Neutrino Oscillations:
some thoughts by a theorist

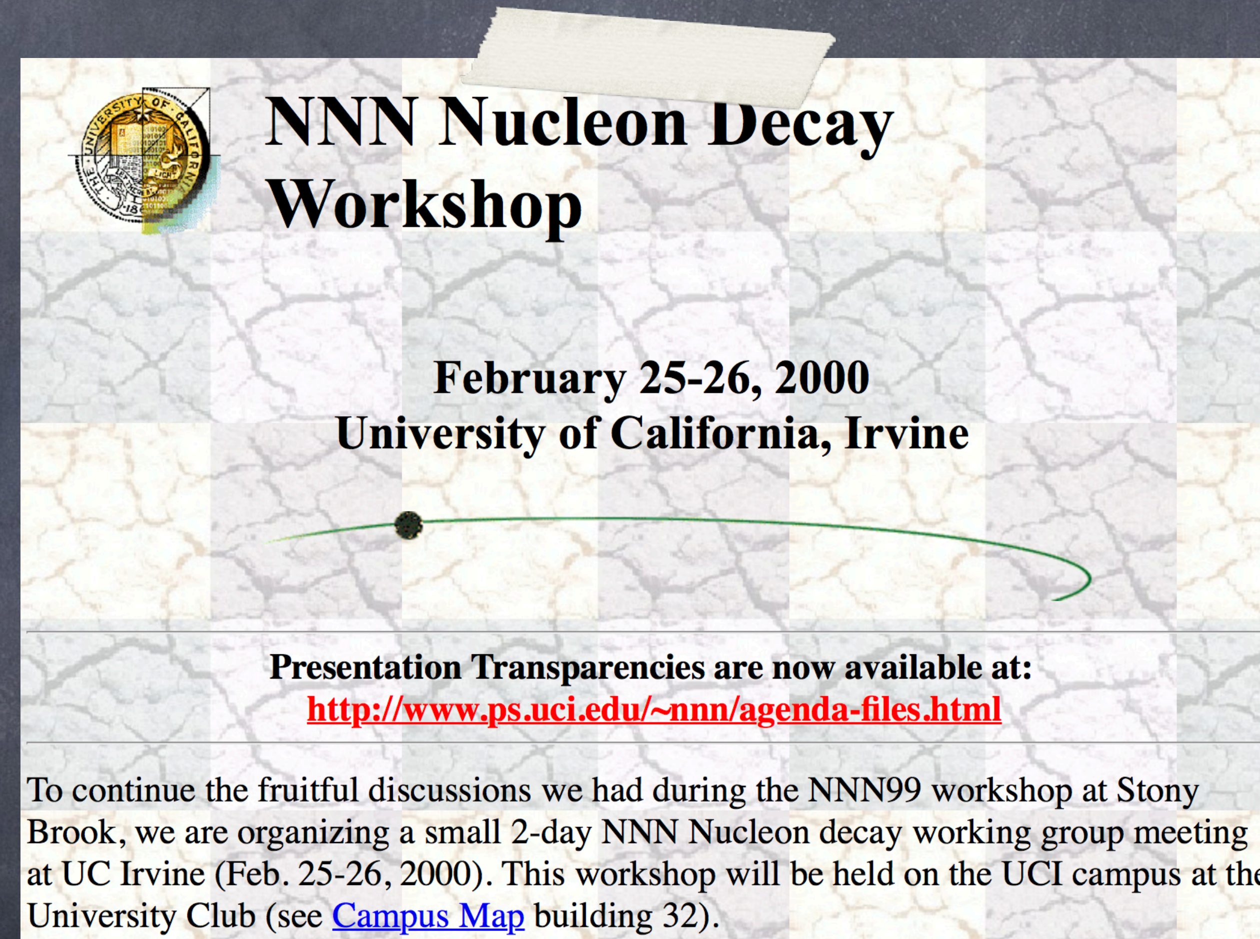
Alex Friedland
Theory group

SLAC NATIONAL ACCELERATOR LABORATORY

November 7, 2019

20th workshop in this series

- NNN 1999: Stony Brook
- NNN 2000: UC Irvine
- ....
- NNN 2018: University of British Columbia/ TRIUMPH
- NNN 2019: University of Medellin, Colombia



NNN Nucleon Decay Workshop

February 25-26, 2000
University of California, Irvine

Presentation Transparencies are now available at:
http://www.ps.uci.edu/~nnn/agenda-files.html

To continue the fruitful discussions we had during the NNN99 workshop at Stony Brook, we are organizing a small 2-day NNN Nucleon decay working group meeting at UC Irvine (Feb. 25-26, 2000). This workshop will be held on the UCI campus at the University Club (see Campus Map building 32).

It may be worth reflecting on
just how far we've come as a field
in the last two decades

Review of Particle Physics: R.M. Barnett *et al.* (Particle Data Group), Phys. Rev. **D54**, 1 (1996)

Massive Neutrinos and Lepton Mixing, Searches for

For excited leptons, see Compositeness Limits below.

See the Particle Listings for a Note giving details of neutrinos, masses, mixing, and the status of experimental searches.

No direct, uncontested evidence for massive neutrinos or lepton mixing has been obtained. Sample limits are:

ν oscillation: $\overline{\nu}_e \not\to \overline{\nu}_e$

$\Delta(m^2) < 0.0075\ \mathrm{eV}^2$, CL = 90% (if $\sin^2 2\theta = 1$)

$\sin^2 2\theta < 0.02$, CL = 90% (if $\Delta(m^2)$ is large)

ν oscillation: $\nu_\mu \to \nu_e$ (θ = mixing angle)

$\Delta(m^2) < 0.09\ \mathrm{eV}^2$, CL = 90% (if $\sin^2 2\theta = 1$)

$\sin^2 2\theta < 2.5 \times 10^{-3}$, CL = 90% (if $\Delta(m^2)$ is large)

PDG 1996

http://pdg.lbl.gov/1996/www_2ltab.ps

Let's pick a review lecture from that period

hep-ph/9810316

SLAC-PUB-7930

THE STANDARD MODEL AND WHY WE BELIEVE IT * †

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Stanford Linear Accelerator Center, Stanford, CA 94309

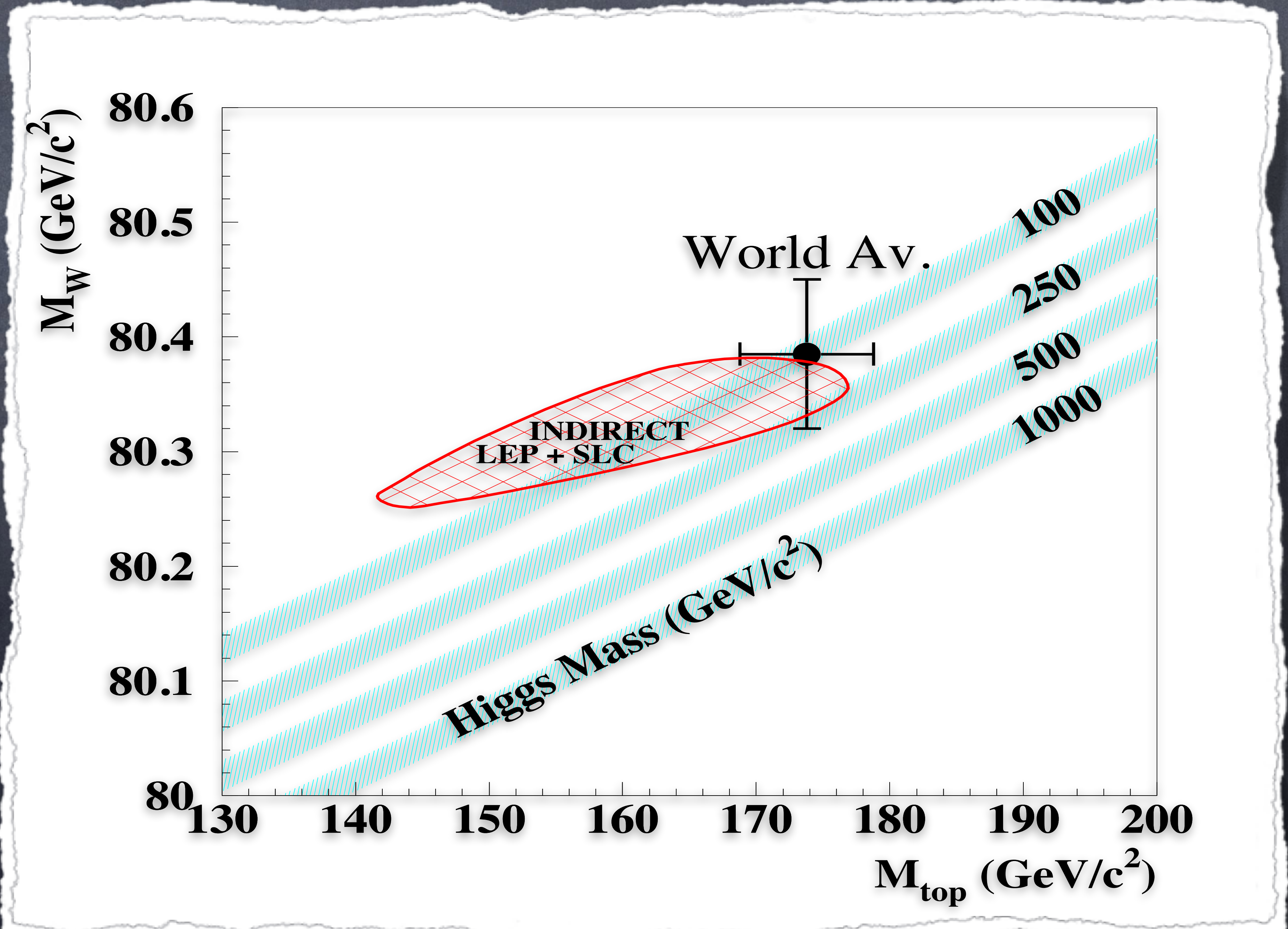
The principle components of the Standard Model and the status of their experimental verification are reviewed.

1 The Standard Model

The Standard Model (SM), which combines the $SU(2)_L \times U(1)_Y$ Glashow - Weinberg - Salam theory of electroweak interactions [1] together with Quantum Chromodynamics,[2] constitutes a remarkable achievement. The formulation of the theory as a renormalizable quantum theory preserves its predictive power beyond tree-level computations and allows for the probing of quantum effects. An array of experimental results confirm every feature of the theory to a high degree of precision, at the level of testing higher order perturbation theory. In fact, at present there are no compelling pieces of evidence that are in conflict with the SM. In these lectures I will review the components of the SM and the extent to which they have been tested.

