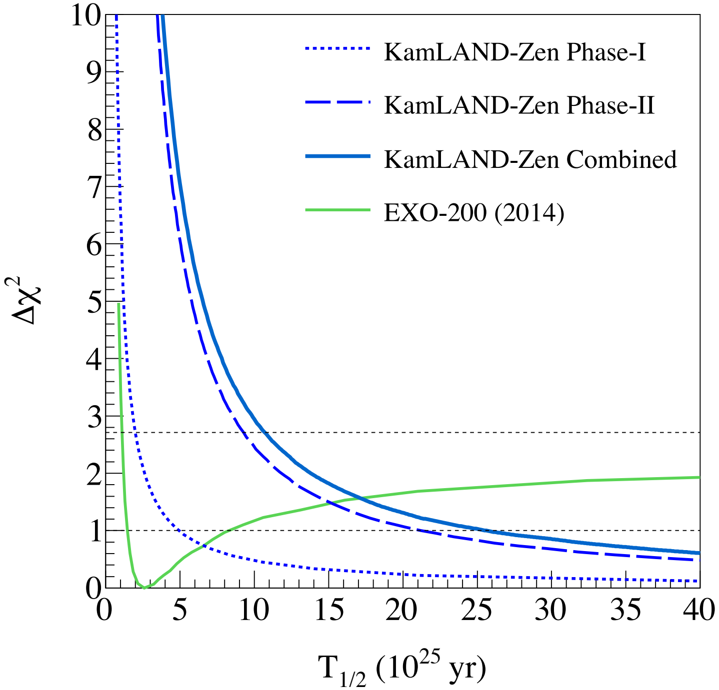


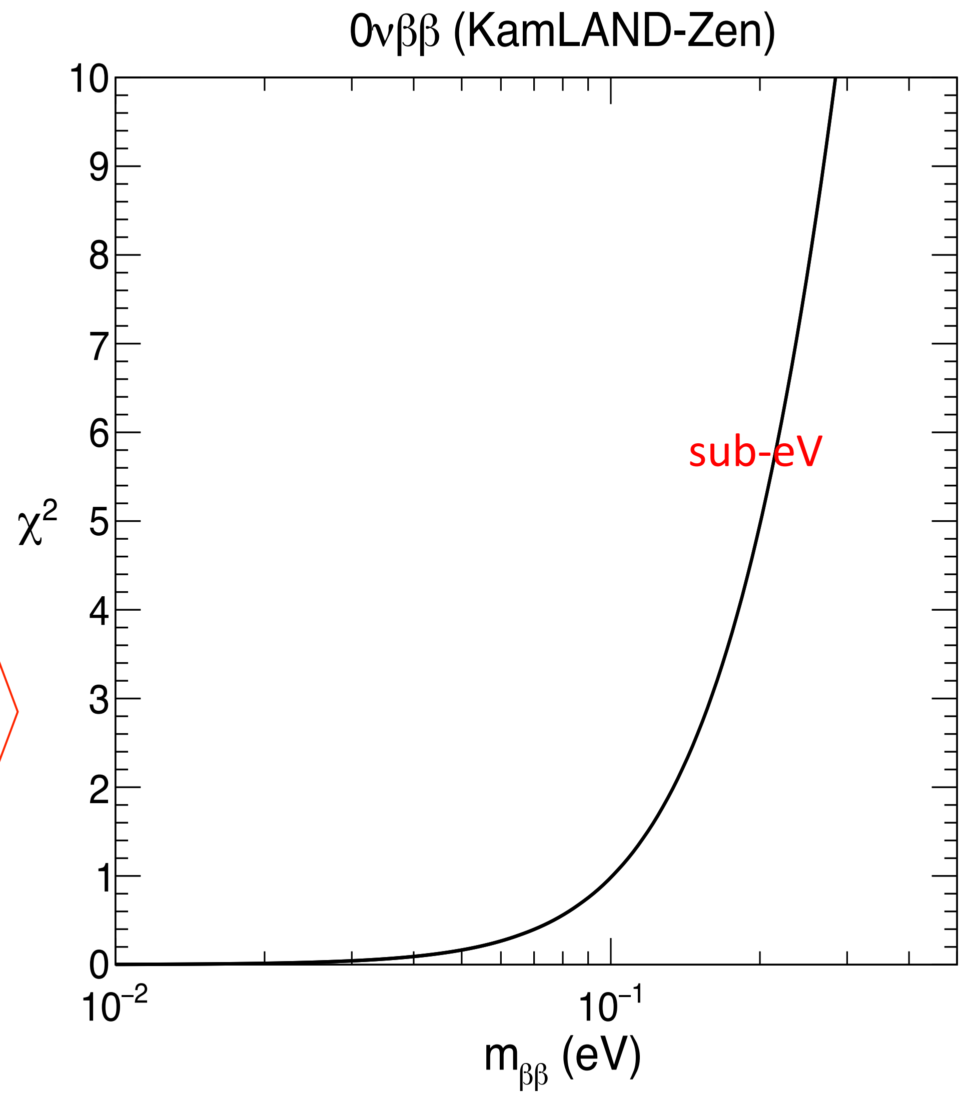
Oscillations



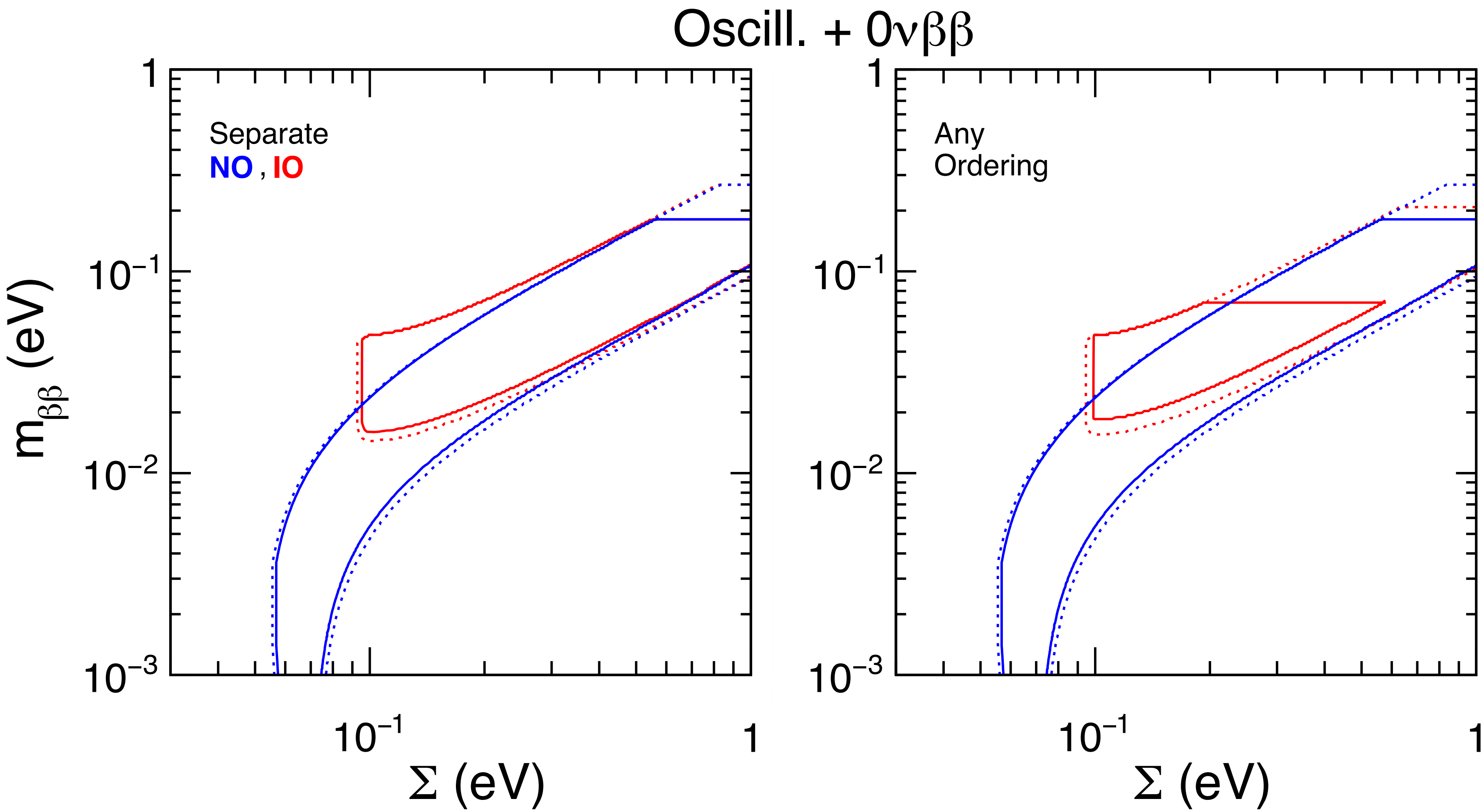
Current leading $0\nu\beta\beta$ constraints

KamLAND-Zen half-life limits





+NME Likelihood based on:
E.L., A. Rotunno, F. Simkovic,
arXiv:1506.04058


Oscill. + 0νββ
Separate
NO , IO
Any
Ordering
1
10−1
10−2
10−3
10−1
1
mββ (eV)
Σ (eV)

Cosmological constraints (circa 2017)

Analysis of various **datasets** within standard (6-param.) **ΛCDM model** augmented with **Σ**
plus one possible 1 extra parameter **A_{lens}**, to account for syst's or nonstandard effects
[**A_{lens}** > 1 may be typically traded for higher values of the sum of neutrino mass **Σ**]

Code: **CosmoMC with NO / IO options explicitly included in Σ,** via the two mass^2 differences
→ unphysical spectra of neutrino masses (e.g., **Σ** = 0) not allowed by construction.
→ expect small NO-IO differences at low Σ, but vanishing at high Σ (degenerate spectrum)

Cosmological constraints (circa 2017)

Analysis of various **datasets** within standard (6-param.) **ΛCDM model** augmented with **Σ**
plus one possible 1 extra parameter **A_{lens}**, to account for syst's or nonstandard effects
[A_{lens} > 1 may be typically traded for higher values of the sum of neutrino mass **Σ**]

