Interpreting and combining neutrino oscillation data

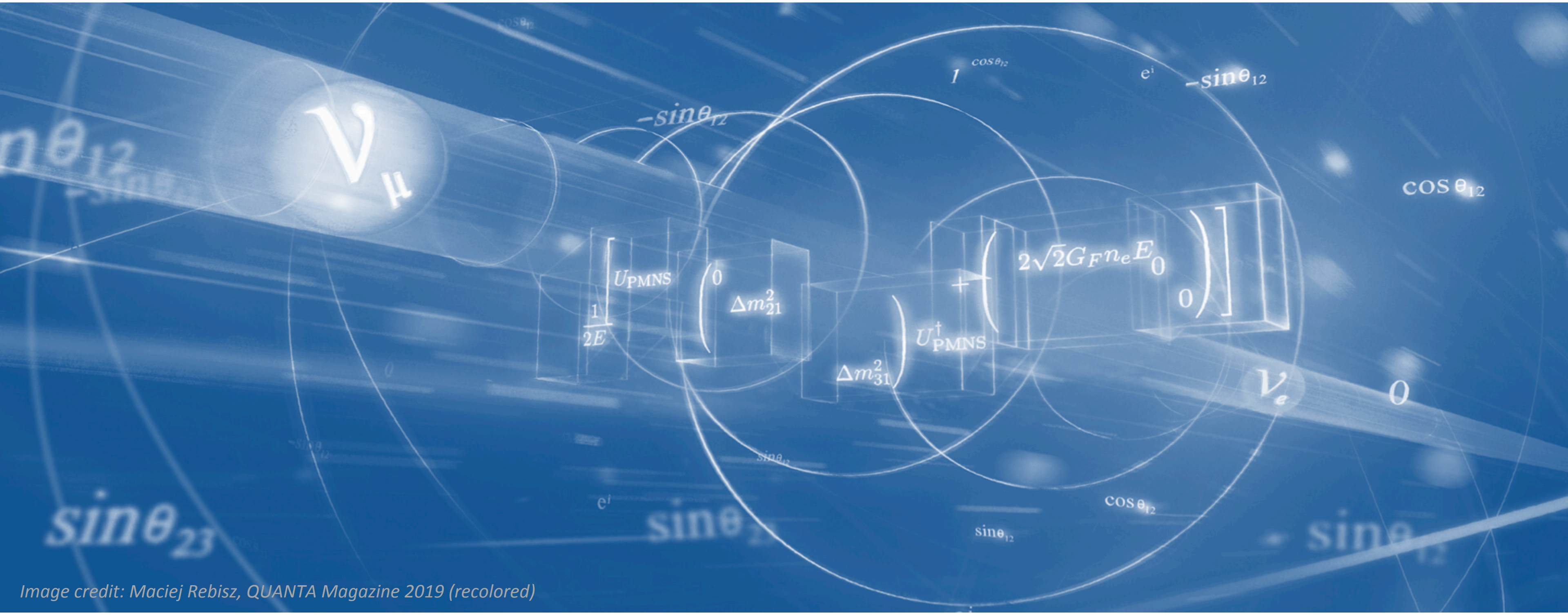


Image credit: Maciej Rebisz, QUANTA Magazine 2019 (recolored)

Eligio Lisi

(INFN, Bari, Italy)

(Re)interpreting the results of new physics searches at the LHC, Feb. 2021

Outline

Prologue

Standard 3ν framework and beyond

Case study 1: atmospheric neutrinos

Case study 2: accelerator neutrinos

Epilogue

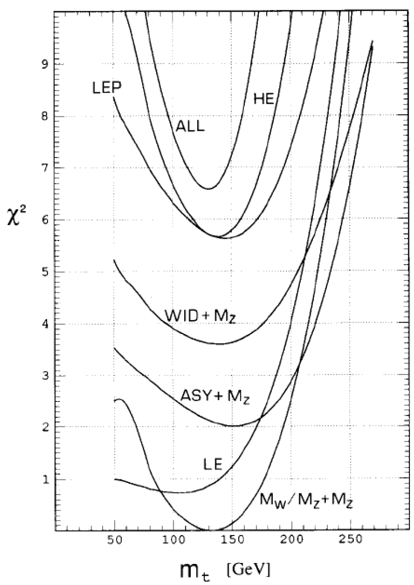
Disclaimer: I am a theorist involved in EW phenomenology, often collaborating with other colleagues, but not belonging to any experimental collaboration.

PROLOGUE

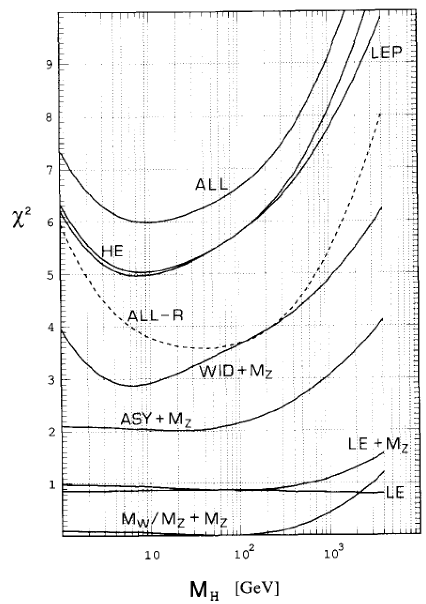
Collider physics: my first love! 30 yrs ago I was captured by the power of global analyses of precision EW data

Global fit to 1991 EW data including LEP (Ellis, Fogli, Lisi, PLB 274, 456-462):

