Kavli IPMU, U. of Tokyo in Kashiwa: “Prospects of Neutrino Physics”, April 8th, 2019

3ν masses, mixings and CPV: Status and challenges

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Image credit: Vectorstock royalty free image (adapted)

OUTLINE

Status of the 3ν paradigm 2018

Preliminary update 2019

Future challenges

Work done in collaboration with:
Francesco Capozzi (MPI Munich), Antonio Marrone (U. Bari), Antonio Palazzo (U. Bari)

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Status of the 3ν paradigm 2018

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Future challenges

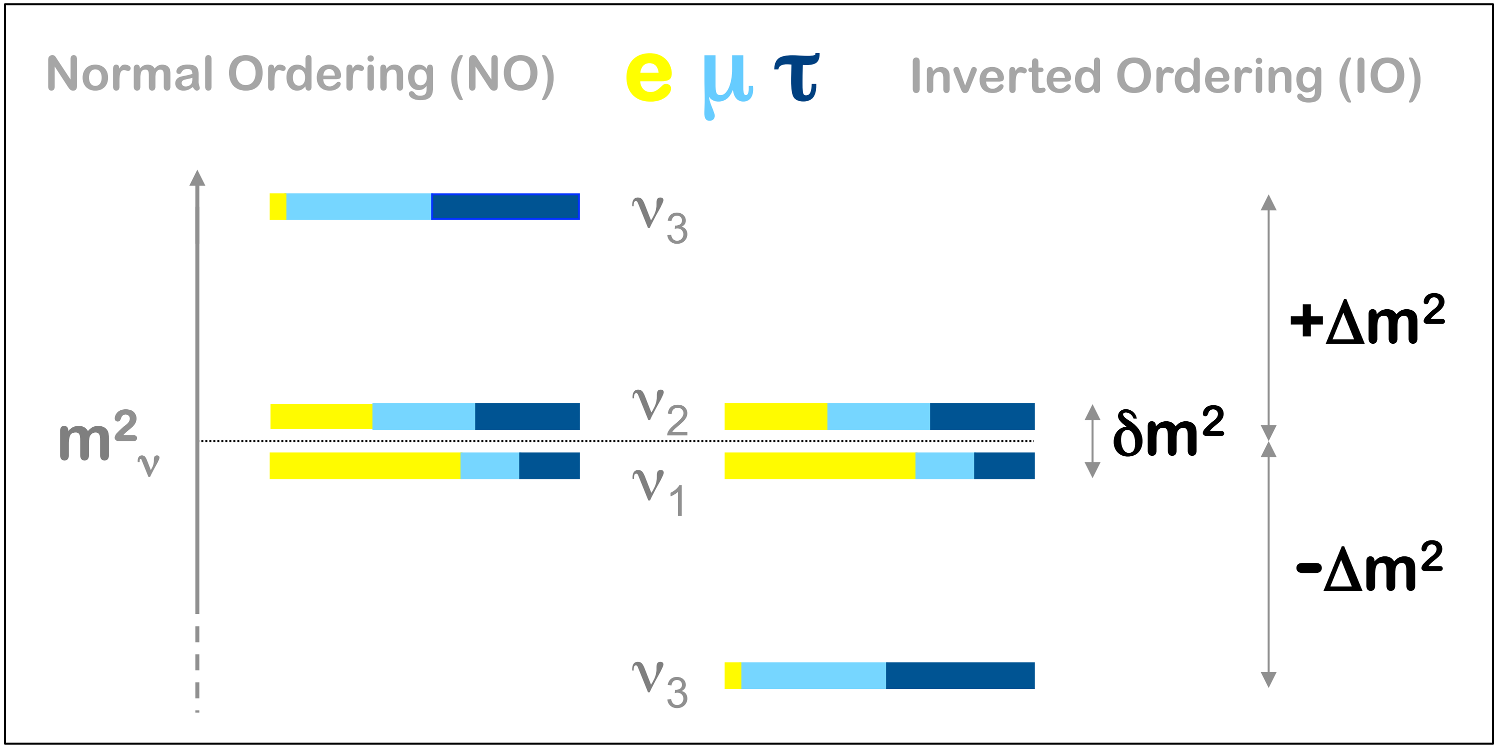
"Broad-brush" 3ν picture (with 1-digit accuracy)

Knowns:

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

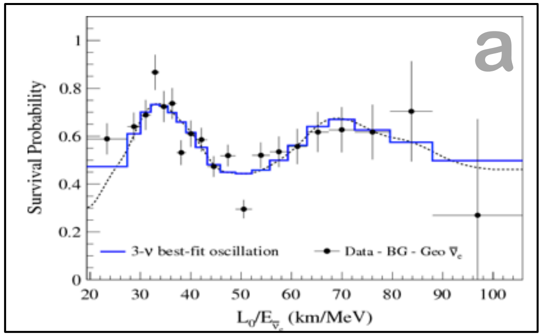
Unknowns:

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

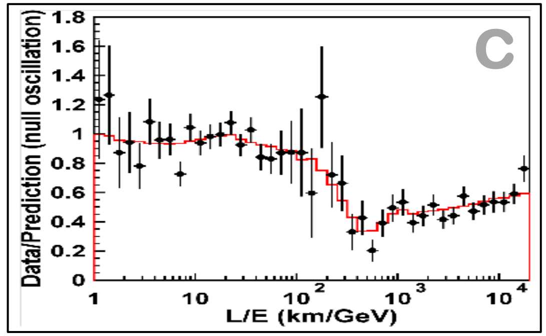


Beautiful data have established this 3ν oscillation framework

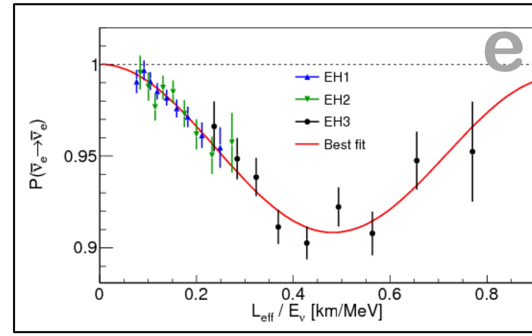
e→e (δm^2 , θ_{12})



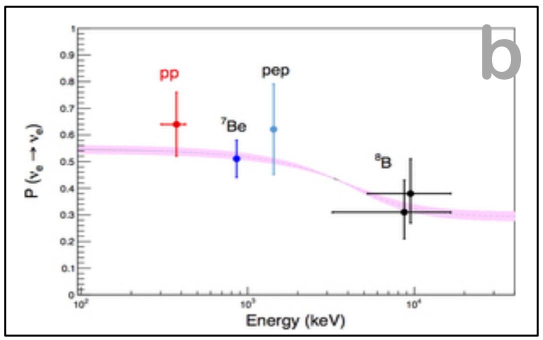
μ→μ (Δm^2 , θ_{23})



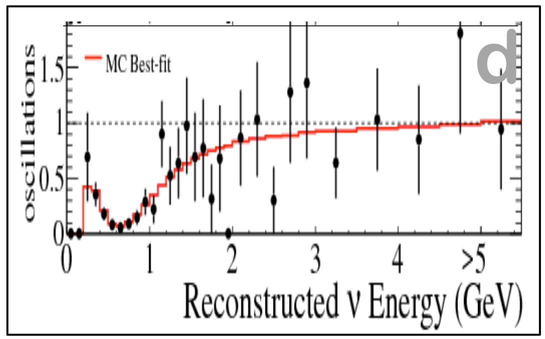
e→e (Δm^2 , θ_{13})



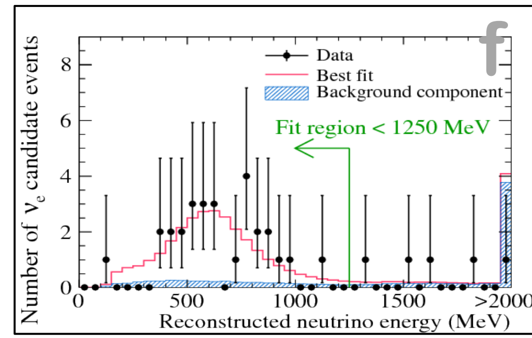
e→e (δm^2 , θ_{12})



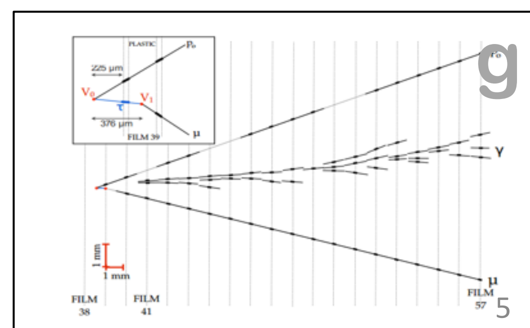
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



μ→τ (Δm^2 , θ_{23})



Shown: only some data sets + leading oscill. sensitivities to mass-mixing neutrino parameters.

Subleading effects involve **CPV** and **NO vs IO** difference, essentially via **μ→e** in LBL accel. and atmospher. expts

LBL accelerators (T2K and NOvA) are dominantly sensitive to **(Δm^2 , θ_{13} , θ_{23})** but also probe δ and **NO vs IO**, provided that (δm^2 , θ_{12}) are fixed by **solar+KL**.

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \simeq\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta m^2}{A-\Delta m^2}\right)^2 \sin^2\left(\frac{A-\Delta m^2}{4E}x\right) \\
&+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\left(\frac{\delta m^2}{A}\right)\left(\frac{\Delta m^2}{A-\Delta m^2}\right)\sin\left(\frac{A}{4E}x\right)\sin\left(\frac{A-\Delta m^2}{4E}x\right)\cos\left(\frac{\Delta m^2}{4E}x\right)\cos\delta \\
&- \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\left(\frac{\delta m^2}{A}\right)\left(\frac{\Delta m^2}{A-\Delta m^2}\right)\sin\left(\frac{A}{4E}x\right)\sin\left(\frac{A-\Delta m^2}{4E}x\right)\sin\left(\frac{\Delta m^2}{4E}x\right)\sin\delta \\
&+ \cos^2\theta_{13}\sin^2 2\theta_{12}\left(\frac{\delta m^2}{A}\right)^2 \sin^2\left(\frac{A}{4E}x\right)\ , \qquad (13)
\end{aligned}
$$

where $A = 2\sqrt{2}G_F N_e E$ governs matter effects, with $A \to -A$ and $\delta \to -\delta$ for $\nu \to \overline{\nu}$, and $\Delta m^2 \to -\Delta m^2$ for normal to inverted ordering. At typical NOvA energies ($E \sim 2$ GeV) it is $|A/\Delta m^2| \sim 0.2$,

[Hereafter: $\Delta m^2 = (\Delta m^2_{31} + \Delta m^2_{32})/2$]

SBL reactors (Daya Bay, RENO, Double Chooz) are dominantly sensitive to **(Δm^2 , θ_{13})** and shrink the θ_{13} range dramatically, with correlated effects on the other parameters

Atmospheric ν searches (mainly Super-Kamiokande, plus IceCube DC) also contribute to probe and to constrain **(Δm^2 , θ_{13} , θ_{23} , δ)** as well as testing **NO vs IO.**

Higher-res. picture → Combined (global) analysis of ν data sets

→

Our analysis includes data in the sequence:

LBL Accel + Solar + KL (KamLand)

LBL Accel + Solar + KL + SBL Reactor

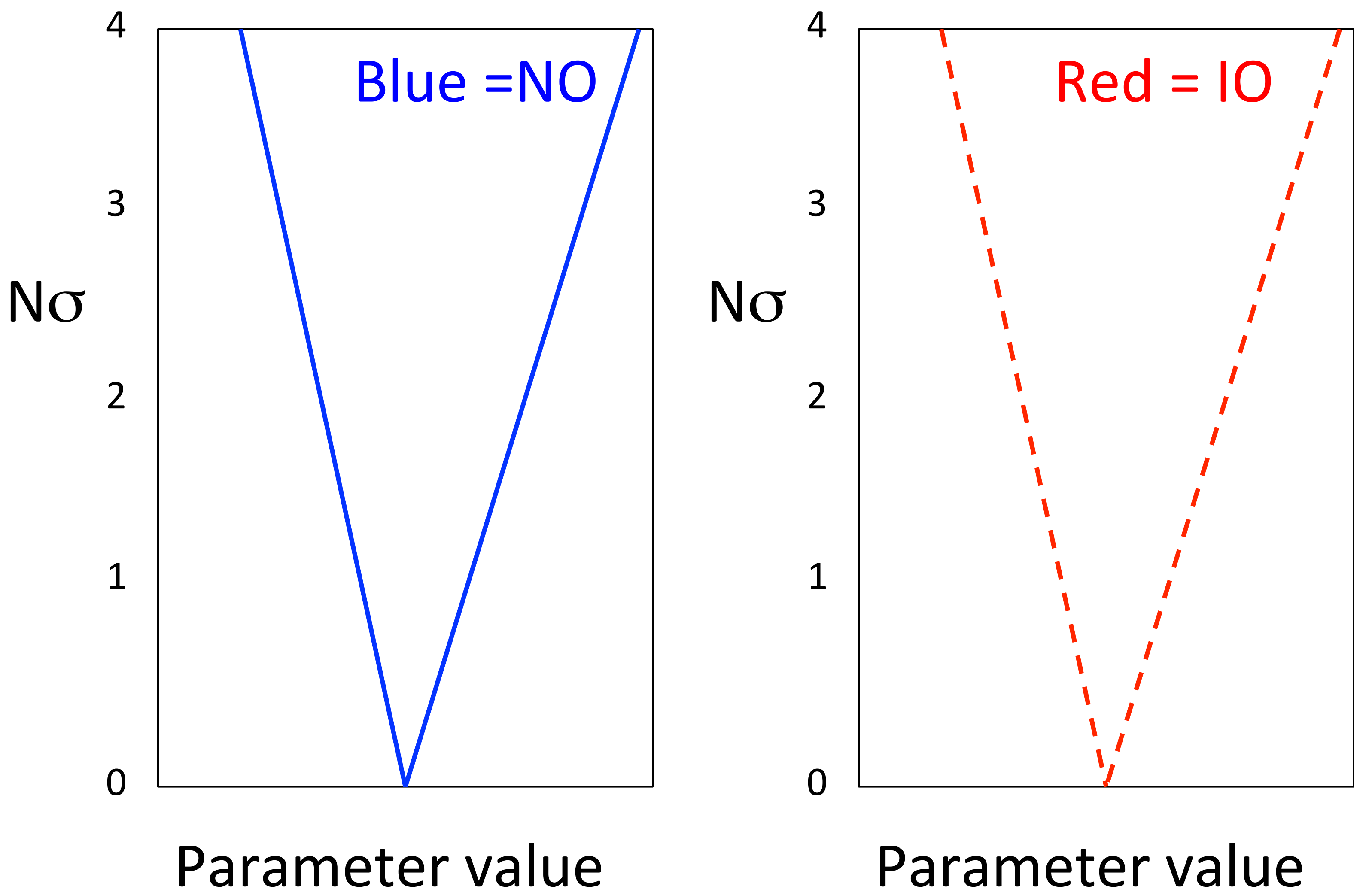
LBL Accel + Solar + KL + SBL Reactor + Atmosph.