SM was supported by lots and lots of high-precision data

Fig. 18



Big open questions circa 1998

- All aspects have impressive agreement with all experimental data

Despite these successes there remain a number of important questions which the SM does not address. These include:

- The fermion masses and mixings and the nature of CP-violation
- Neutrino masses and oscillations
- The number of generations

p. 5

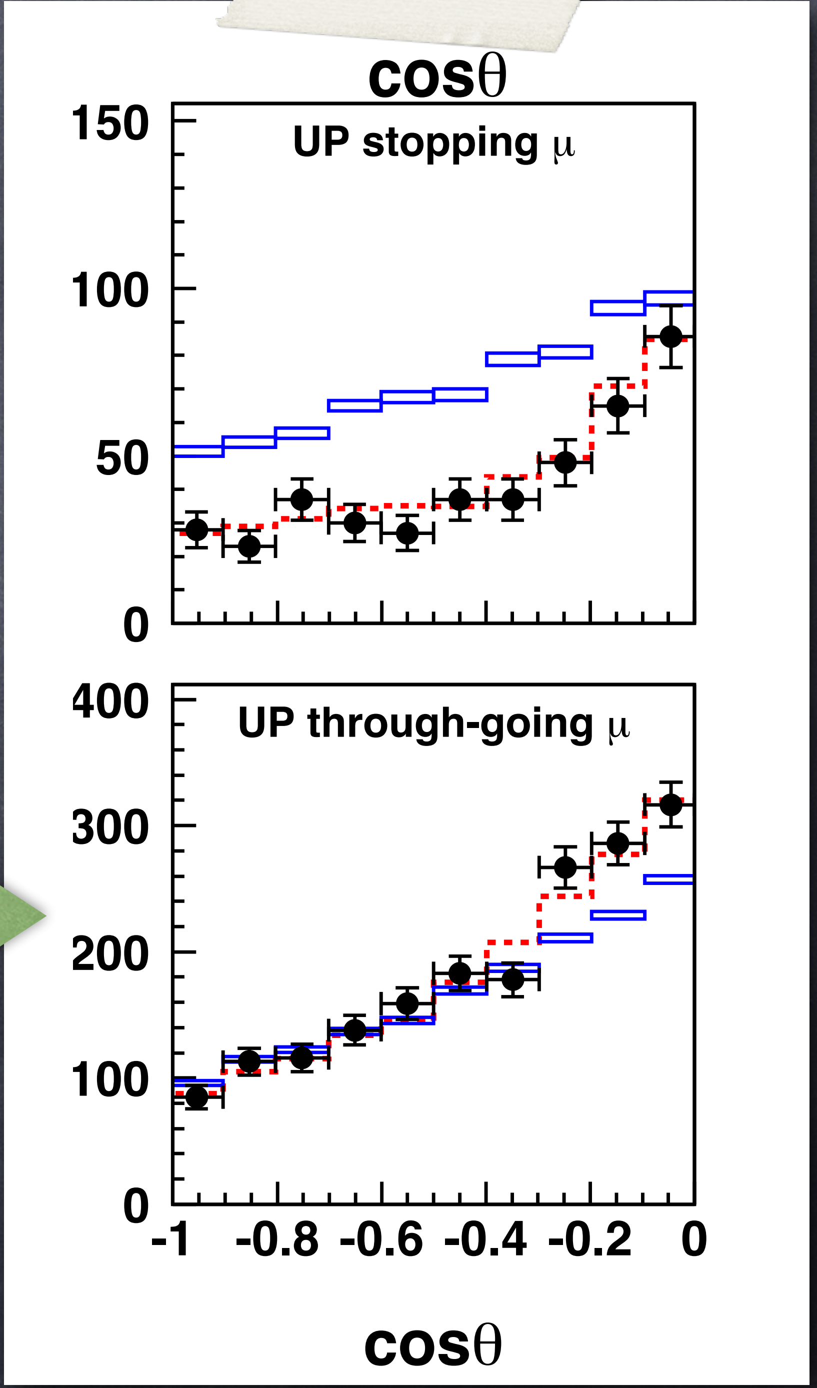
- Unification with the strong and gravitational forces
- Charge quantization, *i.e.*, why does $Q_e = -Q_p$
- Origin of dark matter
- Baryogensis
- Cosmological constant
- Why is spacetime 4 dimensional?

There is now rather convincing evidence that neutrinos have nonzero mass from the apparent observation of neutrino oscillations, where the neutrinos come from π (or K) $\rightarrow\ \mu \rightarrow\ e$ decays in the atmosphere; the mesons are produced in cosmic-ray cascades.

PDG 2000

http://pdg.lbl.gov/2000/lxxx_index.pdf

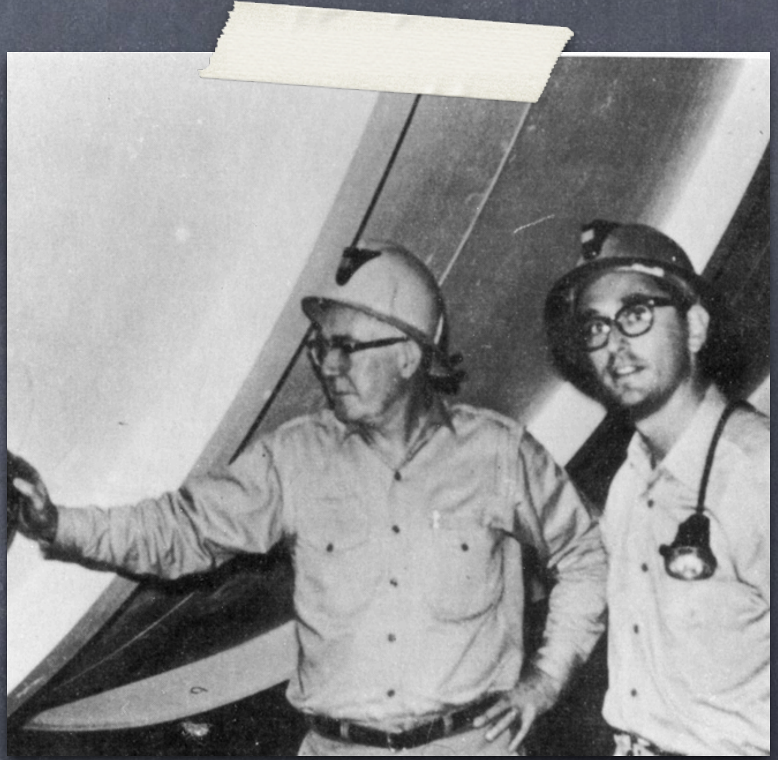
This is what discovery of New Physics looks like



The story of solar neutrinos

- A remarkable and very instructive tale
- The first neutrino oscillation effect was observed in 1968, at Homestake
  - 100,000 gallons of dry-cleaning fluid (tetrachloroethylene) 4,850 feet underground. Every few weeks, extracted Ar, formed by

$$\nu_e +^{37} Cl \rightarrow e^- +^{37} Ar$$



  - Expected ~ 51 atoms of Ar, but saw only ~ 17

BULLETIN BOARD

Volume 21, Number 36 | Published by the BNL Public Relations Office | September 14, 1967

9-1307-66

Solar Neutrinos Are Counted At Brookhaven

- http://www.bnl.gov/bnlweb/raydavis/BB_sept1967.pdf
- No mention of oscillations
- Nobody rushes to repeat this measurement for the next two decades

The theoretical forecast had led scientists to believe that the neutrino emission from the sun would allow from 1.5 to 5 neutrino captures per day. In the single experiment performed to date, Dr. Davis reports that the capture rate in the underground tank was less than 2 neutrinos per day. Knowing this plus the efficiency of neutrino capture allowed Dr. Davis and his group to calculate the flux from the Boron-8 decay to be approximately 60 million solar neutrinos per square inch per second at the earth's surface. Previous calculations had predicted the flux could be anywhere from 40 million to 150 million solar neutrinos per square inch per second at the earth's surface.

MSW, 1985-86

- Mikheev and Smirnov solved the evolution equation in the solar density profile, originally written by Wolfenstein
- Found large conversion possible for small vacuum mixing
- The paper is originally rejected
- They attempt repackaging in the supernova neutrino context, bury the word "resonance"
    - see arxiv:0706.0454

Comments (June 2007)

1. This paper presents, in particular, our first analytic results on the adiabatic conversion of neutrinos in matter. It has been written in summer-fall 1985. In attempt to avoid problems with publication (we had before), we tried to hide the term "resonance", and did not discussed applications to the solar neutrinos; also we have not included references to our previous papers on the resonance enhancement of neutrino oscillations.

This short paper has been submitted to JETP Letters in the fall 1985 and successfully ... rejected. It was resubmitted to JETP in December of 1985. The results of the paper have been reported at the 6th Moriond workshop in January 1986 and included in several later reviews. The paper was reprinted in "Solar Neutrinos: The first Thirty Years", Ed. J. N. Bahcall, et al., Addison-Wesley 1995.

Parts of the HEP community remained skeptical

- Georgi & Luke, Nucl Phys B347, 1-11 (1990)

Most likely, the solar neutrino problem [1] has nothing whatever to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of B^8 neutrinos coming from the sun as well as they do, to within a factor of 2 or 3 [2]. However, one aspect of the solar neutrino data, the apparent modulation of the flux of solar neutrinos with the sun-spot cycle, is certainly

- Other quotes in Bahcall, physics/0406040

Solar neutrinos, circa NNN'2000

- A number of solutions possible, with masses and mixing angles spanning orders of magnitude

