ν mass spectrum and PMNS mixing: A review

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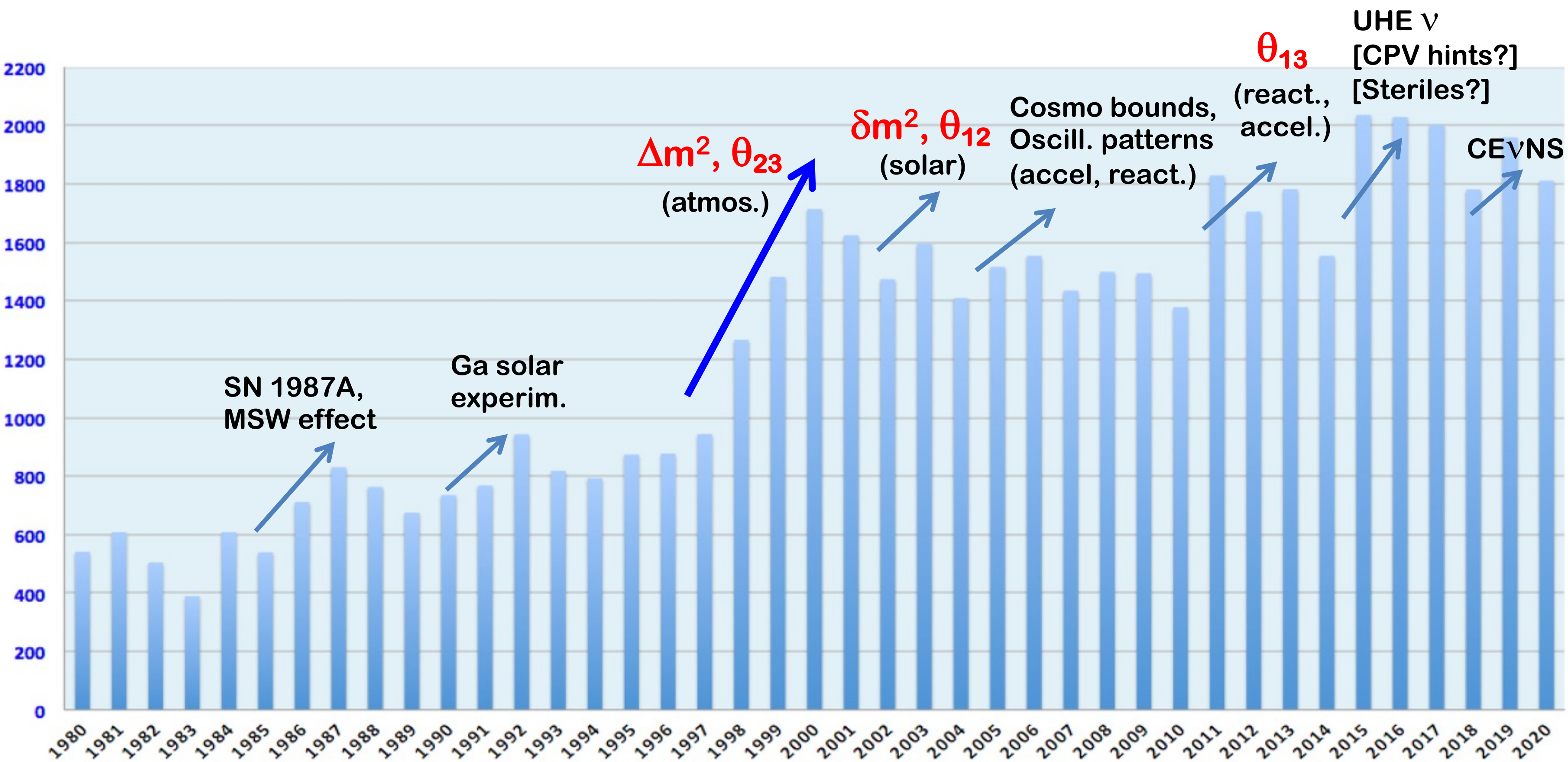
LTPC 2021 – 10th Symposium on Large TPCs – Paris, 17 Dec. 2021

Outline:

- Prologue
- 3ν oscillation: knowns and unknowns
- 3ν absolute mass observables
- Epilogue

PROLOGUE

Papers with *neutrino* in the title, 40-yr trend from INSPIRE



~2k papers/year, vast phenomenology, multi-disciplinary aspects

Great achievements and great challenges

The standard 3ν framework: parameters

Mixing matrix: CKM→ PMNS (Pontecorvo-Maki-Nakagawa-Sakata)

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{bmatrix}$$

2-3 rotation

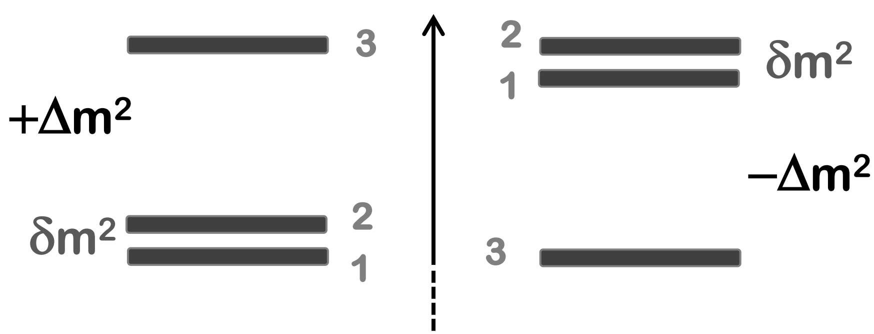
1-3 rotation
+ CPV "Dirac" phase
U(ν) → U*($\overline{\nu}$)

1-2 rotation

Extra CPV phases
[if Majorana]
not tested in oscillat.

Mass [squared] spectrum (E ~ p + m²/2E + "interaction energy")

"Normal" Ordering
N.O.



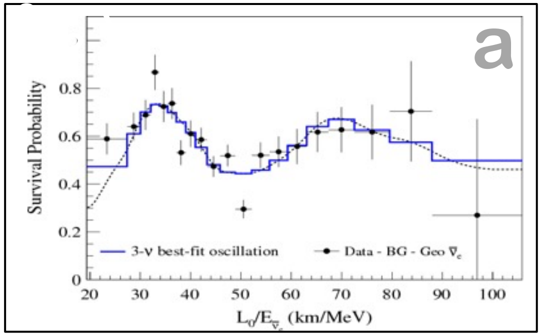
"Inverted" Ordering
I.O.

$$\delta m^2 = \Delta m^2_{21}, \quad \Delta m^2 = (\Delta m^2_{32} + \Delta m^2_{31})/2$$

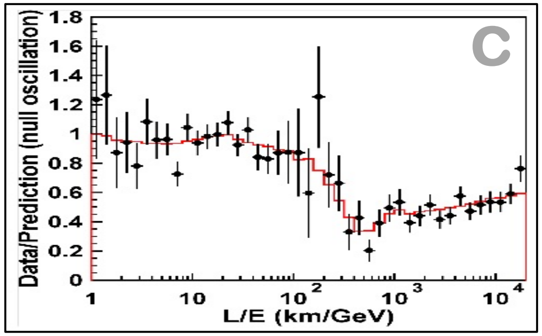
+ interaction energy in matter → ~ $G_F \cdot E \cdot$ density
+ absolute ν mass scale (not tested in oscillations)

Beautiful ν oscillation data have established this 3ν framework...

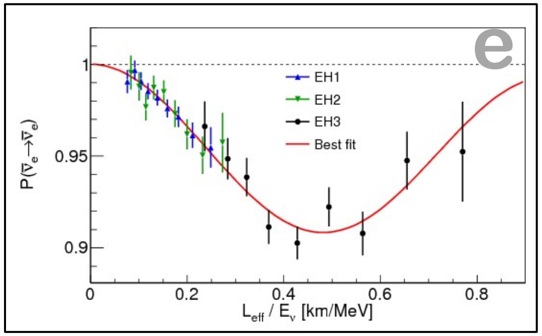
e→e (KamLAND, KL)



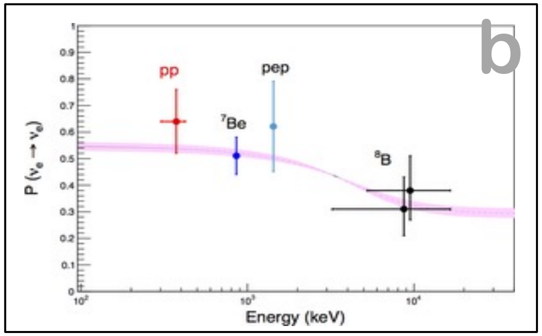
μ→μ (Atmospheric)



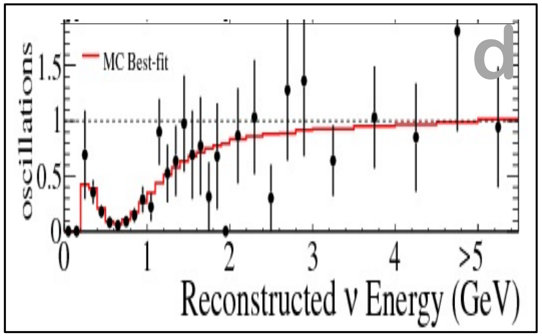
e→e (SBL Reac.)



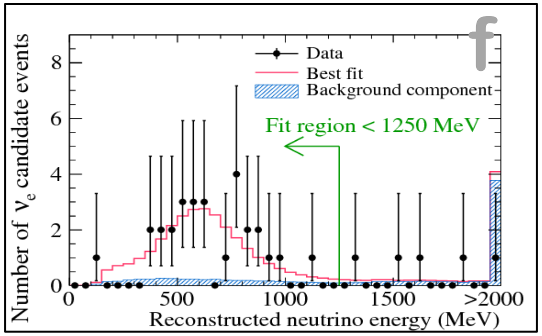
e→e (Solar)



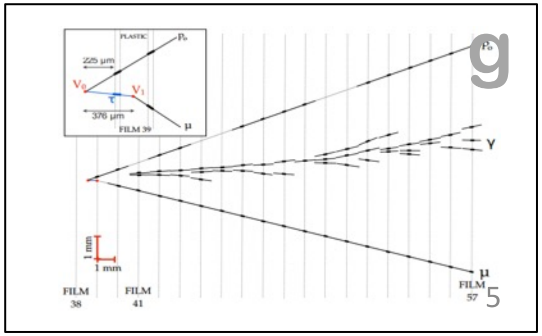
μ→μ (LBL Accel)



μ→e (LBL Accel)



μ→τ (OPERA, SK, DC)

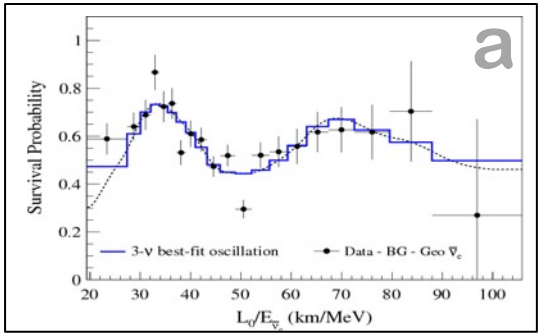


LBL = Long baseline (few x 100 km); **SBL = short baseline** (~1 km)

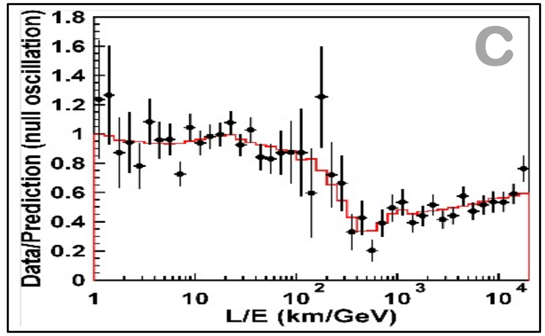
(a) KamLAND reactor [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K LBL accel.; (e) Daya Bay [plot], RENO, Double Chooz SBL reactor; (f) T2K [plot], MINOS, NOvA LBL accel.; (g) OPERA [plot]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

… and consistently measured five ν mass-mixing parameters

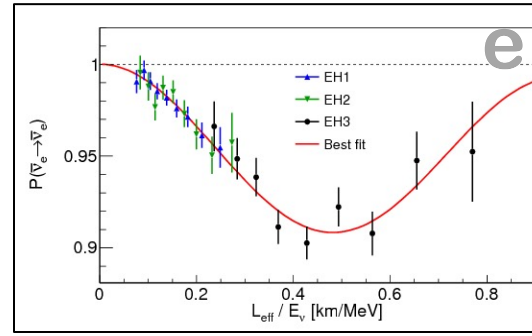
e→e (δm^2 , θ_{12})



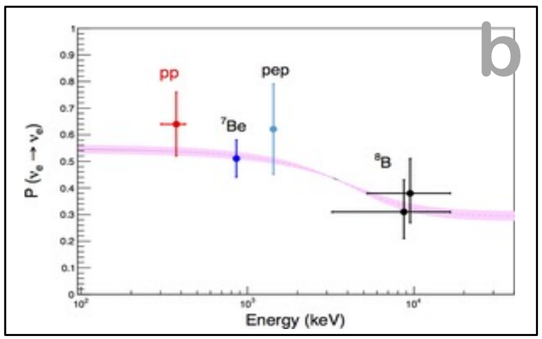
μ→μ (Δm^2 , θ_{23})



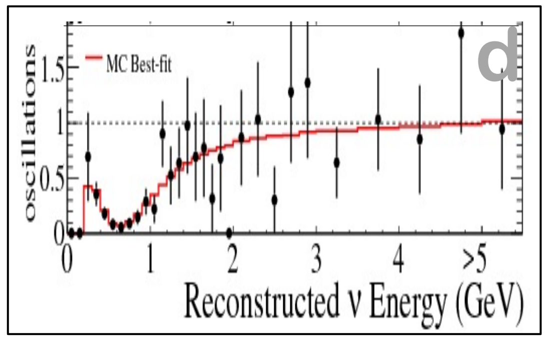
e→e (Δm^2 , θ_{13})



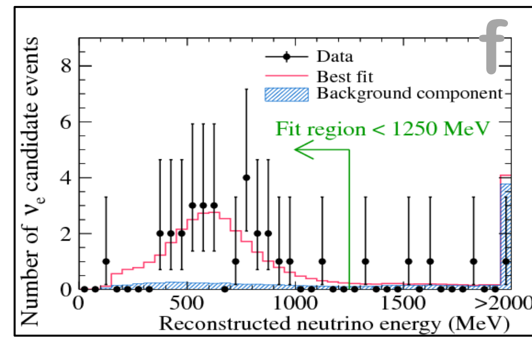
e→e (δm^2 , θ_{12})



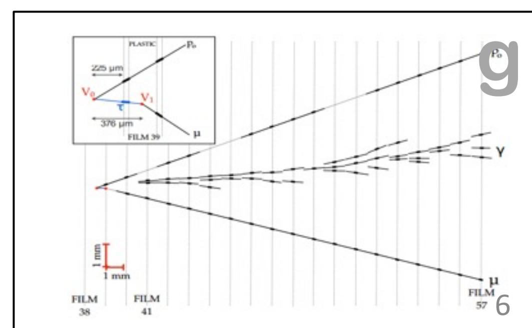
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



μ→τ (Δm^2 , θ_{23})



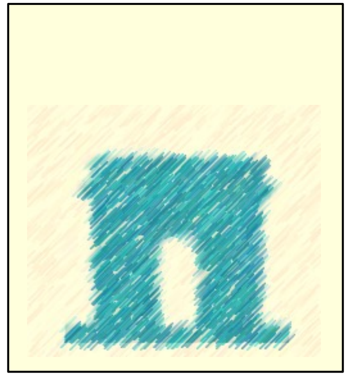
Each leading oscillation parameters (over)constrained by at least two classes of experiments → Consistency

Subleading 3ν effects involve **CPV** and **NO/IO** difference, essentially via $\nu_\mu \to \nu_e$ in LBL accel. and atmosph. expts

Sketchy 3ν picture (1 significant digit)

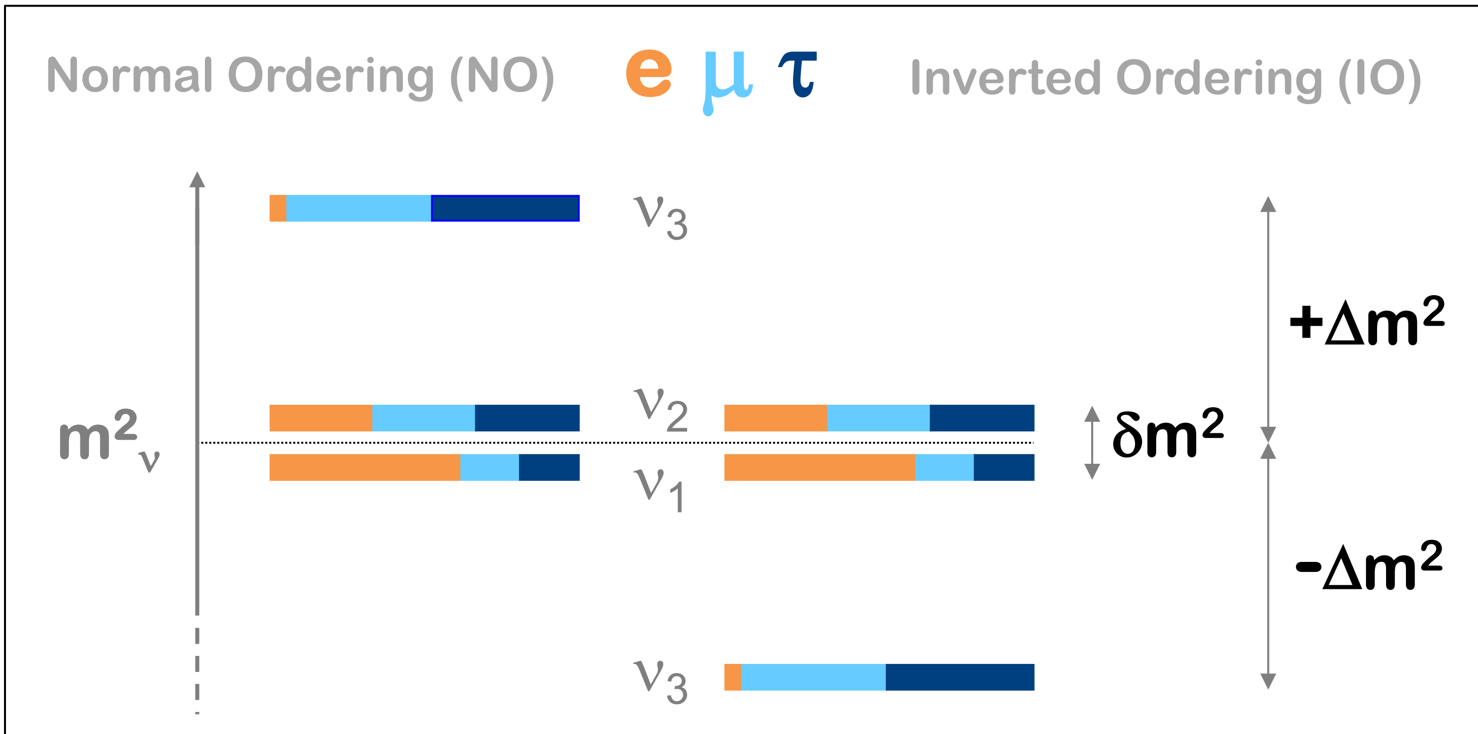
5 knowns:

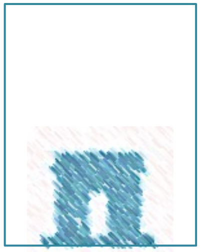
δm^2 ~ 8 x 10^{-5} eV^2
Δm^2 ~ 2 x 10^{-3} eV^2
$\sin^2\theta_{12}$ ~ 0.3
$\sin^2\theta_{23}$ ~ 0.5
$\sin^2\theta_{13}$ ~ 0.02



5 unknowns:

δ **CPV** Dirac phase
sign(Δm^2) → NO/IO
θ_{23} **octant** degeneracy
absolute mass scale
Dirac/Majorana nature





Higher resolut.
& wider picture:
combine info from all ν data

Useful to analyze oscillation data in the following sequence:

LBL Accel + Solar + KL (KamLAND)

minimal set sensitive to all osc. param. δm^2, Δm^2, θ_{13}, θ_{23}, θ_{12}, δ, NO/IO

LBL Accel + Solar + KL + SBL Reactor

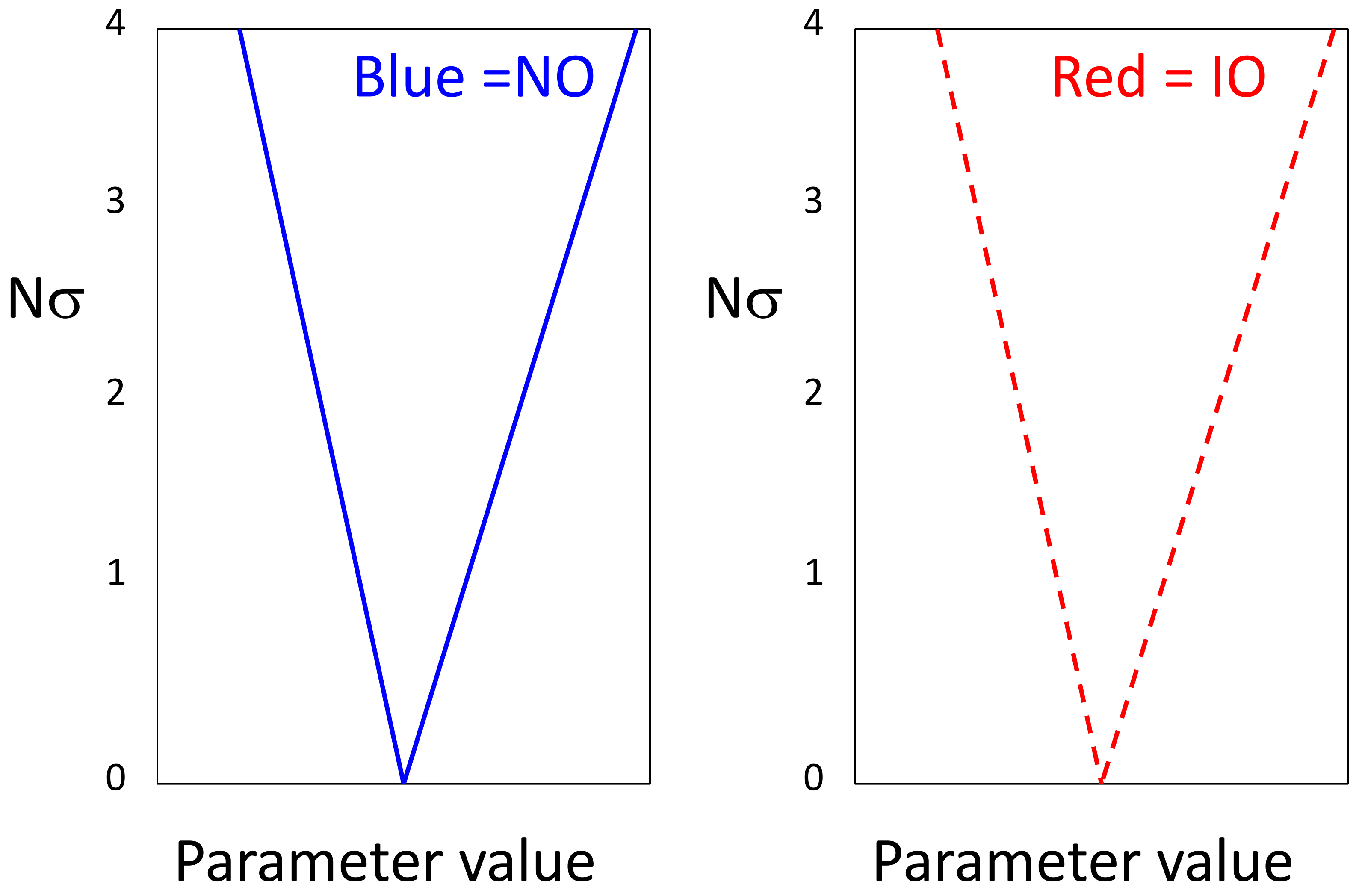
add sensitivity to Δm^2, θ_{13} and affect other parameters via correlations