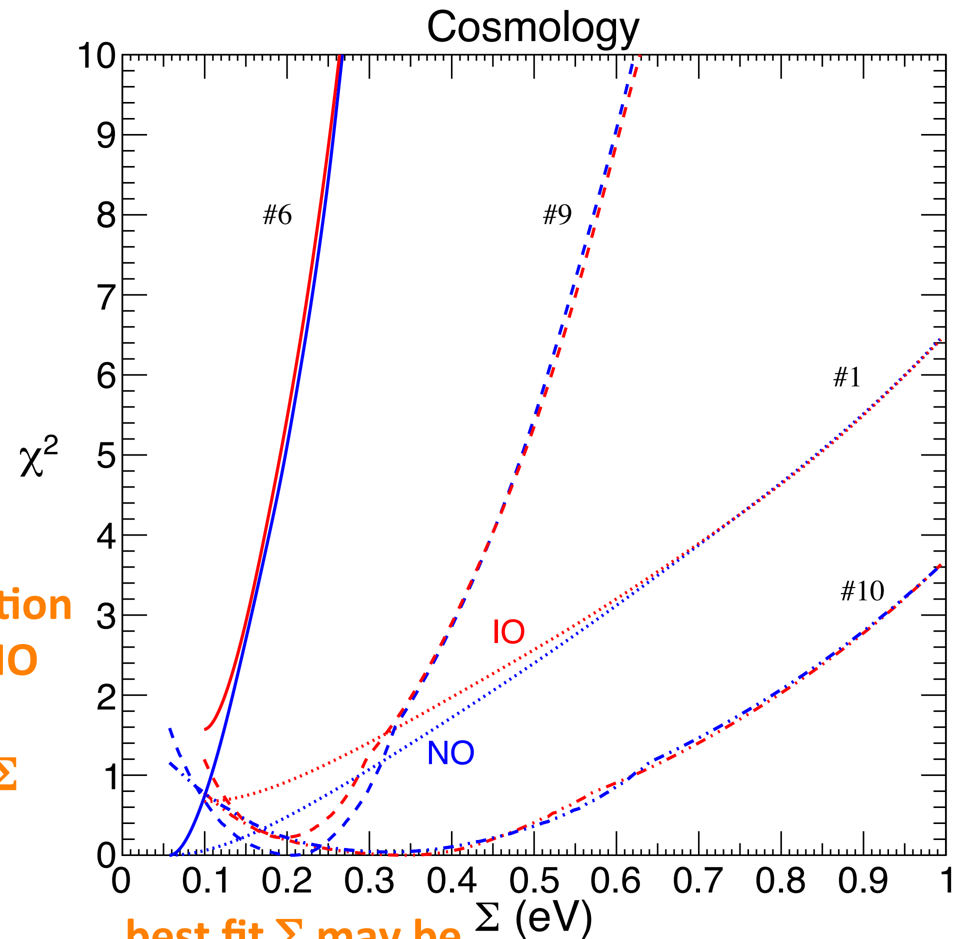
Code: **CosmoMC with NO / IO options explicitly included in Σ,** via the two mass^2 differences
→ unphysical spectra of neutrino masses (e.g., Σ = 0) not allowed by construction.
→ expect small NO-IO differences at low Σ, but vanishing at high Σ (degenerate spectrum)

Results on Σ (upper bounds) **and on $\Delta\chi^2_{IO-NO}$:**

TABLE II: Results of the global 3ν analysis of cosmological data within the standard ΛCDM + Σ and extended ΛCDM + Σ + $A_{\rm lens}$ models. The datasets refer to various combinations of the Planck power angular CMB temperature power spectrum (TT) plus polarization power spectra (TE, EE), reionization optical depth $\tau_{\rm HFI}$, lensing potential power spectrum (lensing), and BAO measurements. For each of the 12 cases we report the 2σ upper bounds on $\Sigma = m_1 + m_2 + m_3$ for NO and IO, together with the $\Delta\chi^2$ difference between the two mass orderings (with one digit after decimal point). For any Σ, the masses m_i are taken to obey the δm^2 and Δm^2 constraints coming from oscillation data. See the text for more details.

#	Model	Cosmological data set	Σ/eV (2σ), NO	Σ/eV (2σ), IO	$\Delta\chi^2_{\rm IO-NO}$
1	ΛCDM + Σ	Planck TT + $\tau_{\rm HFI}$	< 0.72	< 0.80	0.7
2	ΛCDM + Σ	Planck TT + $\tau_{\rm HFI}$ + lensing	< 0.64	< 0.63	0.2
3	ΛCDM + Σ	Planck TT + $\tau_{\rm HFI}$ + BAO	< 0.21	< 0.23	1.2
4	ΛCDM + Σ	Planck TT, TE, EE + $\tau_{\rm HFI}$	< 0.44	< 0.48	0.6
5	ΛCDM + Σ	Planck TT, TE, EE + $\tau_{\rm HFI}$ + lensing	< 0.45	< 0.47	0.3
6	ΛCDM + Σ	Planck TT, TE, EE + $\tau_{\rm HFI}$ + BAO	< 0.18	< 0.20	1.6
7	ΛCDM + Σ + $A_{\rm lens}$	Planck TT + $\tau_{\rm HFI}$	< 1.08	< 1.08	−0.1
8	ΛCDM + Σ + $A_{\rm lens}$	Planck TT + $\tau_{\rm HFI}$ + lensing	< 0.91	< 0.93	0.0
9	ΛCDM + Σ + $A_{\rm lens}$	Planck TT + $\tau_{\rm HFI}$ + BAO	< 0.45	< 0.46	0.2
10	ΛCDM + Σ + $A_{\rm lens}$	Planck TT, TE, EE + $\tau_{\rm HFI}$	< 1.04	< 1.03	0.0
11	ΛCDM + Σ + $A_{\rm lens}$	Planck TT, TE, EE + $\tau_{\rm HFI}$ + lensing	< 0.89	< 0.89	0.1
12	ΛCDM + Σ + $A_{\rm lens}$	Planck TT, TE, EE + $\tau_{\rm HFI}$ + BAO	< 0.31	< 0.32	0.3

