Neutrino masses, mixings & Electroweak Nuclear Physics

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CNNP 2020, Arabella Hotel - Kogelberg Biosphere, South Africa

OUTLINE:

Status of 3ν masses & mixing

The role of nuclear physics

A suggestion for this field

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Status of 3ν masses & mixing

The role of nuclear physics

A suggestion for this field

Based on work by: **F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, A. Melchiorri, and A. Palazzo**, **to appear soon (2020)**. See also previous global analysis results in arXiv:1703.04471 and 1804.09678.

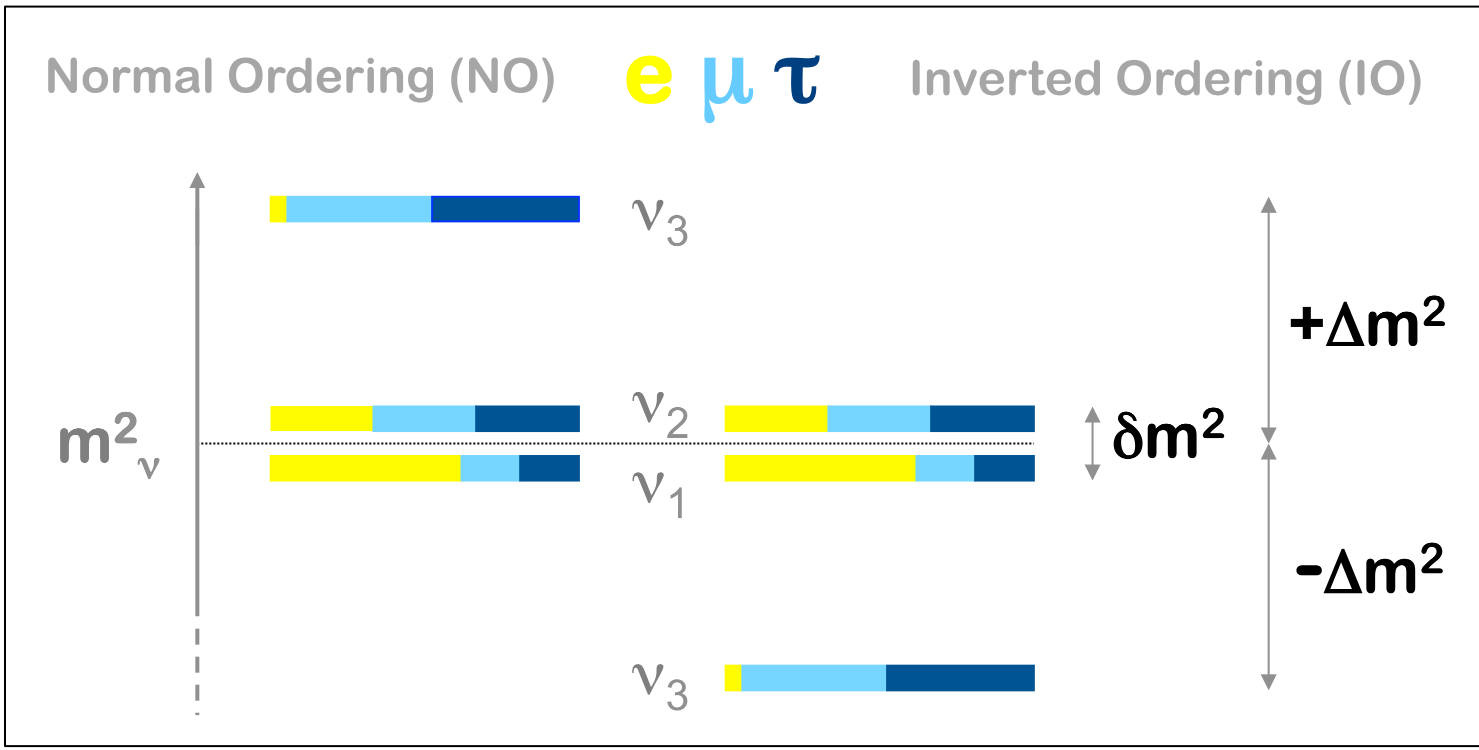
“Broad-brush” 3ν picture (with 1-digit accuracy)

Knowns:

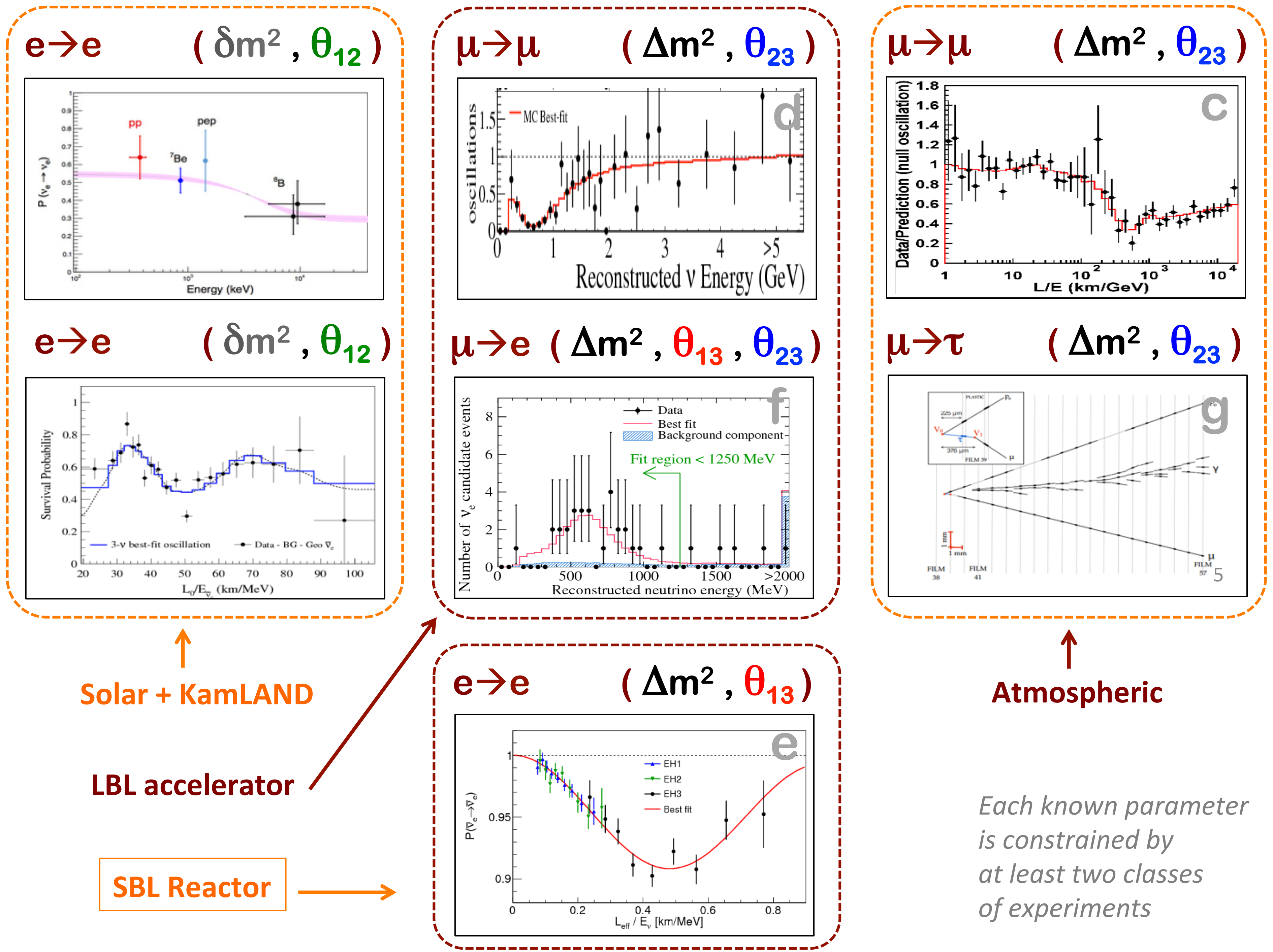
$\delta m^2 \sim 7 \times 10^{-5}$ eV^2
$\Delta m^2 \sim 2 \times 10^{-3}$ eV^2
$\sin^2\theta_{12} \sim 0.3$
$\sin^2\theta_{23} \sim 0.5$
$\sin^2\theta_{13} \sim 0.02$

Unknowns:

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



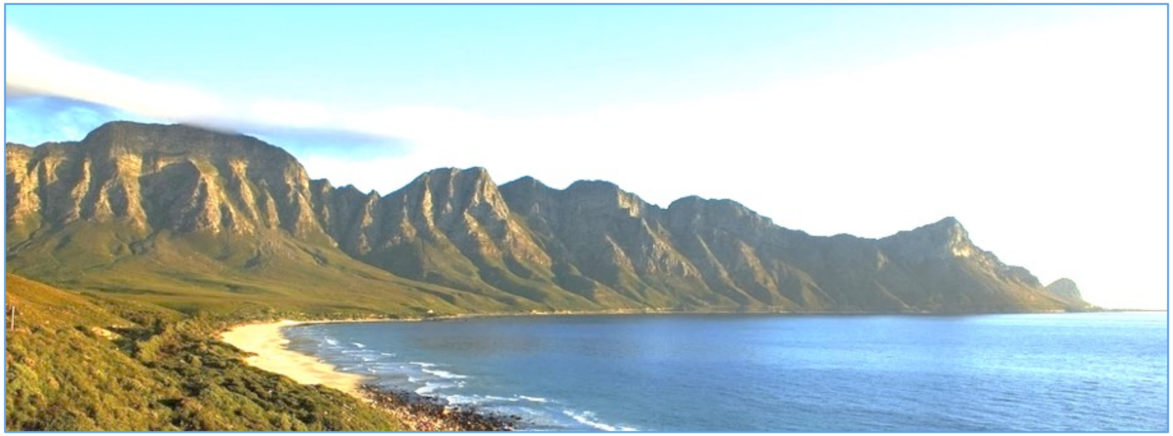
Leading sensitivities →



e→e (δm² , θ12)
pp
pep
7Be
8B
P (νe → νe)
Energy (keV)
e→e (δm² , θ12)
Survival Probability
3-ν best-fit oscillation
Data - BG - Geo ν̄e
L0/Eν̄e (km/MeV)
μ→μ (Δm² , θ23)
d
MC Best-fit
oscillations
Reconstructed ν Energy (GeV)
μ→e (Δm² , θ13 , θ23)
f
Data
Best fit
Background component
Fit region < 1250 MeV
Number of νe candidate events
Reconstructed neutrino energy (MeV)
e→e (Δm² , θ13)
e
EH1
EH2
EH3
Best fit
P(ν̄e→ν̄e)
Leff / Eν [km/MeV]
μ→μ (Δm² , θ23)
c
Data/Prediction (null oscillation)
L/E (km/GeV)
μ→τ (Δm² , θ23)
g
Solar + KamLAND
LBL accelerator
SBL Reactor
Atmospheric
Each known parameter
is constrained by
at least two classes
of experiments

Hi-res, larger picture → Combined analysis of ν oscill. 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

