CERN Council Open Symposium − Update on the European Strategy for Particle Physics

Precision determination of neutrino mass-mixing parameters

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OUTLINE

Introduction

3ν oscillation analysis: 2018→2019

(Some) expected improvements & tests

Conclusions

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Standard 3ν framework: mass-mixing parameters

→ *Introduced by S. Pascoli*

Mixings and phases: CKM→ PMNS (Pontecorvo-Maki-Nakagawa-Sakata)

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

"23" rotation

"13" rotation
+ 1 CPV "Dirac" phase

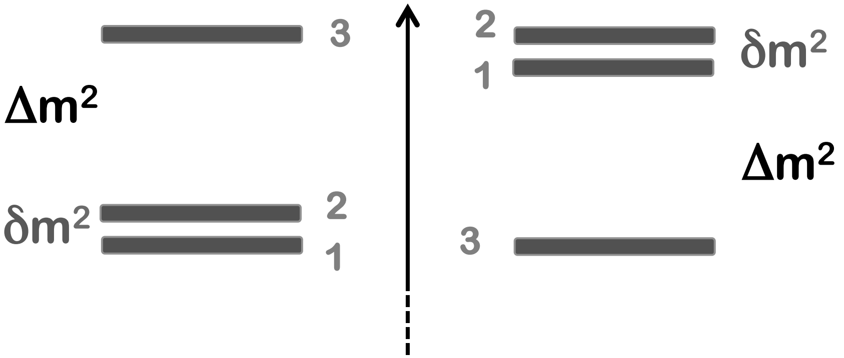
"12" rotation

+2 Extra CPV phases
[if Majorana]
not tested in oscillation

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

"Normal" Ordering

N.O.



"Inverted" Ordering

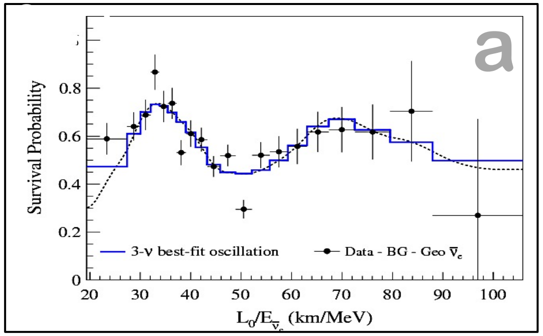
I.O.

+ interactions in matter → effective terms ~ $G_F \cdot E \cdot$ density

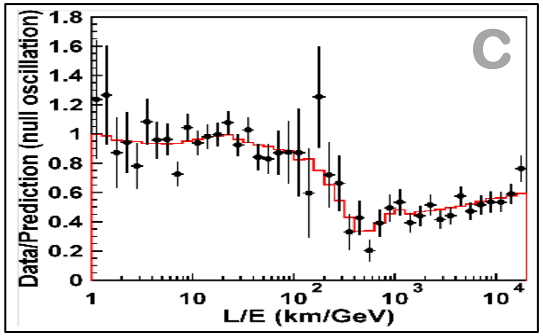
+ absolute mass scale (not tested in oscillations)

Oscillation effects observed in $\alpha \rightarrow \beta$ channels in vacuum and matter…

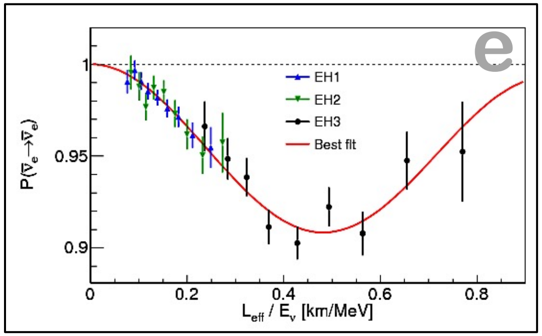
$e \rightarrow e$ (KamLAND)



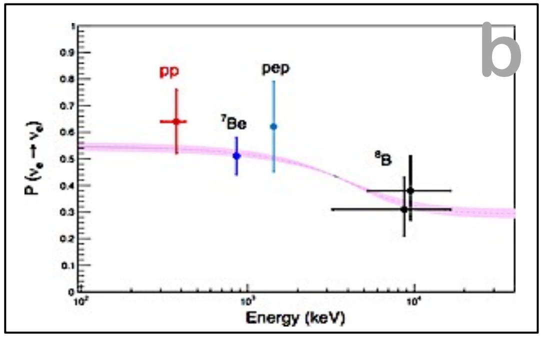
$\mu \rightarrow \mu$ (Atmospheric)



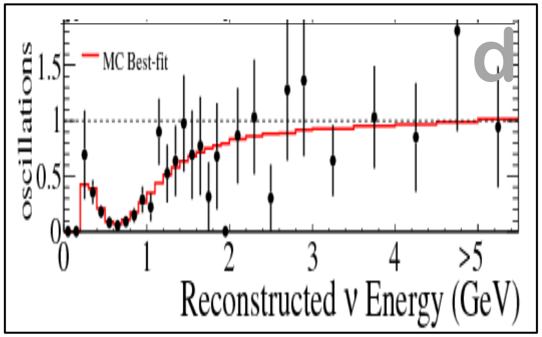
$e \rightarrow e$ (SBL Reac.)



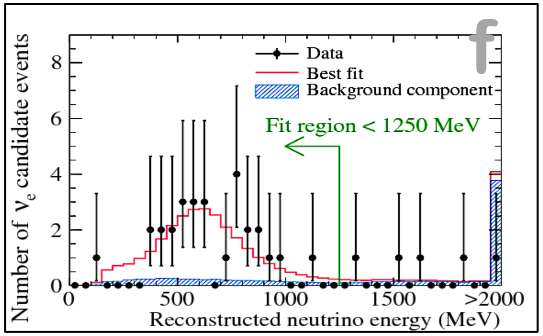
$e \rightarrow e$ (Solar)



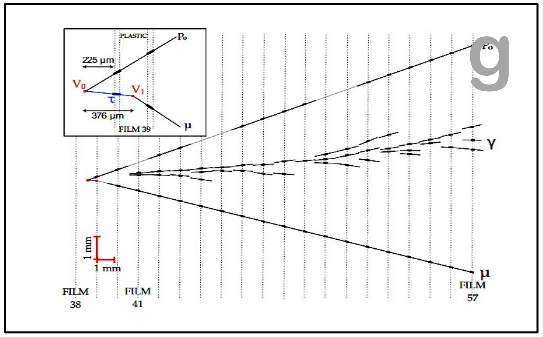
$\mu \rightarrow \mu$ (LBL Accel)



$\mu \rightarrow e$ (LBL Accel)



$\mu \rightarrow \tau$ (OPERA, Atm)

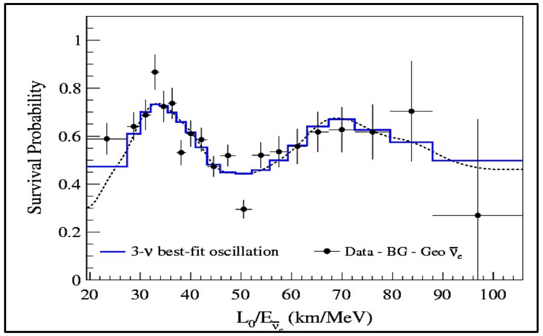


Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor KamLAND, (c) atmospheric, (d) long-baseline accelerator, (e) short-baseline reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

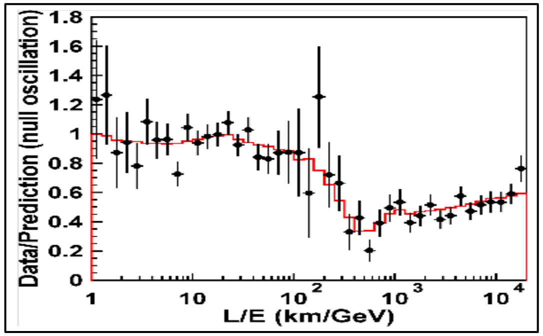
(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS, NOvA; (g) OPERA [plot], Super-K and DeepCore atmospheric.

… successfully converge on five (known) 3ν mass-mixing parameters

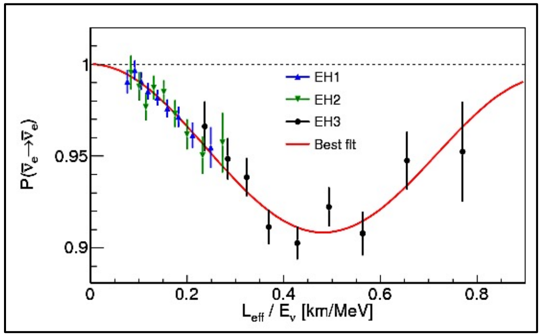
$e \to e$ $(\delta m^2, \theta_{12})$



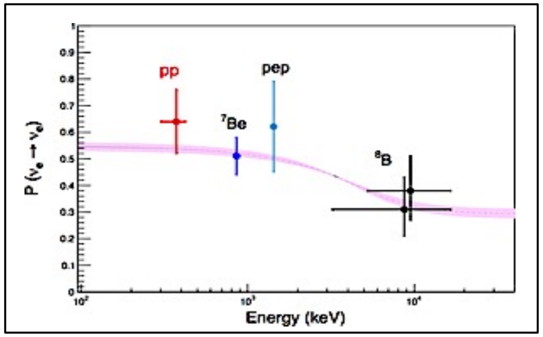
$\mu \to \mu$ $(\Delta m^2, \theta_{23})$



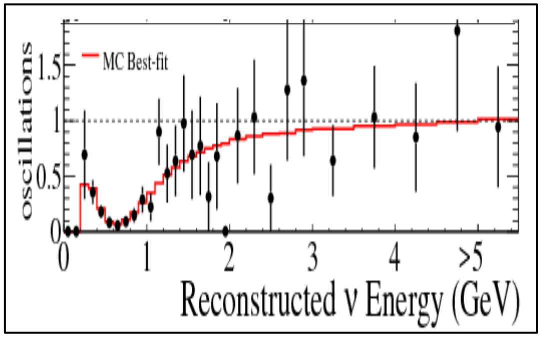
$e \to e$ $(\Delta m^2, \theta_{13})$



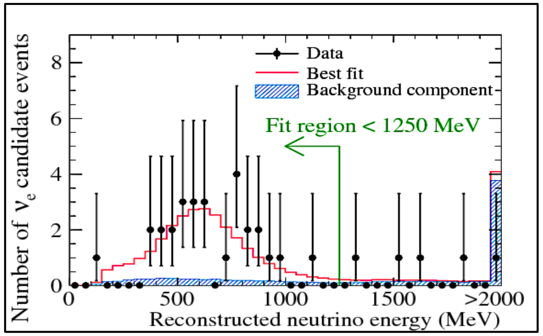
$e \to e$ $(\delta m^2, \theta_{12})$



$\mu \to \mu$ $(\Delta m^2, \theta_{23})$



$\mu \to e$ $(\Delta m^2, \theta_{13}, \theta_{23})$

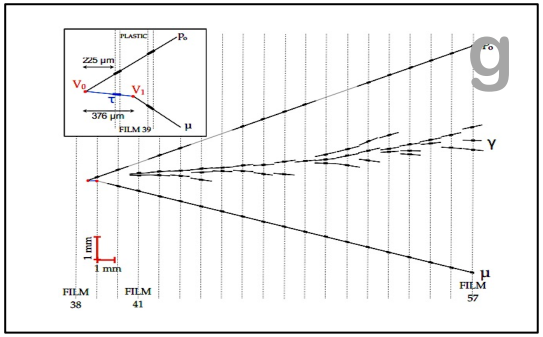


Leading terms: frequency and amplitude → $|\Delta m^2_{ij}|$ and θ_{ij}

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

Subleading terms include **CPV** and **mass-ordering** effects, essentially probed via **$\mu \to e$** appearance in LBL accelerator and atmospheric neutrino experiments → **recent hints on δ, NO/IO**

$\mu \to \tau$ $(\Delta m^2, \theta_{23})$



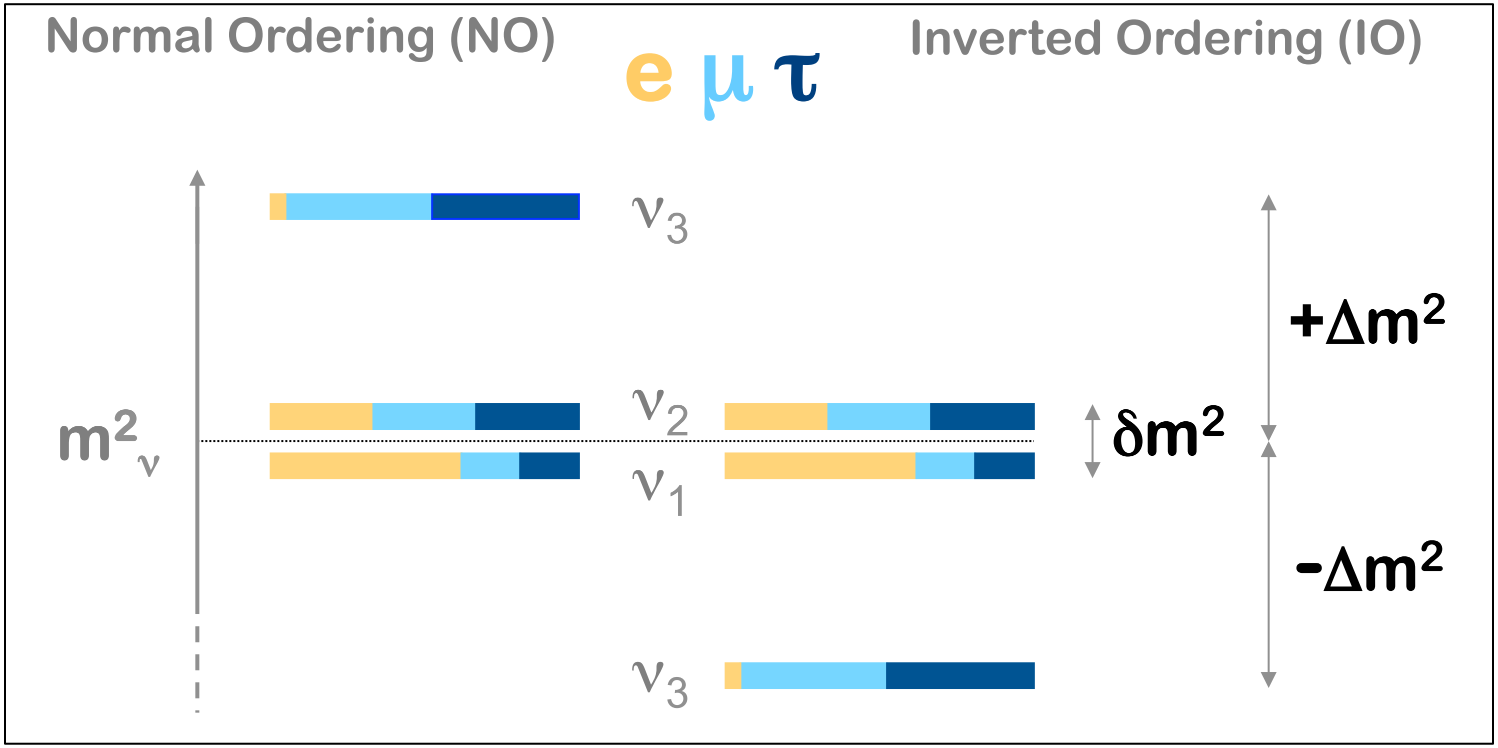
“Broad-brush” 3ν picture (with 1-digit accuracy)