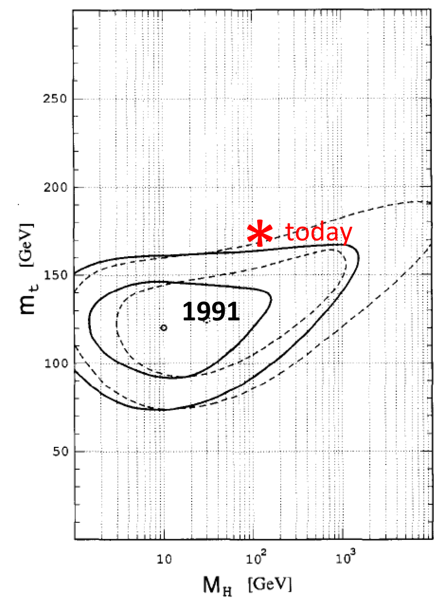
Top mass estimate
at fixed M_H=M_Z



Higgs mass estimate
at fixed m_t=130 GeV



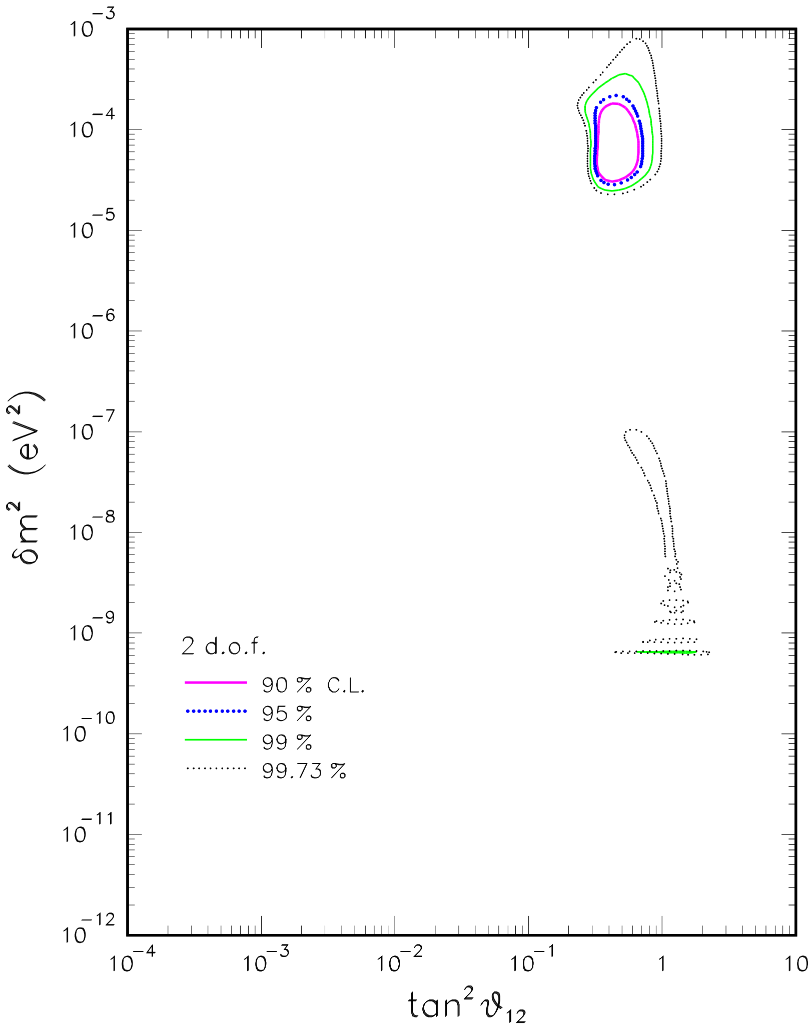
Joint mass estimates
at $\Delta\chi^2$=1 and 2.7

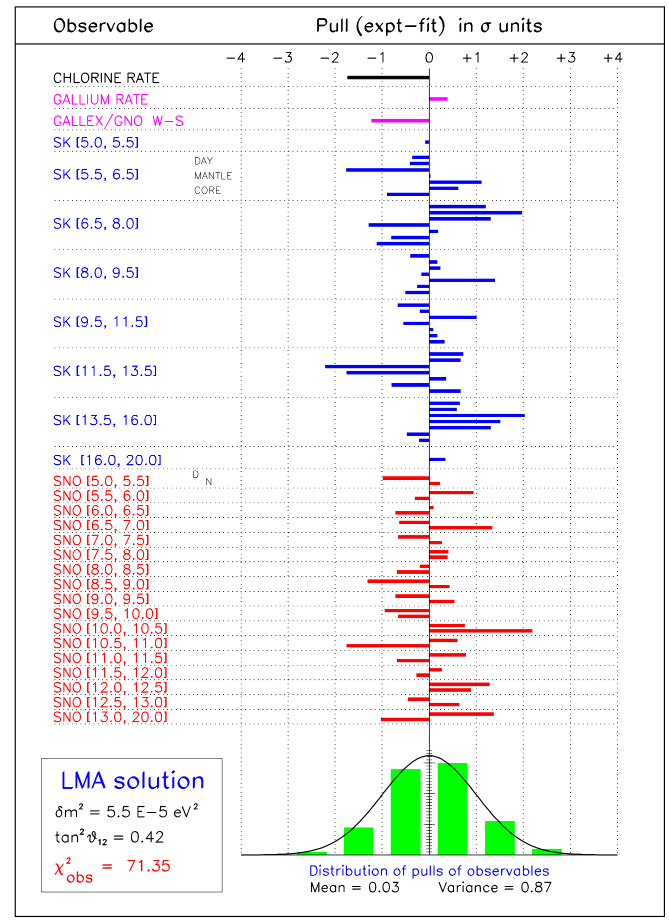


Our estimates were improved in 1992-96, + bounds on SUSY (MSSM) and technicolor
The LEP EWWG eventually took over this field, **while I met my 2nd love... neutrinos!**

HEP experience transferred to pheno analyses of neutrino oscillation data:

E.g.: Mass-mixing bounds plus distribution of pulls for solar neutrinos





Fogli, Lisi, Montanino, Marrone, Palazzo (2002) [hep-ph/0206162], “Bari Group”

