Neutrino Theory and Phenomenology:

Lecture I

NBIA PhD School: Neutrinos Underground & in the Heavens (Copenhagen, DK, 2016)

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The lectures are intended for a broad audience of students with competences in different fields in particle physics

The goal is to "get you (more) interested" in ν physics, by moving from basic neutrino properties and phenomena to more advanced topics at the current frontier of the field.

Some exercises are also proposed on ν oscill. probabilities. (see Tutorial pdf file). Others are contained in the slides.

People interested in further reading can usefully browse the "Neutrino Unbound" website: www.nu.to.infn.it , or just email me for advice about specific topics: eligio.lisi@ba.infn.it

Outline of lectures:

Lecture I
Pedagogical intro + warm-up case study for oscillations

Lecture II
Standard 3ν oscillations: evolution and current status

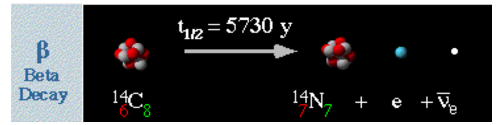
Lecture III
Neutrino absolute masses + open problems in ν physics

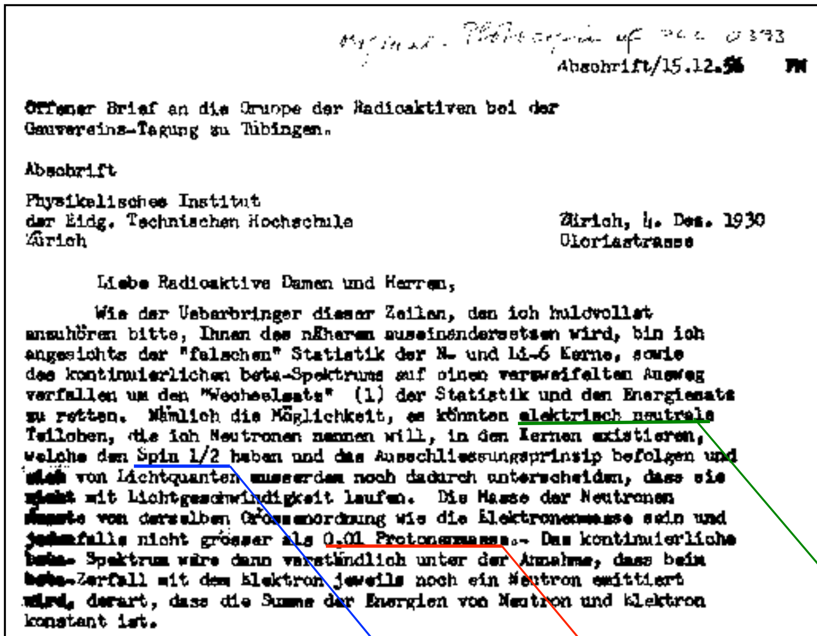
Feel free to stop me and ask questions at any time!

Pedagogical Introduction

The neutrino will celebrate its 86th birthday in December!

This particle was invented in 1930 by Wolfgang Pauli as a “desperate remedy” to explain the continuous β-ray spectrum via a 3-body decay, e.g.,





Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0.01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Kinematics: spin 1/2, tiny mass, zero electric harge

The name “neutrino” (=“little neutral one”, in Italian) was actually invented by Enrico Fermi, who first proposed in 1933-34 a theory for its **dynamics** (weak interactions)

ANNO IV · VOL. II · N. 12 QUINDICINALE 31 DICEMBRE 1933 · XII

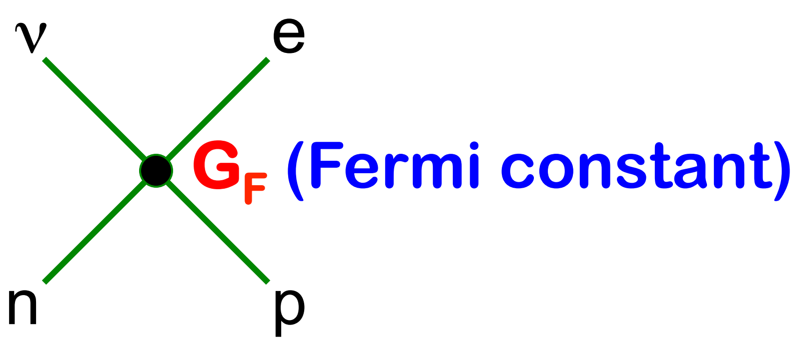
LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi “beta”

Nota del prof. ENRICO FERMI

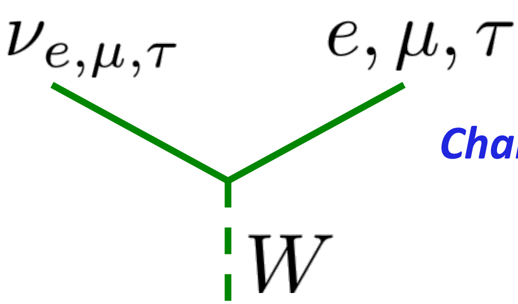
Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.



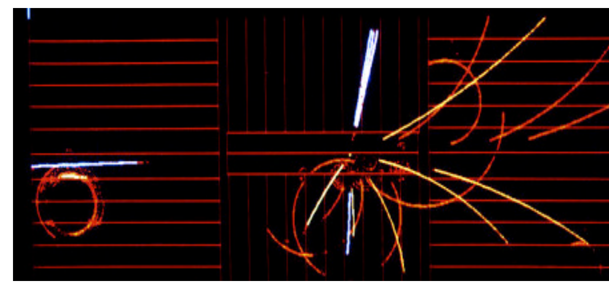
Many decades of research have revealed other properties of the neutrino. For instance, there are 3 different ν "flavors" e μ τ

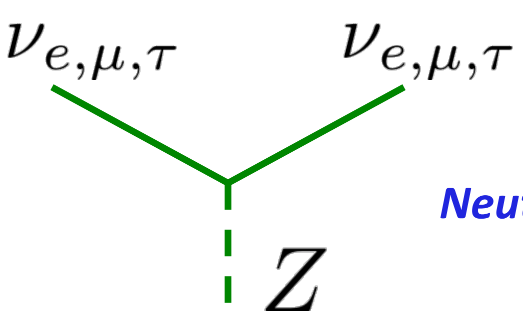
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \quad \begin{matrix} \leftarrow & q = 0 \\ \leftarrow & q = -1 \end{matrix} \quad (\Delta q = 1)$$

and their Fermi interactions are mediated by a charged vector boson W, with a neutral counterpart, the Z boson

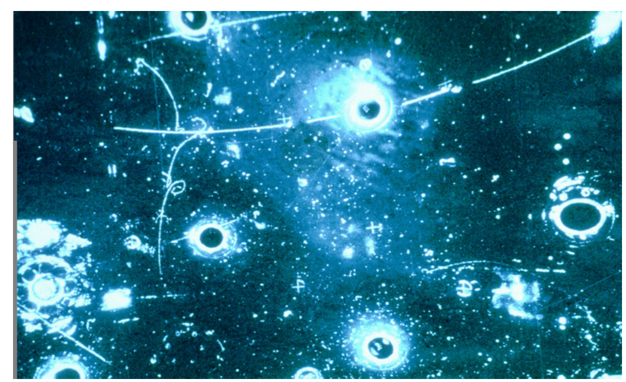


Charged Current (Δq=1)





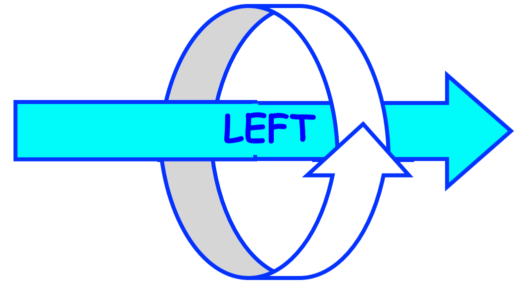
Neutral Current (Δq=0)



Such interactions are chiral (= not mirror-symmetric):

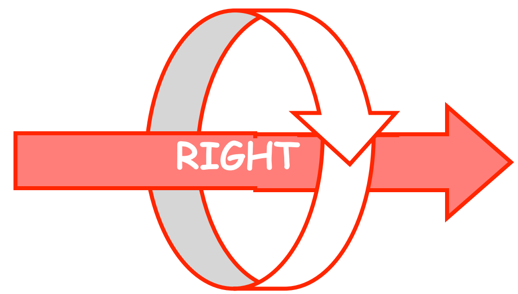
Neutrinos are created in
a left-handed (LH) state

ν



Anti-nus are created in
a right-handed (RH) state

$\bar{\nu}$

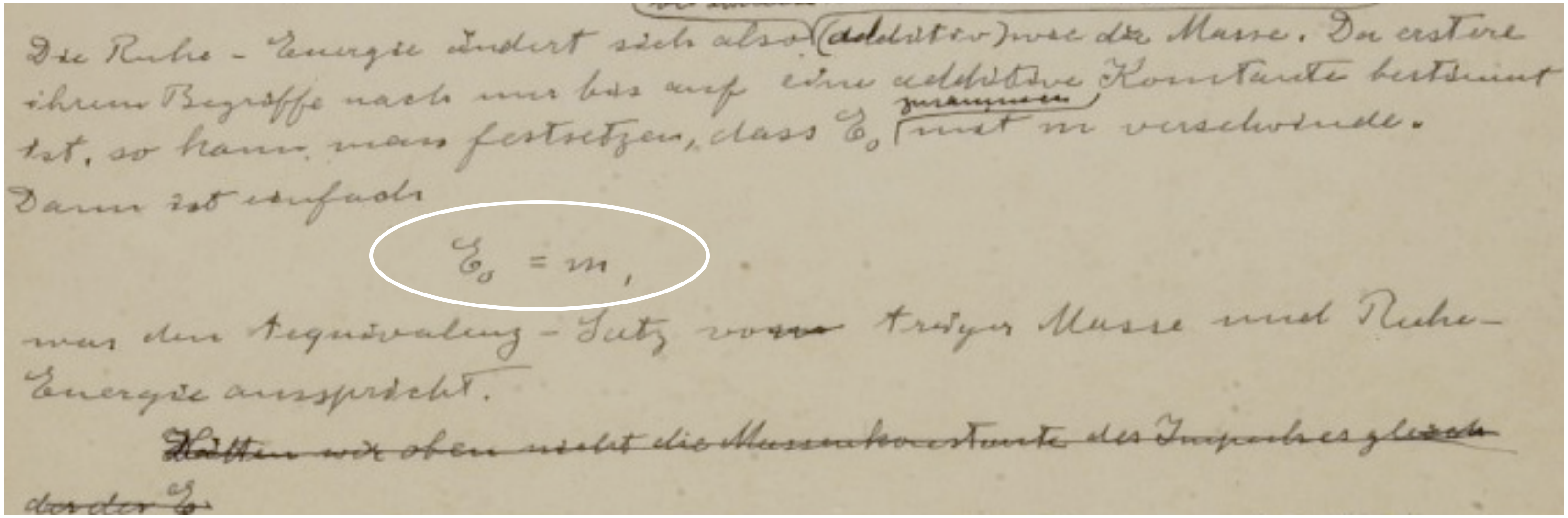


The handedness is a constant of motion only for massless neutrinos.
It is "almost" constant –at O(m/E)- for ultrarelativistic ν with mass m.

We shall "forget" about neutrino handedness and spin for a while, until mass effects at O(m/E) will be reconsidered in Lecture III.

Most of the recent progress in ν physics has actually been driven by another kind of effects, at $O(m^2/E)$: **neutrino flavor oscillations**

The starting point is a century-old equation …


Die Ruhe-Energie ändert sich also (additiv) wie die Masse. Da erstere ihrem Begriffe nach nur bis auf eine additive Konstante bestimmt ist, so kann man festsetzen, dass $\mathfrak{E}_0$ zusammen mit m verschwinde. Dann ist einfach

$$\mathfrak{E}_0 = m,$$

was den Äquivalenz-Satz von träger Masse und Ruhe-Energie ausspricht.