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

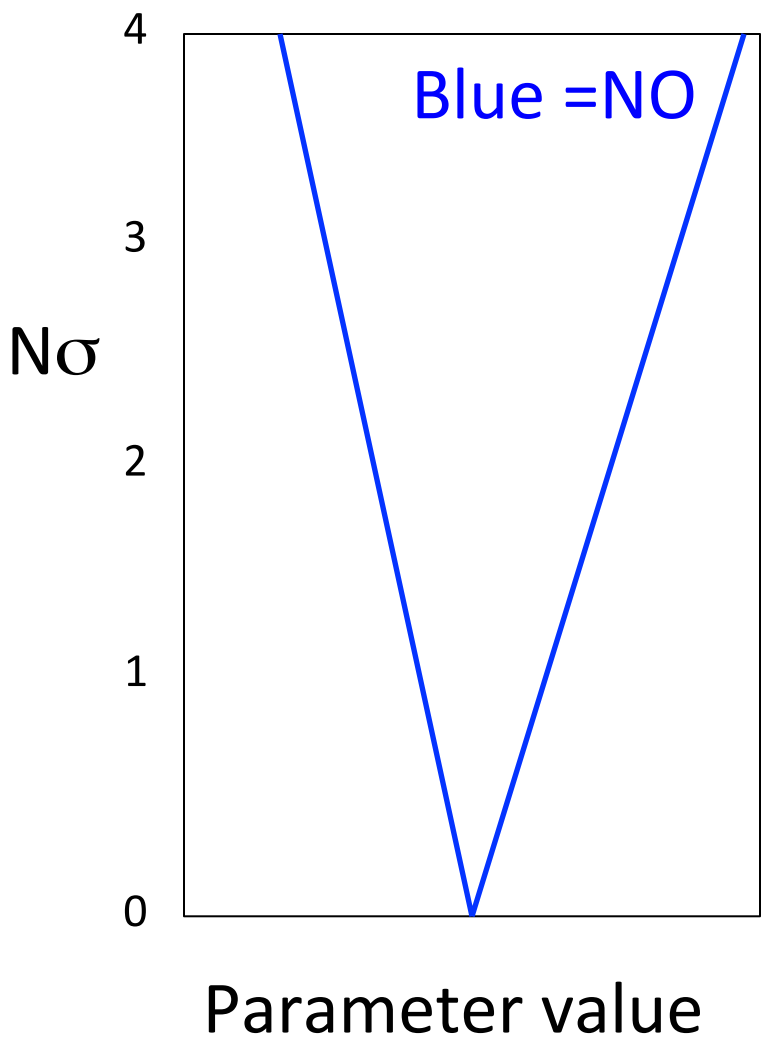
C.L.'s refer to $N\sigma = \sqrt{\Delta\chi^2} = 1, 2, 3, \ldots$

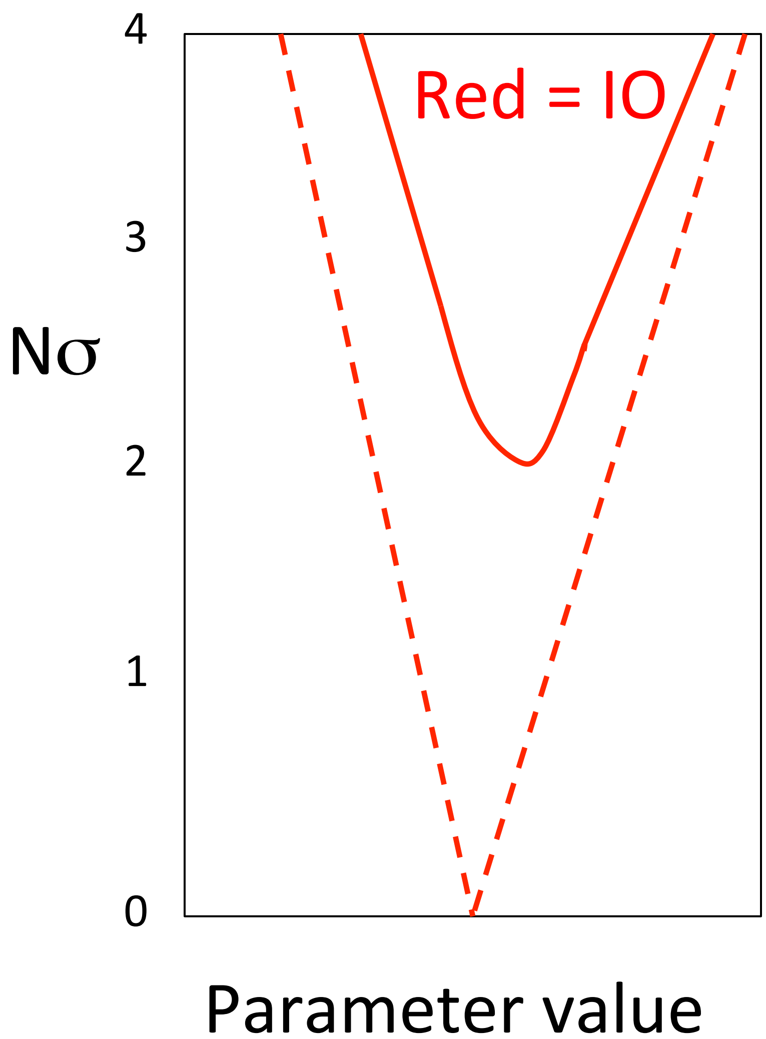
Global fit results: 1804.09678 by F. Capozzi, E. Lisi, A. Marrone, A. Palazzo, PPNP 102, 48 (2018)

In the following figures: Typical Nσ limits would be ~linear and symmetric for ~gaussian errors around the **separate best fits for both NO and IO.**



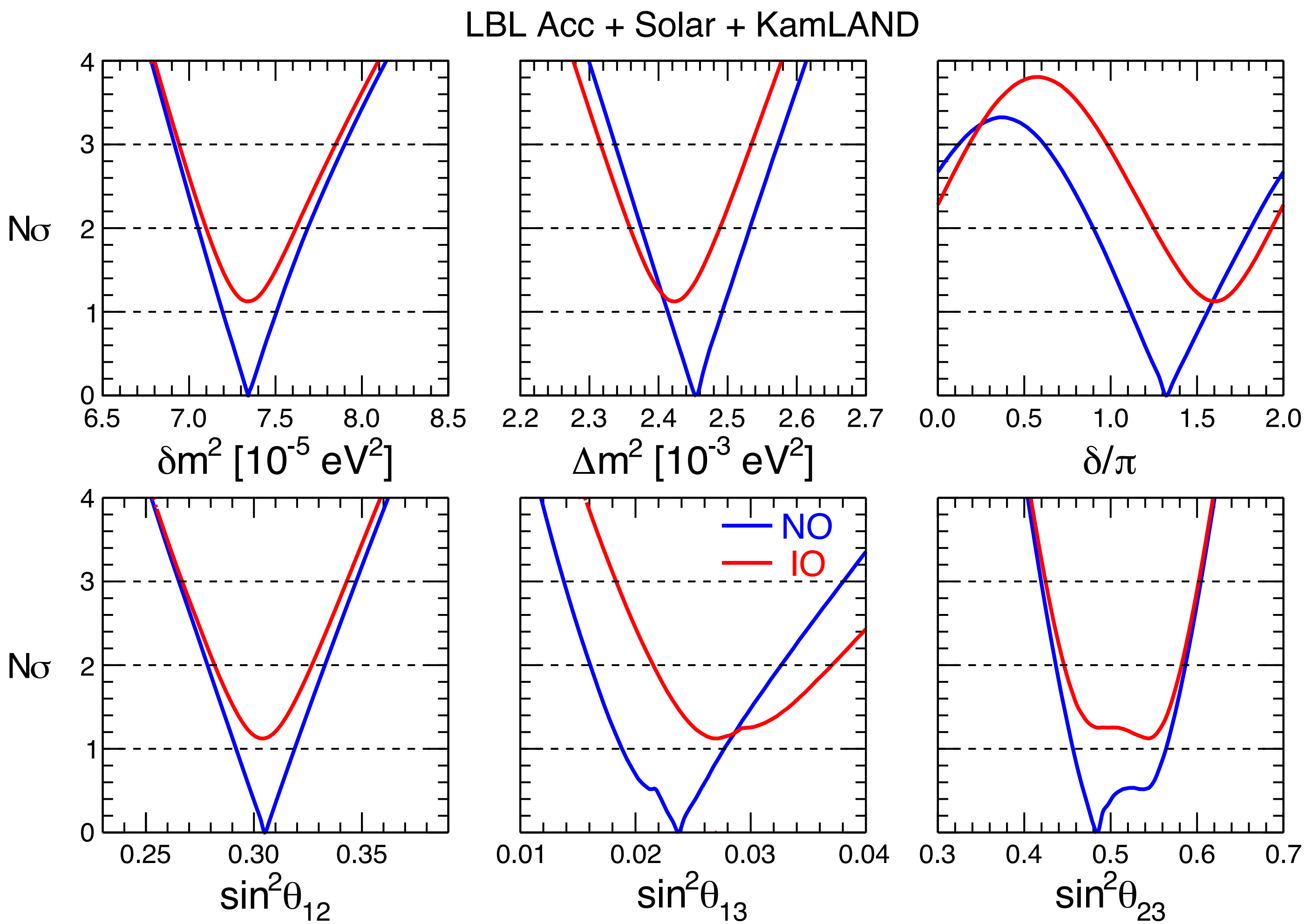
However, **bounds for IO move upwards** if one takes into account that currently **NO gives the absolute best fit**. Recall: **$N\sigma = \sqrt{\Delta\chi^2} = 1, 2, 3\ldots$**





Results from real data →

[Data as of April 2018]



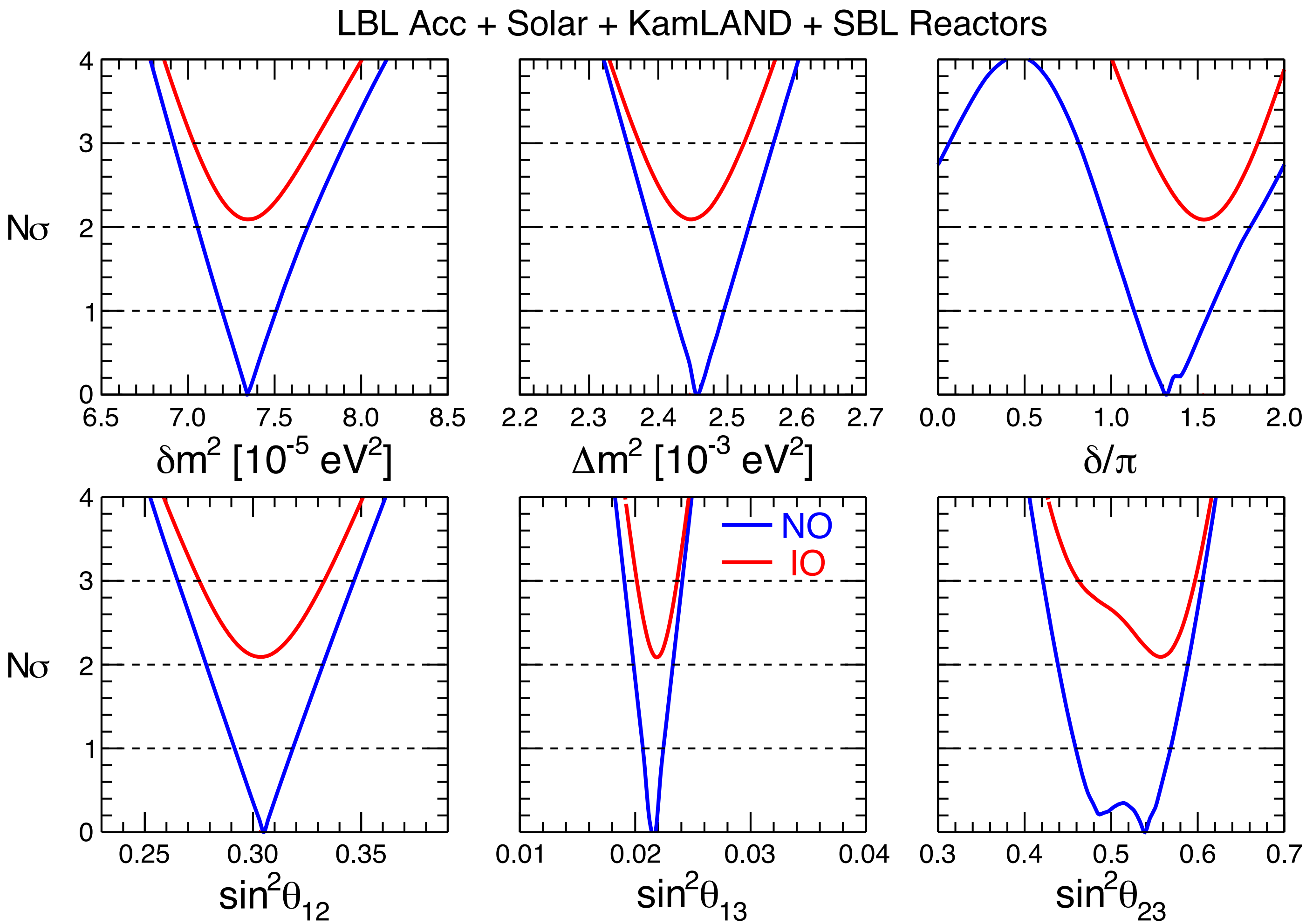
The 2 mass[2] parameters and the 3 mixing angles bound at >4σ level.