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



Note: Primary goal of past + planned expts: new observations & discovery (not precision)

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

→

Useful to analyze(*) oscillation data in the following sequence:

LBL Accel + Solar + KL (KamLAND)

sensitive to all oscillation parameters: 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)

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(*) Analysis 2018 taken from: 1804.09678 by F. Capozzi, E. Lisi, A. Marrone, A. Palazzo

+Preliminary 2019 update (to be finalized after Summer conferences)

see also Extra slides, and E.L. talk at IPMU 2019, indico.ipmu.jp/event/236

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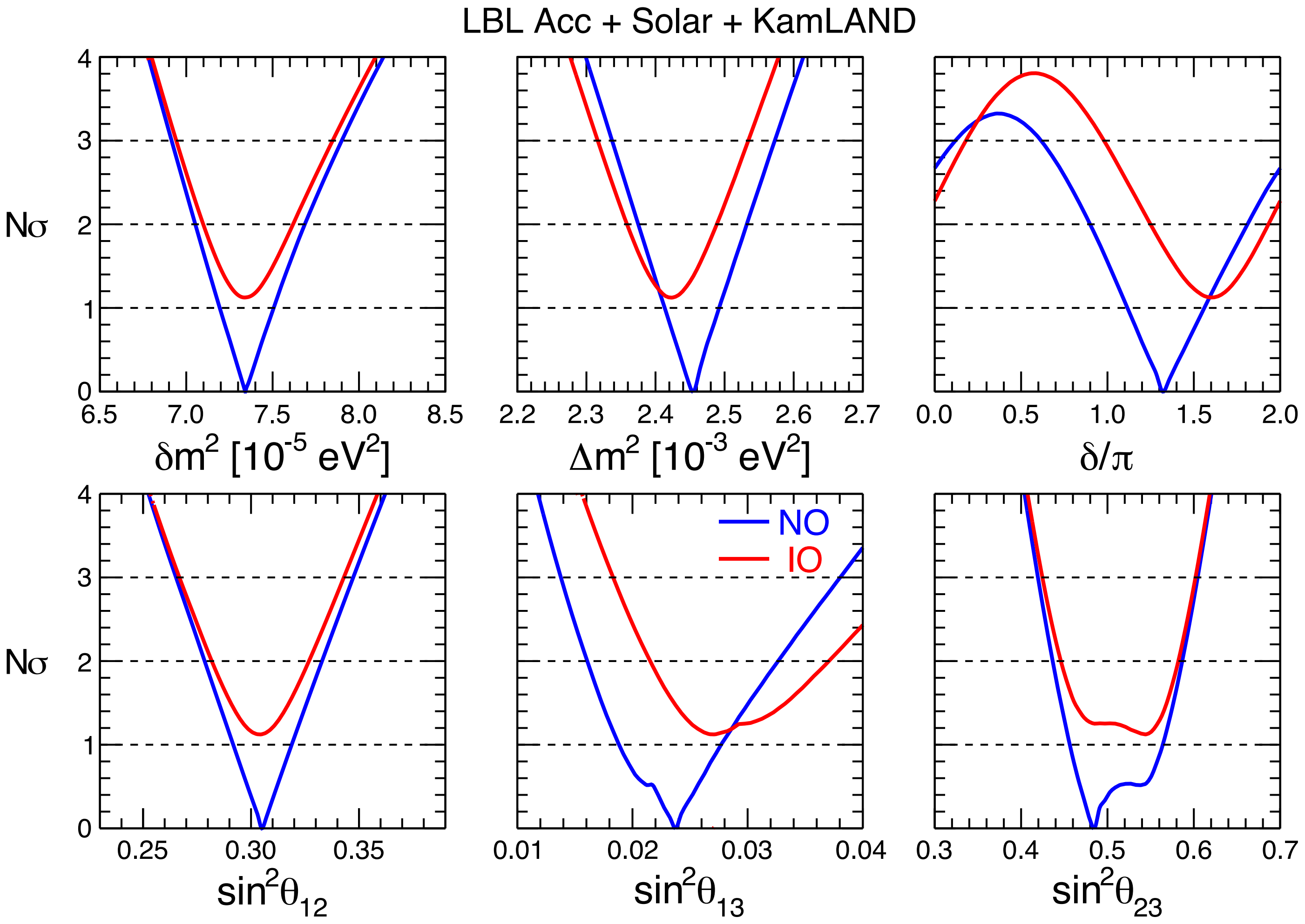
[from 1804.09678]



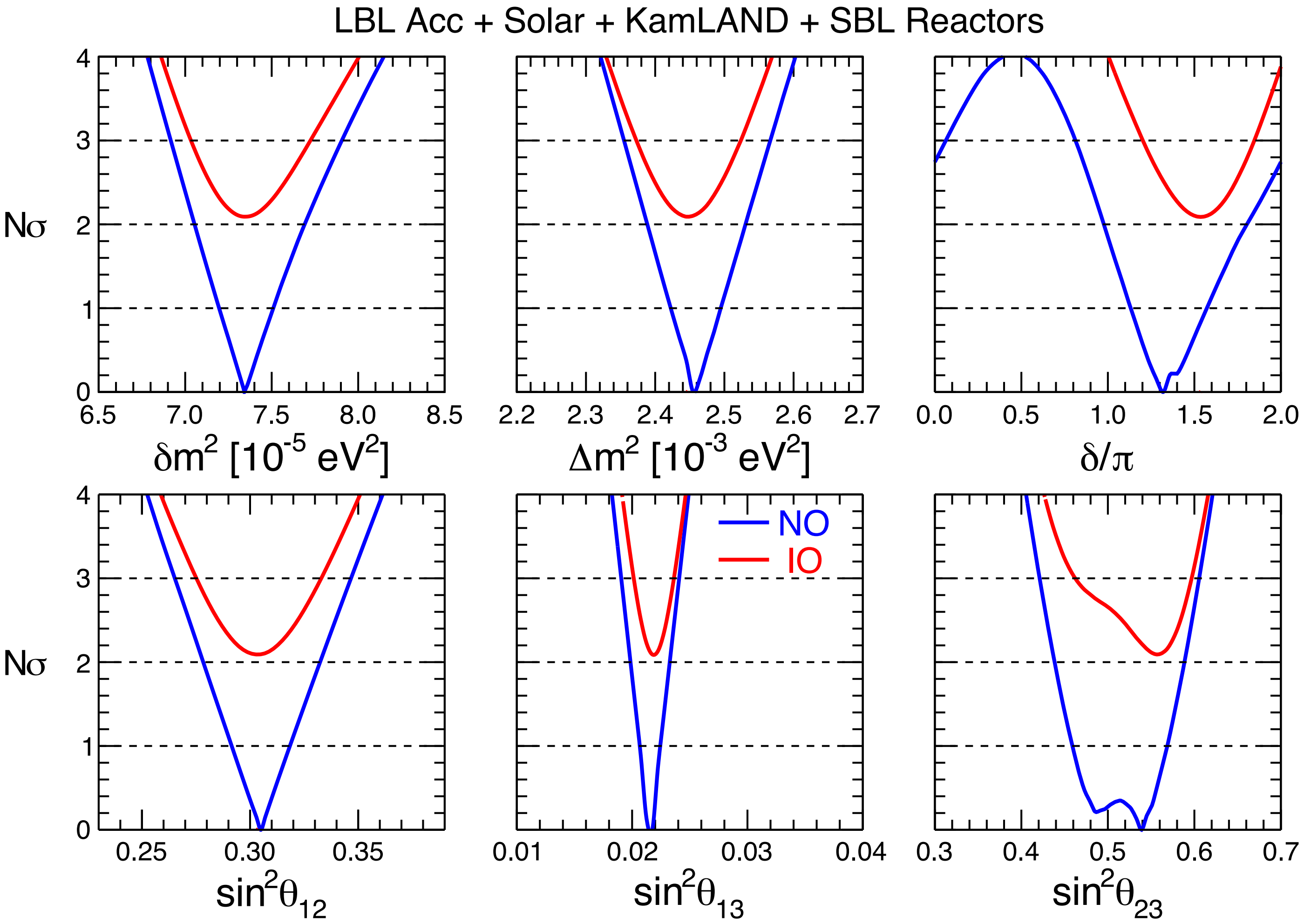
Two mass^2 parameters and three mixing angles: bounds at $>4\sigma$

Hints of ~max CPV with $\delta \sim 3\pi/2$ ($\sin\delta \sim -1$).

NO favored over IO at $\sim 1\sigma$ level.

$N\sigma \equiv \sqrt{\Delta\chi^2}$

[from 1804.09678]

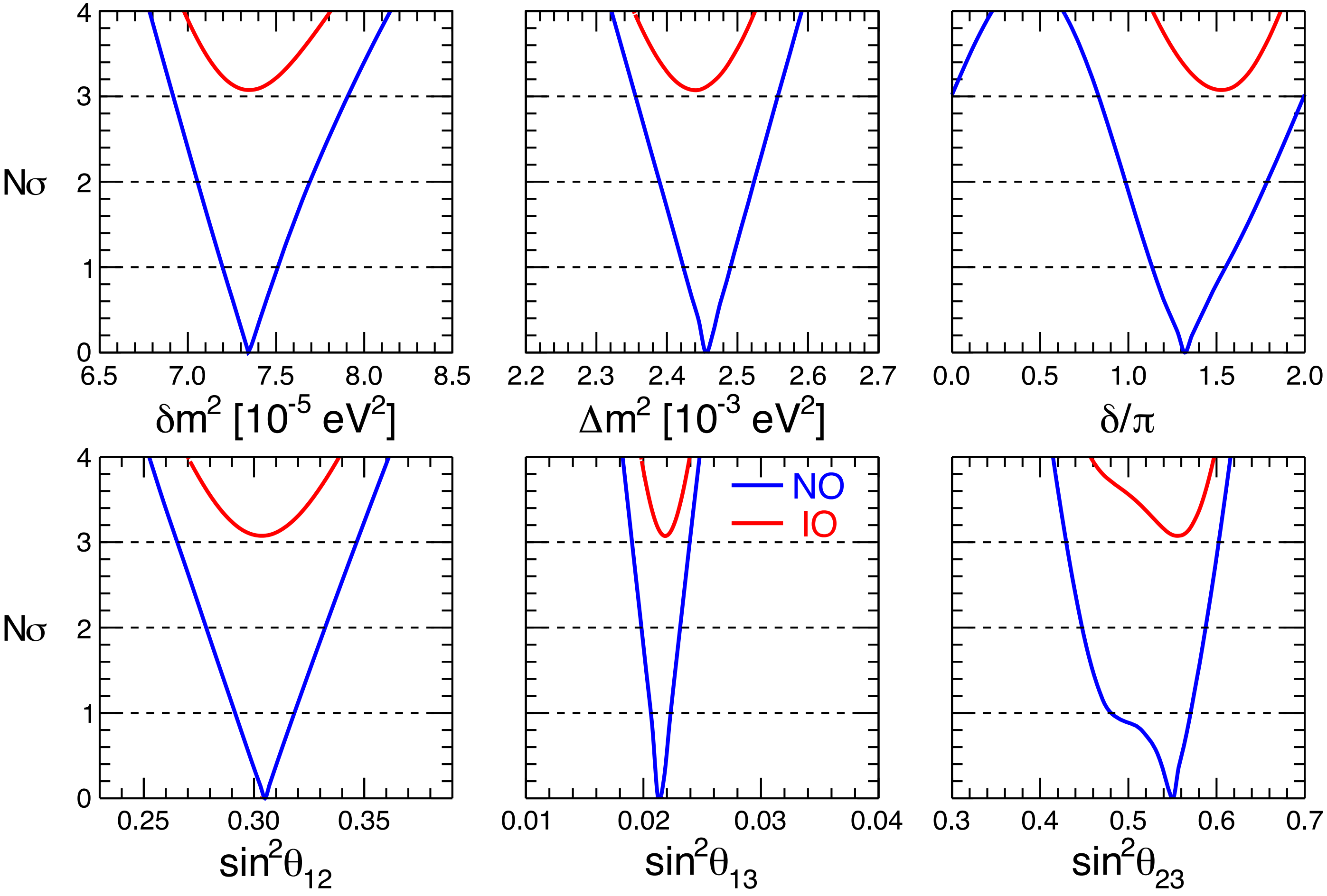


Range of smallest mixing angle θ_{13} dramatically reduced.

Hints of CPV corroborated.

NO favored over IO at ~2σ level.