The standard 3ν framework and beyond

Conventions and jargon

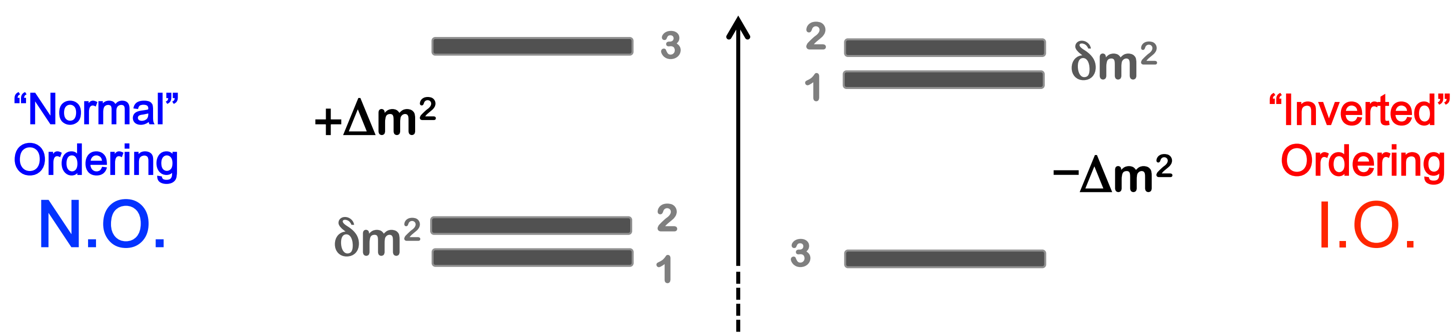
Mixings and phases: CKM→ PMNS (Pontecorvo-Maki-Nakagawa-Sakata)