… namely, for $p \neq 0$:

$$E = \sqrt{m^2 + p^2}$$

(in natural units)

Our ordinary experience takes place in the limit: $p \ll m$

$$E \simeq m + \frac{p^2}{2m}$$

... while for neutrinos the proper limit is: $p \gg m$

$$E \simeq p + \frac{m^2}{2p}$$

Energy difference between two neutrinos ν_i e ν_j with mass m_i e m_j in the same beam $(p_i = p_j \simeq E)$:

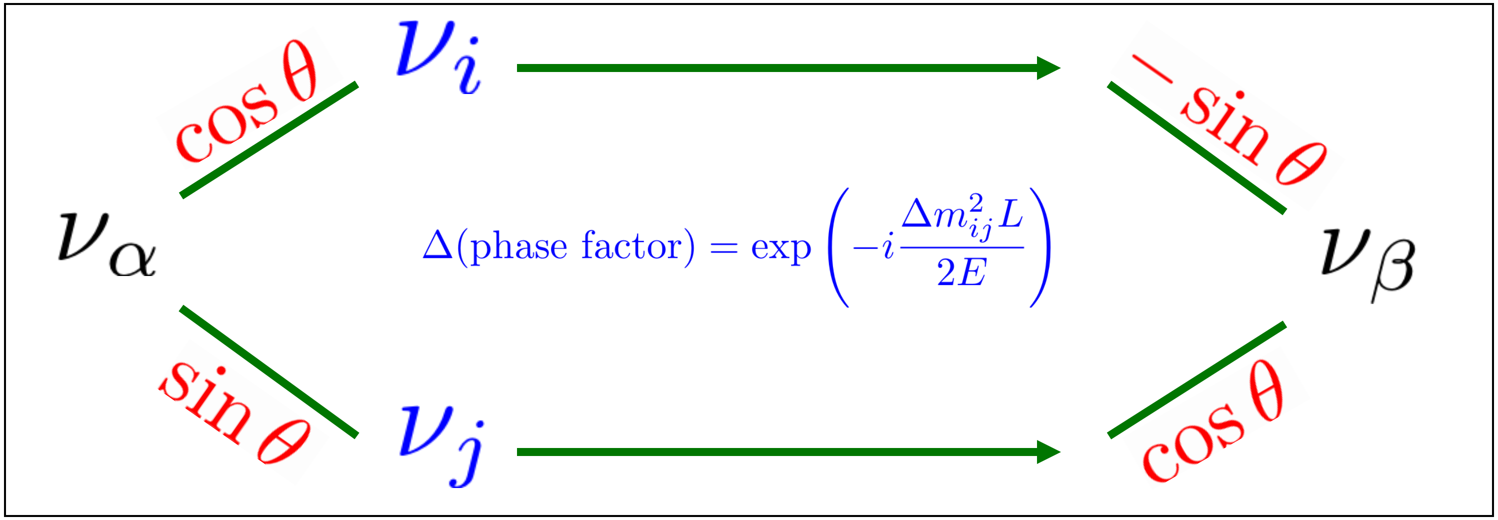
$$\Delta E \simeq \frac{\Delta m_{ij}^2}{2E}$$

PMNS*: neutrinos with definite mass (ν_i and ν_j) might have NO definite flavor (ν_α e ν_β), e.g.,

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

*Pontecorvo; Maki, Nakagawa & Sakata

Analogy with a two-slit interference experiment in vacuum:



This is the simplest case (only 2**ν** involved, no interactions with matter).
It shows that, if neutrinos are massive and mixed (like quarks),
then flavor is not a good quantum number during propagation.
Indeed, it changes ("oscillates") significantly over
a distance L (=x≈Δt) dictated by the uncertainty relation:

$$1 \sim \Delta E \Delta t \simeq \frac{m_i^2 - m_j^2}{2E} L$$

One can easily derive that a neutrino created with **flavor** α can develop in vacuum a different **flavor** β with periodical oscillation probability in **L/E**:

$$P(\nu_\alpha \rightarrow \nu_\beta) = 4\sin^2\theta\cos^2\theta\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

(B. Pontecorvo)

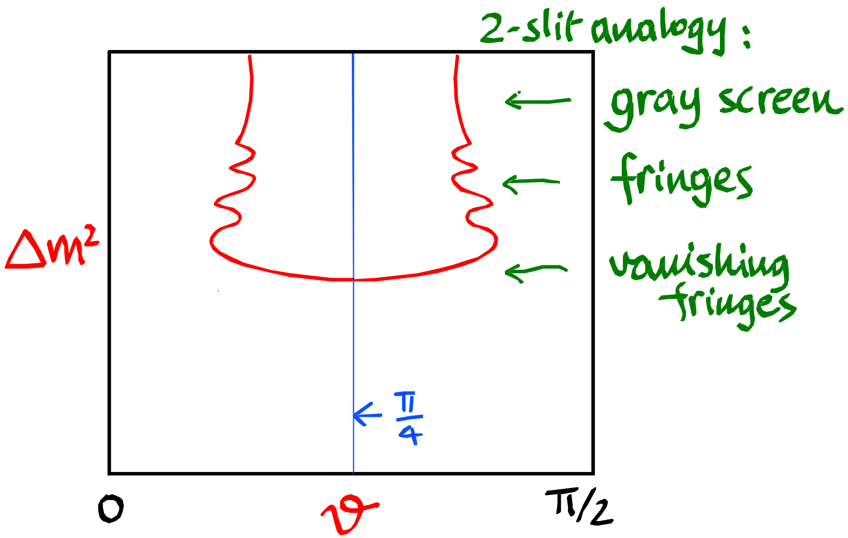
Amplitude
(vanishes for $\theta=0$ or $\pi/2$, is maximal for $\theta=\pi/4$)

Oscillation phase
(vanishes for degenerate masses or small L/E)

Note 1 : This is the flavor "appearance" probability. The "disappearance" probability is the complement to 1.

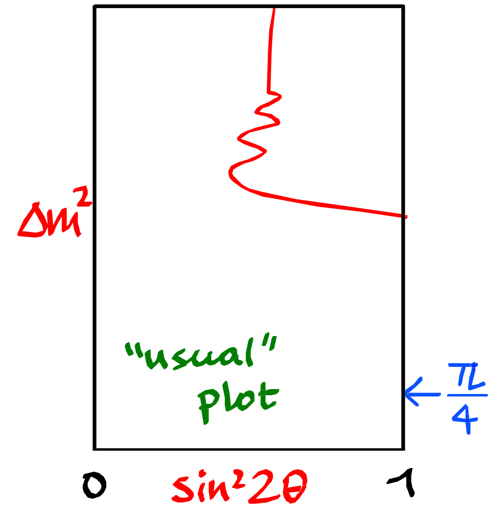
Note 2: The oscillation effect depends on the *difference* of (squared) masses, not on the *absolute masses themselves*.

Typical iso-$\langle P_{\alpha\beta} \rangle$ contours



Octant symmetry: $\theta \to \frac{\pi}{2} - \theta$ in $P_{e\mu}$

If 2nd octant folded onto the 1st one:

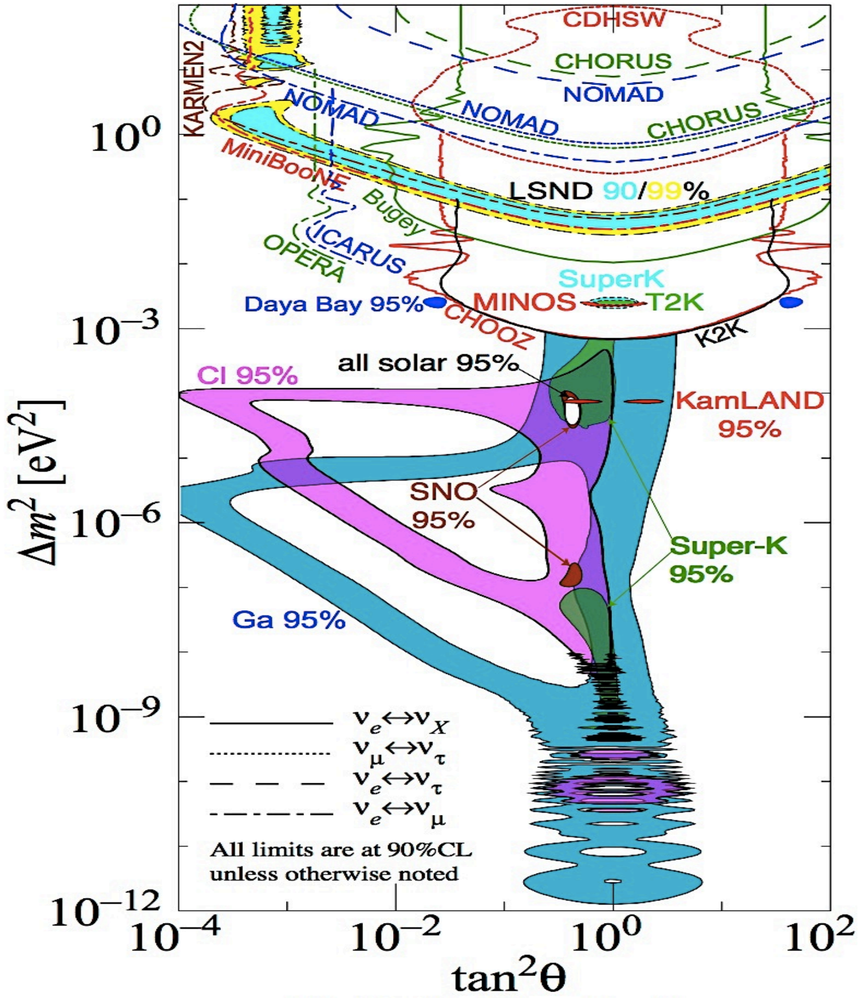


Basically obsolete

In general, better to use $\log \tan^2\theta$
(preserve octant-symmetry) or $\sin^2\theta$

(Note: 2ν Octant symmetry broken by 3ν and/or matter effects)

Octant (a)symmetric 2ν contours from PDG Review:



But... patching 2ν approximations in different oscillation channels, in order to get a full 3ν picture, is no longer a useful approach:

better to go the other way around, from the full 3ν case to 2ν limits

The "standard" 3ν oscillation framework

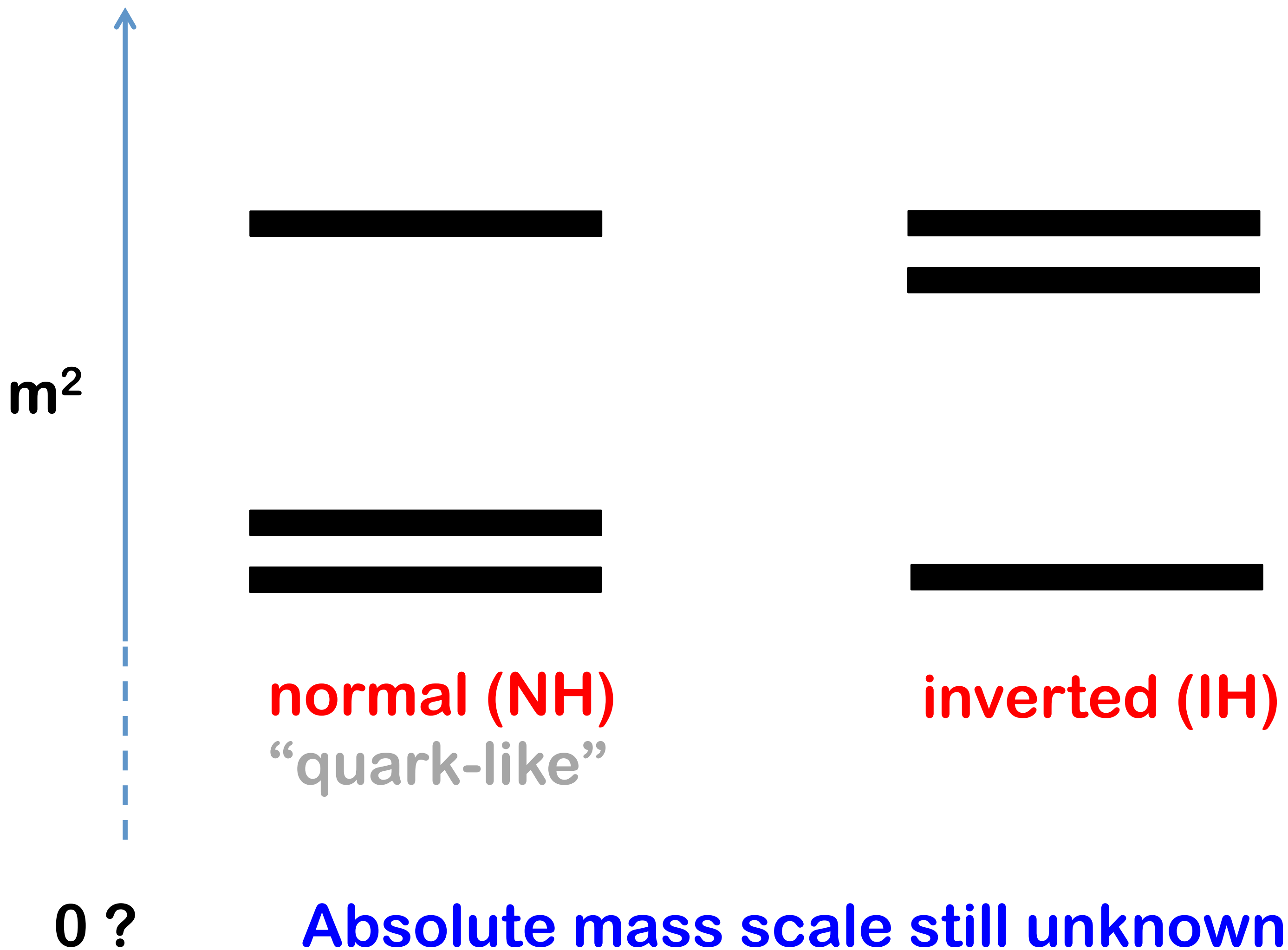
Physics facts and mass notation:

- There are three mass states ν_1, ν_2, ν_3 with masses m_1, m_2, m_3
- For ultrarelativistic ν in vacuum, $E = \sqrt{m_i^2 + p^2} \simeq p + \frac{m_i^2}{2p}$
- Neutrino oscillations probe the differences $\Delta E \propto \Delta m_{ij}^2$
- 3 neutrinos → two independent Δm_{ij}^2, say, δm^2 and Δm^2
- Experimentally, very different scales: $\delta m^2 / \Delta m^2 \sim 1/30$
  Difficult to observe both! Current expts sensitive to a dominant one.