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

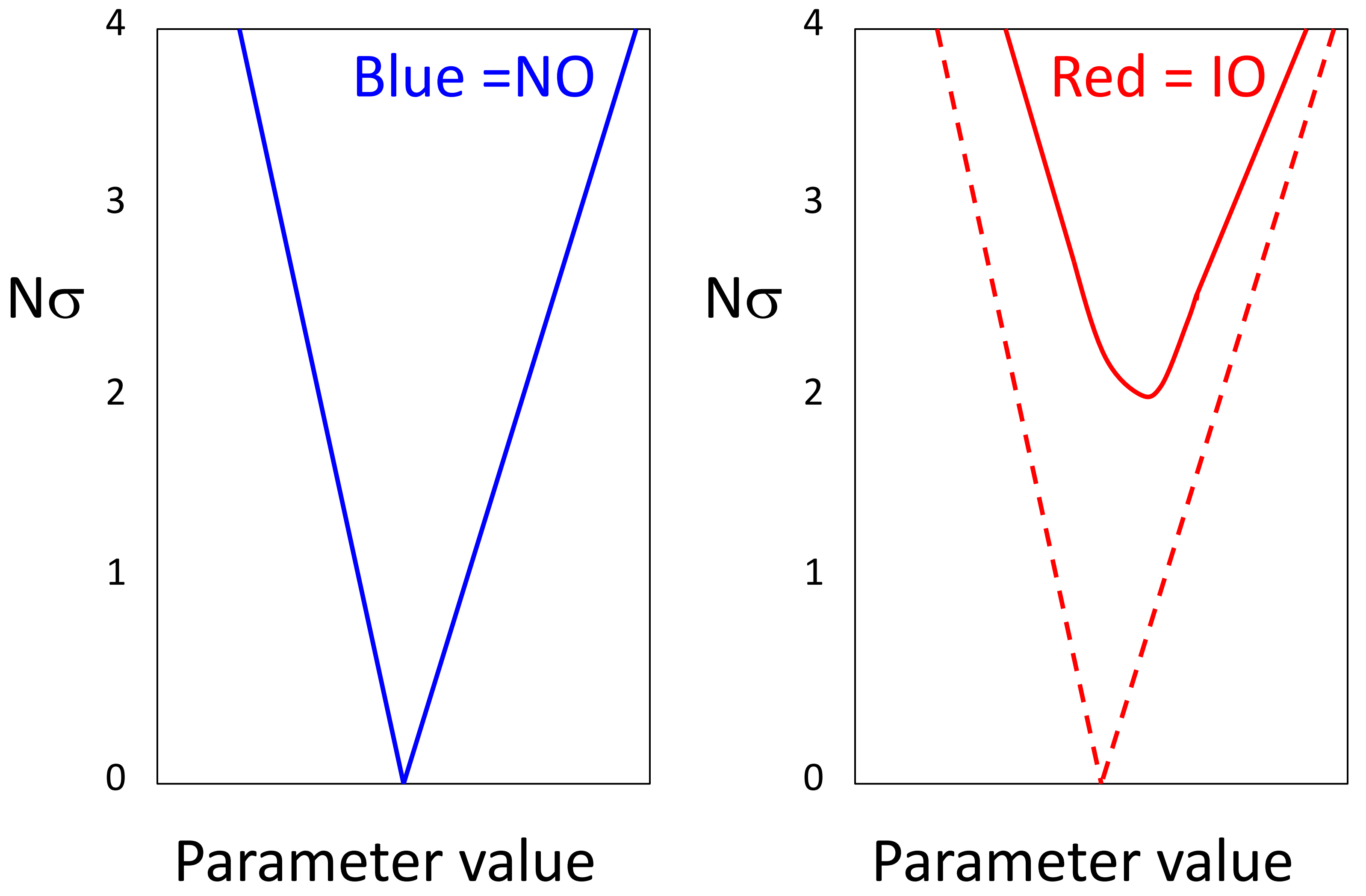
add sensitivity to Δm^2, θ_{23}, δ, NO/IO (but: entangled information in atmos.)

Results from F.Capozzi, E.Di Valentino, E.Lisi, A.Marrone, A.Melchiorri, A.Palazzo: hep-ph 2107.00532

Parameter bounds at $\mathbf{N\sigma} = \sqrt{\Delta\chi^2}$ would scale linearly in the limit of ~ gaussian errors around best fits



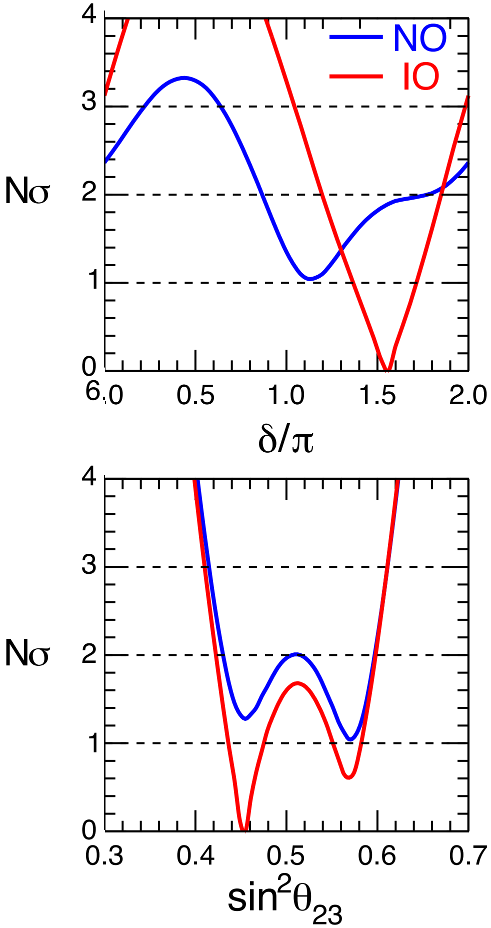
Bounds for one given mass ordering move upwards,
if the other mass ordering is preferred, e.g.:



Results→

Focus on the three oscillation unknowns: NO/IO, δ, θ_{23} octant degen.

LBL Acc + Solar + KamLAND

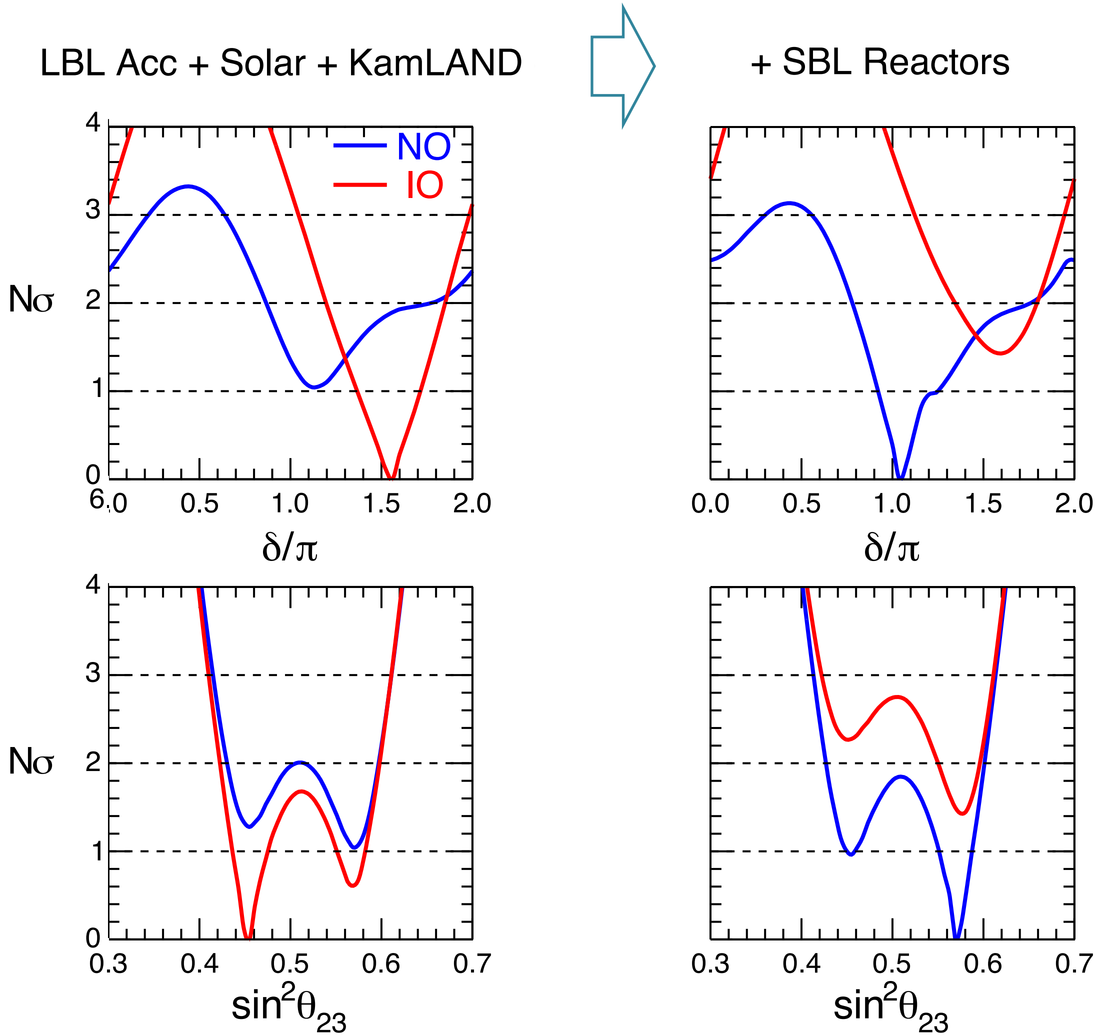


IO favored (~1σ)

δ~1.5π (IO), ~π (NO)

θ_{23} octants ~degenerate

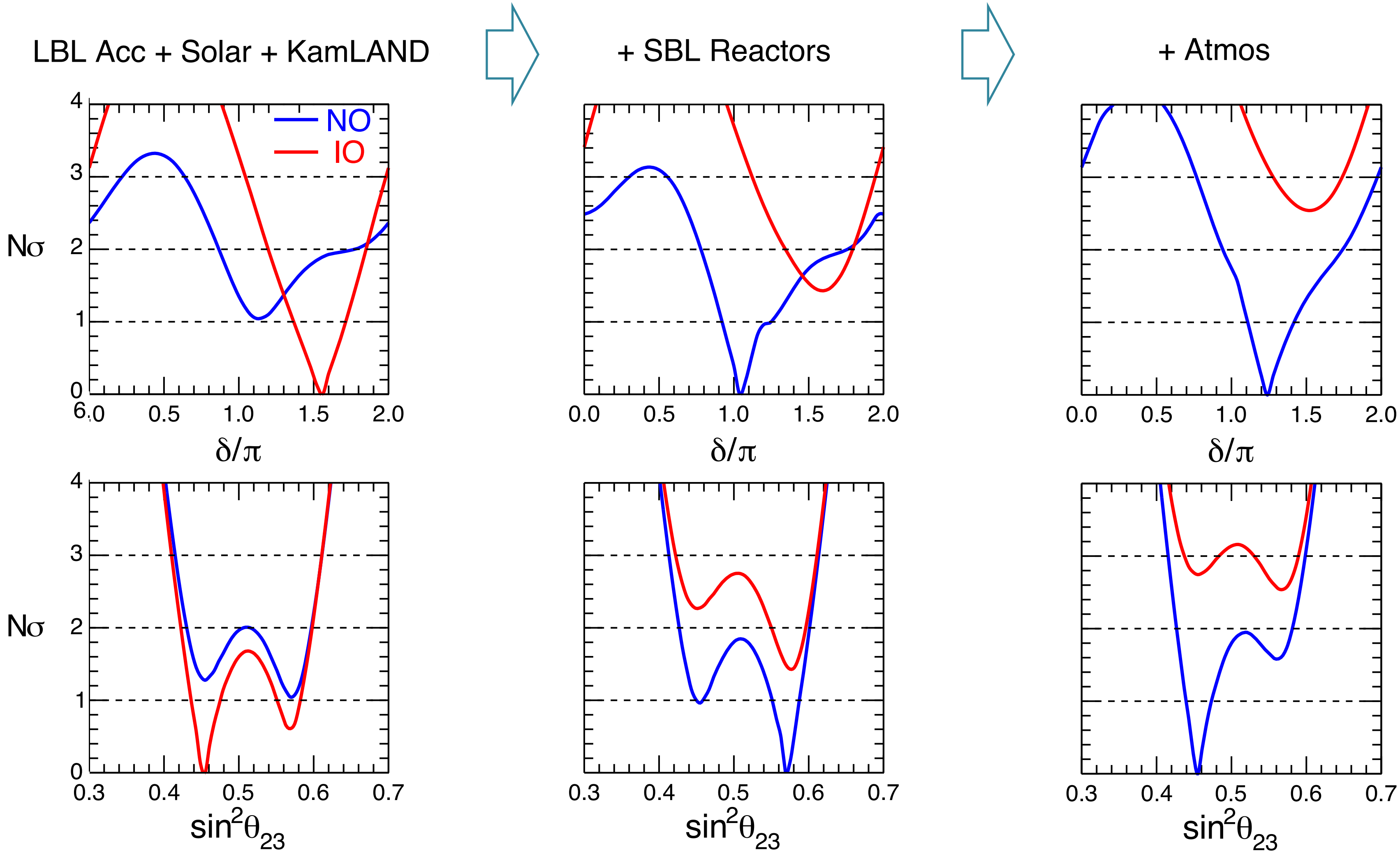
Focus on the three oscillation unknowns: NO/IO, δ, θ_{23} octant degen.



IO favored (~1σ)
δ~1.5π (IO), ~π (NO)
θ_{23} octants ~degenerate

NO favored (~1.5σ)
δ~π (NO), ~1.5π (IO)
θ_{23}~0.57 favored (~1σ)

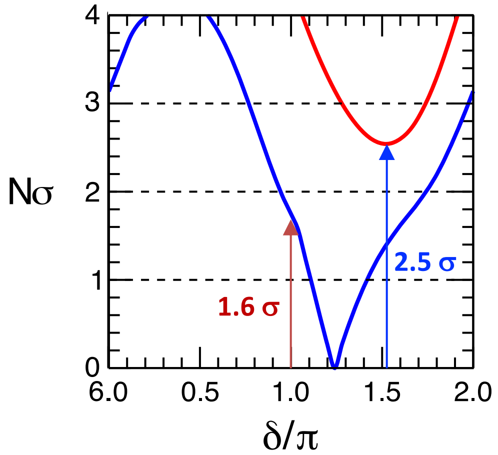
Focus on the three oscillation unknowns: NO/IO, δ, θ_{23} octant degen.

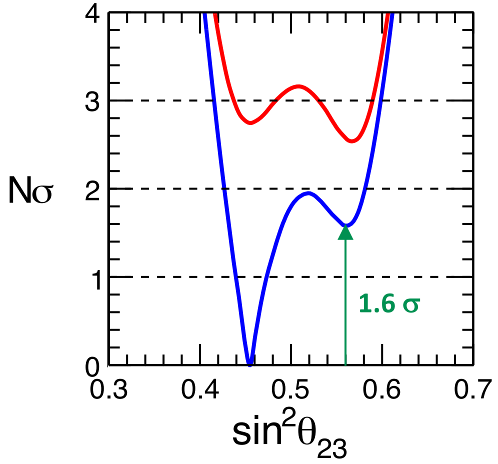


IO favored (~1σ)
δ~1.5π (IO), ~π (NO)
θ_{23} octants ~degenerate

NO favored (~1.5σ)
δ~π (NO), ~1.5π (IO)
θ_{23}~0.57 favored (~1σ)

NO favored (~2.5σ)
δ~1.2π (NO) fav. (~1.6σ)
θ_{23}~0.46 favored (~1.6σ)





NO: may get extra likelihood from cosmology

$\sin\delta > 0$ disfavored (strongly, around $\delta \sim \pi/2$)

θ_{23} octant very fragile; difficult to disentangle

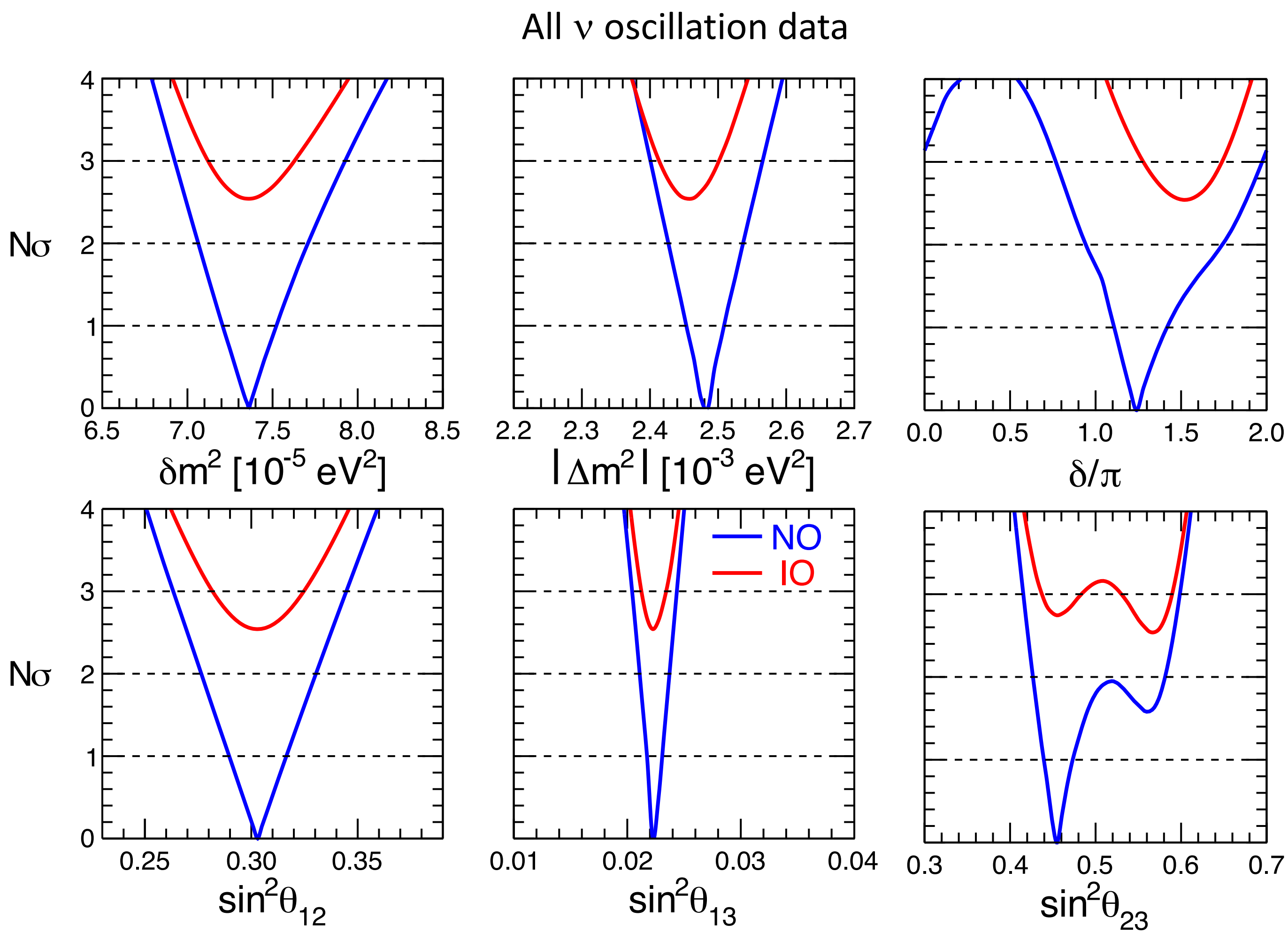
Hints on oscillation **unknowns**

NO	~99% CL
$\sin\delta < 0$	~90% CL
$\theta_{23} < \pi/4$	~90% CL

Summary of known and unknown 3ν oscillation parameters, circa 2021

1σ error of **known** parameters

$|\Delta m^2|$	1.1%
δm^2	2.3%
θ_{13}	3.0%
θ_{12}	4.5%
θ_{23}	~ 6%



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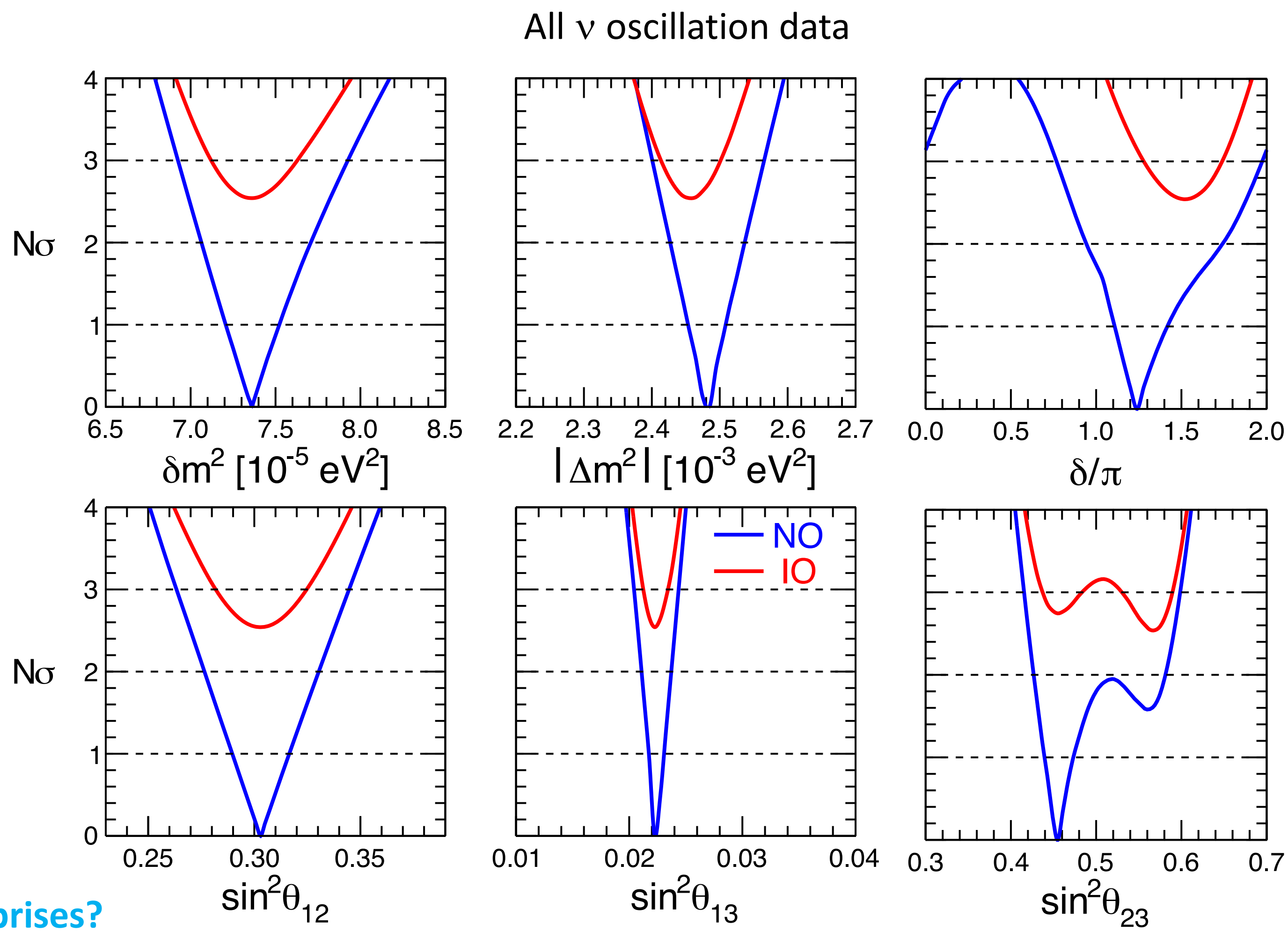


PRECISION

+surprises?