Largest mixing angle θ_{23} close to $\pi/4$, but octant undetermined at 1σ.

CP phase favored around $3\pi/2$ (max CPV with $\sin\delta \sim -1$).

IO slightly disfavored with respect to NO at ~1σ level.

[Data as of April 2018]



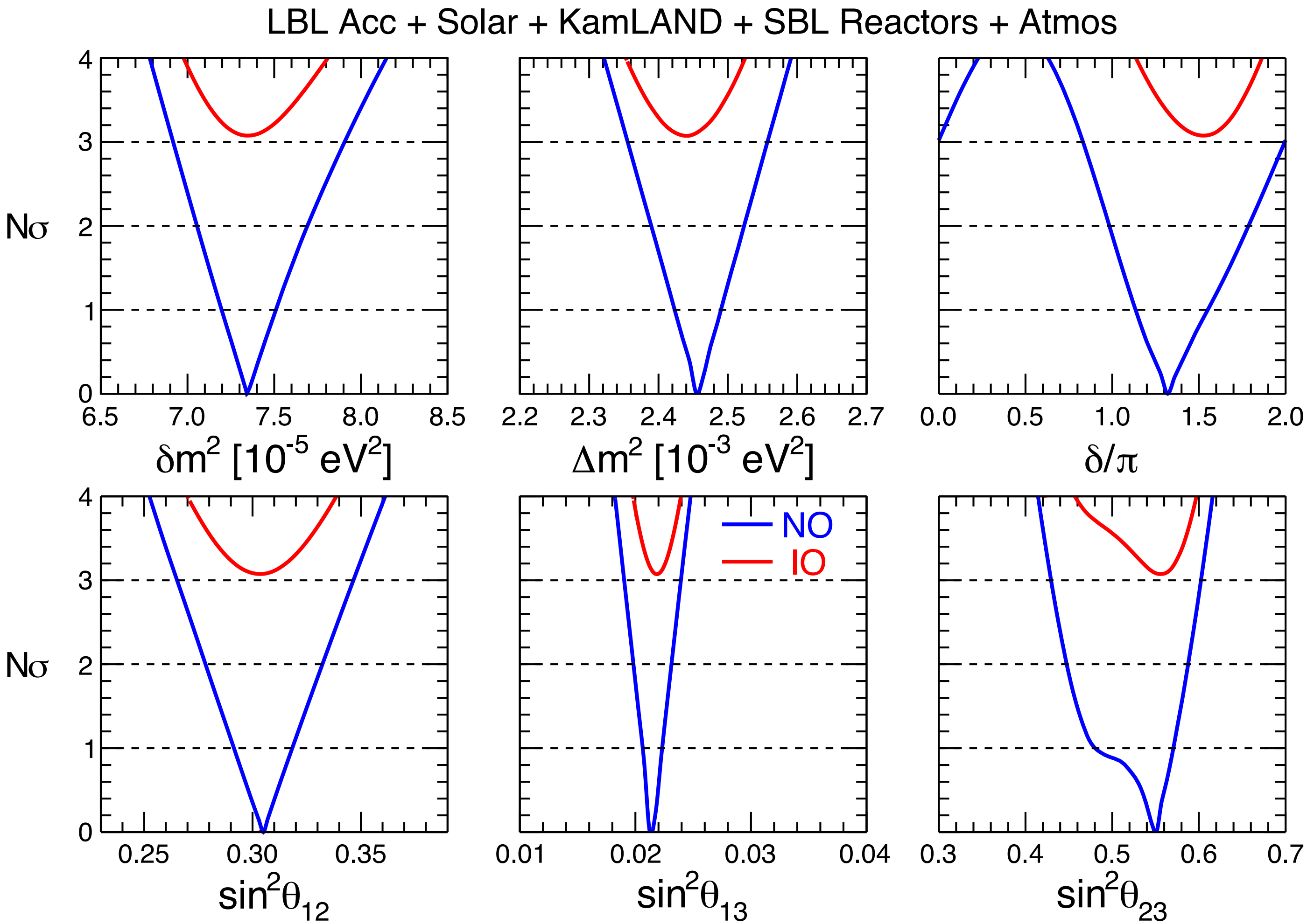
Range of smallest mixing angle θ_{13} dramatically reduced

Largest mixing angle θ_{23} close to $\pi/4$, but octant undetermined at 2σ.

Max CPV at ~$3\pi/2$ favored , CP conservation disfavored at ~2σ in NO.

IO disfavored with respect to NO at ~2σ level.

[Data as of April 2018]



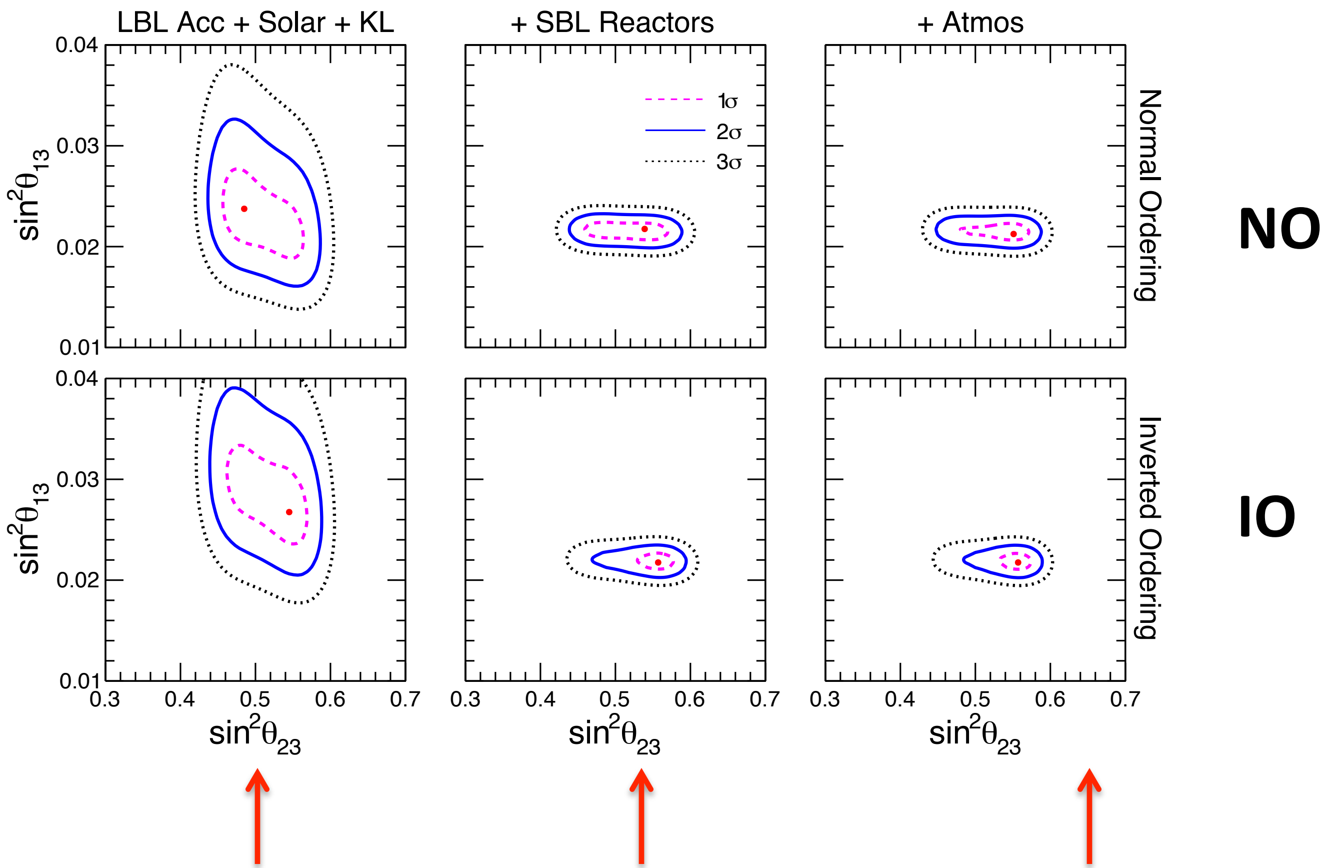
Further improvements for various parameters: 1σ bounds at few % level

Largest mixing angle (2-3) close to π/4, but octant undetermined at 2σ.

CPV: sinδ ~ -1 favored, ~ 0 disfav., ~ +1 exclud. Meaningful bounds at ~3σ.

IO significantly disfavored with respect to NO, at ~3σ level (but: caution!)

Understanding the accelerator + reactor (+atm.) impact on NO preference



Anticorrelation due to leading term in appearance channel at accelerators

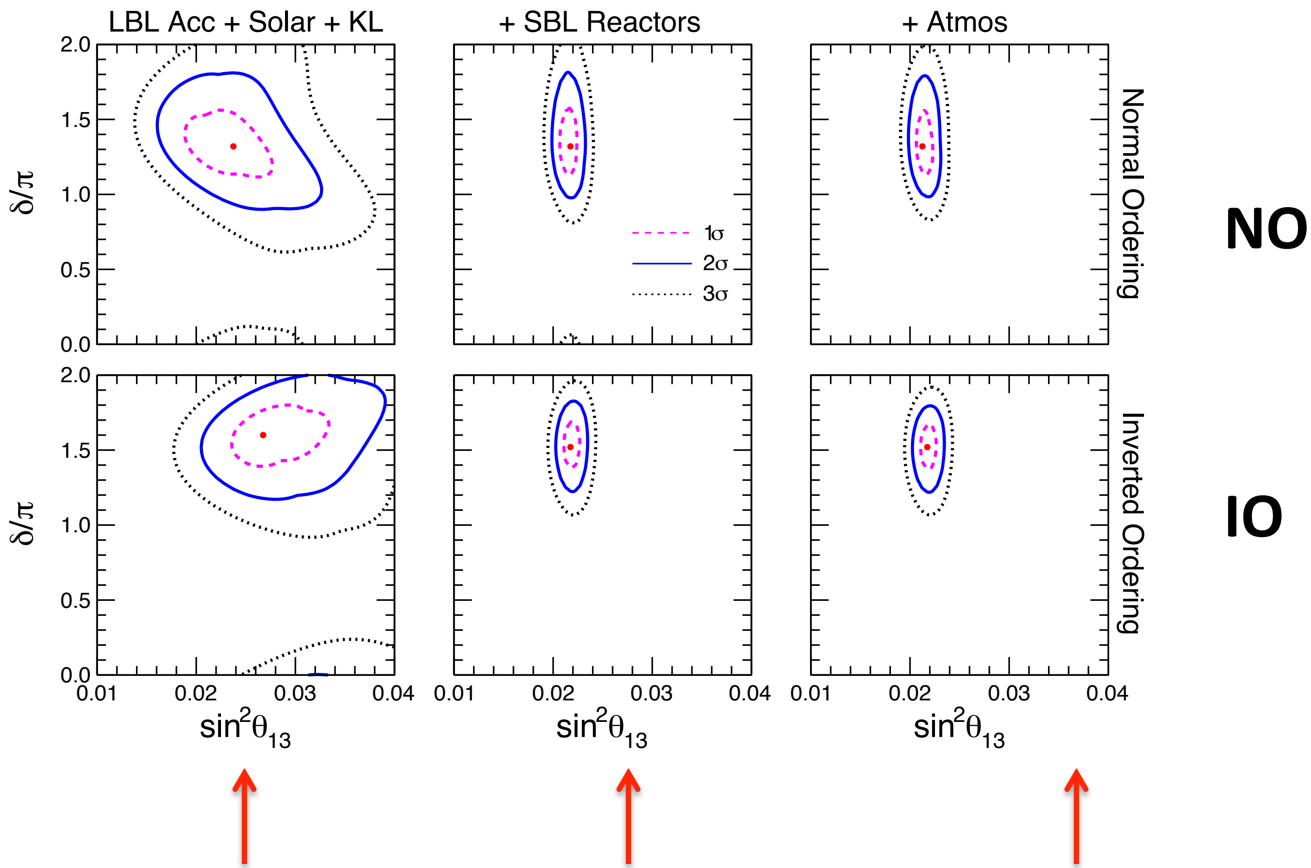
$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta m^2}{A-\Delta m^2}\right)^2 \sin^2\left(\frac{A-\Delta m^2}{4E}x\right)$$

Better agreement with reactors on y-axis for NO

Atmosph. data also contribute (but in a less intuitive way)

Running experiments can further corroborate this picture (if true)

Understanding the accelerator + reactor (+atm.) impact on CPV preference



CPV tested by sub leading terms at accelerators (nu-antinu difference)

$$\sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \left(\frac{\delta m^2}{A}\right)\left(\frac{\Delta m^2}{A-\Delta m^2}\right) \sin\left(\frac{A}{4E}x\right) \sin\left(\frac{A-\Delta m^2}{4E}x\right) \sin\left(\frac{\Delta m^2}{4E}x\right) \sin\delta$$

Reactors not sensitive to CPV, but sharpen range

Atmosph. contribute to test CPV (but in a less intuitive way)

Running experiments can further corroborate this picture (if true)

3ν oscillation parameters summary – 1 year ago [arXiv:1804.09678]

Table 1: Best fit values and allowed ranges at $N\sigma = 1, 2, 3$ for the 3ν oscillation parameters, in either NO or IO. The latter column shows the formal "1σ accuracy" for each parameter, defined as 1/6 of the 3σ range divided by the best-fit value (in percent).

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO	7.34	7.20 – 7.51	7.05 – 7.69	6.92 – 7.91	2.2
	IO	7.34	7.20 – 7.51	7.05 – 7.69	6.92 – 7.91	2.2
$\sin^2\theta_{12}$	NO	3.04	2.91 – 3.18	2.78 – 3.32	2.65 – 3.46	4.4
	IO	3.03	2.90 – 3.17	2.77 – 3.31	2.64 – 3.45	4.4
$\sin^2\theta_{13}/10^{-2}$	NO	2.14	2.07 – 2.23	1.98 – 2.31	1.90 – 2.39	3.8
	IO	2.18	2.11 – 2.26	2.02 – 2.35	1.95 – 2.43	3.7
$\|\Delta m^2\|/10^{-3}$ eV^2	NO	2.455	2.423 – 2.490	2.390 – 2.523	2.355 – 2.557	1.4
	IO	2.441	2.406 – 2.474	2.372 – 2.507	2.338 – 2.540	1.4
$\sin^2\theta_{23}/10^{-1}$	NO	5.51	4.81 – 5.70	4.48 – 5.88	4.30 – 6.02	5.2
	IO	5.57	5.33 – 5.74	4.86 – 5.89	4.44 – 6.03	4.8
δ/π	NO	1.32	1.14 – 1.55	0.98 – 1.79	0.83 – 1.99	14.6
	IO	1.52	1.37 – 1.66	1.22 – 1.79	1.07 – 1.92	9.3

Known parameters constrained at few % level – Precision era!