χ^2 profile for NO, IO in representative cases



convergence of NO, IO curves at high Σ

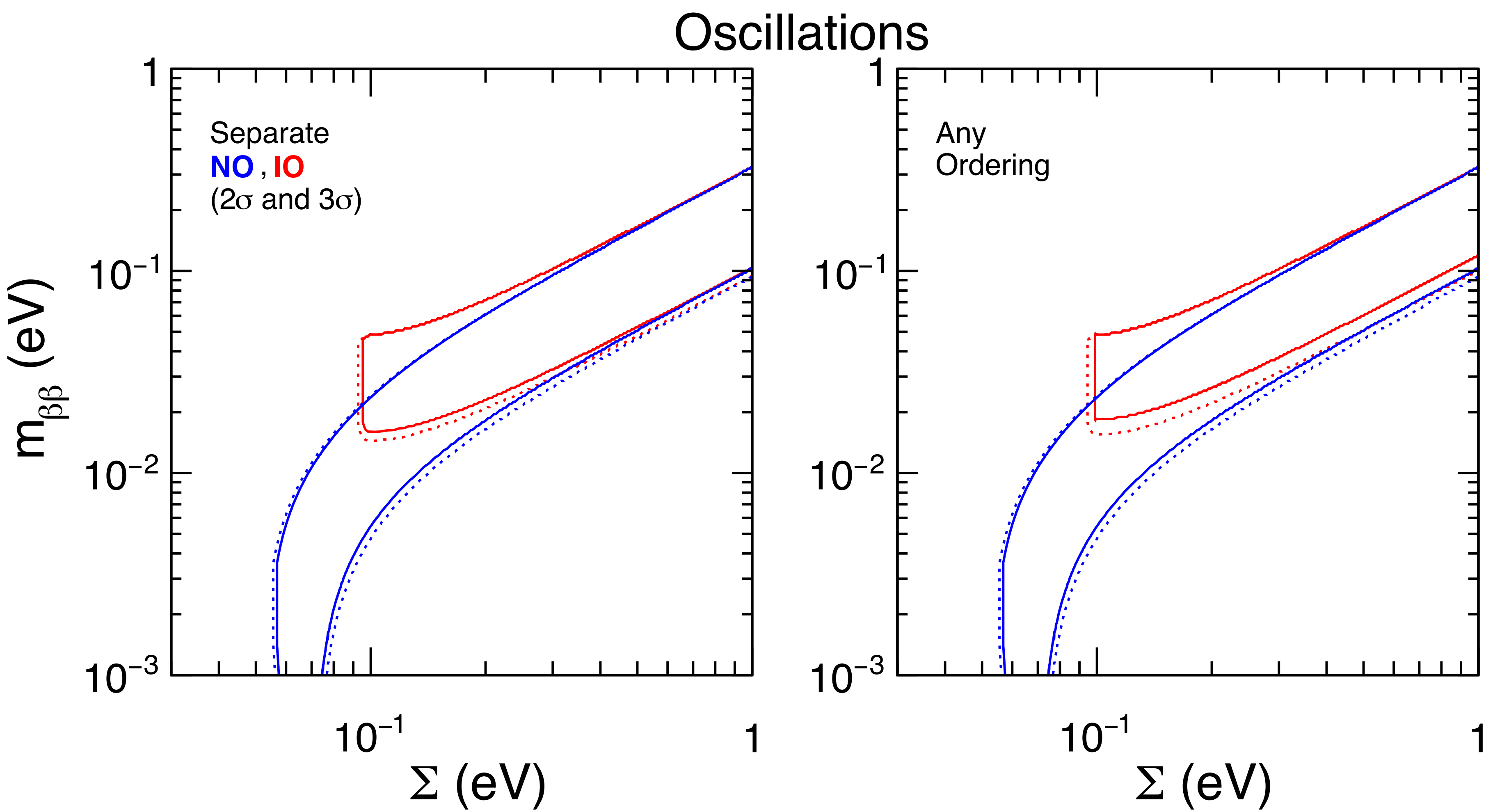
bifurcation of NO, IO curves at low Σ

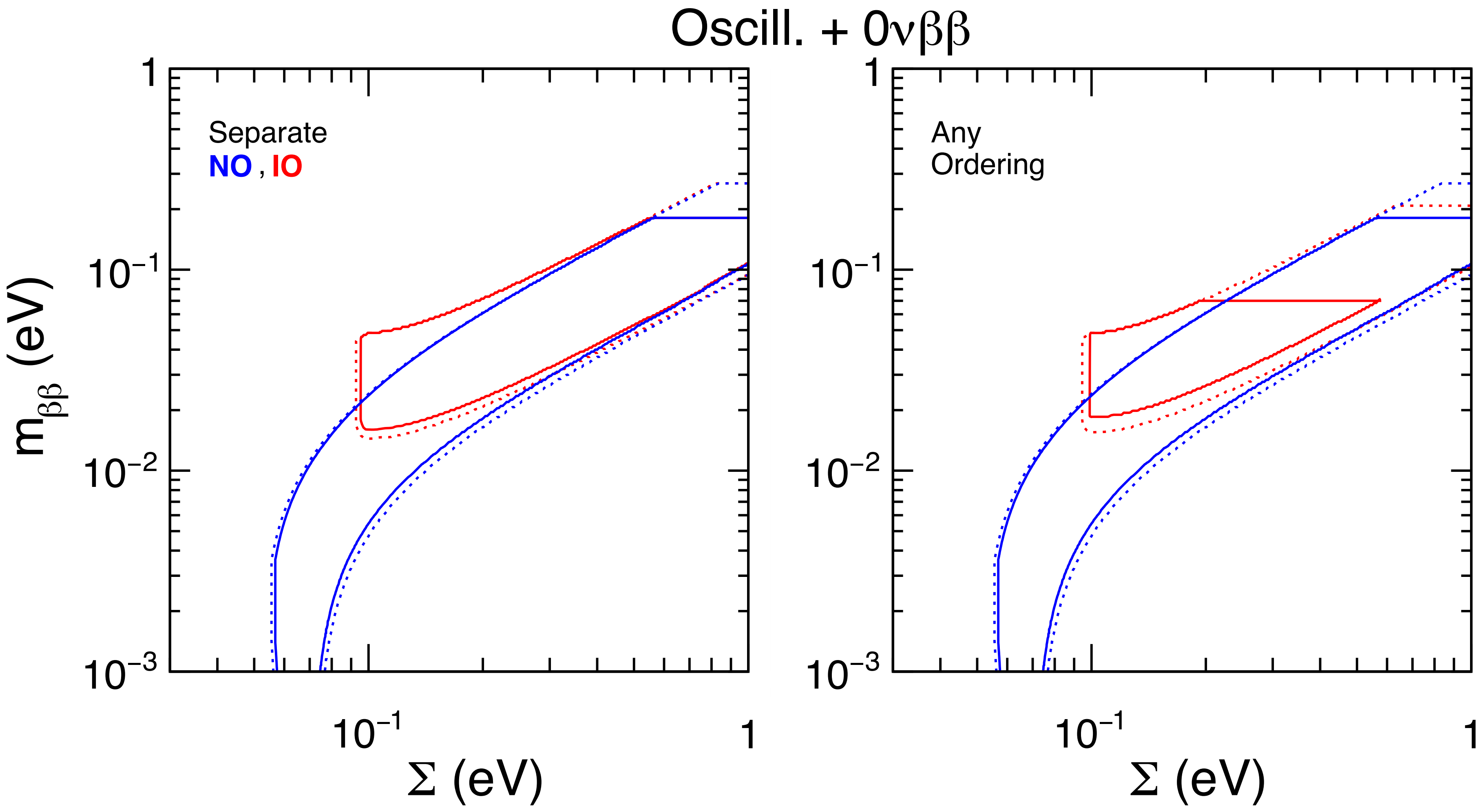
best fit Σ may be above threshold

Thresholds:	**Σ > 0.06 eV (NO)**
	Σ > 0.10 eV (IO)
	Σ = 0: not allowed

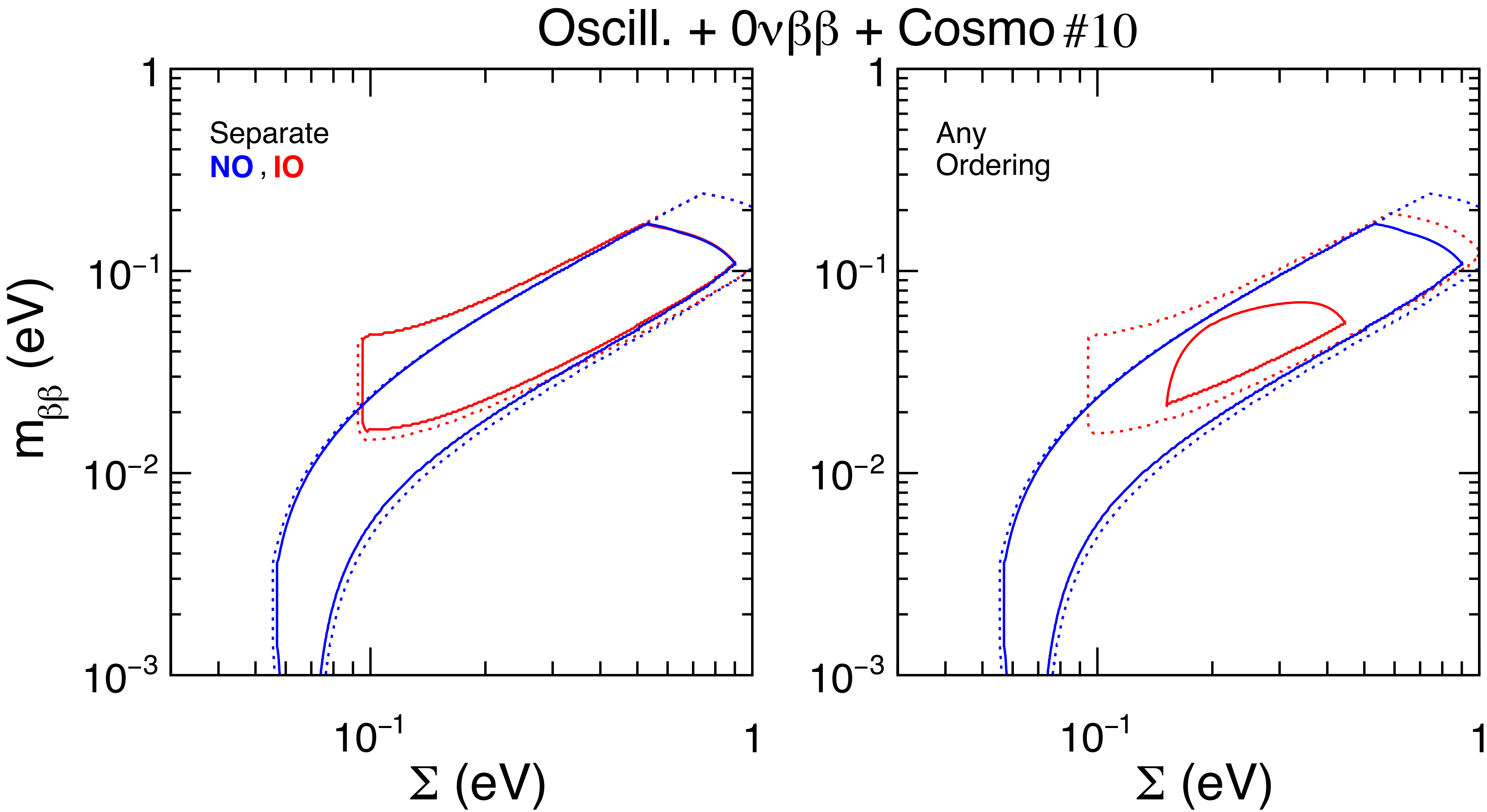
Grand total: combination of oscillation + nonoscillation data

(with increasingly strong cosmological constraints)