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

θ_{23} rotation θ_{13} rotation θ_{12} rotation

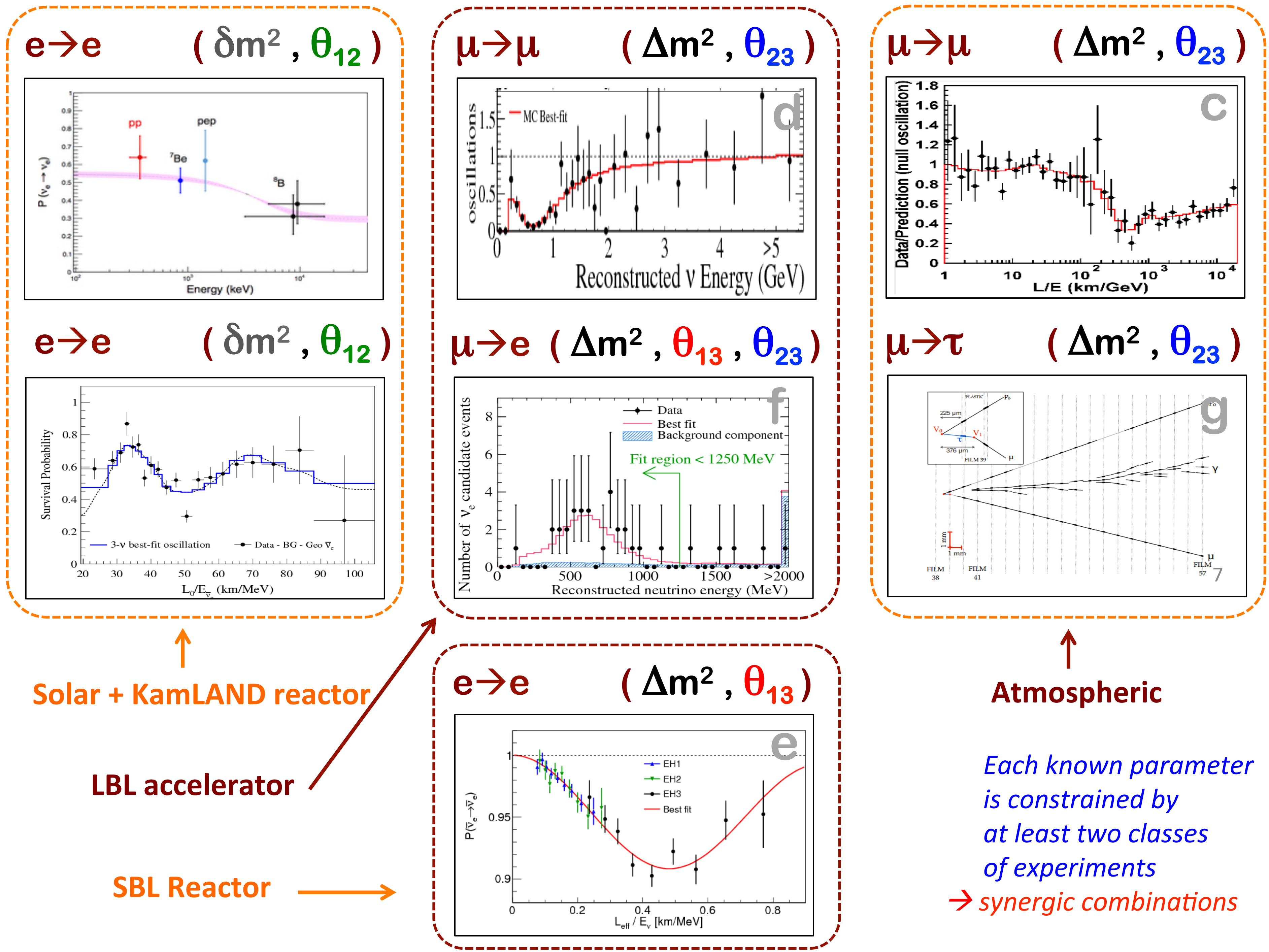
+ CPV "Dirac" phase δ

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



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

Sensitivities of selected data →

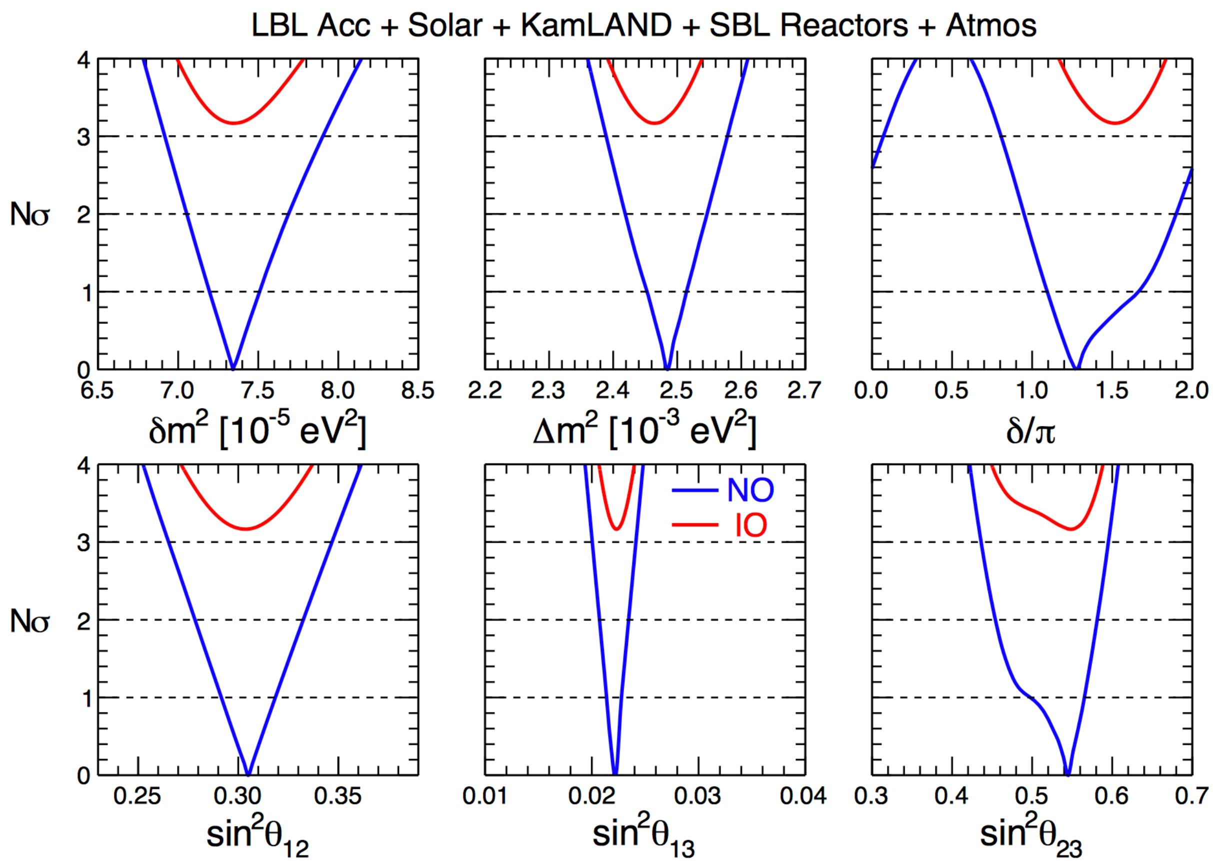


e→e (δm², θ12)
e→e (δm², θ12)
μ→μ (Δm², θ23)
μ→e (Δm², θ13, θ23)
e→e (Δm², θ13)
μ→μ (Δm², θ23)
μ→τ (Δm², θ23)
pp
7Be
pep
8B
Energy (keV)
Survival Probability
3-ν best-fit oscillation
Data - BG - Geo ν̄e
L0/Eν̄e (km/MeV)
MC Best-fit
oscillations
Reconstructed ν Energy (GeV)
d
Number of νe candidate events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

Example of global 3ν analysis [$N\sigma = \sqrt{\Delta\chi^2}$]

Five parameters measured; hints for CPV & NO

hep-ph 2003.08511



Indications on CPV and mass ordering recently weakened. For updates see:
Talk by A. Marrone (Bari group) at Neutel 2021 on 23 feb 2021, https://agenda.infn.it/event/24250
Global analysis by NuFIT group, hep-ph 2007.14792
Global analysis by Valencia group, hep-ph 2006.11237 v2

Beyond the standard 3ν framework

[motivated by theory/data, but no compelling evidence so far]

New (nonstandard) interactions *

- FCNC from four-fermion effective terms ~ $\varepsilon_{\alpha\beta}\, G_F$
- neutrino decay
- neutrino decoherence
- altered neutrino dispersion relations
- long-range interactions

...

New (sterile) neutrino states **

- light (~eV) steriles and related oscillations
- generic states perturbing 3x3 PMNS unitarity
- heavy neutral companions at higher scale

...

Global/partial data analyses exist also for NSI, steriles

* see Farzan & Tortola (review) hep-ph 1710.09360
** see Giunti & Lasserre (review) hep-ph 1901.08330

Interesting info (for 3ν and beyond) mostly encoded in oscillation probability $P_{\alpha\beta}$ that, however, is not an observable...

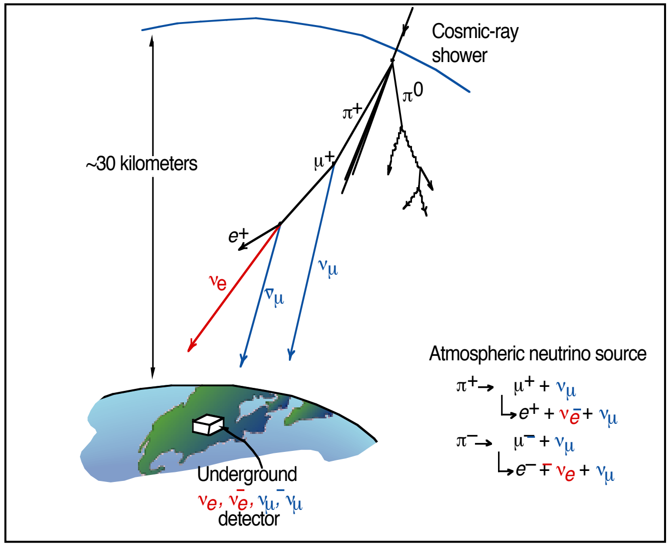
$$\mathbf{R}_\beta \sim \int \mathbf{\Phi}_\alpha \otimes \mathbf{P}_{\alpha\beta} \otimes \sigma_\beta \otimes \epsilon_\beta$$

Observable event rate	Source flux (production)	Propagation (flavor change)	Interaction and detection

→ need to account for many details + uncertainties in these (multi-dimensional) integrals w.r.t. data