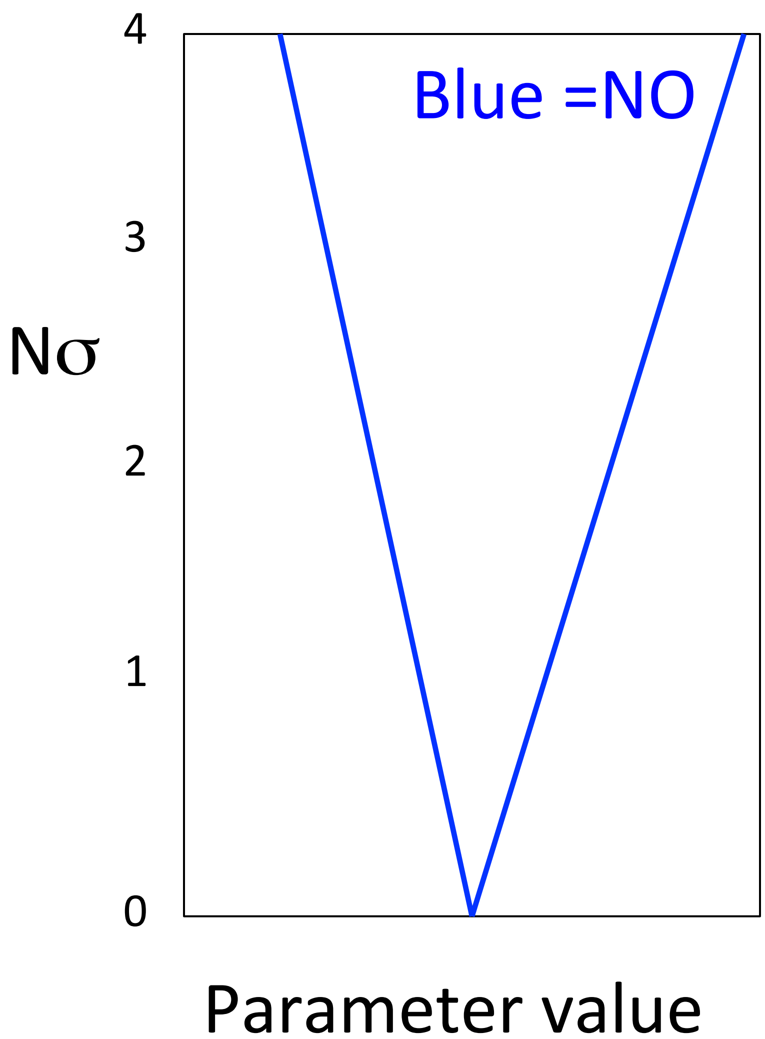
LBL Accel + Solar + KL + SBL Reactor

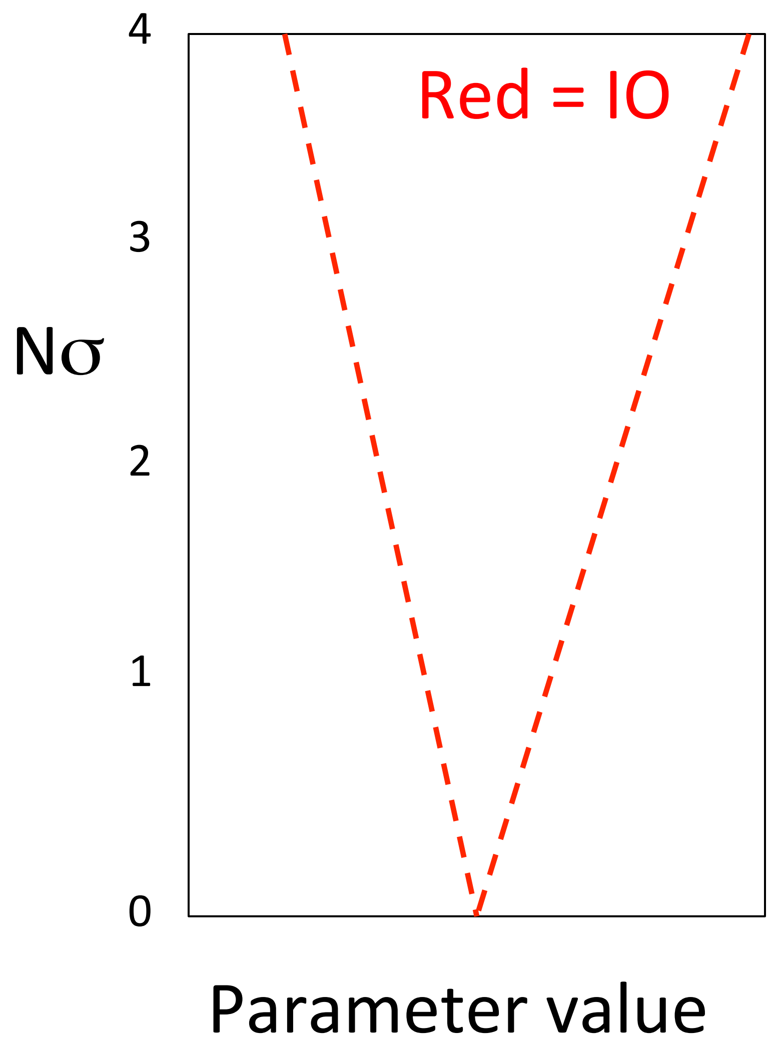
add sensitivity to Δm^2, θ_{13} and affect other parameters via correlations

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

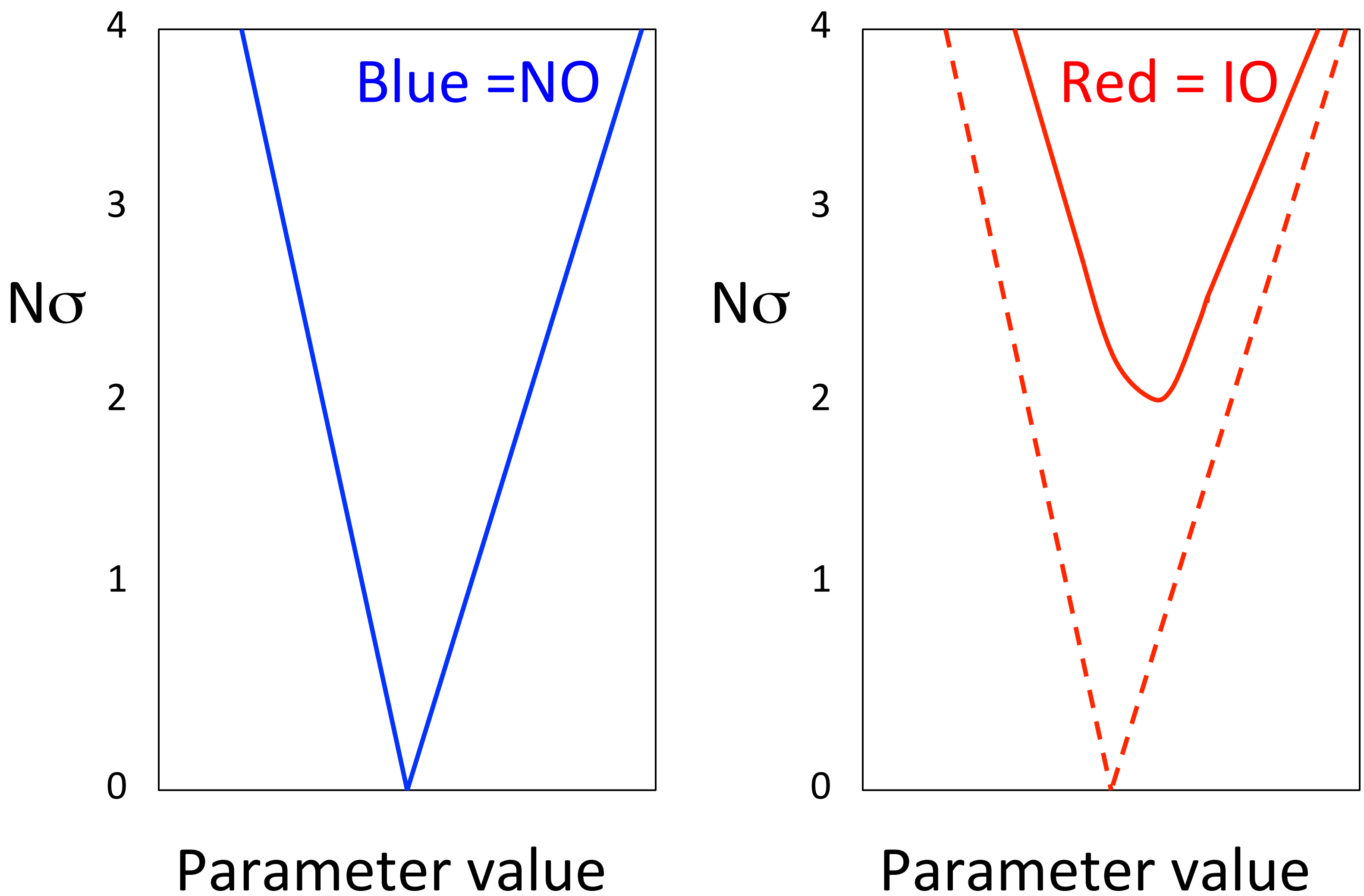
add sensitivity to Δm^2, θ_{23}, δ, NO/IO (but: entangled information)

In the following figures: Typical bounds would be ~linear and symmetric for ~gaussian errors around best fits. Recall: **$N\sigma = \sqrt{\Delta\chi^2} = 1, 2, 3\ldots$**



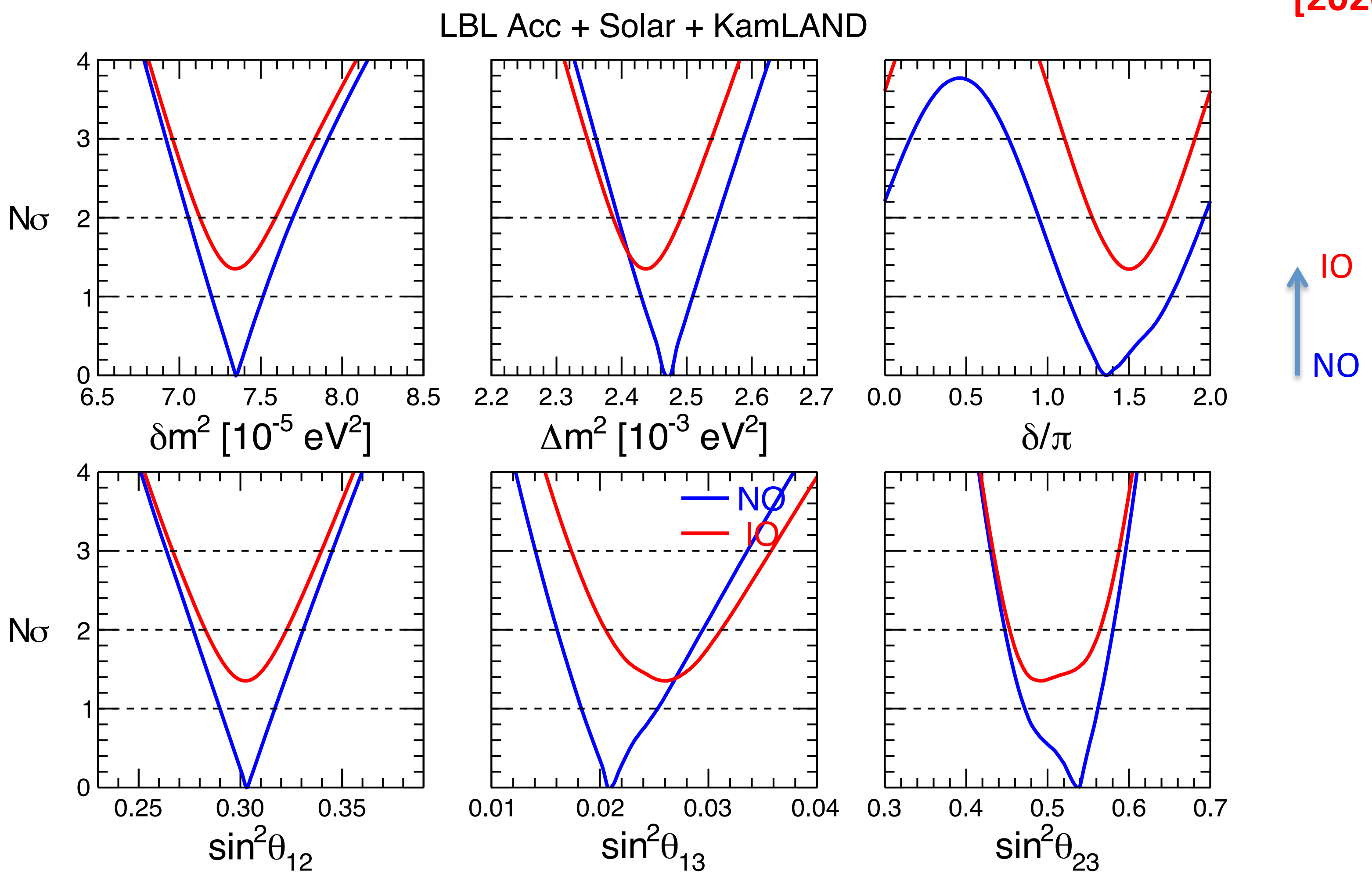


However, **bounds for IO move upwards** if one takes into account that currently **NO gives the absolute best fit**.