Progress expected on all fronts except for θ_{13} (difficult to improve)

DISCOVERY

Hints on oscillation **unknowns**

NO	~99% CL
$\sin\delta < 0$	~90% CL
$\theta_{23} < \pi/4$	~90% CL

From single parameters…

TABLE I: Global 3ν analysis of oscillation parameters: best-fit values and allowed ranges at $N_\sigma = 1$, 2 and 3, for either NO or IO, including all data. The latter column shows the formal "1σ fractional accuracy" for each parameter, defined as 1/6 of the 3σ range, divided by the best-fit value and expressed in percent. We recall that $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$ and that $\delta \in [0, 2\pi]$ (cyclic). The last row reports the difference between the χ^2 minima in IO and NO.

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.36	7.21 – 7.52	7.06 – 7.71	6.93 – 7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.90 – 3.16	2.77 – 3.30	2.63 – 3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.485	2.454 – 2.508	2.427 – 2.537	2.401 – 2.565	1.1
	IO	2.455	2.430 – 2.485	2.403 – 2.513	2.376 – 2.541	1.1
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.17 – 2.30	2.11 – 2.37	2.04 – 2.44	3.0
	IO	2.23	2.17 – 2.29	2.10 – 2.38	2.03 – 2.45	3.1
$\sin^2\theta_{23}/10^{-1}$	NO	4.55	4.40 – 4.73	4.27 – 5.81	4.16 – 5.99	6.7
	IO	5.69	5.48 – 5.82	4.30 – 5.94	4.17 – 6.06	5.5
δ/π	NO	1.24	1.11 – 1.42	0.94 – 1.74	0.77 – 1.97	16
	IO	1.52	1.37 – 1.66	1.22 – 1.78	1.07 – 1.90	9
$\Delta\chi^2_{\rm IO-NO}$	IO−NO	+6.5				

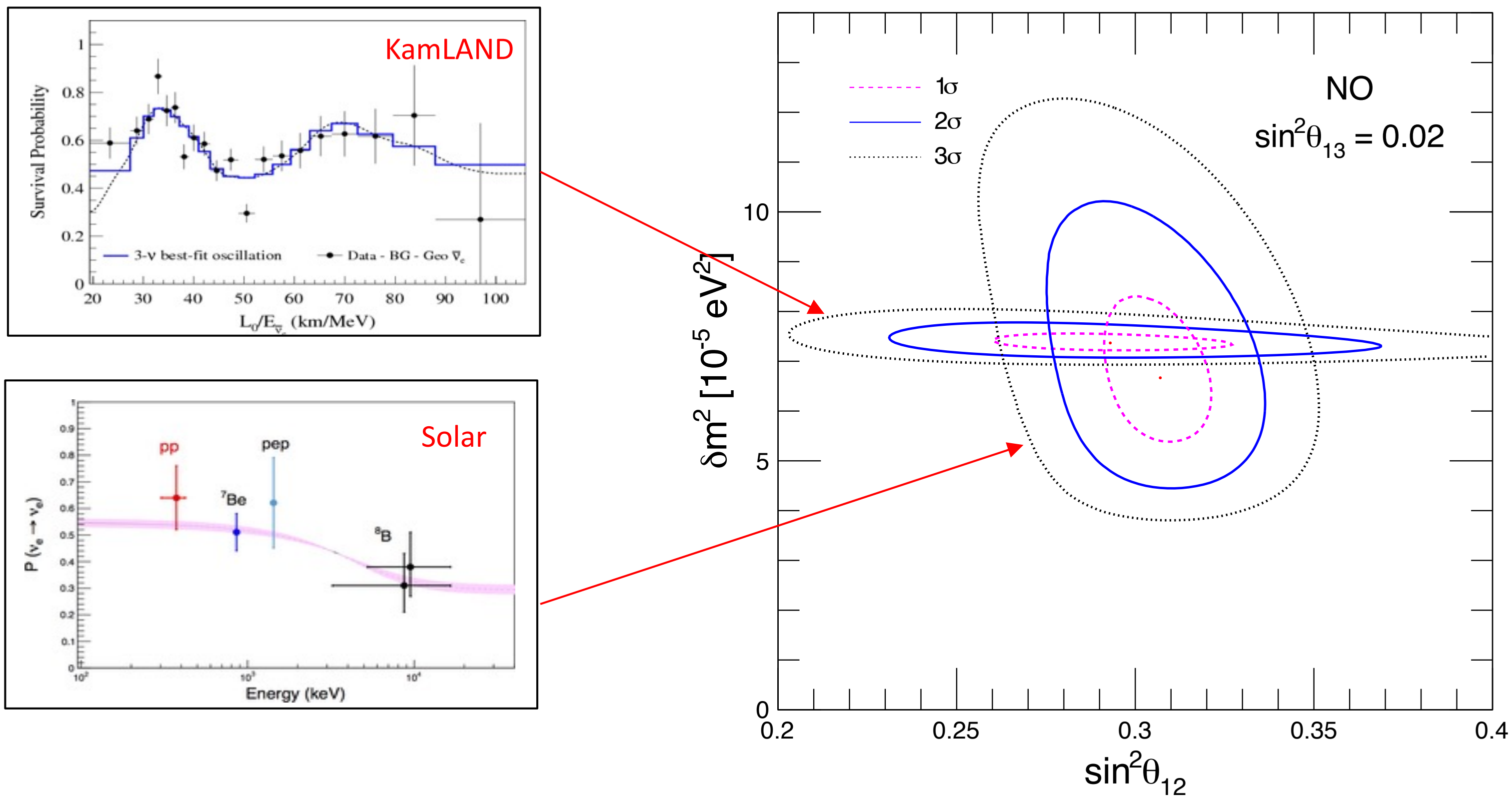
from hep-ph 2107.00532

… to pairs of oscillation observables. Examples of:

Data convergence	(δm^2, θ_{12})
Complementarity:	($\pm\Delta m^2$, θ_{23})
Tension/instability:	**Bi-rate plots** (T2K / NOvA)

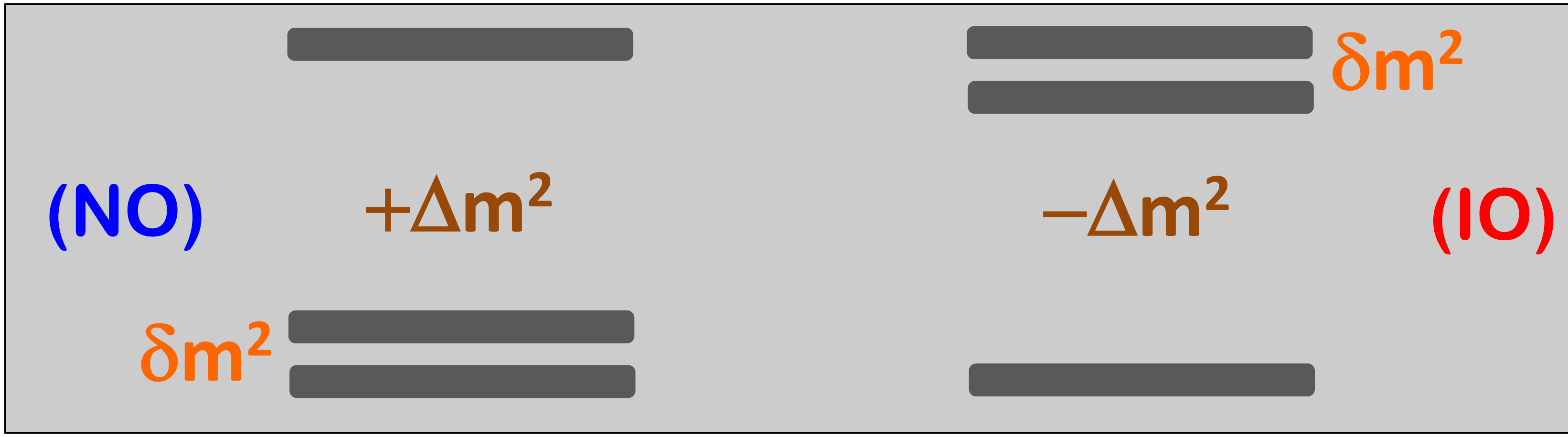
(δm^2, θ_{12}) pair: a success story → (ν_1, ν_2) param. + MSW effect + Sun (pp+CNO)

[Former ~2σ tension between δm^2 values: insignificant after 2020 SK data update]



Future: **MBL reactors (JUNO)** → precision frontier on both oscill. parameters
Large-volume solar ν detect. → precision MSW in Sun + Earth (D/N)

How do oscillation searches probe mass ordering?



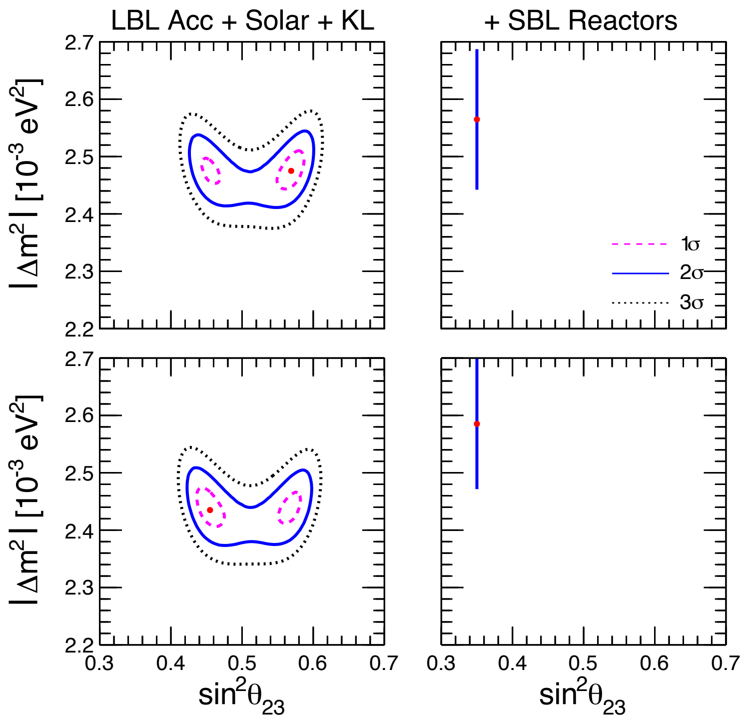
Observe interference effects of oscill. driven by $\pm\Delta m^2$ with oscill. driven by another quantity Q with known sign. Options:

$Q \sim \delta m^2$	(medium-baseline reactors → JUNO)
$Q \sim G_F N_e E$	(ν–matter effects → atm & LBL accel. expt.)
$Q \sim G_F N_\nu E$	(ν–ν collective effects → SN, difficult!)

Additional handle: complementarity of different Δm^2 data in NO/IO →

($\pm\Delta m^2$, θ_{23}) pair

Standalone SBL reactor data ($\pm 2\sigma$)



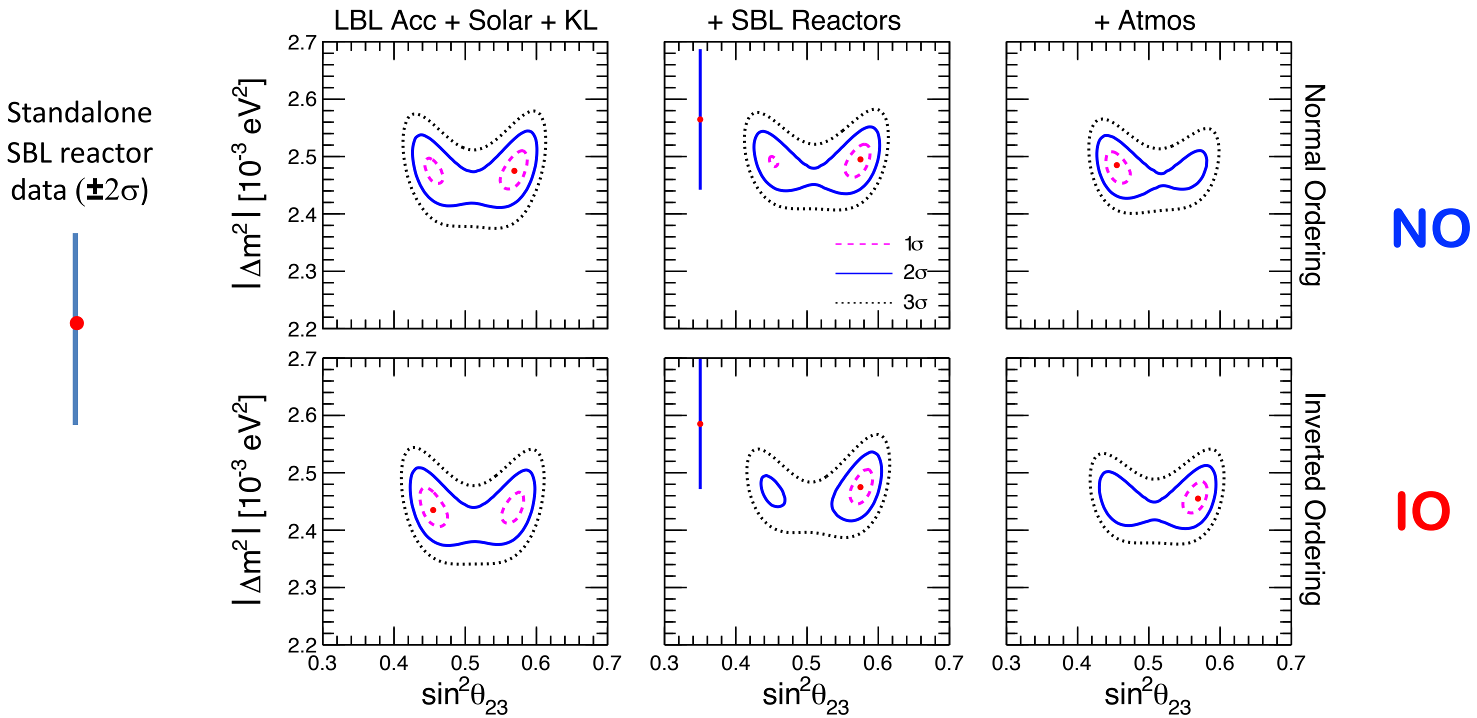
NO

IO

SBL reactors prefer **higher** Δm^2 than LBL accel. (and atmos.) expts.

Relative difference is **smaller** for **NO** and for non-maximal θ_{23} mixing

($\pm\Delta m^2$, θ_{23}) pair



SBL reactors prefer **higher** Δm^2 than LBL accel. (and atmos.) expts.

Relative difference is **smaller** for **NO** and for non-maximal θ_{23} mixing

→ Better agreement reached for **NO** & **nonmax θ_{23}** **at intermediate Δm^2**

→ SBL reactor data not sensitive to sign(Δm^2) and θ_{23}, but affect their likelihood

Future: handle on NO/IO from complementary Δm^2 data (JUNO+Acc/Atm)

How do $\nu_\mu \rightarrow \nu_e$ appearance searches probe CPV?

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TIME REVERSAL VIOLATION IN NEUTRINO OSCILLATION

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Received 11 October 1977

We discuss the possibility of CP or T violation in neutrino oscillation CP requires $\nu_\mu \leftrightarrow \nu_e$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations to be equal Time reversal invariance requires the oscillation probability to be an even function of time Both conditions can be violated, even drastically, if more than two neutrinos exist

For two neutrinos, no CPV:

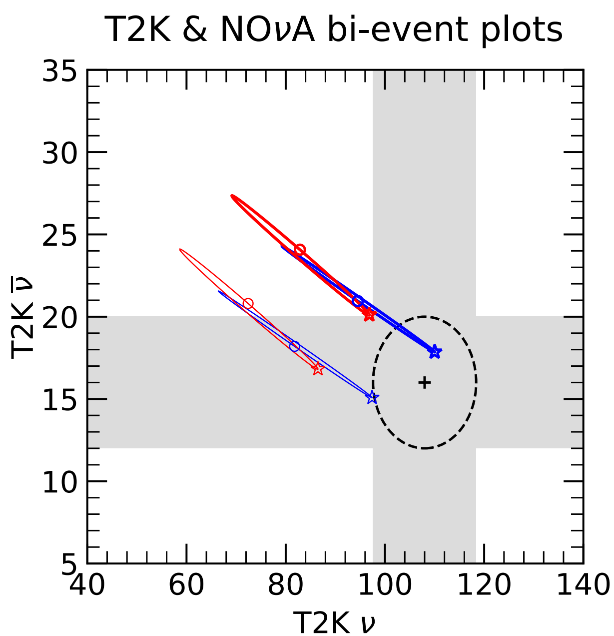
$$\overset{(-)}{\nu}_e = \cos\theta_{12}\,\nu_1 + \sin\theta_{12}\,\nu_2$$

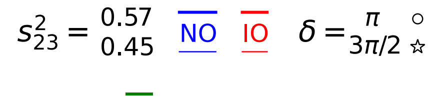
For three neutrinos: new possible CPV phase δ, tested via ν / $\bar{\nu}$

$$\overset{(-)}{\nu}_e = \cos\theta_{13}\,(\cos\theta_{12}\,\nu_1 + \sin\theta_{12}\,\nu_2) + e^{\pm i\delta}\sin\theta_{13}\,\nu_3$$

CPV is a genuine 3ν effect → all parameters (known+unknown) are involved/entangled

Integrated info on ν and $\bar{\nu}$, stat. errors only. [Not used in fits]





T2K (ν+$\bar{\nu}$) prefers:

NO

δ~3π/2 (~max CPV)

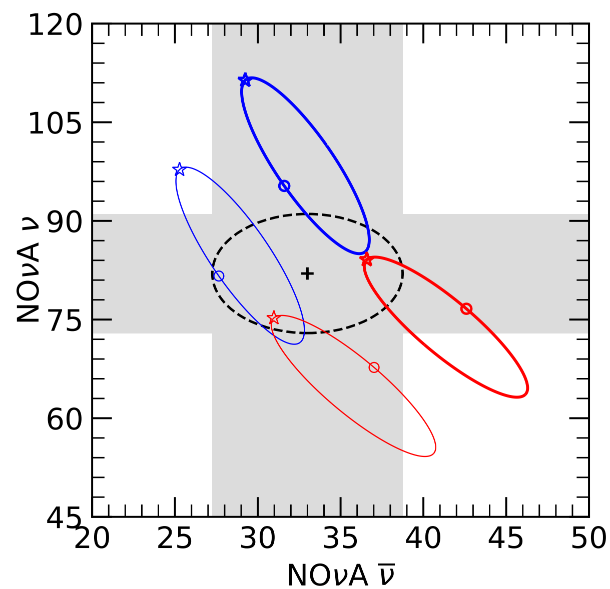
2nd octant

NOVA (ν+$\bar{\nu}$) prefers:

NO

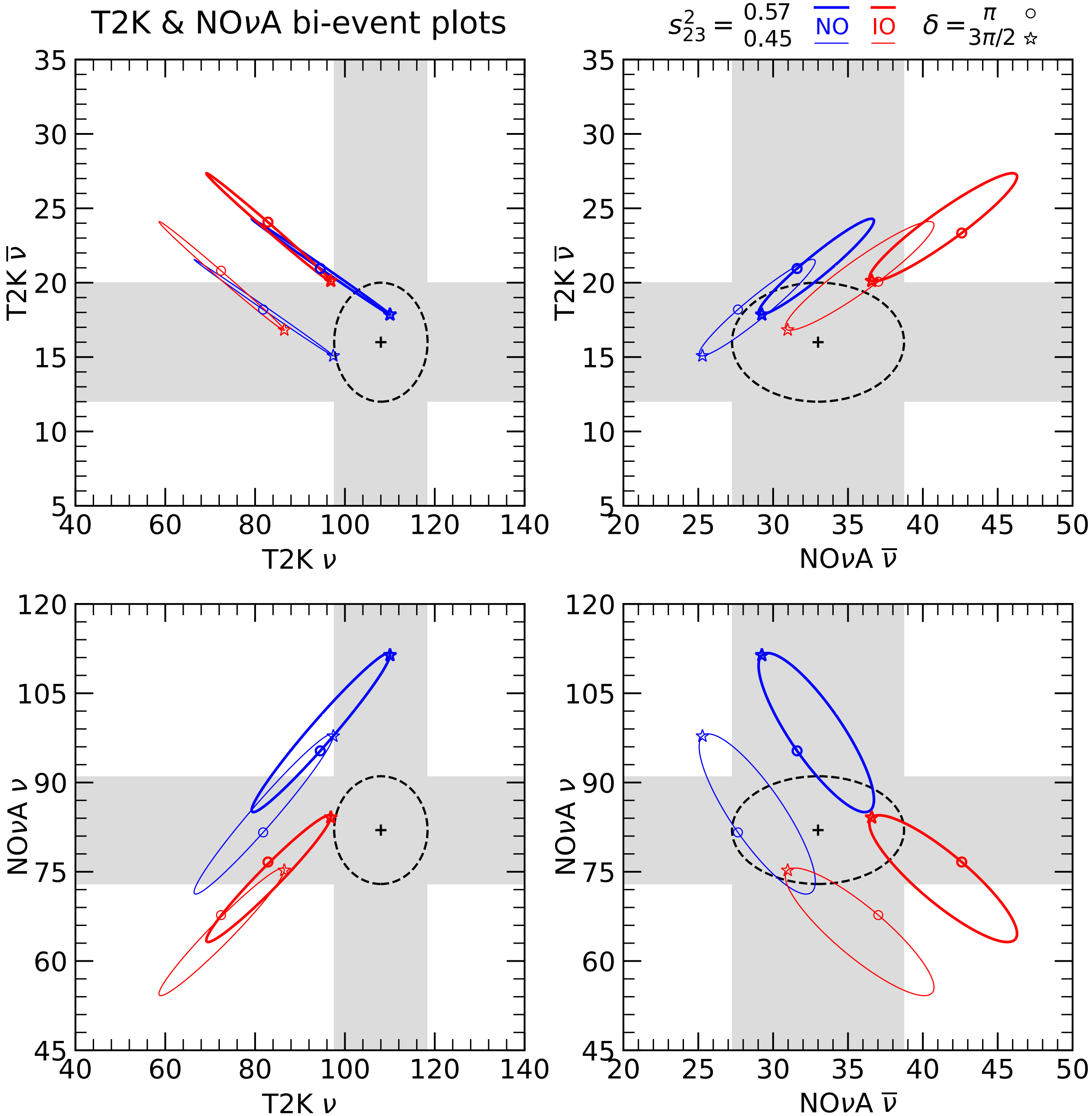
CP conservation

octants ~degenerate

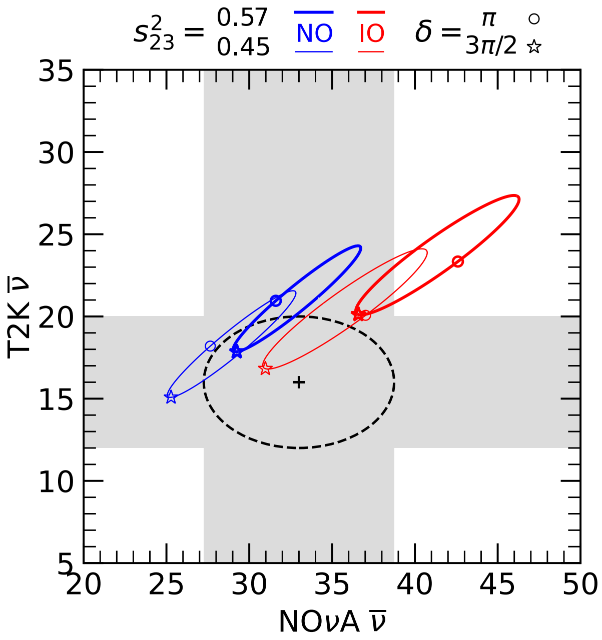


→ T2K and NOVA, separately: NO preferred; CP and octant ambiguous

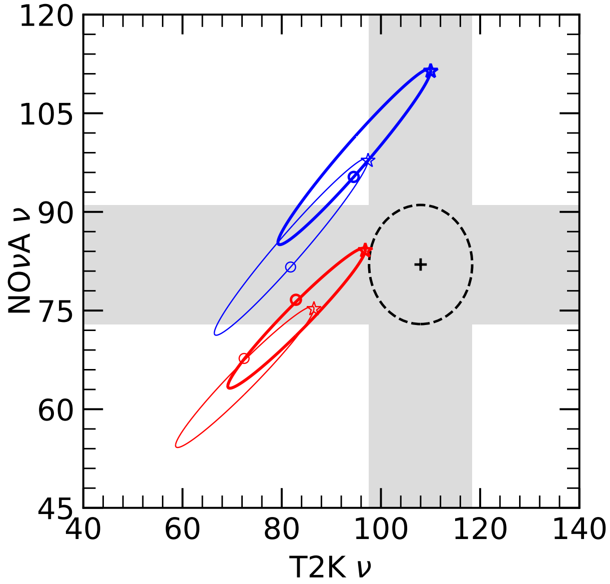
The same info can be reorganized in terms of T2K vs NOvA:



T2K & NOνA bi-event plots



T2K+NOvA (ν) prefer:
IO
δ~3π/2
1st octant



T2K+NOvA ($\bar{\nu}$) prefer:
IO
δ~3π/2
2nd octant

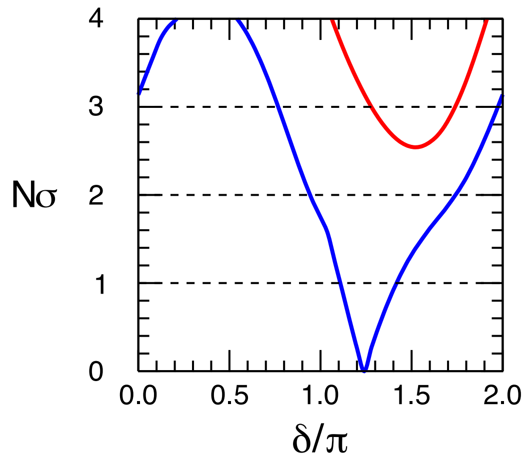
→ T2K and NOVA, jointly: IO and CPV preferred; octant ambiguous

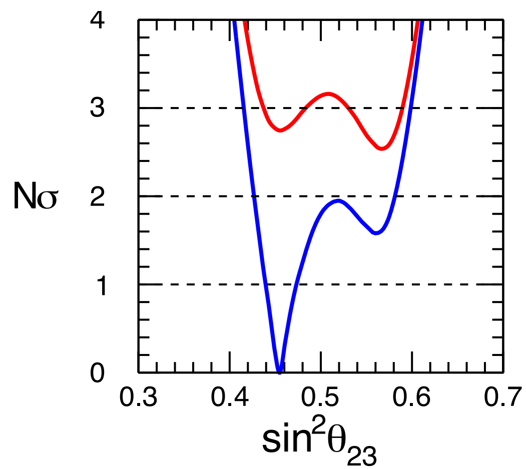
...In the T2K+NOvA combination, still unstable results on three unknowns:

mass ordering (NO vs IO), θ_{23} octant and CP phase δ

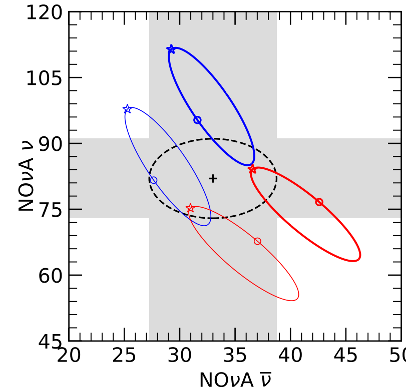
Further data may tilt the current balance, or even point to new physics (NSI?)

LBL Acc + Solar + KamLAND
(current)

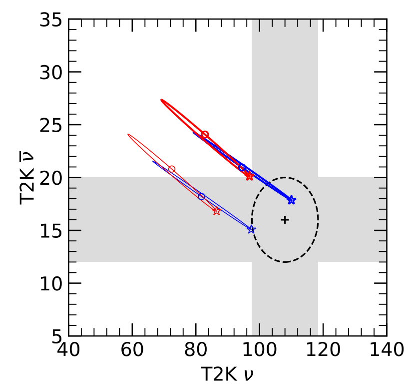




NOvA close to different options within 1σ...



T2K close to the edge of its expected sensitivity...

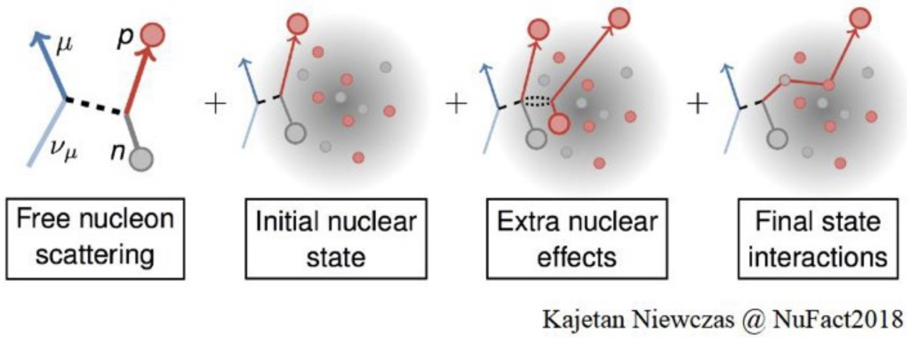


T2K + NOvA joint analysis?

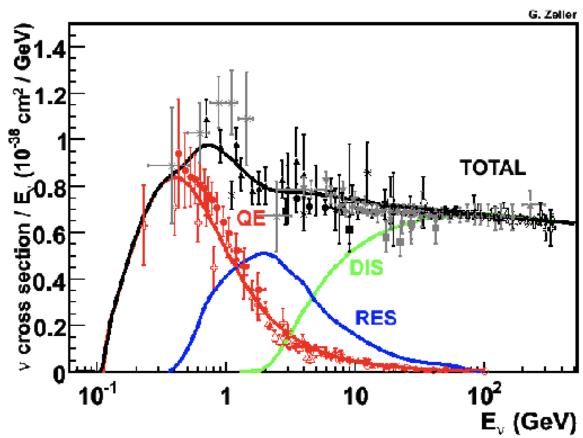
Warning: Parameter covariances and data tensions show the delicate interplay between 2 knowns [Δm^2, θ_{23}] and 3 unknowns [**NO/IO, δ, sign ($\theta_{23} - \pi/4$)**]

There is a general issue that affects all these (un)knowns:
neutrino interactions in nuclei are not known as accurately as desired!

Theory: complex nuclear effects



Experiment: relatively few data

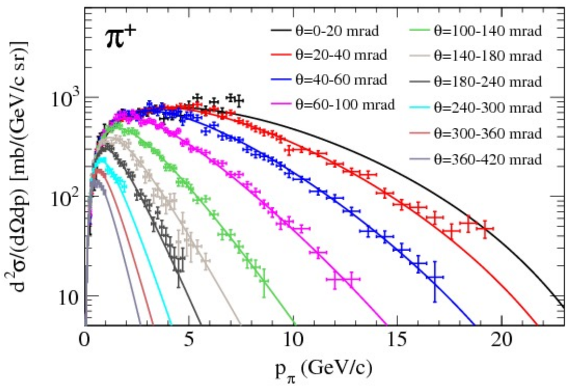


Great effort to improve the situation through dedicated (e.g. ND) experiments and improved nuclear models, but non-negligible uncertainties remain

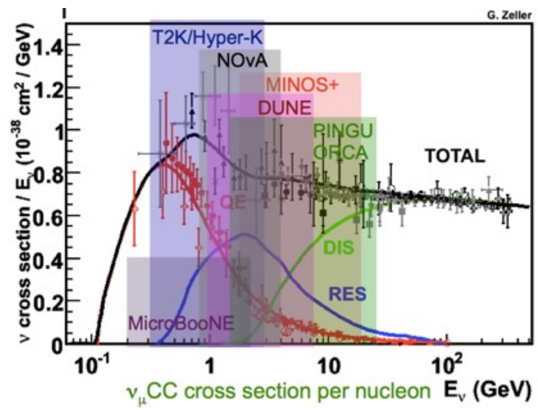
→ **May affect central values and errors of (un)known oscillation parameters**

“Strong interaction” effects on “weak interaction” physics are ubiquitous...

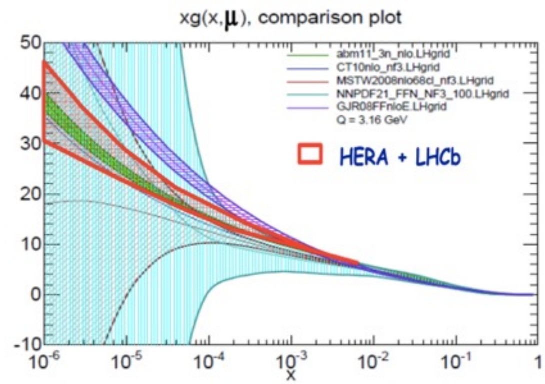
Need hadron production data, e.g. pA → πX, +theory models to improve estimates of atm. and acceler. ν fluxes and errors

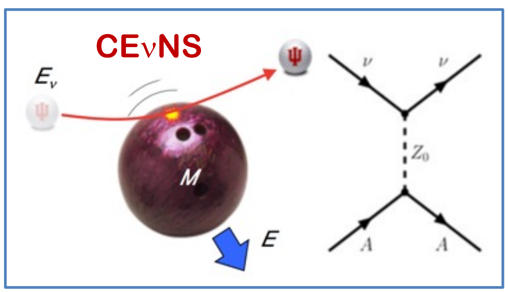


Current understanding of ν cross sections at O(GeV) does not match the needs of (next-generation) ν expts



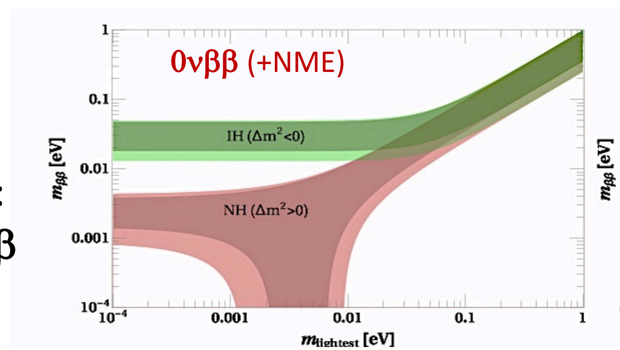
Improved PDFs at low-x via ~forward charm production at LHCb essential to constrain prompt component in UHE ν





Control of nuclear EW response (e.g., form factors) relevant to interpret many low-energy data: coherent scatt., reactor spect., 2β

...



Progress requires further integration of different Expt+Theo communities:

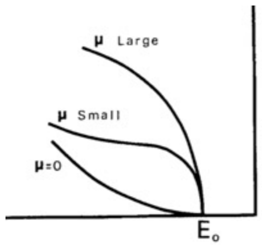
→ (re)emerging field of “Electroweak Nuclear Physics”

Absolute neutrino mass and Dirac/Majorana nature:

Integrating the last 3ν unknowns & their observables (m_β , $m_{\beta\beta}$, Σ)

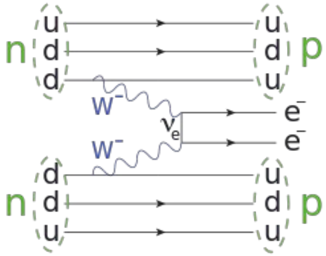
β decay, sensitive to the "effective electron neutrino mass":

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



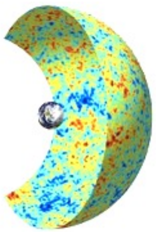
0νββ decay: only if Majorana. "Effective Majorana mass":

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



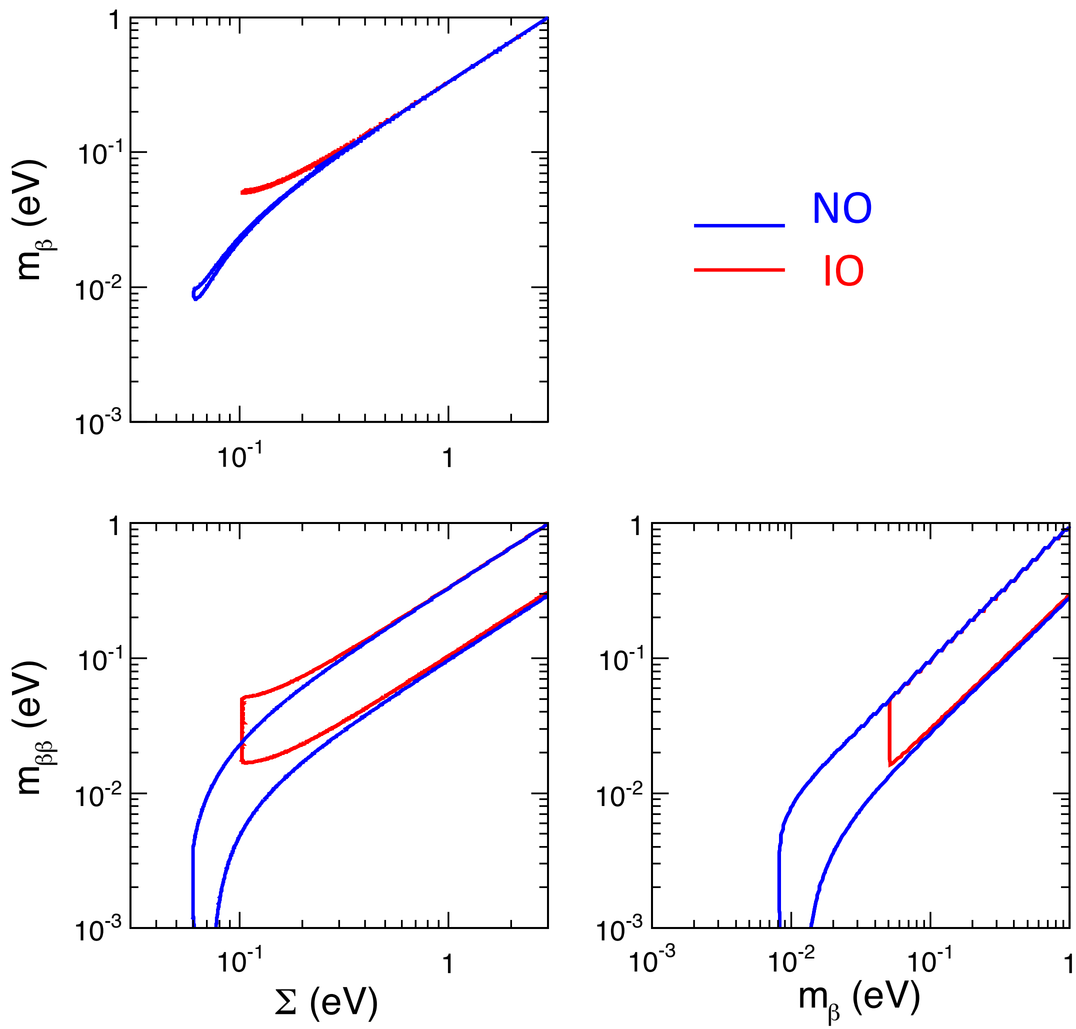
Cosmology: Dominantly sensitive to sum of neutrino masses:

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



Note 1: These observables may provide handles to distinguish NO/IO.
Note 2: Majorana case gives a new source of CPV (unconstrained)
Note 2: The three observables are correlated by oscillation data→

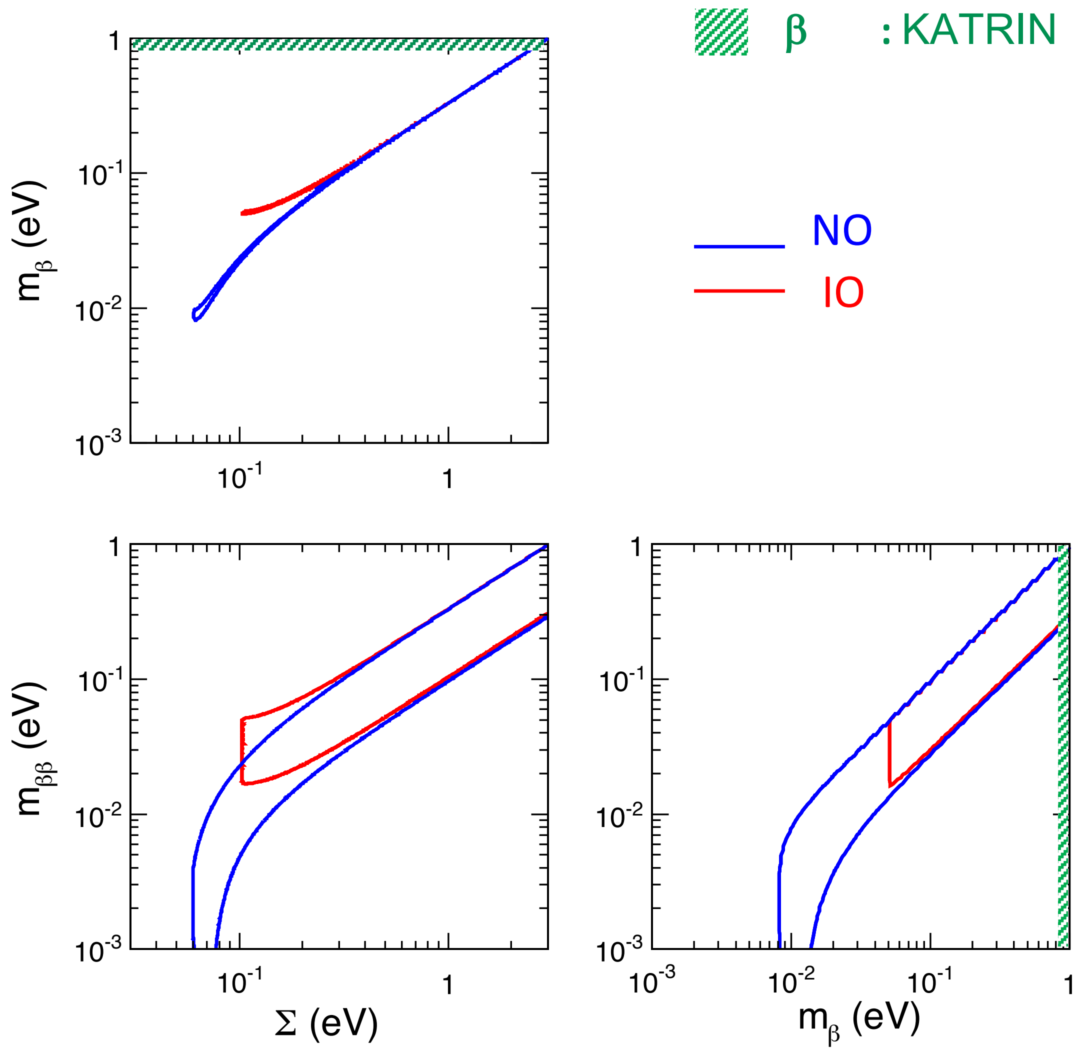
Impact of oscillations on non-oscillation parameter space (2σ)



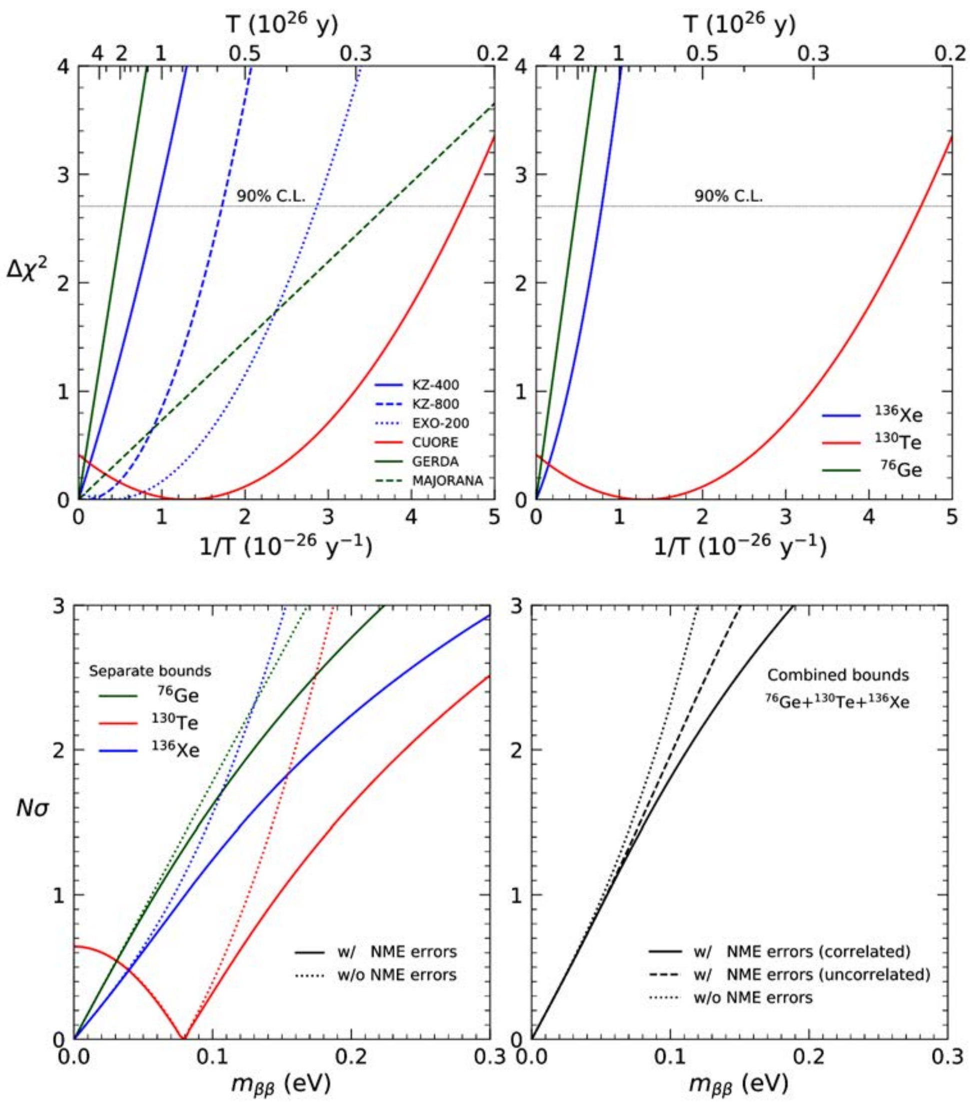
$m_{\beta\beta}$ spread due to Majorana CP phase(s): accessible in principle

(but: no NME errors included here!)