A variety of open research problems for each integrand and each class of experimental data! Two selected cases →

Case study 1:
atmospheric neutrinos (natural beam)



Observables:

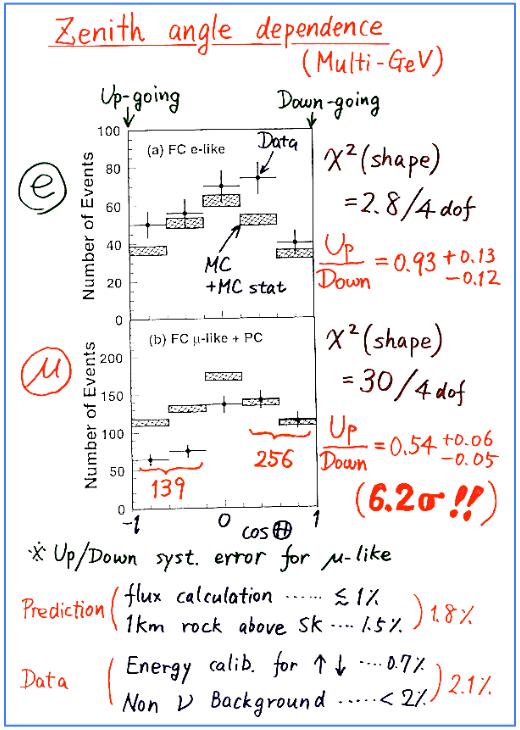
- zenith distribution of final-state $e^{\pm}$ and $\mu^{\pm}$ → loosely trace ν pathlength L
- $e^{\pm}$ and $\mu^{\pm}$ energy and/or event topologies → loosely trace ν energy E

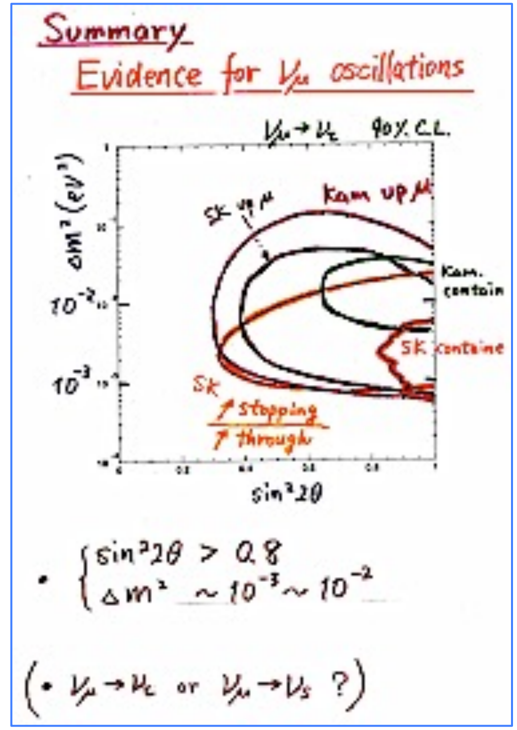
Strenghts:

wide L/E range probed; uncertainties reduced in up/down and μ/e ratios

1998: Nobel-worth discovery of oscillation effects

[Takaaki Kajita for Super-Kamiokande, slides at Neutrino ’98 conference]





Initial interpretation in terms of simple 2ν ($\nu_\mu \rightarrow \nu_\tau$) oscillations

How to reinterpret the SK data in wider scenarios (e.g., 3ν)?

Need to re-compute R_β with your own theory model for $P_{\alpha\beta}$!

$$\mathbf{R}_\beta \sim \int \mathbf{\Phi}_\alpha \otimes \mathbf{P}_{\alpha\beta} \otimes \boldsymbol{\sigma}_\beta \otimes \epsilon_\beta$$

Related issues and their evolution:

1) Unpublished detector info on efficiency/resolution in angle and energy.
"Solved" by private communications + info from detailed PhD theses

2) Undigitized or incomplete info on differential atmos. neutrino fluxes.
Solved by computer-readable outputs from dedicated atmos. simulations

3) Large uncertainties on low-E neutrino (differential) cross sections.
Some progress, but dedicated new measurements still needed (see later).

4) Your own R_β must reproduce SK ones for equal $P_{\alpha\beta}$ - within uncertainties.
Reasonable for many years, until the analysis became too complicated to be reproduced in test cases (outside the experimental collaboration)

Current SuperK analysis:

520 energy-angle bins

155 systematics ("pulls")

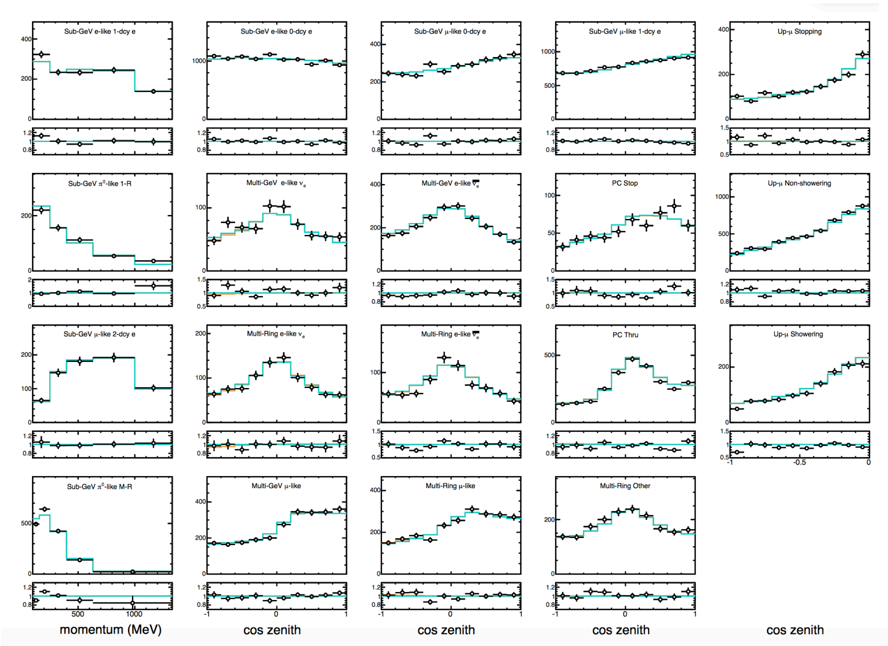
pull "explosion" mentioned by H. Prosper