2020 updated bounds →

[2020]



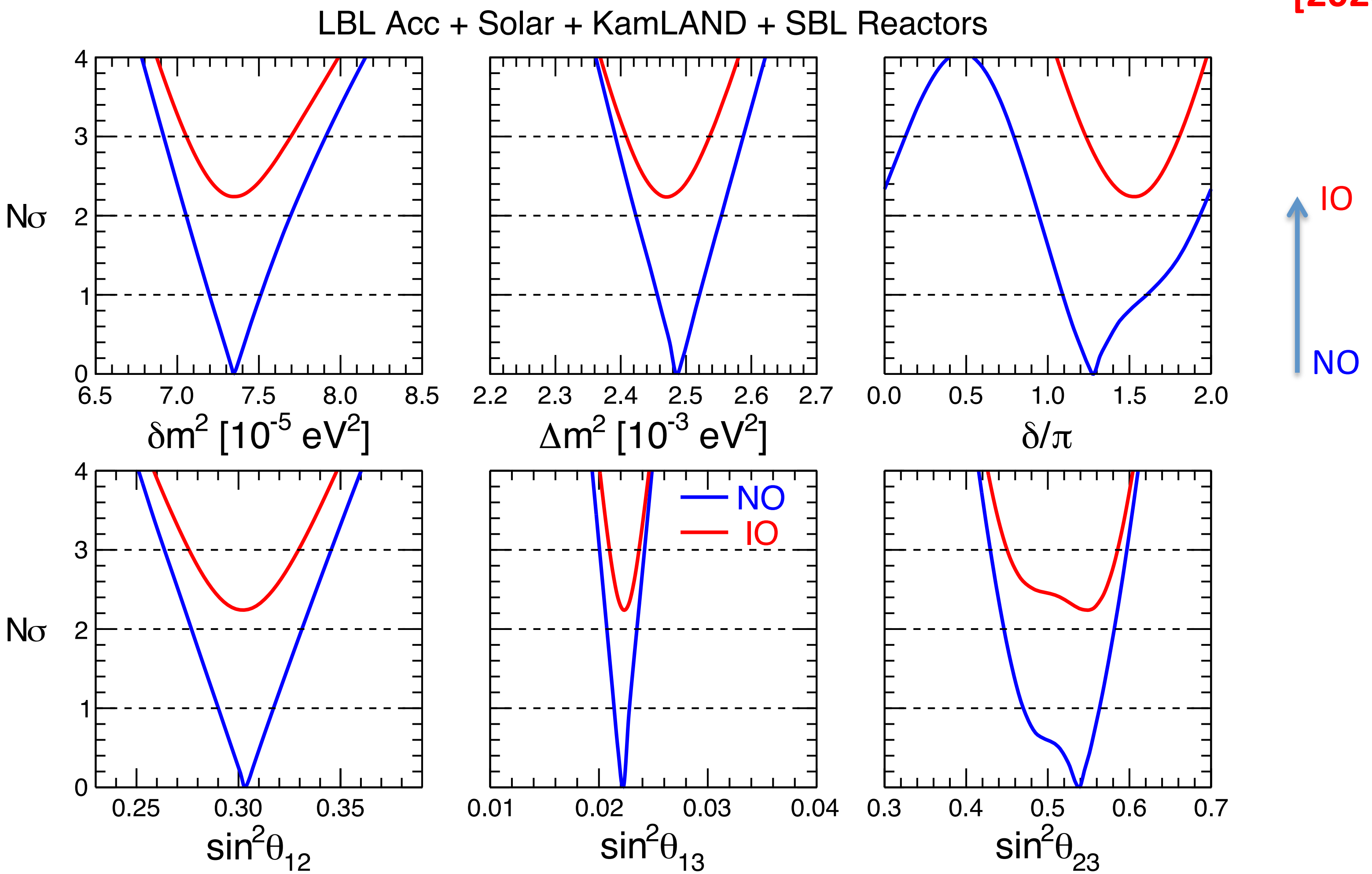
Five parameters (2 mass^2 gaps and 3 mixing angles) measured at >4σ.

IO slightly disfavored with respect to NO at ~1.4σ level.

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

Largest mixing angle θ_{23} slightly above $\pi/4$, but 1st octant allowed at 1σ.

[2020]



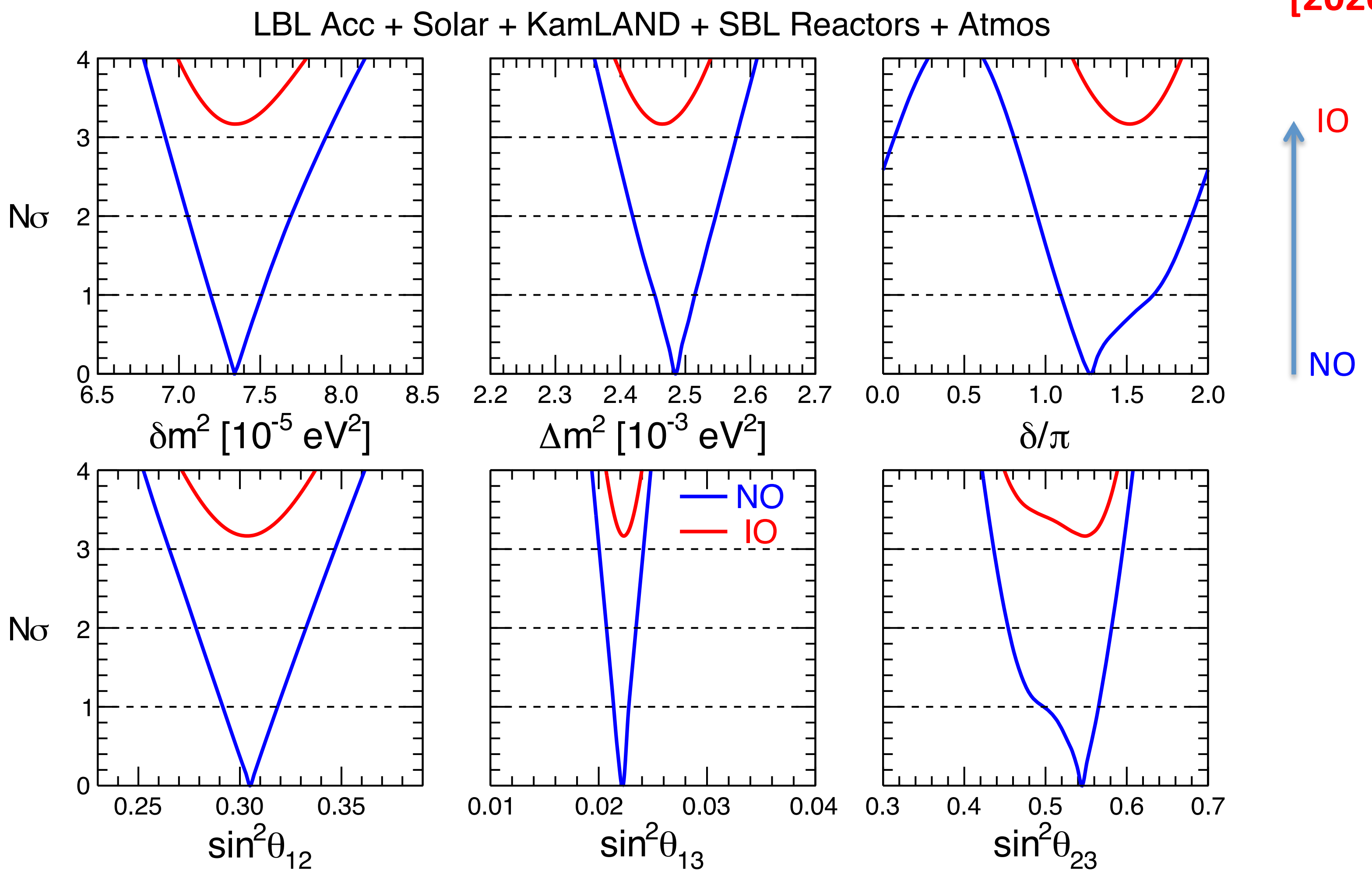
Direct impact of SBL reactors: range of θ_{13} strongly reduced; Δm^2 improved

Indirect impact: IO more disfavored wrt NO, at ~2.2σ level

indirect impact: indications on δ improved

Largest mixing angle θ_{23} slightly above $\pi/4$, but 1st octant allowed at 1σ.

[2020]



Overall convergence of "measurements" and "hints". Ranking hints by CL:

IO significantly disfavored with respect to NO, at $\sim 3.2\sigma$ level

CPV favored (~max): $\delta = \pi$ disfavored at $\sim 1.6\sigma$, δ = 0, 2π disfavored at $\sim 2.6\sigma$

Slight preference for θ_{23} above $\pi/4$ at $\sim 1\sigma$ (caution: fragile!)

3ν picture with more digits: Where we are, circa 2020

Knowns	(with $\sim 1\sigma$ accuracy)
$\Delta m^2 / eV^2 = 2.48 \times 10^{-3}$	(1.3%)
$\delta m^2 / eV^2 = 7.34 \times 10^{-5}$	(2.2%)
$\sin^2\theta_{13} = 0.0222$	(3.0%)
$\sin^2\theta_{12} = 0.304$	(4.5%)
$\sin^2\theta_{23} = 0.545$	(~5%)

Unknowns	(but...)
sign(Δm^2) = ordering	(> 3σ NO)
δ = Dirac CP phase	(1.6σ CPV)
octant of θ_{23}	(1σ 2nd)

Worldwide **neutrino oscillation program** to improve on known parameters and to determine unknowns (also BSM!)

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Worldwide **neutrino oscillation program** to improve on known parameters and to determine unknowns (also BSM!)

