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Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

INFN Istituto Nazionale di Fisica Nucleare

Global analysis of ν mass-mixing parameters: What next?

Kowloon Panorama. Credit: Wikimedia Commons

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International Symposium on Neutrino Physics and Beyond (NPB 2024)

HKUST Jockey Club Institute for Advanced Study, Lee Shau Kee Campus, Hong Kong, China, 19-20 Feb. 2024

Introduction

No ν equivalent (yet) of CERN EWWG for combinations of all precision EW data:
Global ν analyses reported by PDG review still performed by theor. groups

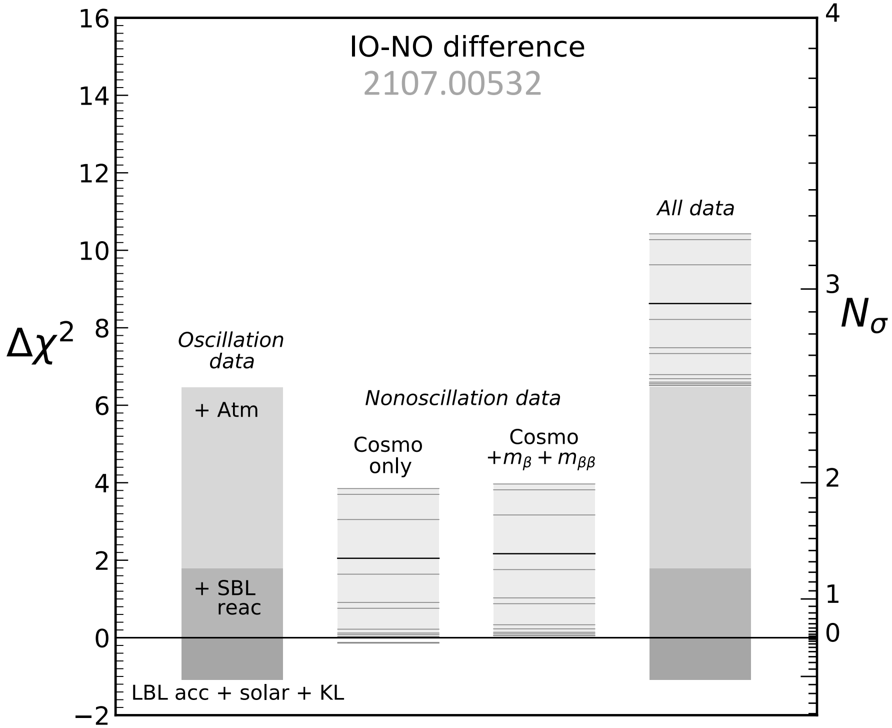
Bari group	Capozzi+	2107.00532
Valencia group	de Salas+	2006.11237
Nu-Fit group	Esteban+	2007.14792 + NuFit 2022

[Next relevant global updates presumably after Neutrino 2024]

Although approximate wrt full-fledged analyses of each dataset by their expt collaboration…

… **global fits useful** to discuss **relations among different data** in terms of combined parameter estimates, hints, tensions, synergies, correlations, degeneracies →

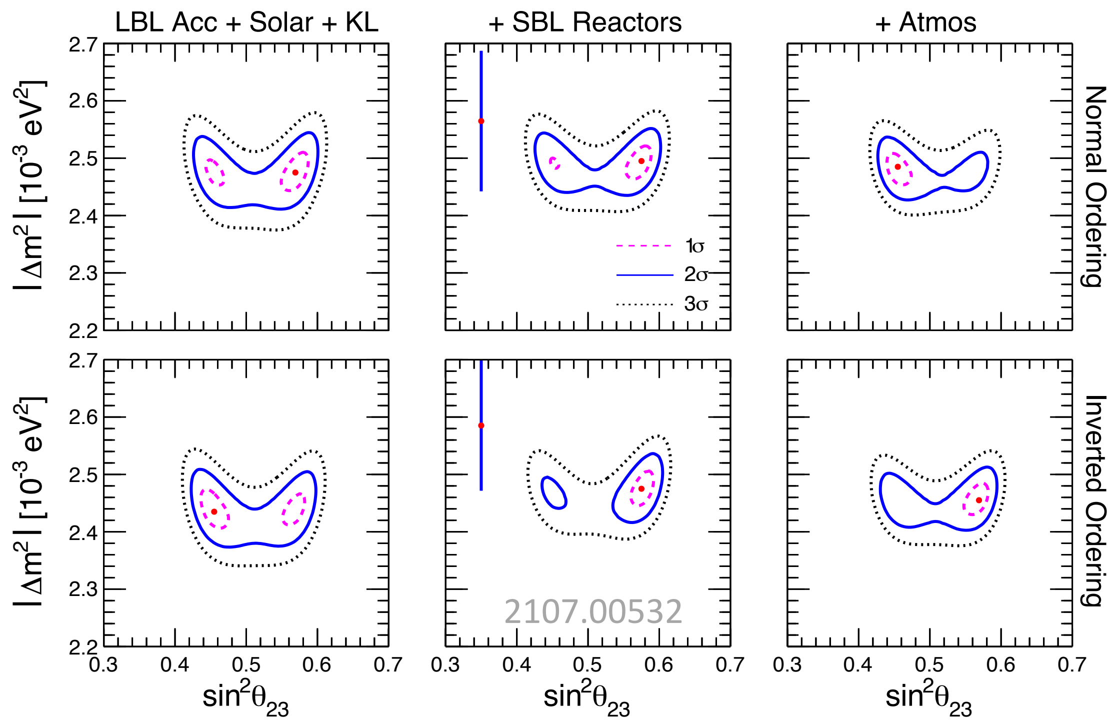
Notable example: Overall ~3σ hint for NO from osc.+nonosc. data…



LBL acc. slightly prefer IO, but adding SBL reactor data tilts preference to NO
despite SBL react. being not sensitive to NO/IO by themselves.
Also called "synergy" of |Δm²| data from different oscillation channels

Already now: accel/reac/atm $|\Delta m^2|$'s agree better in one ordering *wrt* other one

[with side effects also on the other two unknowns: CPV and octant]



Current $|\Delta m^2|$ accuracy ~1.1% from global fit

NO

IO

Further attention to accel/atm %-level errors on $|\Delta m^2|$ (e.g., from nuclear syst.?) as JUNO will achieve sub-% accuracy for $|\Delta m^2|$ (& not only!) with few months data

A plea for public release of JUNO data/flux/syst … in musical language

All oscillation instruments have played only one note so far (at low or high pitch)

JUNO will be the first one playing two notes at the same time: a dyad,
with one note blending two close pitches: a chord…

Credit: Levy Sheet Music Collection, JHU

…Please let all ν musicians reproduce this amazing new tune!

…besides NO/IO, what next in global/joint analyses?

CPV and θ_{23} octant resolution via acc/atm: difficult, may take longer than NO/IO
Increasing role of collaboration-based joint data analyses wrt external groups
Increasing attention to nuclear interaction effects on disapp/appear ν param.

Concerning absolute ν mass: signals likely to appear in cosmology in a decade.
Presumably, variety of analyses by both collaborations and external groups
Scrutiny of underlying ΛCDM model + data variants in cosmo analyses

I'll just touch two issues of interest for near-future (<10y) combined analyses,
concerning the role of (1) nuclear and (2) cosmolog. syst's on ν parameters

(1) Correlated impact of ν interaction models

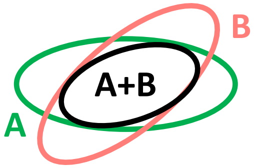
In the context of accel/atmos expt: increasing attention to nuclear model inputs

$\mathbf{E_{reco}}$ uncertainty affects parameter $\mathbf{p=\Delta m^2}$ in disappearance, via $\Delta m^2/E$

Cross-section ratio ($\nu/\bar{\nu}$, μ/e) uncertainties affect $\mathbf{p=\theta_{23}, \theta_{13}, \delta}$ in appearance

So far, systs often separately included in each acc/atm expt. A, B, … for p-estimation:

(1) $\chi^2_{A+B}(p) = \chi^2_A(p) + \chi^2_B(p)$



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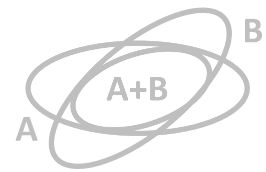
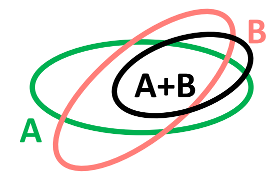


New aspect: include correlated nuclear systs (as it occurred, e.g. for solar expt. + SSM input)

(2) $\chi^2_{A+B}(p) = \chi^2_A(p) + \chi^2_B(p) + \Delta_{AB}(p)$



?

Role of $\Delta_{AB}(p)$ being quantified by **A+B = T2K+NOvA** and **T2K+SKatm**. collaborations

Q: If effect significant, how to include it in (larger) fits, e.g. T2K+NOVA+SK?

A: **Not obvious**… Compare results from approx. (1) and full-fledged fit (2)?
Isolate (un)correlated errors on parameter p? Worth discussing in detail!

Another A+B example that deserves attention: SK + IC-DC (atmos.)