Nonoscillation data: No signal (yet), but upper limits on m_β, $m_{\beta\beta}$, Σ



$0\nu\beta\beta$ – Our combination of data + NME: $m_{\beta\beta} < 0.11$ eV (2σ)

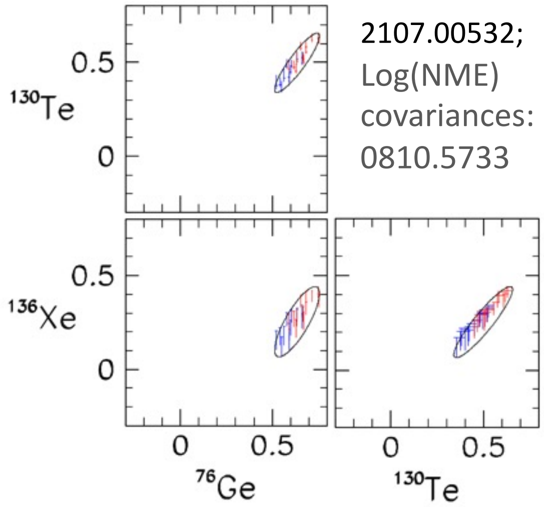


Same-nuclide $0\nu\beta\beta$ data combined in terms of **1/T likelihood profile**

Different-nuclide $0\nu\beta\beta$ data combined through **correlated NME errors**

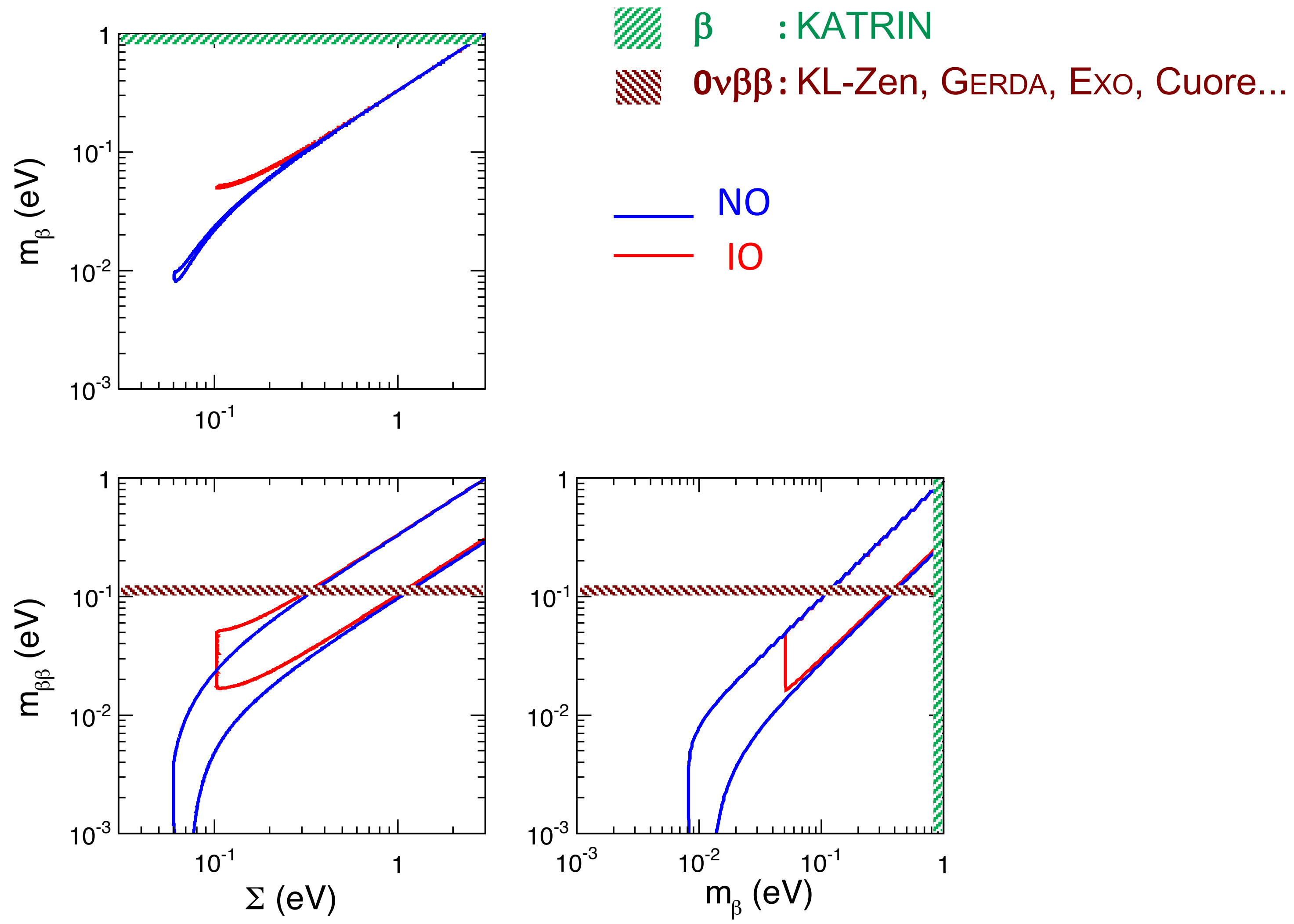
TABLE II: Neutrinoless double beta decay: Details of the adopted parametrization $\Delta\chi^2(S_i) = a_i S_i^2 + b_i S_i + c_i$ for the signal strength $S_i = 1/T_i$, expressed in units of 10^{-26} y^{-1}. The first two columns report the nuclide and the name of the experiment(s). The next three columns report our evaluation of the coefficients (a_i, b_i, c_i), for the various experiments, taken either separately (upper six rows) or in combination for the same nuclide (lower three rows). The sixth column reports our 90% C.L. ($\Delta\chi^2 = 2.706$) half-life limits T_{90} in units of 10^{26} y, to be compared with the experimentally quoted ones in the seventh column (in the same units). Pertinent references are listed in the last column.

Nuclide	Experiment(s)	a_i	b_i	c_i	$T_{90}/10^{26}$ y	T_{90} (expt.)	References
^{76}Ge	GERDA	0.000	4.867	0.000	1.800	1.8	[62]
^{76}Ge	MAJORANA	0.000	0.731	0.000	0.270	0.27	[63]
^{130}Te	CUORE	0.245	−0.637	0.414	0.216	0.22	[64]
^{136}Xe	KamLAND-Zen 400	0.540	2.374	0.000	1.065	1.07	[65, 71]
^{136}Xe	KamLAND-Zen 800 prelim.	1.006	−0.169	0.007	0.580	0.58	[66, 72]
^{136}Xe	EXO-200	0.440	−0.338	0.065	0.350	0.35	[67, 69, 70]
^{76}Ge	GERDA + MAJORANA	0.000	5.598	0.000	2.070	—	This work
^{130}Te	CUORE (same as above)	0.245	−0.637	0.414	0.216	0.22	[64]
^{136}Xe	KamLAND-Zen (400 + 800 prelim.) + EXO-200	1.986	1.867	0.000	1.267	—	This work



2107.00532; Log(NME) covariances: 0810.5733

$0\nu\beta\beta$ bounds: starting to cover non-degenerate mass regions

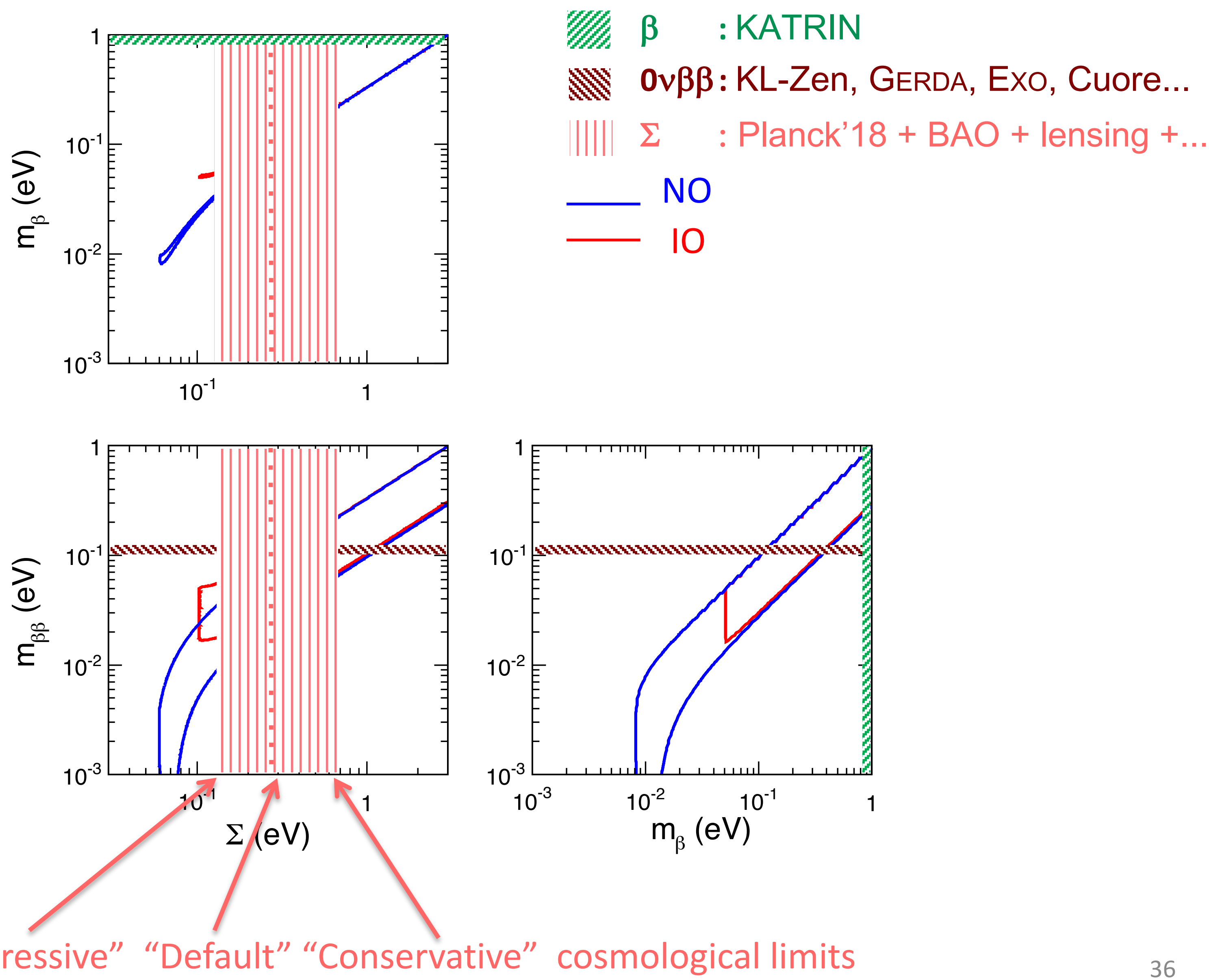


Cosmology: variety of upper bounds, with IO "under pressure"

TABLE IV: Results of the global 3ν analysis of cosmological data within the standard $\Lambda\mathrm{CDM}+\Sigma$ model (possibly augmented with the A_{lens} parameter). The inputs numbered from 0 to 9 are the same as in [11], and refer to various combinations of the Planck 2018 angular CMB temperature power spectrum (TT) plus polarization power spectra (TE, EE), lensing potential power spectrum (lensing), Barion Acoustic Oscillations (BAO), and the Hubble constant from HST observations of Cepheids in the Large Magellanic Cloud, H_0(R19). The inputs numbered from 10 to 12 are new and refer to ACTPol-DR4 and WMAP9 data, in combination with a prior on optical depth to reionization (τ_{prior}), Planck polarization data at large angular scale (lowE), and lensing data. For each case we report the 2σ upper bound on the sum of ν masses Σ (marginalized over NO and IO), together with the $\Delta\chi^2$ difference between IO and NO, using cosmology only. In the last two columns, we report the same information as in the previous two columns, but using cosmological data plus m_β and $m_{\beta\beta}$ constraints. The specific cases numbered 3 and 12 are dubbed as default and alternative, see the text for details.

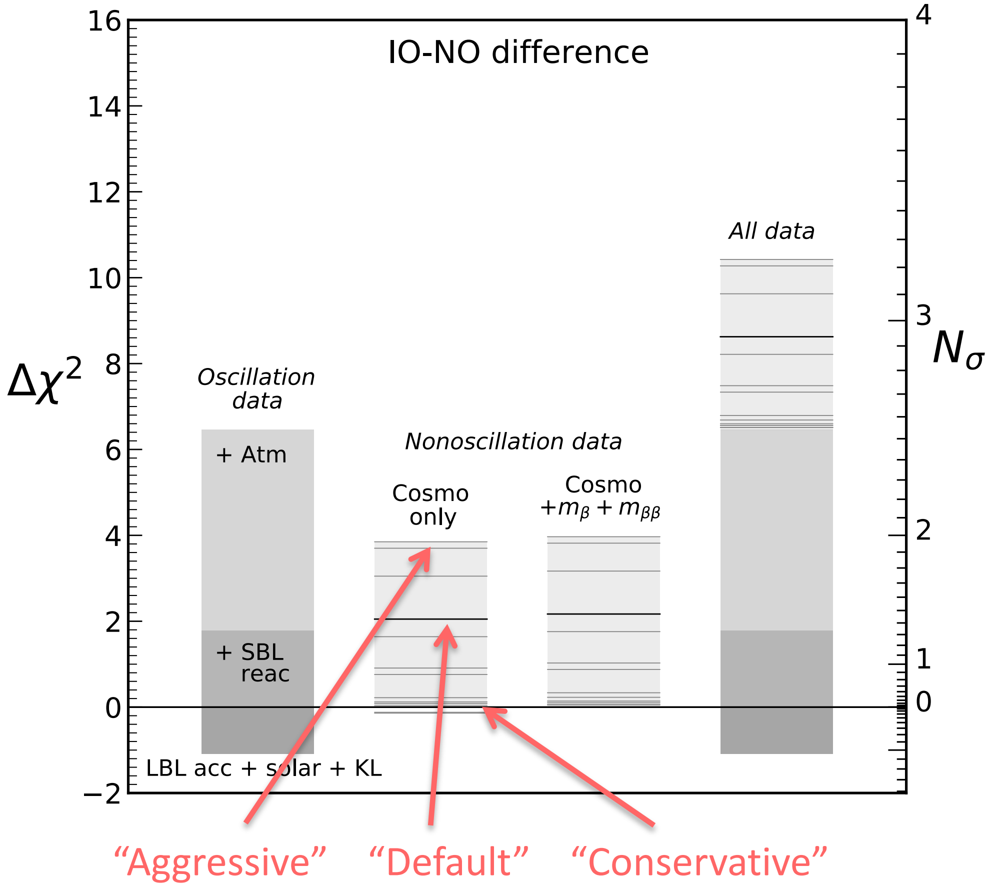
Cosmological inputs for nonoscillation data analysis			Results: Cosmo only		Cosmo + m_β + $m_{\beta\beta}$	
#	Model	Data set	Σ (2σ)	$\Delta\chi^2_{\mathrm{IO-NO}}$	Σ (2σ)	$\Delta\chi^2_{\mathrm{IO-NO}}$
0	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE	< 0.34 eV	0.9	< 0.32 eV	1.0
1	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + lensing	< 0.30 eV	0.8	< 0.28 eV	0.9
2	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + BAO	< 0.17 eV	1.6	< 0.17 eV	1.8
3	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + BAO + lensing	< 0.15 eV	2.0	< 0.15 eV	2.2
4	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + lensing + H_0(R19)	< 0.13 eV	3.9	< 0.13 eV	4.0
5	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + BAO + H_0(R19)	< 0.13 eV	3.1	< 0.13 eV	3.2
6	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + BAO + lensing + H_0(R19)	< 0.12 eV	3.7	< 0.12 eV	3.8
7	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + lensing	< 0.77 eV	0.1	< 0.66 eV	0.1
8	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + BAO	< 0.31 eV	0.2	< 0.30 eV	0.3
9	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + BAO + lensing	< 0.31 eV	0.1	< 0.30 eV	0.2
10	$\Lambda\mathrm{CDM}+\Sigma$	ACT + WMAP + τ_{prior}	< 1.21 eV	−0.1	< 1.00 eV	0.1
11	$\Lambda\mathrm{CDM}+\Sigma$	ACT + WMAP + Planck lowE	< 1.12 eV	−0.1	< 0.87 eV	0.1
12	$\Lambda\mathrm{CDM}+\Sigma$	ACT + WMAP + Planck lowE + lensing	< 0.96 eV	0.0	< 0.85 eV	0.1

Cosmology: variety of upper bounds, with IO "under pressure"



Impact of nonoscillation data on IO-NO difference (global fit)

(envelope of conservative, default, aggressive cases = horizontal lines)



2.5 σ (osc) ⊕ 0.–0.7 σ (nonosc) =

2.5 – 3.2 σ in favor of NO (all ν data)

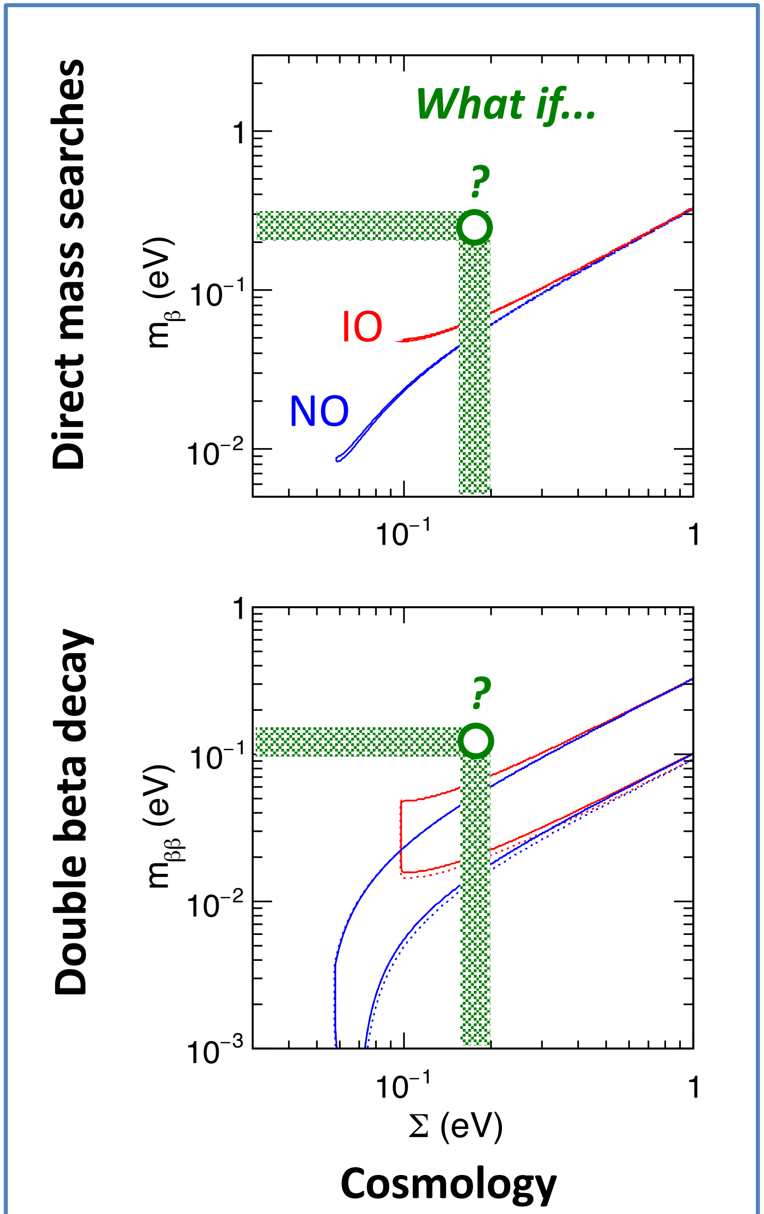
Progress expected on all fronts

Words of caution:

“Half of all 3σ results are wrong”

[J.N. Bahcall]

Future data might also bring us beyond 3ν and re-shape the field…



Lack of convergence among data (barring expt mistakes) **might point towards new possibilities:**

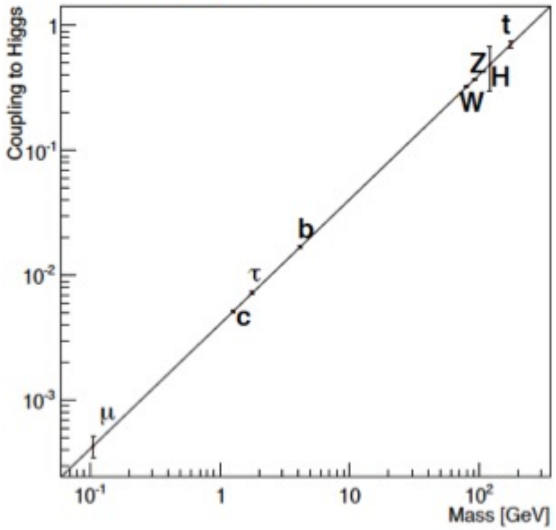
- *Cosmology beyond ΛCDM*
- *Alternative DBD mechanisms*
- *New interactions (NSI)*
- *New neutrino states*
- *…*

Main contender in current ν physics:
Light sterile ν at O(1 eV) scale
but… confusing/unconfirmed hints

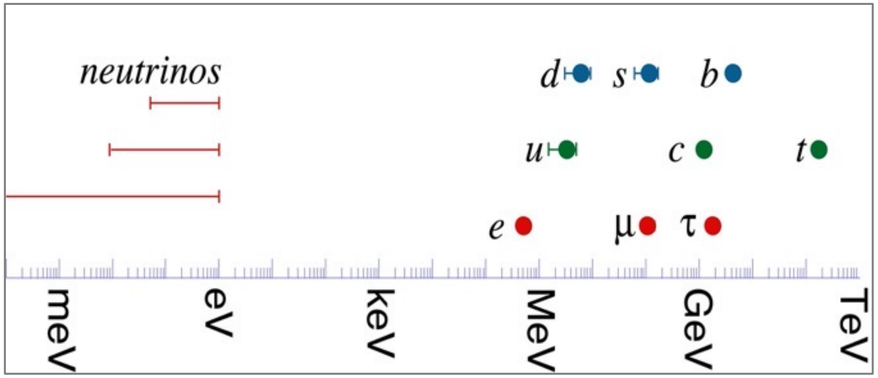
In any case: generic expectations **for new possible ν mass state(s)**