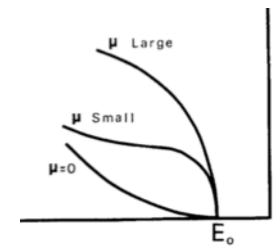
+Nonoscillation searches:

Unknowns	(but...)
Absolute mass scale	(sub-eV)
Dirac/Majorana nature	

3ν framework via non-oscillation searches:
Absolute neutrino masses and observables (m_β , $m_{\beta\beta}$, Σ)

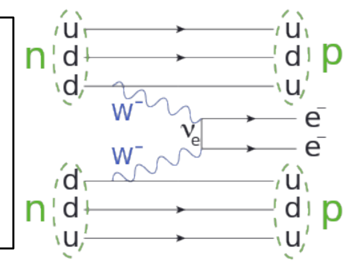
β decay, sensitive to the "effective electron neutrino mass":

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



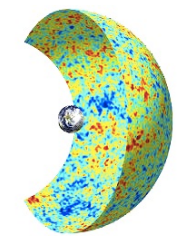
0νββ decay: only if Majorana. "Effective Majorana mass":

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



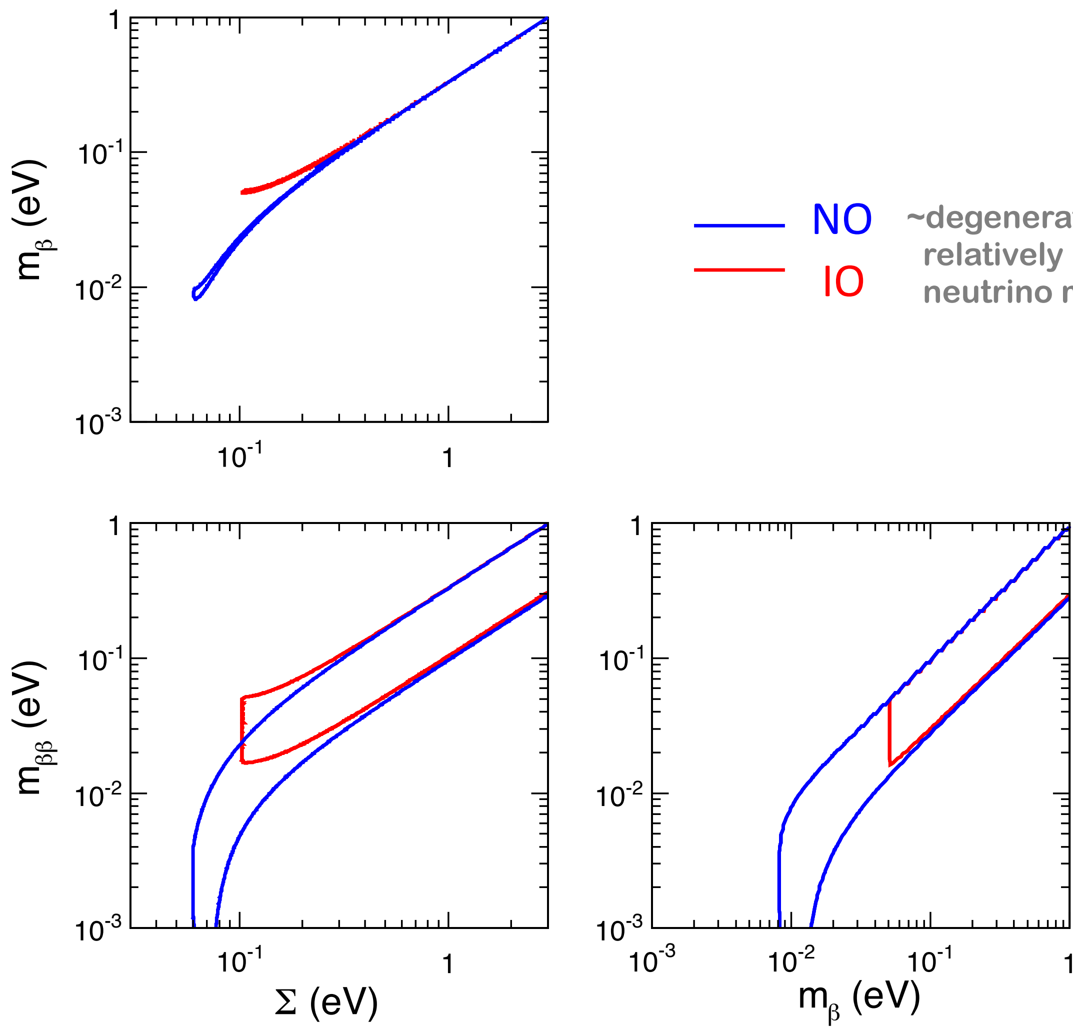
Cosmology: Dominantly sensitive to sum of neutrino masses:

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



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 nonoscillation parameter space



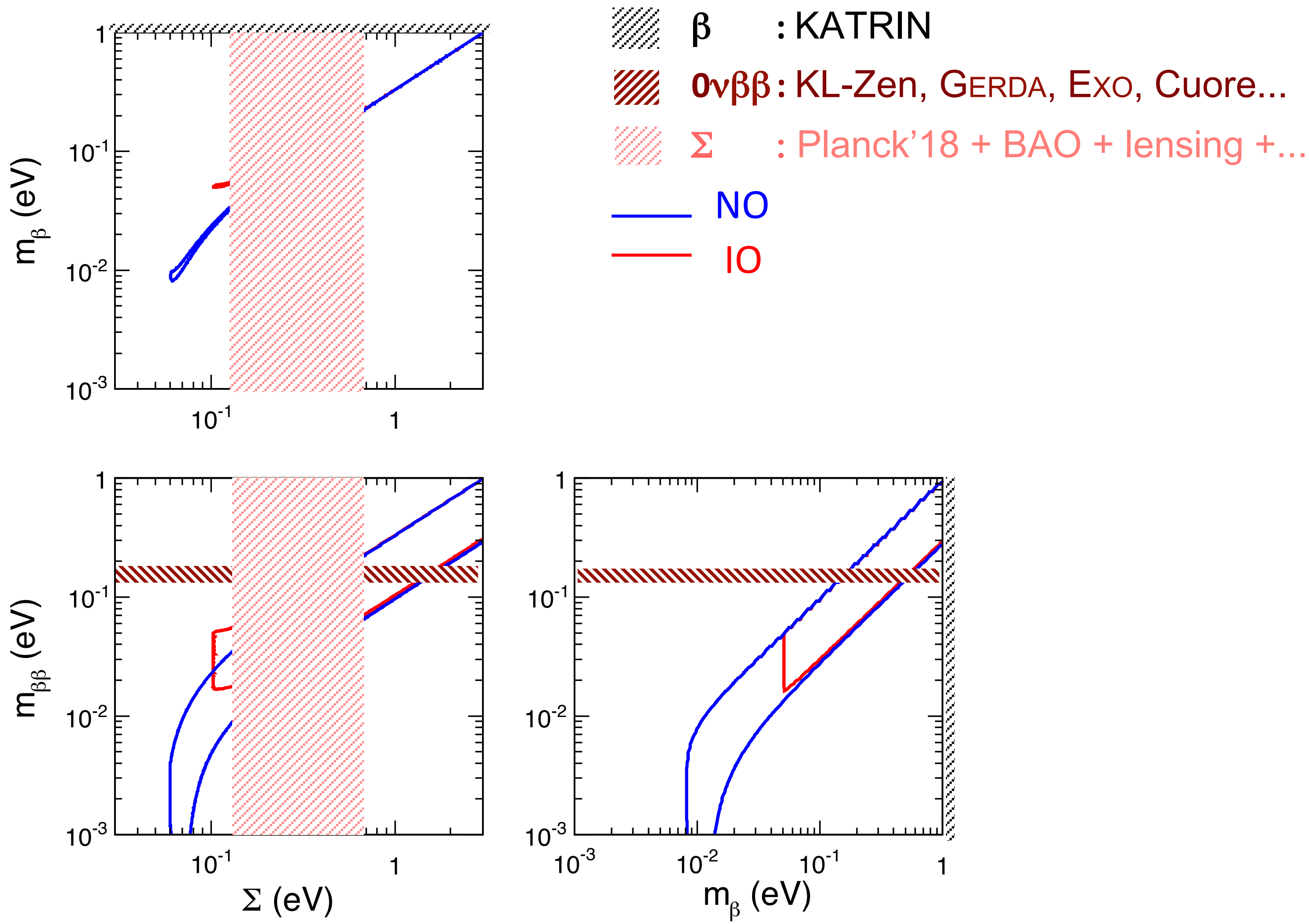
NO
IO

~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!)

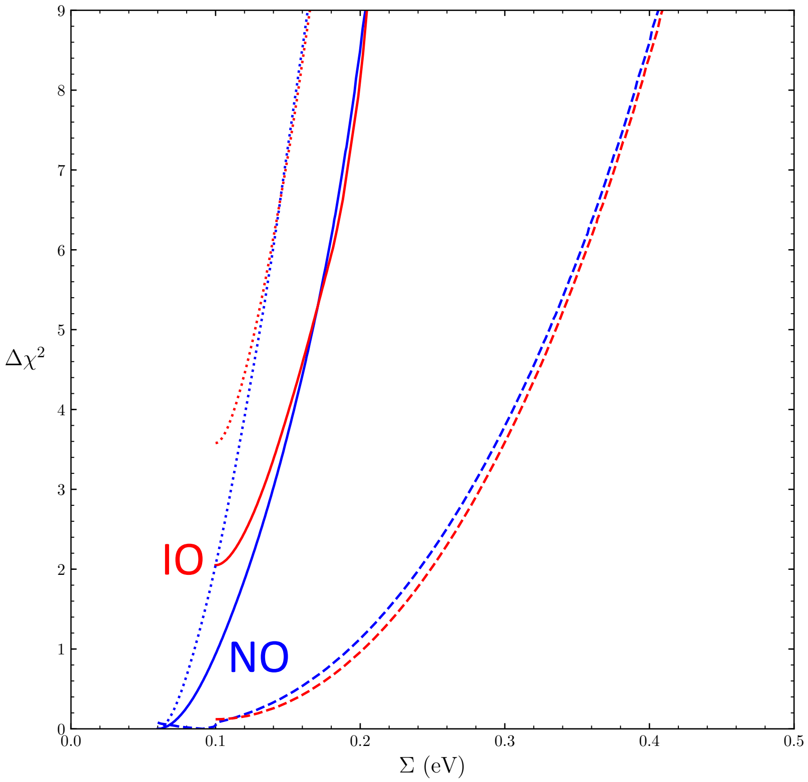
No signal (yet) but upper limits on m_β, $m_{\beta\beta}$, Σ (up to some syst.)



Cosmo data constrain masses and put IO "under pressure" →

Impact of cosmological data on sum of neutrino masses

(examples of “aggressive”, “default”, “conservative” datasets)



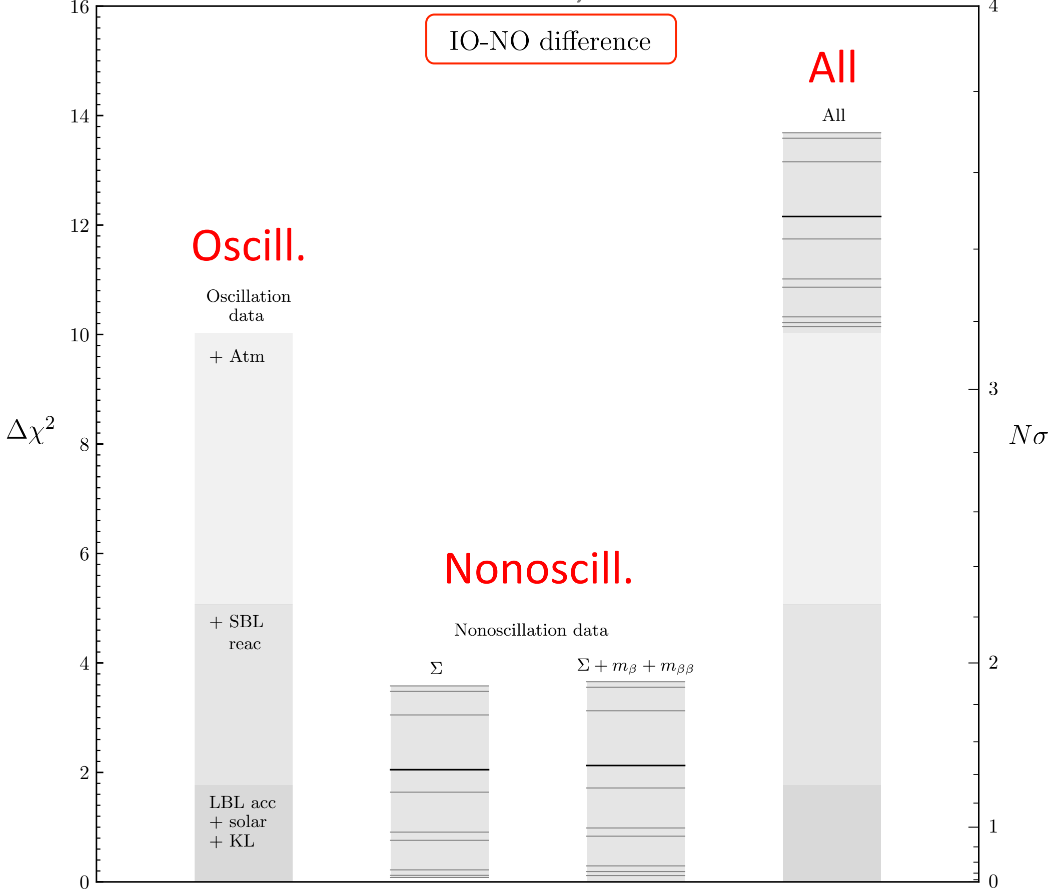
Overall result (oscillation + nonoscillation data):

$\Sigma < 0.12$–0.69 eV at 95% CL.