Latest constraints on leading osc. parameters (Δm^2, θ_{23}) are comparable:

SK 2023, results for **NO & IO** 2311.05105 Public χ^2 maps

IC 2023, results for **NO only** 2304.12236 No public χ^2 map yet

Q: If both χ^2 maps are available, can one add them up (as if ~independent)?

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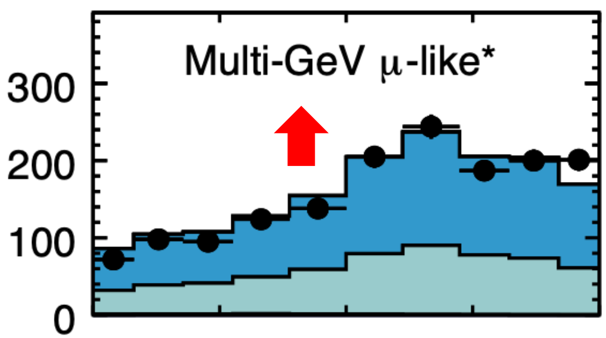
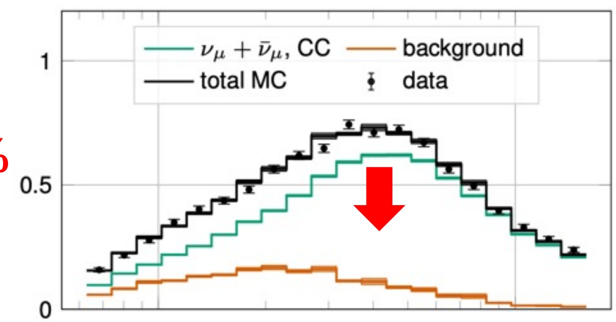
Not obvious. SK & IC share input atmos. flux Φ and cross sec. σ, with correlated $\Phi\sigma$ normaliz. error (20-30%). Effects on joint **p** estimates?

+ Potential issue: $\Phi\sigma$ pulls seem to be opposite in SK and IC (~40% relative norm.?)



SK $\Phi\sigma$

~ +20%



IC $\Phi\sigma$

~ −20%

Pulls should be the same in a joint SK+IC analysis (after local corrections)…

Not just normalization (y-axis) but also energy scale (x-axis) correlations:

SK-atm current error on **E-scale ≃ 1.8%** → approximately transfers to Δm^2
Assume it's mainly due to nuclear interaction model of ν *on water target*.
Then it would systematically apply also to IC, ORCA, and their combination:

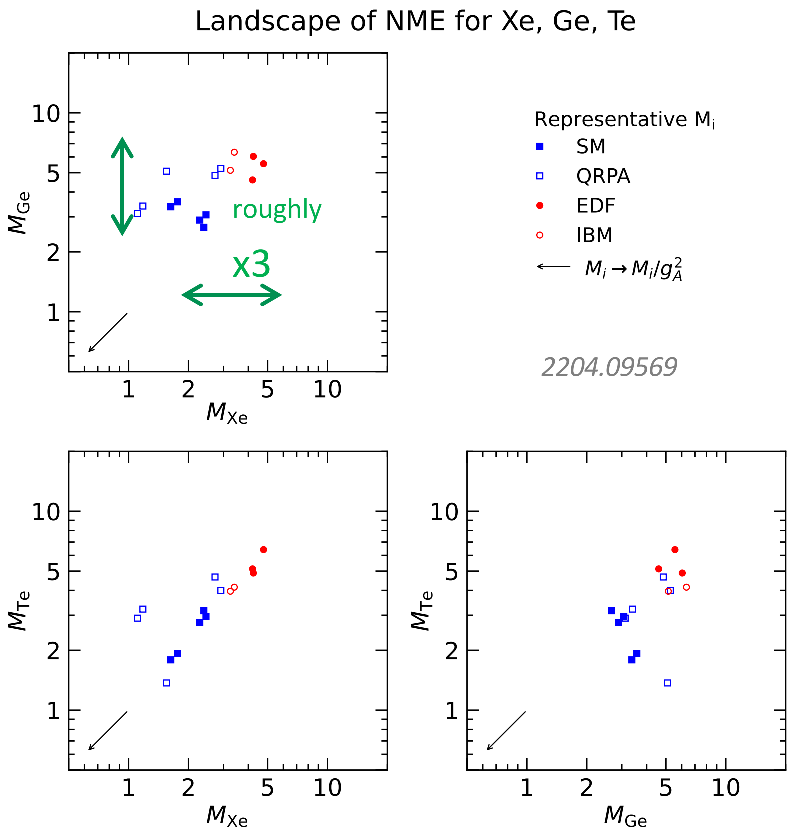
→ **Single/combined SK+IC+ORCA E-scale error on Δm^2 would reach same % floor**

Combined fits of atm(+acc) experiments might need to account for common 1-2% effects (if any).

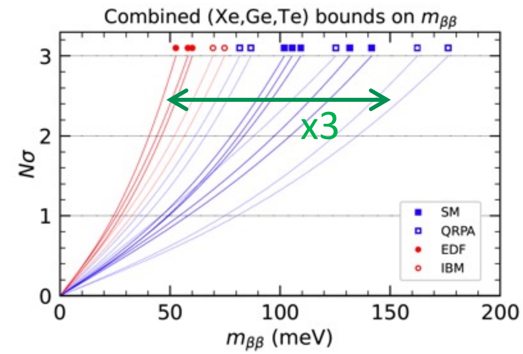
Well known, but worth emphasizing:
(A,B)-correlated syst are not reduced in joint A+B fit (irreducible "floor")
→ limitation to different data "synergy"

Sizeable example: floor to NME and effective Majorana mass error in $0\nu\beta\beta$ decay →

Nuclear Matrix Elements errors: large and correlated in $0\nu\beta\beta$ decay

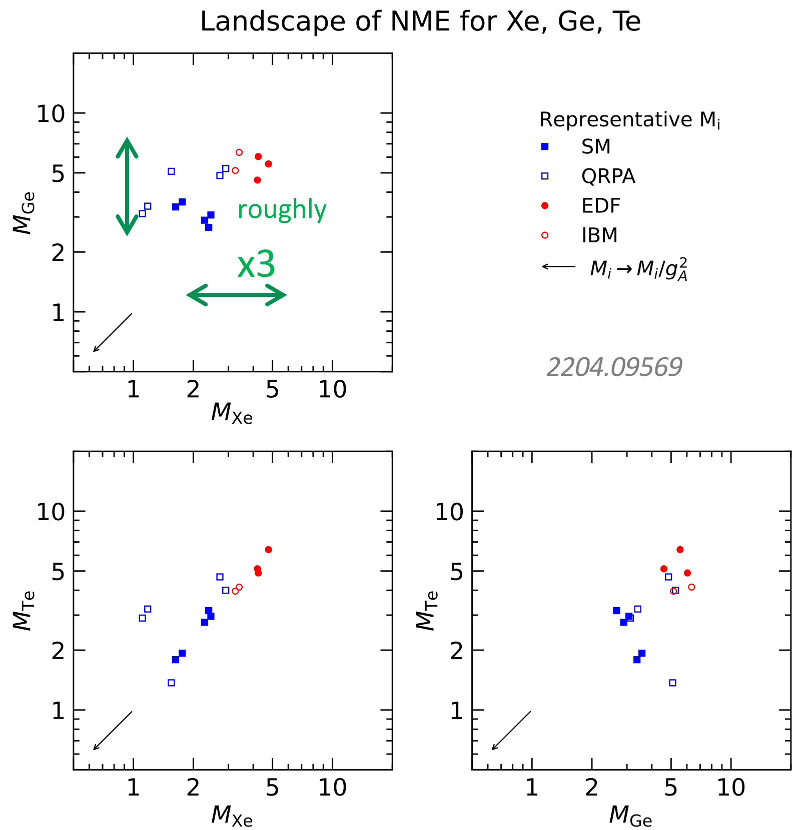


~same if combined



Correlated NME error components degenerate with $m_{\beta\beta}$ in multi-isotope fits

Nuclear Matrix Elements errors: large and correlated in $0\nu\beta\beta$ decay



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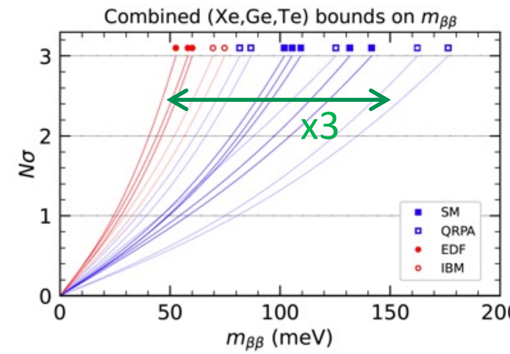
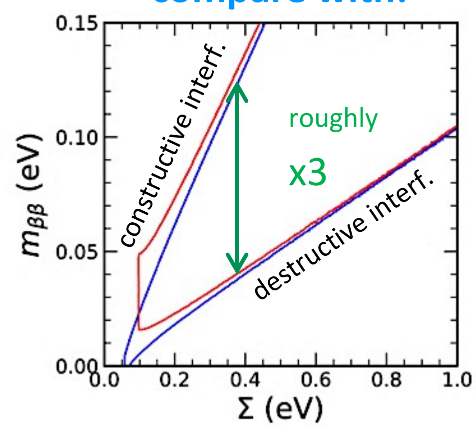


compare with:



Correlated NME error components degenerate with $m_{\beta\beta}$ in multi-isotope fits

+ current NME range (~3x) accidentally similar to $m_{\beta\beta}$ min-max range (~3x)…

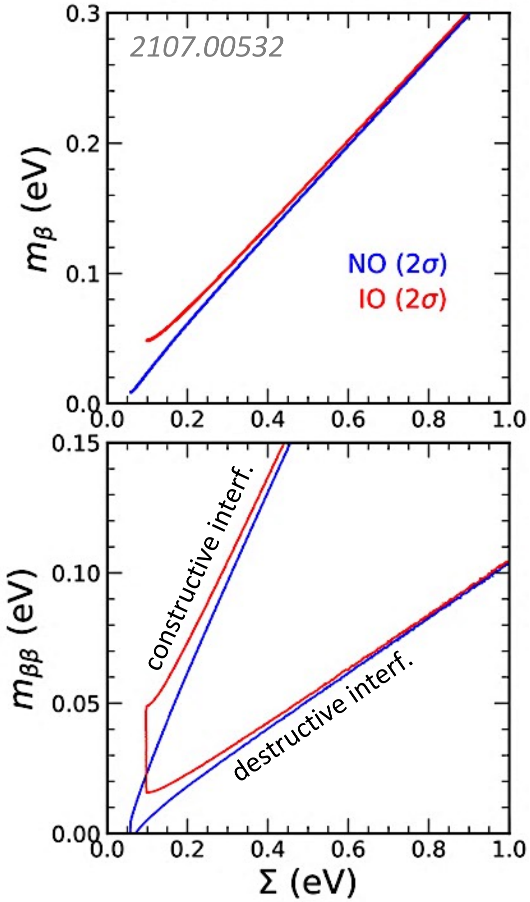
Reduction of NME errors and correlations is mandatory. Ab initio approach?

(2) Improving models:
from the nucleus to the universe…

Total ν mass Σ from cosmology *vs* m_β and $m_{\beta\beta}$:

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

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



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

Σ signal is guaranteed:

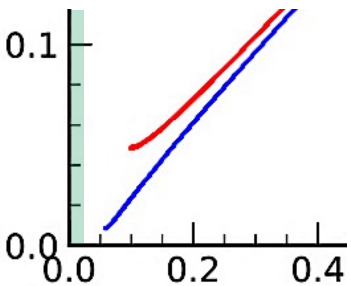
$$\min \Sigma \simeq \begin{cases} 60 \text{ meV} & \text{(NO)} \\ 100 \text{ meV} & \text{(IO)} \end{cases}$$

It might emerge in <10y,
with prospective error:

$$\sigma \simeq 20 \text{ meV (goal)}$$

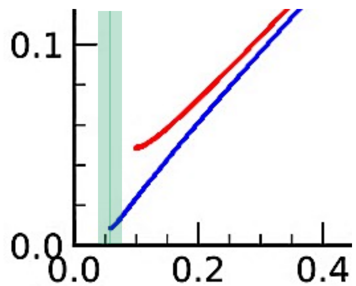
Assuming σ=20 meV, implications of a Σ signal strongly depend on its **central value**, e.g.:

$\Sigma = 0 \pm 20$ meV



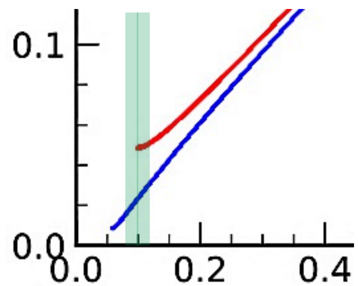
Unphysical at 3σ.
A new tension
in cosmology?

$\Sigma = 60 \pm 20$ meV



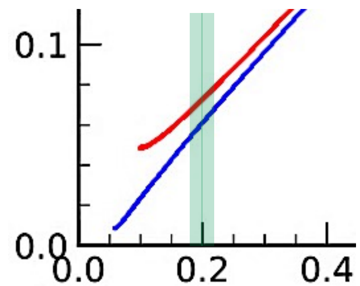
Min(NO) signal at 3σ.
IO disfavored at 2σ.
Consistent with oscill.?

$\Sigma = 100 \pm 20$ meV



Mass signal at 5s.
NO/IO ~undecided
by cosmology

$\Sigma = 200 \pm 20$ meV



Mass signal at > 5s.
NO/IO undecided
by cosmology

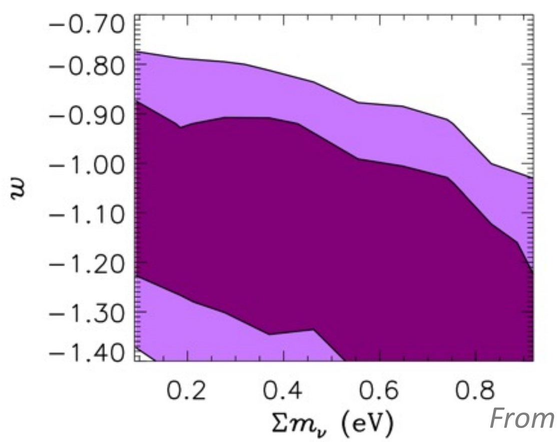
However, central value depends on multi-param data fits assuming a cosmo model

ΛCDM model variants already considered in many analyses → spread of Σ upper bounds

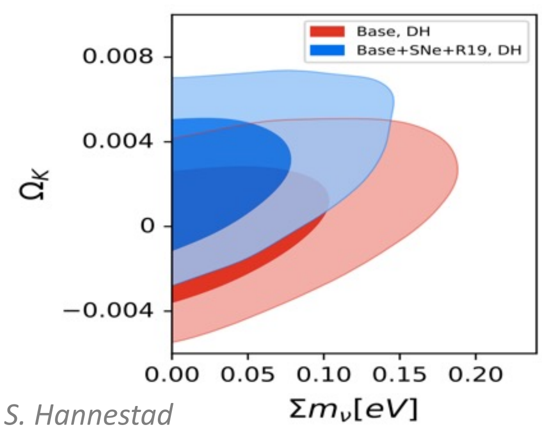
From bounds to **signals**: likely to see a **saga of Σ central values**, for various reasons

- Old tensions (e.g., H_0) might not be solved by new data; new tensions may appear
- ΛCDM might evolve into a richer model (more dof) as DE and DM get "understood"
- Some model dof (e.g., w ≠ -1, curvature...) may be correlated with Σ (see below)
- "Abuse" of statistical priors might enhance claims about Σ signal significance

*Negative correlation with **w***



*Positive correlation with **Ω_k***



From S. Hannestad

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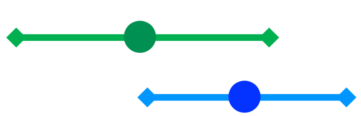
What will it take to get a convincing signal $\Sigma \simeq \Sigma_0 \pm \sigma$? A possible option:

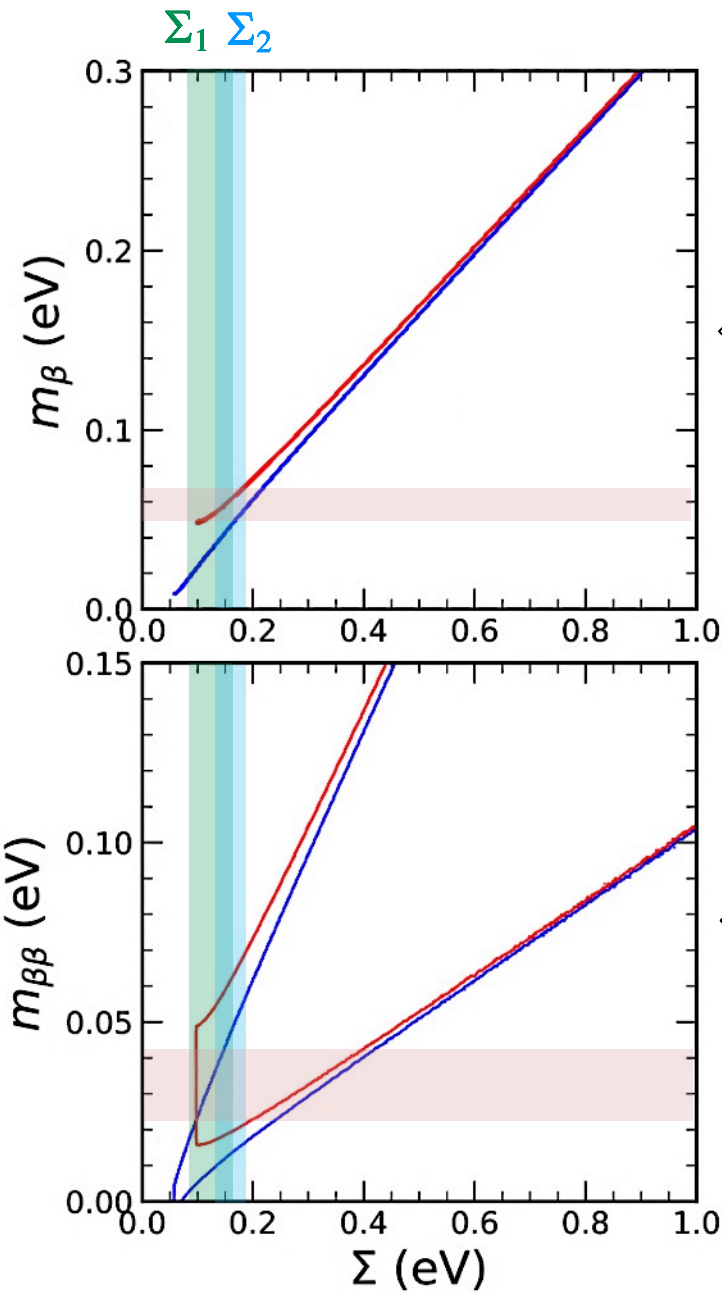
As for osc.(NO/IO): **convergence of ≥2** quasi-independent **lines of evidence** may help