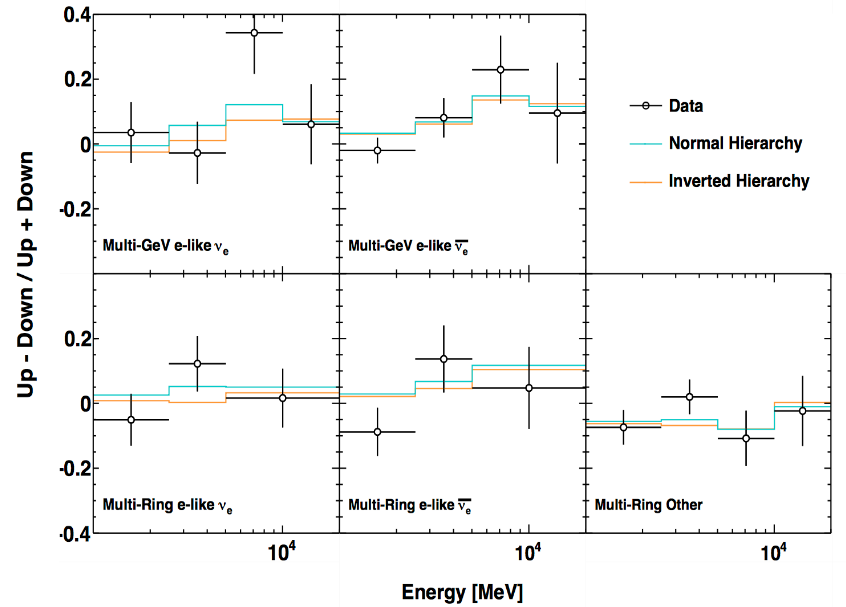
Subleading 3ν effects:

CPV and NO/IO differences

are small (no "distortion" by eye!)

cumulative effects; must avoid approximations





External analyses still OK to bound nonstandard effects (steriles, NSI), but no longer adequate to investigate the emergence of subleading 3ν effects.

Solution (2017): Public SK likelihood (χ^2) as a function of 3ν osc. parameters

Similarly policy adopted by IceCube (IC) for atmospheric neutrino data.

“Public likelihood” approach: OK, but...

From the user’s viewpoint:
feel like using a black box, and cannot extend to other models

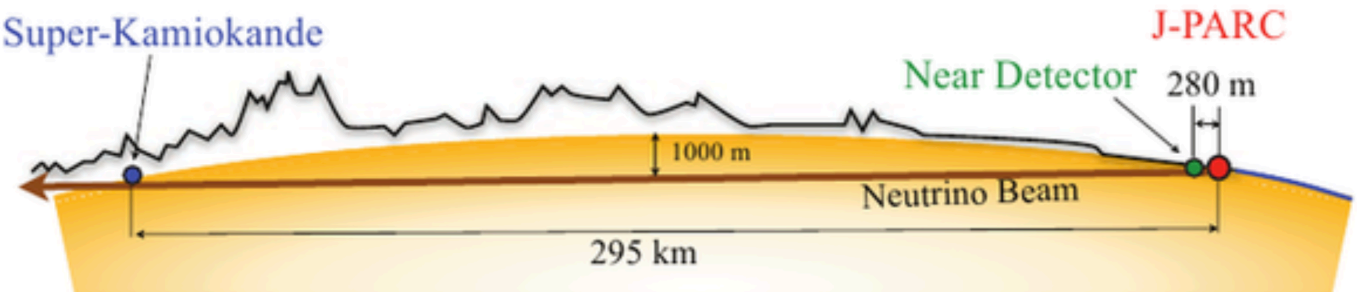
From the experimentalist viewpoint:
an additional burden to keep it updated with new data & inputs

From a general viewpoint:
the sum of two expt’s χ^2 does not account for common syst’s
(atmospheric fluxes, interaction cross sections) E.g. it was noticed that IC and SK tend to to pull flux normalizations in opposite ways.

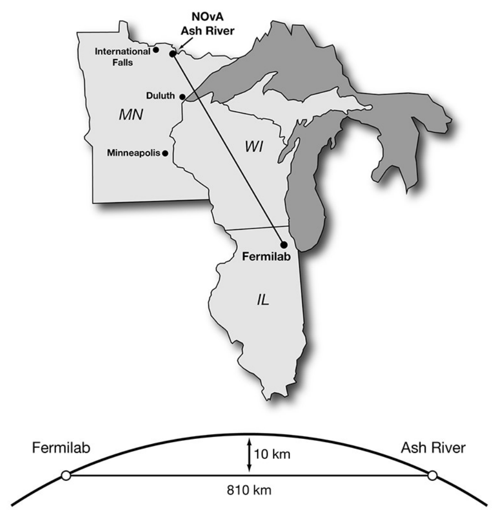
At least for 3ν, ideally, SK and IC should get together, adopt common input differential fluxes and cross sections + uncertainties, and perform a joint data analysis with combined SK+IC likelihood. Unlikely to happen: hard work with minor return in current physics. However, critical revision of inputs + joint data analyses might be needed in future high-statistics experiments planned underground (HK), underwater (KM3) and under-ice (IC upgrades)

Case study 2:
LBL accelerator neutrinos (man-made)