Note: absolute minimum always in NO

Impact of cosmological data on mass ordering

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



Overall result (oscillation + nonoscillation data):

NO favored at 3.2–3.7σ

Significant progress expected in next decade.

OUTLINE:

Status of 3ν masses & mixing

The role of nuclear physics

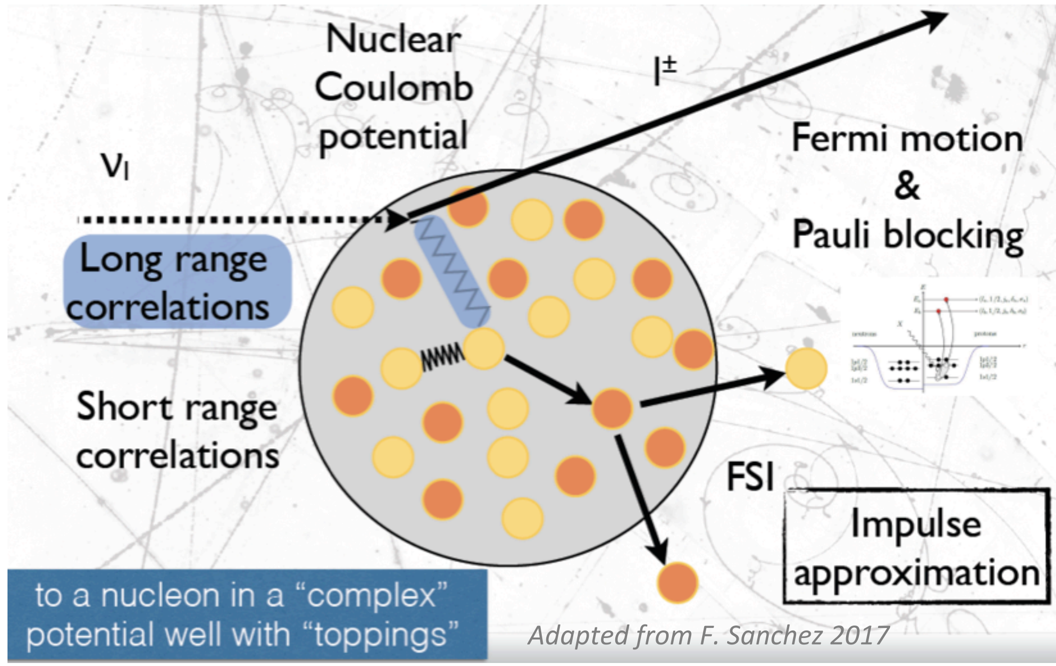
A suggestion for this field

A primary example: Neutrinos as EW probes of nucleus/nucleons

Cross sections

A complex and interdisciplinary issue in ν physics, both expt and theo

From a free nucleon in a potential well…



Adapted from F. Sanchez 2017

We have "standard models" for particle physics and for cosmology, but
but not yet for the nuclear response to electroweak probes

Progress in this field is crucial to get the most from many ν−related data e.g., constrain Δm^2, θ_{13}, θ_{23}, δ, NO/IO with LBL accel.

But... not only cross sections as seen from a "HEP" perspective (NuINT series): there is much more as testified also by this conference (CNNP series)!

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, early universe)

Nuclear astrophysics and neutrinos (nucleosynthesis & solar reactions networks)

EFT vs QCD

Ab initio nuclear structure

EC processes and neutrino mass

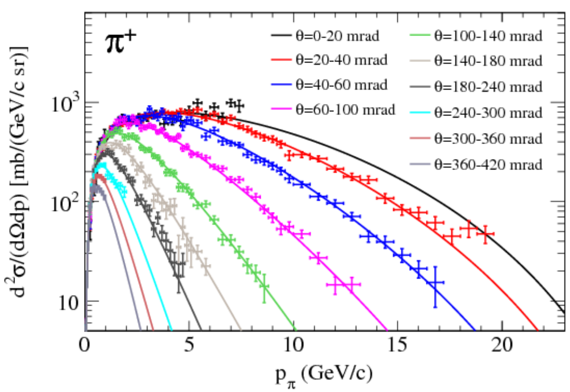
Connections with other EW probes (gammas, electron, possible WIMPs...)

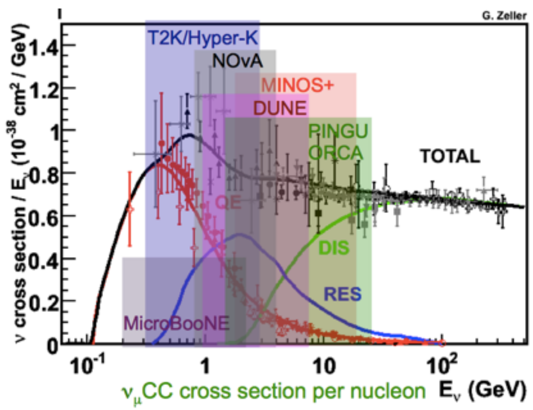
"Strong interaction" effects on "weak interaction" physics are ubiquitous...

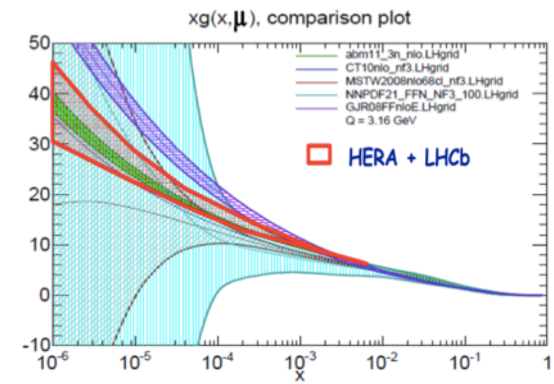
Need hadron production data, e.g. pA → πX, +theory models to improve estimates of atm. and acceler. ν fluxes and errors

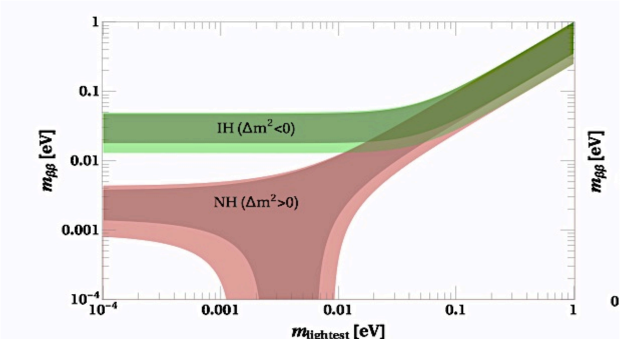
Current understanding of ν cross sections at O(GeV) does not match the needs of (next-generation) ν expts

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

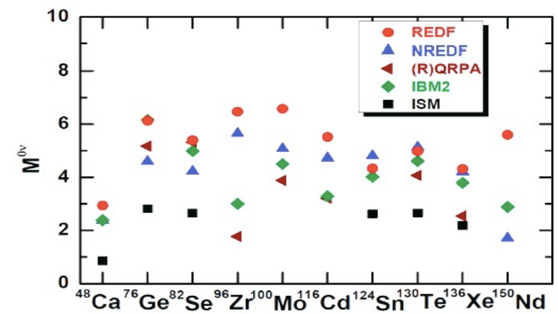








Better control of nuclear EW response (e.g., g_A) relevant to interpret 2β data and to connect them with other data, including reactor spectra...



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)

A really exciting, data-rich,

multifaceted and interdisciplinary

field of research, at the junction of

neutrino and nuclear physics

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But...

... you know, when seen from "outside":

multifaceted = fragmented / dispersive

...and when it comes to fundings and jobs:

interdisciplinary = nobody's child

→ *"ancillary" at most...*

Deserves more proper recognition!

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A suggestion for this field

Learning from another field
(admittedly much wider)
that suffered from being
multifaceted and interdisciplinary:

ASTROPARTICLE PHYSICS

Interconnected aspects of

Particle physics, Astrophysics

Cosmic ray physics, Cosmology,

were not covered under the unifying “name” of...

ASTROPARTICLE PHYSICS

... until it was recognized that important problems

(dark matter, baryon asymmetry and stability, neutrino masses ...)

required to join different communities and competences

Adam giving names (Genesis 2:19)

Artist unknown. Phillip Medhurst Collection

The name "Astroparticle Physics" came into existence in the late '80s, early '90s:

1987	**A. De Rujula and D.V. Nanopoulos (Erice School)**
1988	**A. Salam**
1990	**V.A. Rubakov**
1991	**D.H. Perkins**
1992	**D. Cline and R. Peccei**
1992	**F. Halzen**
1994	**H. Ejiri**

Became a widely recognized "unifying name" around ~2000.

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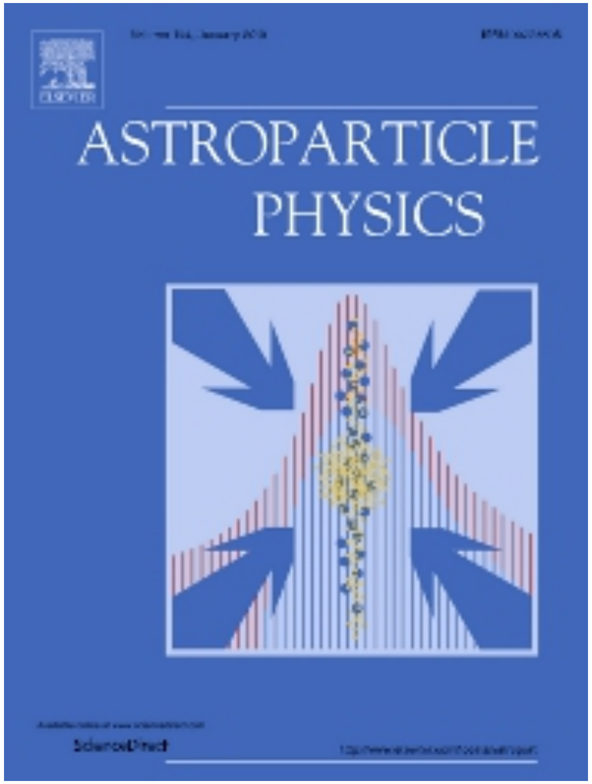
Became a widely recognized "unifying name" around ~2000.

In about the same period, within INFN:

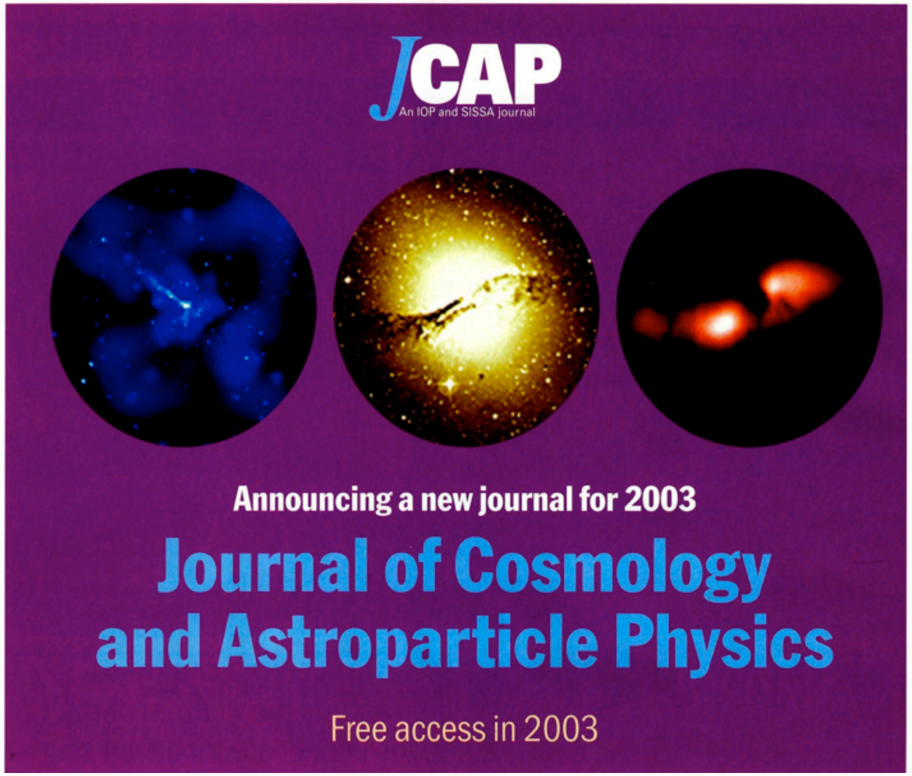
Experimental Committee II: transition from "negative" to "assertive" wording:
Non-accelerator physics → Astroparticle physics

Theoretical Committee IV: includes the topic "Theoretical Astroparticle Physics"
Dedicated PhD courses, Schools, Workshops...