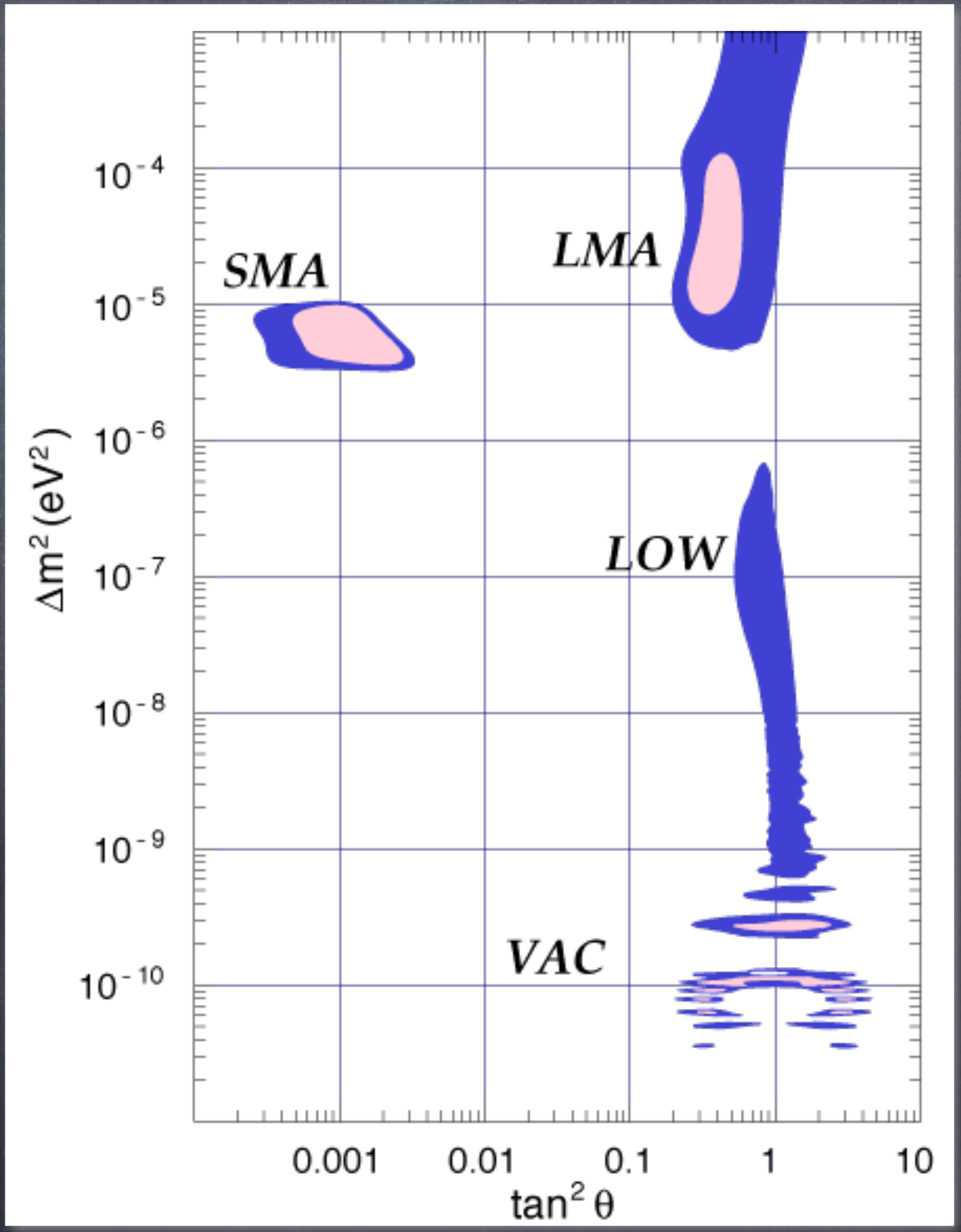
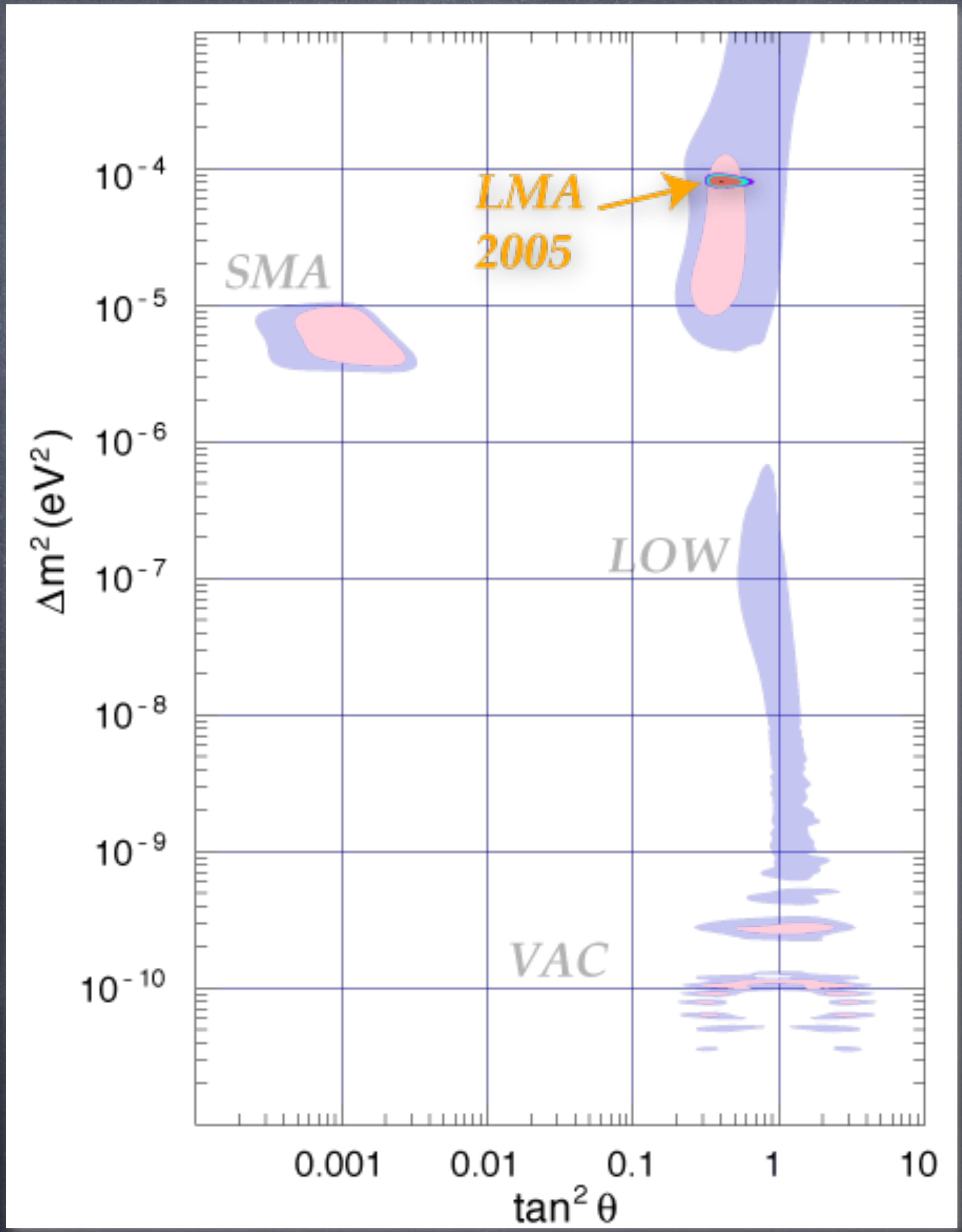


Figure from
A. de Gouvea, A.F., H. Murayama, PLB 490, 125 (2000)

And by 2005

- KamLAND+SNO+Super K+Homestake+GALLEX /SAGE
- KamLAND constrains Δm^2, while the angle θ_{12} is better constrained by the solar data

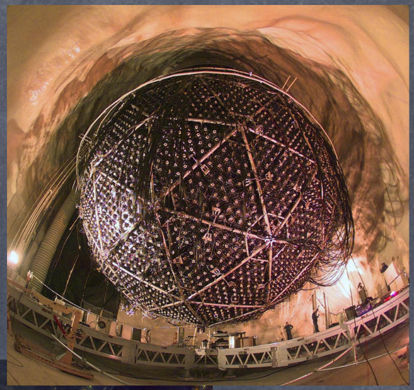


KamLAND Collab., PRL 94, 081801 (2005)
SNO Collab., PRL 92, 181301 (2004)

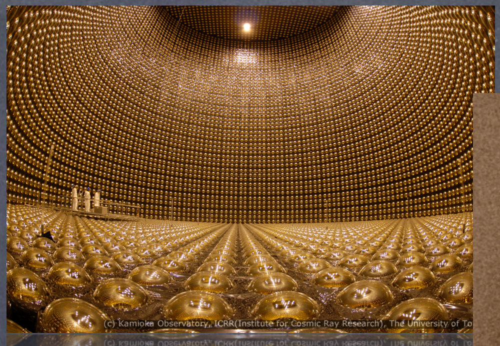
Tremendous progress since

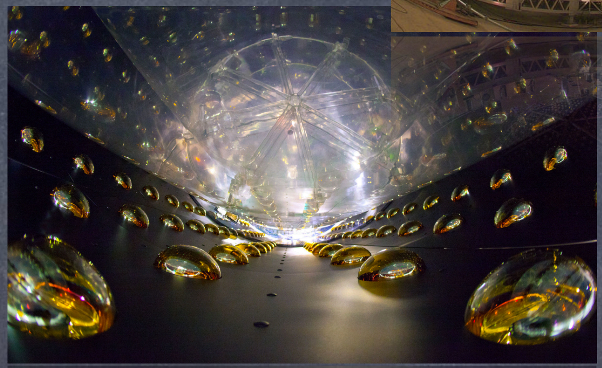
FUNDAMENTAL PHYSICS
BREAKTHROUGH
PRIZE

SNO



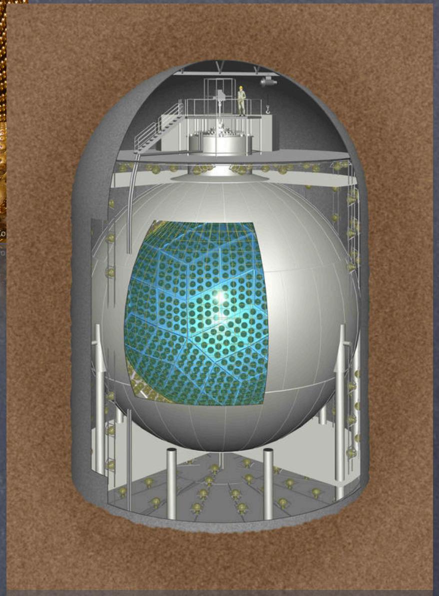
Super-K





Daya Bay

T2K



KamLAND

- Every year, there have been important experimental developments in the field
- E.g., θ_{13}: from unknown to best-measured in a blink of an eye, with major implications from the long-baseline program to supernova neutrinos
- IceCUBE UHE neutrinos, CMB/LSS data, SBL surprises, cross sections, coherent NC …

What's so special about neutrino masses?

From the experimental point of view, neutrinos are absurdly light and, moreover, interact only through the weak force

We can't slow them down to weigh at our leisure

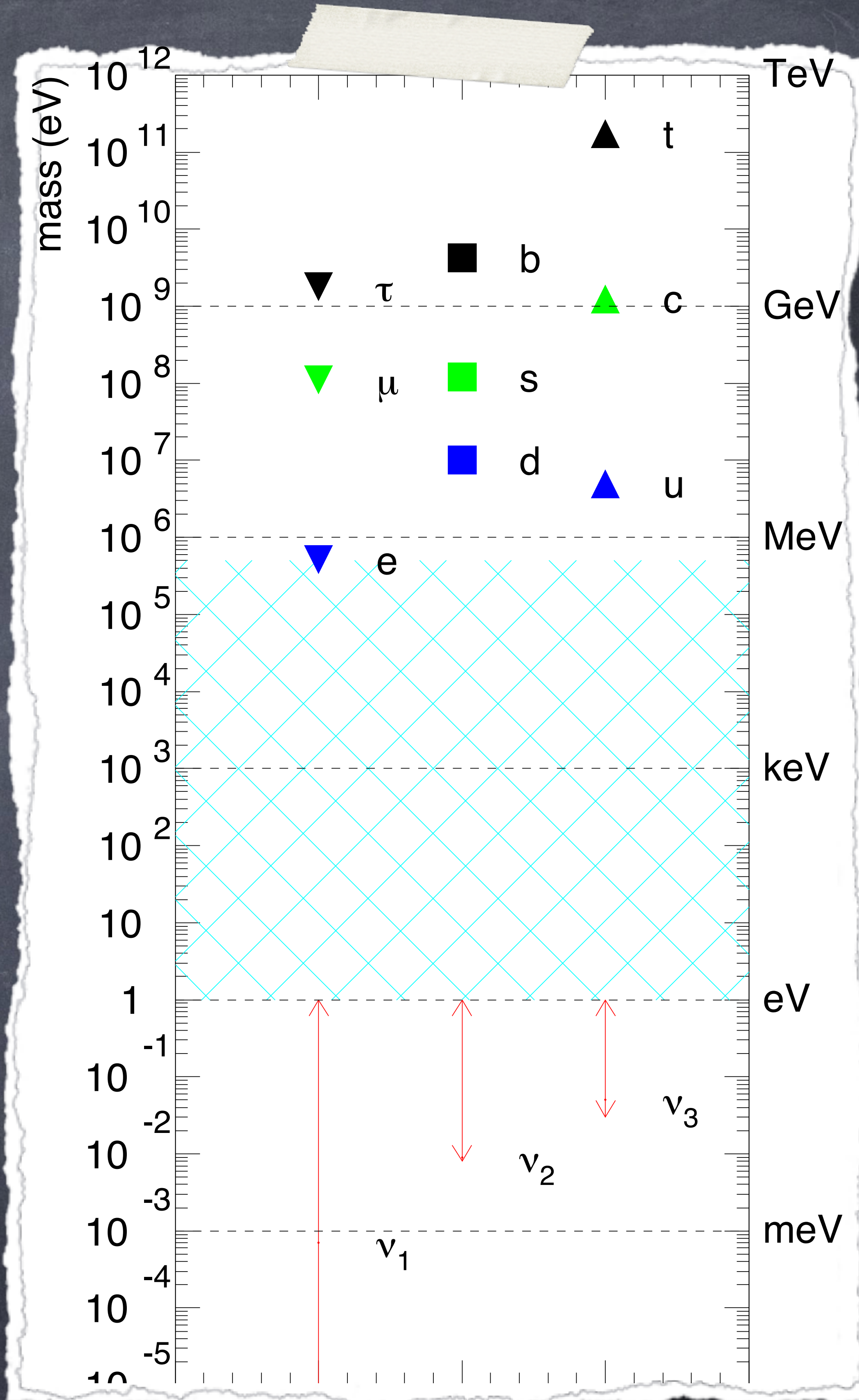


Figure credit: A. de Gouvea

Unusual masses call for unusual methods

- Measure endpoint spectra of a beta decay EXTREMELY accurately
  - beta-decay of tritium; Katrin
- Look for lepton number violation (caused by Majorana mass terms)
  - Neutrinoless double-beta decay; (n)EXO, Majorana, GERDA, KamLAND-Zen, SNO+
- Slow neutrinos down by redshift; use gravity for detection
  - cosmology; CMB, LSS, lensing
- Use interferometry
  - oscillation experiments; reactor, accelerator beams, solar, atmospheric, supernova