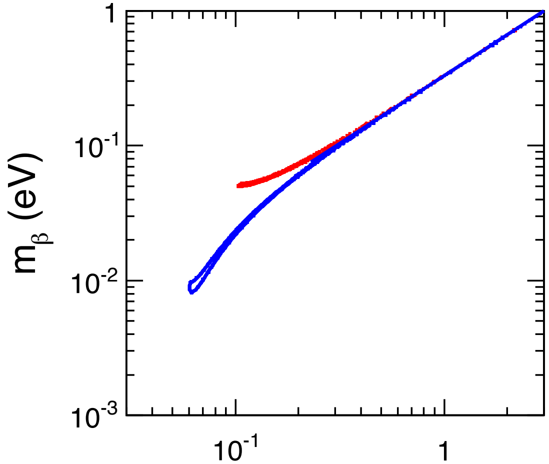
"Unknown" CP phase maybe already "known" at O(10%) - if trend confirmed

Dramatic progress in the last two decades on the PMNS paradigm...

but still a long way to go to reach CKM-level accuracy and redundance!

Hints for nearly maximal CPV and NO will be at center stage in next years

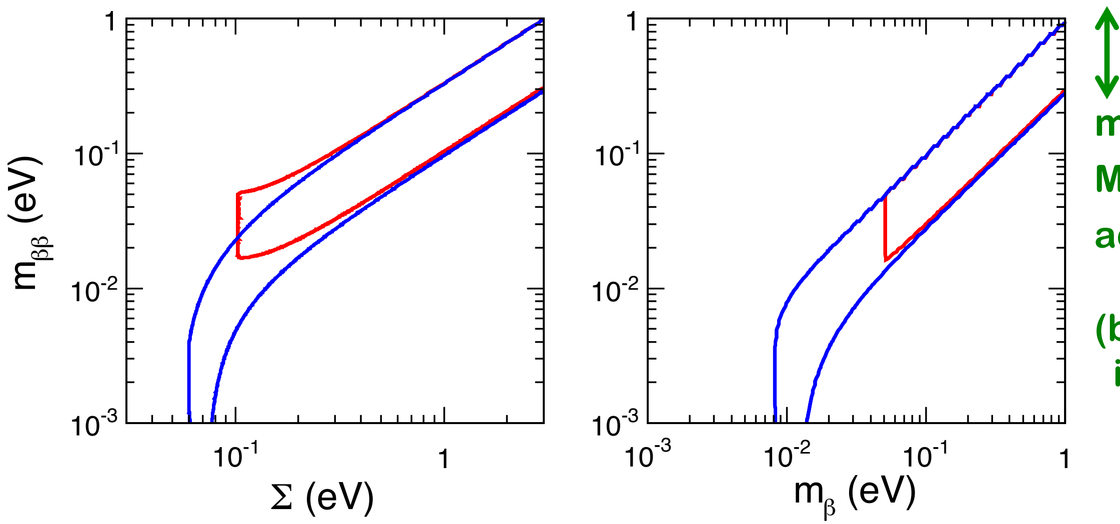
Impact of oscill. data on nonoscill. observables (separate NO and IO)



(m_β , $m_{\beta\beta}$, Σ)

NO
IO

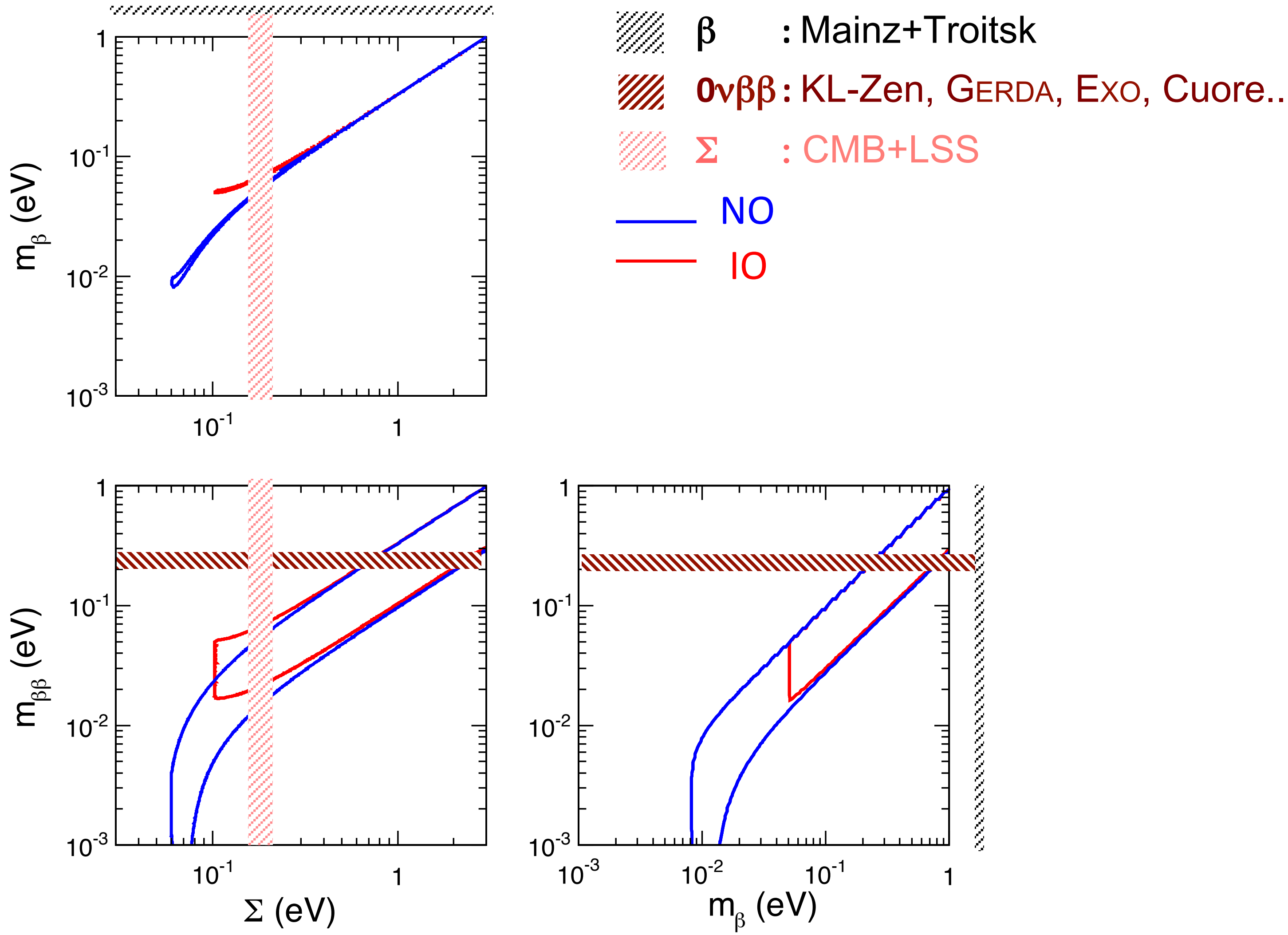
~degenerate for relatively large neutrino masses



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

(but: no NME errors included here!)

Upper limits on m_β, $m_{\beta\beta}$, Σ from nonosc. expts (up to some syst.)



Cosmo data already contribute to put IO “under pressure”.

Major improvements expected in the next decade...

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New results in the last year, included (✓) or not (✗) in this partial update 2019

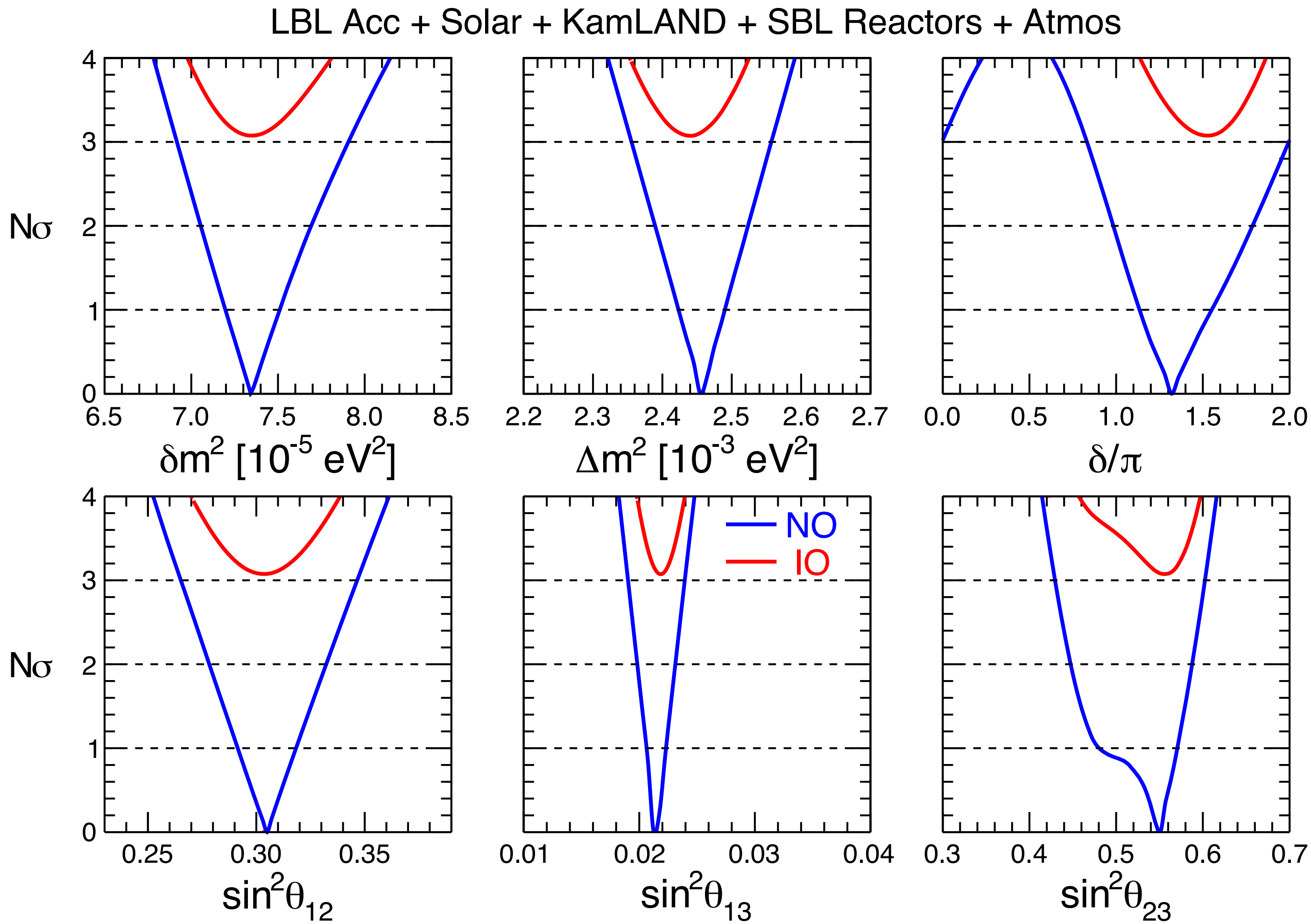
[Capozzi et al. 2019, preliminary, unpublished]

RENO	✓	arXiv:1806.00248
Daya Bay	✓	arXiv:1809.02261
Double Chooz	✗	arXiv:1901.09445
T2K	✓	Neutrino 2018 + other conferences 2018/19
NOvA	✓	Neutrino 2018 + other conferences 2018/19
SK-IV atmos.	✗	arXiv:1901.03230, fiTQun reconstr. algorithm
DeepCore	✗	arXiv:1902.07771, analyses "A" and "B"

Further activity on the experimental side:

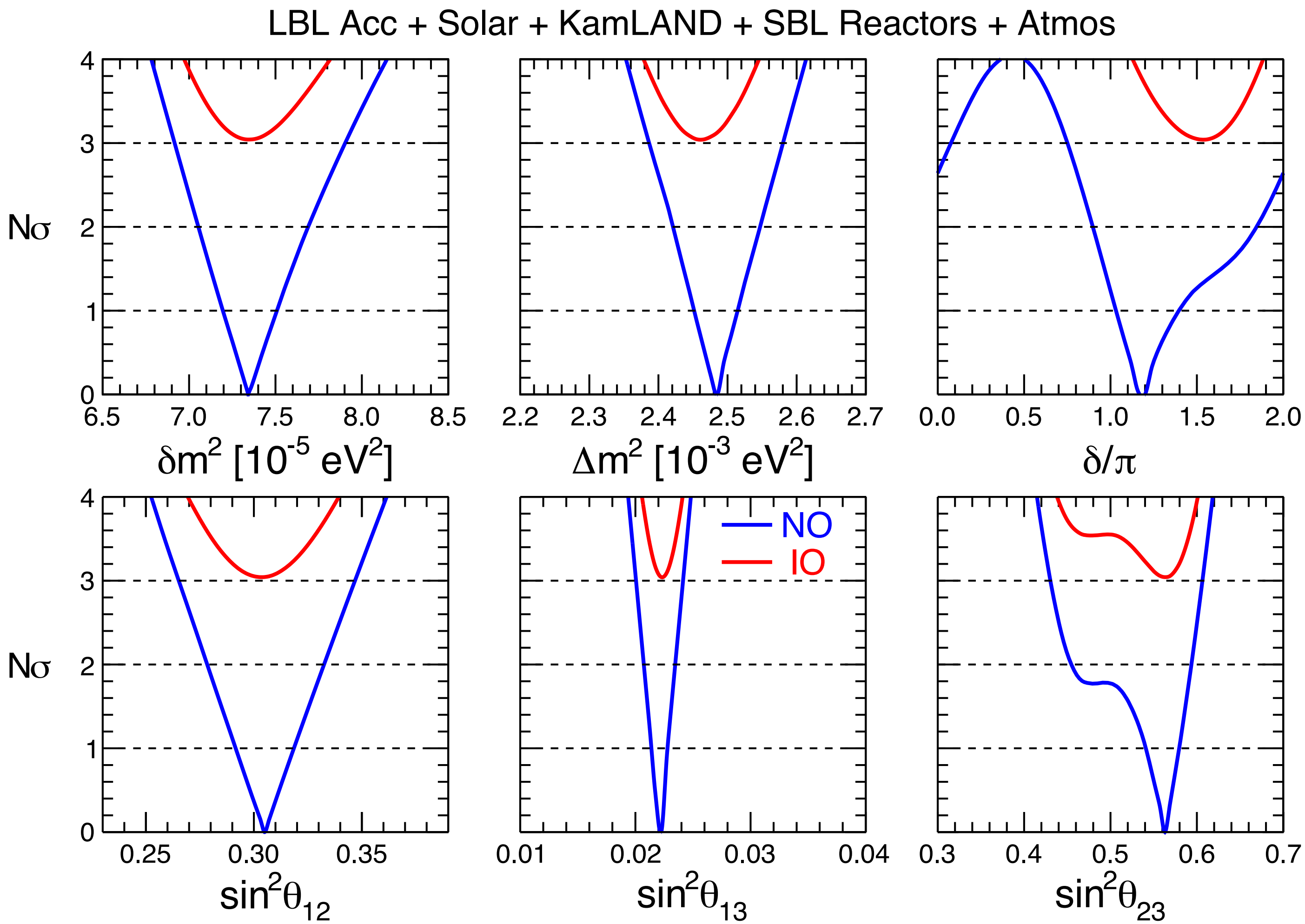
- Common meetings of **SBL reactor expts**. [e.g., ESCAPE 2018] but no joint fit yet
- Agreement for **T2K + NOvA** joint analysis (possibly **T2K + SK ?**) in the next future
- Some updates expected in **Summer 2019** conferences*