$\delta m^2 \simeq 7.5 \times 10^{-5}\ \mathrm{eV}^2$ ← "small" or "solar" splitting

$\Delta m^2 \simeq 2.5 \times 10^{-3}\ \mathrm{eV}^2$ ← "large" or "atmospheric" splitting

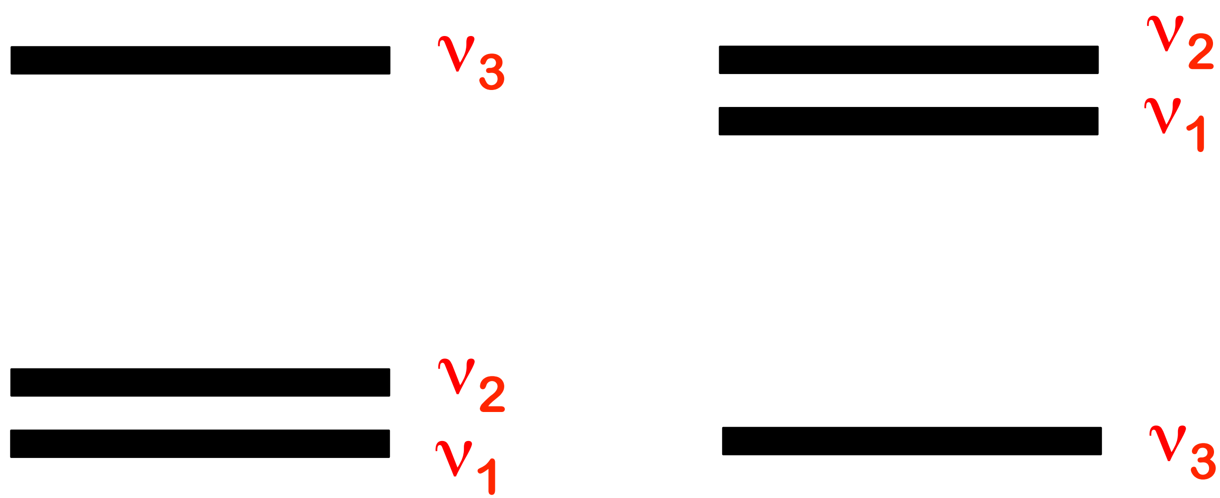
Two possible mass orderings (hierarchies)



Absolute mass scale still unknown,
but upper limits exist: < O(0.1-1) eV^2

PDG convention for 3ν masses:

(ν_1,ν_2) = "close" states, with $m_2>m_1$ in NH and IH
ν_3 = "lone" state, with $m_3>m_{1,2}$ ($<m_{1,2}$) in NH (IH)



Our notation for splittings: Define as independent ones

$$\delta m^2 = m_2^2 - m_1^2 > 0$$

$$\Delta m^2 = \frac{1}{2}(\Delta m_{31}^2 + \Delta m_{32}^2) > 0 \quad \text{(NH)}$$
$$< 0 \quad \text{(IH)}$$

See also the tutorial

PDG convention for 3ν mixing:

Three Euler rotations, one being complex

$$\nu_\alpha = U_{\alpha i}\nu_i \qquad \begin{array}{c}\alpha = e,\ \mu,\ \tau \\ i = 1,\ 2,\ 3\end{array}$$

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

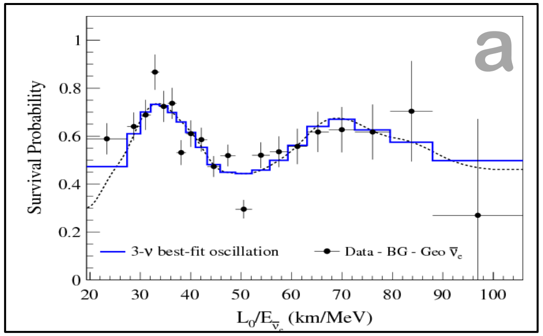
This ordering happens to be particularly useful for phenomenologically interesting limits

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

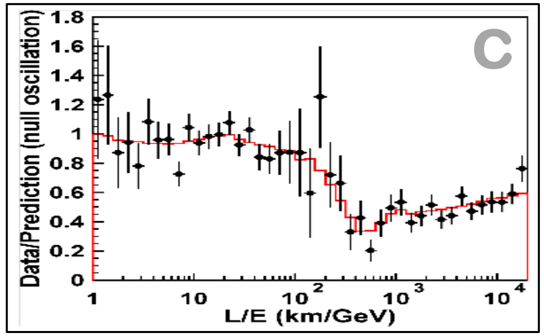
$$UU^\dagger = 1 \qquad U \to U^* \text{ for } \overline{\nu} \qquad c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$$

3ν can explain α → β oscillations seen in vacuum and matter…

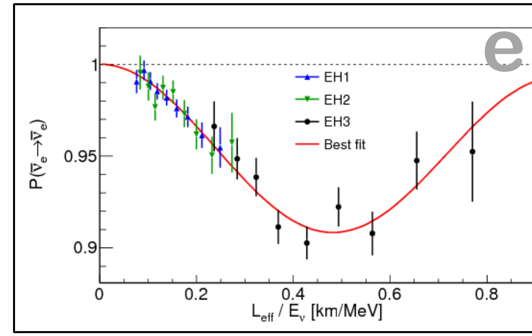
e→e



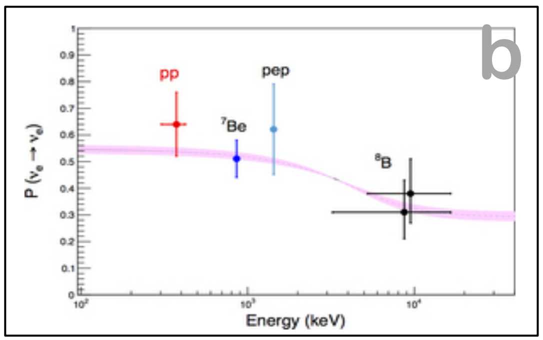
μ→μ



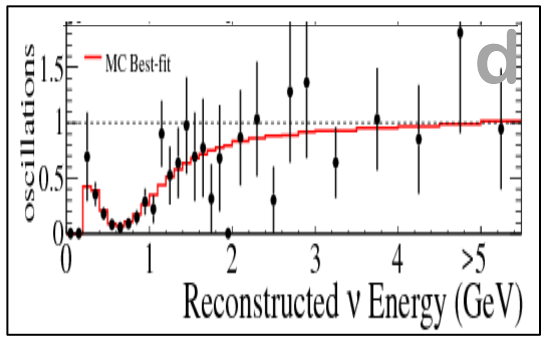
e→e



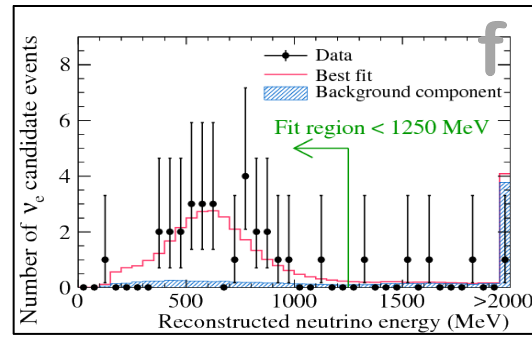
e→e



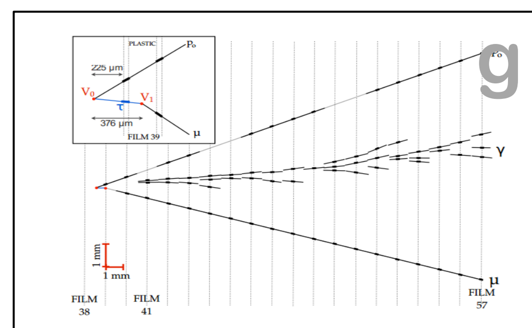
μ→μ



μ→e



μ→τ

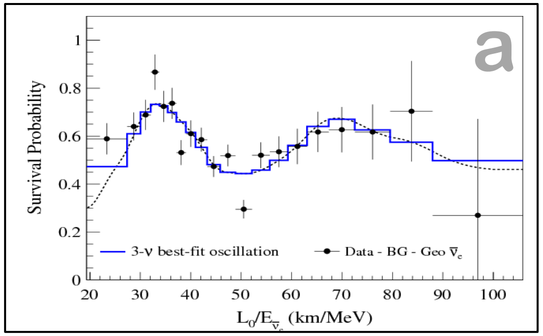


Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline accelerator, (e) short-baseline reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

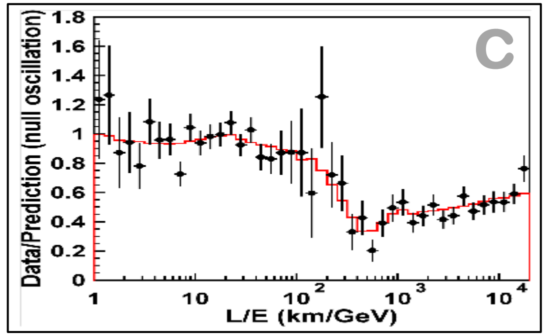
(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS, NOvA; (g) OPERA [plot], Super-K atmospheric.

...with dominant 3ν parameters:

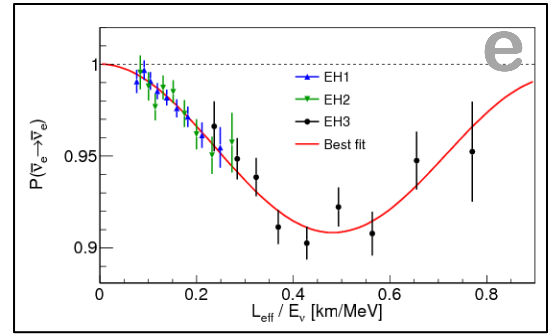
e→e (δm^2 , θ_{12})



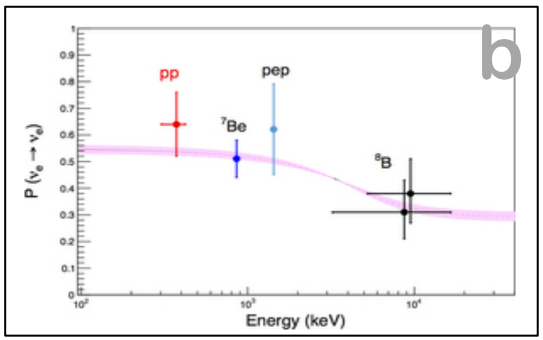
μ→μ (Δm^2 , θ_{23})



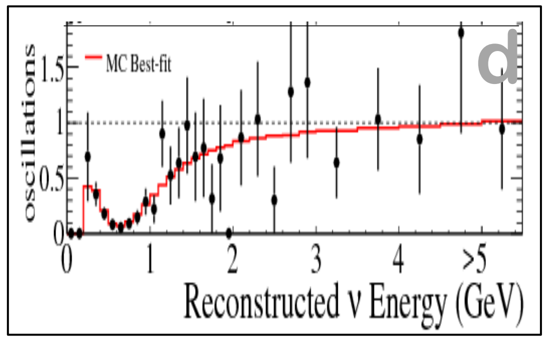
e→e (Δm^2 , θ_{13})



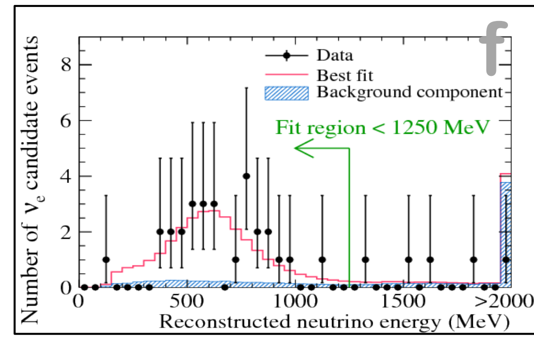
e→e (δm^2 , θ_{12})



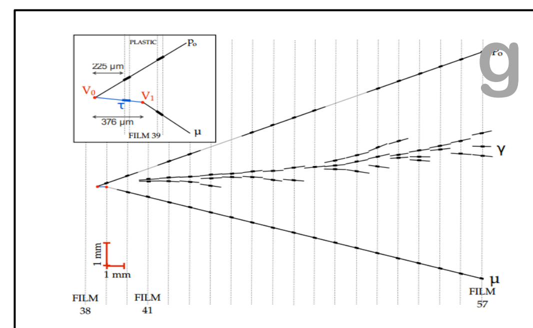
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



μ→τ (Δm^2 , θ_{23})

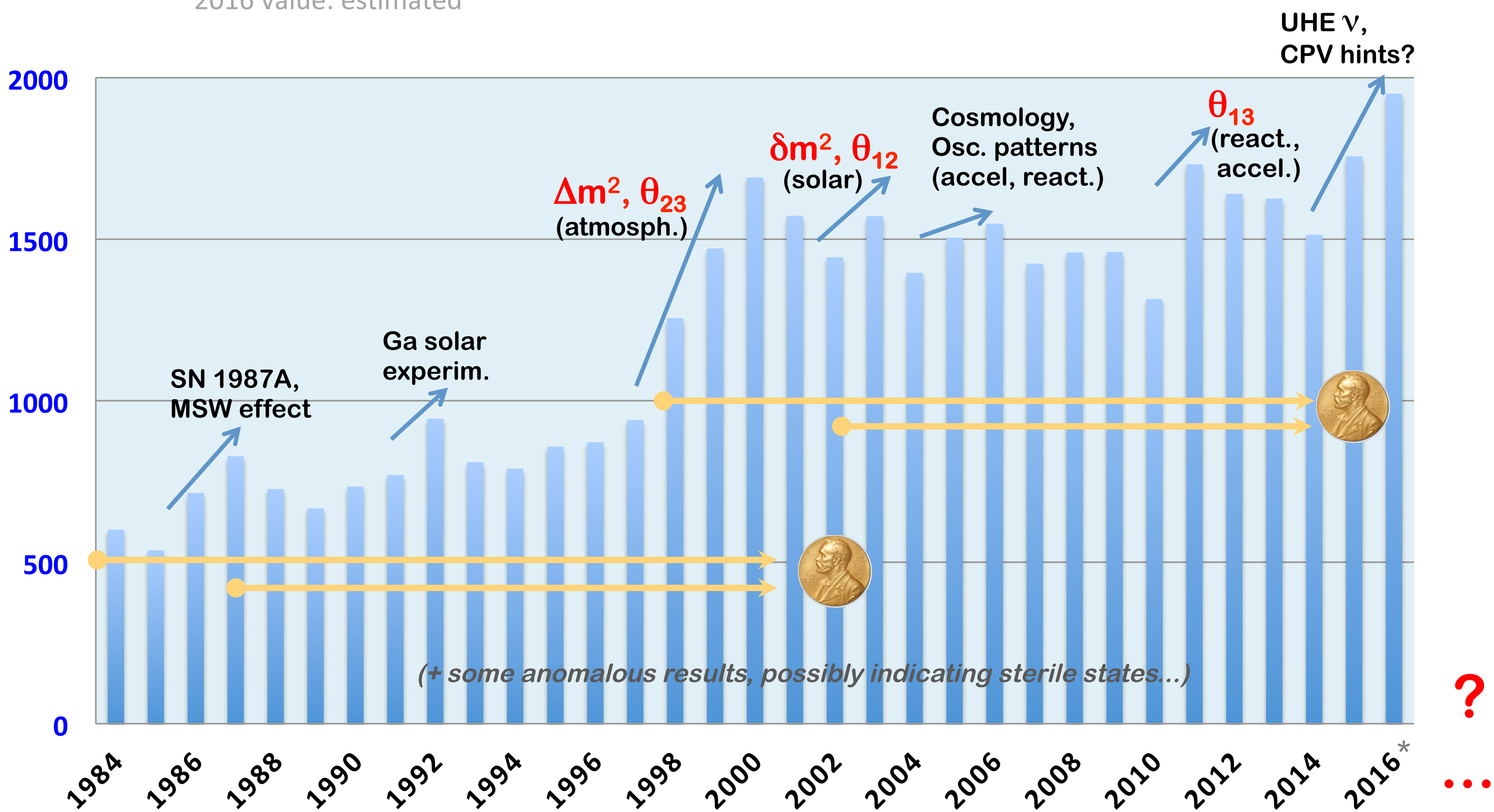


Established so far:

δm^2 $|\Delta m^2|$ θ_{12} θ_{23} θ_{13}

Preprints with #neutrino# in title (from InSpires)

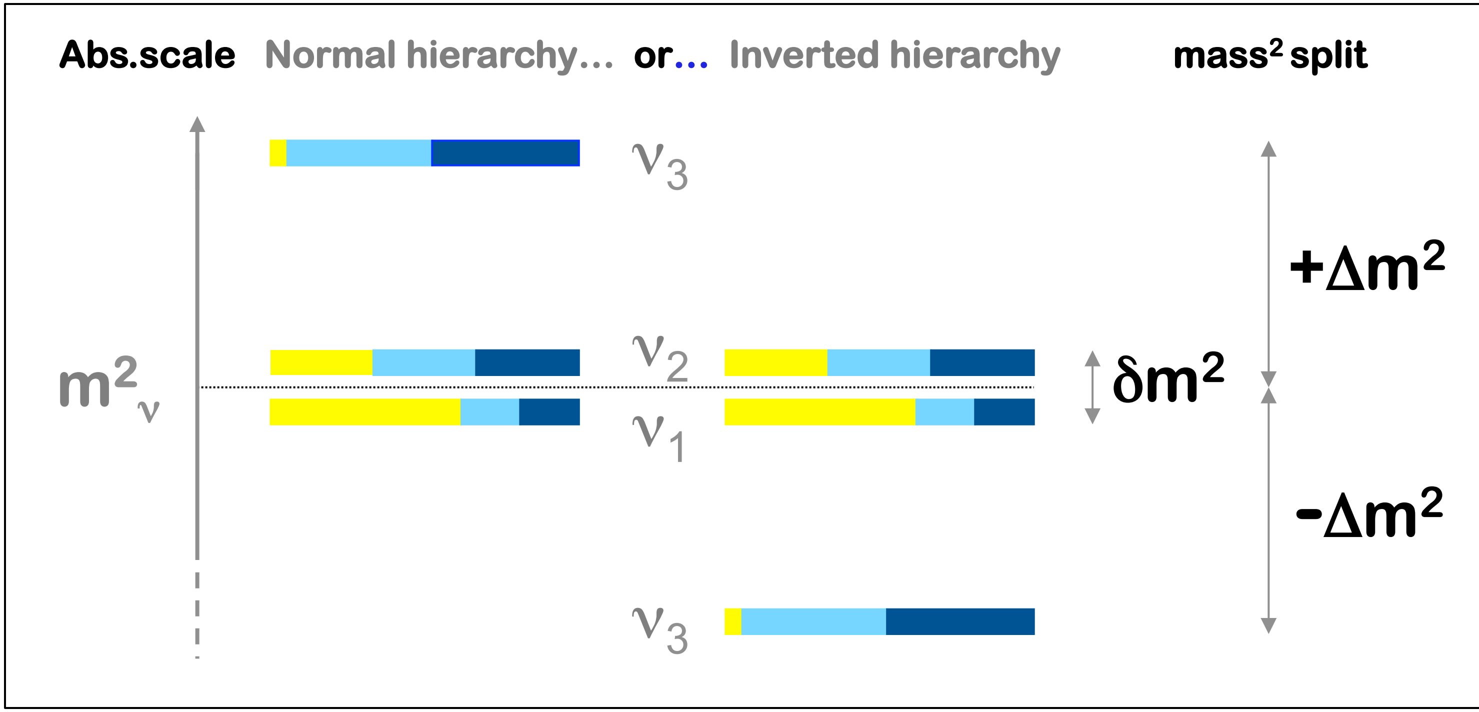
*2016 value: estimated



... the future is yours!

Present 3ν knowledge in one slide (with 1-digit accuracy)

e μ τ



We have seen:

δm^2 ~ 7×10^{-5} eV^2
Δm^2 ~ 2×10^{-3} eV^2
$\sin^2\theta_{12}$ ~ 0.3
$\sin^2\theta_{23}$ ~ 0.5
$\sin^2\theta_{13}$ ~ 0.02

We would like to see:

δ (CP)
sign(Δm^2)
octant(θ_{23})
absolute mass scale
Dirac/Majorana nature

+ Physics beyond 3ν?

(anomalies, new states or interactions)

We shall now look into neutrino flavor evolution in more detail, both in vacuum and in matter.

The presence of two small parameters,

$$\delta m^2 / \Delta m^2 \sim 3 \times 10^{-2}$$

$$\sin^2\theta_{13} \sim 2 \times 10^{-2}$$

will often simplify formalism & understanding.

Neutrino flavor evolution

- It is $m_i << E$ in almost all cases of phenomenological interest
- We can then set $\beta = \mathbf{v/c} \simeq \mathbf{1}, \quad \mathbf{x} \simeq \mathbf{t}, \quad \partial_\mathbf{x} \simeq \partial_\mathbf{t}$
- Chirality flips LH→RH of amplitude $O(m_i/E)$ can be ignored
- For propagation purposes, neutrinos akin to "scalar" states $|\nu>$
- State evolution governed by Hamiltonian: $\mathbf{i}\frac{\mathbf{d}}{\mathbf{dx}}|\nu\rangle = \hat{\mathbf{H}}|\nu\rangle$
- Formal solution (evolution operator): $|\nu(\mathbf{x})\rangle = \hat{\mathbf{S}}(\mathbf{x}, \mathbf{0})|\nu(\mathbf{0})\rangle$
- $S_{\beta\alpha}$ components in flavor basis = amplitudes for $\nu_\alpha \rightarrow \nu_\beta$
- Flavor evolution probabilities: $P_{\alpha\beta} = P(\nu_\alpha \rightarrow \nu_\beta) = |S_{\beta\alpha}|^2$
- $\alpha=\beta$: flavor disappearance channel, $P_{\alpha\alpha} \leq 1$
- $\alpha\neq\beta$: flavor appearance channel, $P_{\alpha\beta} \geq 0$

Three-neutrino flavor evolution in vacuum

The hamiltonian is exceedingly simple in the mass basis $(\nu_1, \nu_2, \nu_3)^T$:

$$\mathbf{H_{mass}} = \begin{pmatrix} E_1 & & \\ & E_2 & \\ & & E_3 \end{pmatrix} \simeq \mathbf{p} \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} + \frac{\mathbf{1}}{\mathbf{2E}} \begin{pmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_3^2 \end{pmatrix}$$

(and even simpler than that, since terms proportional to unity decouple)

In flavor basis $(\nu_e, \nu_\mu, \nu_\tau)^T$ it becomes nondiagonal (→ flavor not conserved):

$$\mathbf{H_{flavor}} = \mathbf{U}\,\mathbf{H_{mass}}\,\mathbf{U}^\dagger$$

Let us work out (tutorials) and discuss (slides) some implications of this simple hamiltonian →

3ν oscillations in vacuum: general case

Prove that

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i<j} \mathrm{Re}\, J_{\alpha\beta}^{ij} \sin^2\left(\frac{\Delta m_{ij}^2\, x}{4E}\right) - 2 \sum_{i<j} \mathrm{Im}\, J_{\alpha\beta}^{ij} \sin\left(\frac{\Delta m_{ij}^2\, x}{2E}\right)$$

where

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

$$J_{\alpha\beta}^{ij} = U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j}$$ ← Jarlskog invariant

$$\frac{\Delta m_{ij}^2}{4E} = 1.267 \left(\frac{\Delta m_{ij}^2}{eV^2}\right)\left(\frac{x}{m}\right)\left(\frac{MeV}{E}\right)$$

(See tutorials)

In general, $P_{\alpha\beta}$ 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 take into account detailed phenomenology

Many open research problems for each of these ingredients, in all subfields of neutrino physics.

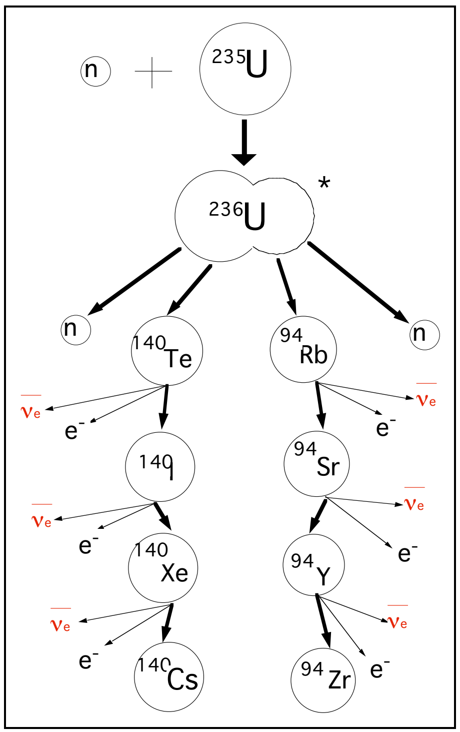
Warm-up case study for oscillation phenomenology:

Short-baseline (SBL) reactors

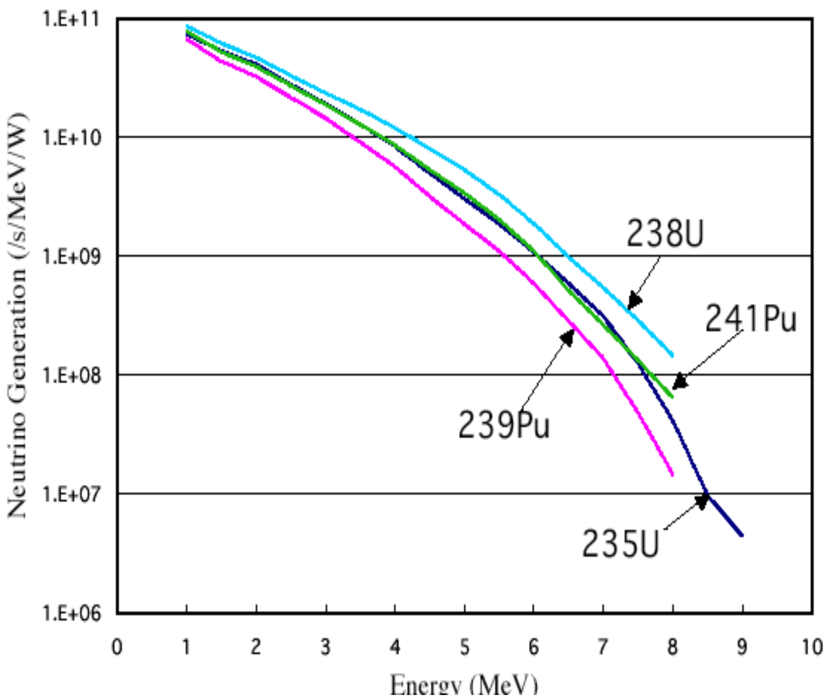
Production

Reactors: Intense sources of anti-ν_e (~6×10^{20}/s/reactor)

Typically, 6 neutron decays to reach stable matter from fission:



~200 MeV per fission / 6 decays: Typical available neutrino energy E~ few MeV



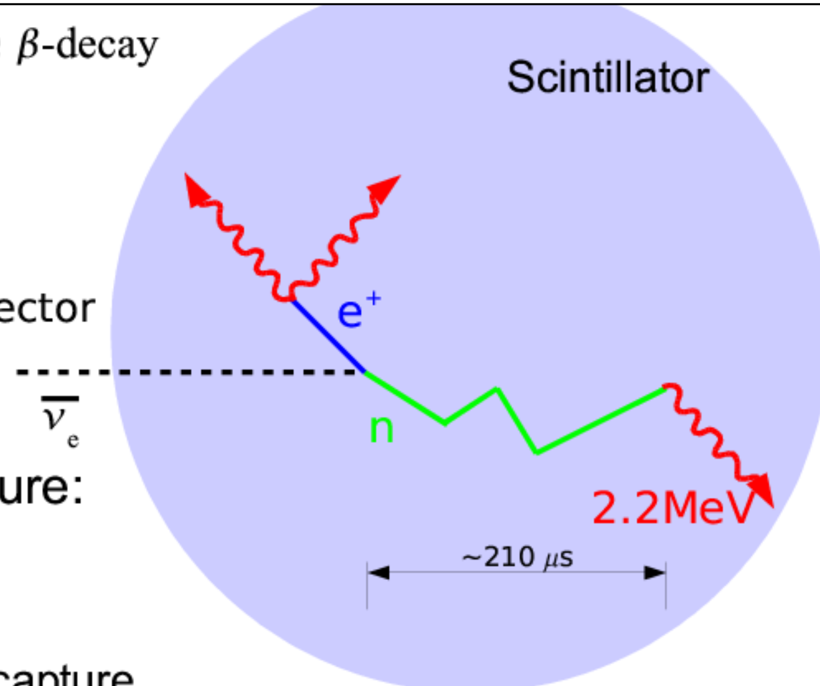
Detection

Reaction Process: inverse β-decay

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

$$n + p \rightarrow d + \gamma$$

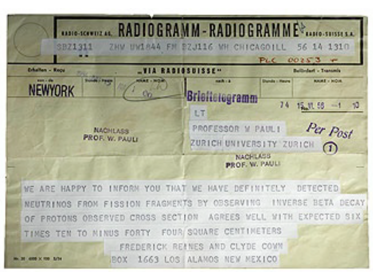
Scintillator is target and detector



- Distinct two-step signature:
  - prompt event: positron

    $E_\nu \approx E_{e^+} + 0.8\ MeV$
  - delayed event: neutron capture after ~210μs
    - 2.2 MeV gamma

Delayed coincidence: good background rejection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NEWYORK
Brieftelegramm
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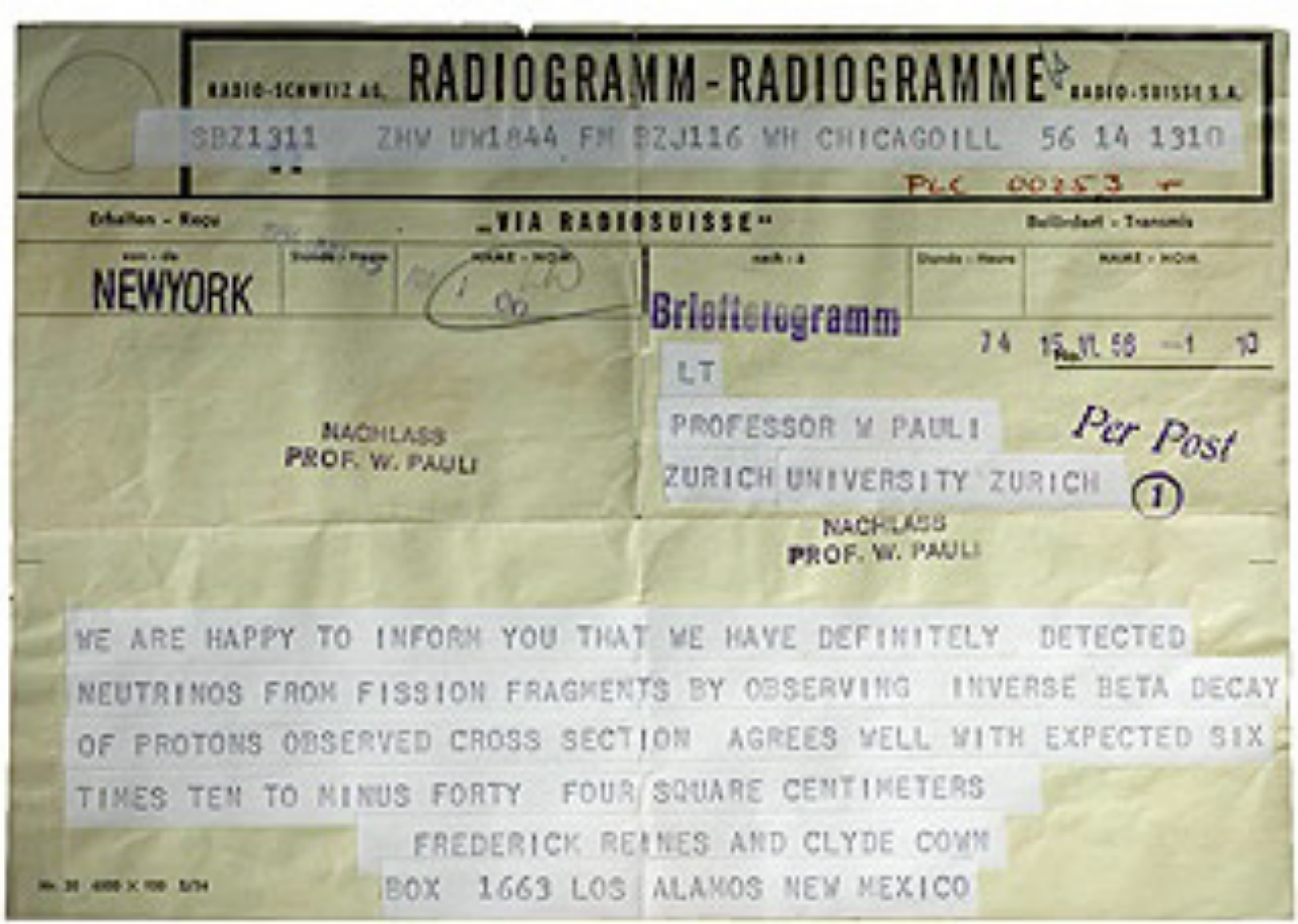
PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH
Per Post
NACHLASS PROF. W. PAULI
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS
FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO

← This reaction allowed experimental ν discovery in 1956 (Reines & Cowan)



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Reply by telegram:

"Thanks for message. Everything comes to him who knows how to wait. Pauli."

Propagation

Exercise: $3\nu \to 2\nu$ reduction for SBL reactor expts.

Short-baseline reactor experiments look for $\bar{\nu}_e$ oscillations at $x = L \sim O(1\,\text{km})$ and $E \sim$ few MeV. At these energies, CC reactions in the final state can produce e^+ but not μ^+ or τ^+; therefore, only $P(\bar{\nu}_e \to \bar{\nu}_e)$ is observable (disappearance) but not $P(\bar{\nu}_e \to \bar{\nu}_\mu)$ or $P(\bar{\nu}_e \to \bar{\nu}_\tau)$ (appearance). Moreover, it is $\delta m^2 L/4E \ll 1$, while $\Delta m^2 L/4E \sim \mathcal{O}(1)$.

Prove that, in the limit $\delta m^2 \simeq 0$, effective 2ν oscillations occur:

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \underbrace{\sin^2 2\theta_{13}}_{\text{oscillation amplitude}} \; \underbrace{\sin^2\left(\frac{\Delta m^2 L}{4E}\right)}_{\text{oscillating factor}}$$

Try to get an intuitive understanding of the dependence on θ_{13} only.

Solution – From the previous exercise (with $U \to U^*$), the only nonzero oscillating terms for $\alpha\beta = ee$ and $\delta m^2 = m_2^2 - m_1^2 \simeq 0$ are multiplied by: $J_{ee}^{13} = U_{e1}^* U_{e3} U_{e3}^* U_{e1} = |U_{e1}|^2 |U_{e3}|^2$ and $J_{ee}^{23} = |U_{e2}|^2 |U_{e3}|^2$. Then: $\mathrm{Im}(J_{ee}^{13}) = 0 = \mathrm{Im}(J_{ee}^{23})$ and

$$P(\bar\nu_e \to \bar\nu_e) = 1 - 4\left(|U_{e1}|^2|U_{e3}|^2 + |U_{e2}|^2|U_{e3}|^2\right)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$= 1 - 4|U_{e3}|^2(1 - |U_{e3}|^2)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) \qquad \leftarrow |U_{e3}|^2 = s_{13}^2$$

$$= 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Intuitively: two of the three mixing rotations have ~no effect

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = (23)\,(13)\,(12)\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

→ only (13) physical

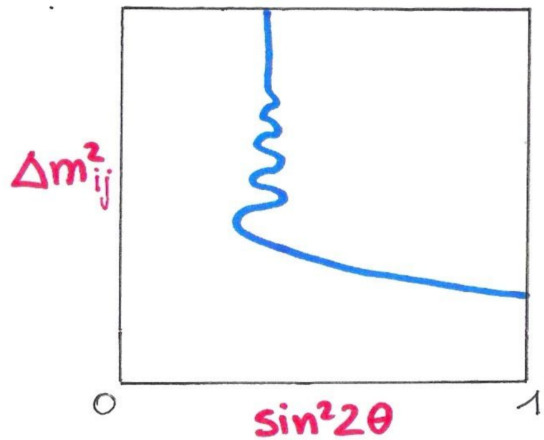
(23): mixes unobservable flavors (ν_μ, ν_τ)

(12): mixes ~degenerate states (ν_1, ν_2)

Note that, in this case, δ is unobservable, as well as sign$(\pm\Delta m^2)$, and $P(\bar\nu_e \to \bar\nu_e) = P(\nu_e \to \nu_e)$.

Generic experimental constraints in 2ν approxim.

- Experiments measure some "averaged" $P_{\alpha\beta} \simeq \sin^2 2\theta \left\langle \sin^2\left(\frac{\Delta m^2_{ij}\, x}{4E}\right)\right\rangle$
- Curve of iso-$P_{\alpha\beta}$:

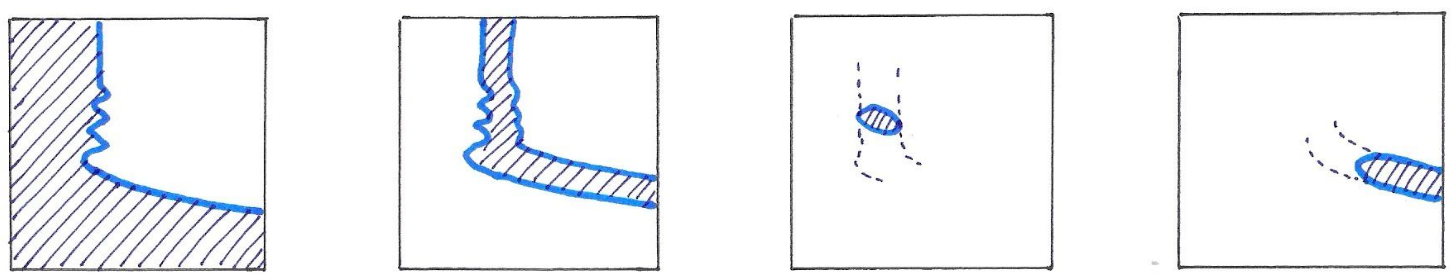


← $\frac{\Delta m^2_{ij} x}{4E} \gg 1$, $\langle \cdots \rangle \sim \frac{1}{2}$, fast oscillations

← $\frac{\Delta m^2_{ij} x}{4E} \sim \mathcal{O}(1)$

← $\frac{\Delta m^2_{ij} x}{4E} \ll 1$, vanishing oscillations

- Possible expt. constraints:



No signal

Signal

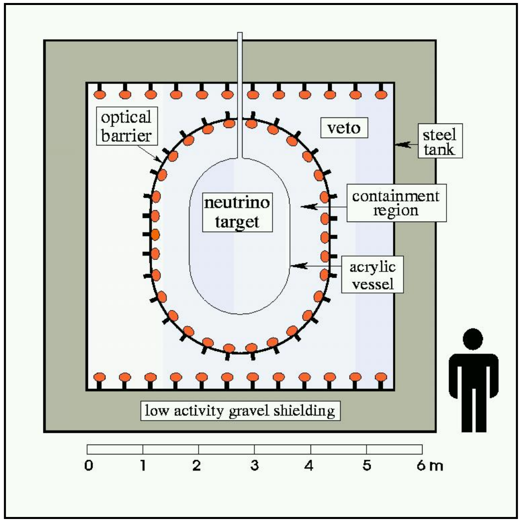
Precise signal at small mixing

Precise signal at large mixing

(need ≥ 2 expts or spectral data in 1 expt)

The short-baseline reactor experiment CHOOZ (1998+)

L ~1 km →

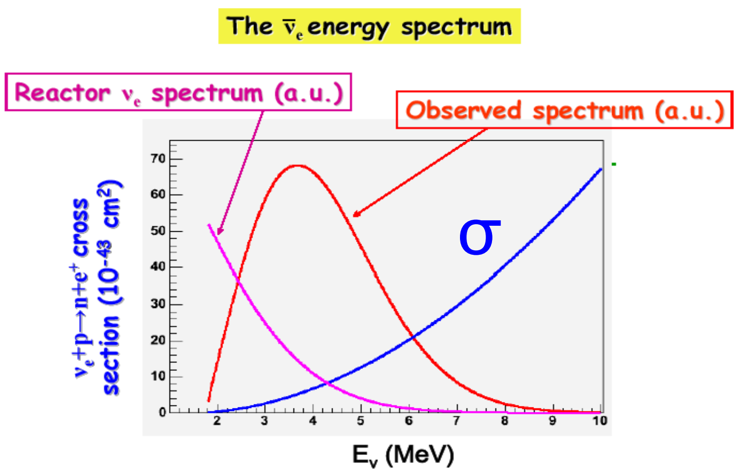


Probably (one of) the most cited negative results ever!