[from 1804.09678]



LBL Acc + Solar + KamLAND + SBL Reactors + Atmos

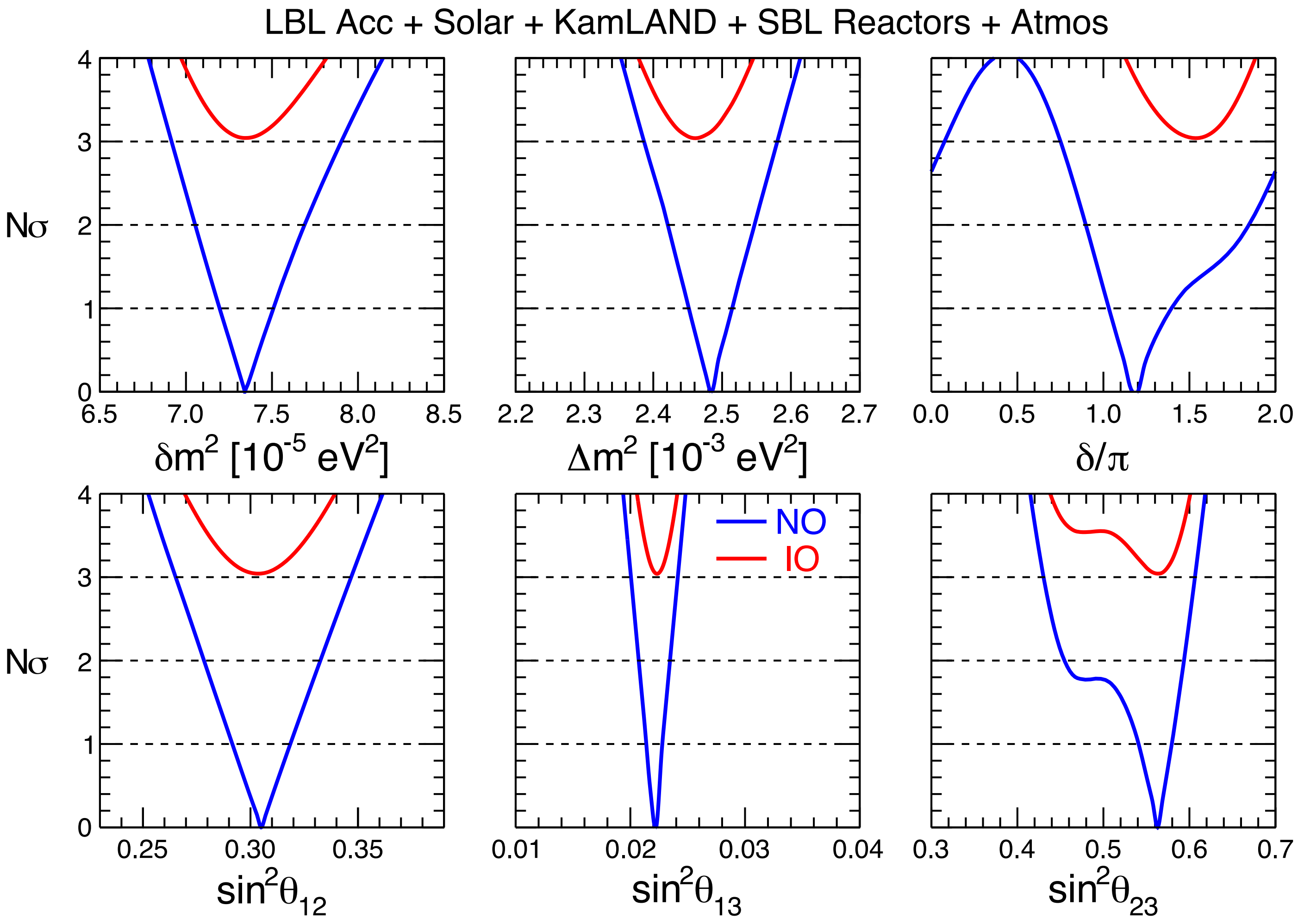
Further improvements for various parameters: 1σ bounds at few % level

Largest angle θ_{23} close to π/4, but octant undetermined at 2σ.

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

NO favored over IO at ~3σ level.

Prelim. update 2019



Slight increase of best fit values for θ_{13}, θ_{23}, Δm^2, with slightly smaller errors.

θ_{23}: preference for 2nd octant, but 1st one allowed at ~2σ.

CPV still favored with $\sin\delta<0$, but with weaker significance (← NOvA vs T2K)

Stable hint for NO favored over IO at ~3σ level.

2019 prelim. update of known oscillation parameters:

Central values and 1σ errors

("1σ" = 1/6 of ±3σ range)

Oscillation parameter		Best-fit (NO)	(IO)	"1σ" error
Δm^2	$/10^{-3}$ eV^2	2.49	2.47	1.3 %
δm^2	$/10^{-5}$ eV^2	7.34	7.34	2.2 %
$\sin^2\theta_{13}$	$/10^{-2}$	2.23	2.24	3.0 %
$\sin^2\theta_{12}$	$/10^{-1}$	3.04	3.03	4.4 %
$\sin^2\theta_{23}$		0.56	0.56	~ 5 %

Dramatic progress in the last ~20 years: From discovery to precision!

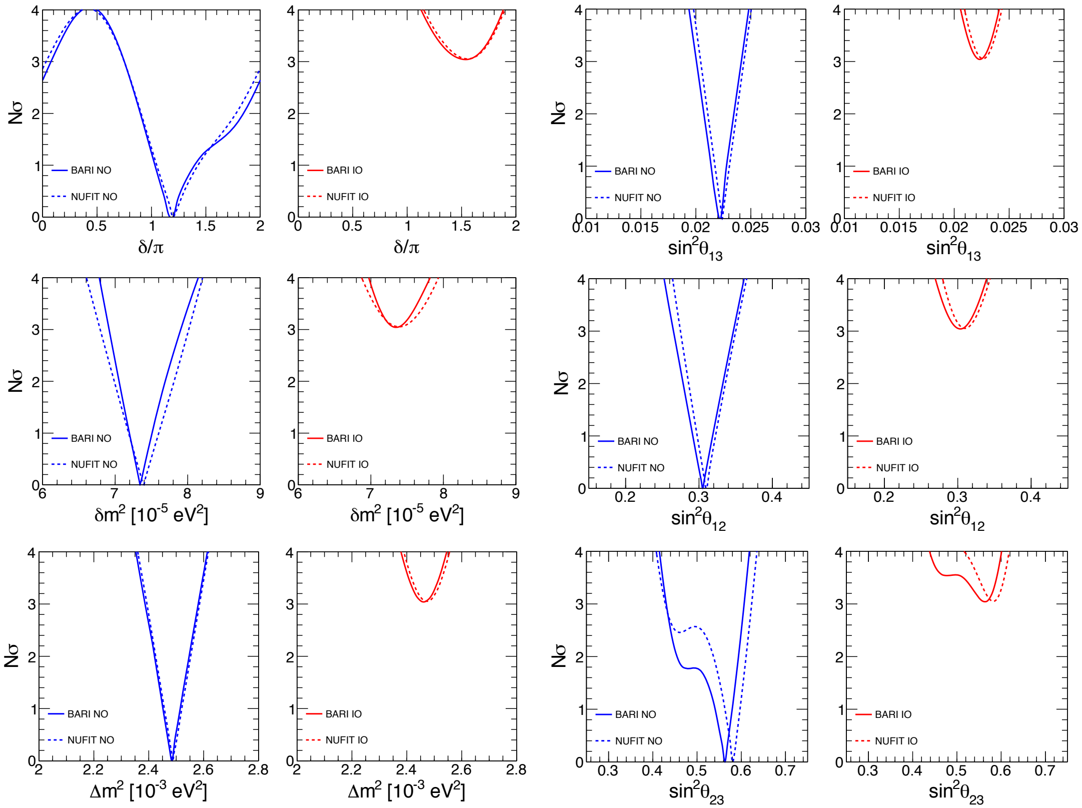
Important lesson learned so far: Diversity is important!

Use different sources, detectors, flavor channels, baselines, energies...

Good agreement of our 2019 update (“BARI”) with NuFIT 4.0 (“NUFIT”, 1811.05487)

[basically using the same relevant input data sets]

except perhaps for the “bimodal” and fragile p.d.f. of $\sin^2\theta_{23}$



[See also Valencia group results 1708.01186 (not shown) for pre-Nu2018 analysis

Trends in precision oscillation analyses: will progressively require **joint work of different collaborations/communities, beyond the reach of single phenomenology groups.**

A few reasons (out of many) for this transition:

Complexity. Some neutrino data sets are becoming too vast and complicated to be analyzed outside the collaborations. "A.I." techniques will enhance the issue.

Uniformity. Comparable standards should be used in the same class of expts. E.g., similar statistical techniques, comparable set/size for systematics...

Common inputs. Some physics ingredients (cross sections, fluxes, backgrounds...) are shared −totally or in part- by different experiments → correlations.

Data preservation. As in other communities (HEP, CR, GW), neutrino data should be formatted and stored in a way to be (easily) accessible now and in the future.

"Metrology". As far as we know, ν mass-mixing parameters are fundamental constants of Nature, to be measured with the highest possible accuracy.

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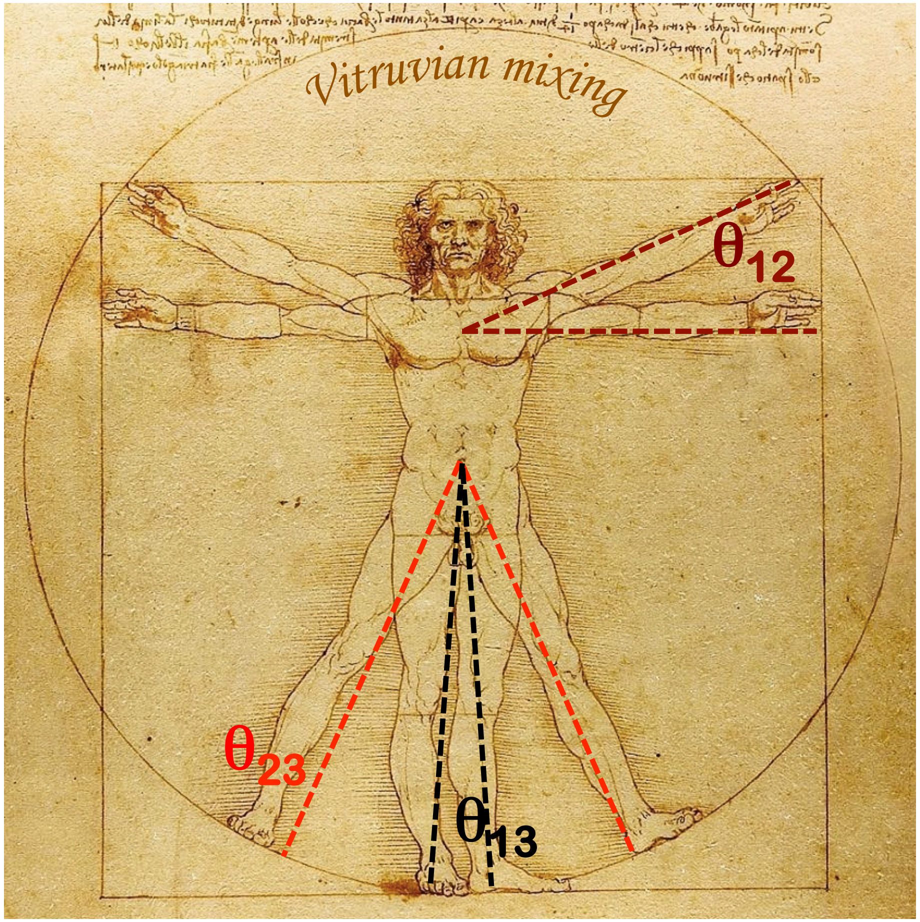
Within 3ν: Theory vs precision data → *talk by S. Pascoli*

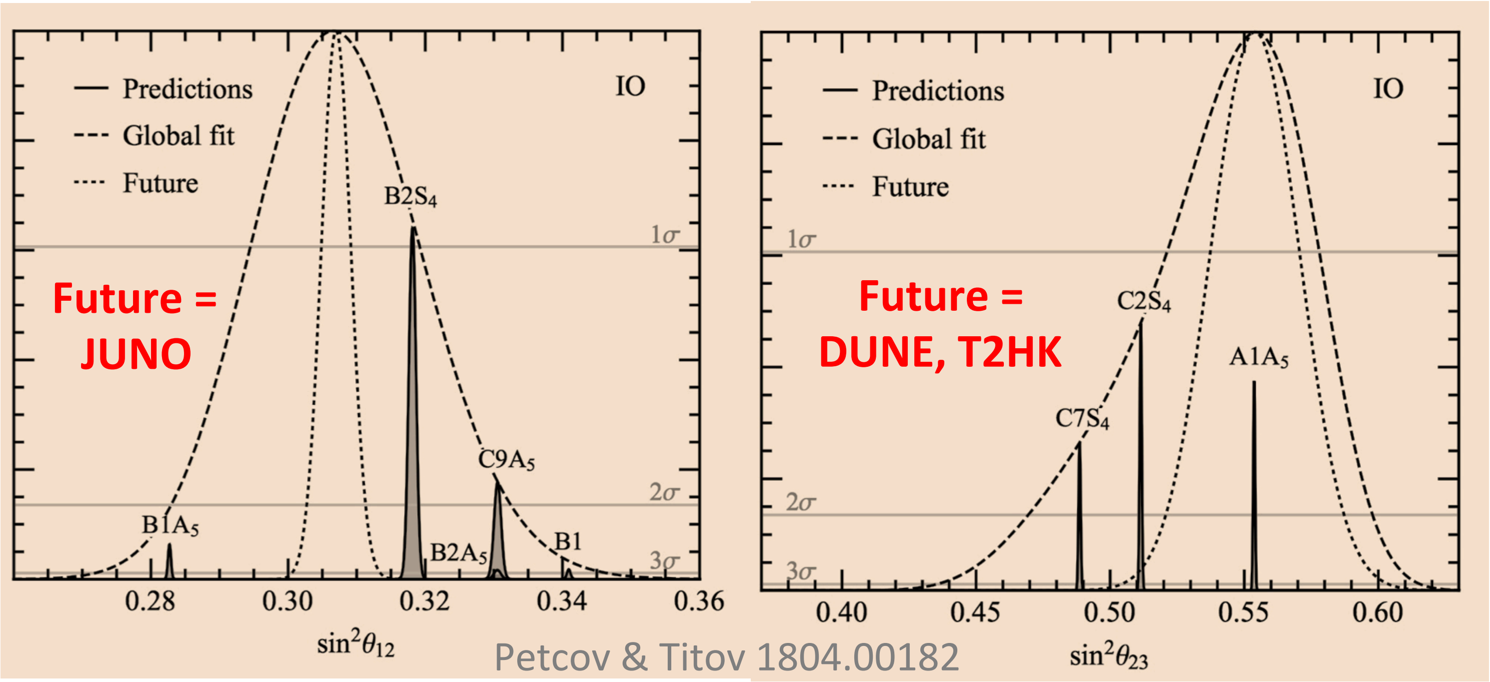
Are the PMNS parameters "accidental", or suggestive of a "pattern"?