**We shall wait for new data/publications before finalizing the 2019 update*



LBL Acc + Solar + KamLAND + SBL Reactors + Atmos
Nσ
δm² [10⁻⁵ eV²]
Δm² [10⁻³ eV²]
δ/π
sin²θ12
sin²θ13
sin²θ23
NO
IO

← 2018



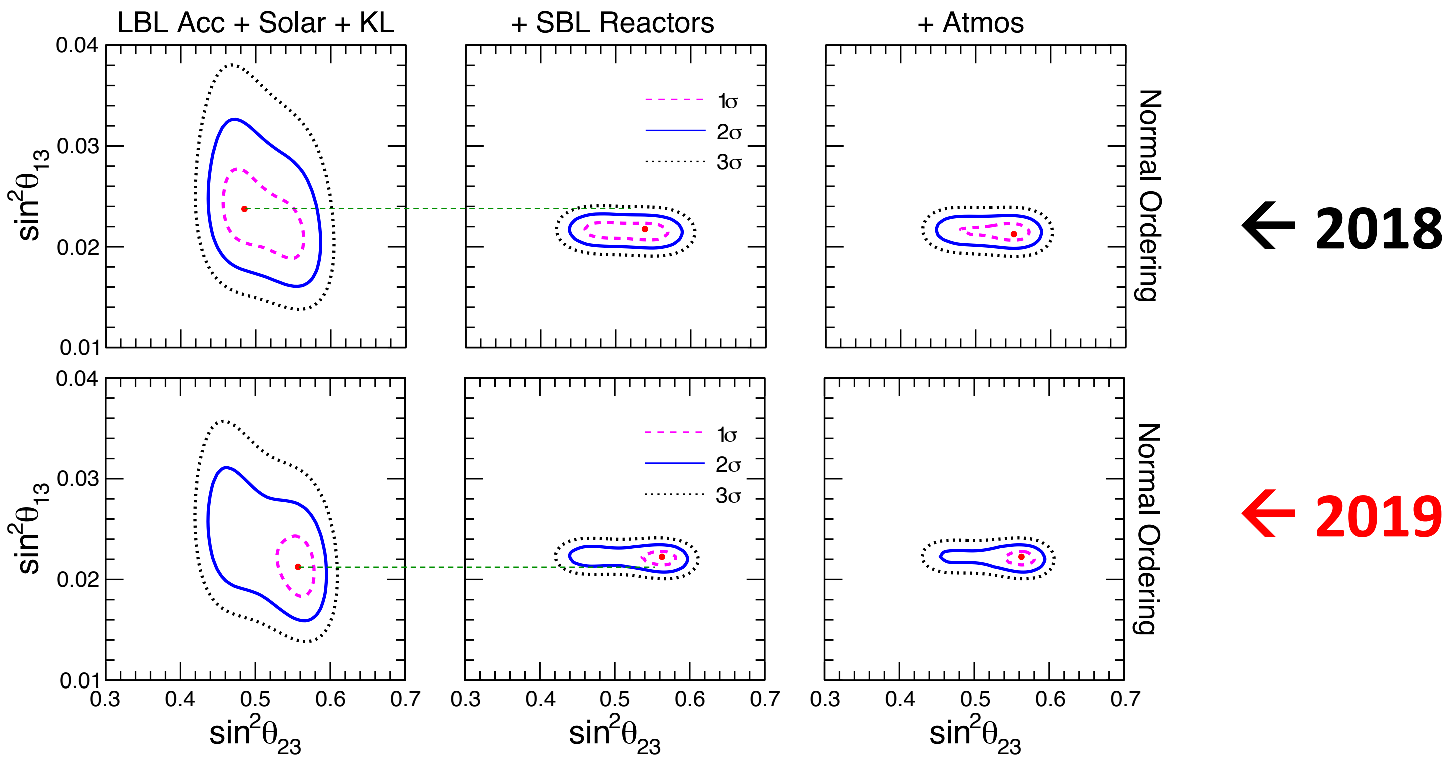
← 2019

NO: Slight increase of best fit values for θ_{13}, θ_{23}, Δm^2, with slightly smaller errors

NO: Slight decrease of best-fit value of δ, with weaker CPV significance

IO: Remains disfavored with respect to NO at ~3σ level → Stable hint in favor of NO

Covariances of ($\sin^2\theta_{23}$, $\sin^2\theta_{13}$) for Normal Ordering



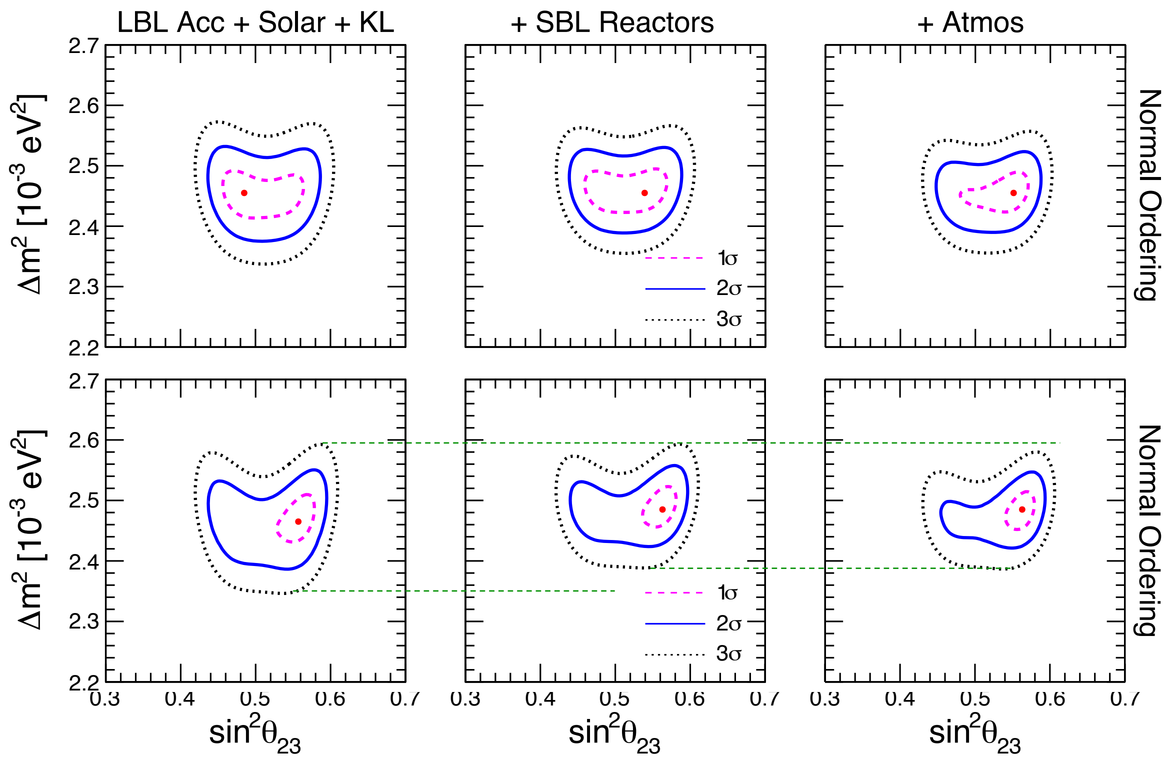
$\sin^2\theta_{23}$: Slight preference for 2nd octant already from LBL+Solar+KL data

$\sin^2\theta_{13}$: Slightly higher θ_{13} with smaller errors from SBL reactors

Best fit LBL+Solar+KL in better agreement w.r.t. SBL reactors

→indirectly, adds preference for 2^{nd} octant of θ_{23}

Covariances of $(\sin^2\theta_{23}, \Delta m^2)$ for Normal Ordering

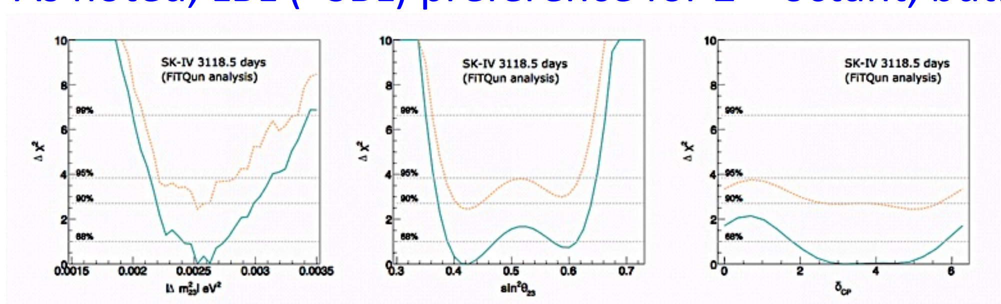


← 2018

← 2019

Δm^2: Note impact of SBL reactors + atmos. data in reducing its range

$\sin^2\theta_{23}$: As noted, LBL (+SBL) preference for 2nd octant, but... SK-IV?



SK-IV 2019
fiTQun
[not included]

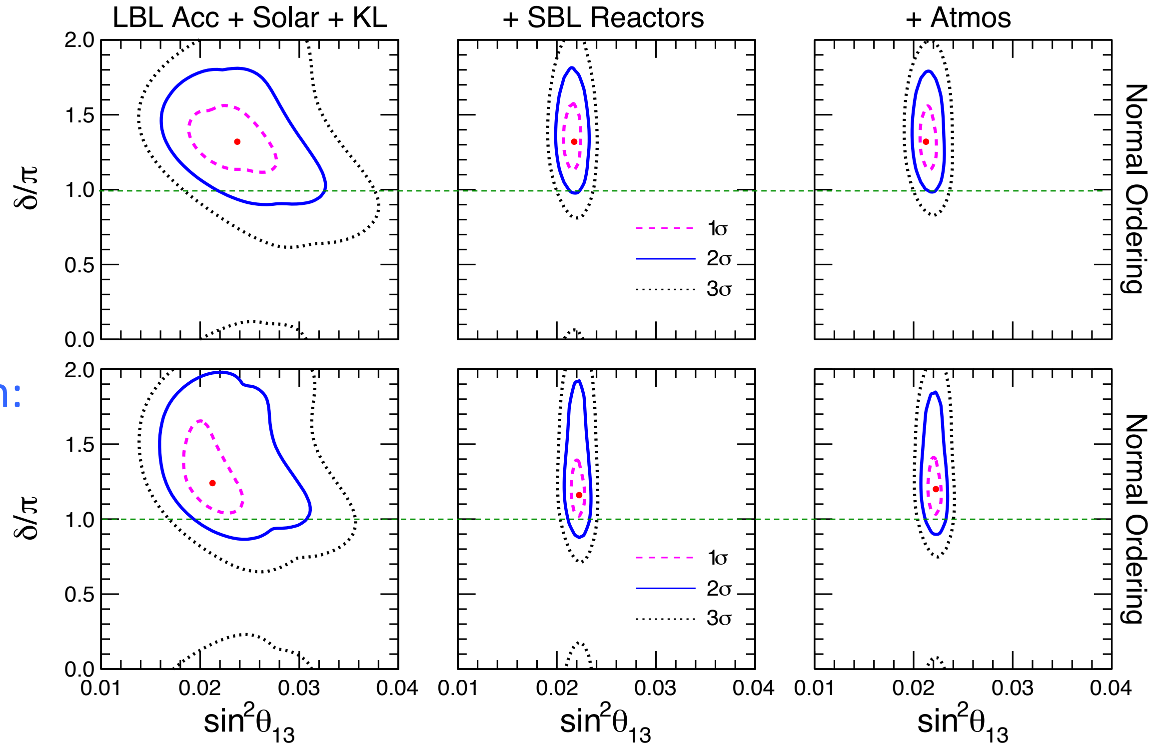
[Octant may still flip up and down in the future...]