From the theoretical point of view

- Most people would bet neutrinos are probably Majorana (seesaw). One cannot just write down a "bare" Majorana mass term, gauge invariance requires that it come from a dim-5 operator
    - (LH)(LH)/Λ-> νν<v>^{2} /Λ
    - Weinberg in the 1970s noted that this is the only possible dim-5 operator; beyond dim 5, lots more stuff

$$\bar{L}\sigma^{\mu\nu}W^{\mu\nu}He_R, \;\; \bar{L}H\sigma^{\mu\nu}W^{\mu\nu}LH, \;\; (LL)q_Rq_R, \;\; ...$$

- That's already profound: neutrino physics is in a position where the GUT physics would have been had we discovered proton decay
    - finally, a nonrenormalizable operator; a message from new physics at a very high scale, violating accidental symmetry of the SM; this new scale could explain our origin (leptogenesis)

Yet, it can be even more interesting

- Implicit in the power-counting logic is the belief that the nearest scale of new physics Λ is extremely high
- Upon accepting such belief, one may want to stop doing most of the experimental particle physics
  - with the possible exception of nucleon decay searches and
  - searches for other dim 5 operators, e.g., axion $aF\tilde{F}$
- If, on the other hand, new physics is at, or below, ~10 TeV, other high-dimension operators come into play

Light new physics?

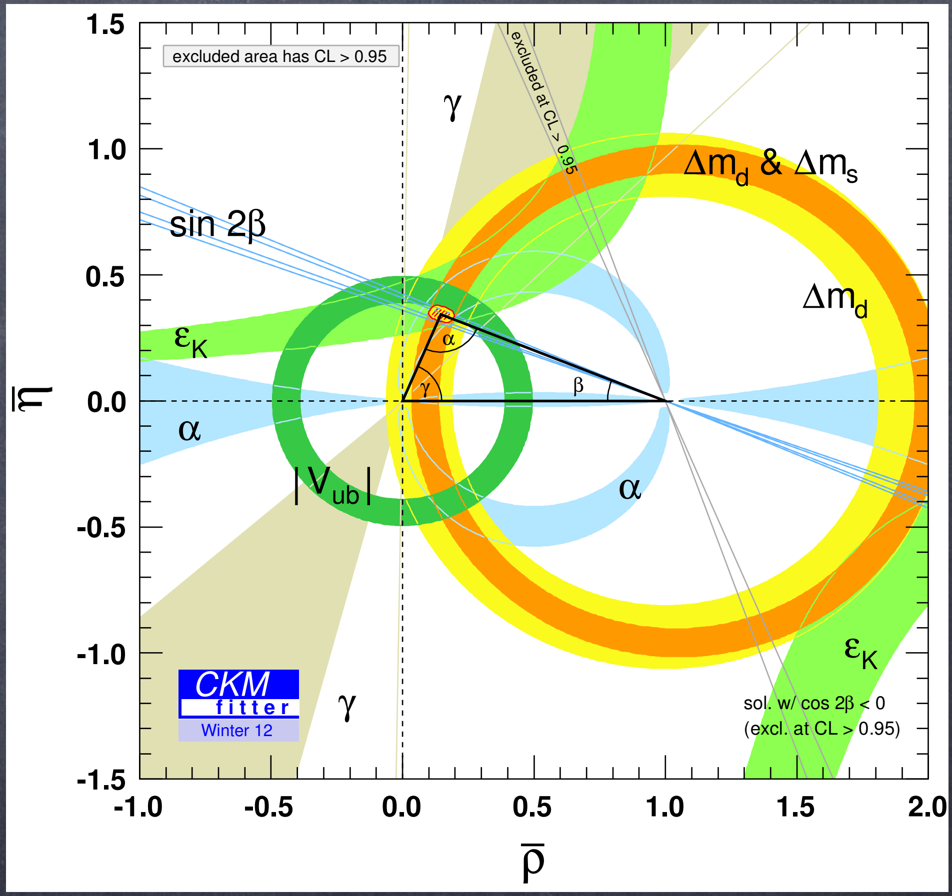
- In the extreme case, new physics could be light, right under our nose, just extremely weakly coupled
- We already search for it everywhere we can, we should definitely look in the place where we found physics beyond the Standard Model
  - Light right-handed neutrino partners
  - Light DM/Dark sectors
  - Hidden neutrino interactions
  - …
- It's an experimental question

SM model works much better that it should

- On the one hand, Nature should have no unprotected masses
  - All unprotected masses stay at the scale of new physics by loop corrections
  - It's gratifying that besides the Higgs all other elementary particles have protected masses
- On the other hand, every possible higher-dimensional operator we are sensitive to is just not there!
  - besides neutrino masses
- We don't know what this means; we've been humbled by Nature

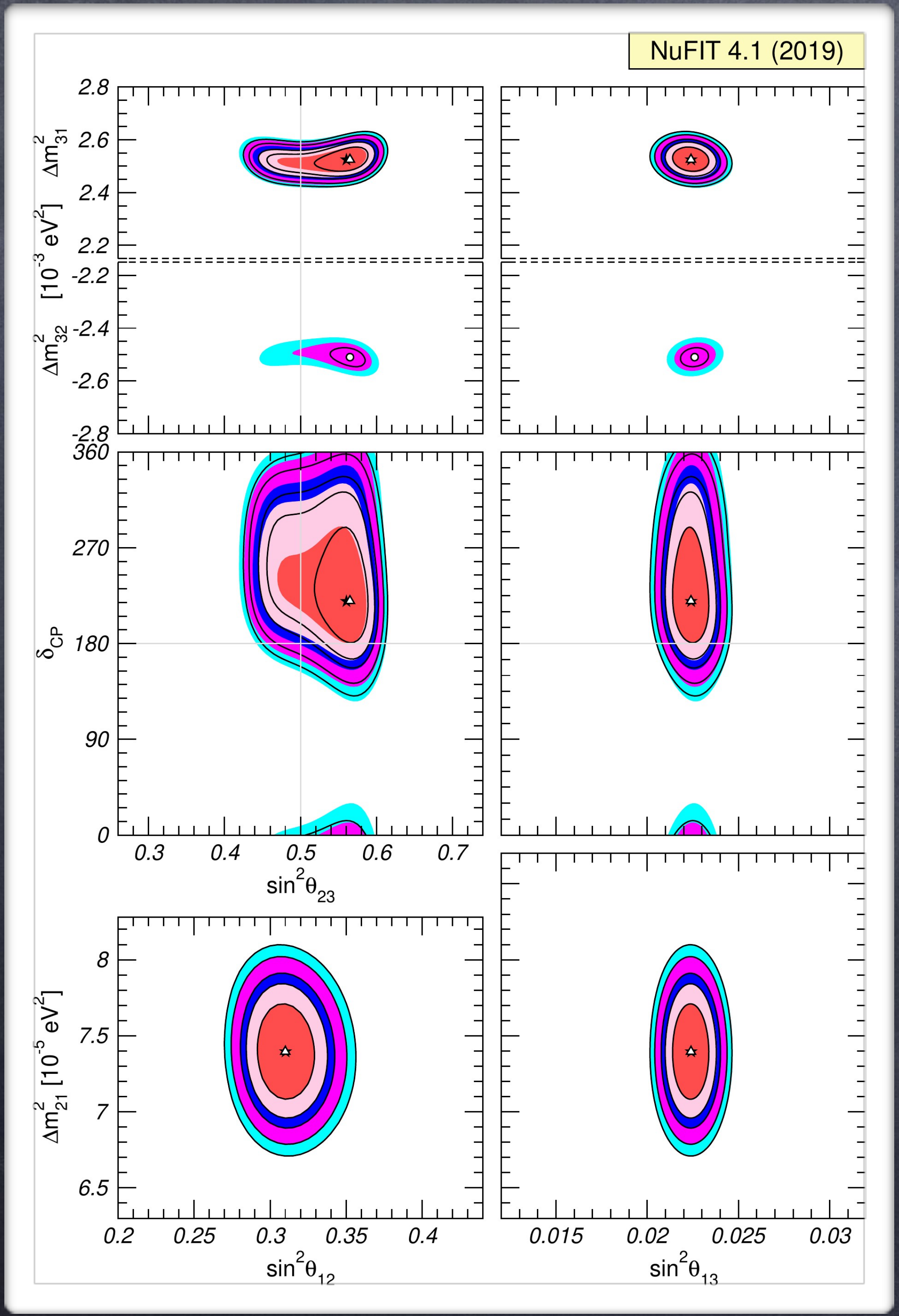
Why is the SM so successful?

- The strategy should be to cast your net wide and look for possible new effects everywhere
- In the case of neutrinos, this means overmeasure and overconstrain the sector to look for more new physics
  - That's what we are doing!