Σ_1 from dataset_1 (e.g., mostly CMB or high-z data or else …)

Σ_2 from dataset_2 (e.g., mostly LSS or low-z data or else …)

especially if robust w.r.t. some model variants: demanding requirements…



⇔

In any case: for settled NO/IO, any estimate for Σ will be in one-to-one correspondence with a m_β estimate

Viceversa, a m_β measurement can (dis)confirm Σ and (de)stabilize this corner of the cosmological model.

Find guaranteed m_β signal at any cost!

⇔

Weaker correspondence of Σ with $m_{\beta\beta}$, due to x3 variations of both NME and interfer. of unknown Majorana phases.

Viceversa: $m_{\beta\beta}$ >0 signal with less than x3 tot error may constrain cases of max constructive vs max destructive interf.

Major. phase as far-future fit param.?

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Conclusions

Completion of the 3ν framework (or NPB 3ν ?) will require **integration** of old and new (non)oscill. **data plus refined model inputs** → global/joint data fits will prove useful. **JUNO** will soon play an important role in this context, **by itself and in combination**.

At increasing level of accuracy, some issues may arise from input model uncertainties (e.g. nuclear, cosmological) common to two or more experiments in combined analyses. **Correlated effects** of model variants: **to be further explored** on (non)oscill. parameters

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…Let me end with 1st public announcement of **NOW 2024, 2-8 Sept. (Otranto, Italy)** **www.ba.infn.it/now** (basic webpage, to be updates soon). **Save the dates and…**

Thank you for your attention!

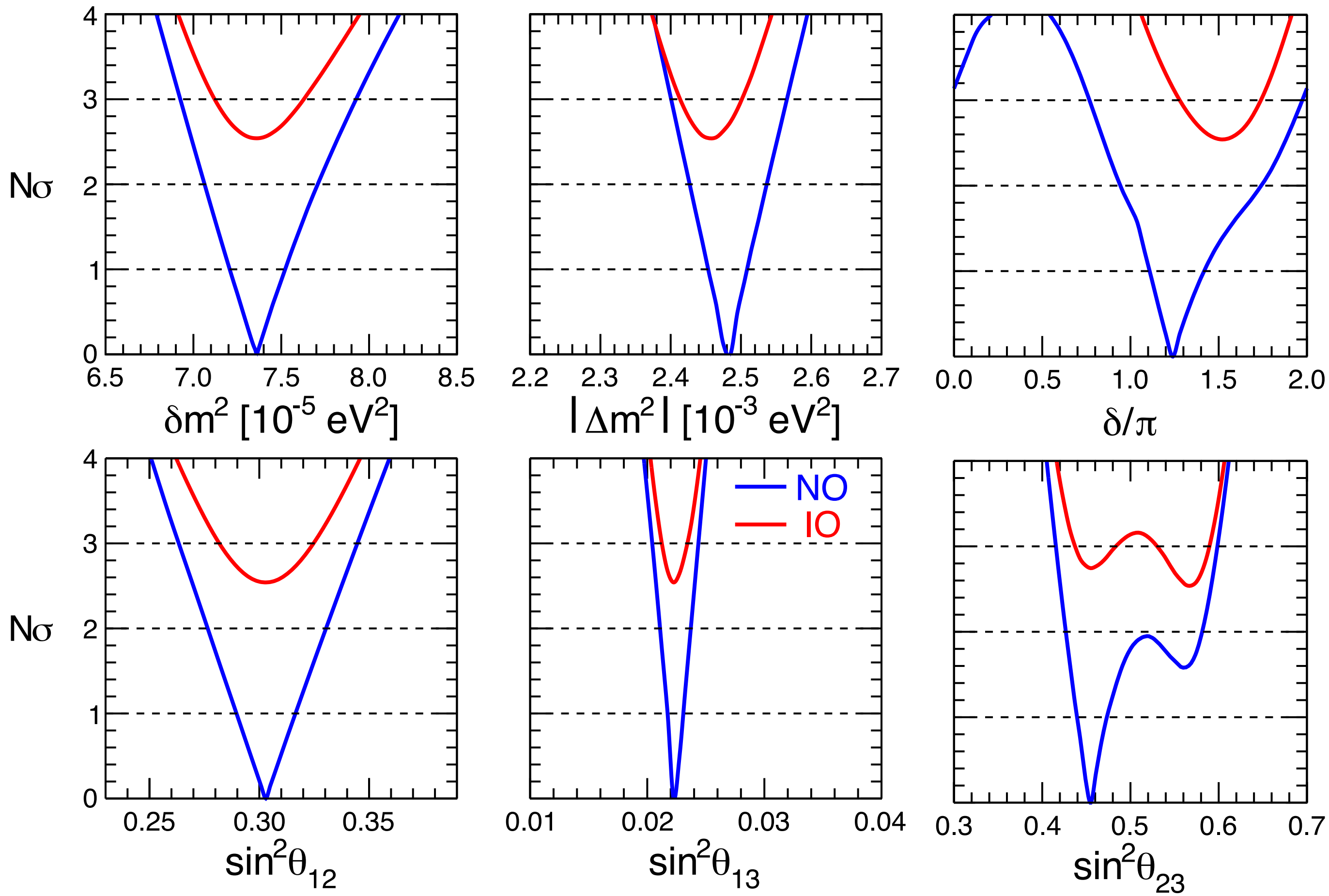
Extra slides

Known and unknown 3ν oscillation parameters - from 2107.00532

1σ error of **known** parameters

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

All ν oscillation data



Hints on oscillation **unknowns** **(2021)**

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

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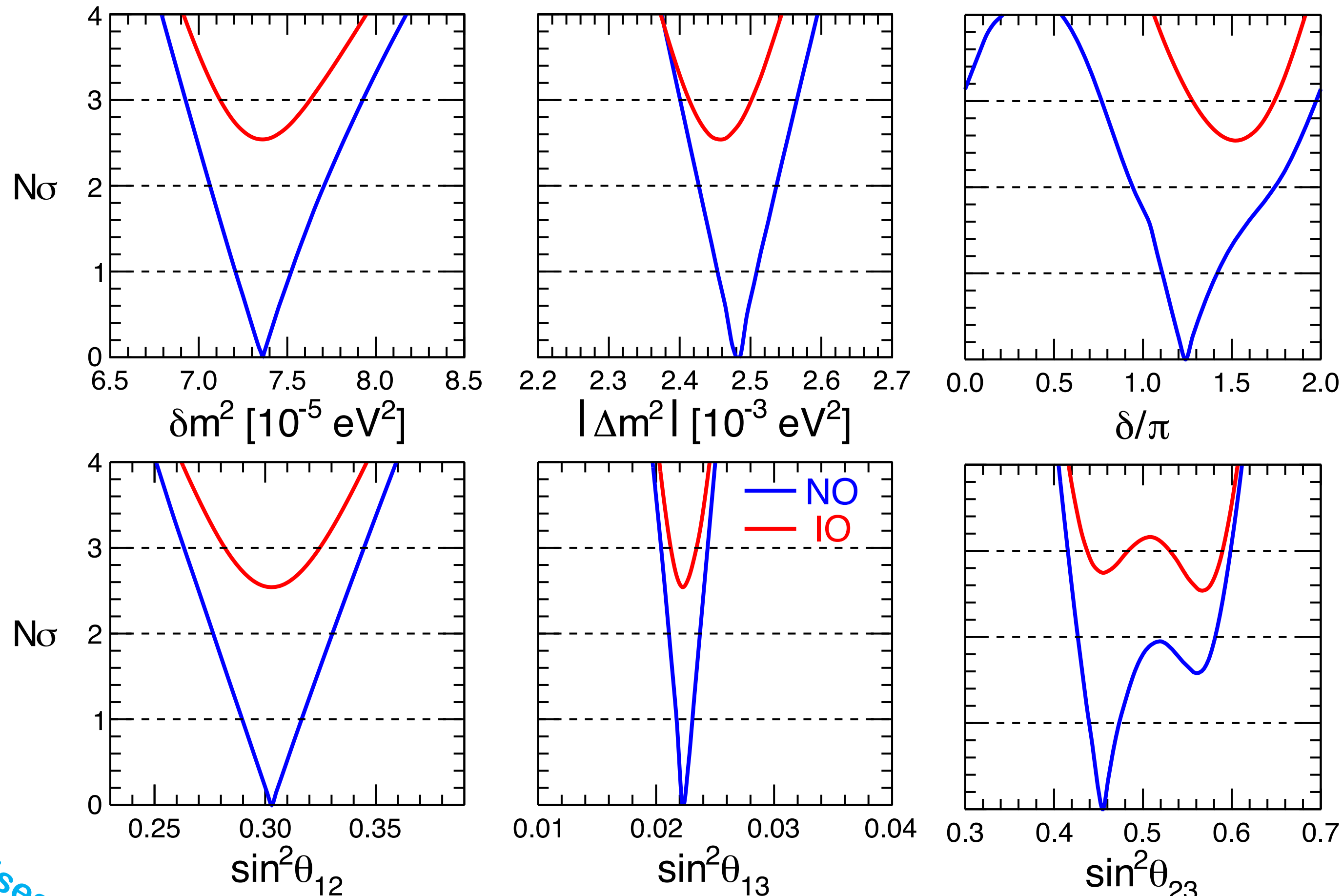