Many interesting ideas, but no obvious answer/guidance so far

If one posits no particular structure but **random entries** in the mixing matrix ("anarchy"), then higher precision data would bring **no further insights.**

If one assumes **specific lepton flavor symmetries** (e.g. A4, S4, A5...), then (some) neutrino parameters are predicted and/or correlated, and **future precision measurements can significantly help model selection:**



Future = JUNO

Future = DUNE, T2HK

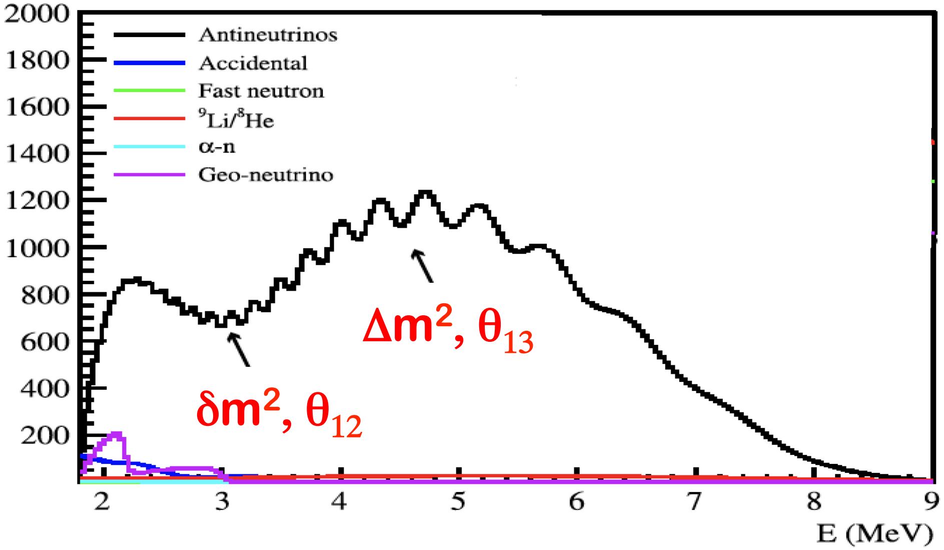
Petcov & Titov 1804.00182

Between extremes: difficult to set "model-independent" goals for accuracy

Expectations for JUNO reactor experiment (Input # 19)

At “medium” baseline ~50 km, will probe two oscillations

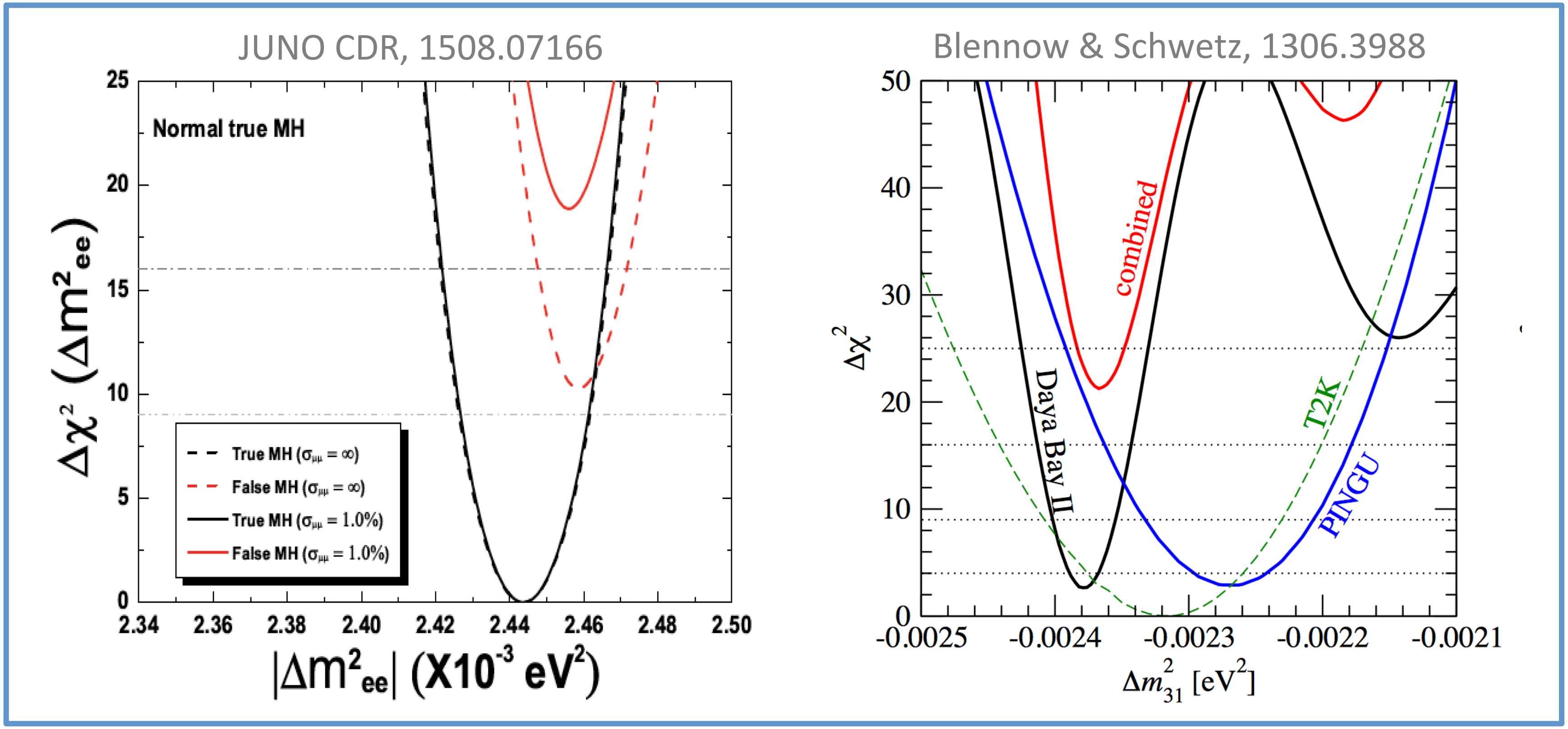
Main goal: distinguish NO vs IO at 3-4σ in 6y.



Significant improvements expected on 3 out of 4 oscillation parameters:

Parameter		1σ, 2019	JUNO, ~2021 + 6y
δm^2	$/10^{-3}$ eV^2	2.2 %	0.6 %
$\sin^2\theta_{12}$	$/10^{-1}$	4.4 %	0.7 %
Δm^2	$/10^{-3}$ eV^2	1.3 %	0.5 %
$\sin^2\theta_{13}$	$/10^{-2}$	3.0 %	[not better]

A “guaranteed” complementarity: better NO/IO discrimination by combining **JUNO + improved Δm^2 from LBL accel. and Atmospheric expts** [reason: for wrong ordering, Δm^2 misfits differ in different expts]


JUNO CDR, 1508.07166

Blennow & Schwetz, 1306.3988

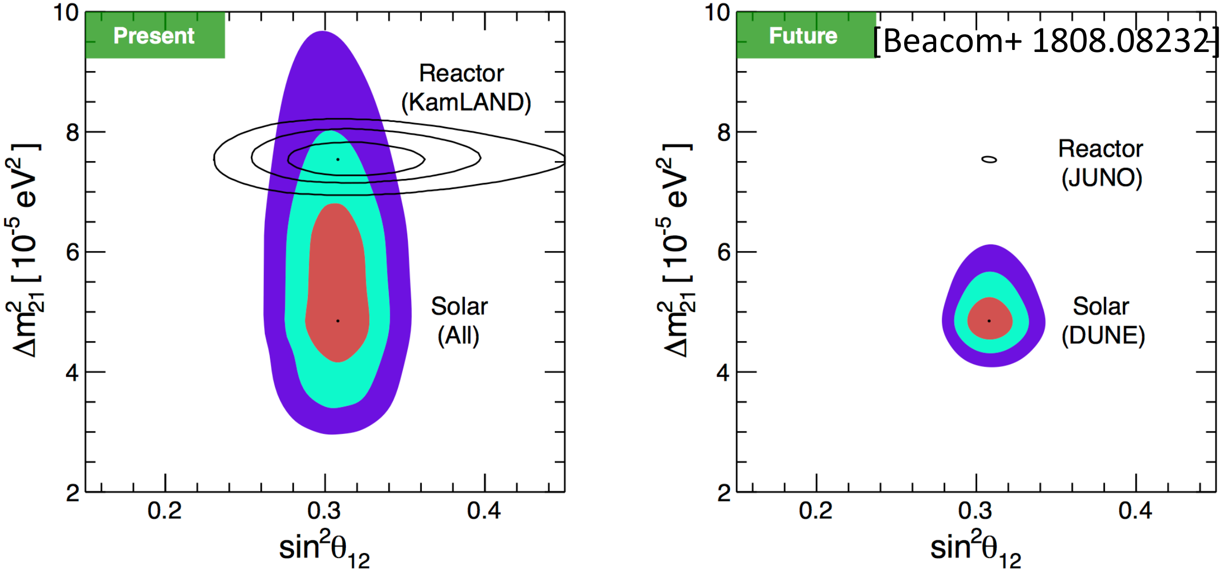
At lower significance, this complementarity is already at work in available data!

In general, we need diversity of approaches, also to test overall 3ν consistency

→ *talk by M. Mezzetto*

Long term: **JUNO (osc. in vacuum) + high-precision solar ν data (osc. in matter)** **might test the slight solar vs KamLAND "tension" (~2σ)** currently emerging from global fits in the determination of **δm^2**

Hypothetical outcome of a proposed DUNE-based solar ν experiment vs JUNO:



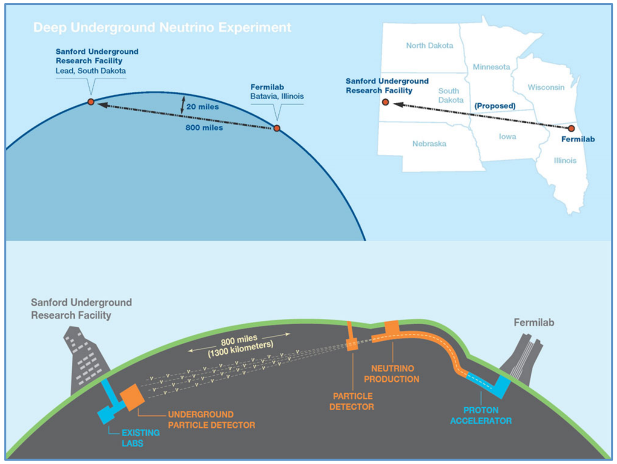
[Beacom+ 1808.08232]

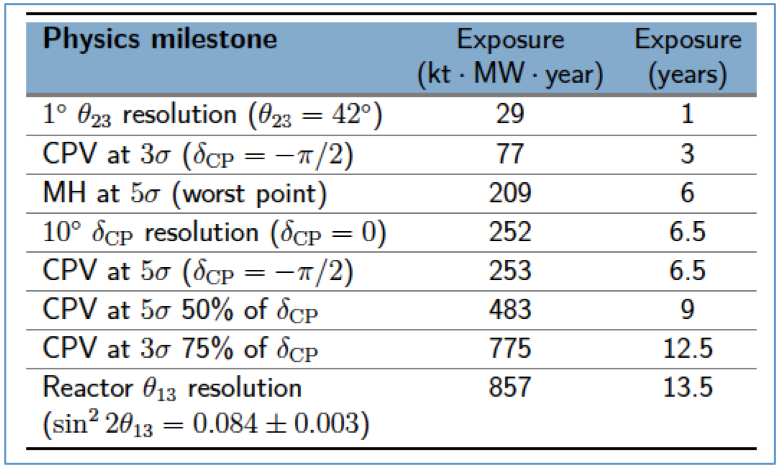
Also: HyperK solar day-night tests. A discrepancy might point beyond standard 3ν, **e.g., nonstandard interactions (NSI) of neutrinos in the solar+Earth matter.**

[Recently: NSI also testable with coherent elastic neutrino-nucleus scattering]

Expectations for DUNE, LBL accel. expt [Input #126 + 1807.10334]

Disappearance + appearance → Can probe several 3ν knowns and unknowns:





Physics milestone	Exposure (kt · MW · year)	Exposure (years)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	29	1
CPV at 3σ ($\delta_{\rm CP} = -\pi/2$)	77	3
MH at 5σ (worst point)	209	6
10° $\delta_{\rm CP}$ resolution ($\delta_{\rm CP} = 0$)	252	6.5
CPV at 5σ ($\delta_{\rm CP} = -\pi/2$)	253	6.5
CPV at 5σ 50% of $\delta_{\rm CP}$	483	9
CPV at 3σ 75% of $\delta_{\rm CP}$	775	12.5
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	857	13.5

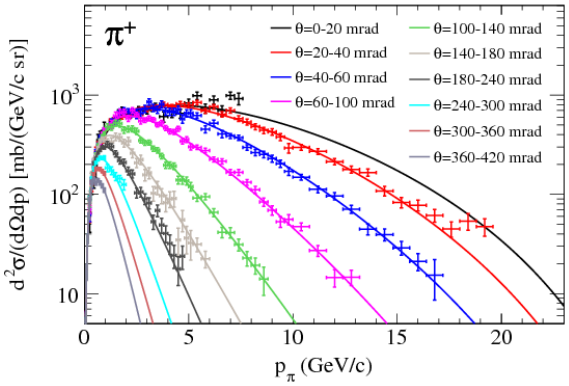
Parameter	**1σ, 2019**	**DUNE, from Input #45 [EU Town meeting]** *assuming systematics scaling with statistics*
Δm^2	**1.3 %**	**~ 0.3 %**
$\sin^2\theta_{23}$	**~ 5 %**	**~ 1 % → octant resolution**
$\sin^2\theta_{13}$	**3.0 %**	**~ comparable to reactors**