EPILOGUE: Linking two fundamental research programs

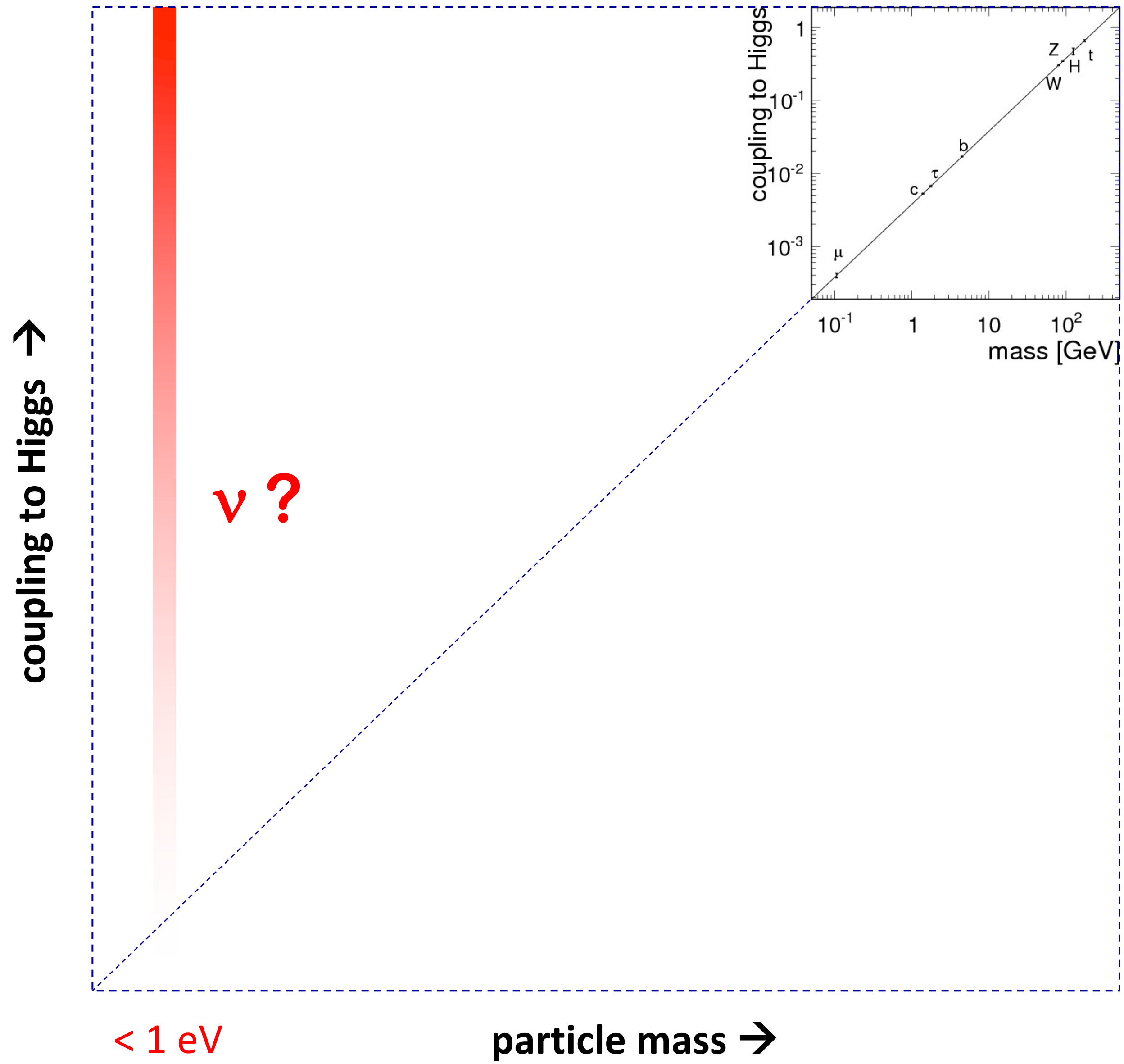
1. Test Higgs sector



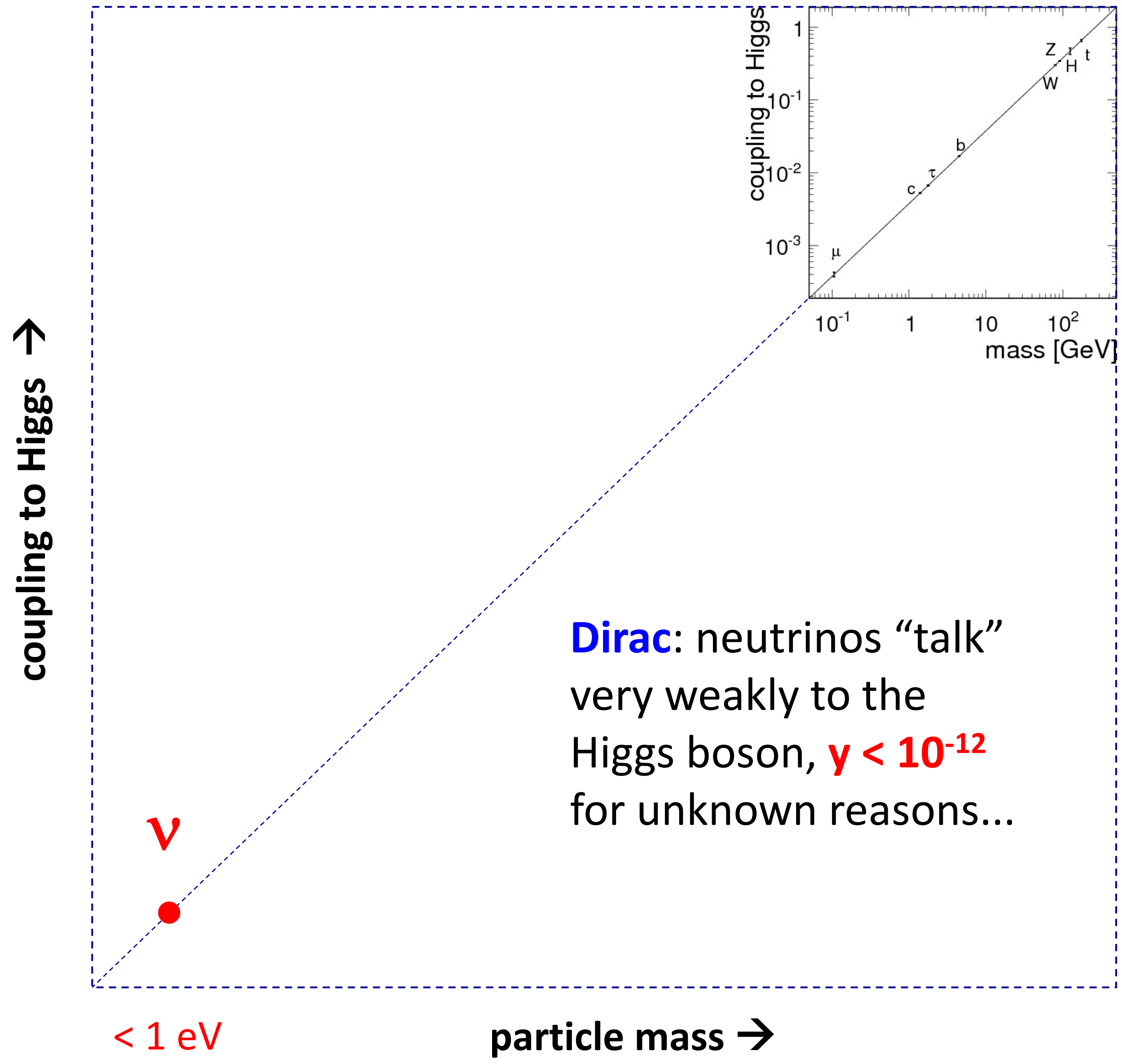
2. Find ν masses



1 + 2 Where are the ν's on this plot? Why are they so light?

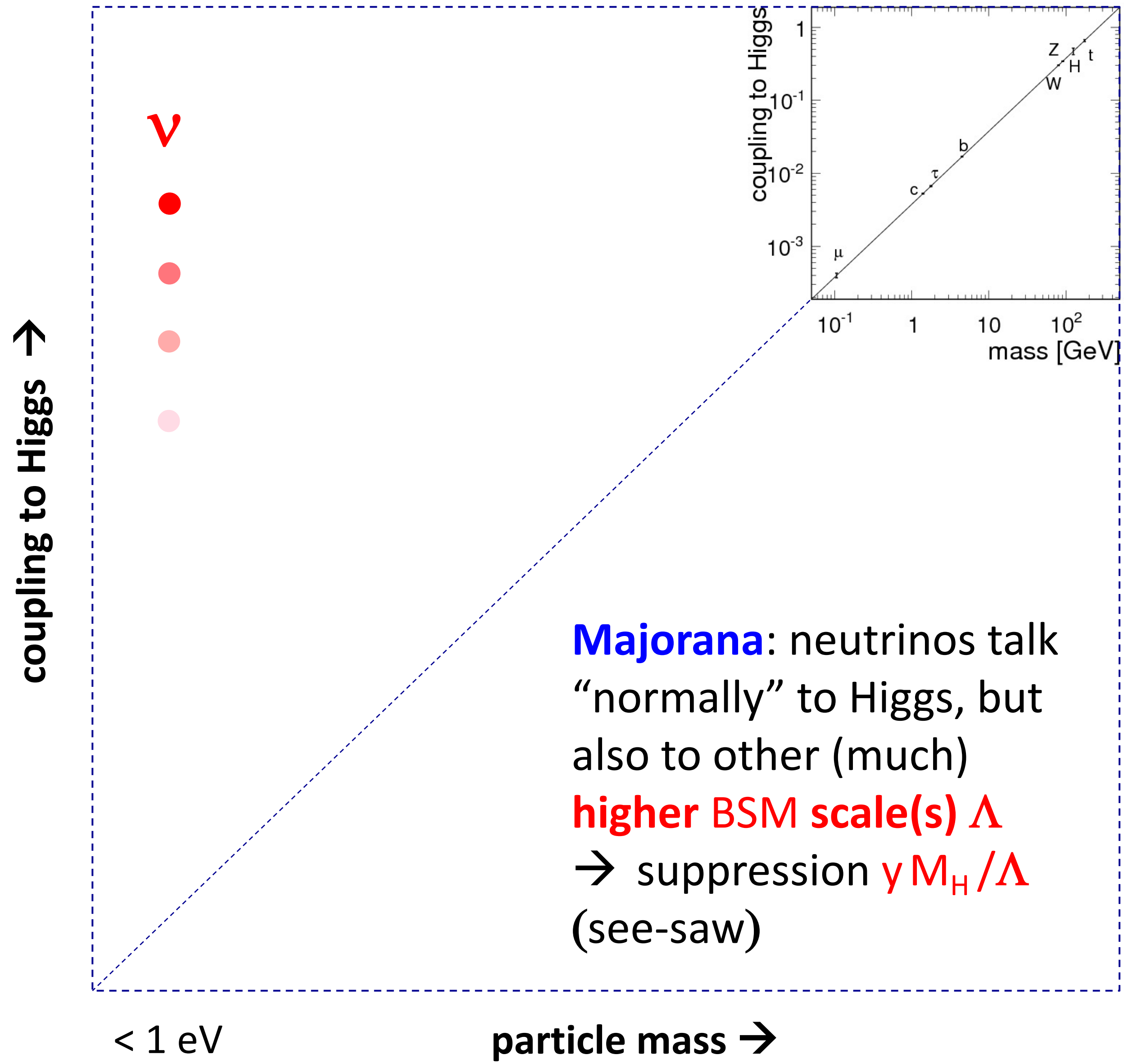


Options:



Dirac: neutrinos "talk" very weakly to the Higgs boson, **$y < 10^{-12}$** for unknown reasons...

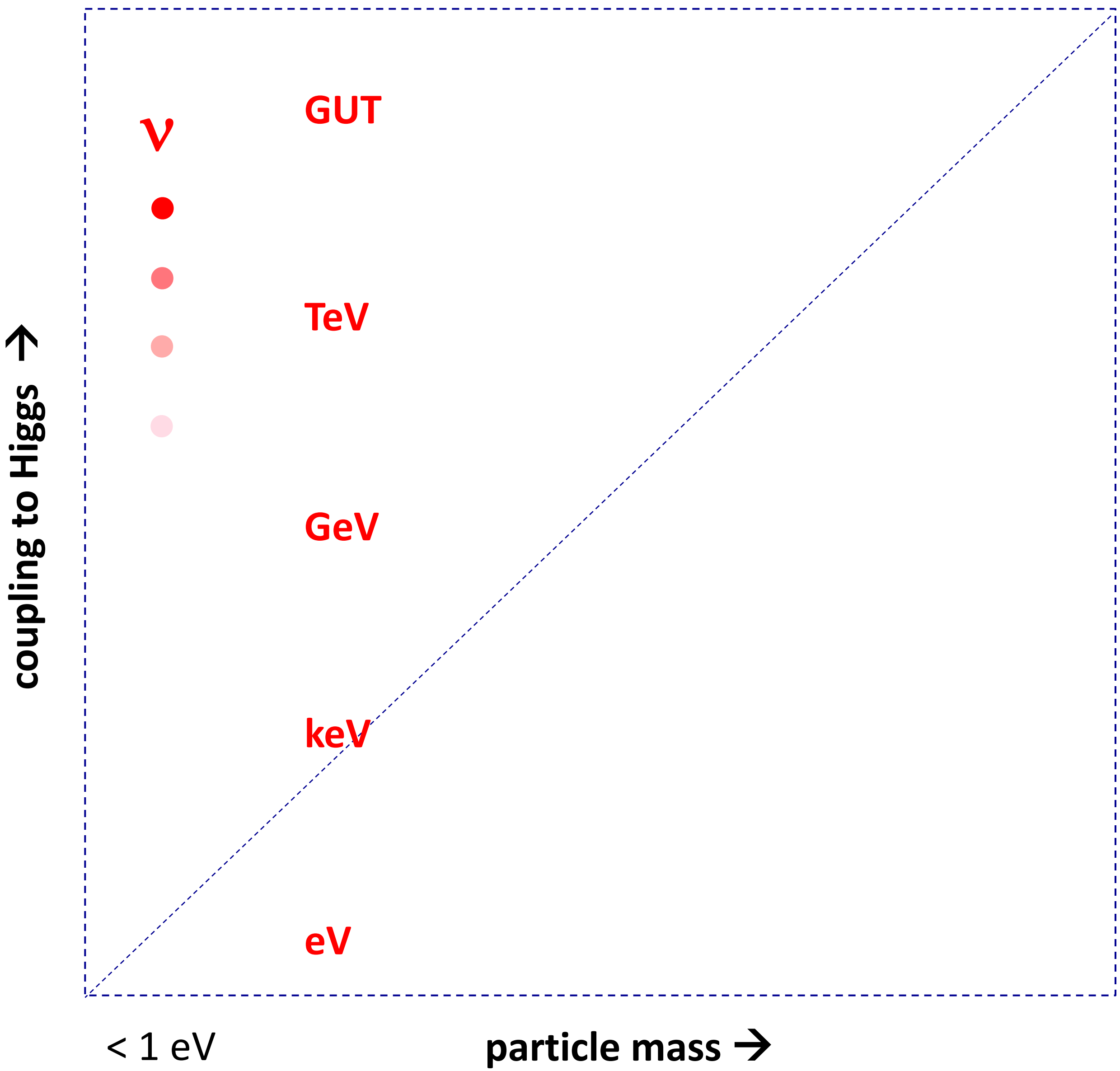
Options:



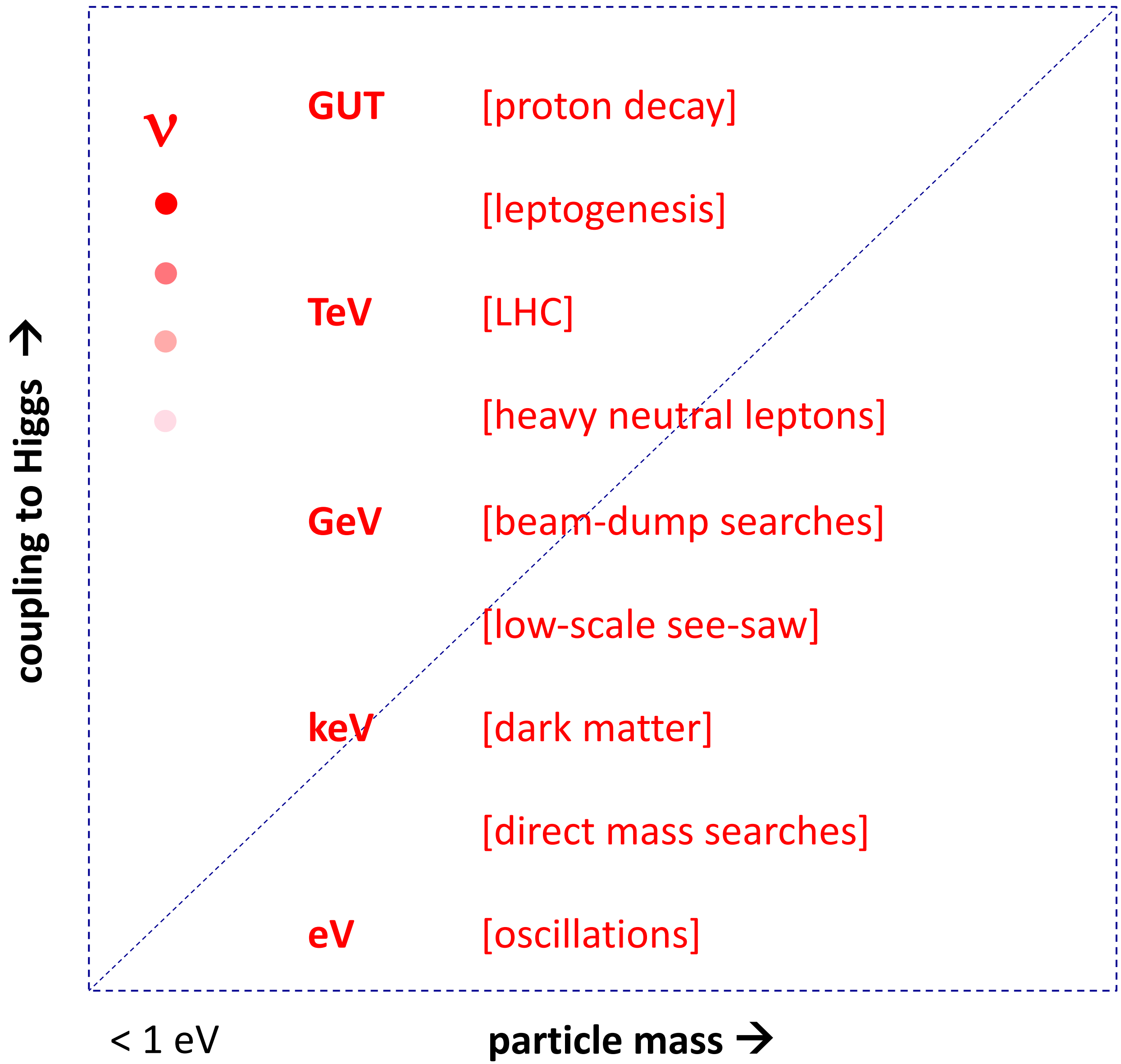
Majorana: neutrinos talk "normally" to Higgs, but also to other (much) **higher** BSM **scale(s)** Λ

→ suppression $y\,M_H/\Lambda$ (see-saw)

New mass states could emerge at different new scales …



… and contribute to a wide research program:



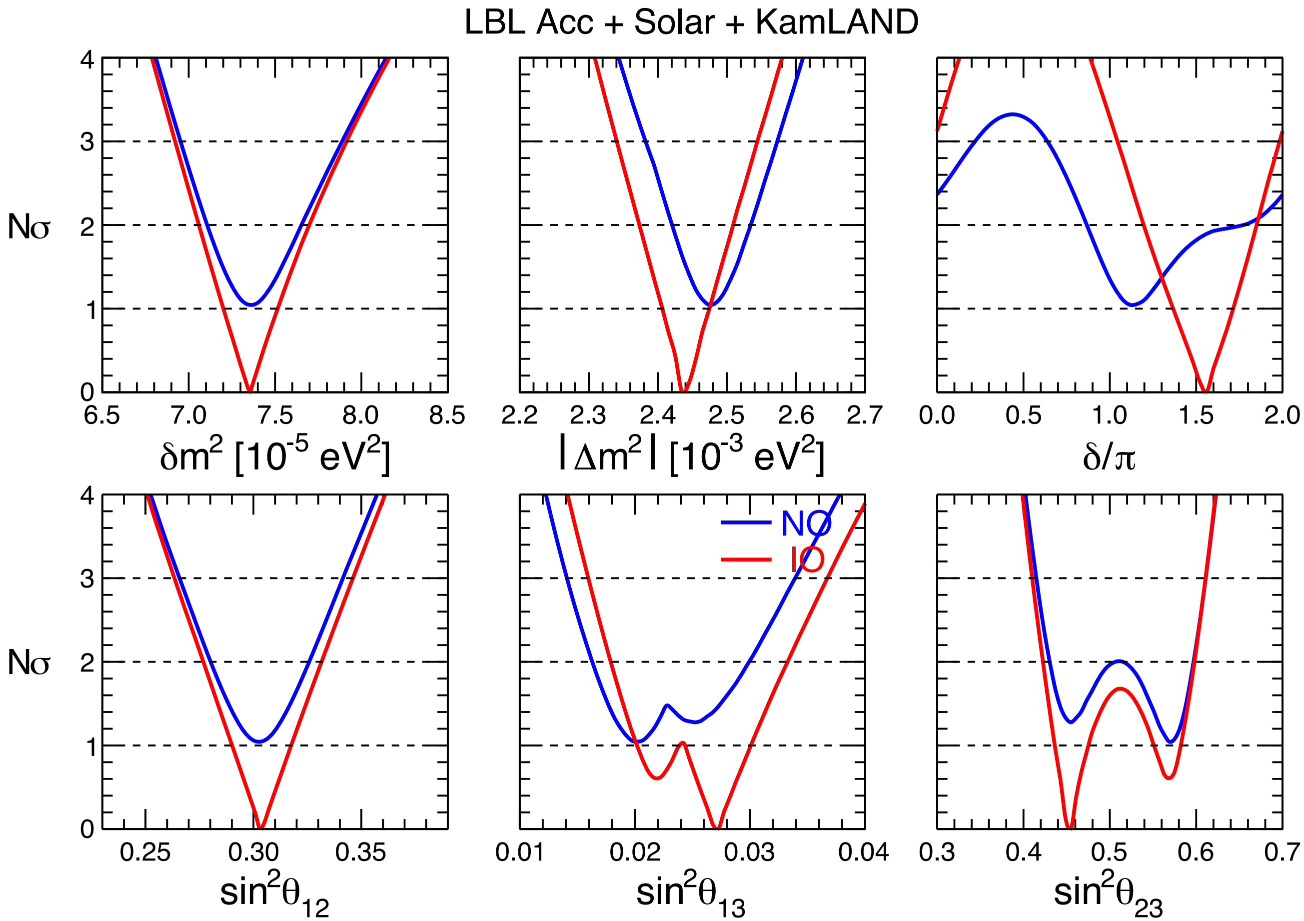
While completing the 3ν framework, be open to surprises!