Covariances of (δ, $\sin^2\theta_{13}$) for Normal Ordering

CP conservation:

δ=π @ 1.3σ

δ=0, 2π @ 2.6σ



← 2018

← 2019

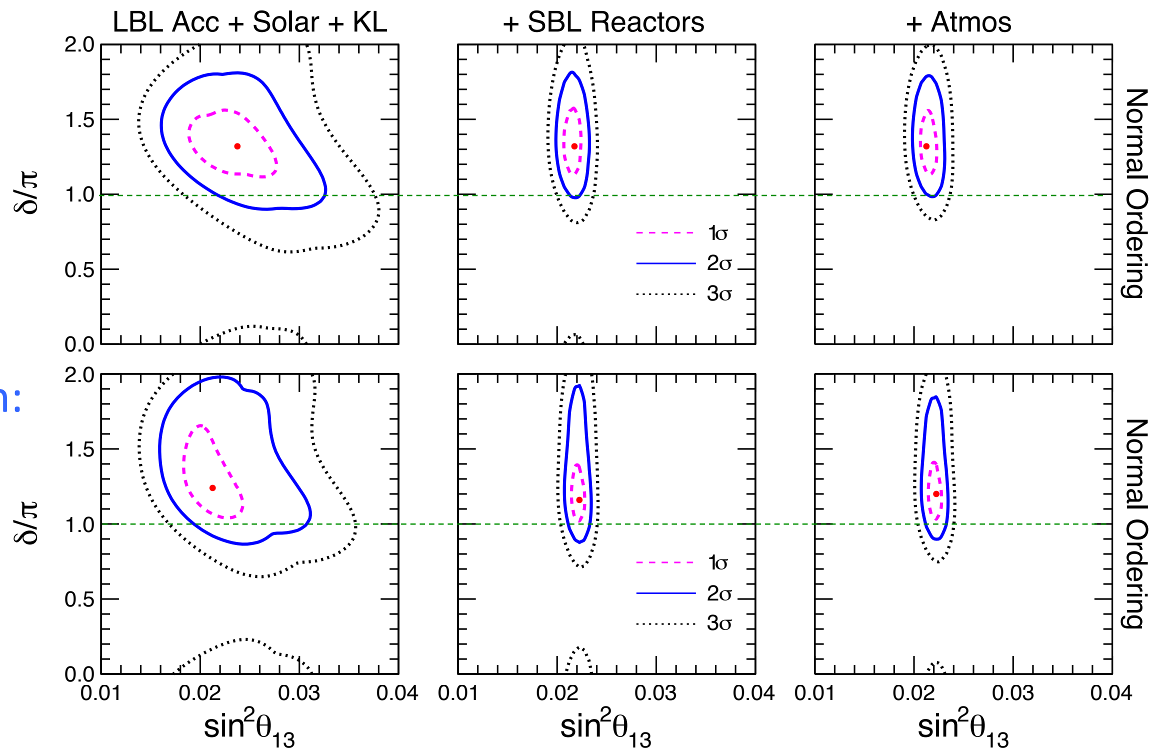
Dirac CP phase: **CPV favored, but CPC is "less disfavored" wrt 2018:**
mainly due to NOvA constraints being "out of phase" wrt T2K in NO.
Need to wait for higher statistics (and possible T2K+NOvA joint fit).

Covariances of (δ, $\sin^2\theta_{13}$) for Normal Ordering

CP conservation:

$\delta=\pi$ @ 1.3σ

$\delta=0, 2\pi$ @ 2.6σ



← 2018

← 2019

Dirac CP phase: **CPV favored, but CPC is "less disfavored" wrt 2018:**
mainly due to NOvA constraints being "out of phase" wrt T2K in NO.
Need to wait for higher statistics (and possible T2K+NOvA joint fit).

[Finally: **no significant update about non-oscillation observables.**
But: progress in understanding sub-eV cosmological constraints
in attacking the g_A issue in DBD NME, and in KATRIN data taking!]

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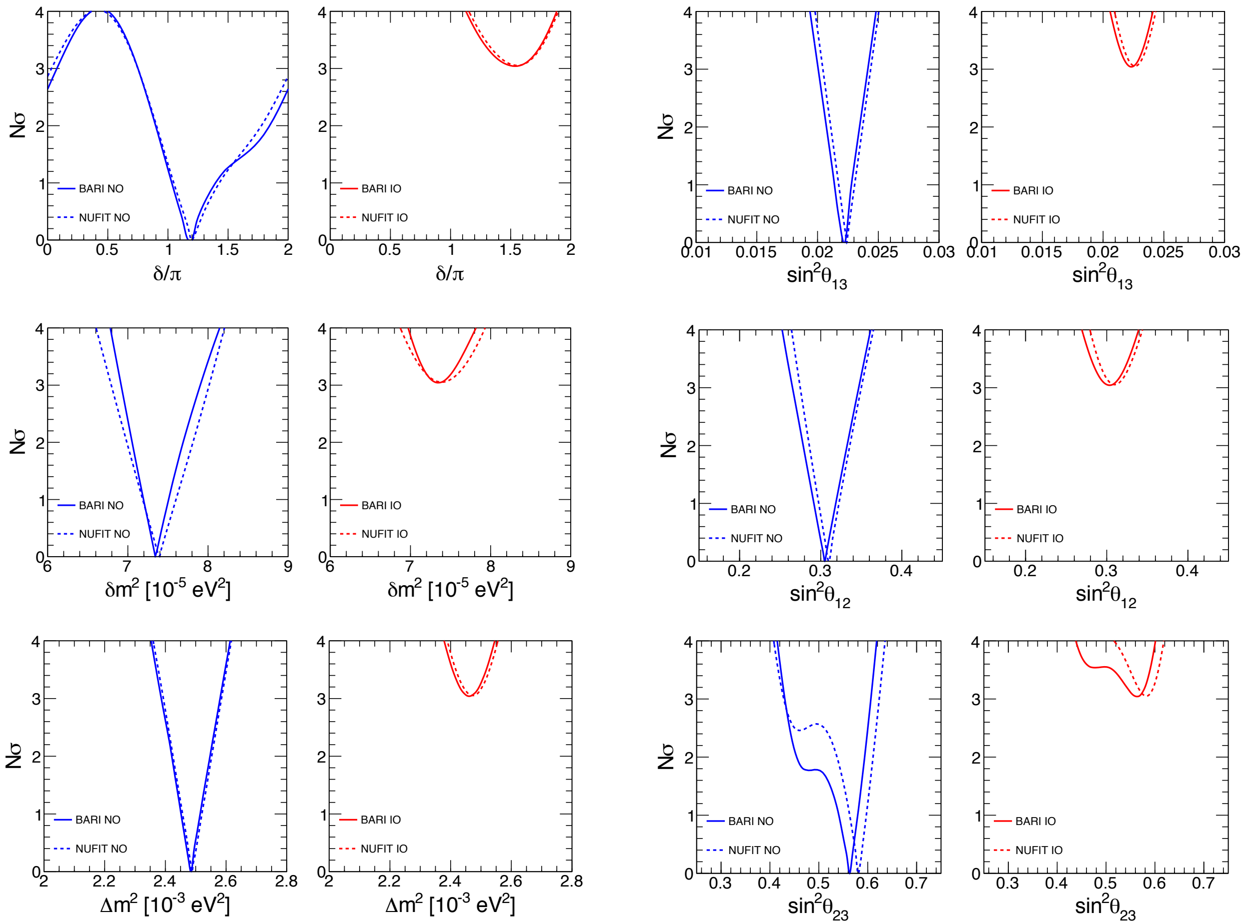
[in data analyses]

Comparison of this 2019 partial update ("BARI") with NuFIT 4.0 results ("NUFIT")

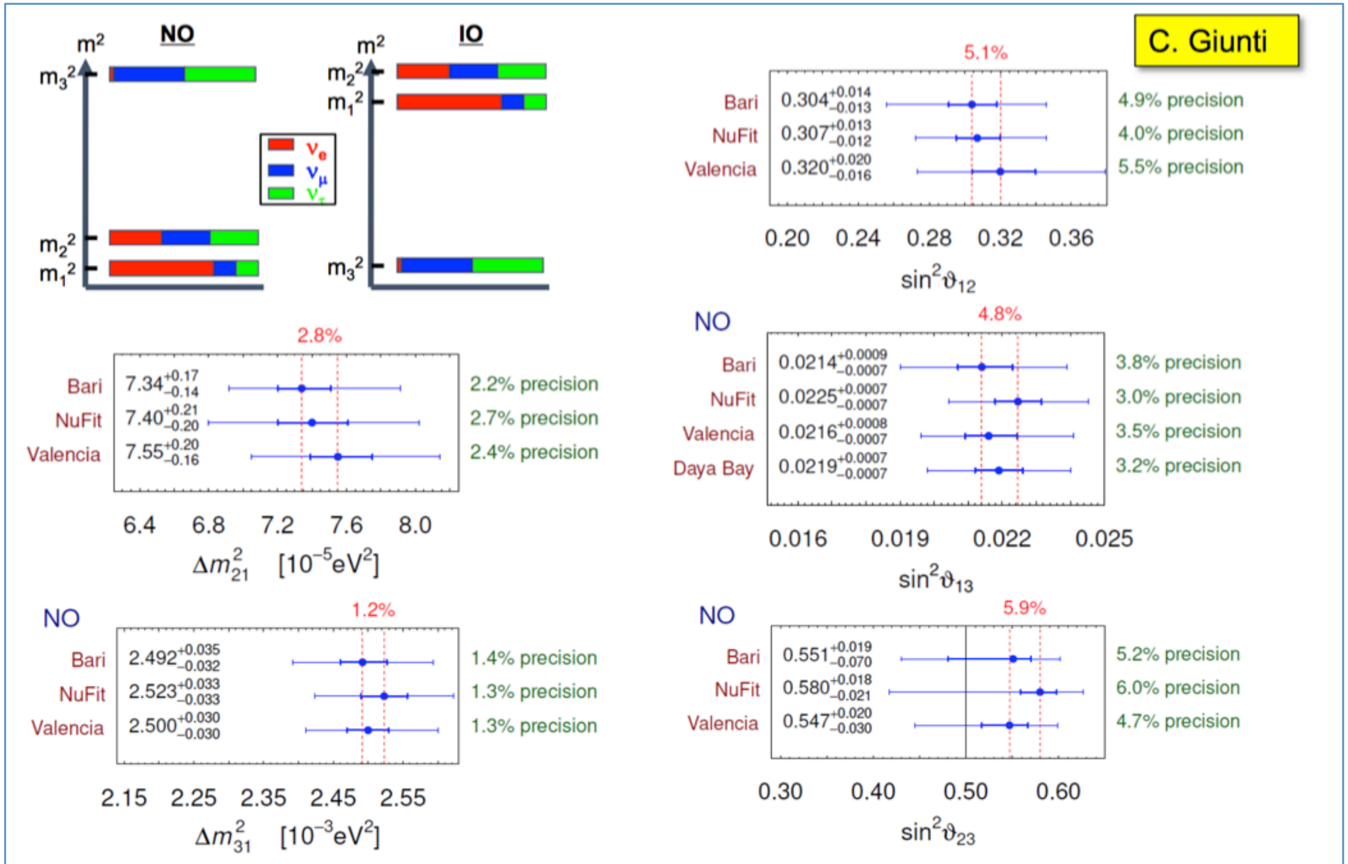
[basically using the same relevant input data sets]



Agreement as good as it can be expected from independent phenom. analyses

[except perhaps for the "bimodal" -and relatively fragile- p.d.f. of $\sin^2\theta_{23}$]

From the summary talk by M. Nakahata at NNN 2018 (quoting talk by C. Giunti):



M.N. → Note: differences between global fit groups should be resolved.

But I'd like to share with you a different viewpoint...

...At least for the standard 3ν framework, global data analyses will progressively require **joint work of diverse [experimental] collaborations**, rather than of phenomenol. groups.

Just a few reasons (out of many) for this transition:

Complexity. Some data sets are becoming too complicated to be analyzed outside the collaborations. E.g. SK-atm with O(400) bins and O(100) systematics. Use of "AI" techniques will enhance this problem. But: "black-box" results to be avoided!

Uniformity. Comparable standards should be used in the same class of expts. E.g. no other atmospheric expt. includes as many sources of syst's as SK (yet). Statistical techniques also need some kind of agreement (freq./Bayes/MC/FC)

Common inputs. Some ingredients (normalizations, cross sections, fluxes etc.) are shared −totally or in part- by different experiments, and are thus correlated. Obvious past example: SSM+solar. Future: SK+T2K, T2K+NOvA, SK+ICDC, SBL reac.

Data preservation. Like in other HEP or CR communities, data should be stored and formatted in a way to be accessible for later (re)use. Prints (articles, figures, PhD theses etc.) replaced by databases? Agreements among expts needed.

Metrology. The 3ν oscill. parameters represent fundamental "frequencies" and "amplitudes" in Nature, to be determined with the best possible accuracy.

Two examples →

IceCube DC 2019, prior and posterior pulls (below). Differences wrt SK priors/posteriors.

Not an ideal situation: e.g. overall flux normalizations may go in different directions.

This info gets lost by combining DC & SK analyses as if they were totally independent...

...to be contrasted with solar ν analyses, where the same SSM pulls act on all observables.

Table 2 Systematics treated as nuisance parameters in the likelihood analysis, including normalization (N), detector response (D), oscillation (O), flux (F), and neutrino-nucleon interaction (I) uncertainties. These parameters are discussed in more detail in [38]. The table gives the baseline value and, if the parameter is used with a prior in the likelihood, the standard deviation of the Gaussian prior, as well as the experimental best-fit values for both analyses and ordering hypotheses.