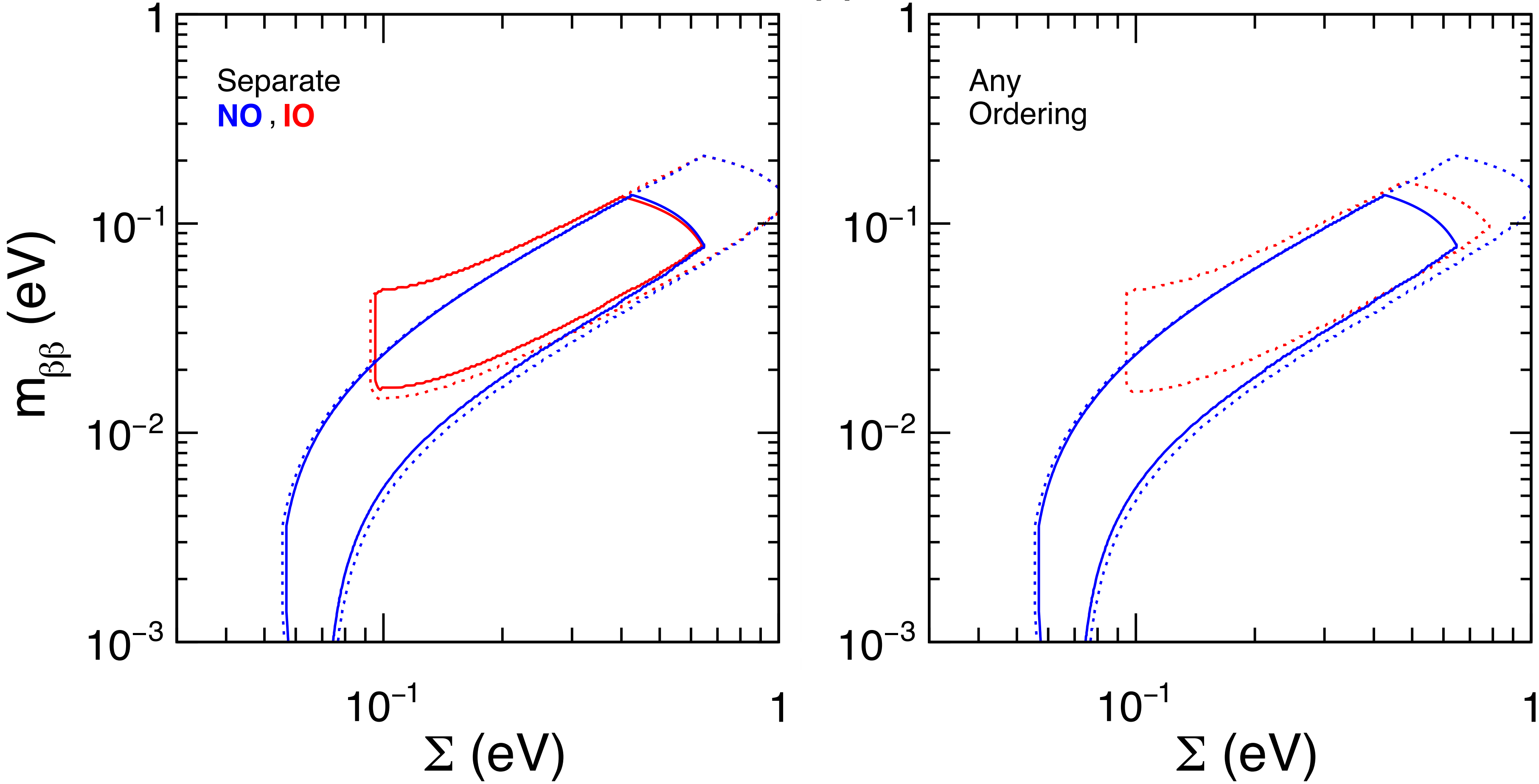


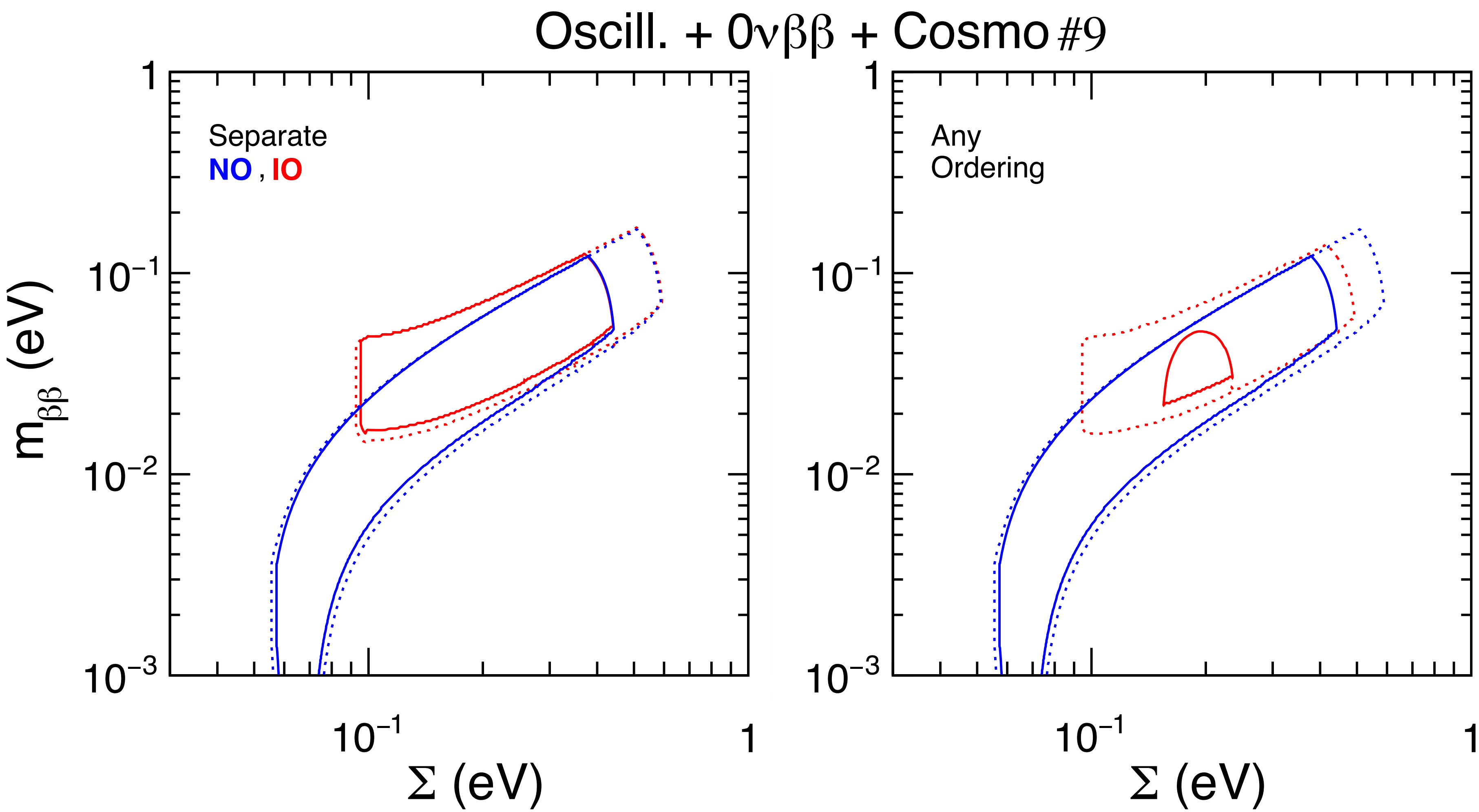
Oscill. + 0νββ
Separate
NO , IO
Any
Ordering
1
10−1
10−2
10−3
mββ (eV)
10−1
1
Σ (eV)



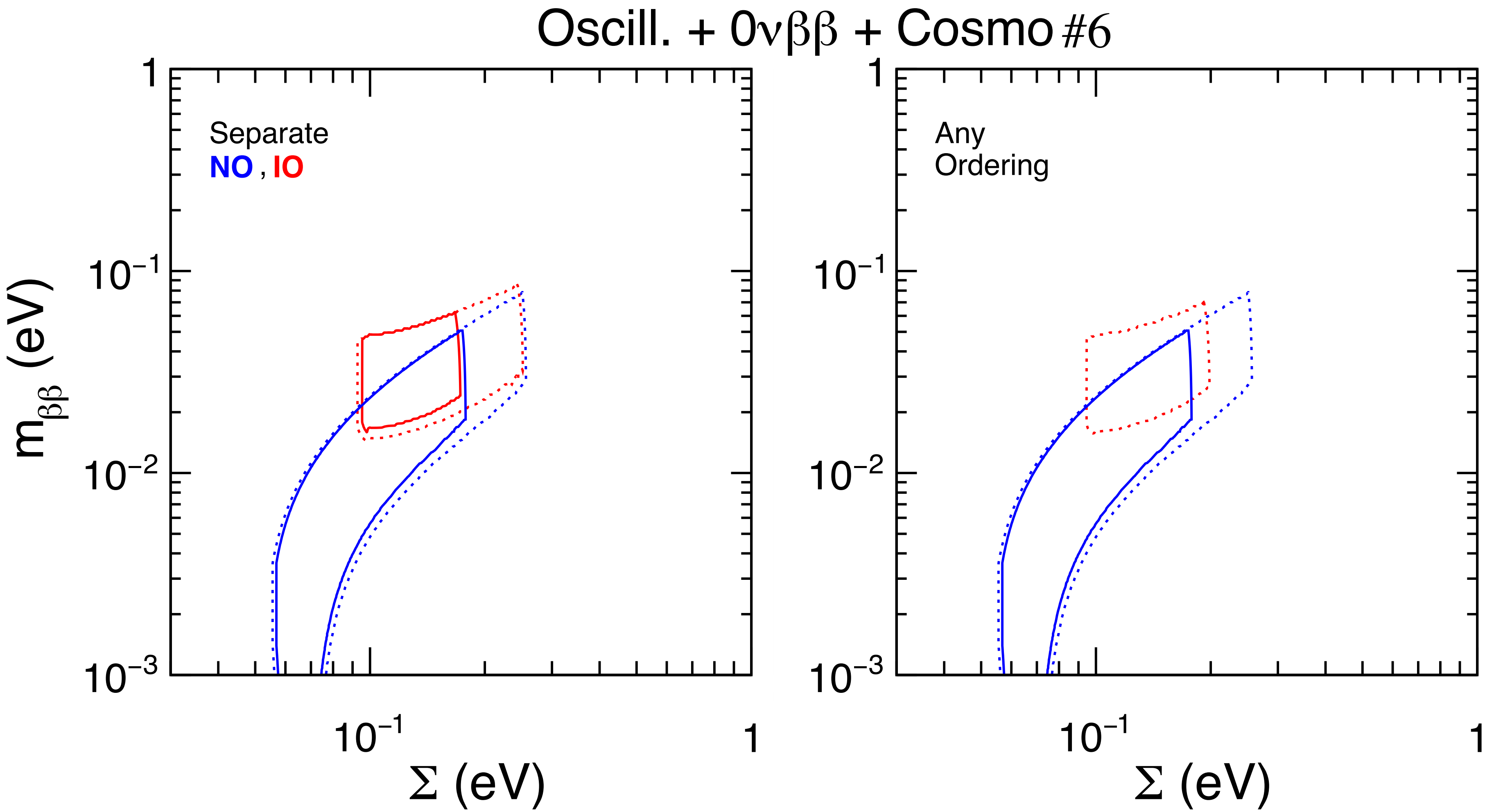
[Case with "conservative" bounds from cosmology]

Oscill. + 0νββ + Cosmo #1





[RHS plot (inner red curve) shows how a cosmological "claim" of **Σ>0** could look like]



[Case with "aggressive" bounds from cosmology]

Grand total of IO-NO differences:

	LBL+Sol+KL		+SBL Reac		+Atmos		+DBD, Cosmo
$\Delta\chi^2$ (IO-NO)	+1.1	⇨	+1.1	⇨	+3.6	⇨	+3.6 ... +4.4

Small but coherent steps: **N.O. favored**... Overall preference at $1.9\sigma - 2.1\sigma$

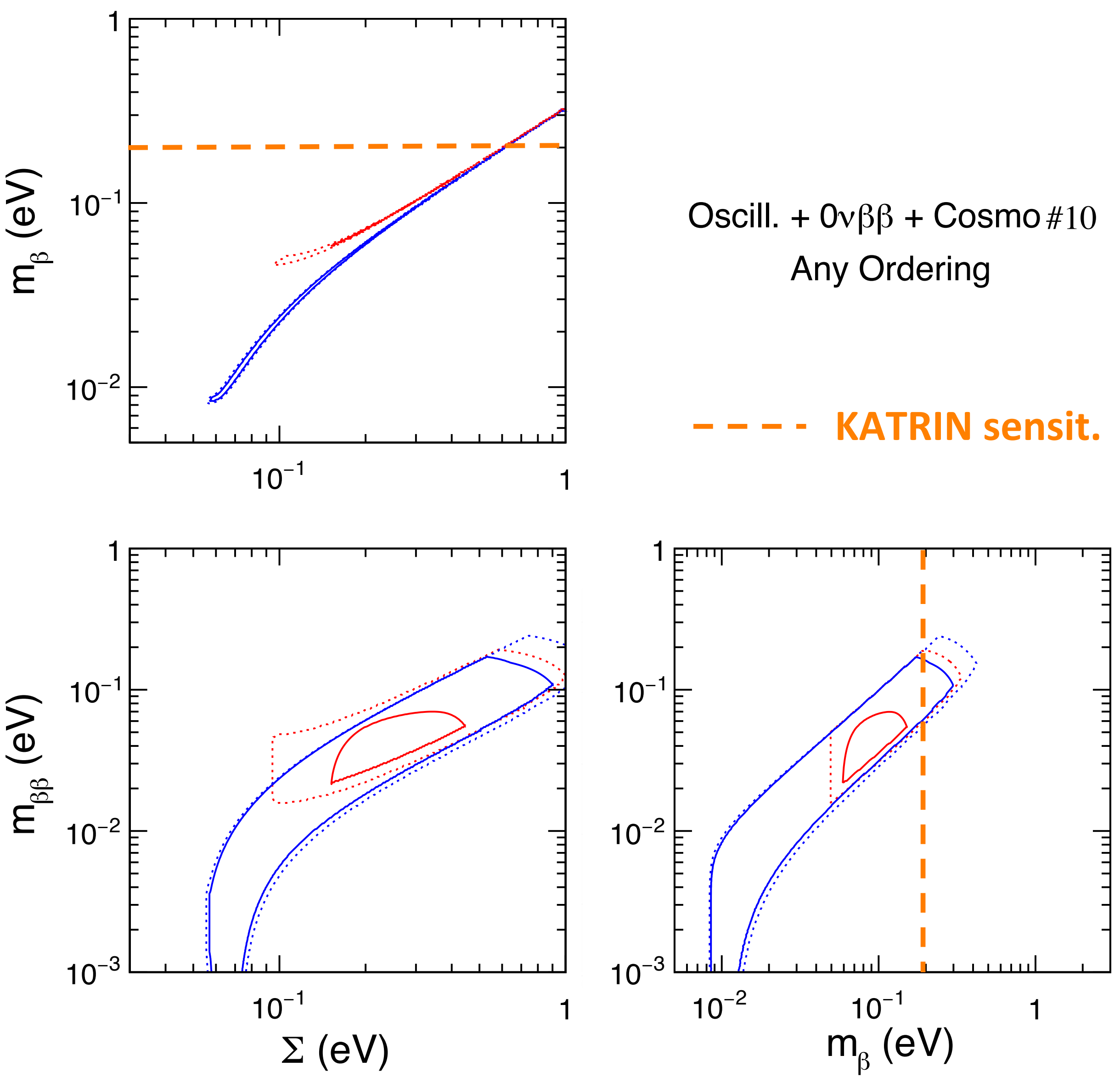
TABLE III: Values of $\Delta\chi^2_{\mathrm{IO-NO}}$ from the global analysis of oscillation and non oscillation data (numbered according to the adopted cosmological datasets as in Table II), to be compared with the value 3.6 from oscillation data only [Eq. (9)]. An overall preference emerges for NO,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

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

The statistical significance of possible hints about ordering is currently debated.
If they are not fluctuations, expect (fractional) improvements in upcoming years
Dedicated projects are planned with reactor, atmospheric, accelerator neutrinos