T2K



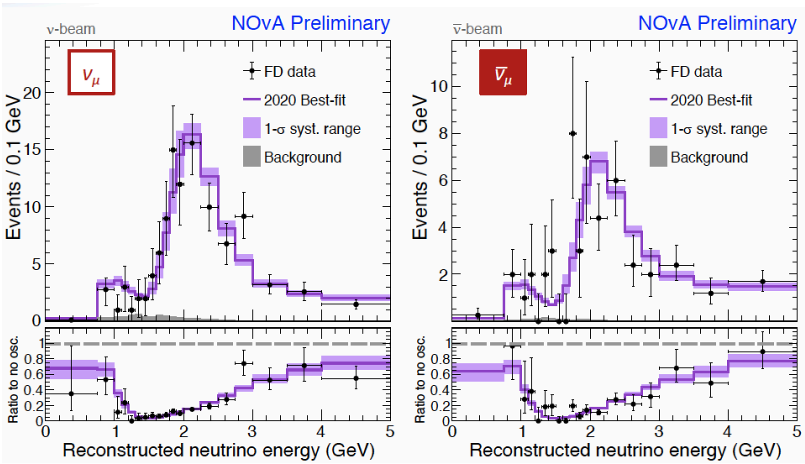
NOvA



L fixed, E ~ (sub)GeV, can switch $\nu_\mu/\bar{\nu}_\mu$ beam, use near/far detector calibration.
Sensitive to NO-IO (via matter effects) and to CPV δ in appearance mode $\nu_\mu \rightarrow \nu_e$

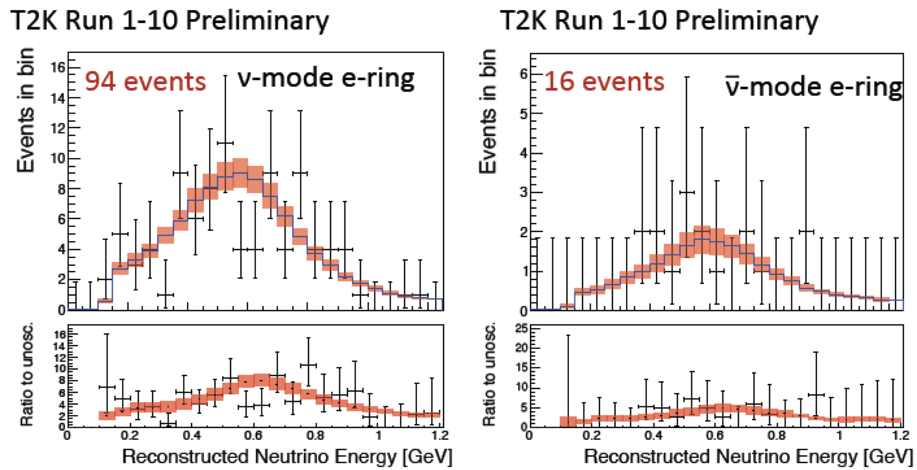
Examples of 2020 data: energy distributions

NOvA disappearance, probes Δm^2 , θ_{23}



(and similarly for T2K, not shown)

T2K appearance, probes NO/IO , δ



(and similarly for NOvA, not shown)

Note x-axis: not E_{lepton}, but reconstructed neutrino energy E_{rec}

possible mainly via CC quasielastic (QE) events

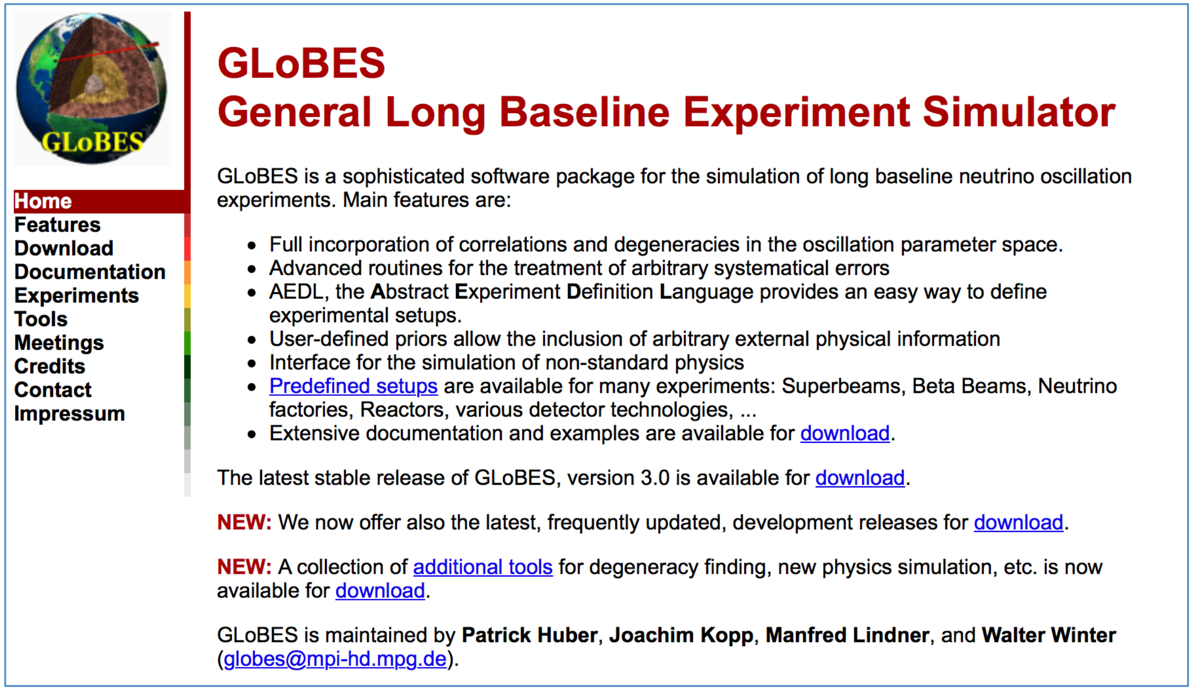
$$\nu + n \to l^- + p \qquad \text{or} \qquad \bar{\nu} + p \to l^+ + n$$

→ "migration matrices" or "resolution functions" $R(E_{true}, E_{rec})$

intended to make life simpler to external users

(map your theory predictions in E_{true} onto observables in E_{rec})

In addition, useful public software exist to simulate LBL accelerator experiments with good approximation



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GLoBES
General Long Baseline Experiment Simulator

GLoBES is a sophisticated software package for the simulation of long baseline neutrino oscillation experiments. Main features are:

- Full incorporation of correlations and degeneracies in the oscillation parameter space.
- Advanced routines for the treatment of arbitrary systematical errors
- AEDL, the **A**bstract **E**xperiment **D**efinition **L**anguage provides an easy way to define experimental setups.
- User-defined priors allow the inclusion of arbitrary external physical information
- Interface for the simulation of non-standard physics
- Predefined setups are available for many experiments: Superbeams, Beta Beams, Neutrino factories, Reactors, various detector technologies, ...
- Extensive documentation and examples are available for download.