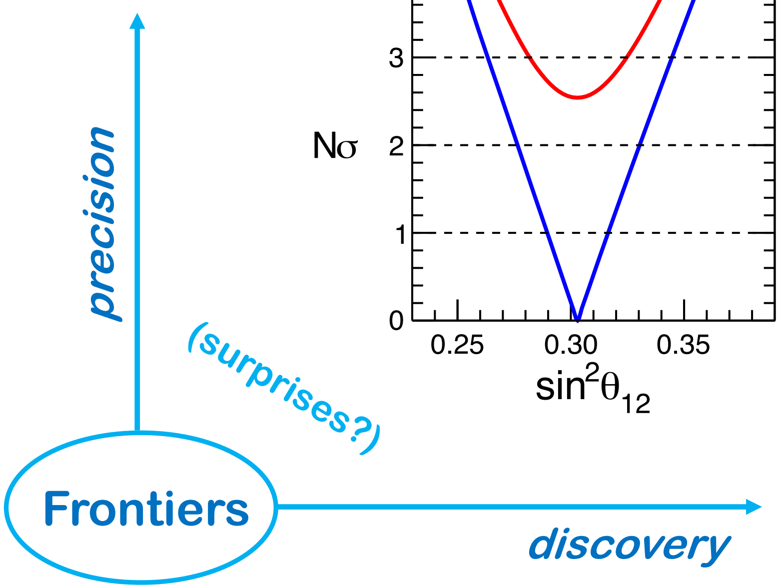

Hints on oscillation **unknowns** **(2021)**

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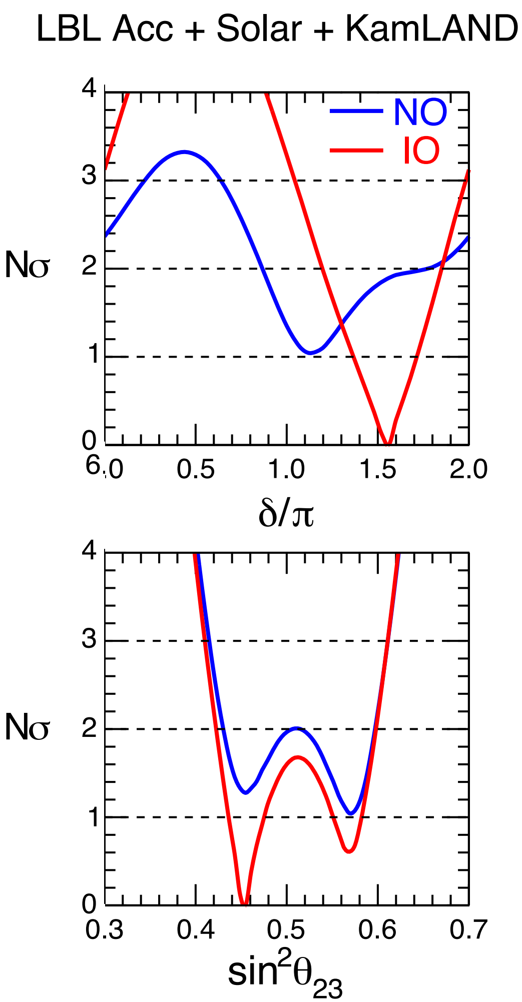
Focus on the three oscillation unknowns: NO/IO, δ, θ_{23} octant degen.



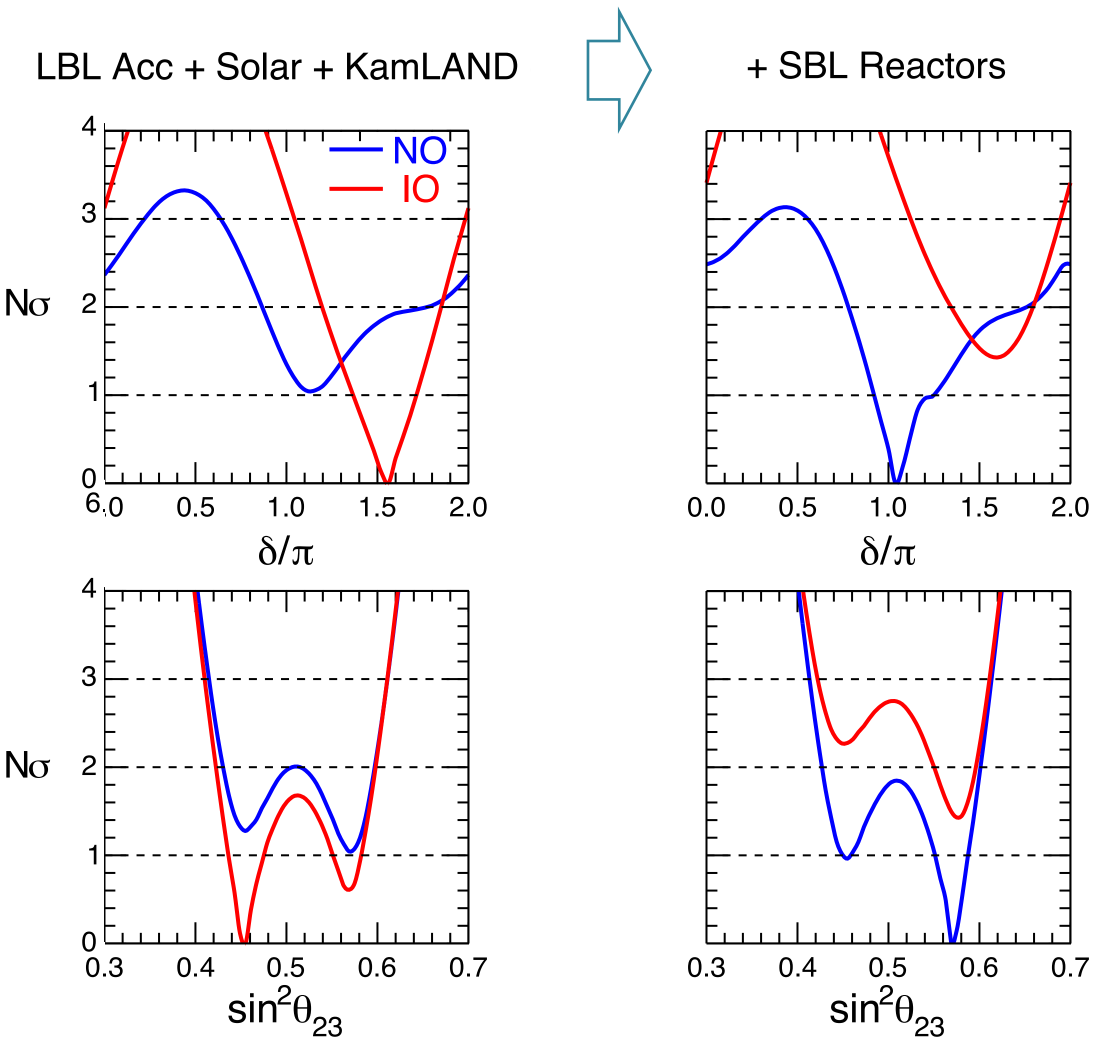
IO favored ($\sim 1\sigma$)

$\delta \sim 1.5\pi$ (IO), $\sim\pi$ (NO)

θ_{23} octants ~degenerate

[confusing T2K-NOvA tension]

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



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$\delta \sim 1.5\pi$ (IO), $\sim \pi$ (NO)