T2HK: same ballpark. But: Difficult to anticipate DUNE/T2K accuracy

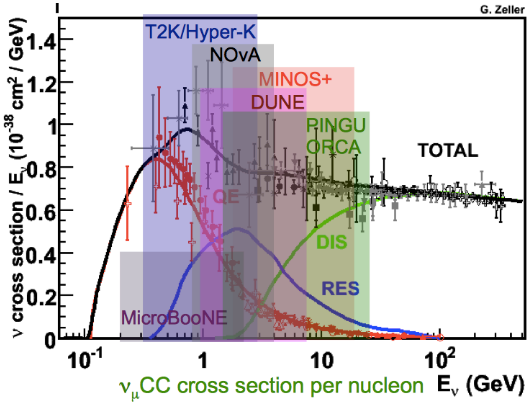
due to current cross-section uncertainties. [Not an issue for IBD in JUNO]

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

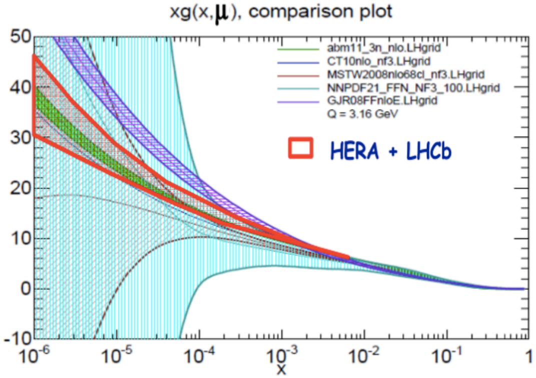
Need hadron production data, e.g. pA → πX, +theory models to improve estimates of atm. and acceler. ν fluxes and errors

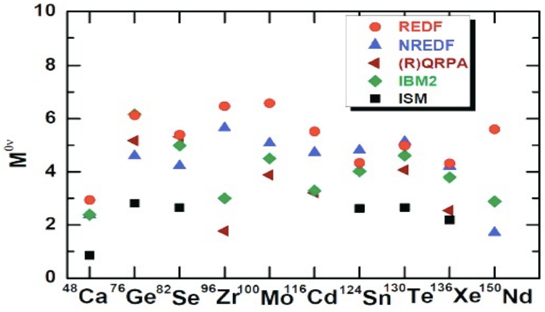


Current understanding of ν cross sections at O(GeV) does not match the needs of (next-generation) ν expts



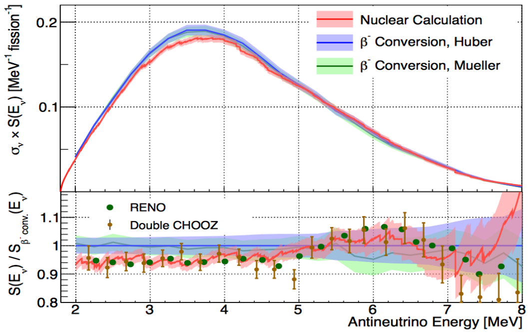
Improved PDFs at low-x via ~forward charm production at LHCb essential to constrain prompt component in UHE ν





Better control of nuclear EW response (e.g., g_A) relevant to interpret 2β and β decay data, fine structure of react. spectra

→ *talk by F. Sanchez*

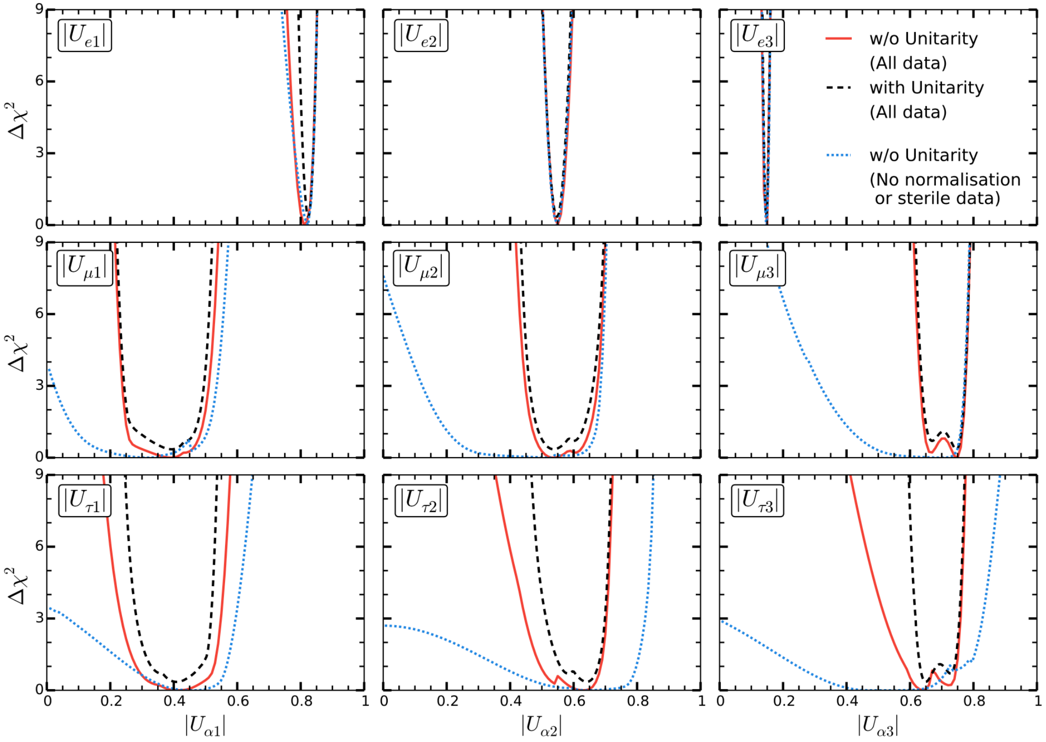


Progress requires joint contributions from different disciplines & communities: not just “ancillary” data, but an emerging field of “electroweak nuclear physics”

Progress on flux and cross section predictions also needed to get precise absolute normalizations of events → important for "unitarity" tests

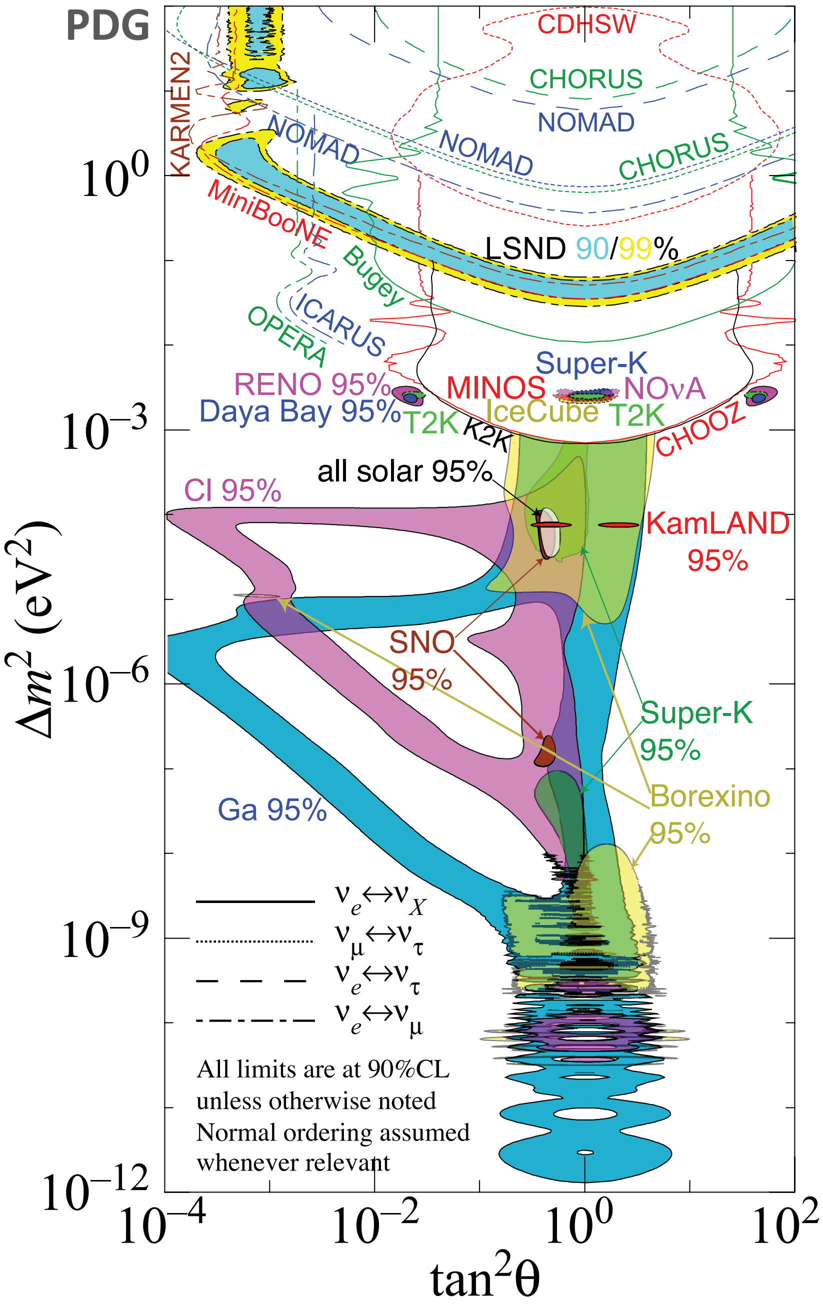
["leakage" of PMNS elements embedded in a matrix larger than 3x3]

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



Stronger constraints by assuming specific models for new sterile states which might appear anywhere from ~eV scale to GUT scale

→ *talks by Pascoli, Mertens, Fleming, Serra*



Learning from neutrino oscillation searches:

We need to cast wide nets to search for new neutrino states (and interactions)...

These searches may meet precision measurements when an anomaly in the “standard” framework is found (e.g. light steriles)

Complementarities and “redundance” needed to eliminate “fake news”

Persisting anomalies will motivate and set targets for further efforts, until the next discovery phase!

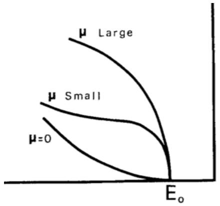
Another expt. way of testing the 3ν framework: oscillation vs nonoscillation data

Absolute mass observables (m_β , $m_{\beta\beta}$, Σ)

→ *Talk by S. Mertens*

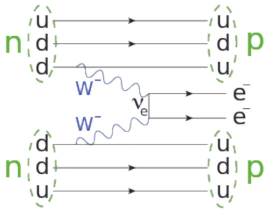
β **decay**, sensitive to the "effective electron neutrino mass":

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



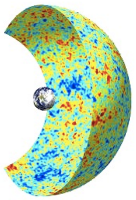
0νββ decay: only if Majorana. "Effective Majorana mass":

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



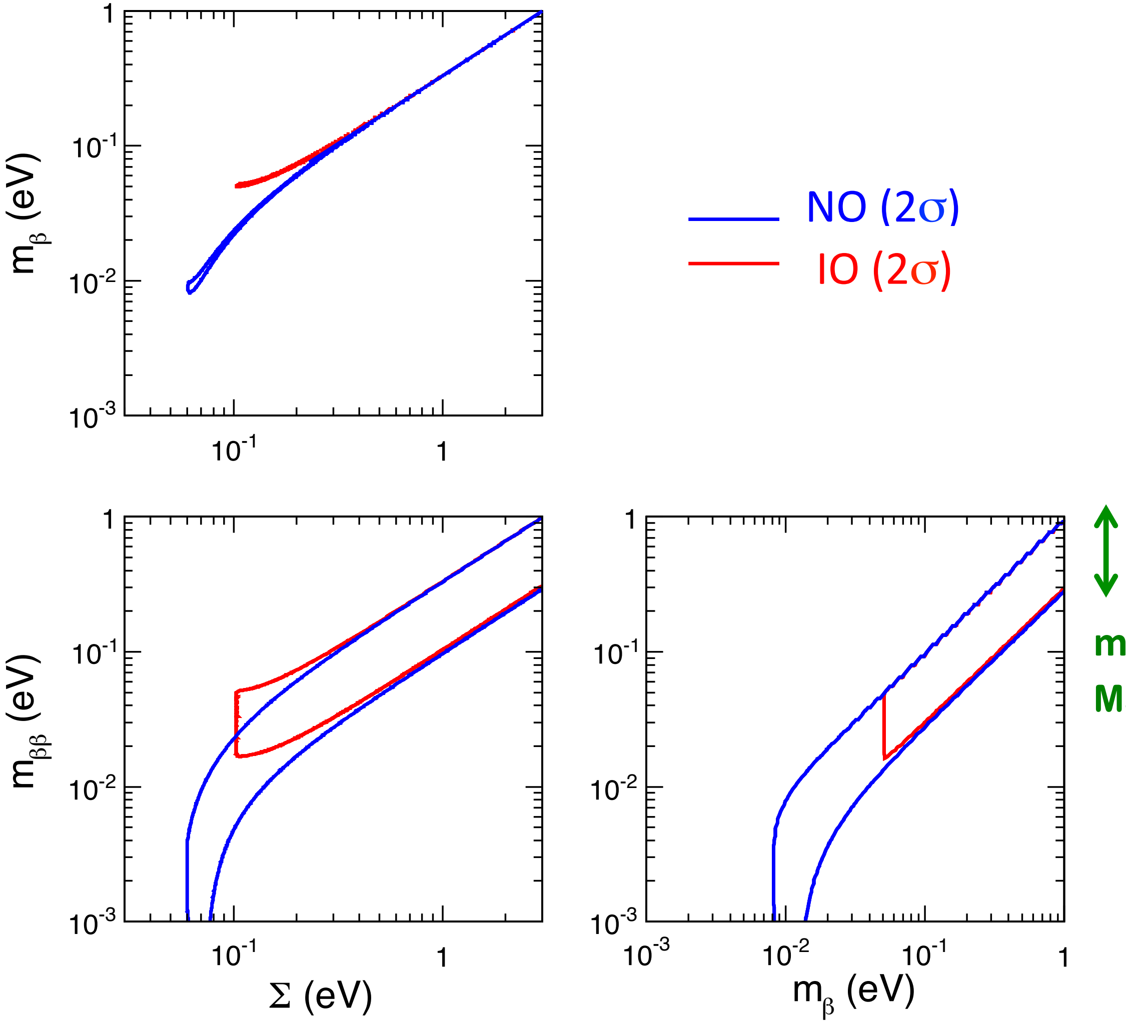
Cosmology: Dominantly sensitive to sum of neutrino masses:

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



Absolute mass data should lie within the strips allowed by 3ν oscillations

(Oscillation accuracy already sufficient. Need non-oscillation signals!)