Also: Two dedicated international Journals



1992+



2003+

These actions helped to establish a common scientific language and sinergies of different competences and communities that recognized themselves within the same "Astroparticle" field

Astroparticle Physics European Consortium

August 2017

appec.org

Executive Summary

Astroparticle physics is the fascinating field of research at the intersection of astronomy, particle physics and cosmology. It simultaneously addresses challenging questions relating to the micro-cosmos (the world of elementary particles and their fundamental interactions) and the macro-cosmos (the world of celestial objects and their evolution) and, as a result, is well-placed to advance our understanding of the Universe beyond the *Standard Model of particle physics* and the *Big Bang Model of cosmology*.

One of its paths is targeted at a better understanding of cataclysmic events such as: supernovas – the titanic explosions marking the final evolutionary stage of massive stars; mergers of multi-solar-mass black-hole or neutron-star binaries; and, most compelling of all, the violent birth and subsequent evolution of our infant Universe. This quest is pursued using the combined and often complementary power of all 'cosmic' messengers: *cosmic rays*, *electromagnetic waves* (i.e. 'light' but also photons at all energies), *neutrinos* and *gravitational waves*. Another path aims to elucidate long-standing mysteries such as the true nature of *Dark Matter* and *Dark Energy*, the intricacies of *neutrinos* and the occurrence (or non-occurrence) of *proton decay*.

The field of astroparticle physics has quickly established itself as an extremely successful endeavour. Since 2001 four Nobel Prizes (2002, 2006, 2011 and 2015) have been awarded to astroparticle physics and the recent – revolutionary – first direct detections of gravitational waves is literally opening an entirely new and exhilarating window onto our Universe. We look forward to an equally exciting and productive future.

Many of the next generation of astroparticle physics research infrastructures require substantial capital investment and, for Europe to remain competitive in this rapidly evolving global field of research both on the ground and in space, a clear, collective, resource-aware strategy is essential. As a relatively new field, European astroparticle physics does not benefit from a natural and strong inter-governmental

APPEC General Assembly 2016

ii

In the current landscape of (sub)nuclear physics and astrophysics,
maybe it's worth trying to better characterize the field(s) at the junction of

neutrino and nuclear physics

in analogy with the astroparticle physics experience *(albeit on a smaller scale)*,
having in mind long-term and ambitious goals, including e.g. a possible

"unified model" for the nuclear response to EW probes

It is left to further discussion (if any!) to evaluate if such perspective is worthwhile.
I have no practical suggestions, but let me just give my two cents for a general name:

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Electroweak Nuclear Physics

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Electroweak Nuclear Physics

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

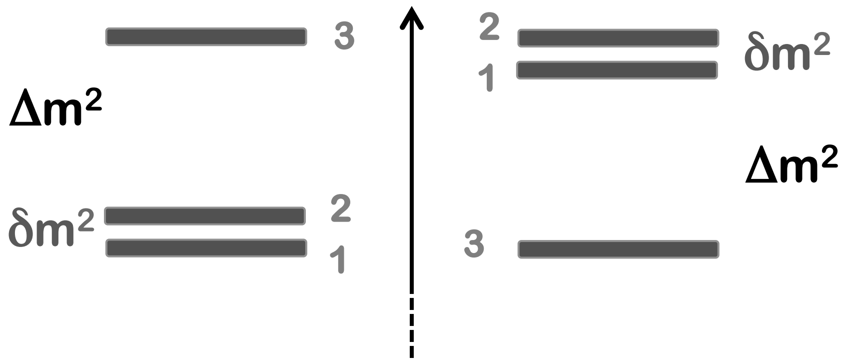
1-3 rotation
+ CPV "Dirac" phase

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.

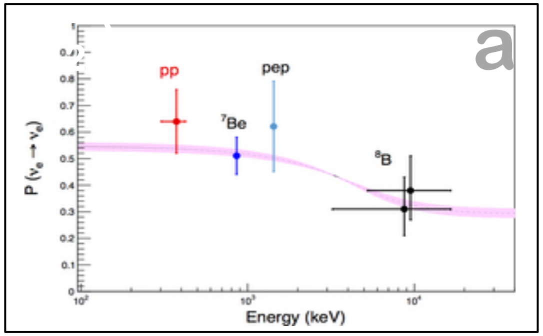


"Inverted" Ordering
I.O.

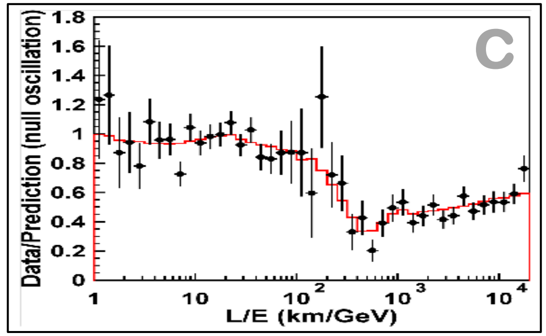
+ interactions in matter → effective terms ~ $G_F \cdot E \cdot$ density
+ absolute mass scale (not tested in oscillations)

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

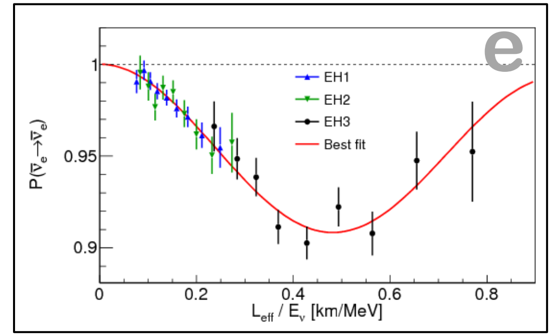
e→e (Solar)



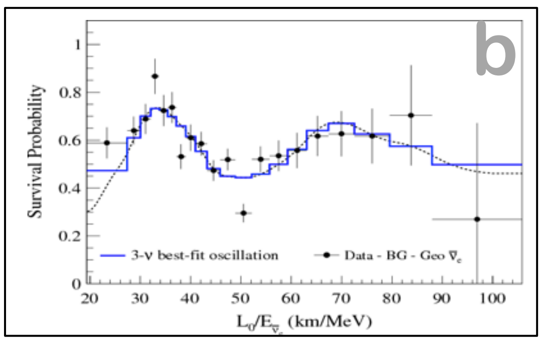
μ→μ (Atmospheric)



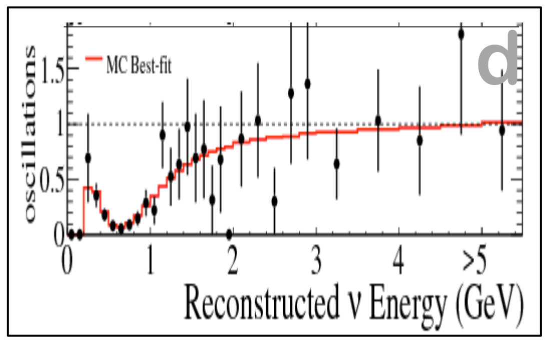
e→e (SBL Reac.)



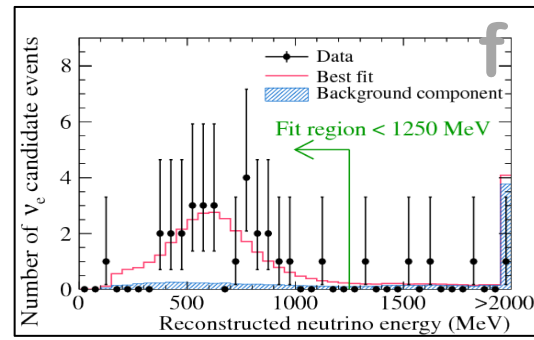
e→e (KamLAND, KL)



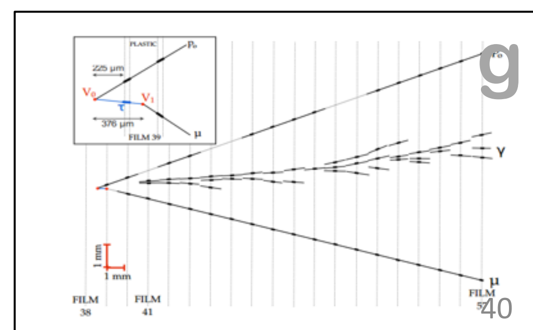
μ→μ (LBL Accel)



μ→e (LBL Accel)



μ→τ (OPERA, SK, DC)

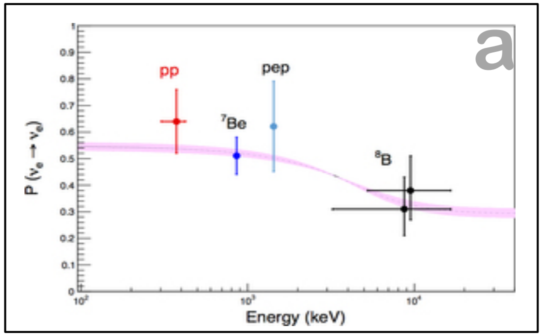


Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline LBL accelerator, (e) short-baseline SBL reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

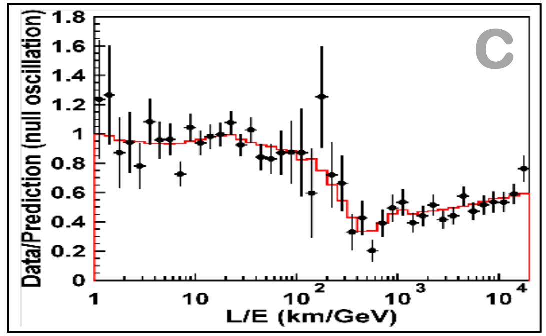
(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore (DC), MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS, NOvA; (g) OPERA [plot], Super-K and IC-DC atmospheric.