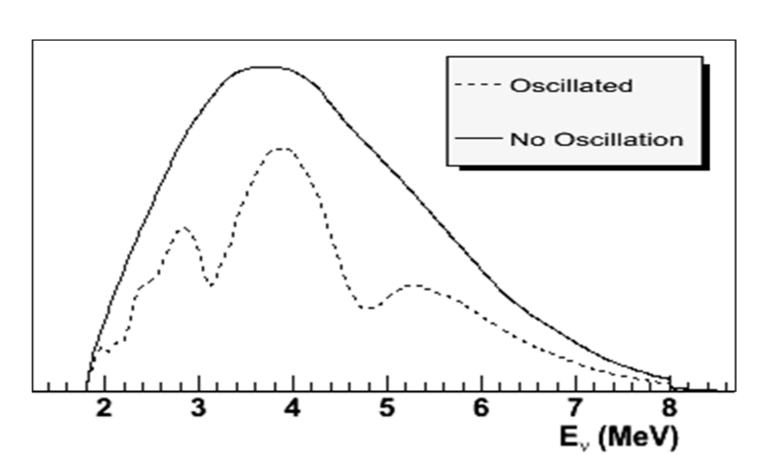
First data: Phys. Lett. B 466, 415 (1999) >1700 cites
Final data: Eur. Phys. J. C 27, 331 (2003) >1200 cites

CHOOZ reactor results (1998-2003)

Expected spectrum (no oscill.):

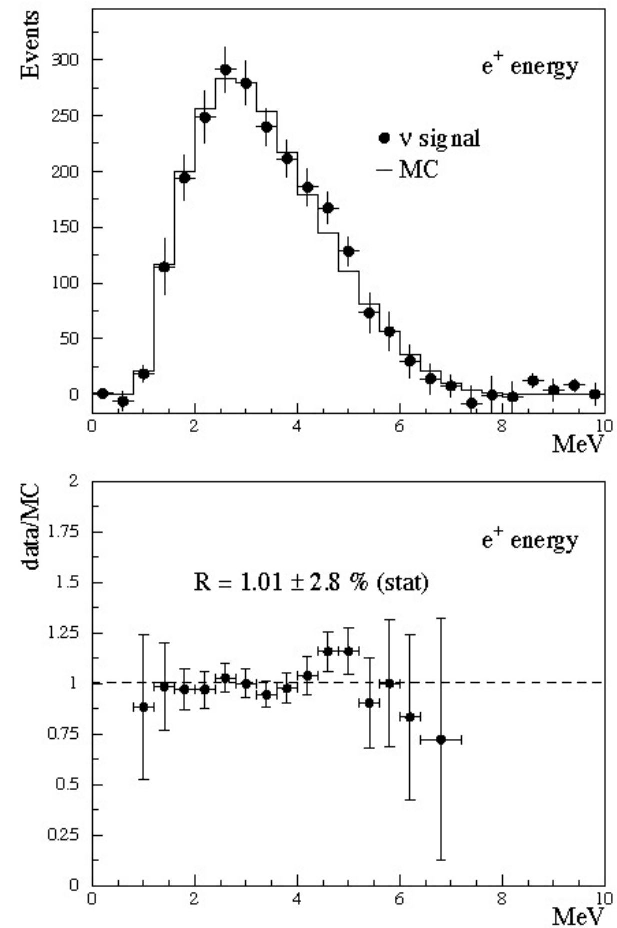


With oscillations (qualitative):



CHOOZ: no oscillations

within few % error



Interpretation

One mass scale dominance:

$P_{ee} = 1 - \sin^2(2\theta_{13}) \sin^2(\Delta m^2 L/4E_\nu)$

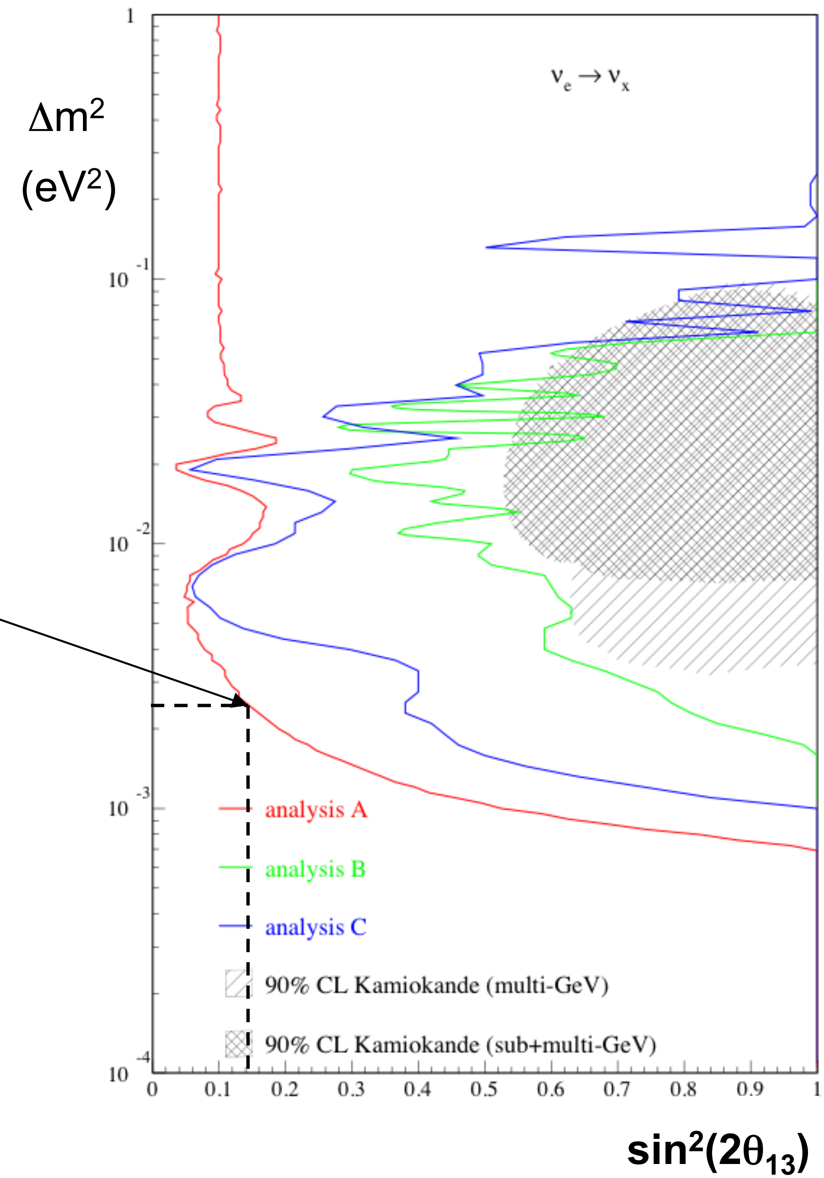
For any value of Δm^2 in the range allowed by atmospheric data (next Lect.), get stringent upper bound on θ_{13}

$\sin^2 \theta_{13}$ < few %
(depending on Δm^2)

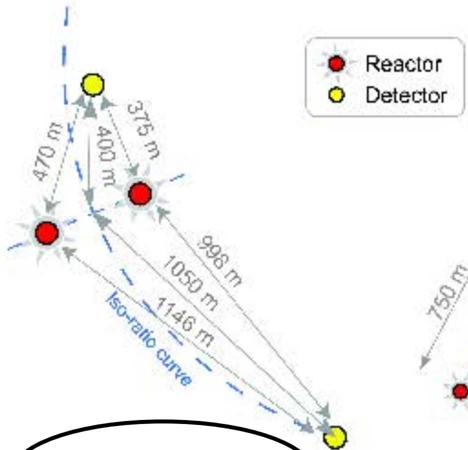
... Nobody could know at that time, but θ_{13} was just behind the corner (less than a factor of two in sensitivity!)

In any case, it was clear that, to reach higher θ_{13} sensitivity, need to use a second (close) detector to reduce systematics by far/near comparison →

CHOOZ exclusion plot

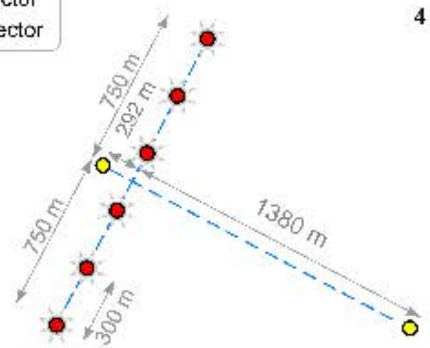


Current SBL reactor expts with near & far detectors (ND & FD)



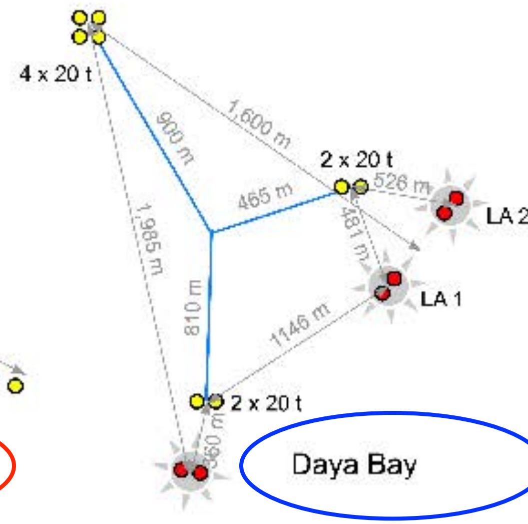
Double Chooz

Running with FD,
+ND this year



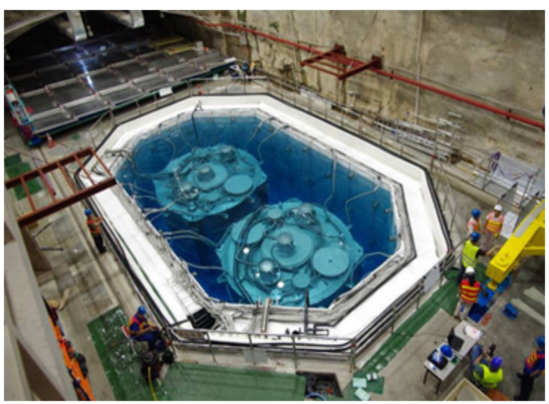
RENO

Running with
ND & FD



Daya Bay

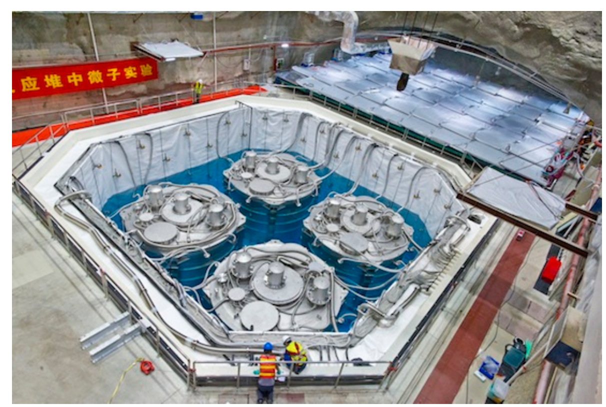
Running with
ND & FD



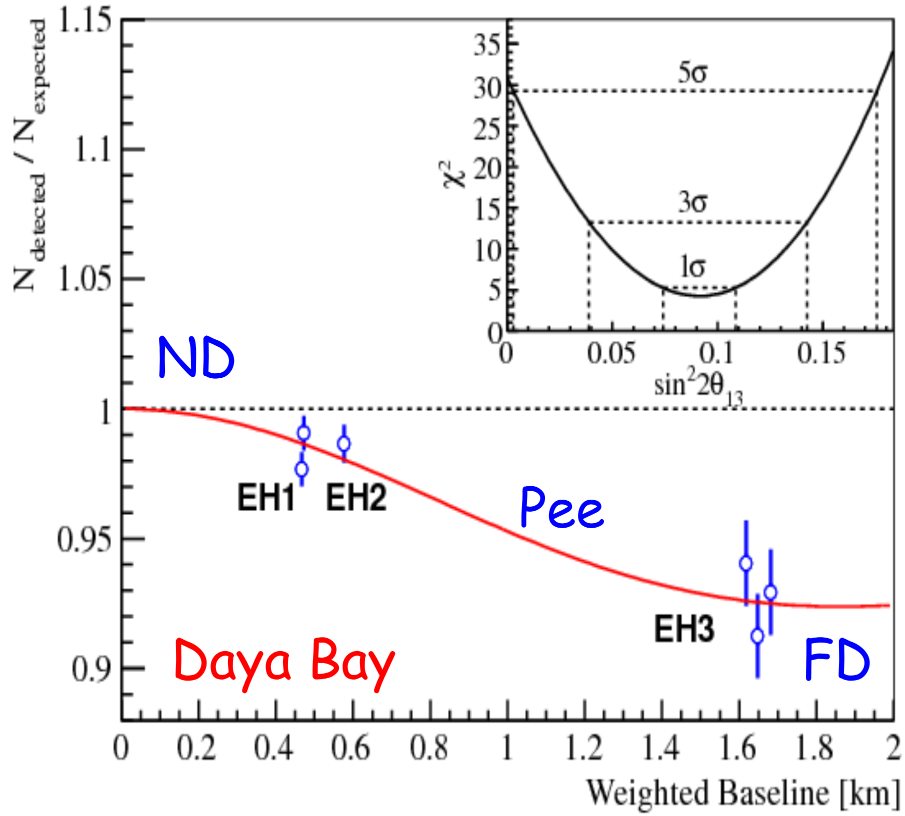
E.g, for Daya Bay:

← ND

FD →



2012: discovery of $\theta_{13}>0$! ($\sin^2\theta_{13}\sim 0.022$ at ~fixed Δm^2)