$m_{\beta\beta}$ spread due to Majorana CP phase(s)

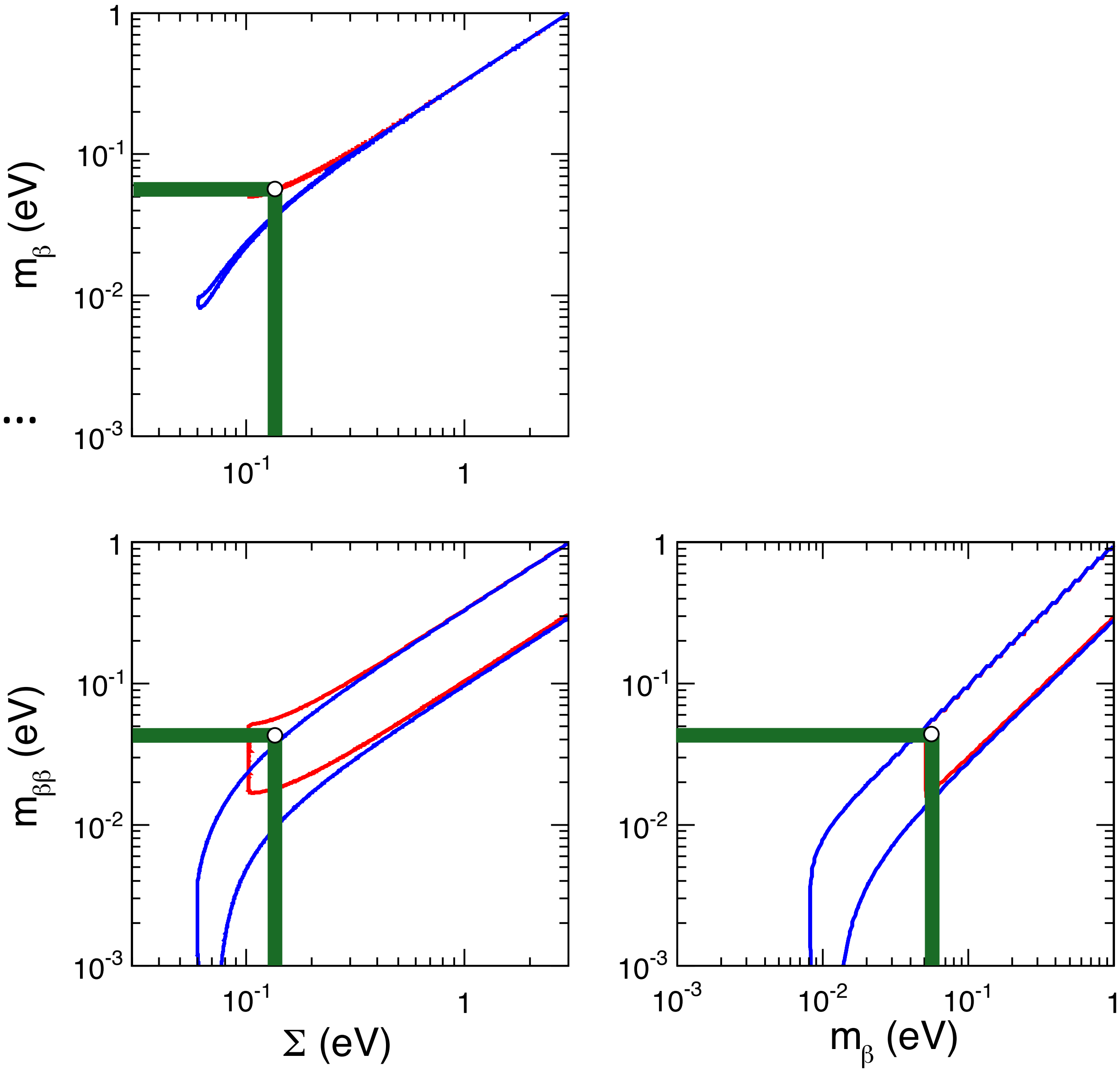
In principle, with precise and converging non-oscillation signals one could, e.g.

Determine the mass scale…

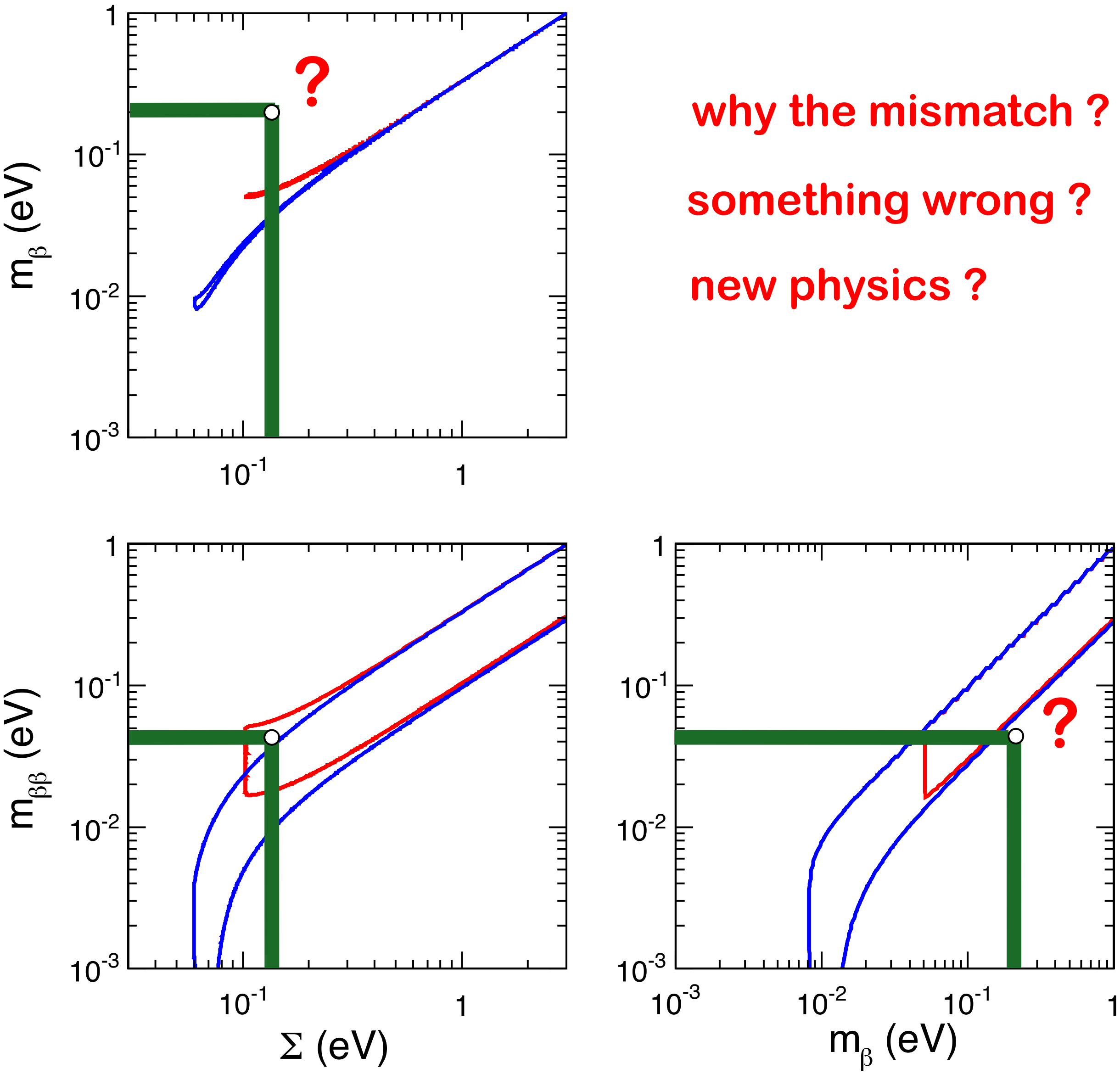
Check 3ν consistency …

Identify the hierarchy …

Probe the Majorana phase(s) …



But alternative situations might also occur….



why the mismatch ?

something wrong ?

new physics ?

OUTLINE

Introduction

3ν oscillation analysis: 2018→2019

(Some) expected improvements & tests

Conclusions

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

- 3ν framework established by the convergence of many data sets.
- Five known parameters are being measured with increasing accuracy; but still a long way to reach CKM levels in PMNS matrix...
- Five unknowns remains, with hints in favor of NO, CPV, $\theta_{23} > \pi/4$
- Accuracy of known parameters (except θ_{13}) expected to improve significantly in next-generation expts, JUNO + DUNE + (T2)HK + ...

Knowns:

δm^2 ~ 7 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

Unknowns:

δ = Dirac CPV phase
sign(Δm^2) = ordering
octant(θ_{23})
absolute mass scale
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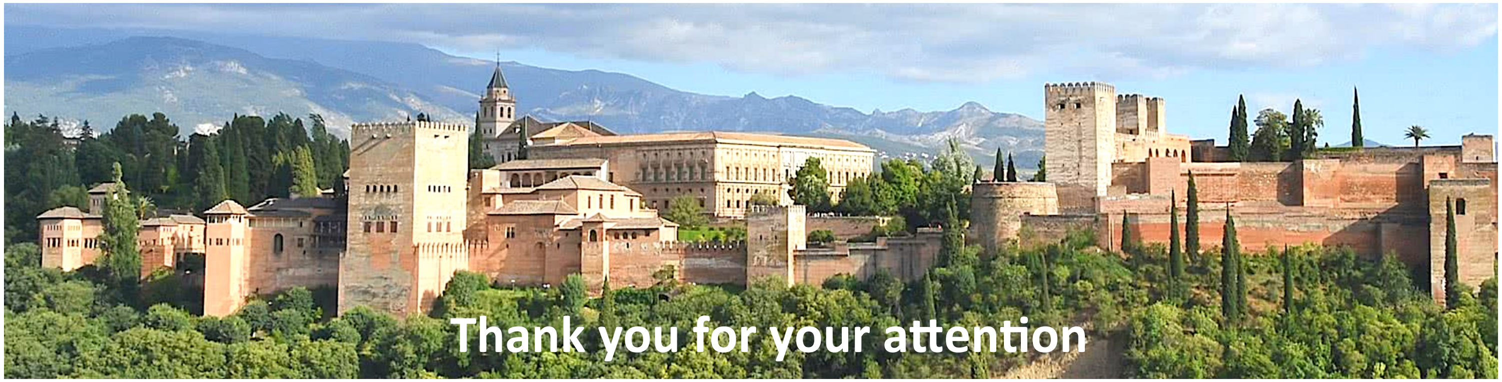
- Accuracy of known parameters (except θ_{13}) expected to improve significantly in next-generation expts, JUNO + DUNE + (T2)HK + ...
- Progress in electroweak nuclear physics needed to reach many goals
- Combined 3ν analyses of high-stat datasets will face new challenges and call for joint efforts of different collaborations & communities
- Precise (non)oscillation parameters will allow unprecedented tests of the 3ν framework → may show cracks (new states / inter.)
- Past experience and expectations show strategic importance of keeping **diversity and complementarity** of approaches: (non)osc., natural/artificial beams, detectors, channels, L, E, matter/vacuum...



Thank you for your attention

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EXTRA SLIDES
on global 3ν analysis

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

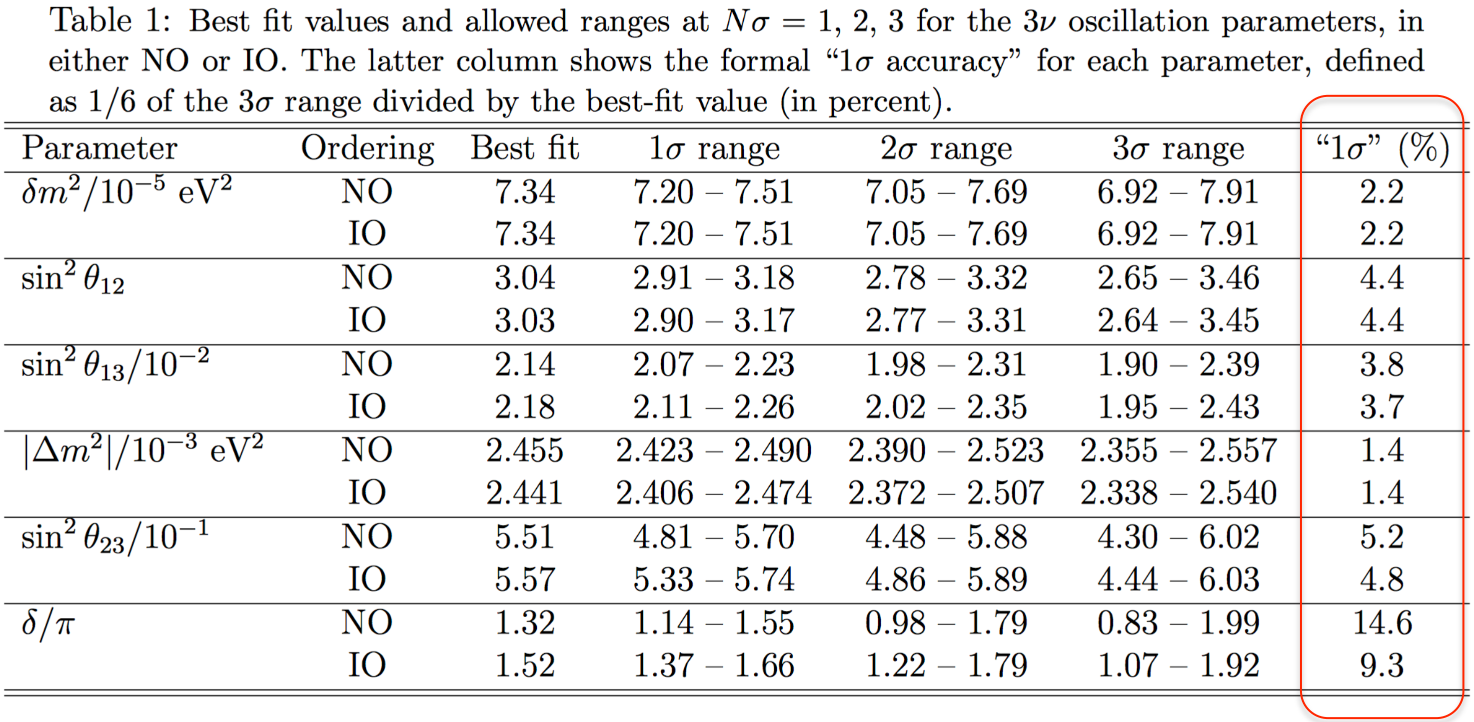


Table 1: Best fit values and allowed ranges at $N\sigma = 1, 2, 3$ for the 3ν oscillation parameters, in either NO or IO. The latter column shows the formal "1σ accuracy" for each parameter, defined as 1/6 of the 3σ range divided by the best-fit value (in percent).