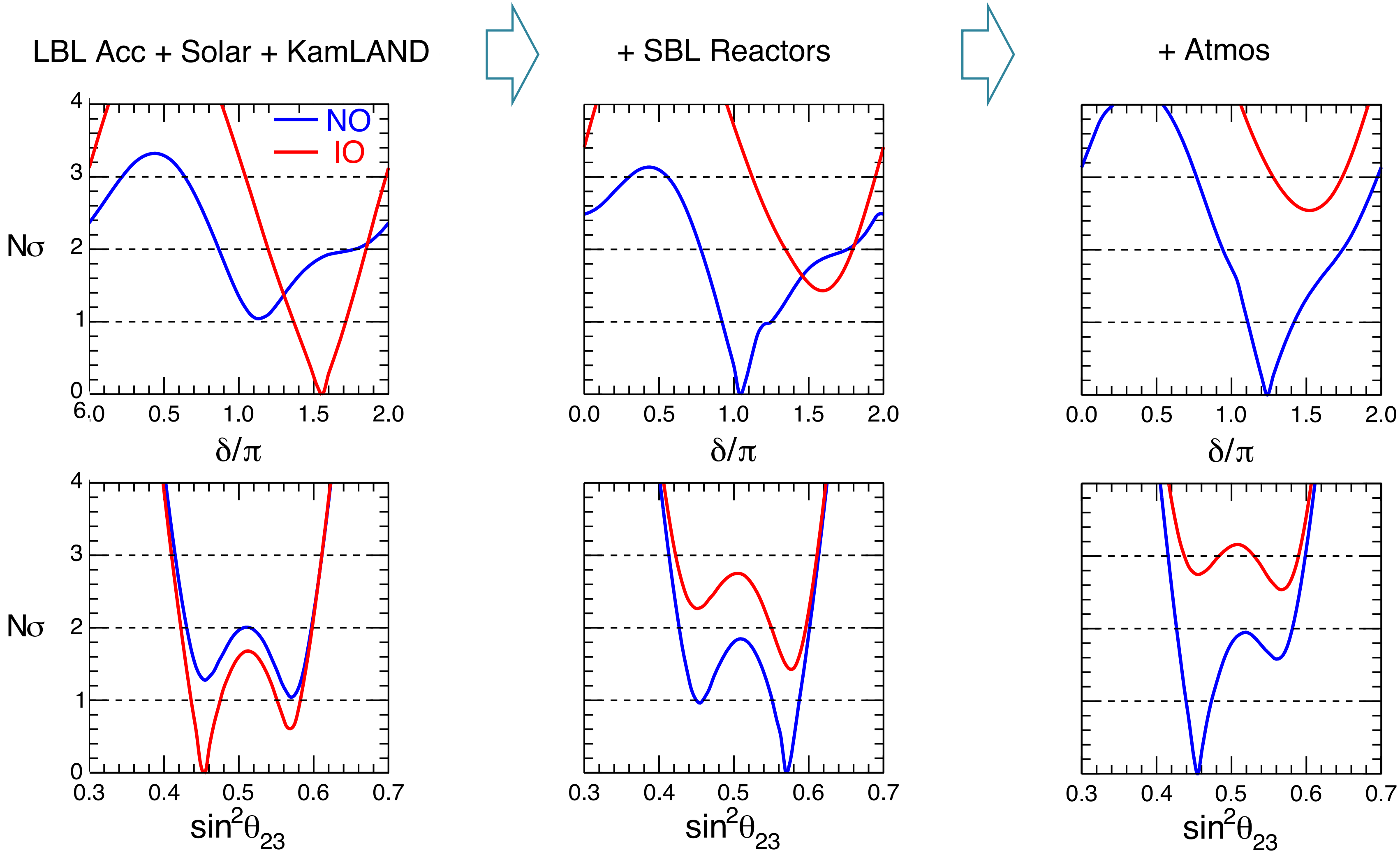
θ_{23} octants ~degenerate

NO favored ($\sim 1.5\sigma$)

$\delta \sim \pi$ (NO), $\sim 1.5\pi$ (IO)

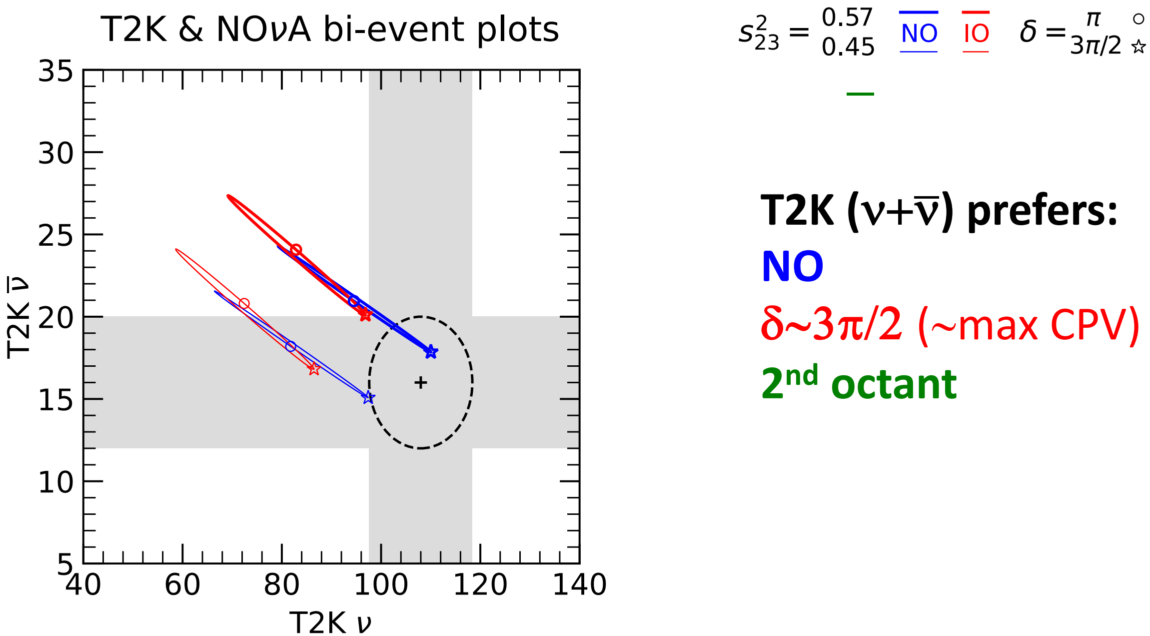
$\theta_{23} \sim 0.57$ favored ($\sim 1\sigma$)

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



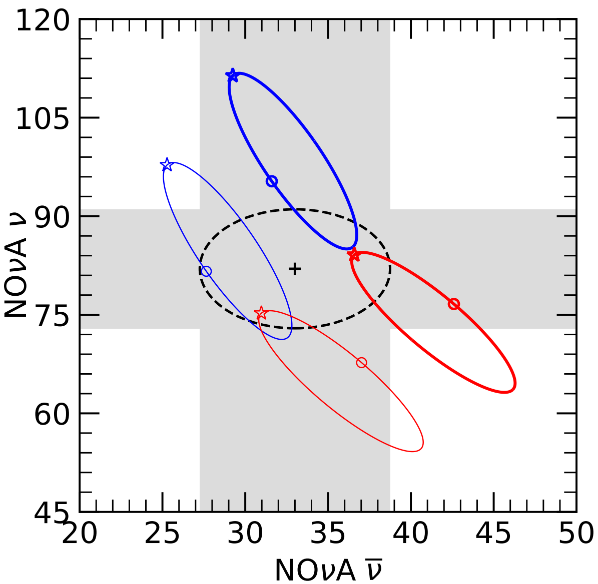
IO favored (~1σ)	**NO** favored (~1.5σ)	**NO** favored (~2.5σ)
$\delta \sim 1.5\pi$ (IO), $\sim\pi$ (NO)	$\delta \sim \pi$ (NO), $\sim 1.5\pi$ (IO)	$\delta \sim 1.2\pi$ (NO) fav. (~1.6σ)
θ_{23} octants ~degenerate	$\theta_{23} \sim 0.57$ favored (~1σ)	$\theta_{23} \sim 0.46$ favored (~1.6σ)

Integrated info on ν and $\bar{\nu}$, stat. errors only. [Not used in fits] 2107.00532