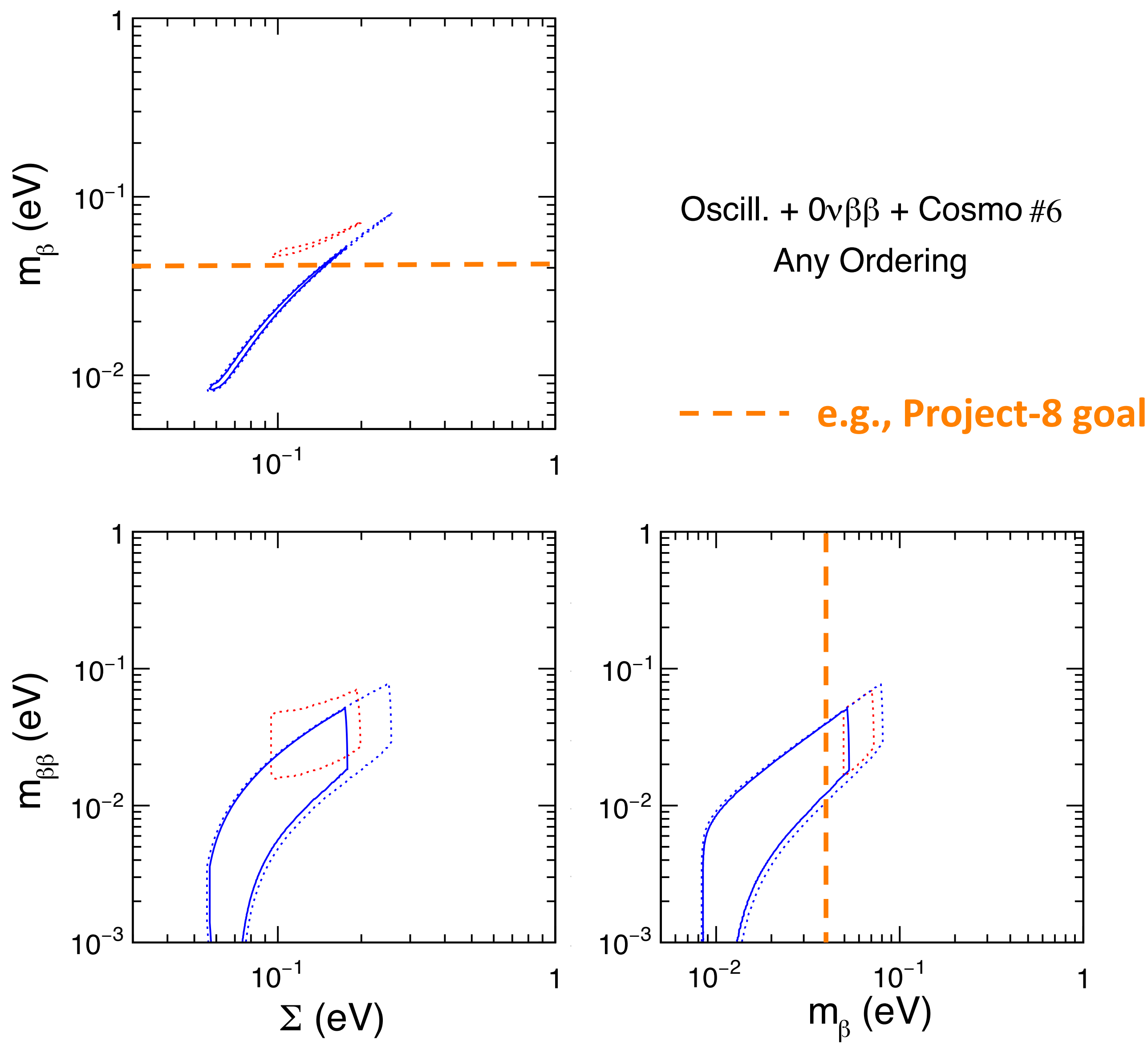
Implications for β-decay (weak cosmo bounds)

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$



Implications for β-decay (strong cosmo bounds)

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$



SUMMARY

- **Status of known 3ν oscillation parameters:**
  Precision era (but PMNS accuracy far from CKM)

- **Trends of unknown oscillation parameters:**
  Favoring **CPV** with $\sin\delta<0$, nonmax θ_{23}, and NO

- **Status of constraints from $0\nu\beta\beta$ & Cosmology:**
  Sub-eV sensitivity; Cosmo analysis with NO vs IO

- **Oscillation + nonoscillation global analysis:**
  Corroborates **NO with respect to IO** at $\sim2\sigma$ level

PROSPECTS - oscillations

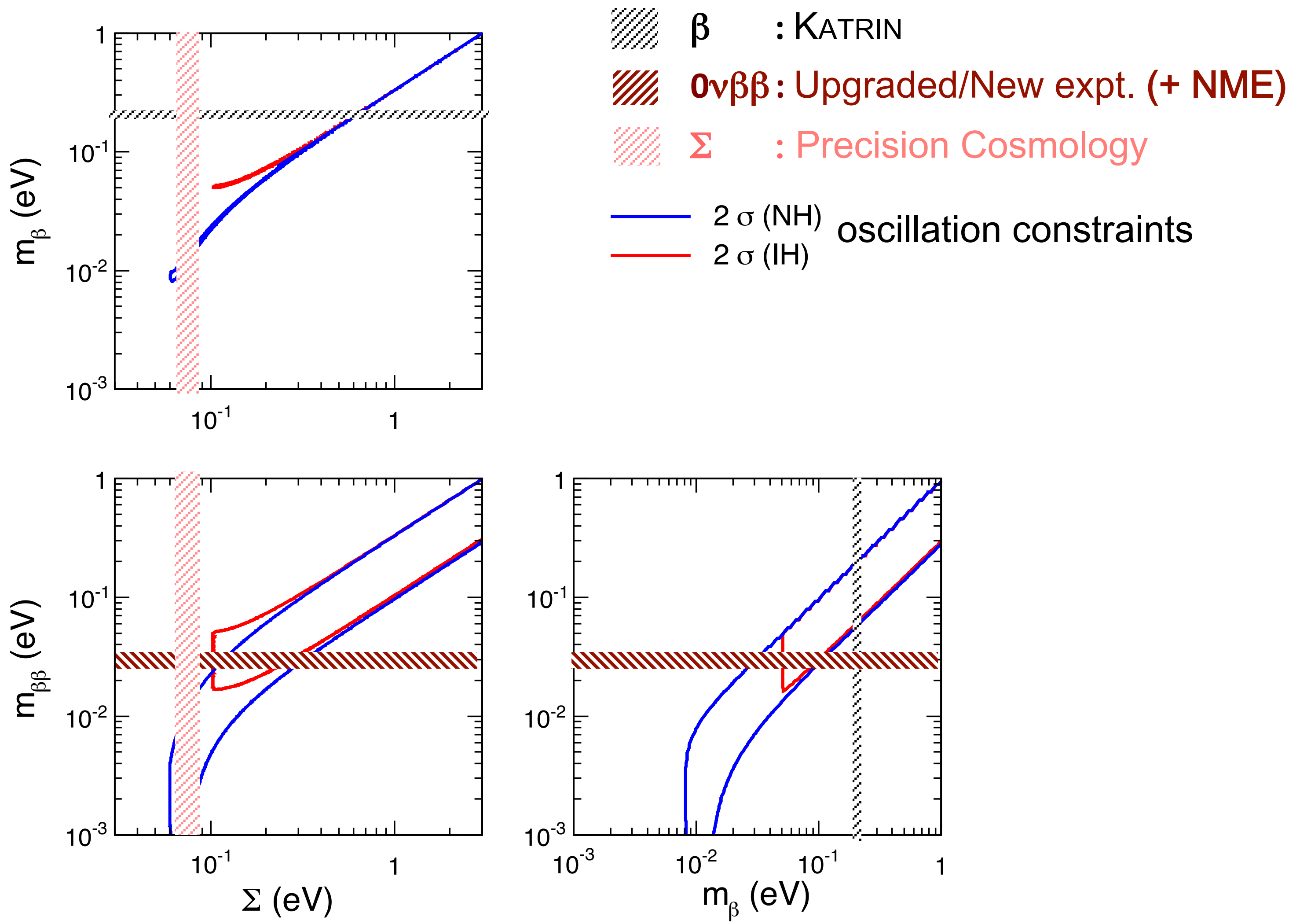
- **Known 3ν oscillation parameters:**
  Higher accuracy with LBL acceler., JUNO react. + others

- **CPV:**
  If **sinδ ~ -1**, then **T2K+NOvA may probe CPV** at ~3σ
  Higher C.L. requires future LBL acc. (DUNE, Hyper-K)

- **Hierarchy:**
  Expect progress from T2K+NOvA and future expts:
  JUNO reactor, LBL acceler., Large-volume atmospheric

- **Octant of θ_{23} (if significantly nonmaximal):**
  Lifting degeneracy **possible, but not easy** at high CL

Non-oscillations: Upper limits on m_β, $m_{\beta\beta}$, Σ in ~10 years ?

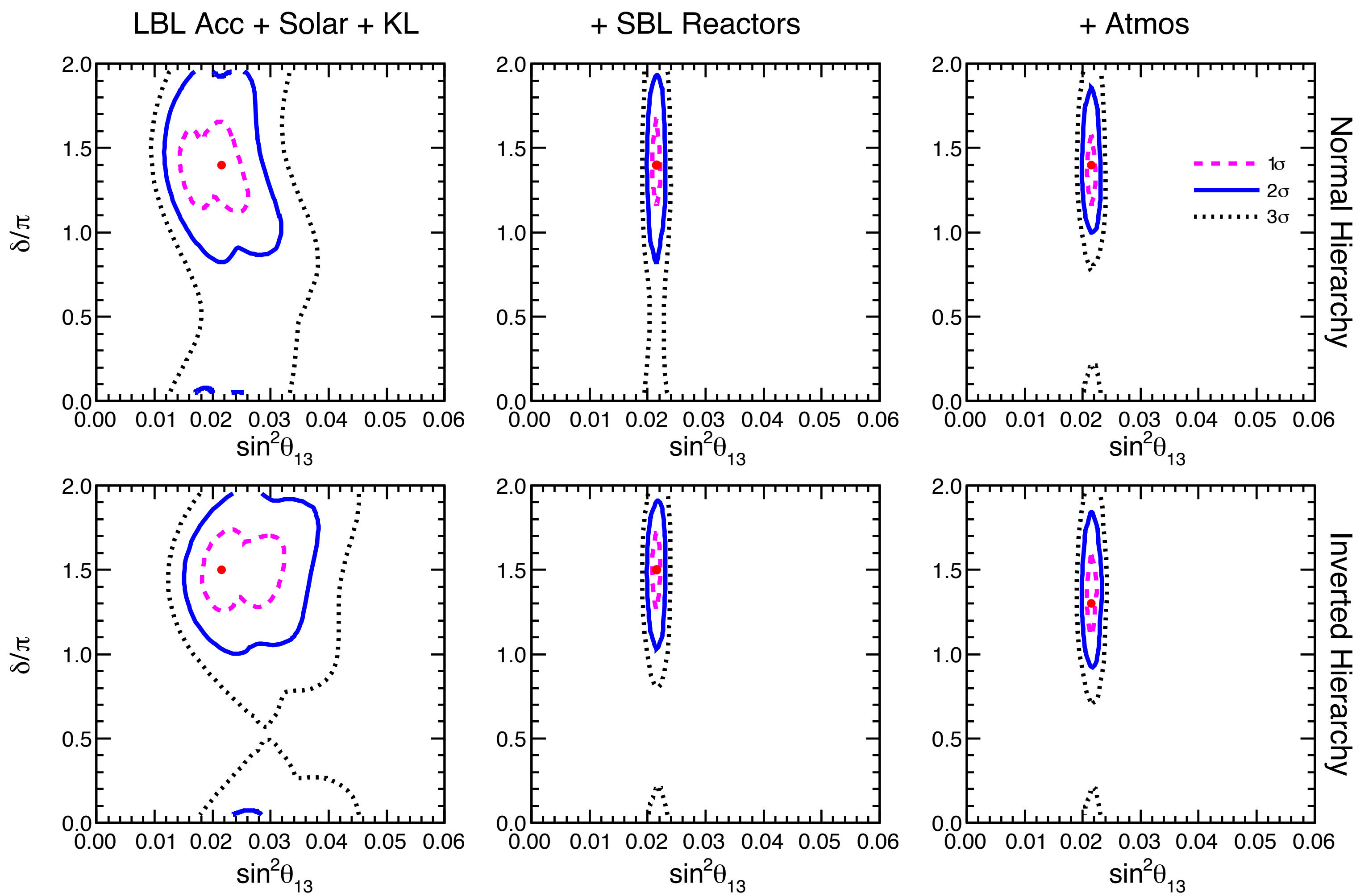


Large phase space for discoveries... and surprises (beyond 3ν?)