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

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

[Capozzi, Lisi, Marrone, Palazzo, preliminary, unpublished]

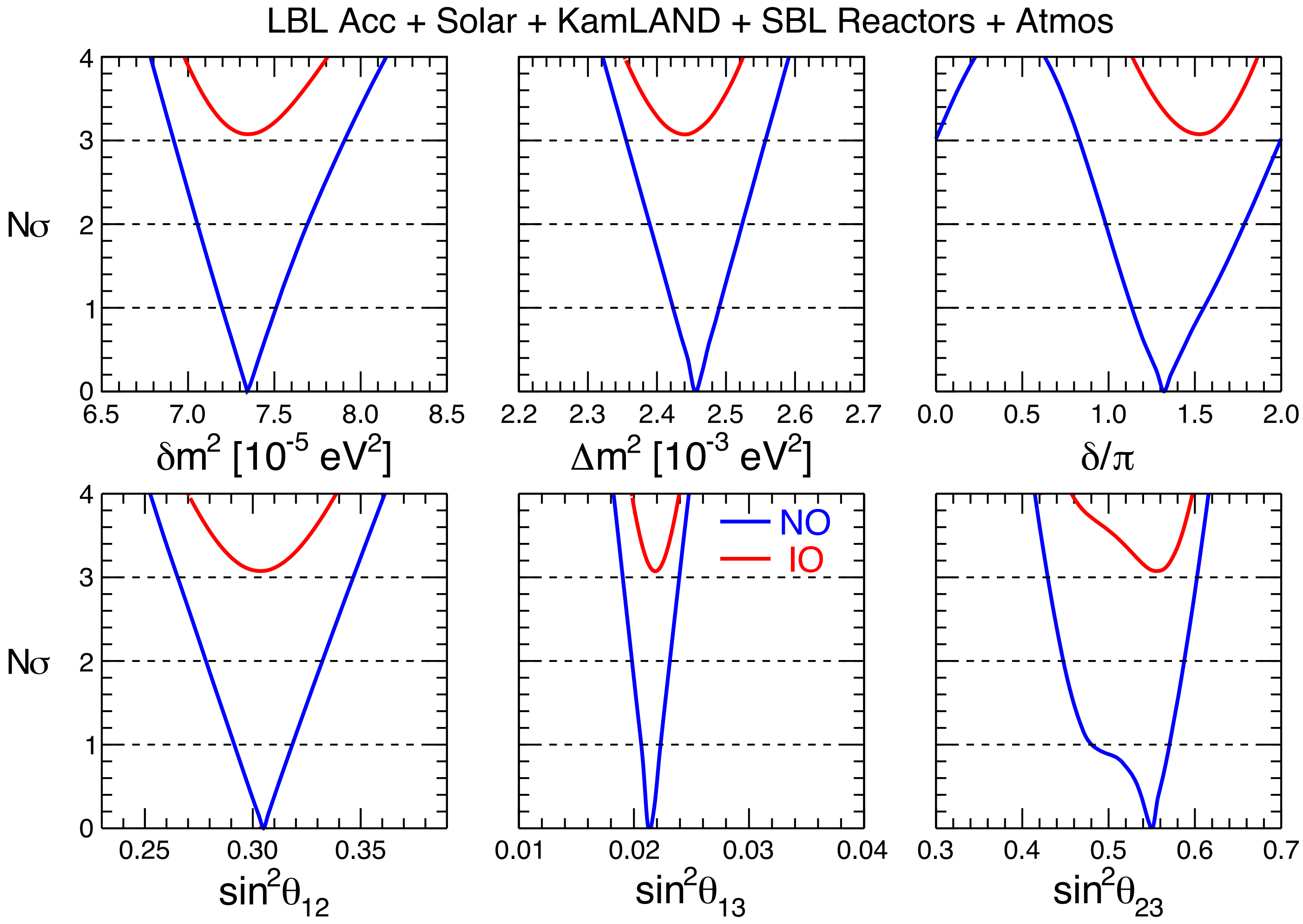
RENO	✓	arXiv:1806.00248
Daya Bay	✓	arXiv:1809.02261
Double Chooz	✗	arXiv:1901.09445
T2K	✓	Neutrino 2018 + other conferences 2018/19
NOvA	✓	Neutrino 2018 + other conferences 2018/19
SK-IV atmos.	✗	arXiv:1901.03230, fiTQun reconstr. algorithm
DeepCore	✗	arXiv:1902.07771, analyses "A" and "B"

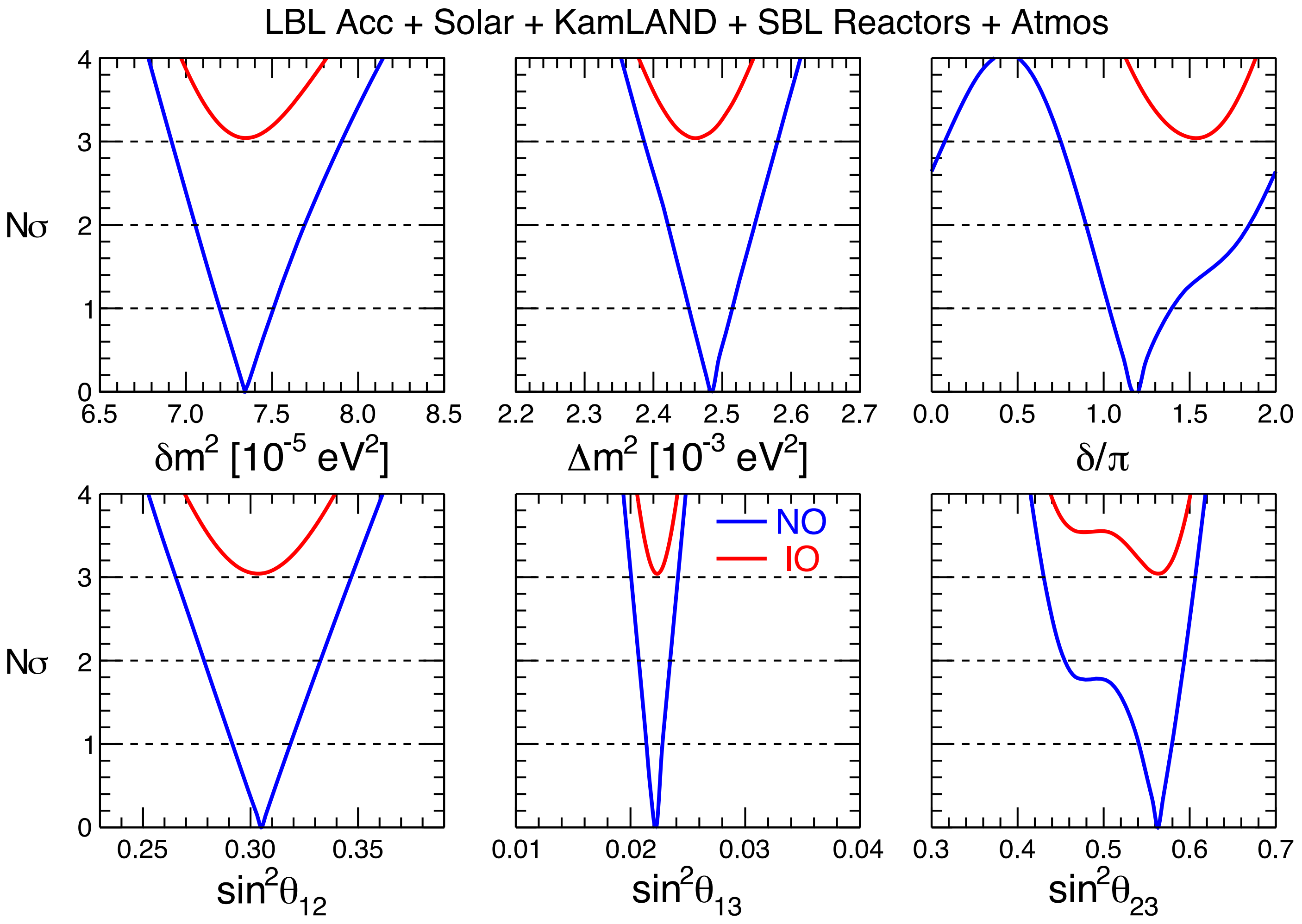
Further activity on the experimental side:

- 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*

← 2018


LBL Acc + Solar + KamLAND + SBL Reactors + Atmos



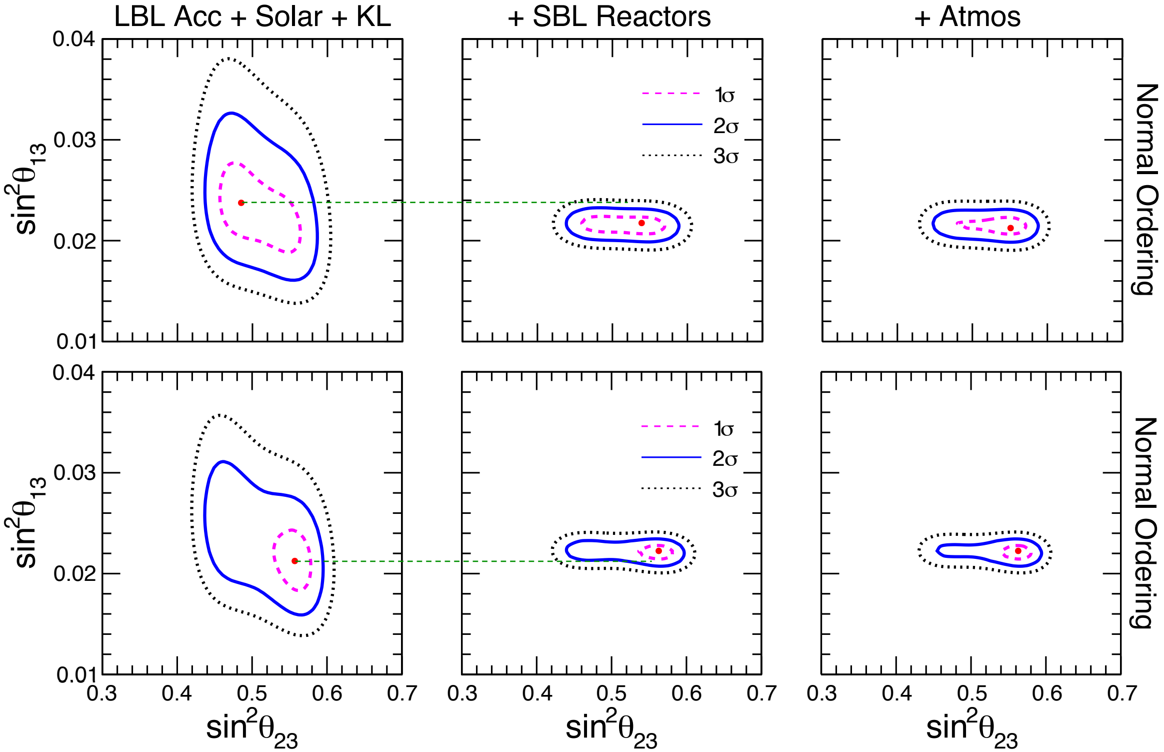
← **2019**

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



← 2018

← 2019

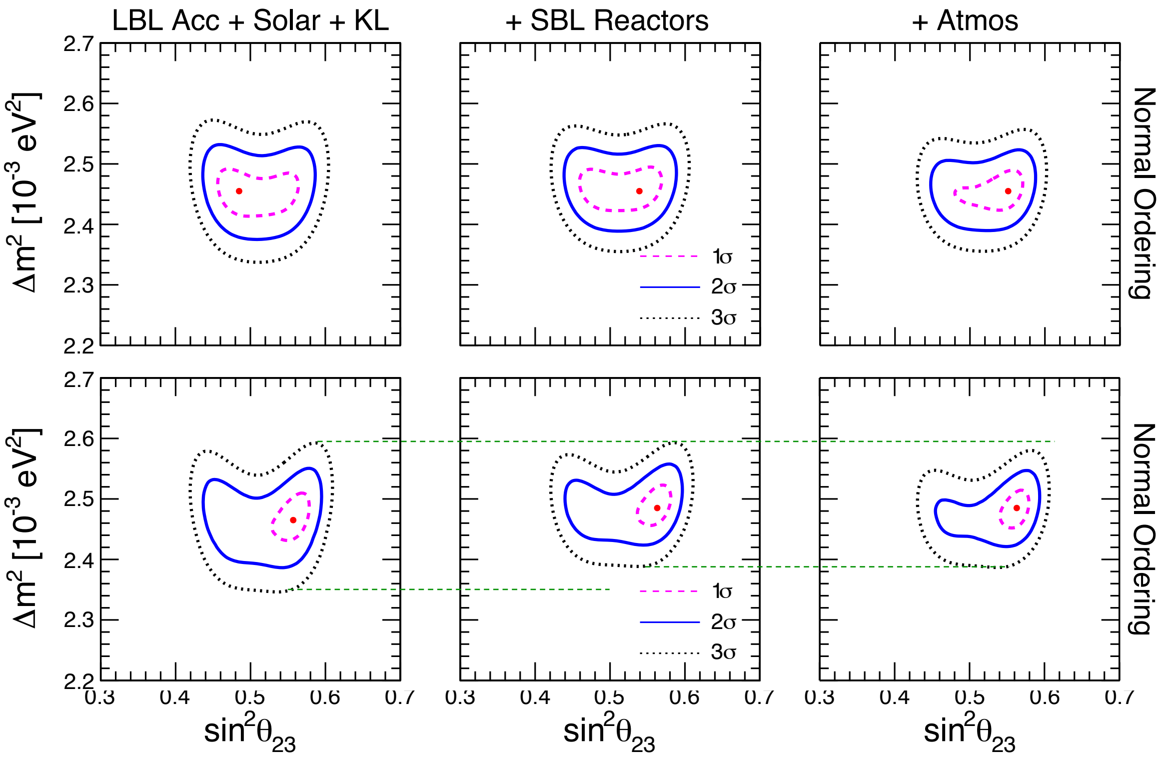
$\sin^2\theta_{23}$: Slight preference for 2nd octant already from LBL+Solar+KL data