Need something like this for the neutrino sector

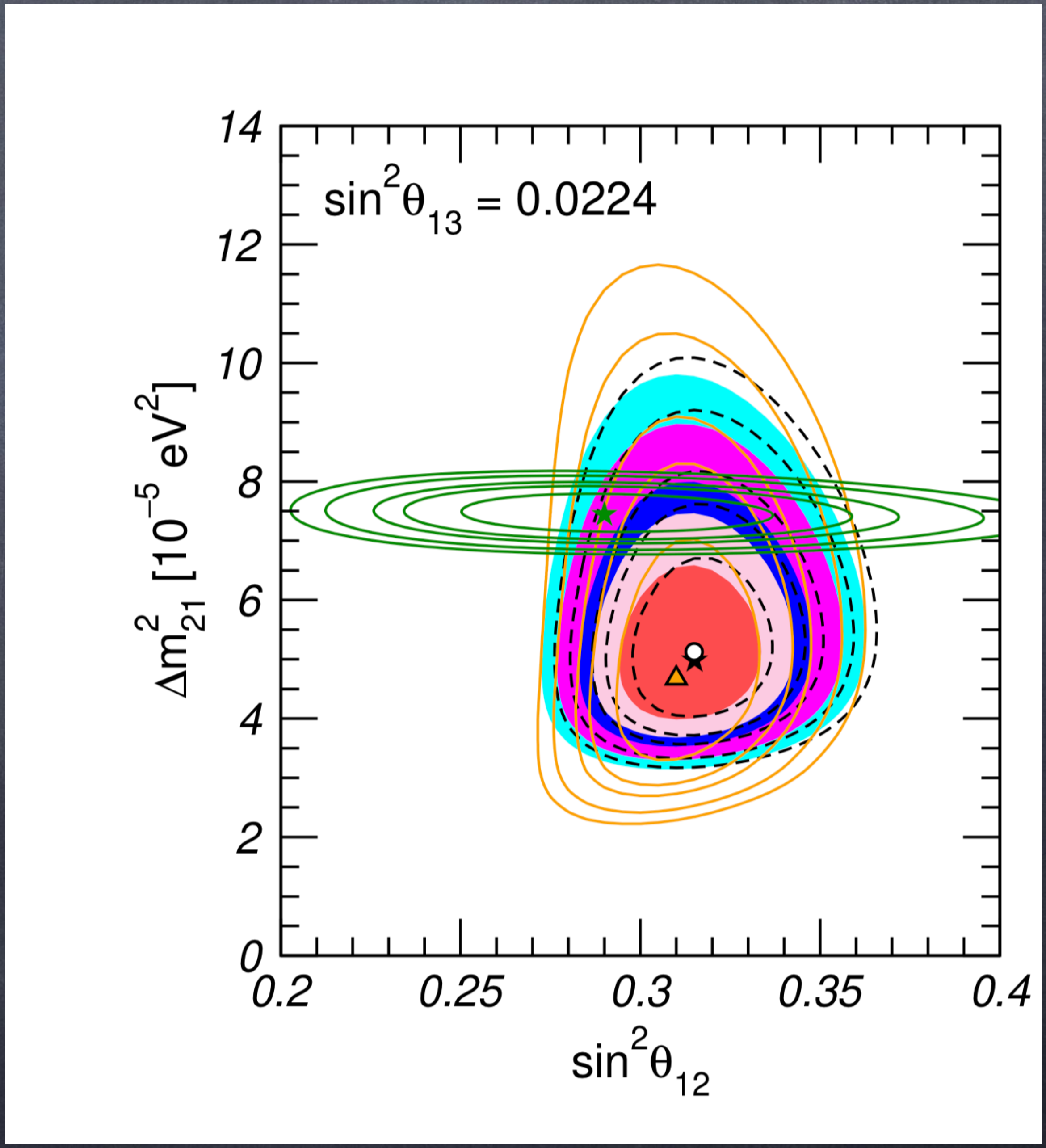
What do we know today?



[Experimental results compiled by NU-FIT arXiv:1811.05487]()

Behind each chi2 panel there is an interesting physics story

- For example, solar vs KamLAND
- KamLAND spectrum dips measure Δm^2_{12} well
- With this value, one expects an upturn in the solar neutrino spectrum at low energies at SNO/SK4
- Also, D/N asymmetry observed in SK is larger than expected from KamLAND



New physics? NSI effects on solar neutrino spectra, D/N signal long known

hep-ph/0402266 and many others

where level jumping can take place is narrow, defined by $A \simeq \Delta$ [21]. A neutrino produced at a lower density evolves adiabatically, while a neutrino produced at a higher density may undergo level crossing. The probability P_c in the latter case is given to a very good accuracy by the formula for the linear profile, with an appropriate gradient taken along the neutrino trajectory,

$$P_c \simeq \Theta(A - \Delta) e^{-\gamma(\cos 2\theta_{\rm rel}+1)/2}, \tag{12}$$

where $\Theta(x)$ is the step function, $\Theta(x) = 1$ for $x > 0$ and $\Theta(x) = 0$ otherwise. We emphasize that our results differ from the similar ones given in [5,22] in three important respects: (i) they are valid for all, not just small values of α (which is essential for our application), (ii) they include the angle ϕ, and (iii) the argument of the Θ function does not contain $\cos 2\theta$, as follows from [21]. We stress that for large values of α and $\phi \simeq \pi/2$ adiabaticity is violated for large values of θ.

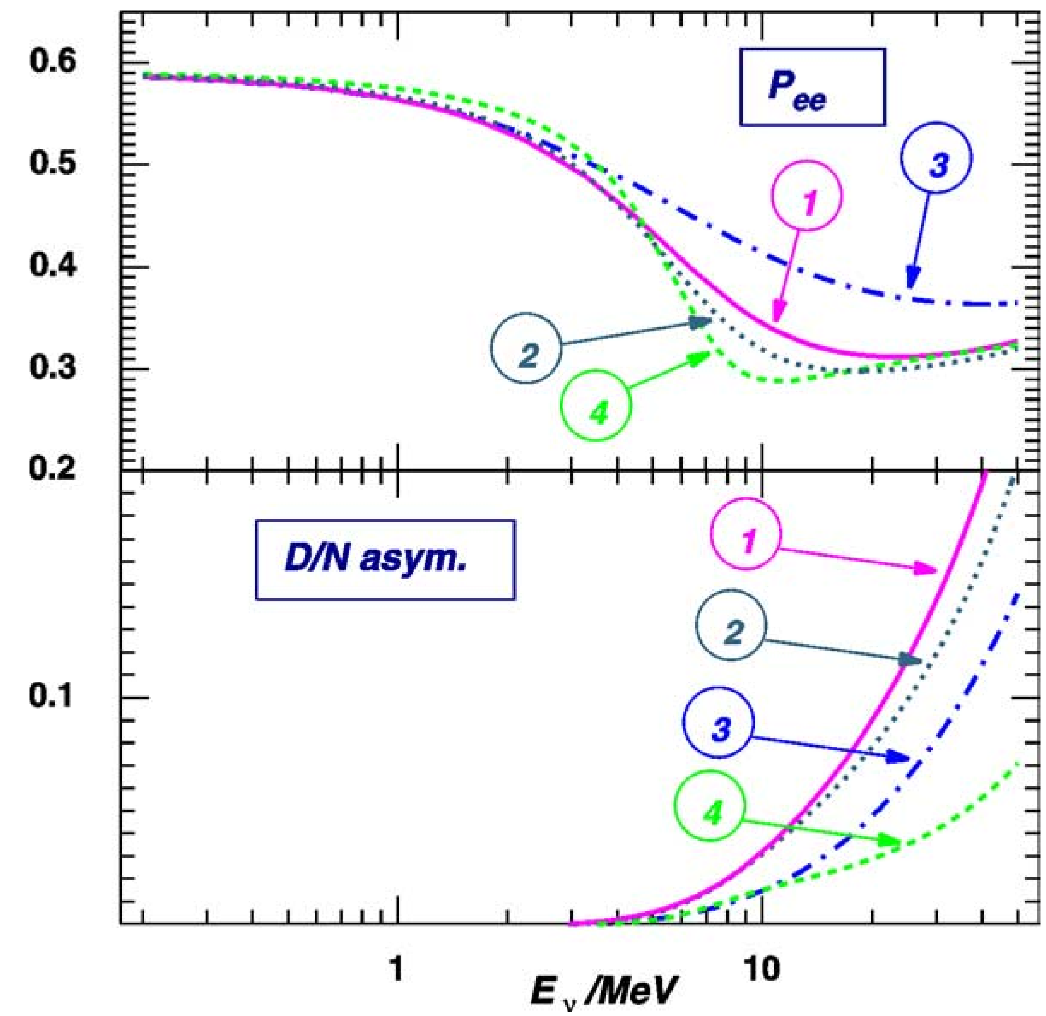
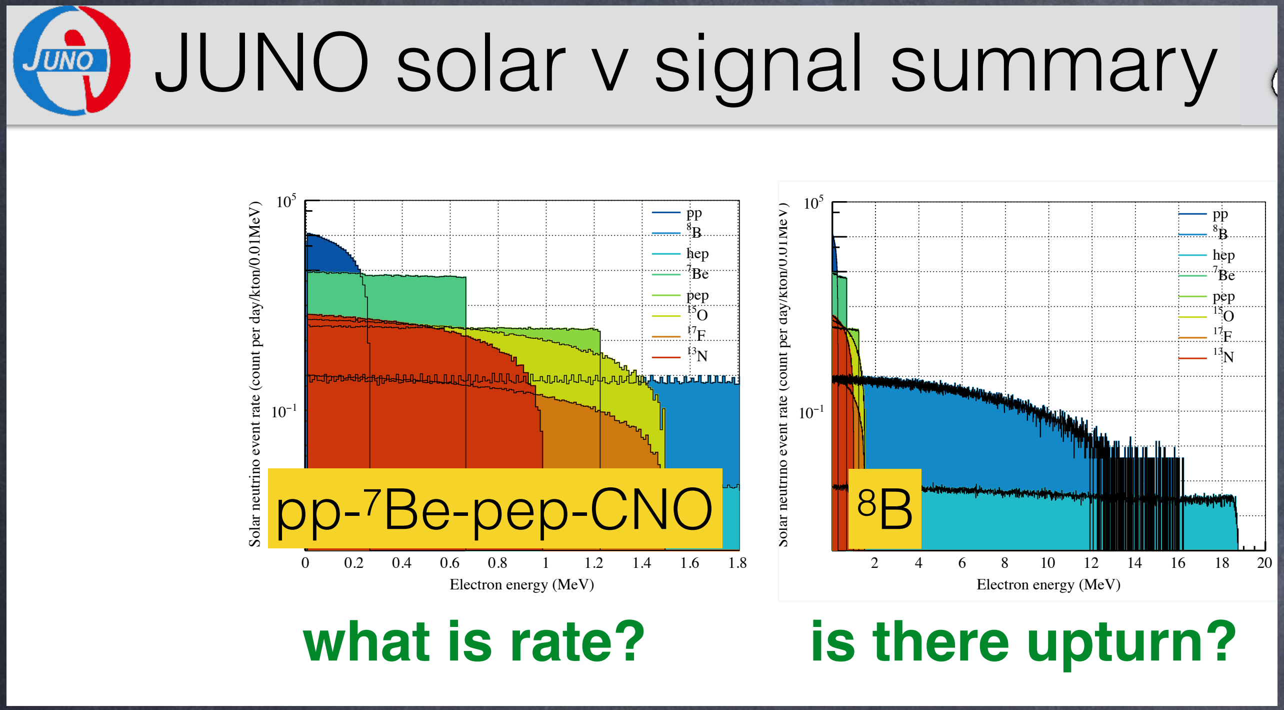


Fig. 1. The electron neutrino survival probability and the day/night asymmetry as a function of energy for $\Delta m^2 = 7 \times 10^{-5}$ eV^2, $\tan^2\theta = 0.4$ and several representative values of the NSI para-

JUNO and COHERENT give us brand new tools to address this problem!