ν

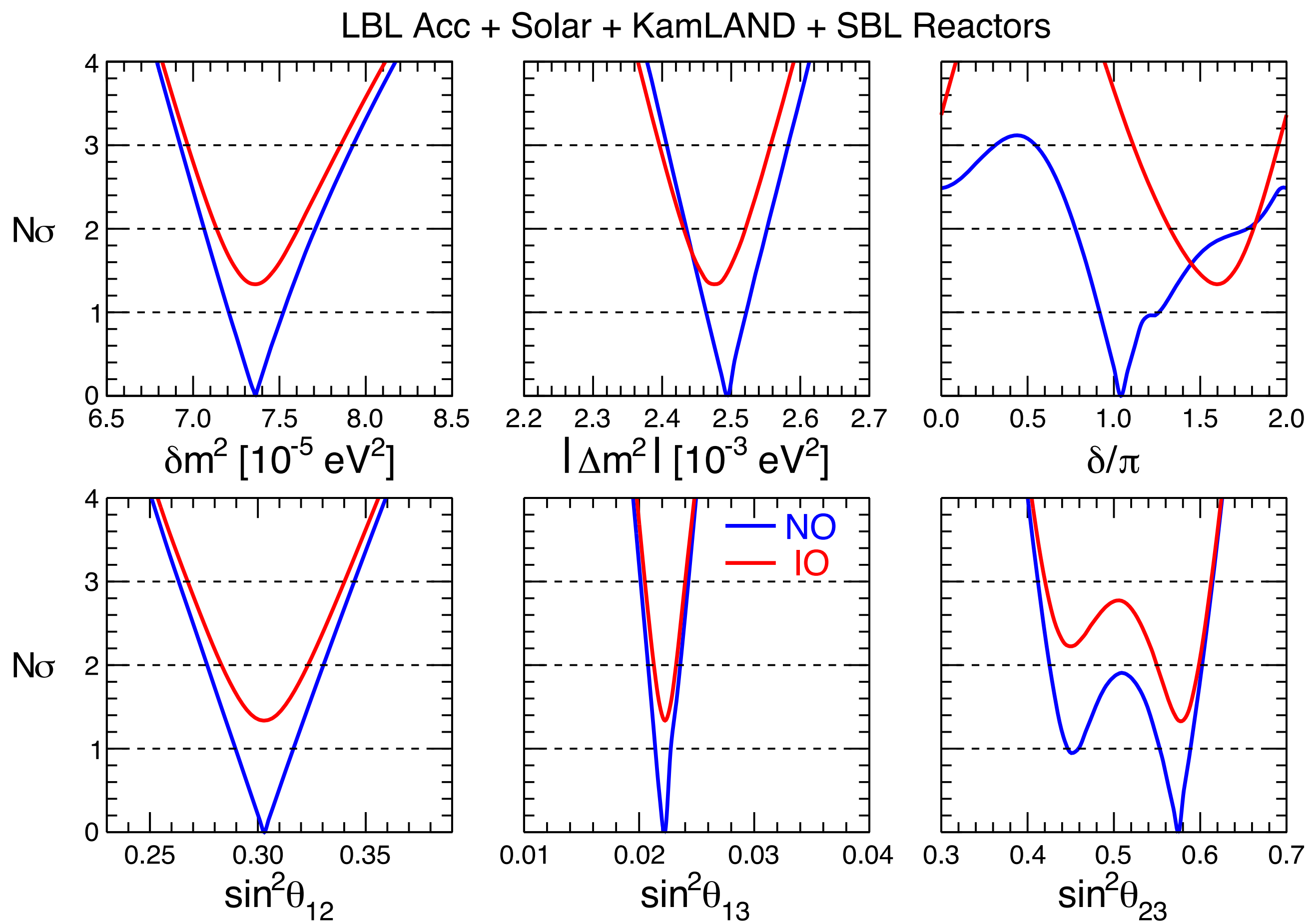
LTPC 20XY

Thank you
for your attention

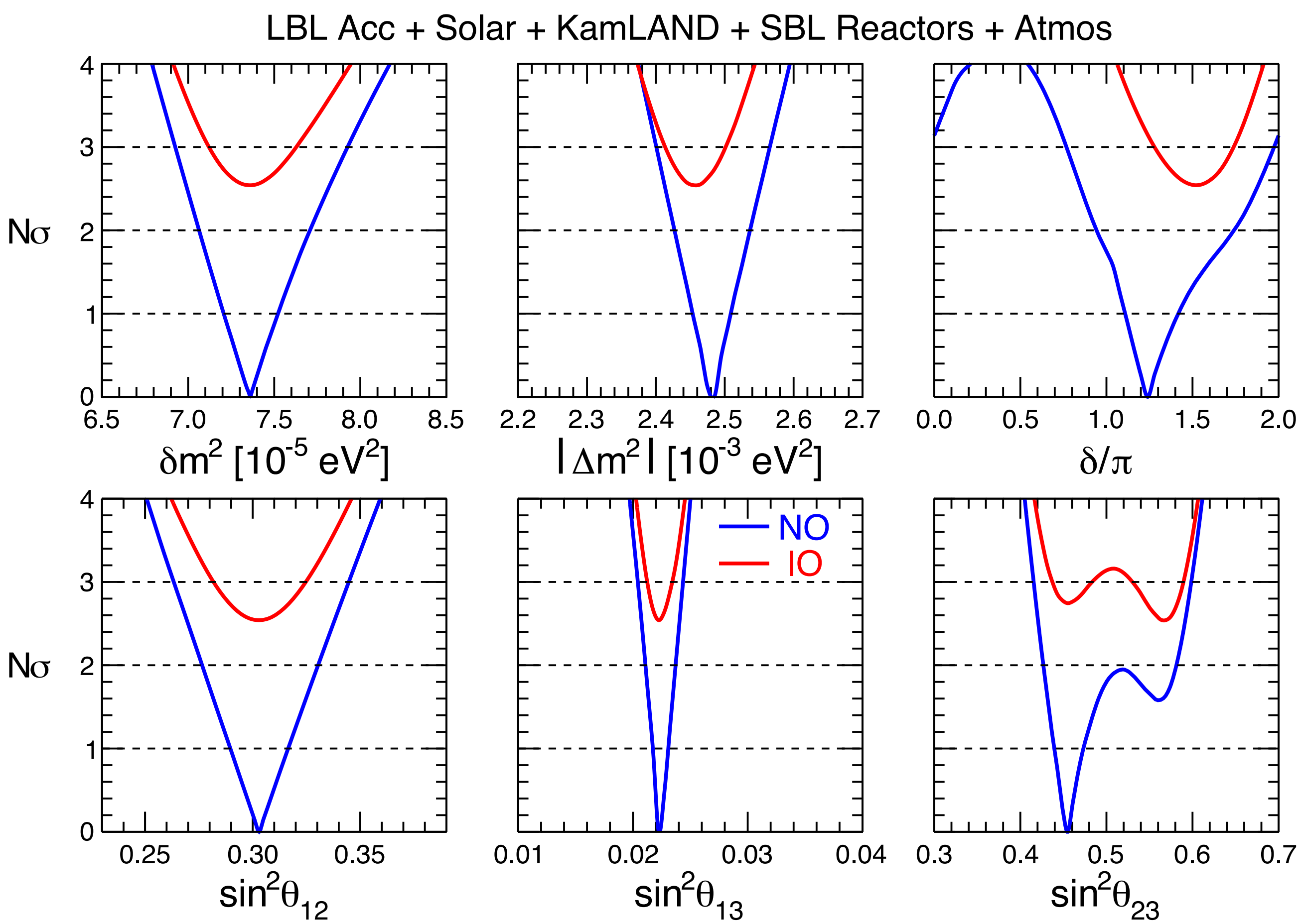
Extra slides



- Upper and and lower bounds at >>3σ for **δm^2, Δm^2, θ_{12}, θ_{13}, θ_{23}**
- Weak preference for **IO** at ~1σ. Note different **Δm^2** in NO/IO
- Octant degeneracy of **θ_{23}** also affects **θ_{13}** via correlations in $\nu_\mu \rightarrow \nu_e$
- Preference for $\delta \sim 3\pi/2$ (CP violation) in **IO**, but not in NO

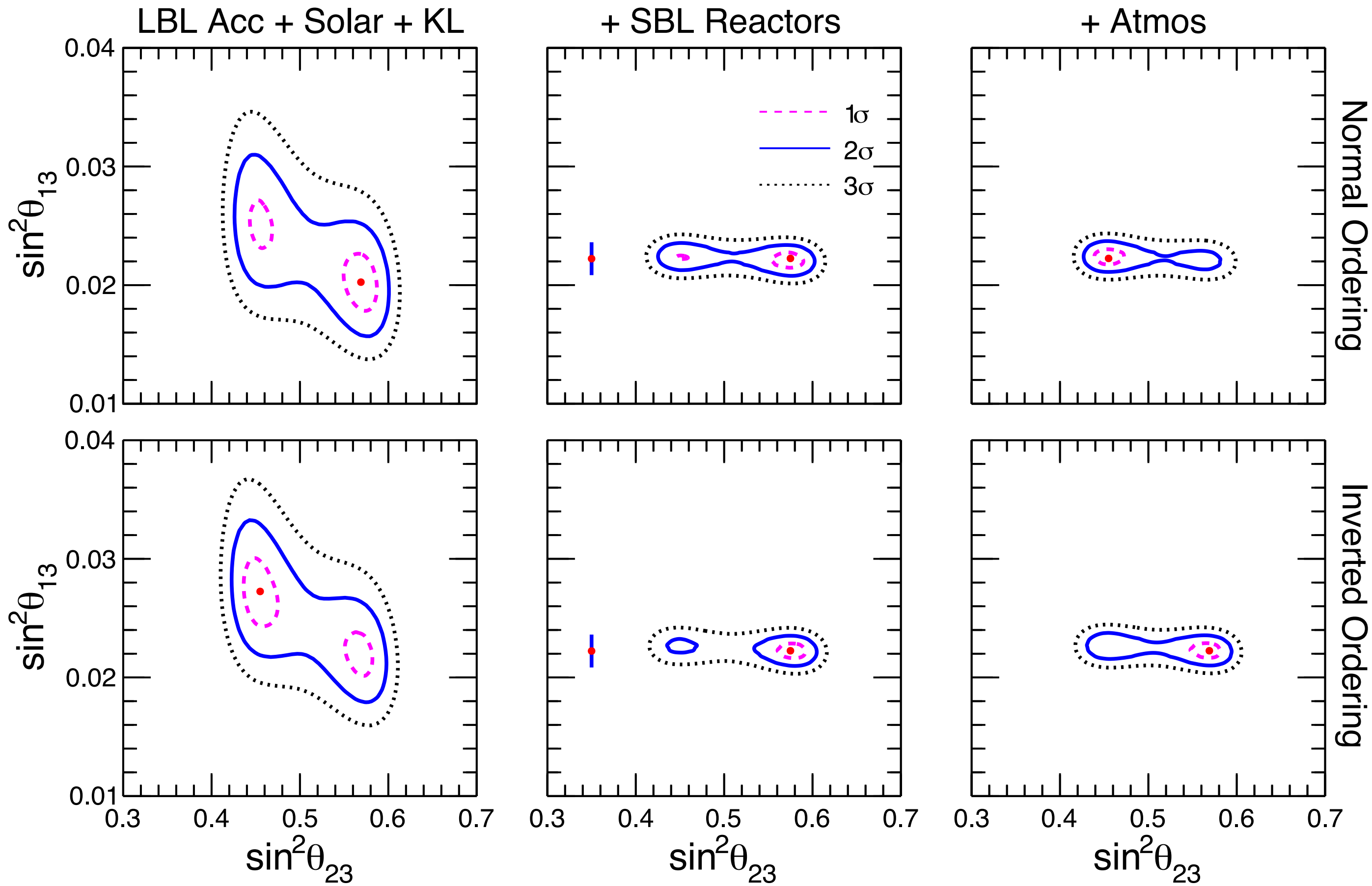


- Bounds on θ_{13} and Δm^2 strengthened
- Preference for **NO** at $\sim 1.5\sigma$. Note overall higher Δm^2 in both NO and IO
- Octant degeneracy of θ_{23} weakly broken, 2nd octant preferred at $\sim 1\sigma$
- Preference for $\delta \sim \pi$ (CP conservation) in **NO**, while $\delta \sim 3\pi/2$ in IO



- Increased preference for **NO** (2.5σ)
- Preference flips to 1st octant of θ_{23} (1.6σ)
- CP phase: best fits around $\delta \sim 1.2\pi$ in **NO** and $\delta \sim 3\pi/2$ in **IO**

(θ_{13} , θ_{23}) covariance

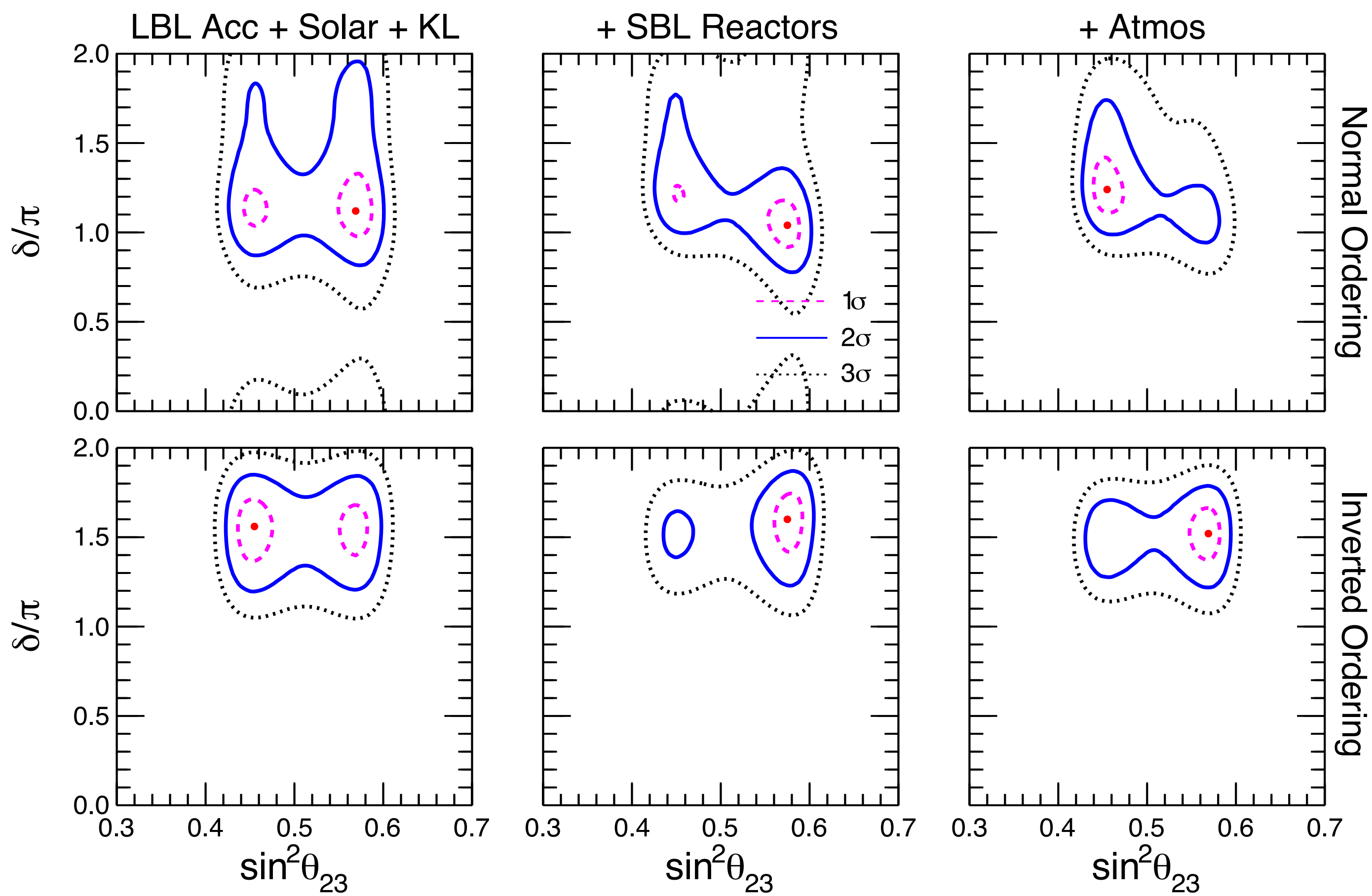


Anticorrelation due to leading $\nu_\mu \rightarrow \nu_e$ term $\sim \sin^2\theta_{23}\ \sin^2 2\theta_{13}$

Narrow and "low" θ_{13} reactor angle selects 2nd octant

1st octant preferred by atmospheric data in NO (not in IO) → fragile!

(δ , θ_{23}) covariance



Bounds on Σ

Cosmology: data / model variants

TABLE IV: Results of the global 3ν analysis of cosmological data within the standard ΛCDM $+ \Sigma$ model (possibly augmented with the $A_{\rm lens}$ parameter). The inputs numbered from 0 to 9 are the same as in [11], and refer to various combinations of the Planck 2018 angular CMB temperature power spectrum (TT) plus polarization power spectra (TE, EE), lensing potential power spectrum (lensing), Baryon Acoustic Oscillations (BAO), and the Hubble constant from HST observations of Cepheids in the Large Magellanic Cloud, H_0(R19). The inputs numbered from 10 to 12 are new and refer to ACTPol-DR4 and WMAP9 data, in combination with a prior on optical depth to reionization ($\tau_{\rm prior}$), Planck polarization data at large angular scale (lowE), and lensing data. For each case we report the 2σ upper bound on the sum of ν masses Σ (marginalized over NO and IO), together with the $\Delta\chi^2$ difference between IO and NO, using cosmology only. In the last two columns, we report the same information as in the previous two columns, but using cosmological data plus m_β and $m_{\beta\beta}$ constraints. The specific cases numbered 3 and 12 are dubbed as default and alternative, see the text for details.

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1	ΛCDM + Σ	Planck TT, TE, EE + lensing	< 0.30 eV	0.8	< 0.28 eV	0.9
2	ΛCDM + Σ	Planck TT, TE, EE + BAO	< 0.17 eV	1.6	< 0.17 eV	1.8
3	ΛCDM + Σ	Planck TT, TE, EE + BAO + lensing	< 0.15 eV	2.0	< 0.15 eV	2.2
4	ΛCDM + Σ	Planck TT, TE, EE + lensing + H_0(R19)	< 0.13 eV	3.9	< 0.13 eV	4.0
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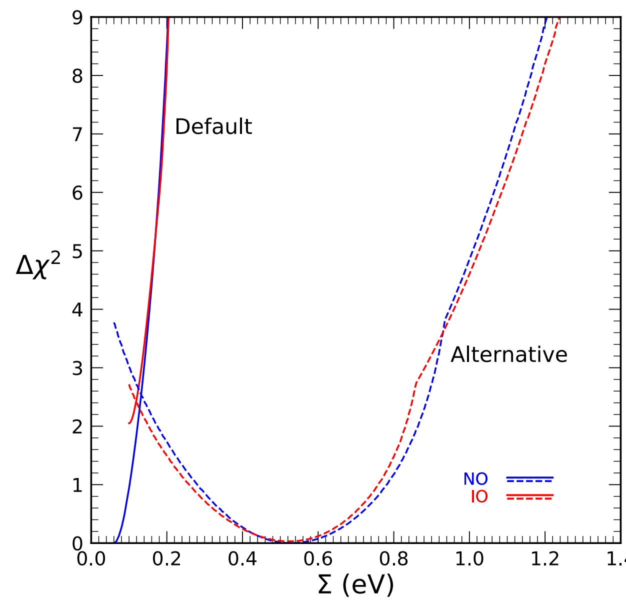
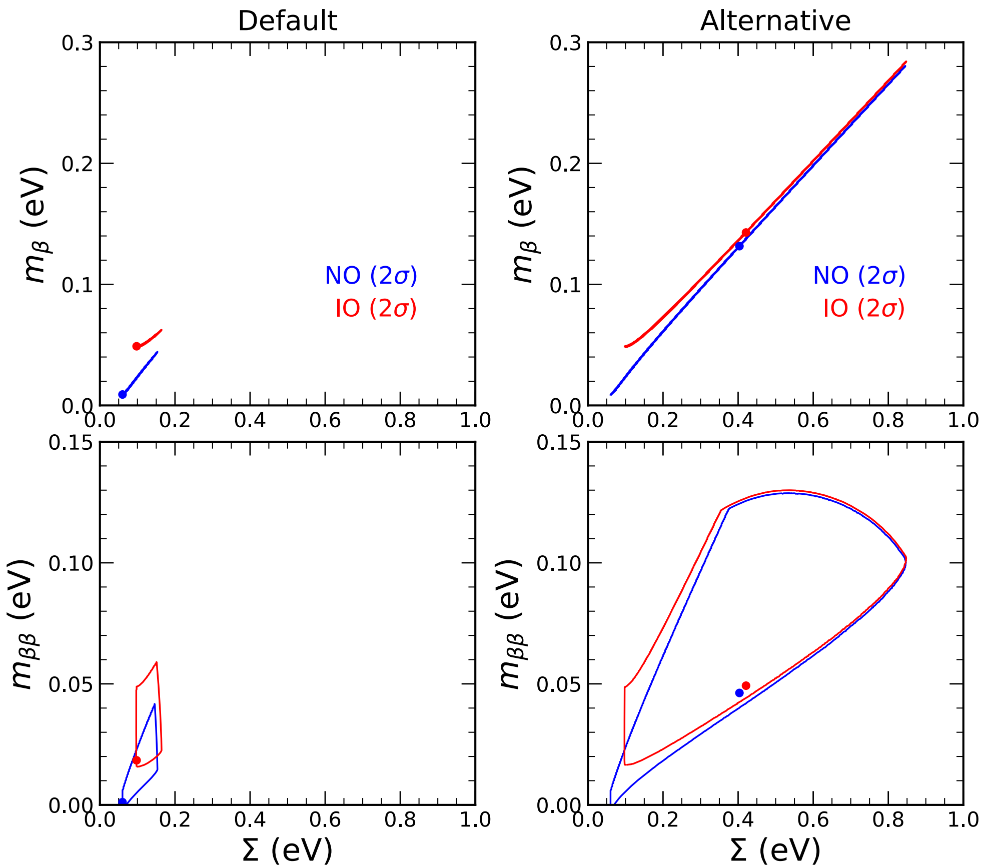
12	ΛCDM + Σ	ACT + WMAP + Planck lowE + lensing	< 0.96 eV	0.0	< 0.85 eV	0.1

(Default = #3, Alternative = #12)

Representative cases

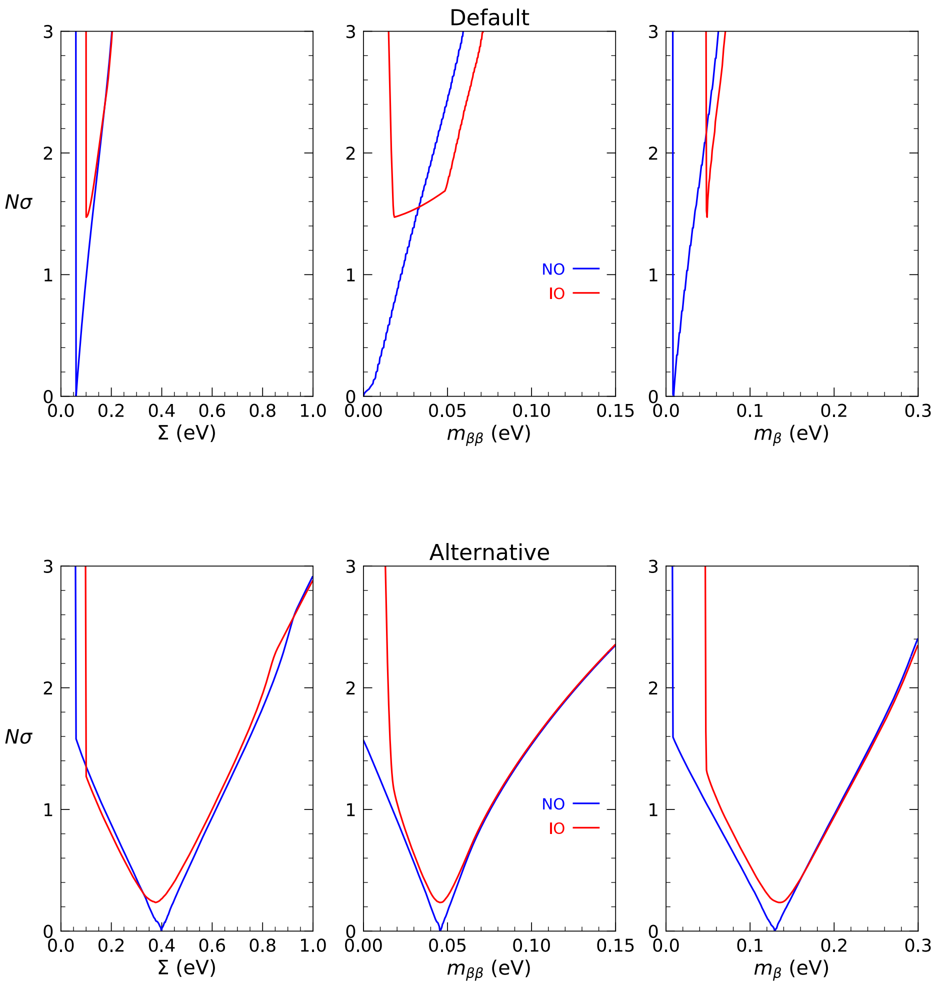


Joint bounds on (m_β , $m_{\beta\beta}$, Σ)



hep-ph 2107.00532

Separate bounds on (m_β , $m_{\beta\beta}$, Σ)



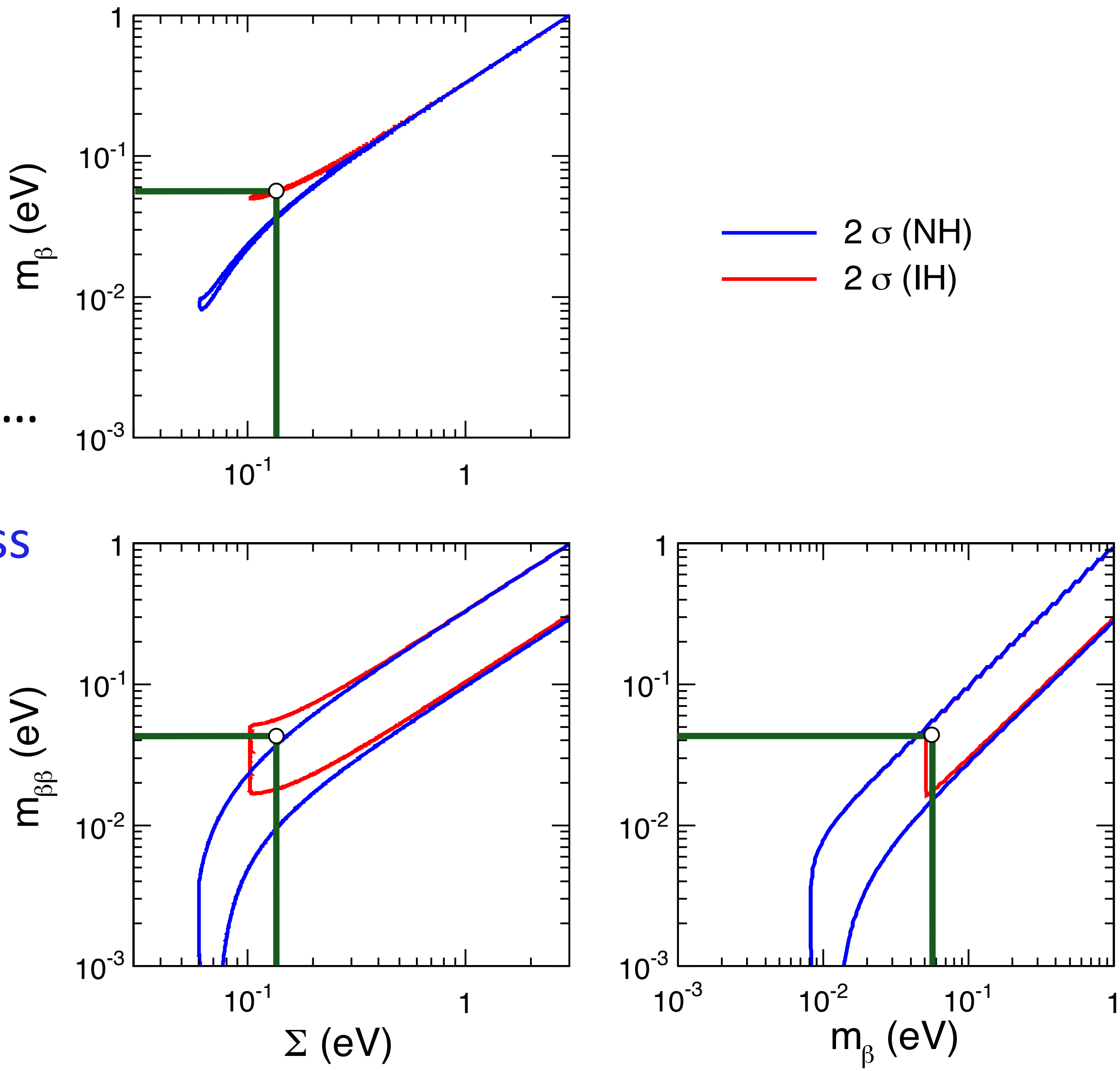
Far future: with precise and converging non-oscillation signals one could...