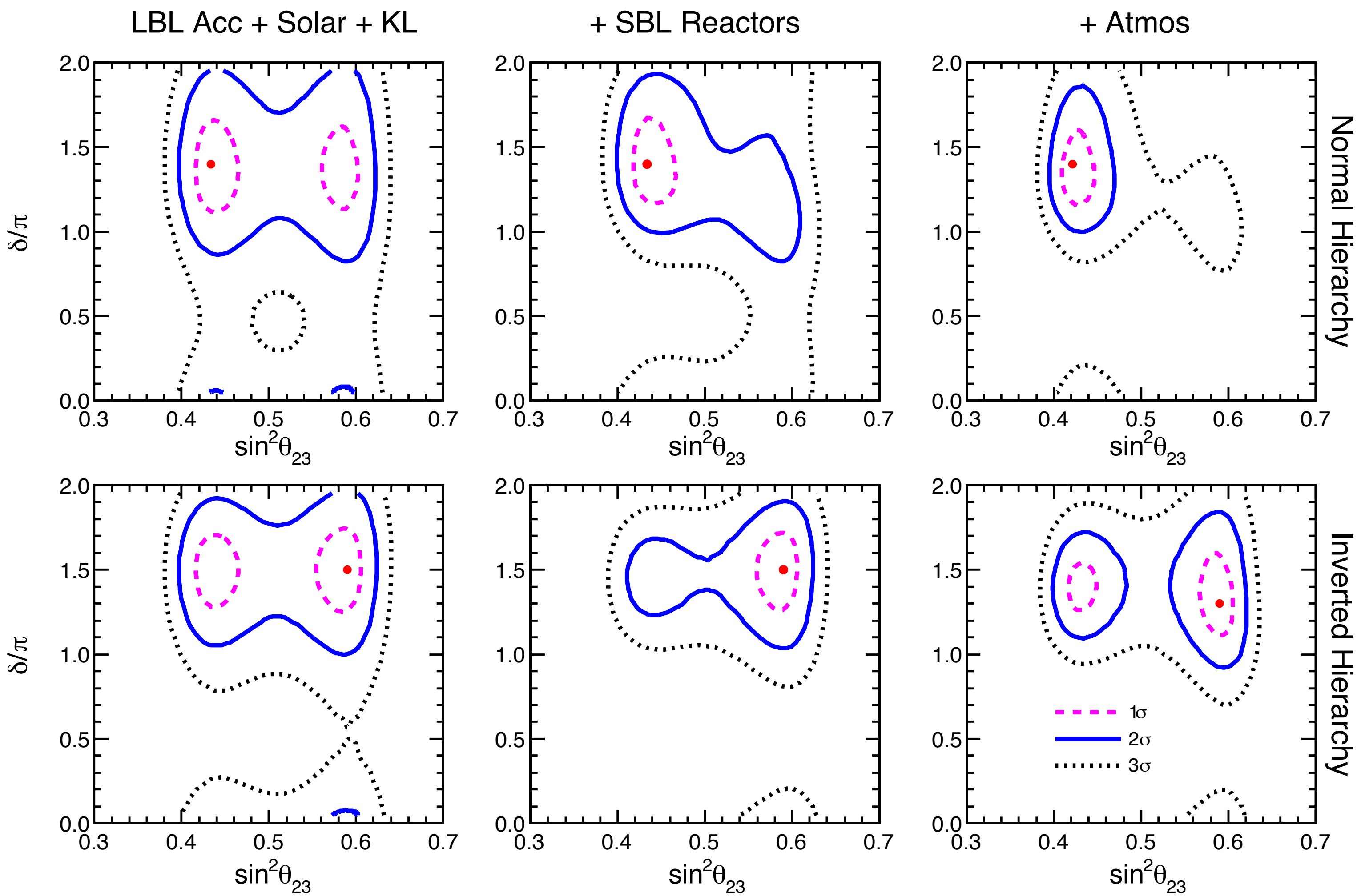
Thank you for your attention

Extra slides

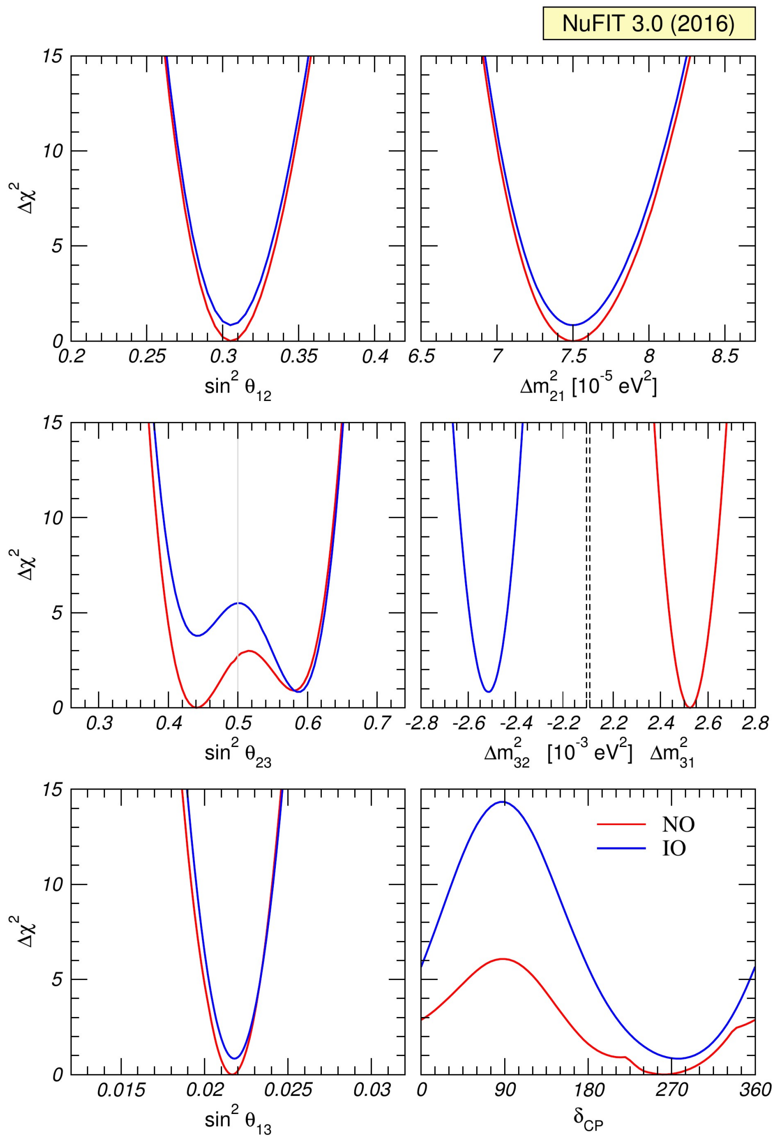
Supplementary to arXiv:1703.04471



Supplementary to arXiv:1703.04471



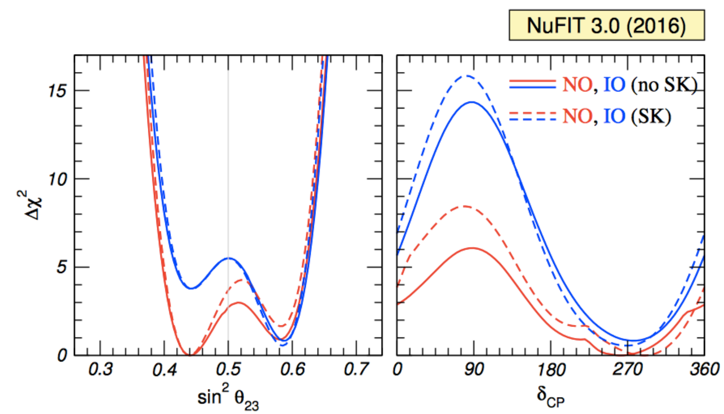
NuFIT: I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, T. Schwetz



← All – SK atmospheric

All + SK atmospheric

↓



arXiv:1611.01514

Bayesian...

arXiv:1703.03425v2 [astro-ph.CO] 4 Jun 2017

Strong Bayesian Evidence for the Normal Neutrino Hierarchy

Fergus Simpson,[1] Raul Jimenez,[1,2] Carlos Pena-Garay,[3,4] Licia Verde[1,2]

[1]ICCUB, University of Barcelona (UB-IEEC), Marti i Franques 1, Barcelona, 08028, Spain.
[2]ICREA, Pg. Lluis Companys 23, Barcelona, 08010, Spain.
[3]I2SysBio, CSIC-UVEG, P.O. 22085, Valencia, 46071, Spain.
[4]LSC, Estación de Canfranc, 22880, Spain.

E-mail: fergus2@gmail.com; raul.jimenez@icc.ub.edu; liciaverde@icc.ub.edu; penagaray@gmail.com;

Abstract. The configuration of the three neutrino masses can take two forms, known as the normal and inverted hierarchies. We compute the Bayesian evidence associated with these two hierarchies. Previous studies found a mild preference for the normal hierarchy, and this was driven by the asymmetric manner in which cosmological data has confined the available parameter space. Here we identify the presence of a second asymmetry, which is imposed by data from neutrino oscillations. By combining constraints on the squared-mass splittings [1] with the limit on the sum of neutrino masses of $\Sigma m_\nu < 0.13$ eV [2], and using a minimally informative prior on the masses, we infer odds of 42:1 in favour of the normal hierarchy, which is classified as "strong" in the Jeffreys' scale. We explore how these odds may evolve in light of higher precision cosmological data, and discuss the implications of this finding with regards to the nature of neutrinos. Finally the individual masses are inferred to be $m_1 = 3.80^{+26.2}_{-3.73}$ meV; $m_2 = 8.8^{+18}_{-1.2}$ meV; $m_3 = 50.4^{+5.8}_{-1.2}$ meV (95% credible intervals).