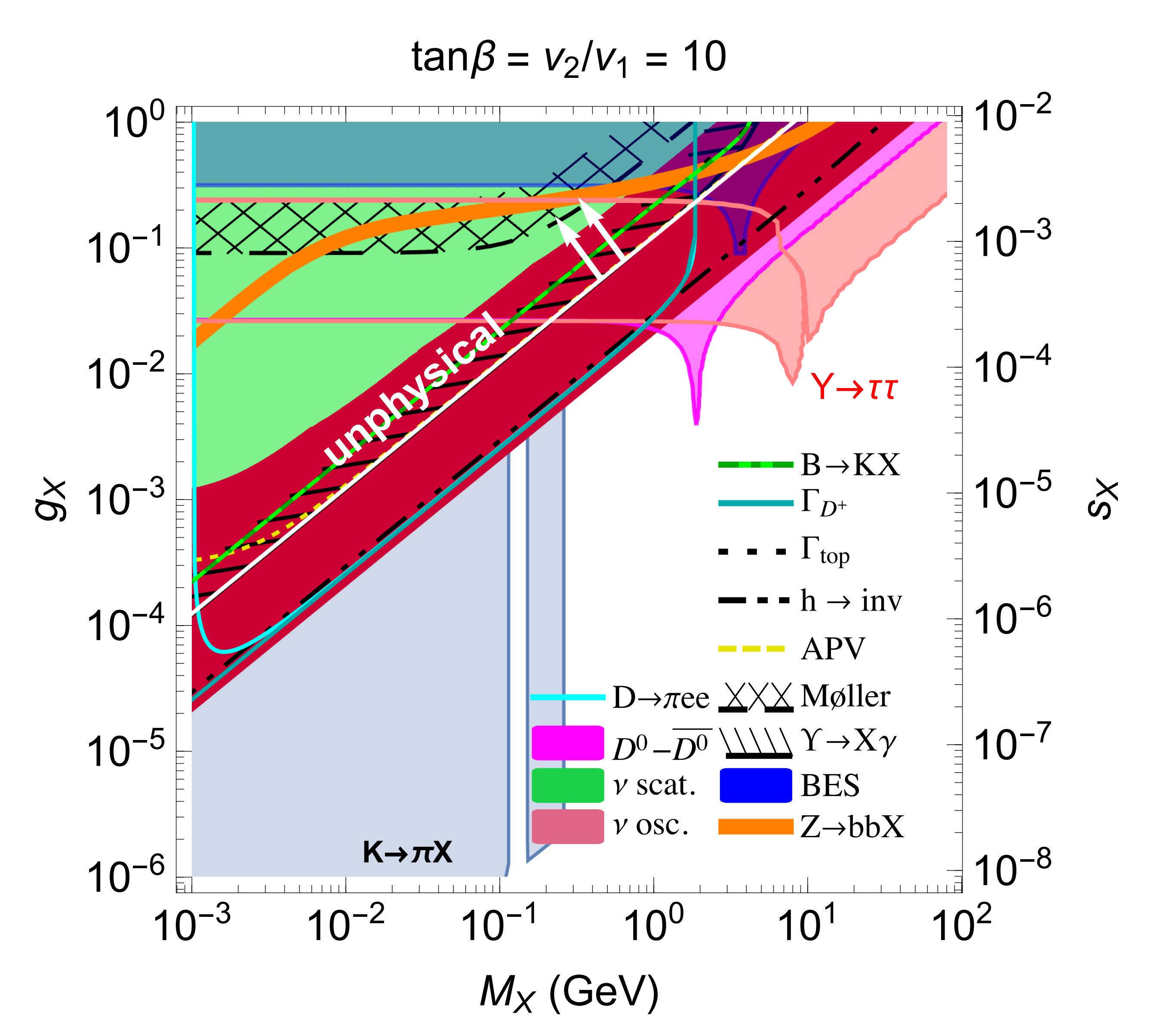


Slide from Xuefeng Ding on JUNO

Slide from Phil Barbeau on COHERENT

From the theoretical point of view, BSM physics requires a global study

- Example New Physics scenario: weakly gauging 3rd generation
- flavor physics below the Fermi scale
- Dozens of constraints!
  - From rare meson decays to atomic parity violations, to NSI oscillation effects
- Neutrino physics is intertwined with the rest of the field



See K.Babu, A. F., P. Machado, I. Mocioiu, arXiv:1705.01822 for details

The 23-sector

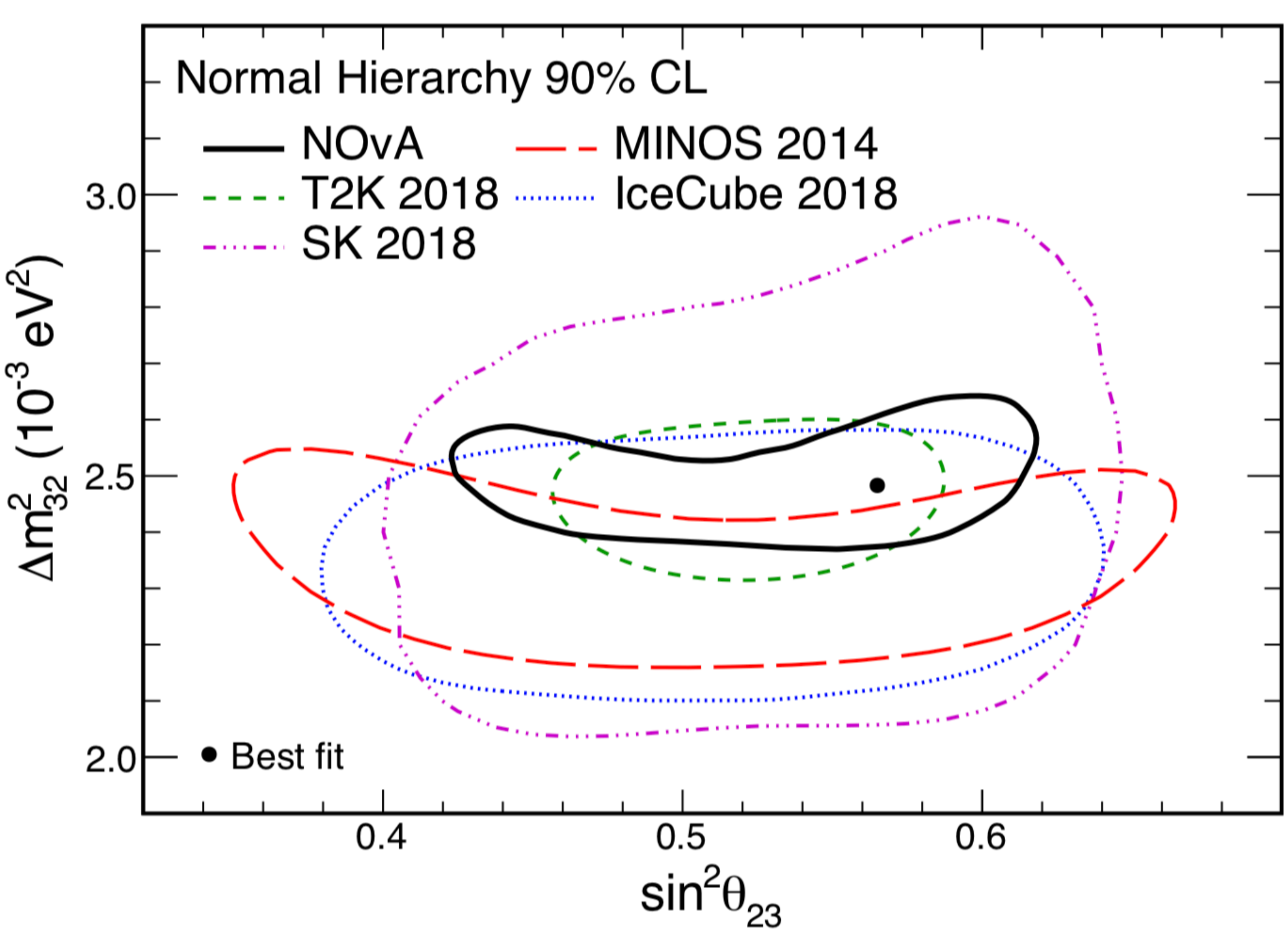
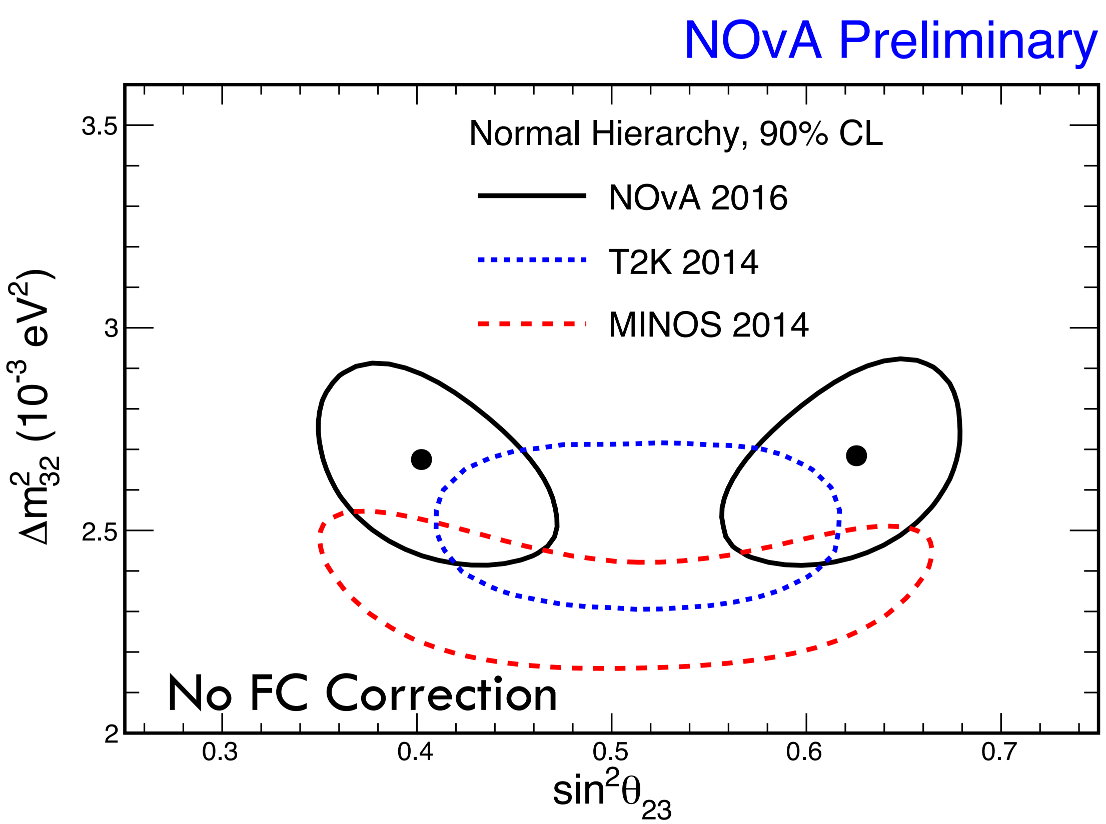
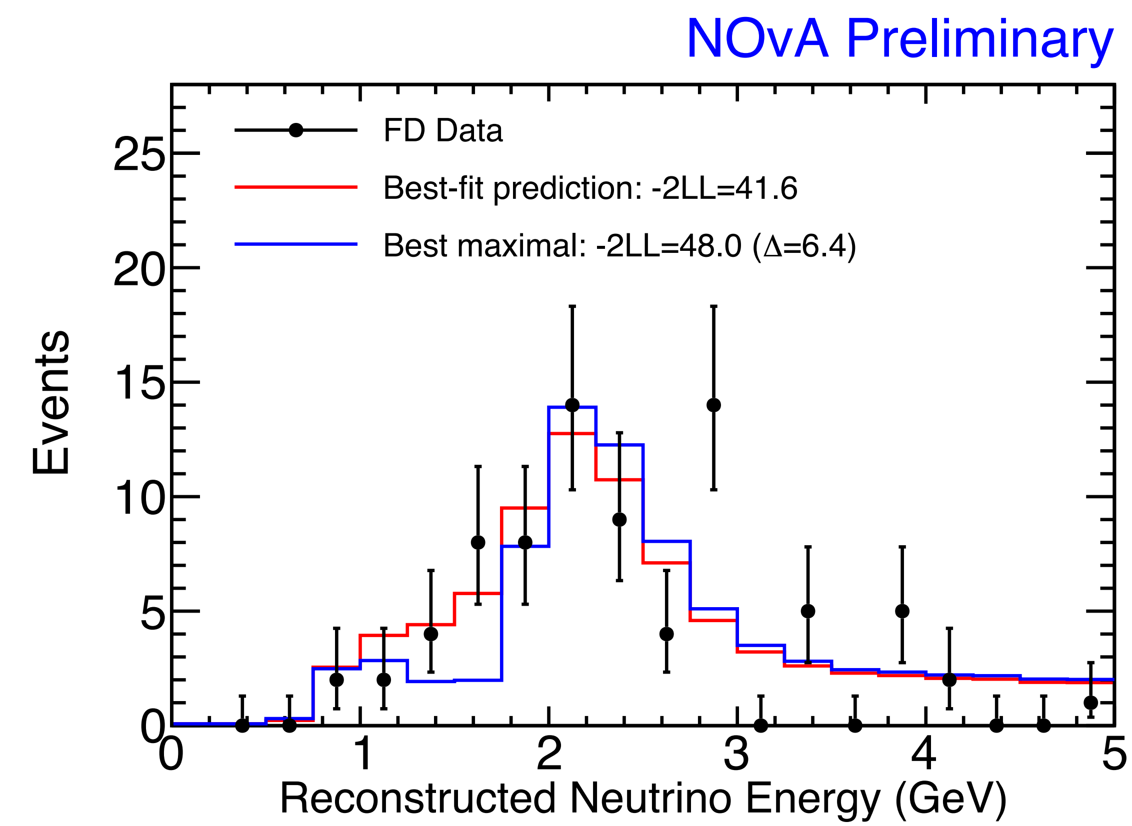