Determine the mass scale...

Check 3ν consistency ...

Identify mass ordering ...

Probe the Majorana phase(s) ...



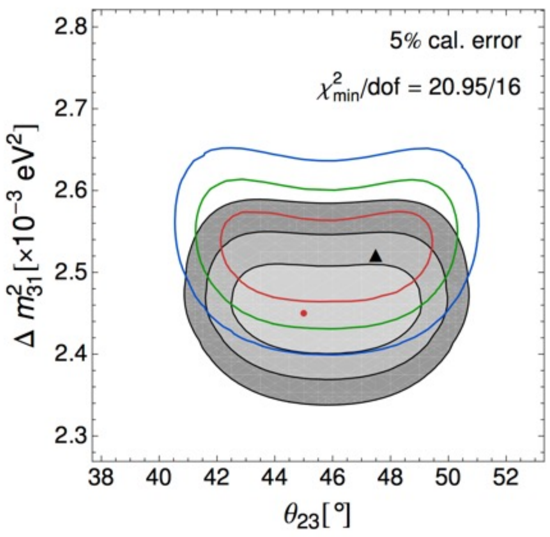
Neutrino-nuclear interactions and LBL accelerator experiments

Cross section uncertainties may affect:

Δm^2 (via E_{rec}), θ_{23} (via spectral norm+shape), δ (via ν–$\bar{\nu}$ interaction differences)

Exercise to estimate bias:

Generate data with one Xsec model and analyze them with a different model

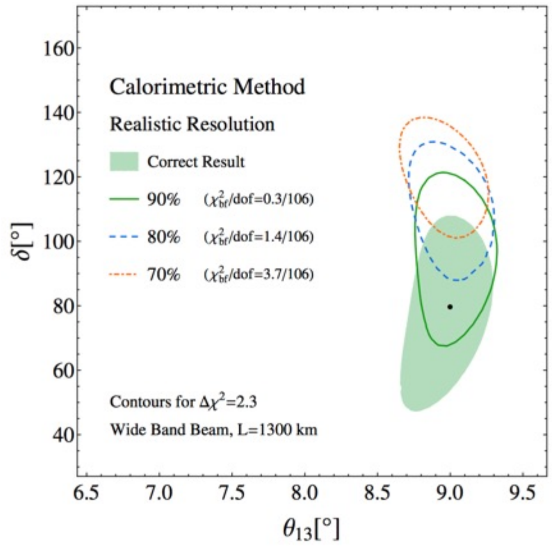


← Biased → ranges of

Δm^2, θ_{23}

δ

[Benhar+ 1501.06448, Alvarez+ 1706.03621, and refs. therein]



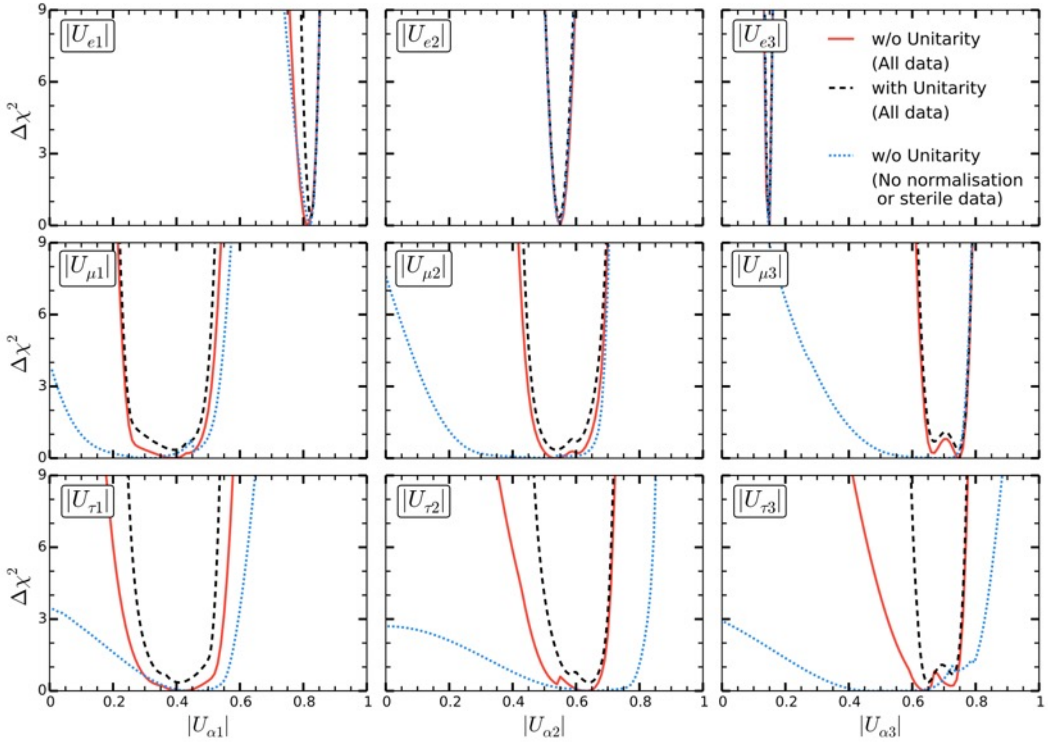
Effects reduced -but not zeroed- by tuning model(s) to ND data.

Remind: No model currently explains all available Xsection data!

Current 1% global-fit formal accuracy on Δm^2 might be optimistic

Progress on flux and cross section predictions also needed to get precise absolute normalizations of events → important for "unitarity" tests
["leakage" of PMNS elements embedded in a matrix larger than 3x3]

E.g., Parke & Ross-Lonergan 1508.05095, model-independent



Stronger constraints by assuming specific models for new (sterile) neutrino states ...which might appear anywhere from the ~eV scale (hints?) to the GUT scale! Surprises may include not only extra states, but also new interactions

There is much more than just cross sections for LBL accel. expts!

Need to know better the nuclear response to EW probes in various contexts

Beta decays for nuclear reactor spectra

Coherent Elastic Neutrino Nucleus Scattering

Charge exchange processes for DBD NME

Effective neutrino axial current: coupling strength and form factors

Neutrinos in very dense fermion backgrounds (SN, mergers, early universe)

Nuclear astrophysics and neutrinos (nucleosynthesis & solar reactions networks)

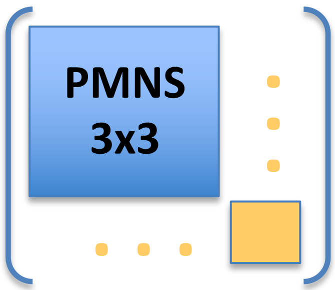
EFT vs QCD

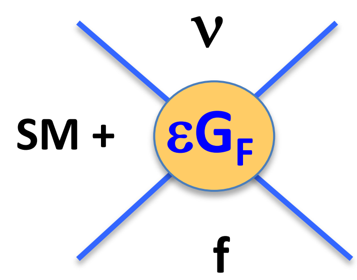
Ab initio nuclear structure

Connections with other EW probes (gammas, electron, possible WIMPs...)

Stress-tests of the 3ν paradigm

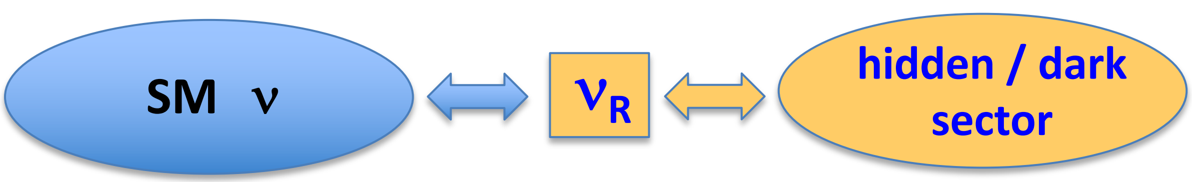
Testing the resilience of the 3ν paradigm to **extra ν states** or to **new interactions:**
Approach often involves PMNS unitarity violations or nonstandard FCNC, FDNC (NSI)





Extra parameters may dilute hints of PMNS unknowns: CPV, θ_{23} octant, ordering.
Rich phenomenology in (non)oscillation experiments + astrophysics & cosmology
No evidence so far, except possible **O(eV) sterile ν** anomalies [not discussed here]

Going further: consider both extra states and interactions: RH neutrinos as a **bridge** ("portal") to weakly coupled **BSM physics** ("hidden" or "dark" sector), e.g. **DM**



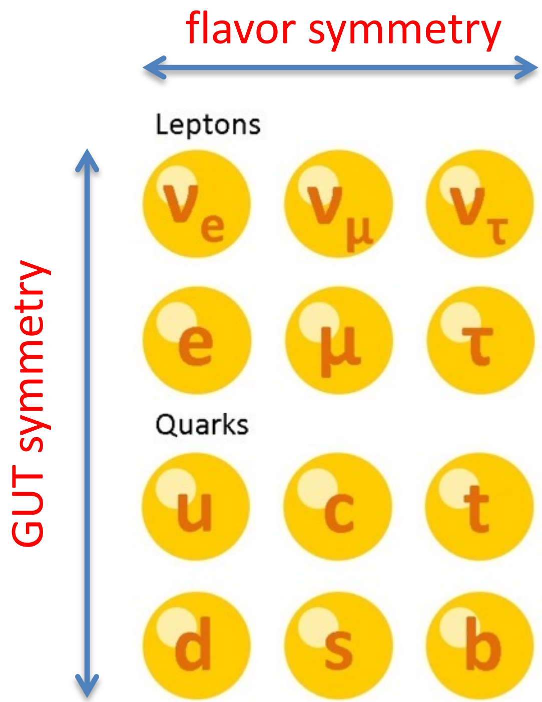
Low-scale BSM "portal" scenarios can provide new stress tests of the 3ν paradigm (as well as of $3\nu+1\nu_s$ models), e.g. via **modified neutrino dispersion relations**.

Mixings: Many interesting ideas, but still looking for an "illumination"...

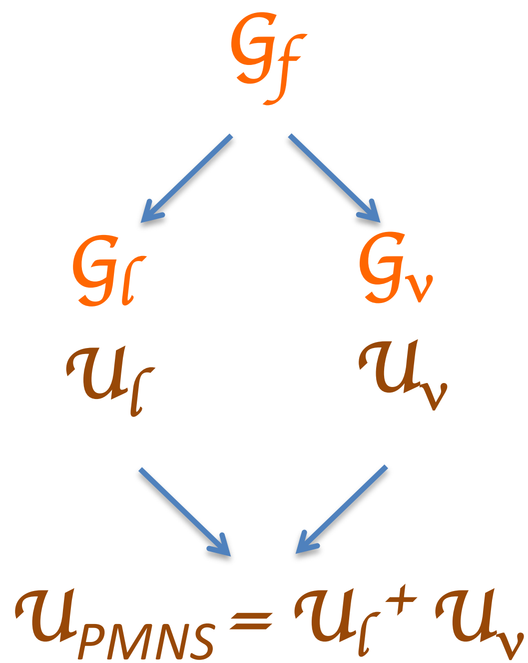
No organizing principle ("anarchy")	
Discrete family simmetries ("geometry")	linear relations between $\theta_{13}\cos\delta$ and θ_{12}, θ_{23}
Continuous flavor simmetries ("dynamics")	links between neutrino masses/angles/phases
Common quark/lepton features ("complementarity")	links between θ_{13} and θ_C

Model building with symmetries

New high scale(s) with higher symmetries



Flavor symmetries: group patterns



Examples:

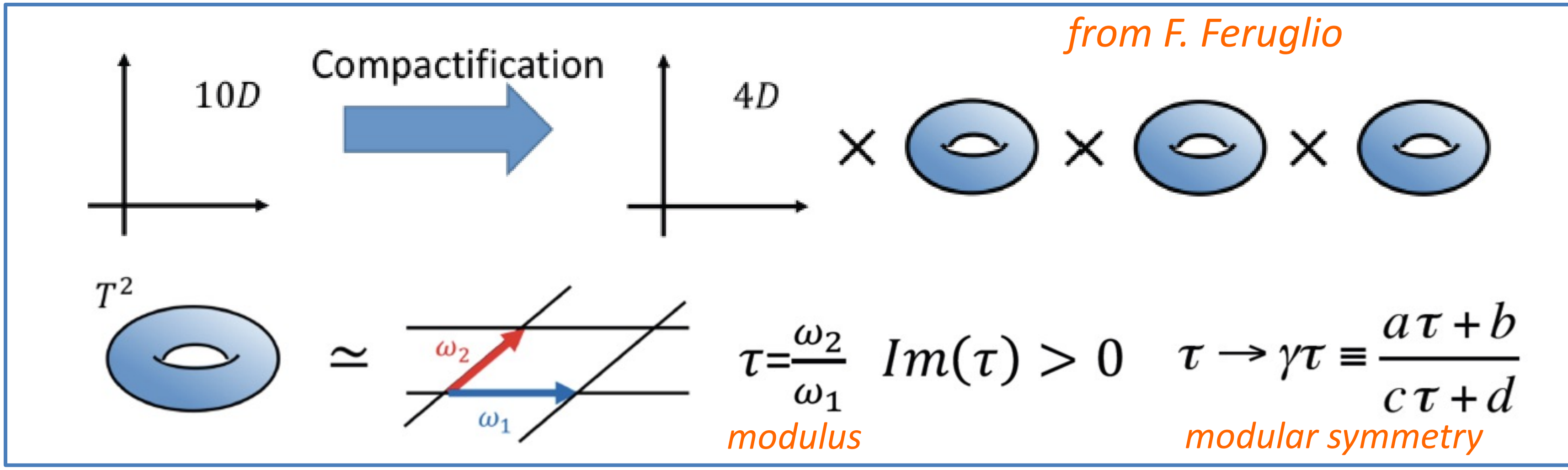
GUT→ $\mathcal{U}_\ell \approx \mathcal{V}_{CKM}$

$\mathcal{G}$ ← Permutations

Occam's razor?

Symmetry models often involve a large and carefully crafted scalar sector (e.g., flavons + vev's)

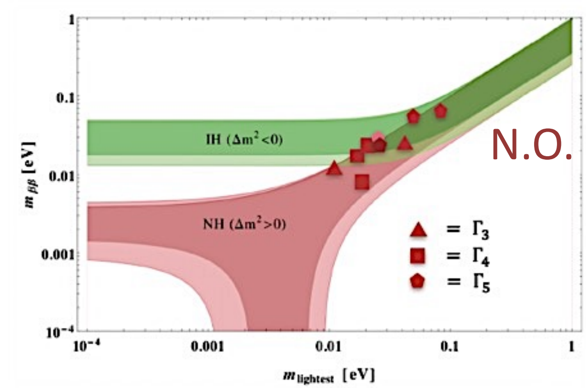
Can symmetries emerge in a "more economical" way? Yes! E.g.: Modular Invariance
[inspired by string theory & compactified extra dimensions; requires supersymmetry.]



Yukawa's Y=Y(τ) become highly symmetric/constrained:

obtain masses, mixings and phases with # parameters < # observables → predictions, e.g., →

Recently: extend modular invariance to all fermions' Y



Time-honored ideas continue to illuminate the path forward!

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perspective

Symmetry and emergence

[**Edward Witten**, arXiv:1710.01791]

In a modern understanding of particle physics, global symmetries are approximate and gauge symmetries may be emergent. This view, which has echoes in condensed-matter physics, is supported by a variety of arguments from experiment and theory.

No reason for global symmetries to be exact, from different theoretical perspectives.

No global lepton number conservation	$\mathcal{L}_1 = \frac{1}{M} HHLL$	**Majorana neutrinos, $\nu = \bar{\nu}$**
No global baryon number conservation	$\mathcal{L}_2 = \frac{1}{M^2} QQQL$	**Proton decay**
No a priori CP conservation in QCD	$\frac{\theta}{32\pi^2} \varepsilon^{\mu\nu\alpha\beta} \mathrm{tr}\, F_{\mu\nu} F_{\alpha\beta}$	**Axion**

General arguments not weakened by absence of new physics at the LHC scale.

Any of these three possible discoveries would be a historical landmark in science.

In particular: Majorana ν
may offer a great opportunity
to probe **a scale M >> v** (EWSB)
via the see-saw mechanism...

$$\mathcal{L}_1 = \frac{1}{M} HHLL$$

M (same as GUT and p-decay?)

v

heavy **N**

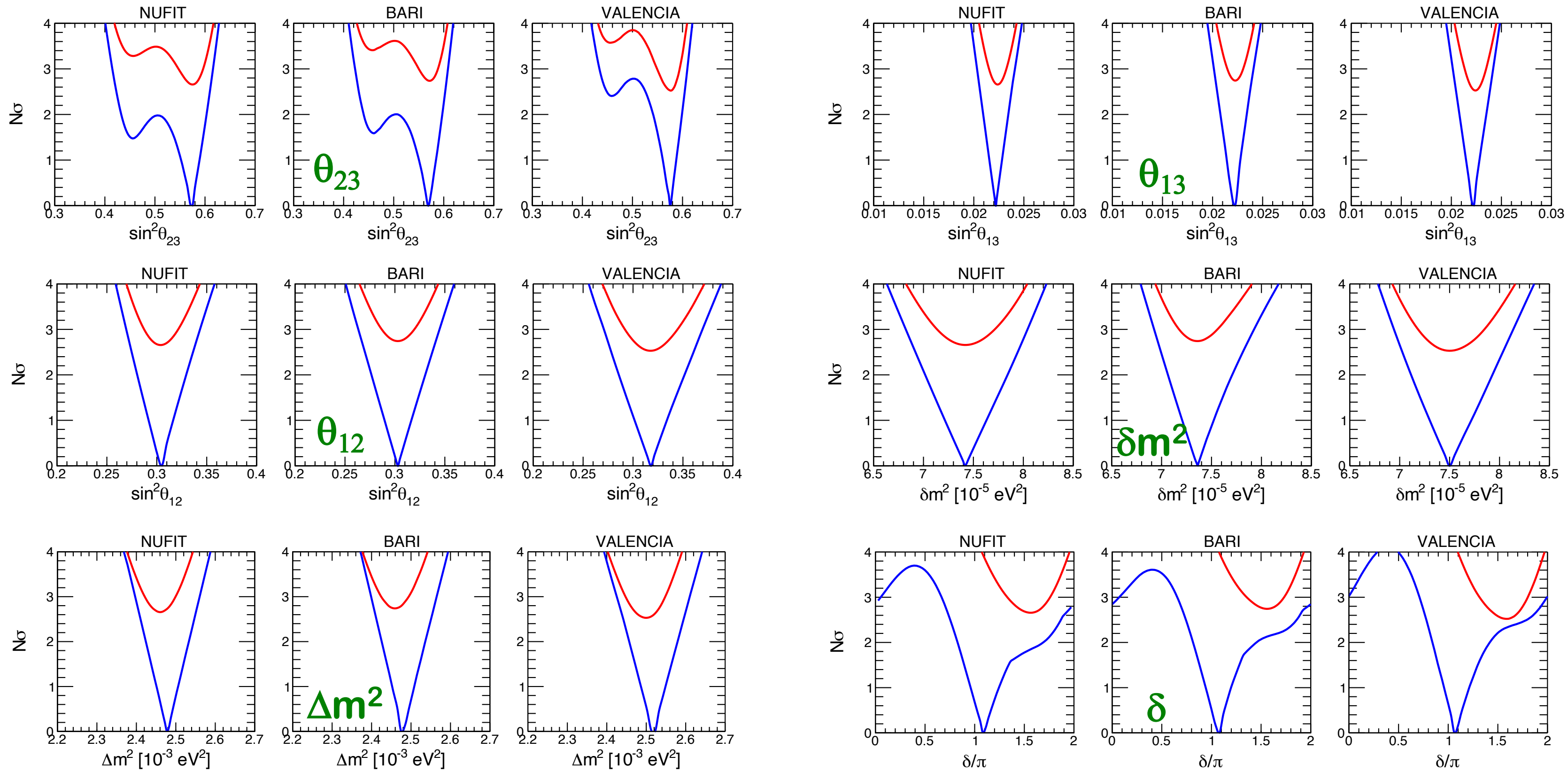
light **ν**

m(ν) ~ Y² v²/M

... and to address fundamental physics issues, such as:

- lepton number violation and associated phenomena (0νββ)
- new sources of CP violation at low and high scales
- **baryon (matter-antimatt.) asymmetry of the universe (BAU)...**

Comparison among independent global neutrino oscillation data analyses



BARI: 2003.08511

NUFIT: 2007.19742 [with Δm^2_{13} and Δm^2_{23} converted to our Δm^2]

VALENCIA: 2006.11237v2 [with Δm^2_{13} and Δm^2_{23} converted to our Δm^2]