Bayesian...

arXiv:1703.04585v1 [astro-ph.CO] 14 Mar 2017

Comment on "Strong Evidence for the Normal Neutrino Hierarchy"

T. Schwetz,[a] K. Freese,[b,c] M. Gerbino,[b] E. Giusarma,[d] S. Hannestad,[e] M. Lattanzi,[f] O. Mena,[g] S. Vagnozzi[b]

[a]Institut für Kernphysik, Karlsruhe Institute of Technology, 76021 Karlsruhe, Germany
[b]Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, SE-10691 Stockholm, Sweden
[c]Michigan Center for Theoretical Physics, Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA
[d]McWilliams Center for Cosmology, Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213, USA; Lawrence Berkeley National Laboratory (LBNL), Physics Division, Berkeley, CA 94720-8153, USA; Berkeley Center for Cosmological Physics, University of California, Berkeley, CA 94720, USA
[e]Department of Physics and Astronomy, Aarhus University, Ny Munkegade, DK-8000 Aarhus C, Denmark
[f]Instituto Nazionale di Fisica Nucleare (INFN), Sezione di Ferrara, I-44122 Ferrara, Italy
[g]Instituto de Fisica Corpuscular (IFIC), Universidad de Valencia-CSIC, E-46980, Valencia, Spain

E-mail: schwetz@kit.edu, martina.gerbino@fysik.su.se

Abstract. In the preprint arxiv:1703.03425 "strong evidence" for the normal neutrino mass ordering is claimed. The authors obtain Bayesian odds of 42:1 in favour of the normal ordering. Their conclusion is based on adopting a flat logarithmic prior for the three neutrino masses. Such an assumption favours a hierarchical spectrum for the masses, which is much easier to accommodate for the normal mass ordering, and hence their prior assumption makes the inverted ordering much less likely *a priori*. We argue that the claimed "evidence" for normal ordering is almost entirely driven by the adopted prior and not due to the data itself.

Frequentist...

arXiv:1703.10829v1 [astro-ph.CO]

Cosmological constraints on the neutrino mass including systematic uncertainties

F. Couchot[1], S. Henrot-Versillé*[1], O. Perdereau[1], S. Plaszczynski[1], B. Rouillé d'Orfeuil[1], M. Spinelli[1,2], and M. Tristram[1]

[1] Laboratoire de l'Accélérateur Linéaire, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
[2] Department of Physics and Astronomy, University of the Western Cape, Robert Sobukwe Road, Bellville 7535, South Africa

April 3, 2017

Abstract

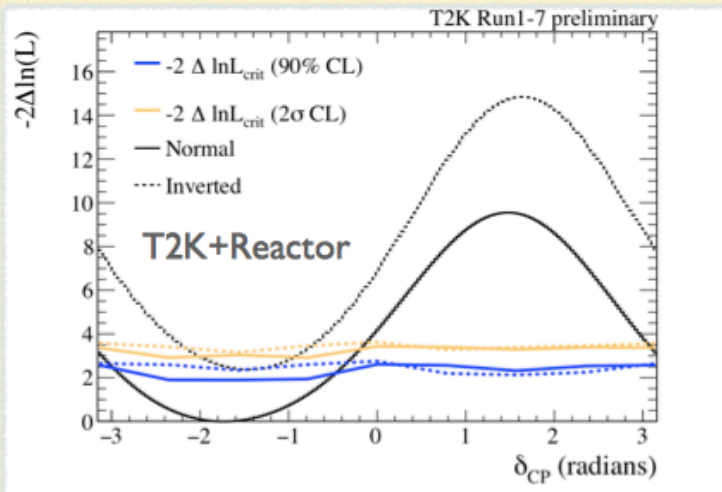
When combining cosmological and oscillations results to constrain the neutrino sector, the question of the propagation of systematic uncertainties is often raised. We address it in the context of the derivation of an upper bound on the sum of the neutrino masses (Σm_ν) with recent cosmological data. This work is performed within the ΛCDM model extended to Σm_ν, for which we advocate the use of three mass-degenerate neutrinos. We focus on the study of systematic uncertainties linked to the foregrounds modelling in CMB data analysis, and on the impact of the present knowledge of the reionisation optical depth. This is done through the use of different likelihoods, built from PLANCK data. Limits on Σm_ν are derived with various combinations of data, including latest BAO and SNIa results. We also discuss the impact of the preference of current CMB data for amplitudes of the gravitational lensing distortions higher than expected within the ΛCDM model, and add the PLANCK CMB lensing. We then derive a robust upper limit: $\Sigma m_\nu < 0.17$ eV at 95% CL, including 0.01 eV of foreground systematics. We also discuss the neutrino mass repartition and show that today's data do not allow to disentangle normal from inverted hierarchy. The impact on the other cosmological parameters is also reported, for different assumptions on the neutrino mass repartition, and different high and low multipoles CMB likelihoods.

... and more ...

... debated topic in cosmology!

T2K, A. Izmaylov at Neutrino Telescopes 2017 in Venice

ANALYSIS RESULTS: θ_{13} AND δ_{CP}



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

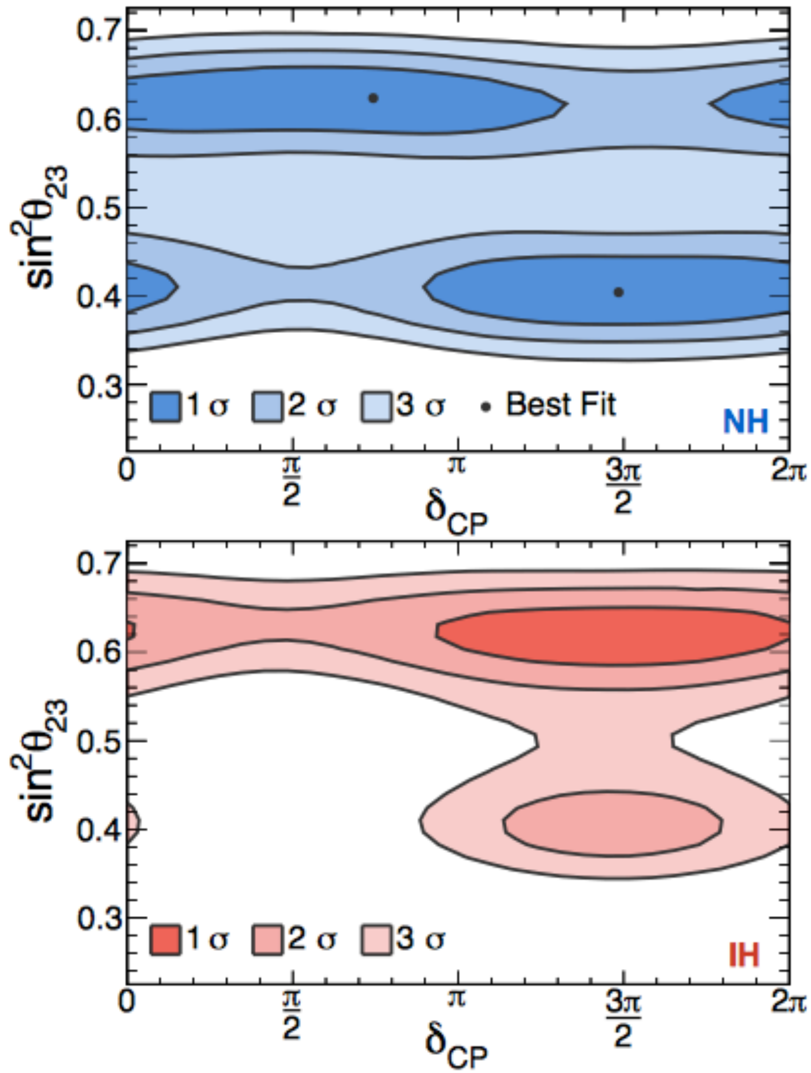
- Exclude sin(δ_{CP})=0 at 90% C.L.
- Observed events favour large CPV (δ_{CP} ≈-π /2) and normal mass hierarchy
- Data implies more CPV → stronger limits than expected
  - "Statistical fluctuation"? → need further data

ν_μ -> ν_e Oscillation Results

- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - Constrain $\sin^2 2\theta_{13} = 0.085 \pm 0.005$ from reactor experiments
  - Simultaneous fit NOvA disappearance data
- Global best fit, two degenerate points in Normal Hierarchy

$$\delta_{cp} = 1.48\pi, \sin^2(\theta_{23}) = 0.404$$
$$\delta_{cp} = 0.74\pi, \sin^2(\theta_{23}) = 0.623$$

  - best fit IH-NH, $\Delta\chi2=0.47$
  - Lower octant, IH is disfavoured at greater than 93% C.L for all values of δ_{CP}