The latest stable release of GLoBES, version 3.0 is available for download.

NEW: We now offer also the latest, frequently updated, development releases for download.

NEW: A collection of additional tools for degeneracy finding, new physics simulation, etc. is now available for download.

GLoBES is maintained by **Patrick Huber**, **Joachim Kopp**, **Manfred Lindner**, and **Walter Winter** (globes@mpi-hd.mpg.de).

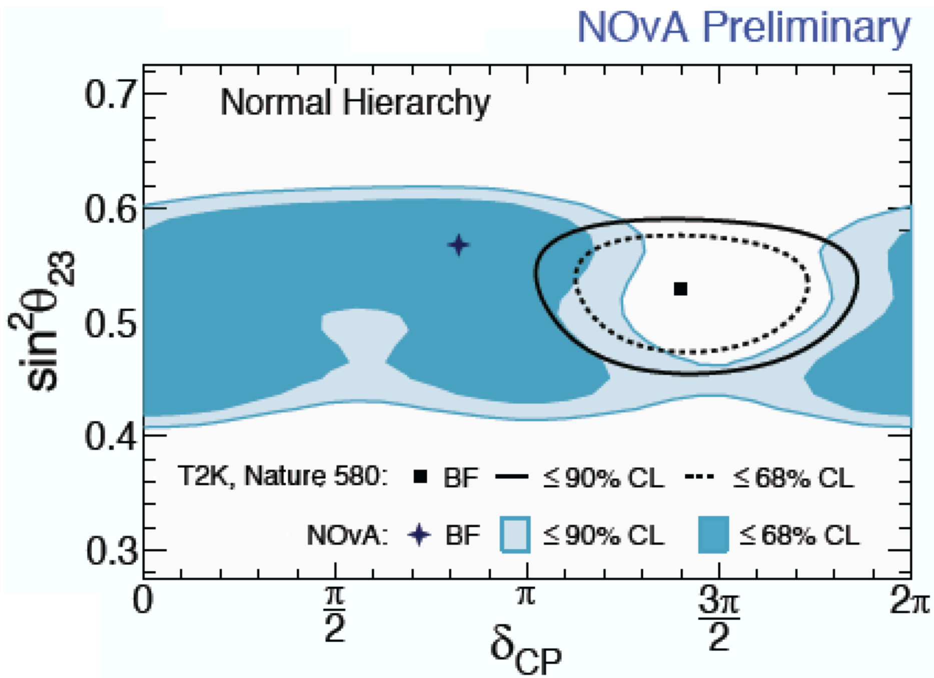
In principle, an ideal situation that has allowed many LBL data re-interpretations within 3ν and beyond (NSI, steriles, etc.)

[Also: T2K+NOvA might make a future joint 3ν data analysis]

But Nature is full of surprises... Current problem:

Tension between T2K and NOvA appearance data within 3ν.

Example: some disagreement on preferred CPV ranges



Ongoing discussion in the community...

Statistical fluctuations?

New physics beyond 3ν? (e.g., NSI over different L)

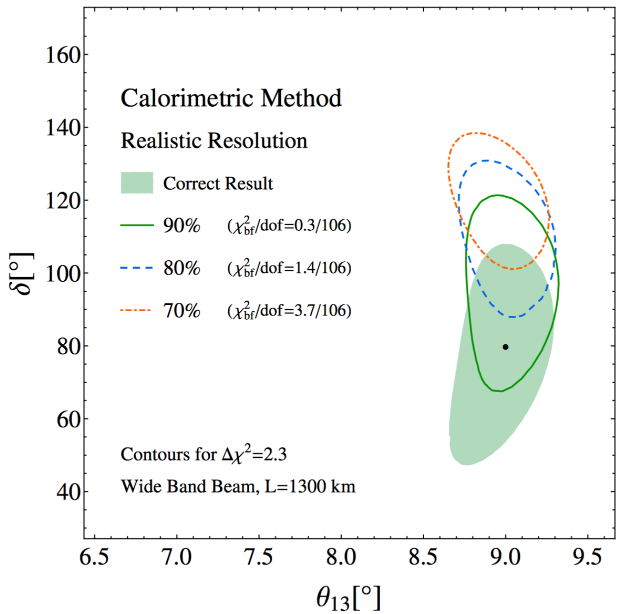
Systematics?

A potential systematic in the relation $R(E_{true}, E_{rec})$?

Intended to make life simpler... but it depends on **nuclear models** for neutrino interactions on nucleons/nuclei. Data too old or not adequate to current needs...

→ **tune nuclear models to near-detector (ND) data to reduce uncertainties.**

But: T2K tunes **NEUT model** to its ND, while NOvA tunes **GENIE model** to its ND.
Is a consistent interaction model emerging? *Note: External users cannot tune...*



In principle, biases in Erec may also bias CPV phase [← Benhar+ 1501.06448]

To be checked if this may play a role in T2K vs NOvA.
Need better understanding of ν – nuclear interactions!

EPILOGUE

There is a large and increasing amount of neutrino oscillation data, allowing for precision analyses of (non)standard neutrino scenarios.

Usually, published information is enough to allow re-interpretation of expt data by external users, unless you want to squeeze and claim subdominant effects from the data, rather than just get upper bounds.

In such cases, similar experiments might join forces and attempt combined data analyses, but there is still some resistance in doing so.

Public likelihoods or other tools (as migration matrices etc.) are useful to some extent, but may also hide systematics: it's not just matter of statistical or software tools, but also of underlying physics.

In may realms of neutrino physics, we need a better understanding of the nuclear response to EW probes (in ν production and detection)

→ emerging field of Electro Weak Nuclear Physics?

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THANK YOU FOR YOUR ATTENTION