… and consistently measured five ν mass-mixing parameters

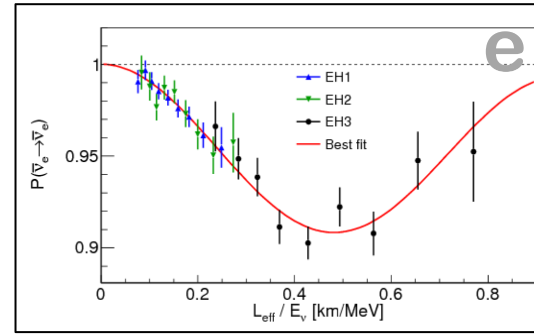
e→e (δm^2 , θ_{12})



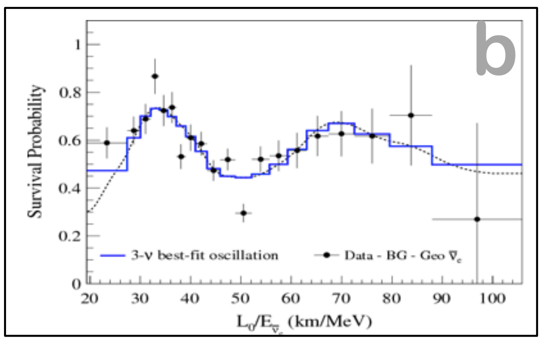
μ→μ (Δm^2 , θ_{23})



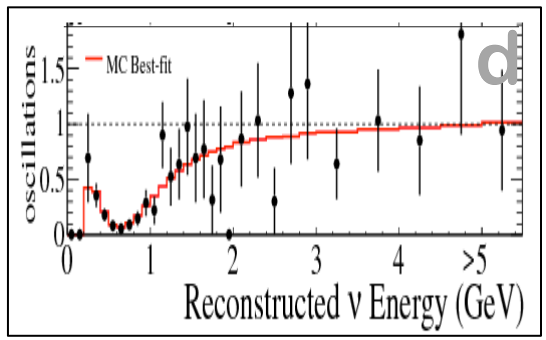
e→e (Δm^2 , θ_{13})



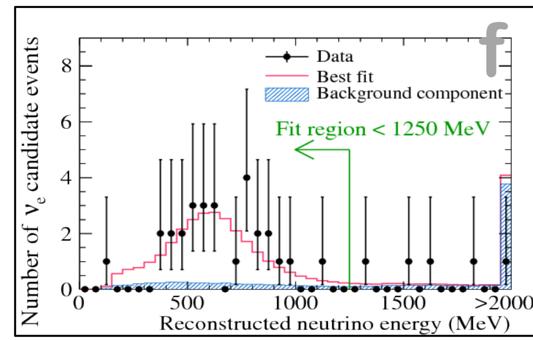
e→e (δm^2 , θ_{12})



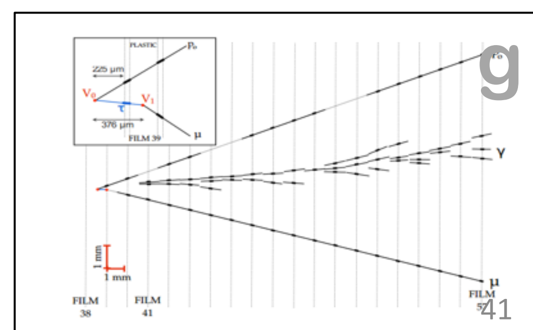
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})

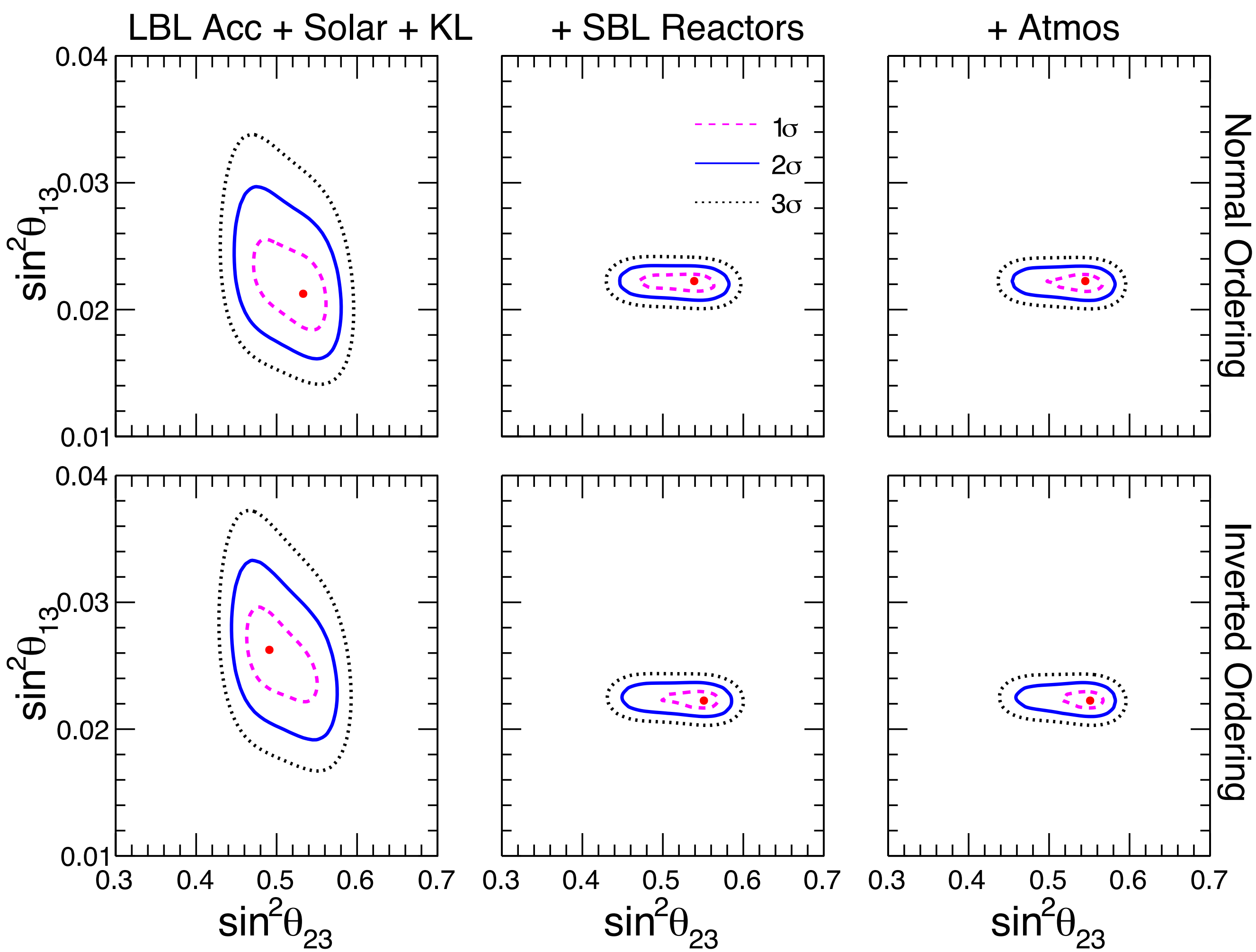


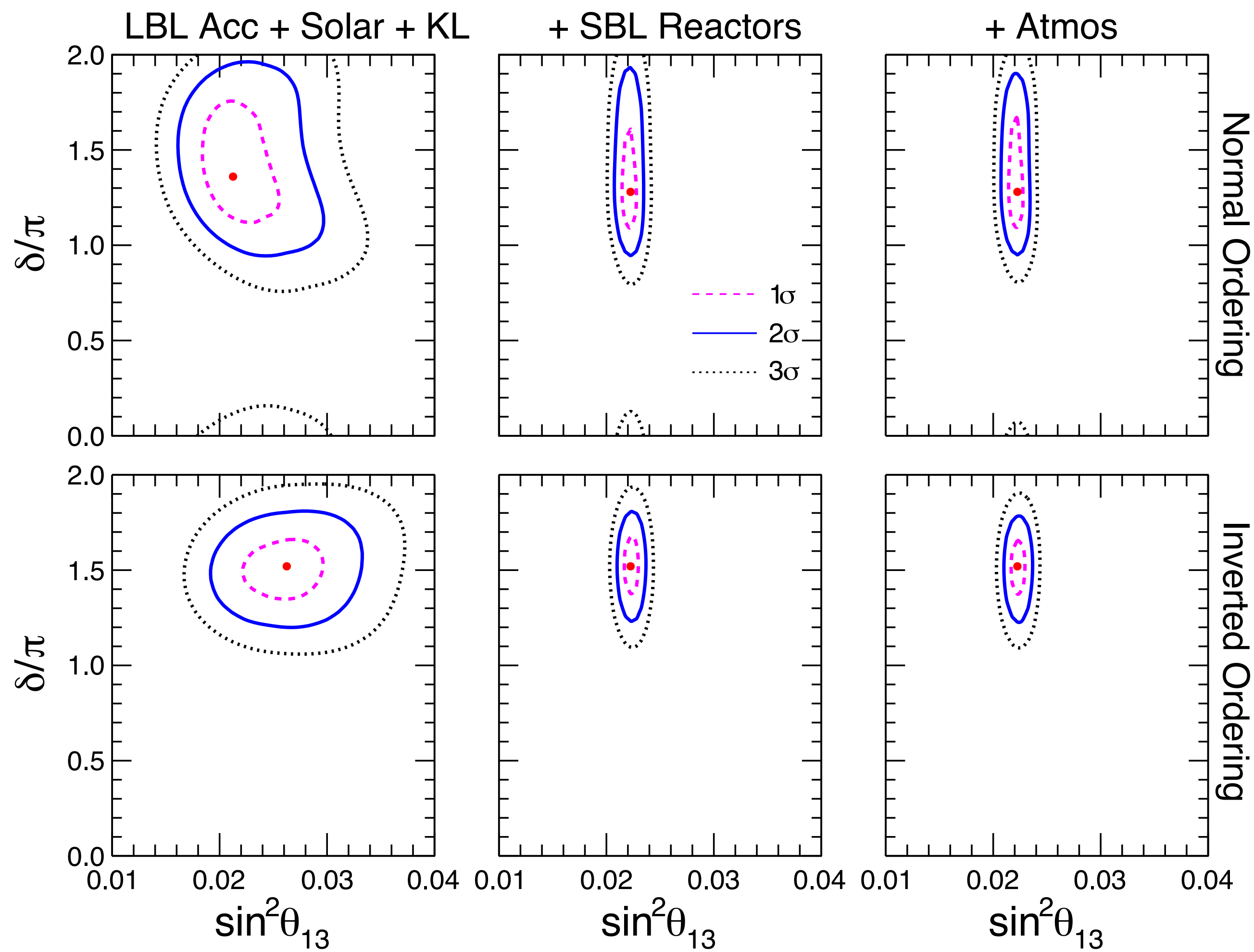
μ→τ (Δm^2 , θ_{23})



Each leading oscillation parameters (over)constrained by at least two classes of measurements → 3ν consistency

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


LBL Acc + Solar + KL
+ SBL Reactors
+ Atmos
Normal Ordering
Inverted Ordering
1σ
2σ
3σ
$\sin^2\theta_{13}$
$\sin^2\theta_{23}$
0.01
0.02
0.03
0.04
0.3
0.4
0.5
0.6
0.7

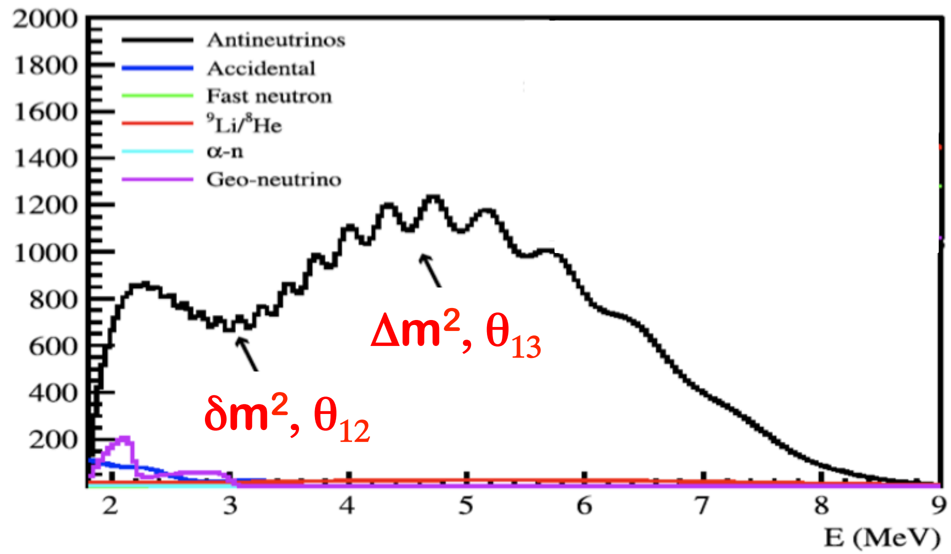


LBL Acc + Solar + KL
+ SBL Reactors
+ Atmos
Normal Ordering
Inverted Ordering
δ/π
sin²θ13
1σ
2σ
3σ
0.0
0.5
1.0
1.5
2.0
0.01
0.02
0.03
0.04