Figure from NOvA, arXiv:1906.04907

NOvA at Neutrino 2016





Best Fit (in NH):

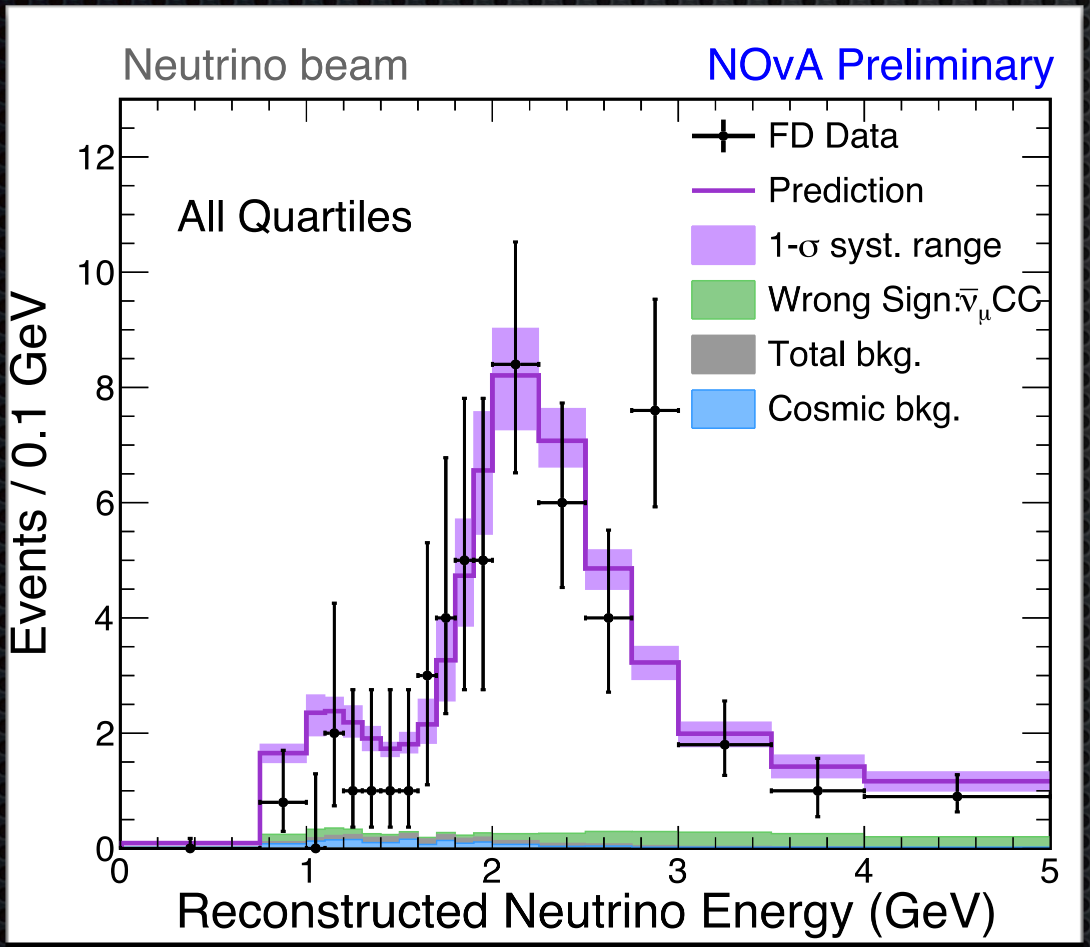
$$\left|\Delta m^2_{32}\right| = 2.67 \pm 0.12 \times 10^{-3}\mathrm{eV}^2$$

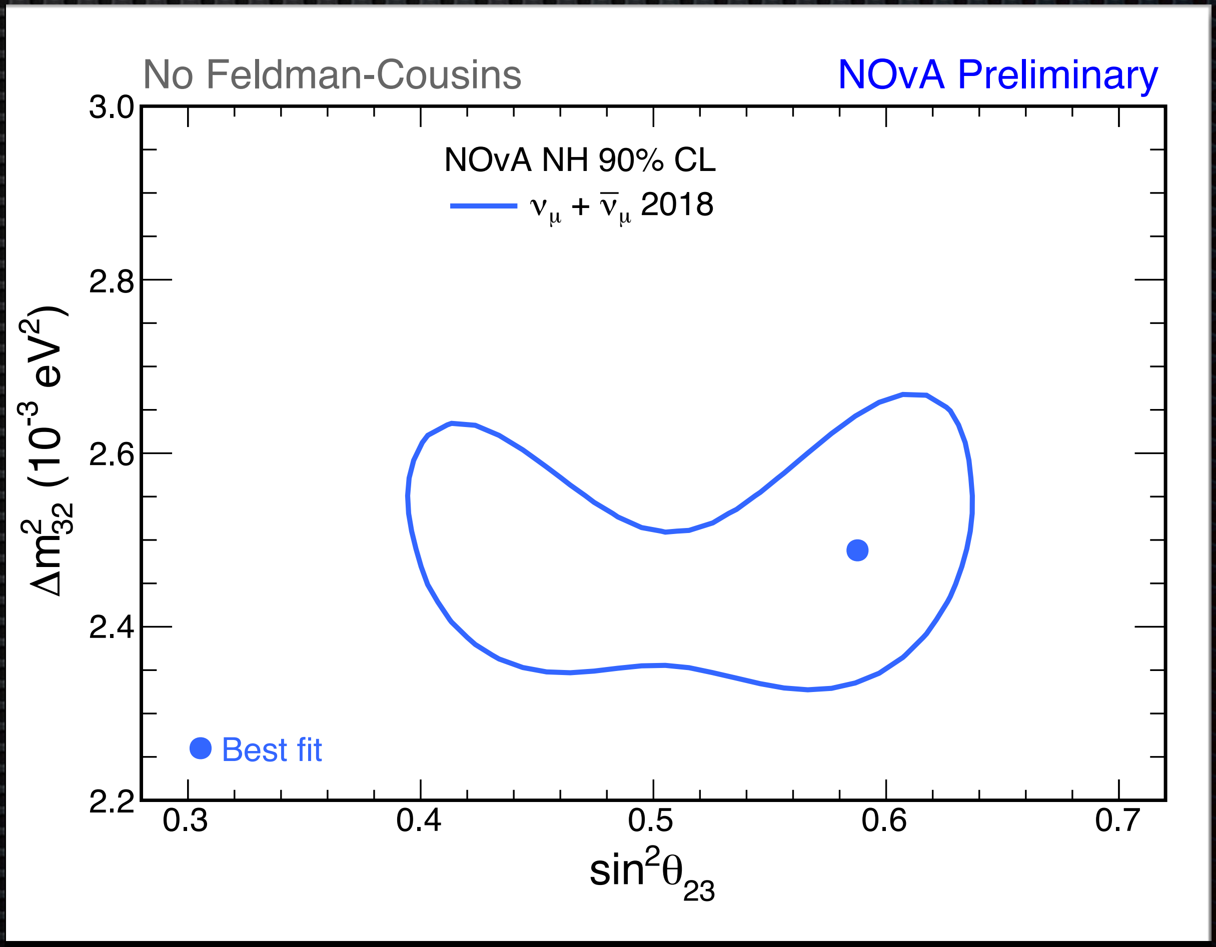
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

Maximal mixing excluded at 2.5σ

NOvA at Neutrino 2018

Refined energy reconstruction





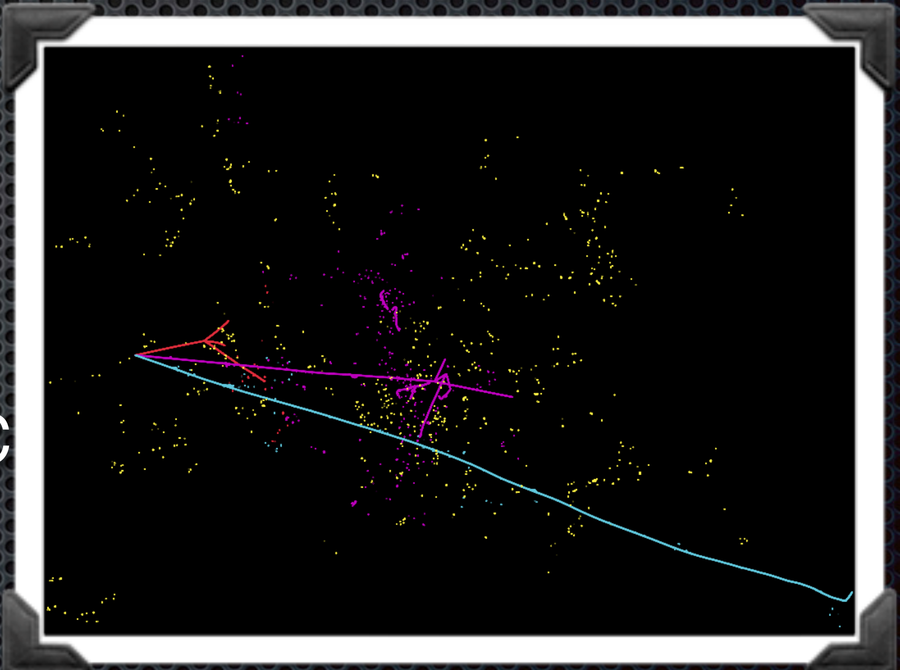
- Maximal mixing is no longer strongly disfavored

Measuring neutrino energy at precision beam experiments

- Beams of 1-4 GeV produce a variety of final states, with one or more protons, pions, and neutrons

- To reconstruct neutrino energy, NOvA and DUNE use the calorimetric method: add up the energy from all final-state particles