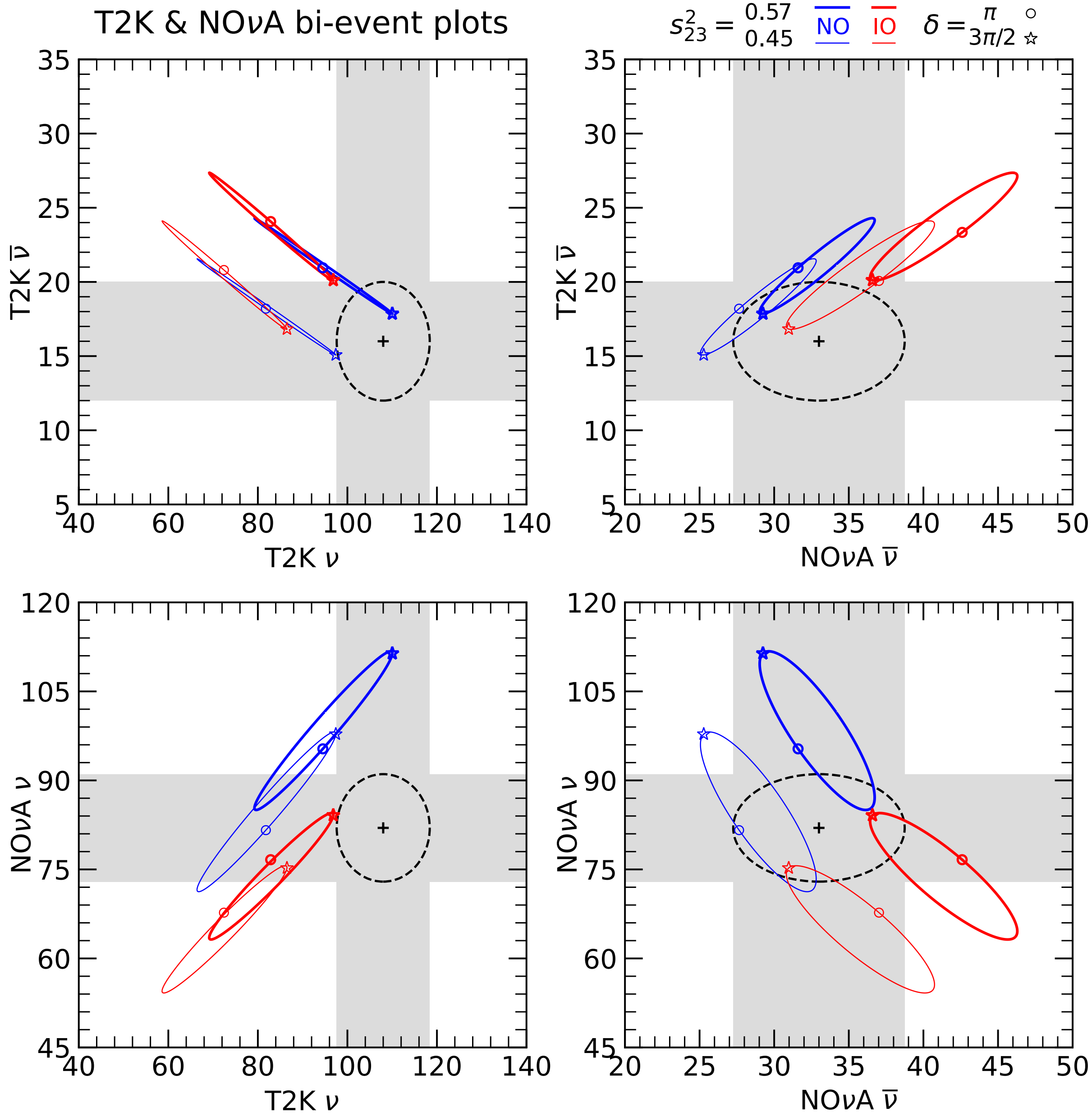
T2K (ν+$\bar{\nu}$) prefers:
NO
δ~3π/2 (~max CPV)
2nd octant

NOVA (ν+$\bar{\nu}$) prefers:
NO
CP conservation
octants ~degenerate

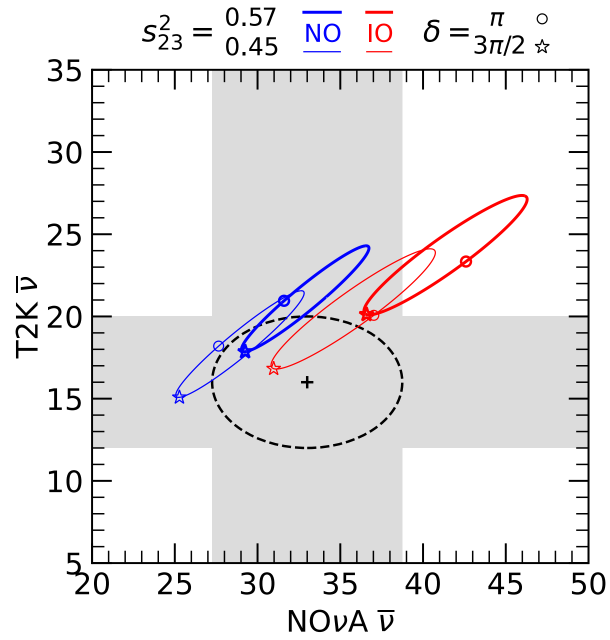


→ **T2K and NOVA, separately: NO preferred; CP and octant ambiguous**

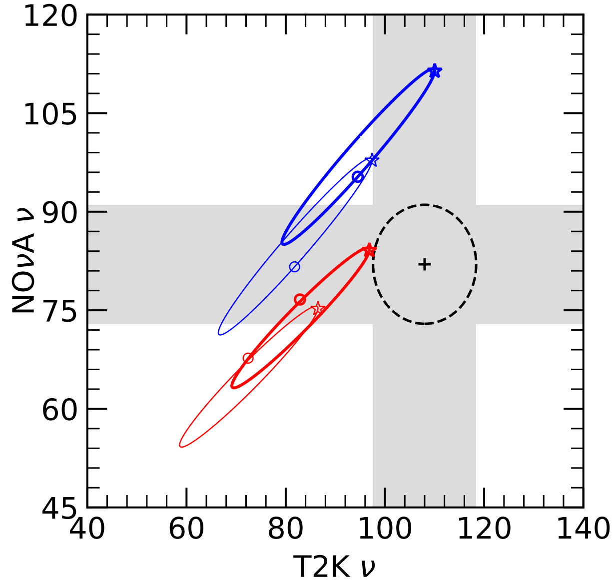
The same info can be reorganized in terms of T2K vs NOvA:



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

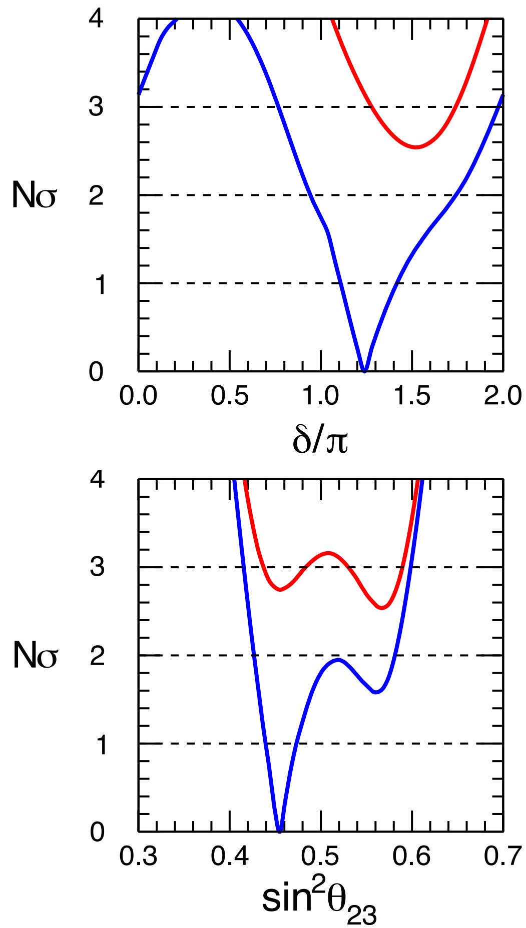
→ **T2K and NOVA, jointly: IO and CPV preferred; octant ambiguous**

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

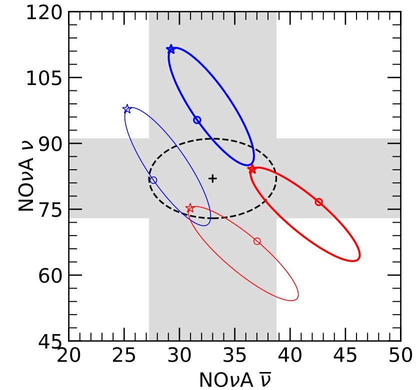
mass ordering (NO vs IO), θ_{23} octant and CP phase δ

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

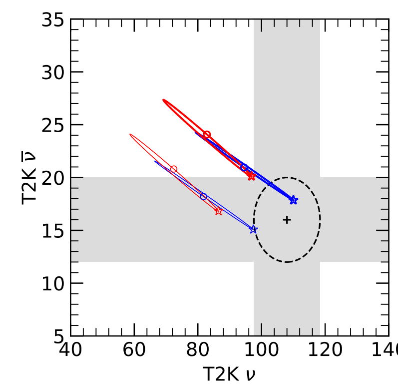
LBL Acc + Solar + KamLAND
(current)



NOvA close to different options within 1σ...



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

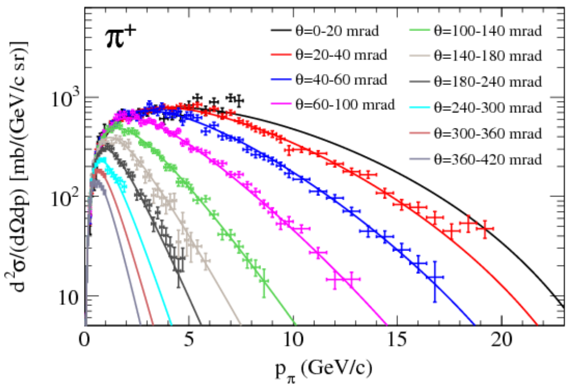


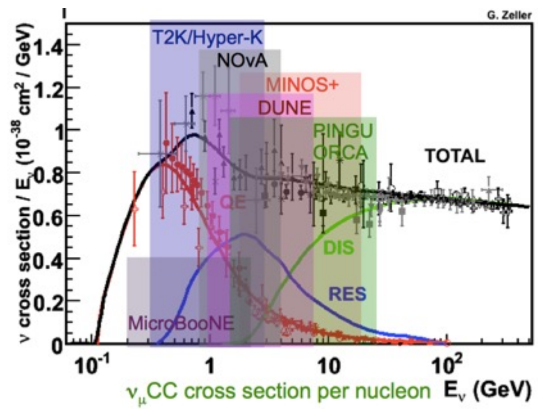
“Strong interaction” effects on “weak interaction” physics are ubiquitous...