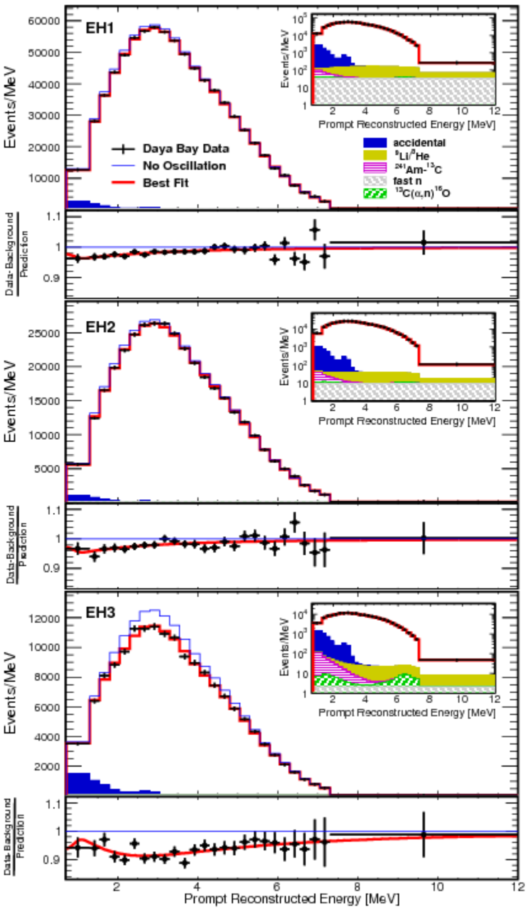


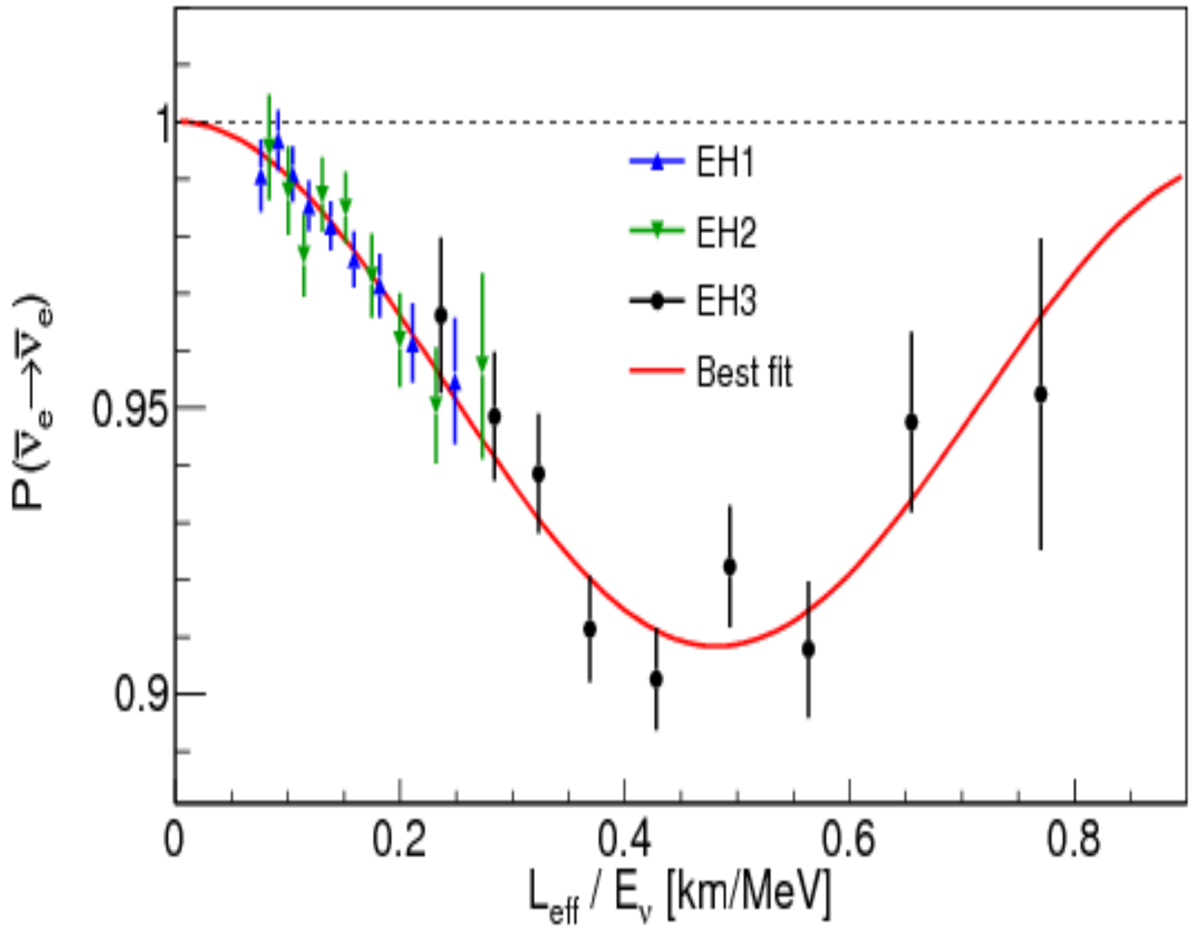
Daya Bay (& RENO): disappearance at FD w.r.t. ~unoscillated at ND

Double Chooz results (FD only) were also consistent with Daya Bay & RENO.

Interestingly, approximate value of θ_{13} was previously hinted from other data: weaker signals were also coming from other experiments before 2012 (see Lec. II).

2013: more data → spectral analys. → ½ osc. cycle in L/E!





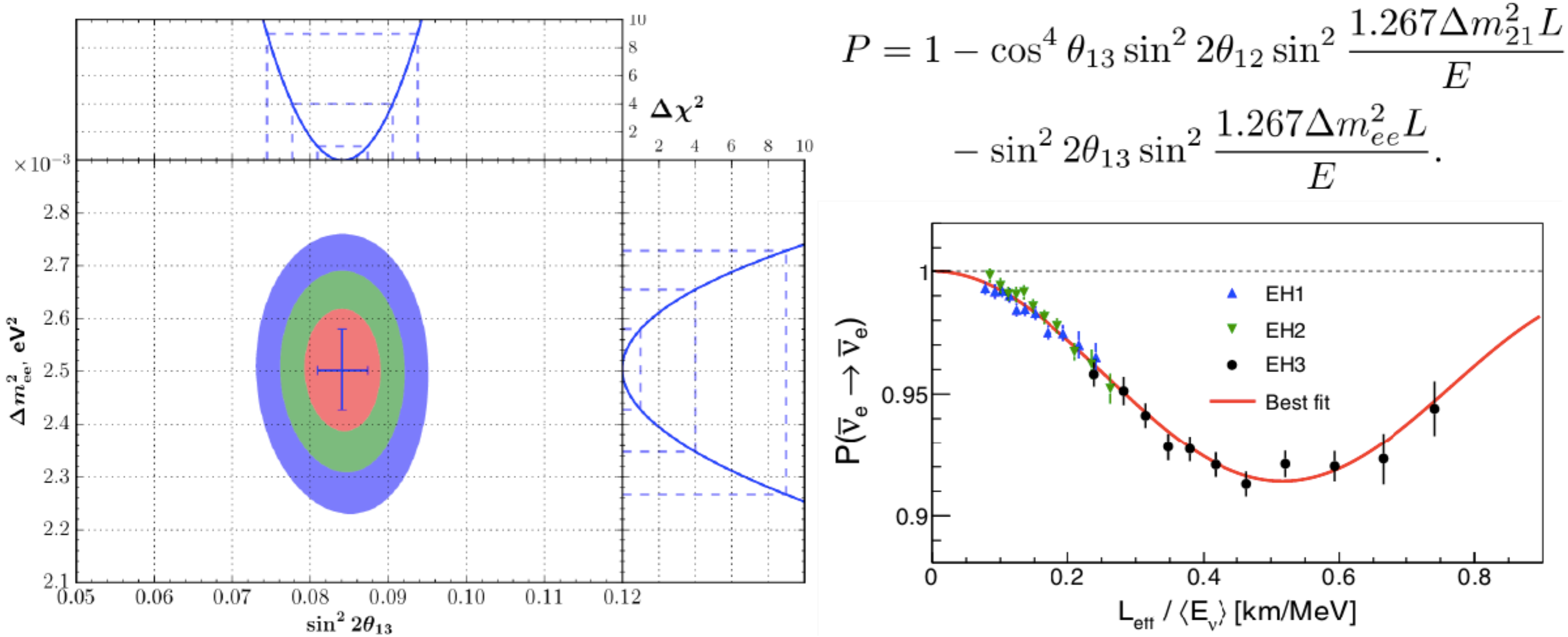
(Above: Daya Bay data. 1/2 cycle also observed in RENO, with less statistics)

Most recent Daya Bay results (Neutrino 2016, July, London)

(see also RENO and Double Chooz results at the same Conference)

Current accuracy requires to go beyond the 2ν approximation (see exercises in tutorial): ↓

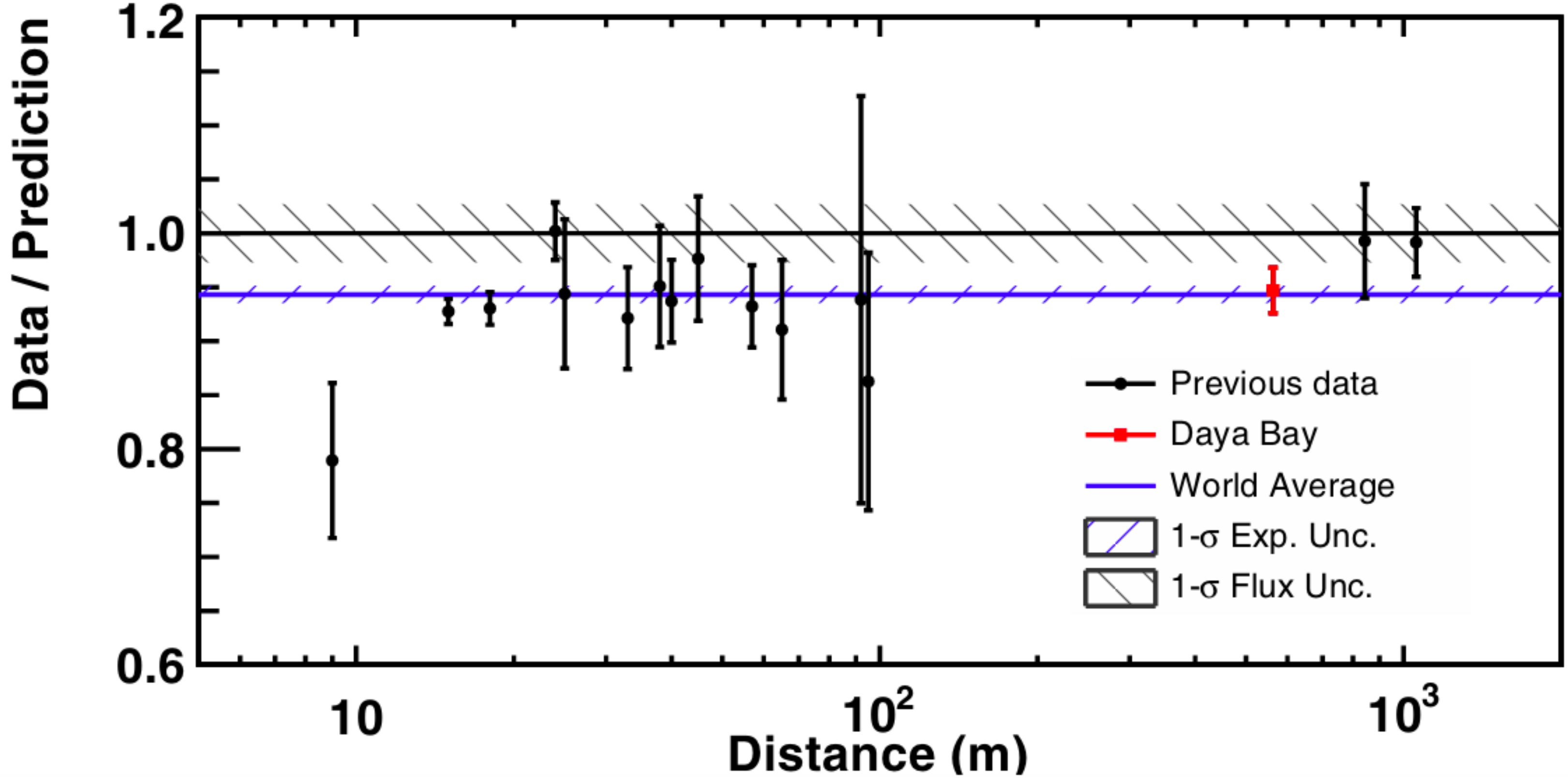
$$P = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{1.267\Delta m^2_{21}L}{E} - \sin^2 2\theta_{13}\sin^2\frac{1.267\Delta m^2_{ee}L}{E}.$$



↑ Precise measurement of both Δm^2 ("mass") and θ_{13} ("mixing") oscill. parameters in $\nu_e \to \nu_e$ channel

↑ Position of oscillation dip in L/E determines Δm^2, while depth fixes θ_{13}

Some open problems in this field... (1)