$\sin^2\theta_{13}$: 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 2nd octant of θ_{23}

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

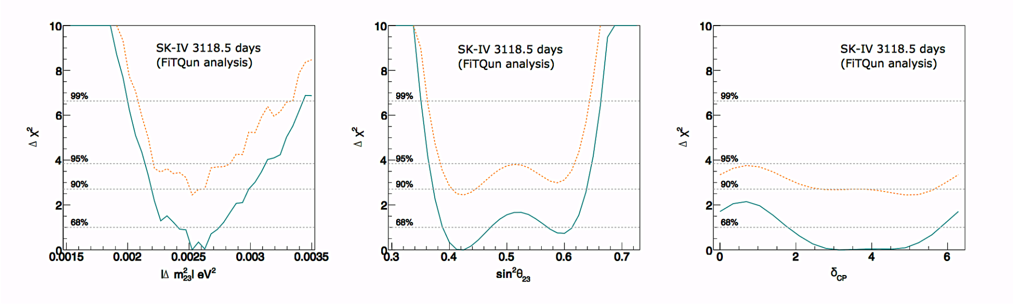


← 2018

← 2019

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

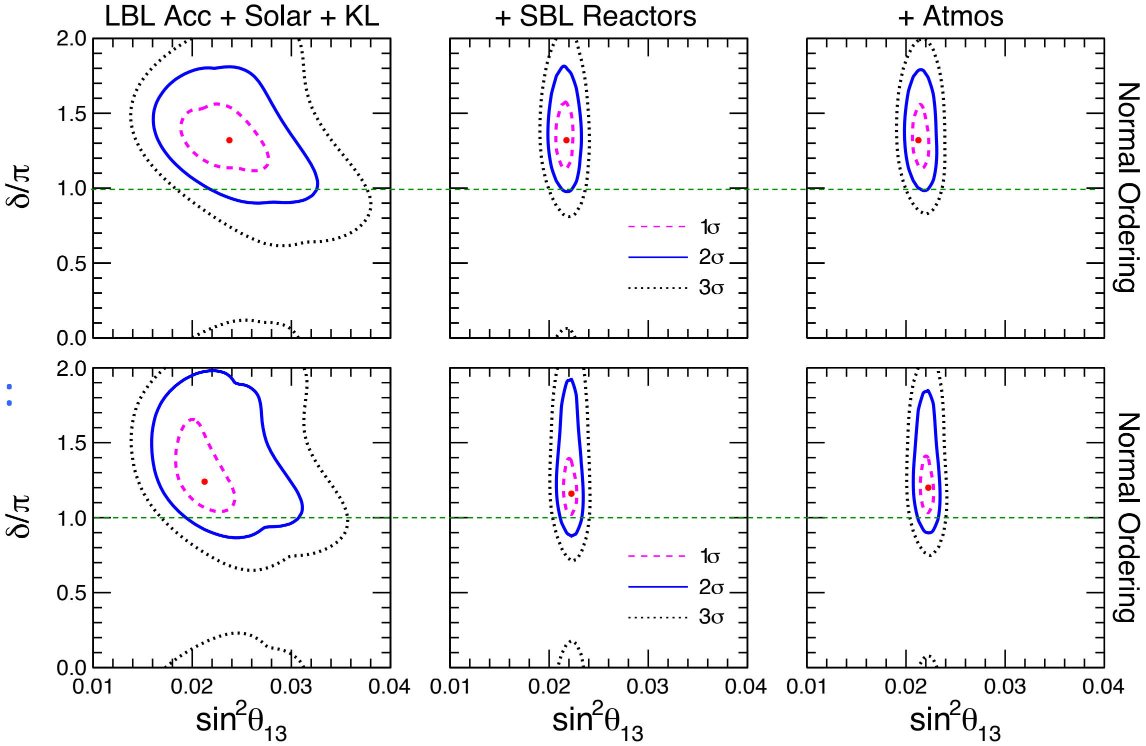
$\sin^2\theta_{23}$: As noted, LBL (+SBL) preference for 2nd octant, but... SK-IV?



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



← **2018**

← **2019**

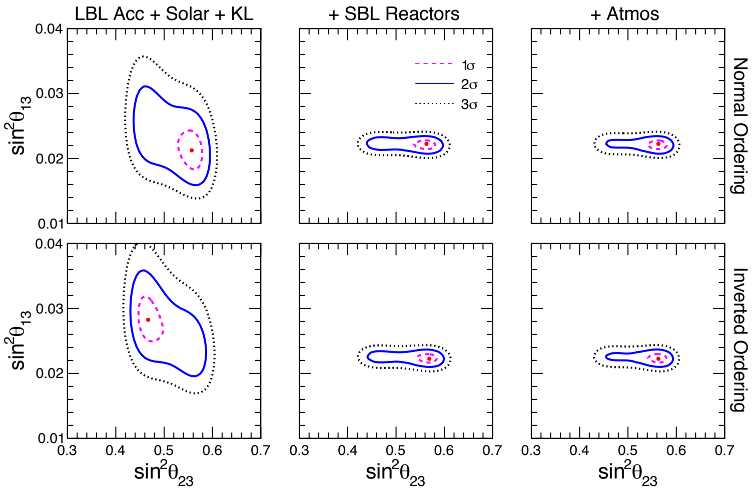
CP conservation:

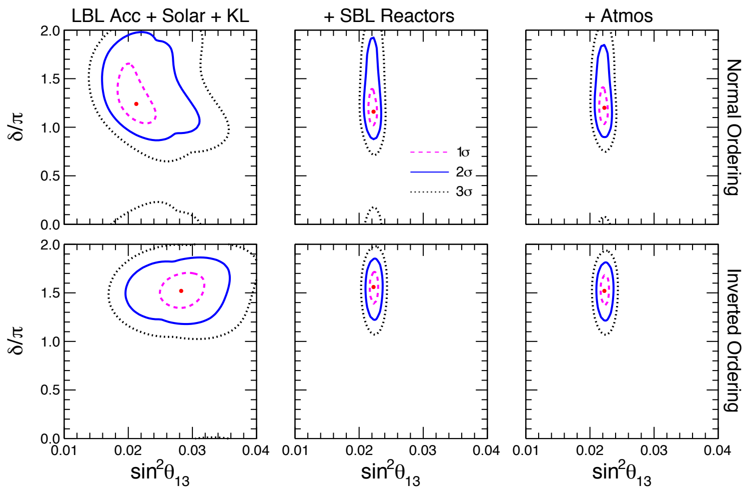
$\delta=\pi$ @ 1.3σ

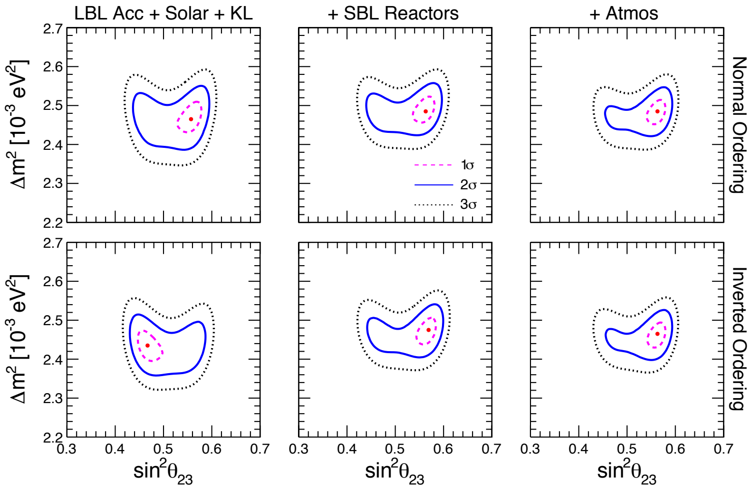
$\delta=0, 2\pi$ @ 2.6σ

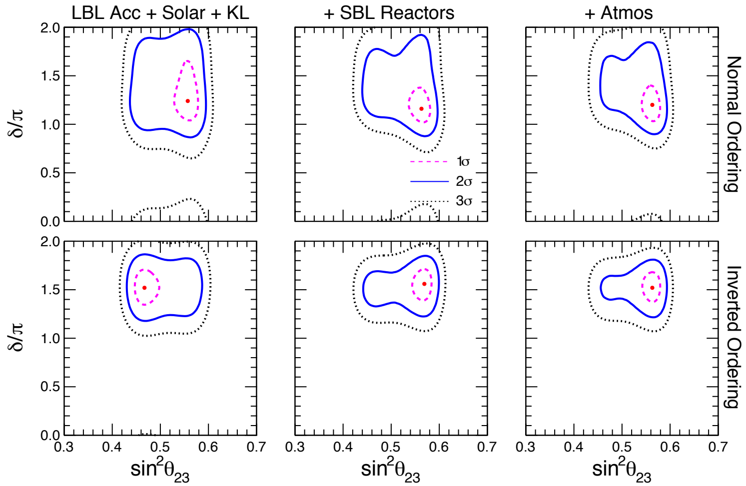
Dirac CP phase: **CPV favored, but CPC is "less disfavored" wrt 2018:**
mainly due to NOvA constraints being "out of phase" wrt T2K in NO.
Need to wait for higher statistics (and possible T2K+NOvA joint fit).

Covariances, 2019 preliminary update

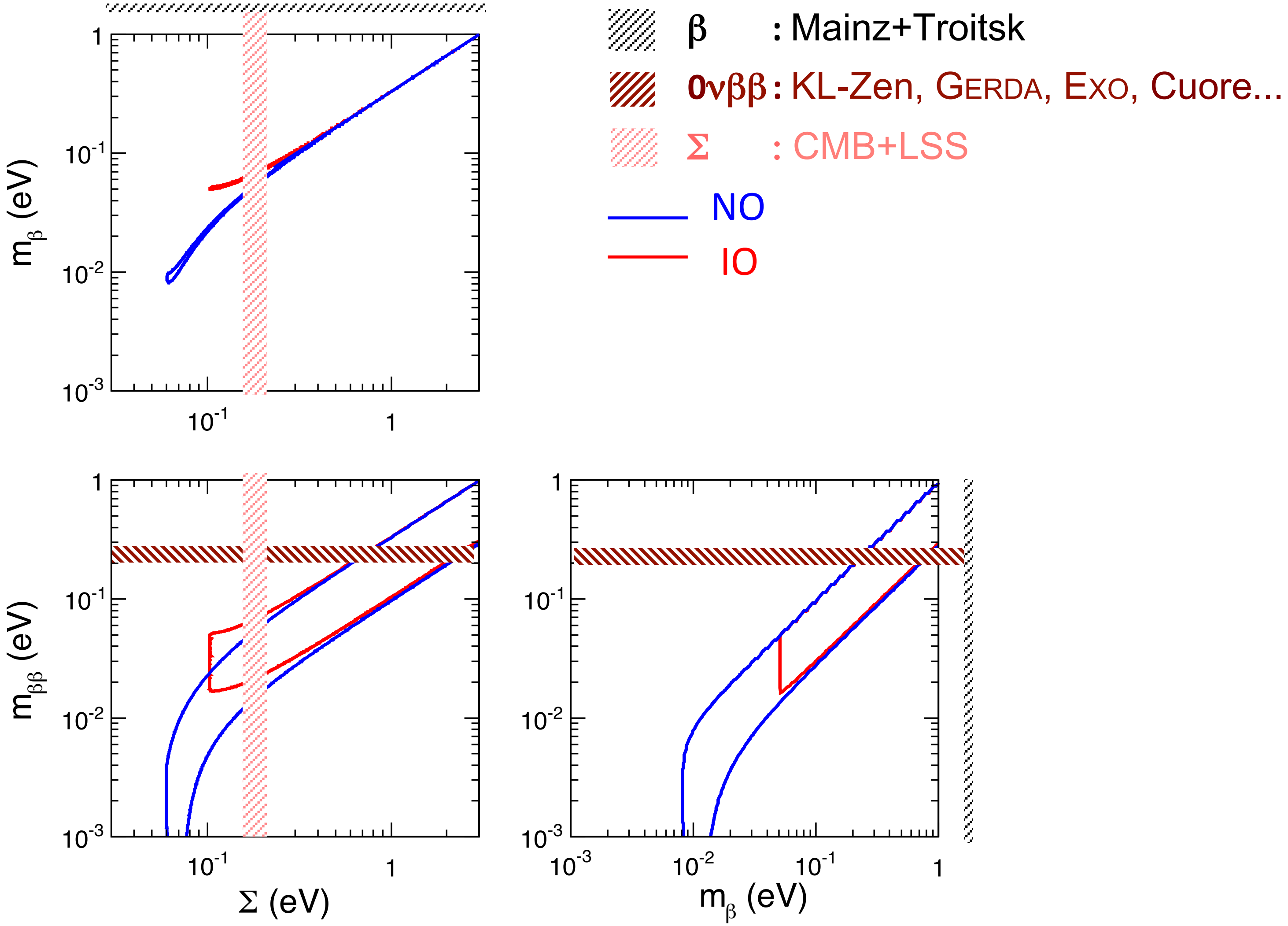








Upper limits on m_β, $m_{\beta\beta}$, Σ from nonosc. expts (up to some syst.)



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

Major improvements expected in the next decade

“Solar” oscillation parameters