Label	Type	Description of Parameter	Baseline±Prior	Analysis $\mathcal{A}$ NO	Analysis $\mathcal{A}$ IO	Analysis $\mathcal{B}$ NO	Analysis $\mathcal{B}$ IO
N_ν	N, F	normalization of total neutrino template	1[a]	0.83	0.84	0.98	0.99
N_{ν_e}	N, F	normalization of ν_e flux before oscillations	1 ± 0.05[ad]	1.00	1.00	1.37	1.38
$N_{\rm NC}$	N, I	normalization of NC events	1 ± 0.2[a]	0.74	0.75	0.99	0.99
N_μ	N, F	normalization of atmos. muon events	1[a]	1.35	1.34	0.2%[c]	0.2%[c]
$\epsilon_{\rm opt}$	D	overall optical efficiency [11]	1 ± 0.1[ad]	1.00	1.00	0.92	0.92
$\epsilon_{\rm lateral}$	D	lateral dependence of optical efficiency [11]	0 ± 1[b]	0.68	0.68	-0.46	-0.46
$\epsilon_{\rm head-on}$	D	head-on optical efficiency [11]	0[b]	-1.01	-1.01	-2.00	-1.92
$\Delta m^2_{31}/(10^{-3}\,{\rm eV}^2)$	O	atmospheric mass-splitting	2.5(NO)/−2.43(IO)	2.626	-2.511	2.462	-2.348
$\sin^2(\theta_{23})$	O	atmospheric neutrino mixing angle	0.455	0.476	0.485	0.558	0.539
γ_ν	F	neutrino spectral index unc. [44]	0.0 ± 0.1[d]	0.073	0.071	-0.025	-0.027
γ_μ	F	atmospheric muon spectrum unc. [36, 45]	0.0 ± 1.0[b]	0.04	0.04	–	–
$\sigma_\nu^{\rm zenith}$	F	zenith-dependent unc. in $\nu/\bar{\nu}$ flux [46]	0.0 ± 1.0[bd]	-0.12	-0.11	-0.86	-0.89
$\Delta(\nu/\bar{\nu})$	F	energy-dependent unc. in $\nu/\bar{\nu}$ ratio [46]	0.0 ± 1.0[b]	-1.03	-1.02	0.05	0.07
$M_A^{\rm res}$/GeV	I	axial mass unc. of resonant events [47]	1.12 ± 0.22	1.091	1.095	1.003	0.999
$M_A^{\rm qe}$/GeV	I	axial mass unc. of quasi-elastic events [47]	0.99 ± 0.25	0.862	0.867	0.881	0.888

[a] relative to the nominal value of this parameter
[b] parametrized with respect to the value and the uncertainty obtained from the provided reference
[c] given as fraction of the total sample, since no Monte Carlo prediction exists to compare to
[d] no prior used for likelihood in Analysis $\mathcal{B}$

←opposite pull in SK

IceCube DC 2019, prior and posterior pulls (below). Differences wrt SK priors/posteriors.

Not an ideal situation: e.g. overall flux normalizations may go in different directions.

This info gets lost by combining DC & SK analyses as if they were totally independent...

...to be contrasted with solar ν analyses, where the same SSM pulls act on all observables.

Table 2 Systematics treated as nuisance parameters in the likelihood analysis, including normalization (N), detector response (D), oscillation (O), flux (F), and neutrino-nucleon interaction (I) uncertainties. These parameters are discussed in more detail in [38]. The table gives the baseline value and, if the parameter is used with a prior in the likelihood, the standard deviation of the Gaussian prior, as well as the experimental best-fit values for both analyses and ordering hypotheses.

Label	Type	Description of Parameter	Baseline±Prior	Analysis $\mathcal{A}$ NO	Analysis $\mathcal{A}$ IO	Analysis $\mathcal{B}$ NO	Analysis $\mathcal{B}$ IO
N_ν	N, F	normalization of total neutrino template	1[a]	0.83	0.84	0.98	0.99
N_{ν_e}	N, F	normalization of ν_e flux before oscillations	1 ± 0.05[a,d]	1.00	1.00	1.37	1.38
N_{NC}	N, I	normalization of NC events	1 ± 0.2[a]	0.74	0.75	0.99	0.99
N_μ	N, F	normalization of atmos. muon events	1[a]	1.35	1.34	0.2%[c]	0.2%[c]
ϵ_{opt}	D	overall optical efficiency [11]	1 ± 0.1[a,d]	1.00	1.00	0.92	0.92
$\epsilon_{lateral}$	D	lateral dependence of optical efficiency [11]	0 ± 1[b]	0.68	0.68	-0.46	-0.46
$\epsilon_{head-on}$	D	head-on optical efficiency [11]	0[b]	-1.01	-1.01	-2.00	-1.92
$\Delta m^2_{31}/(10^{-3}\,eV^2)$	O	atmospheric mass-splitting	2.5(NO)/−2.43(IO)	2.626	-2.511	2.462	-2.348
$\sin^2(\theta_{23})$	O	atmospheric neutrino mixing angle	0.455	0.476	0.485	0.558	0.539
γ_ν	F	neutrino spectral index unc. [44]	0.0 ± 0.1[d]	0.073	0.071	-0.025	-0.027
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←opposite pull in SK

Expt+Theo+Stat work needed to reach “standard models” for atmospheric ν fluxes and their cross-sections in water - especially in view of high-stat PINGU, ORCA, HyperK, that will require an improved understanding of energy-angle spectral uncertainties

Similarly: hard work needed to reach “standard” reactor ν spectra and uncertanties.

Not easy tasks (discrete → shape errors), but we should invest more on them.

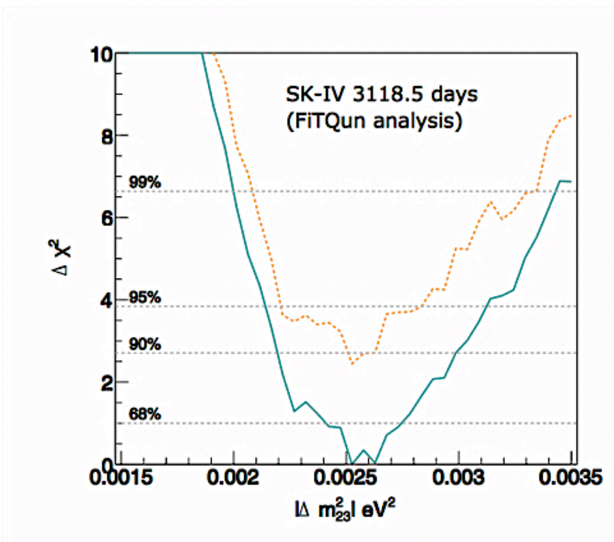
Complexity issues: avoiding "black-box" attitude towards processed data samples.

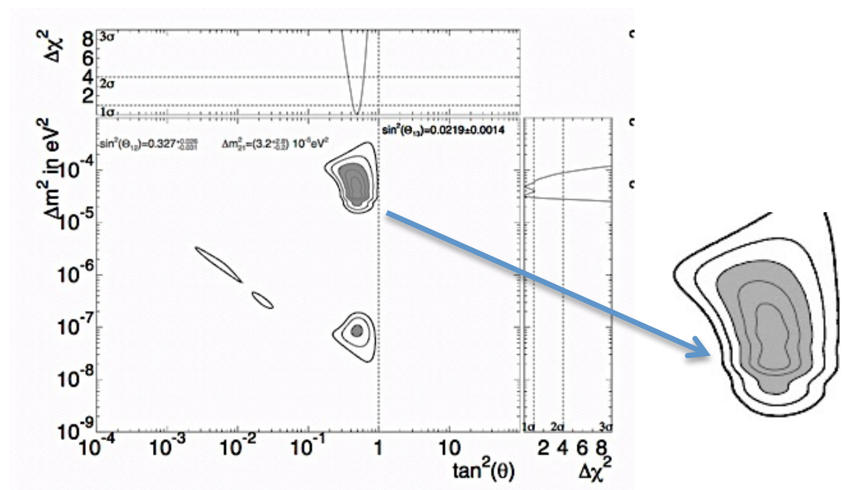
Various experimental data analyses are (or will be) so complicated to be ~unreproducible outside the collaborations. However, the discussion of the main analysis ingredients (physics + detector + statistics + other issues) must remain open to the community.

E.g., the current χ^2 output of the SK-IV fiTQun−atm analysis shows some Δ**m²** "fuzziness".

But: Physics is "smooth" in Δ**m²**. Fuzziness also in SK solar neutrino LMA analysis.

Artifacts? E.g.: Insufficient energy sampling - incomplete oscillation averaging?





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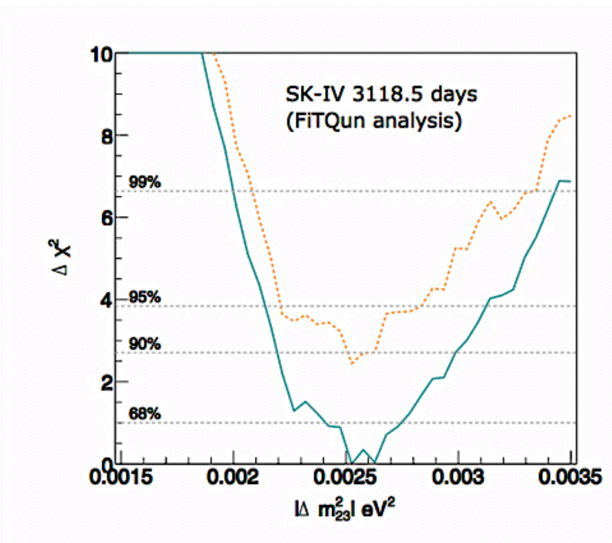

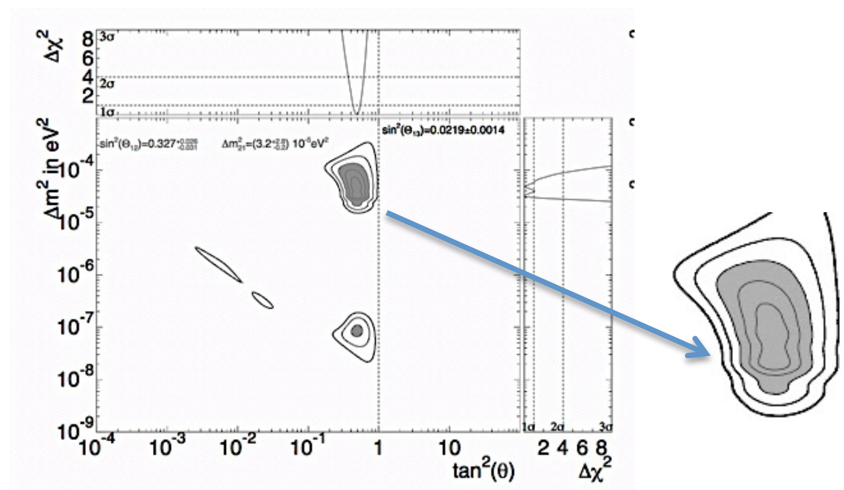

→ Releasing χ^2 maps is a useful service, but cannot replace critical treatment of data.
We should always aim at public and informed discussions about neutrino data analyses.
No "deep learning" [techniques] **without "deep understanding"** [attitude]**!**

Conclusions

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

- 3ν framework established by convergence of many data sets
- Five known parameters are being measured with increasing accuracy
- Five unknowns remain to be determined, with hints in favor of:

  NO vs IO at the level of $\sim 3\sigma$ (oscillation data) + "ε" (cosmology)
  CPV with $\delta \sim 1.2\pi$ (but CPC allowed at 1.3σ)
  θ_{23} in 2nd octant (but 1st octant allowed at $<2\sigma$ level)
  [→ All very interesting... but not compelling yet]

- Absolute mass scale: hiding in the sub-eV range, but not for long...
- Dirac/Majorana nature: hiding... for how long?
- Combined 3ν analyses of high-stat datasets will face new challenges

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Thank you for your attention

EXTRA

3ν paradigm: parameters

Mixings and phases: 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

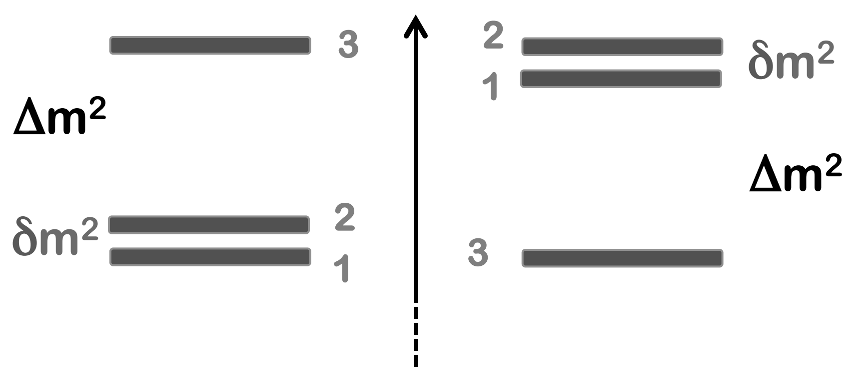
1-3 rotation
+ CPV "Dirac" phase

1-2 rotation

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

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

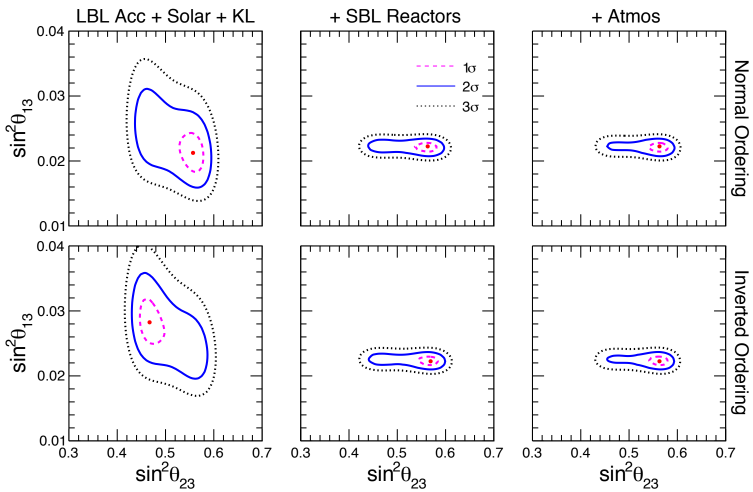
"Normal" Ordering
N.O.

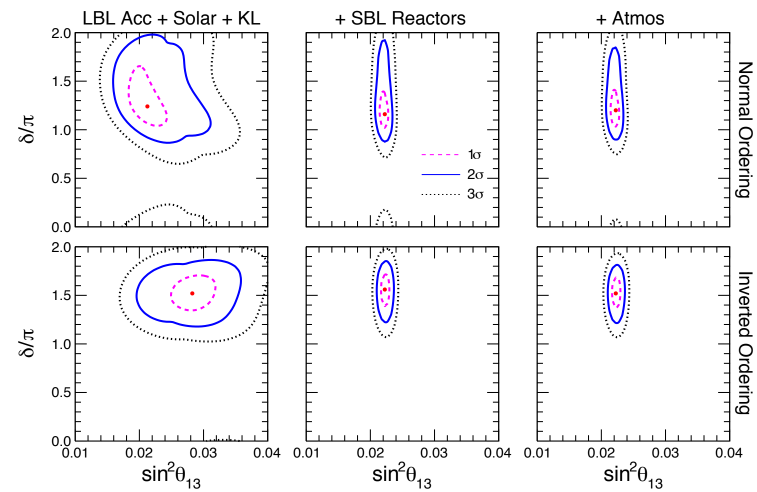


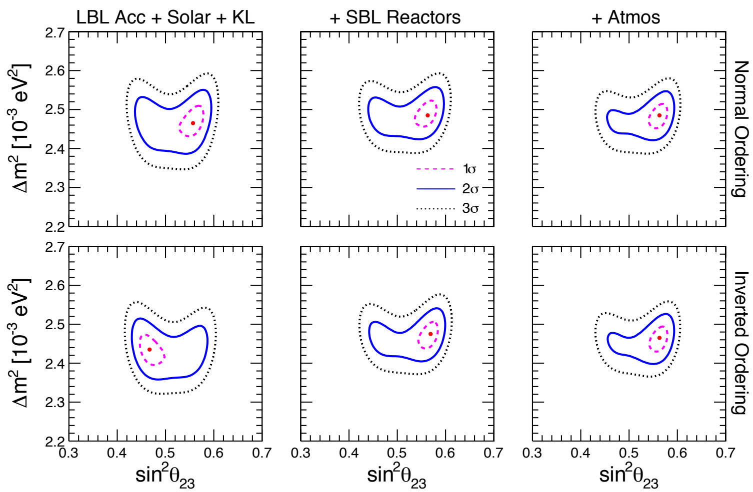
"Inverted" Ordering
I.O.