Expectations for JUNO reactor experiment

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

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

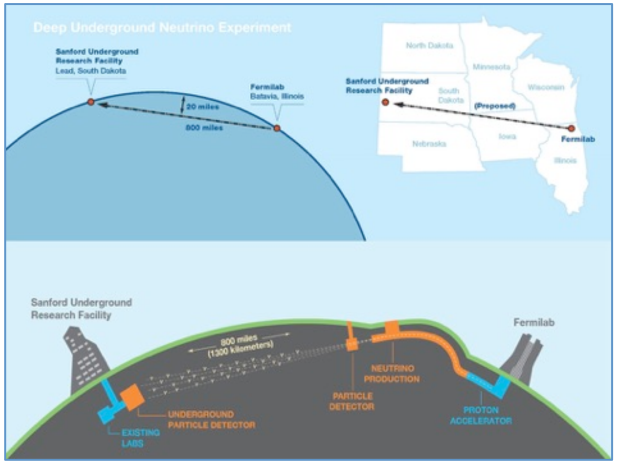


Significant improvements expected on 3 out of 4 oscillation parameters:

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]

Expectations for DUNE LBL accel. expt (T2HK: same ballpark)

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 ($\delta_{CP} = -\pi/2$)	77	3
MH at 5σ (worst point)	209	6
10° δ_{CP} resolution ($\delta_{CP} = 0$)	252	6.5
CPV at 5σ ($\delta_{CP} = -\pi/2$)	253	6.5
CPV at 5σ 50% of δ_{CP}	483	9
CPV at 3σ 75% of δ_{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, 202X-203Y *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

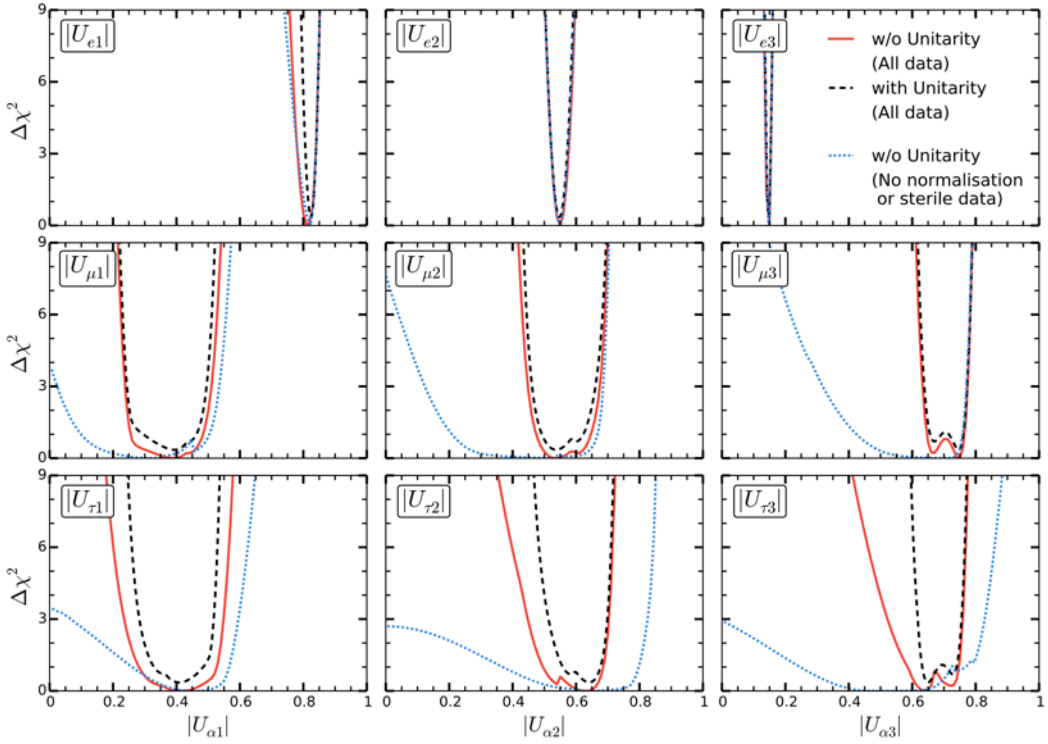
But: Difficult to really anticipate DUNE (T2HK) accuracy

due to cross-section uncertainties → need progress in **"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) 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

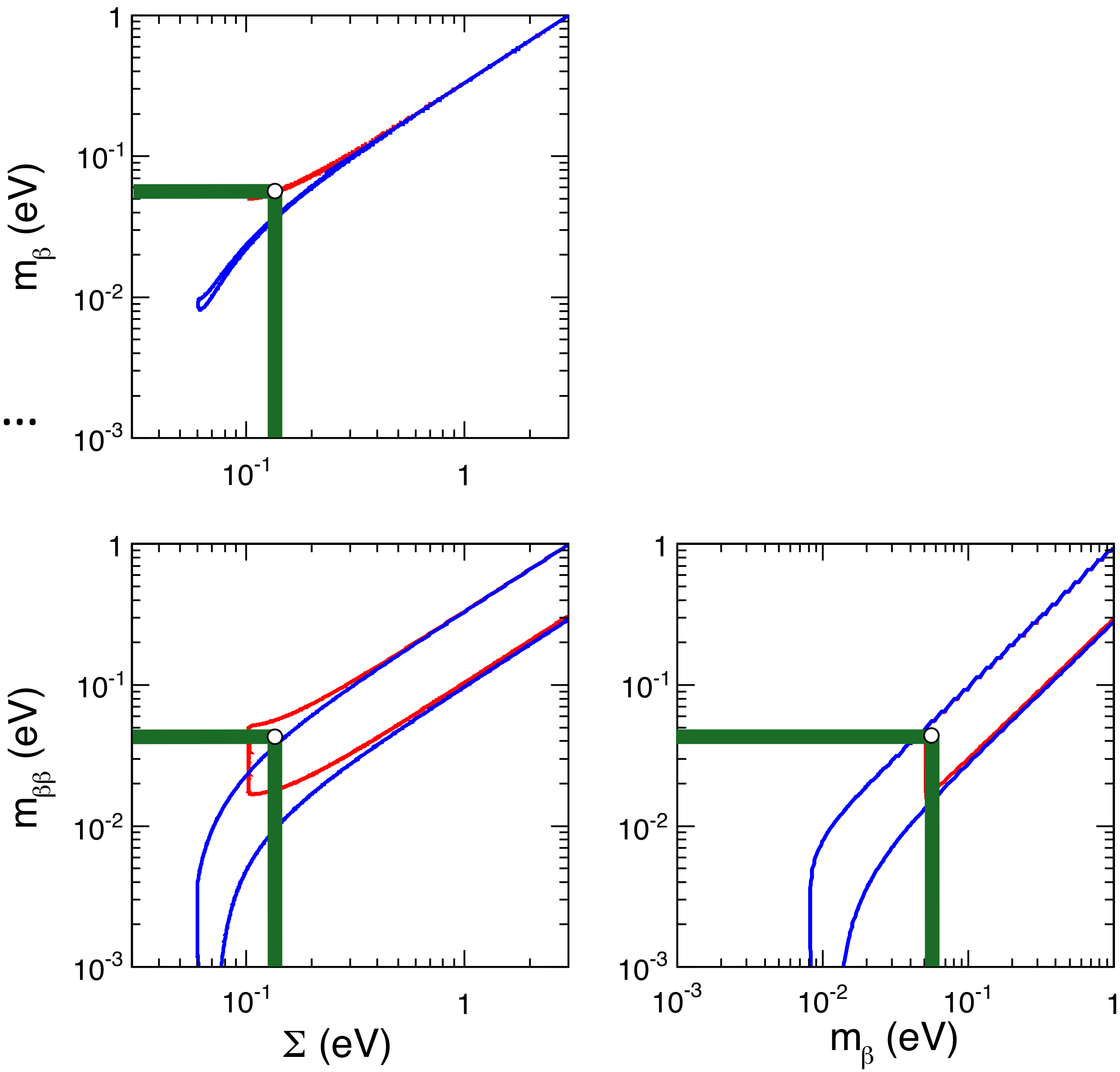
In principle: with precise and converging non-oscillation signals one could, e.g.

Determine the mass scale…

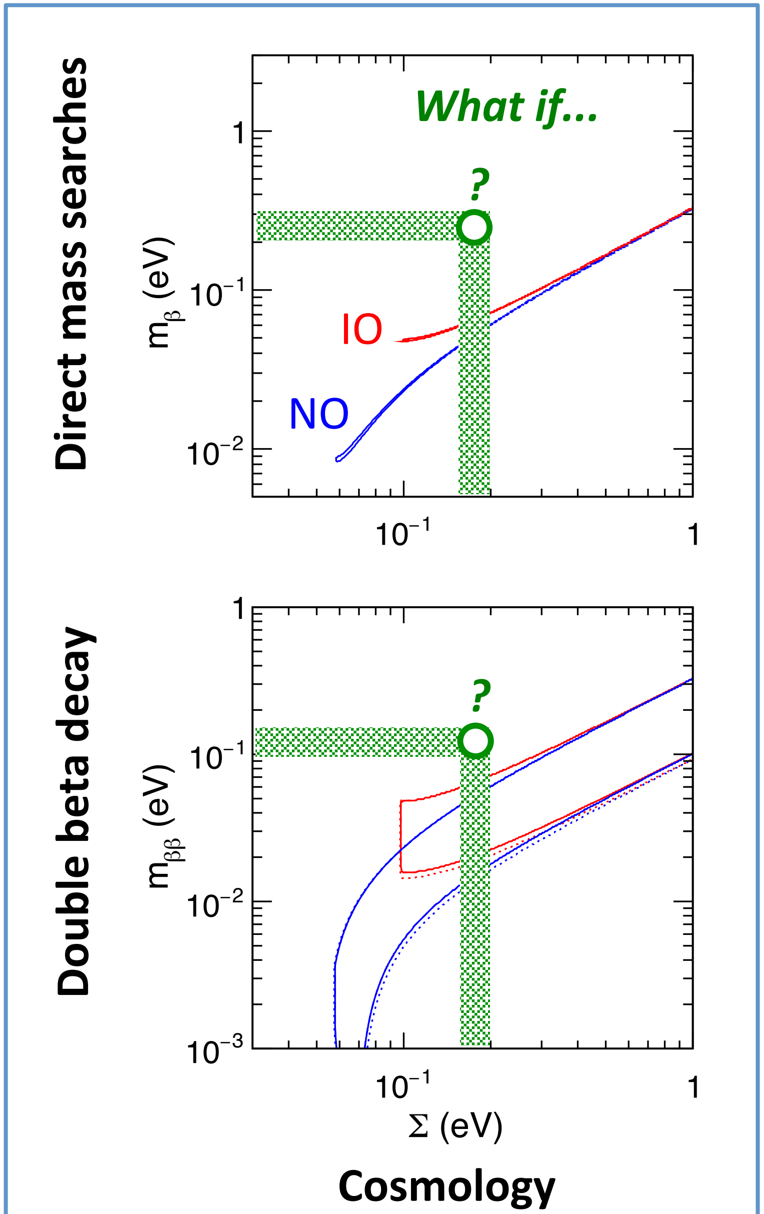
Check 3ν consistency …

Identify the hierarchy …

Probe the Majorana phase(s) …



... but data might well bring us beyond 3ν and re-shape the field!



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

- *Nonstandard $0\nu\beta\beta$ mechanisms*
- *Cosmology beyond ΛCDM*
- *New neutrino states*
- *New interactions*
- *Nonstandard ν properties*
- *New phenomena in propagation*
- *...*

Main contender in current ν physics:

Light sterile ν at O(eV) scale