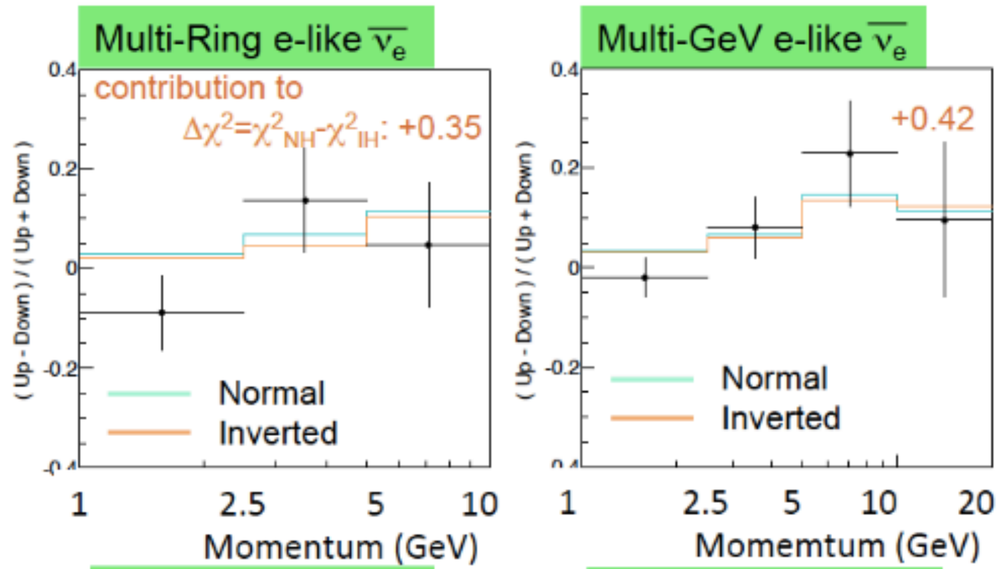
arXiv:1703.03328

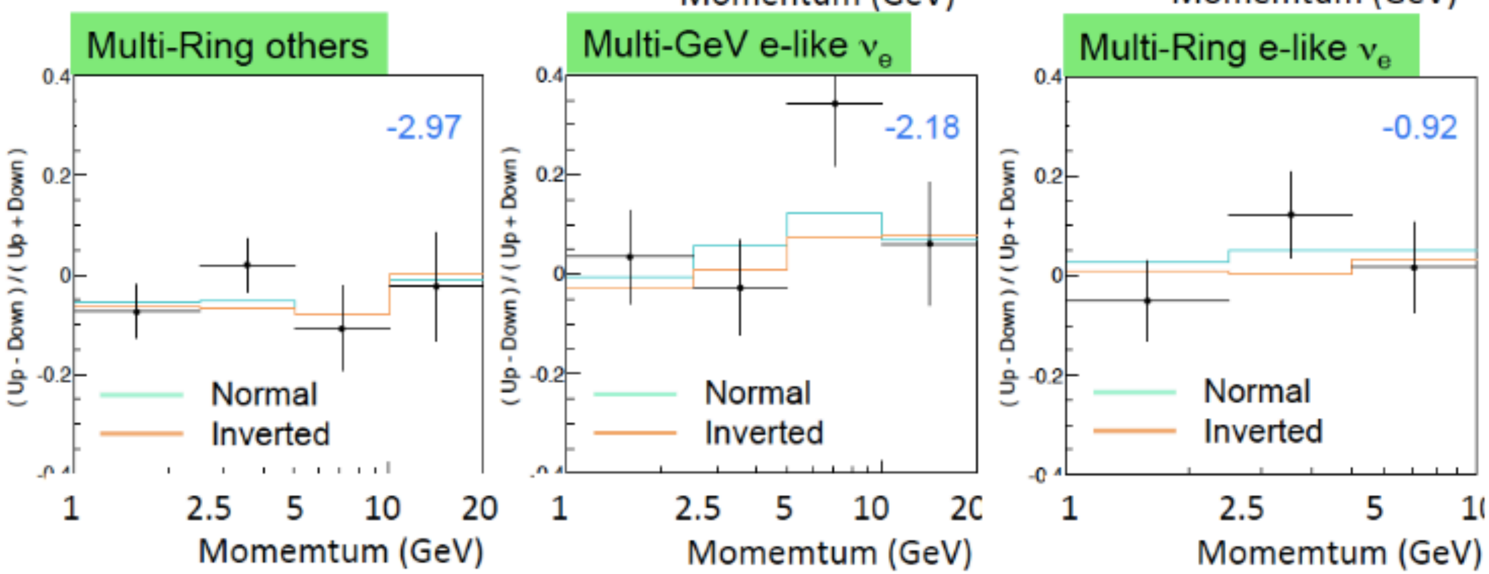
Super-Kamiokande atmospheric: E. Kearns at APS 2017 April Meeting

Hierarchy Sensitive Samples

$$\frac{\text{UP-DOWN}}{\text{UP+DOWN}}$$

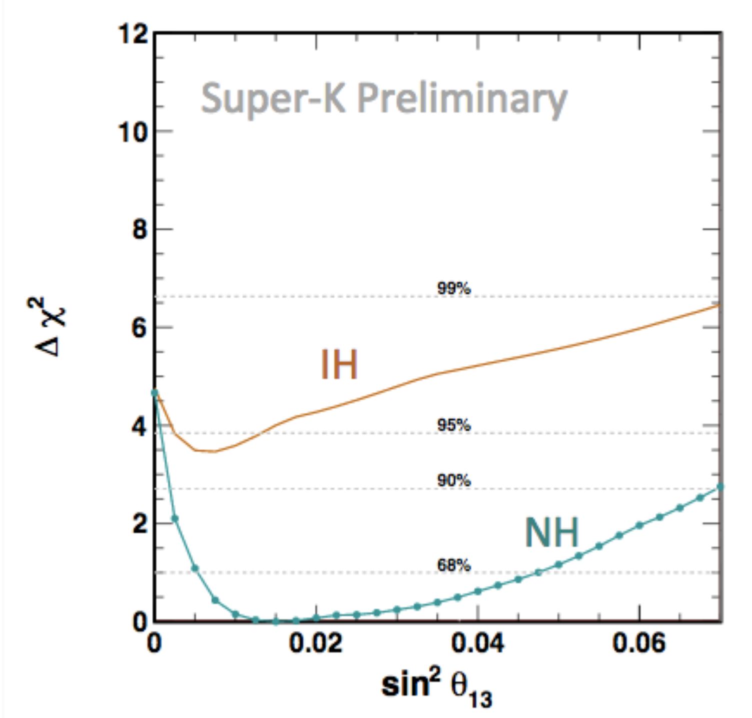
as a func. of p

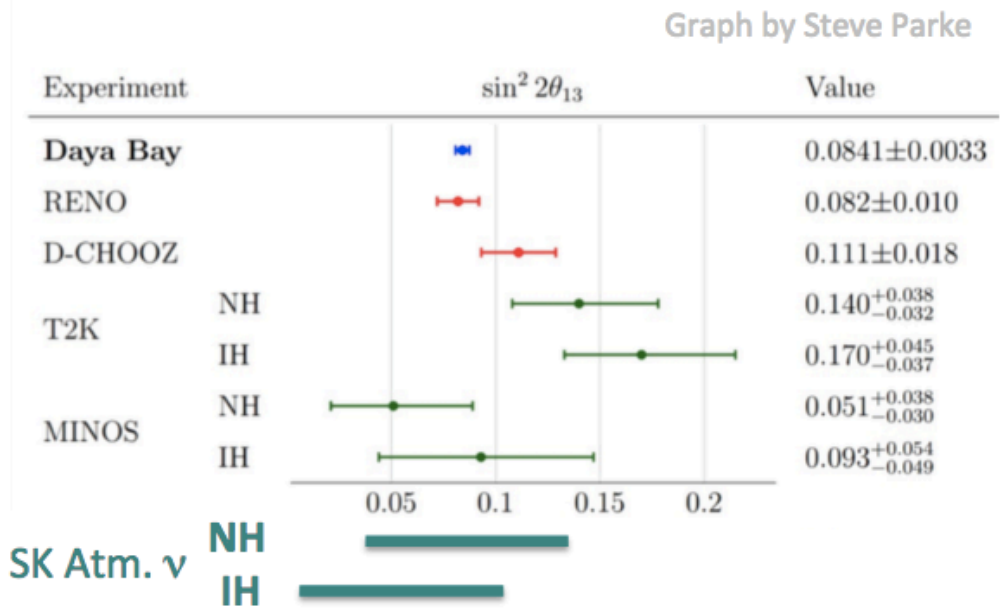




Super-Kamiokande atmospheric: E. Kearns at APS 2017 April Meeting

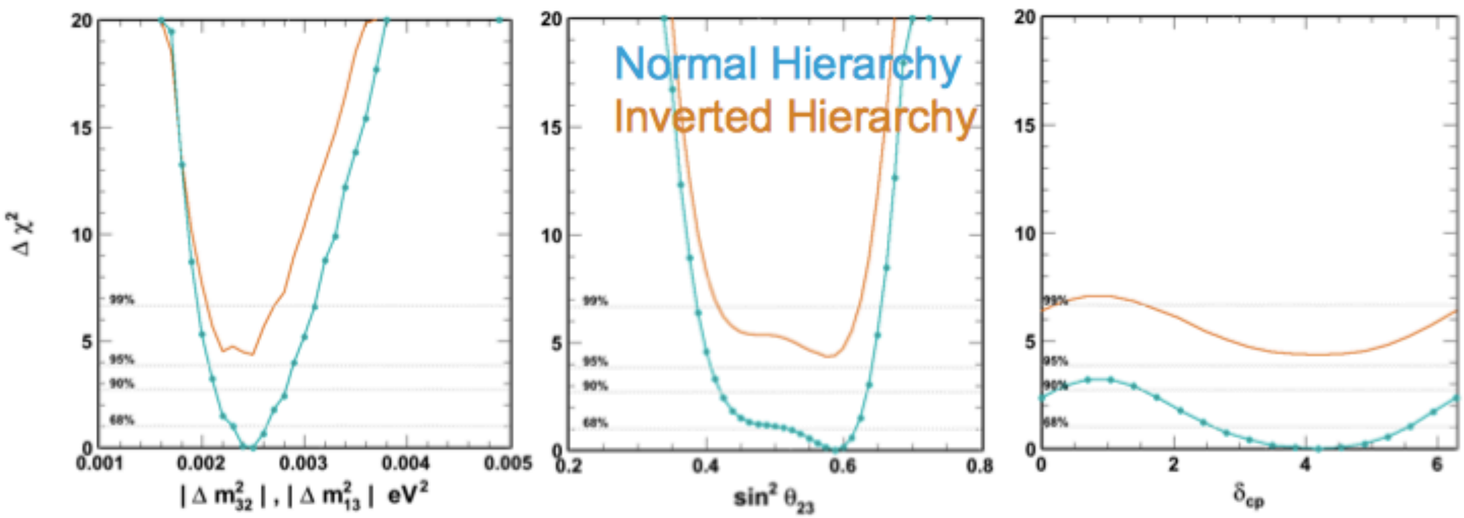
θ_{13} Free – Atm. ν only





Super-Kamiokande, M. Shiozawa at Neutrino Telescopes 2017 in Venice

Atmν data fit w/ fixed θ_{13}



Fit (517 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert eV^2$
SK (IH)	576.08	0.0219 (fix)	4.189	0.575	2.5×10^{-3}
SK (NH)	571.74	0.0219 (fix)	4.189	0.587	2.5×10^{-3}

- Mass hierarchy: $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -4.3$ (-3.1 expected)
- Under IH hypothesis, the probability to obtain -4.3 or less is 3.1% ($\sin^2\theta_{23}$=0.6) and 0.7%($\sin^2\theta_{23}$=0.4).
- Under NH hypothesis, it is as large as 45% ($\sin^2\theta_{23}$=0.6)

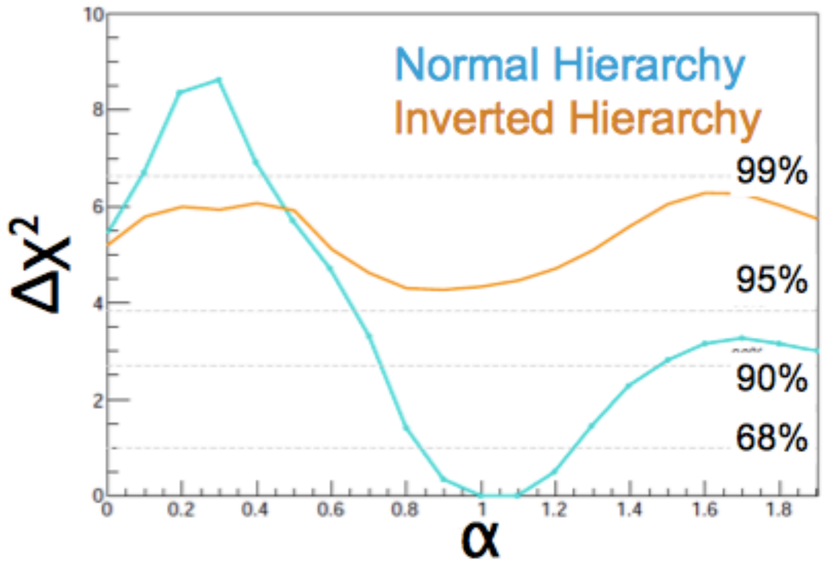
Super-Kamiokande, M. Shiozawa at Neutrino Telescopes 2017 in Venice

Matter effect fit

$$H_{\text{matter}} = \begin{pmatrix} \frac{m_1^2}{2E} & 0 & 0 \\ 0 & \frac{m_2^2}{2E} & 0 \\ 0 & 0 & \frac{m_3^2}{2E} \end{pmatrix} + U^\dagger \begin{pmatrix} \alpha a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} U$$

α: scale factor

a=sqrt(2) $G_f N_e$



- Best fit α=1 for NH, consistent w/ standard matter effect
- $\Delta\chi^2$=5.2 for α=0, Data disfavors zero matter-effect by >2σ

MSW amplitude in solar+reactor data: G.L. Fogli and E. Lisi, New J.Phys. 6 (2004) 139