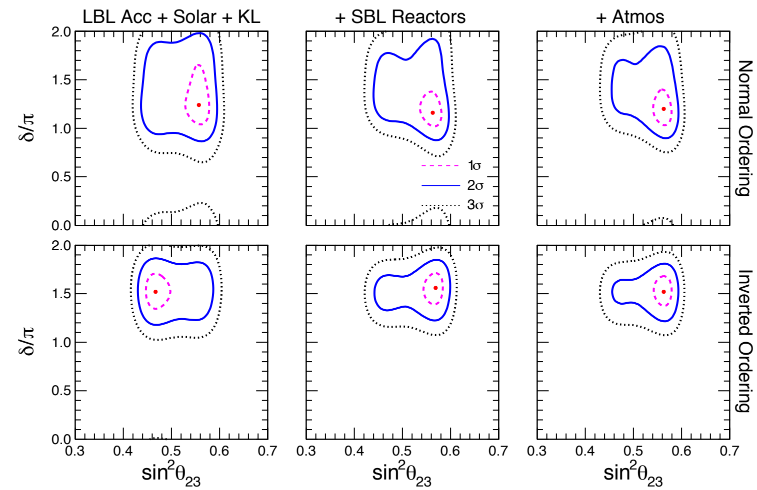
+ interactions in matter → effective terms ~ $G_F \cdot E \cdot$ density
+ absolute mass scale (not tested in oscillations)

Covariances, 2019 preliminary update

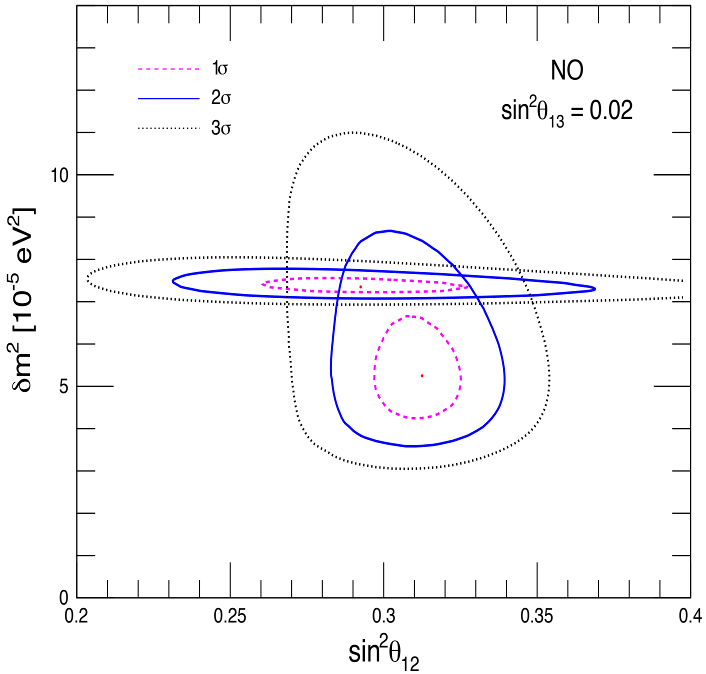


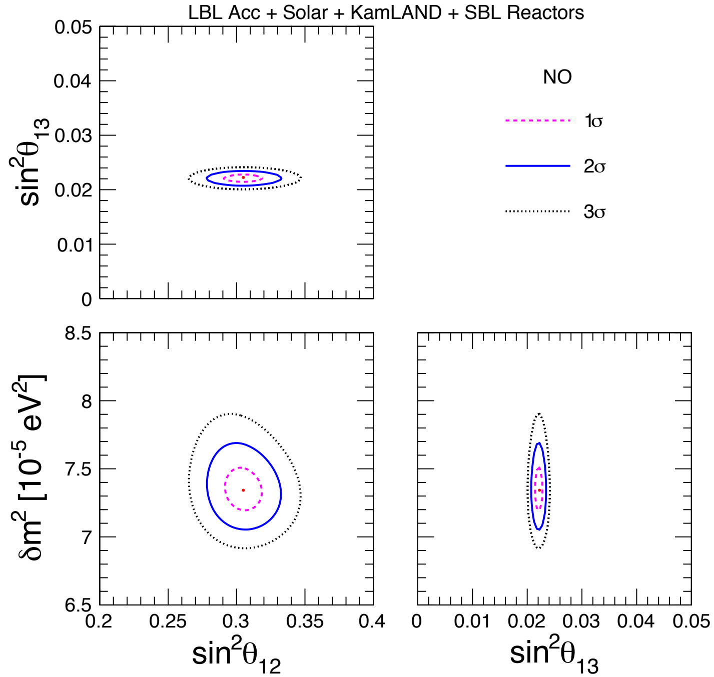






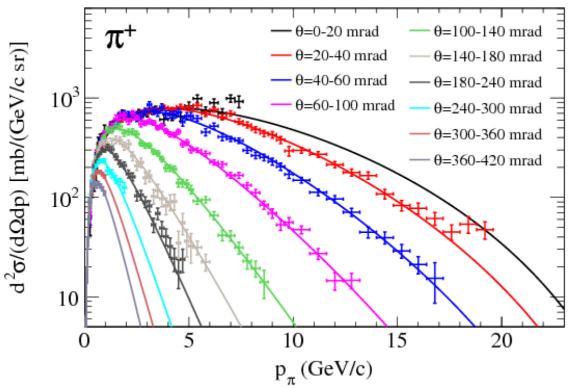
“Solar” oscillation parameters

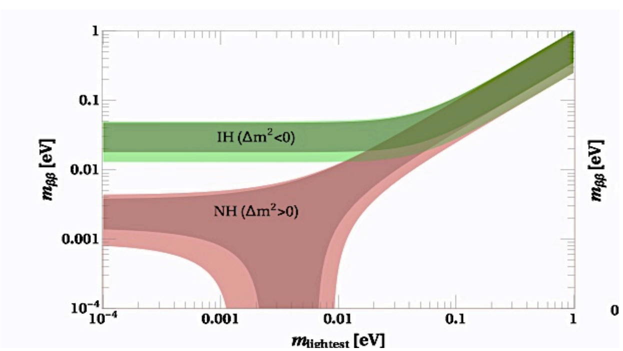




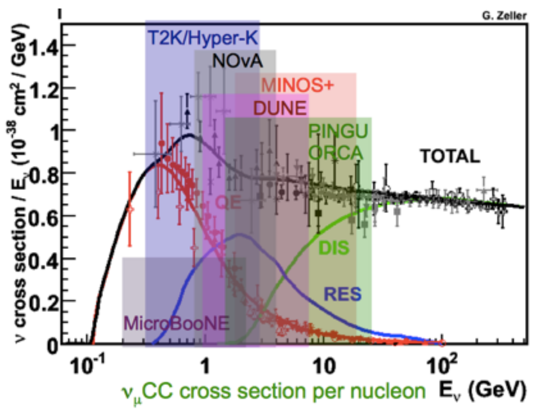
“Strong interaction” effects on “weak interaction” physics are ubiquitous…

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





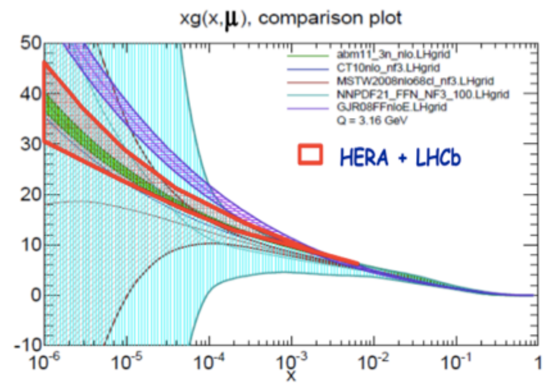
Current understanding of ν cross sections at O(GeV) does not match the needs of (next-generation) ν expts

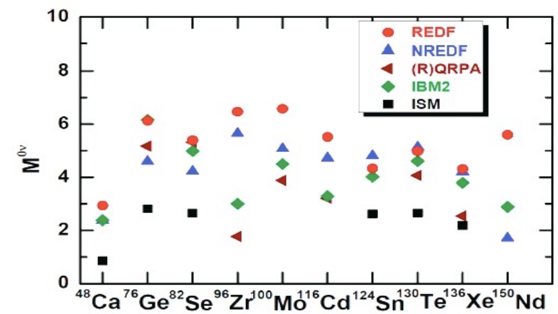


Better control of nuclear EW response (e.g., **g_A**) relevant to interpret 2β data and to connect them with other data

…

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



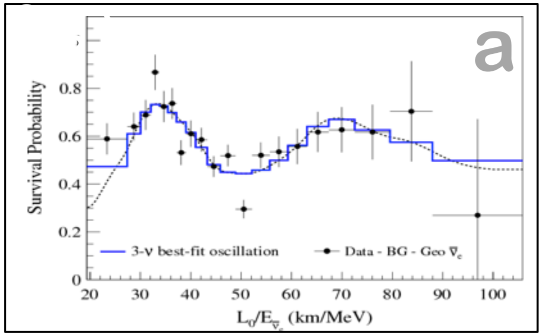


Progress requires joint contributions from different disciplines & communities

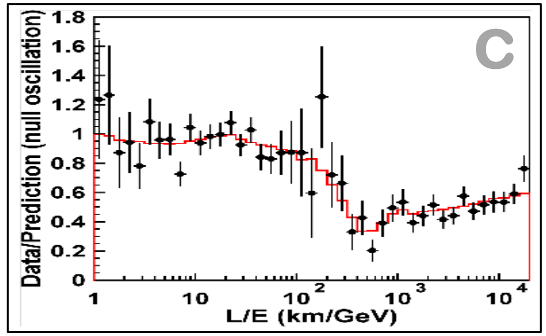
In the long-term: Lattice QCD? Recent calculations of axial coupling and form factor (g_A, m_A)

ν flavor oscillation experiments: α → β in vacuum and matter

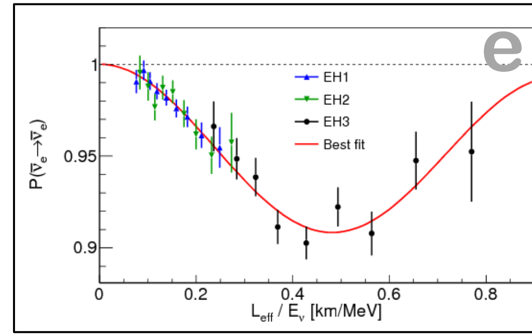
e→e (KamLAND)



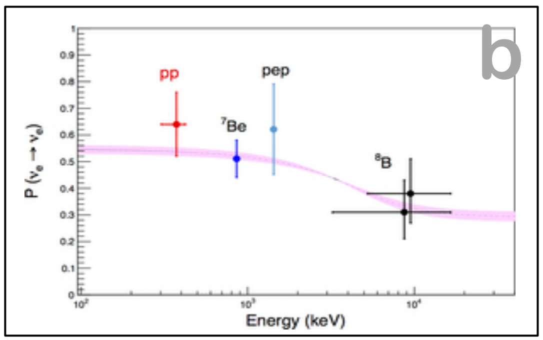
μ→μ (Atmospheric)



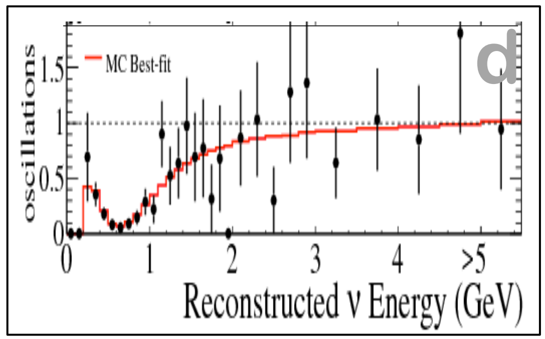
e→e (SBL Reac.)



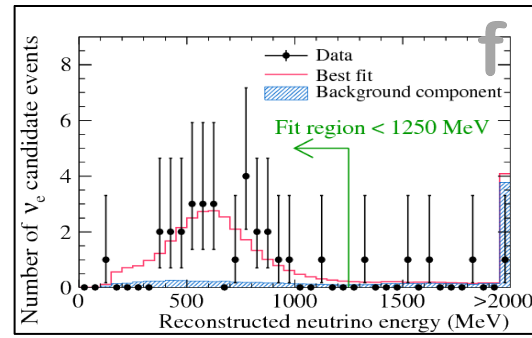
e→e (Solar)



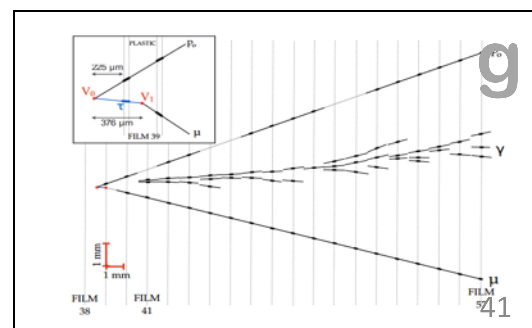
μ→μ (LBL Accel)



μ→e (LBL Accel)



μ→τ (OPERA, SK)



Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline LBL accelerator, (e) short-baseline SBL 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), NOvA, MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS, NOvA; (g) OPERA [plot], Super-K atmospheric.