- These detectors are not perfectly hermetic, have missing energy channels



see A.F., S. Li, arXiv:1811.06159,

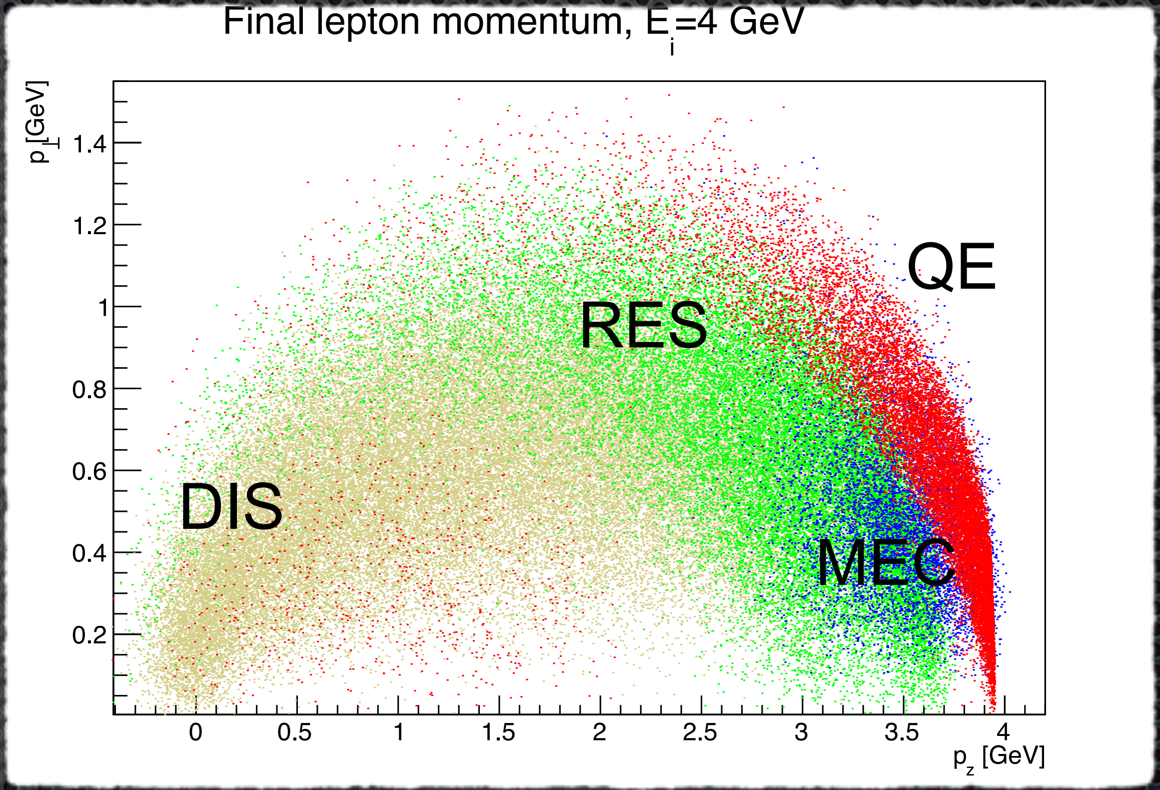
10.1103/PhysRevD.99.036009

How cross section uncertainties enter oscillation studies

- Generator predictions are used to fill the missing information (subthreshold energy deposits, missing particle-ID info, nuclear breakup by wandering neutrons, etc, etc)
- Accurate predictions for both charge lepton and the hadronic system (energies, composition) are key
- One of the most urgent theoretical topics in neutrino physics right now
- Mistakes can have profound consequences

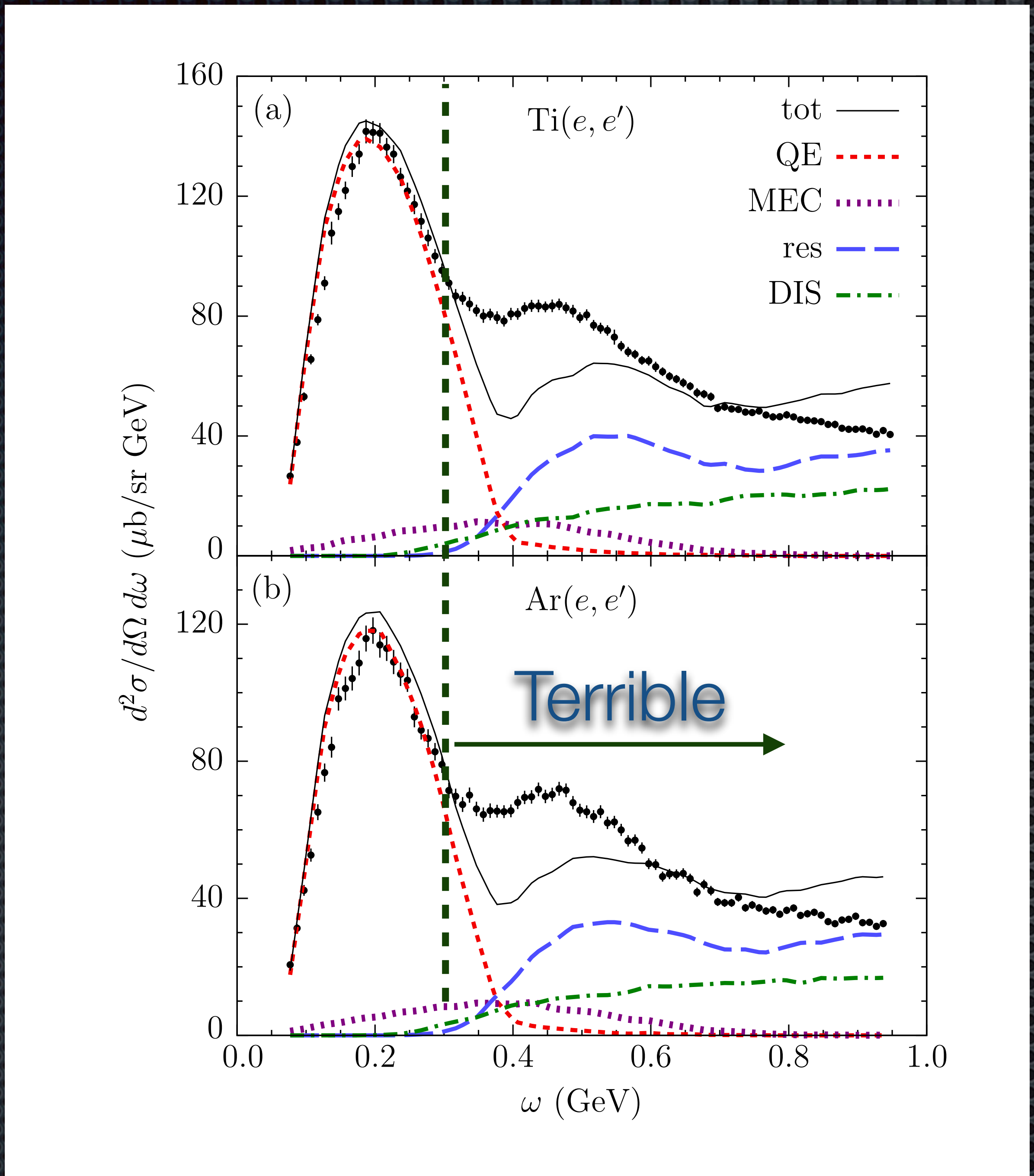
Neutrino scattering at several GeV

- A number of physical processes: quasi-elastic, resonant and non-resonant pion production, DIS-like, multi-nucleon. Generator codes, e.g. GENIE, try to model this physics.



- We need to test/validate all this physics as much as possible
  - how *each component* is constrained by the world's best data

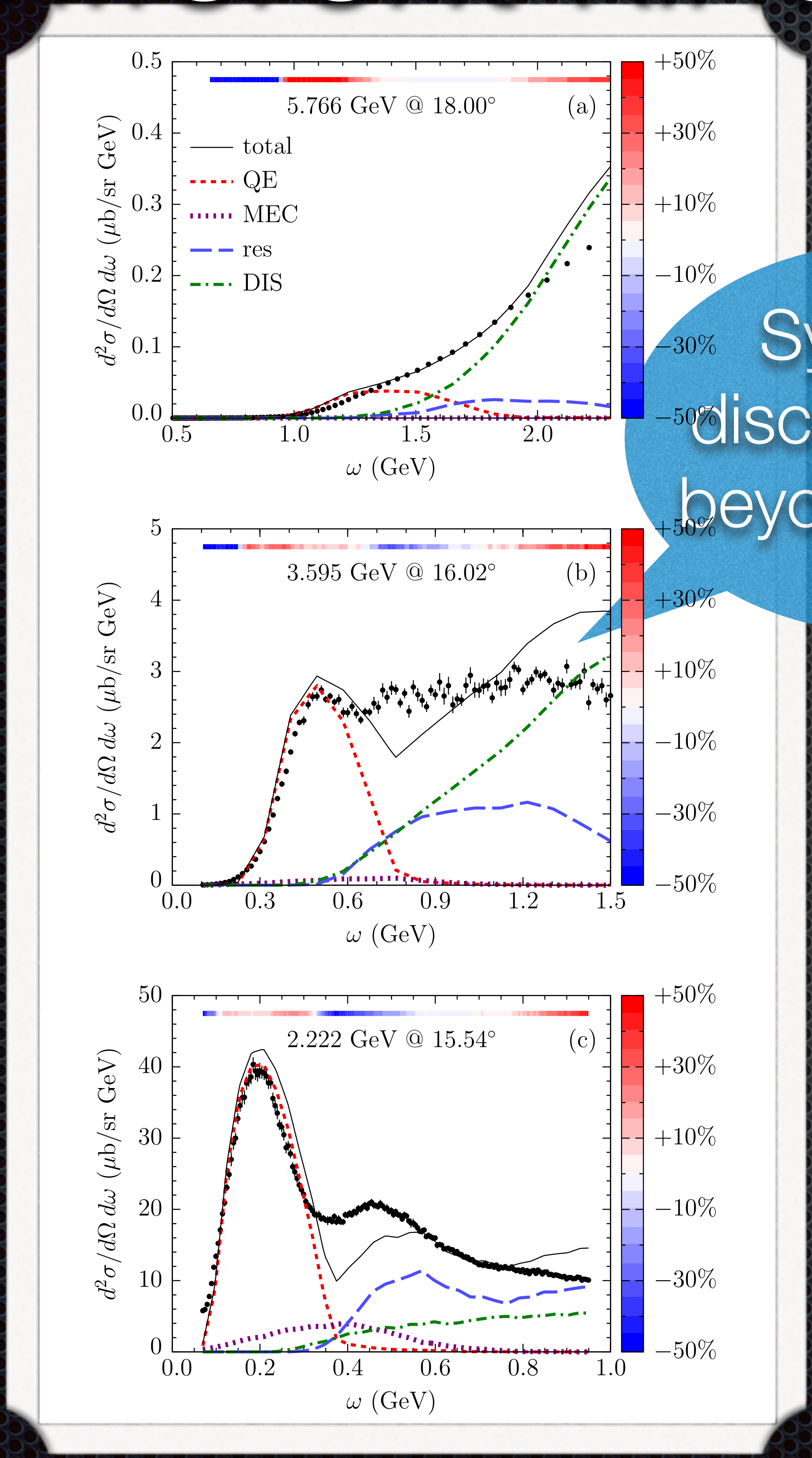
Electron scattering comparison



Ankowski, A.F., 1911.xxxxx

- Everything beyond the QE peak is in dramatic disagreement

Different kinematical regimes



Systemic discrepancies beyond CCQE

- Chronic problems with many other datasets
- Comparisons with Hydrogen and Deuterium Decisive
- Synergy between experimentalists and theorists required
- Stay tuned!

Conclusions

- Neutrino physics is at the forefront of particle physics: this is where new physics is!
- In 20 years of since the first NNN meeting, our field moved from the initial discovery phase into today's precision era
  - Early robust observables of factor of 2 or 3 became precision goals of 5-10% or less
- Modern experiments require better theory, from hadronic physics in neutrino-nucleus scattering to global analyses of new physics scenarios