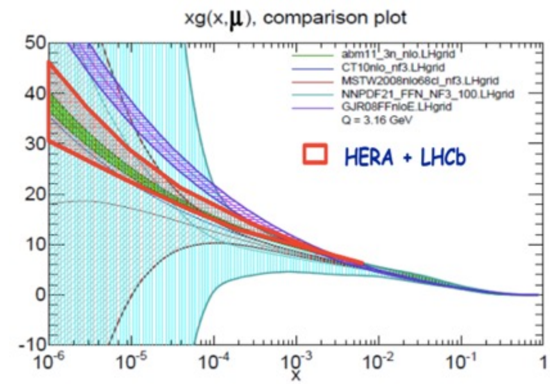
Need hadron production data, e.g. pA → πX, +theory models to improve estimates of atmos. and acceler. ν fluxes and errors

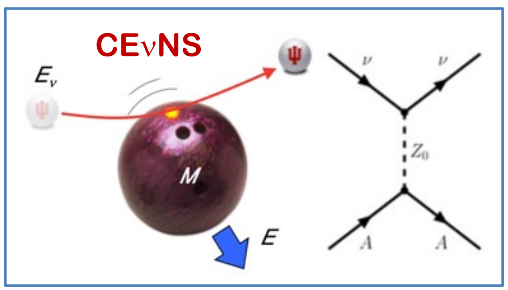
Current understanding of ν cross sections at O(GeV) does not match the needs of (next-generation) ν expts

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



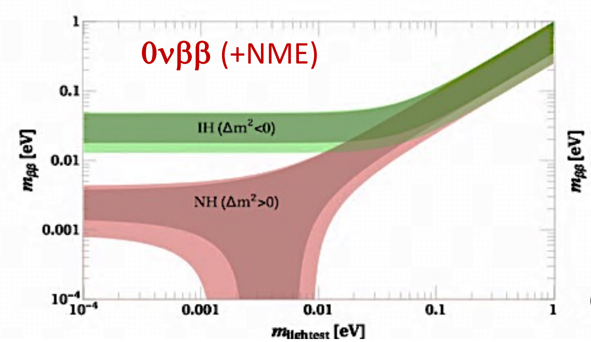






Control of nuclear EW response (e.g., form factors) relevant to interpret many low-energy data: coherent scatt., reactor spect., 2β

...

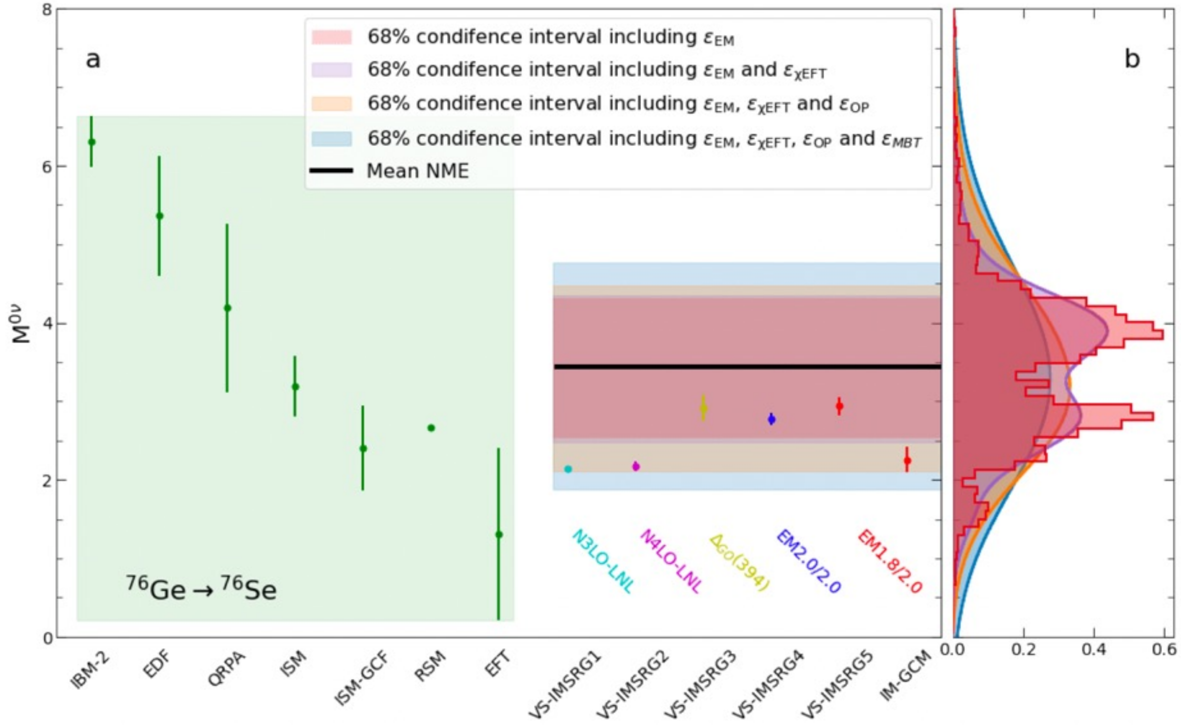


Progress requires further integration of (astro)particle+nuclear expertise:

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

Possible NME roadmap: Ab-initio nuclear theory + calibration with benchmark data?

Snowmass Roadmap 2203.12169. E.g., recent NME pdf for ^{76}Ge, Belley+ 2308.15634



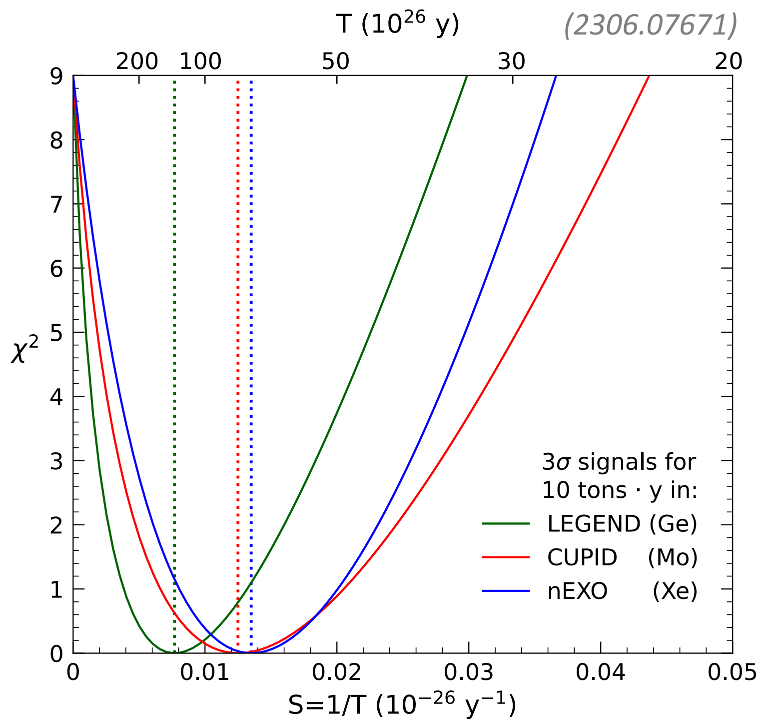
Emerging improvements w.r.t. usual x3 spread in each isotope.

Different benchmark data for different isotopes might break correlations.

Realistic hope to reduce NME (co)variances, in view of ton-scale expt efforts

Prospective $0\nu\beta\beta$ signals with 10 ton-yr exposures

Signal strength likelihood for 3σ evidence in ton-scale expt:



In each expt., statistical ±1σ for $m_{\beta\beta} \propto \sqrt{S}$ smaller than "x3 variation"

(even better for >3σ evidence, or by combining ≥ 2 experiments)

m_β signal is guaranteed: $\min m_\beta \simeq \begin{cases} 9\ \text{meV} & \text{(NO)} \\ 50\ \text{meV} & \text{(IO)} \end{cases}$

While Σ requires to model the whole universe, m_β requires to model source + detector
→ Instrinsically robust and pivotal role of β decay.

One must find the m_β signal at any cost!

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Realistic path to go from ~200 meV (KATRIN) to ~50 meV (PROJECT 8) in ~10 yrs

*If lucky, in **NPB 203X** we might see **two absolute mass signals** and investigate them in detail: **a new frontier of global analyses***

*If not: **path m_β ~ 50 → ~ 9 meV** needs to be envisaged. Very hard, but absolutely necessary!*