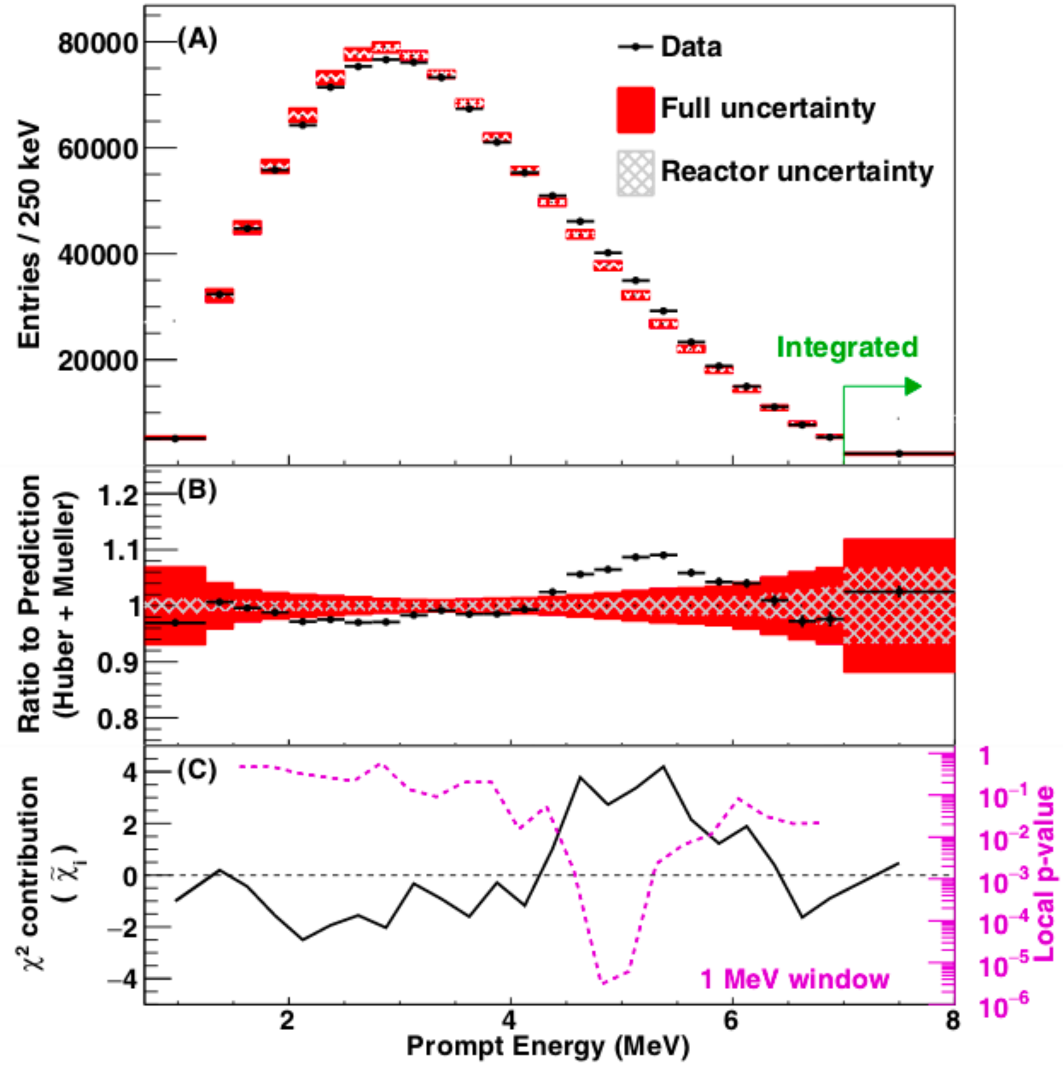
Absolute flux normalization somewhat below expectations:
overestimated flux, or fast disappearance into a new ν state?
(“reactor ν anomaly” and oscillations into “sterile neutrinos”)

Some open problems in this field… (2)

Flux spectrum shape somewhat different from expectations: ~5 MeV "bump"

Incomplete nuclear physics description of decay chains?

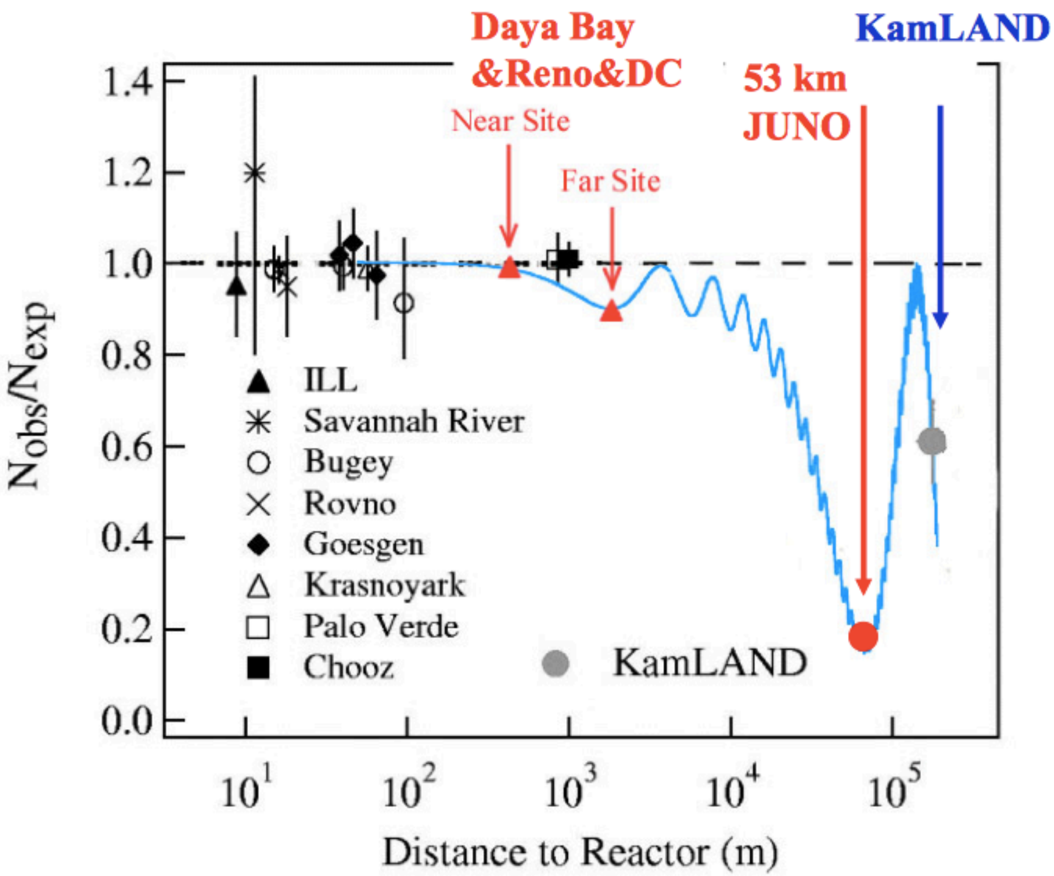
(probably unrelated to oscillations, but affects systematics)



Some open problems in this field... (3)

Can one reach the accuracy needed to observe also the oscillations driven by δm^2, as well as the interference between δm^2 and $\pm\Delta m^2$ → mass hierarchy effects?

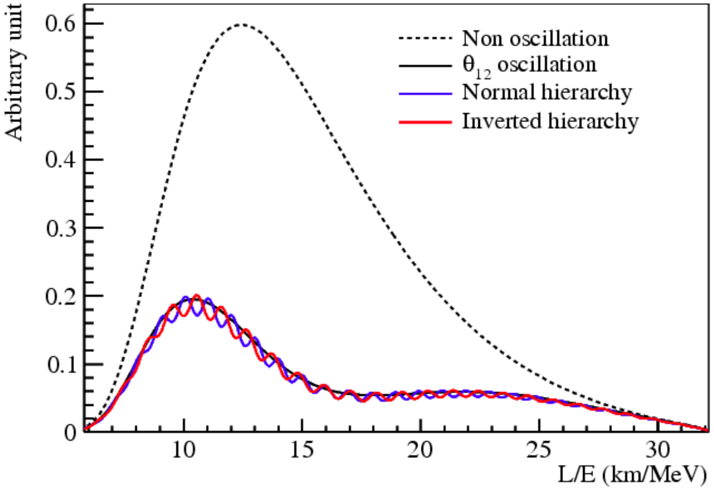
Not only a problem of accuracy but also of L/E → L~50 km ("medium baselines") needed to observe both oscillations at the same time within the reactor spectrum band width in energy



→ JUNO, RENO-50

From JUNO proposal,
arXiv:1507.05613v2, p. 36:

Hierarchy effects → advancement or retardation of "phase" ±ϕ for the fast-oscillating component



JUNO is designed to resolve the neutrino MH using precision spectral measurements of reactor antineutrino oscillations. Before giving the quantitative calculation of the MH sensitivity, we shall briefly review the principle of this method. The electron antineutrino survival probability in vacuum can be written as [69, 79, 94]:

$$
\begin{aligned}
P_{\bar\nu_e\to\bar\nu_e} &= 1-\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31}+\sin^2\theta_{12}\sin^2\Delta_{32})-\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \qquad (2.1)\\
&= 1-\frac{1}{2}\sin^2 2\theta_{13}\left[1-\sqrt{1-\sin^2 2\theta_{12}\sin^2\Delta_{21}}\cos(2|\Delta_{ee}|\pm\phi)\right]-\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21},
\end{aligned}
$$

where $\Delta_{ij}\equiv\Delta m^2_{ij}L/4E$, in which L is the baseline, E is the antineutrino energy,

$$
\sin\phi=\frac{c_{12}^2\sin(2s_{12}^2\Delta_{21})-s_{12}^2\sin(2c_{12}^2\Delta_{21})}{\sqrt{1-\sin^2 2\theta_{12}\sin^2\Delta_{21}}},\quad \cos\phi=\frac{c_{12}^2\cos(2s_{12}^2\Delta_{21})+s_{12}^2\cos(2c_{12}^2\Delta_{21})}{\sqrt{1-\sin^2 2\theta_{12}\sin^2\Delta_{21}}},
$$

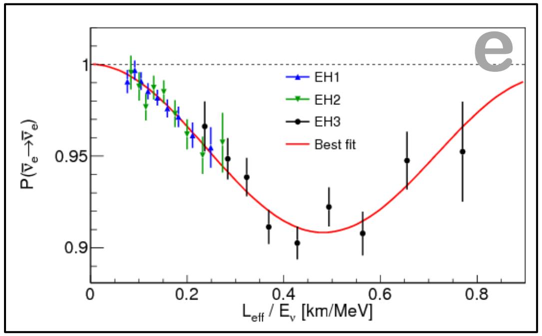
and [95, 96]

$$
\Delta m^2_{ee}=\cos^2\theta_{12}\Delta m^2_{31}+\sin^2\theta_{12}\Delta m^2_{32}\,. \qquad (2.2)
$$

(see also tutorial). **Very challenging goal, at the frontier of the field!**

Today's summary: Intro + …

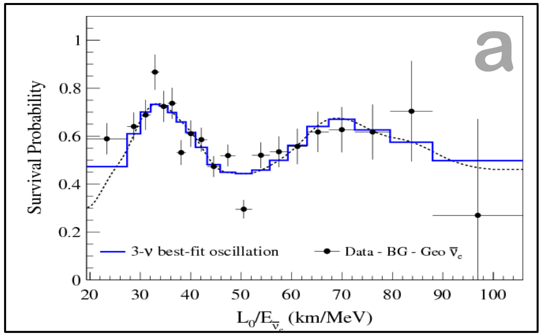
e→e (Δm^2 , θ_{13})



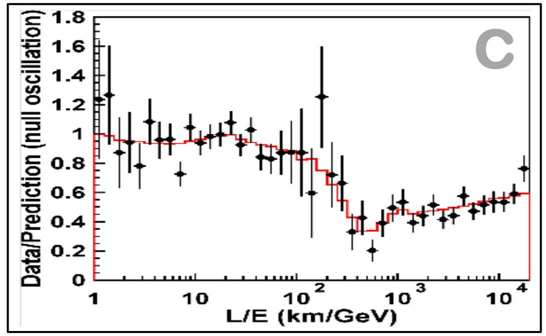
$|\Delta m^2|$ θ_{13}

Next lecture:

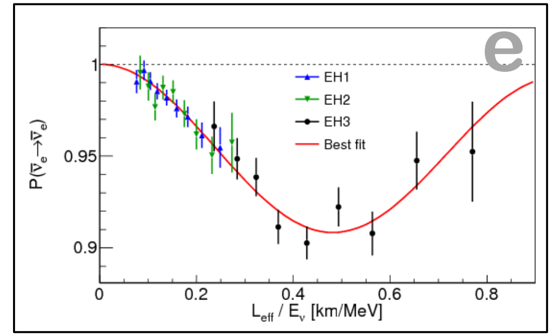
$e \rightarrow e$ (δm^2 , θ_{12})



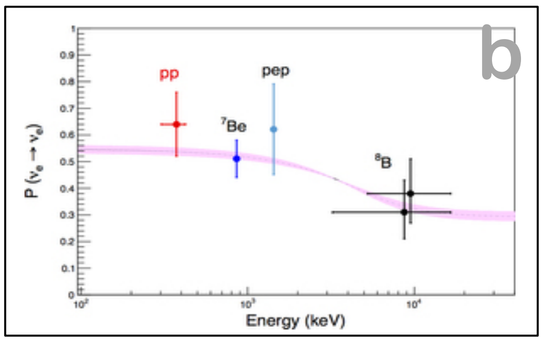
$\mu \rightarrow \mu$ (Δm^2 , θ_{23})



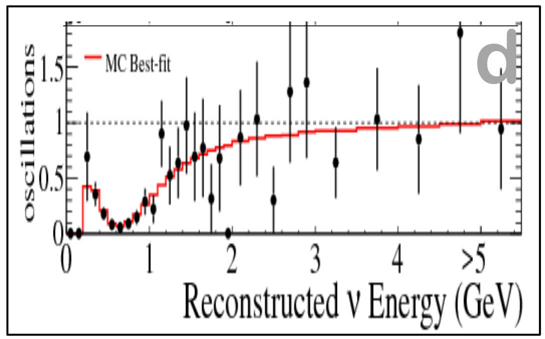
$e \rightarrow e$ (Δm^2 , θ_{13})



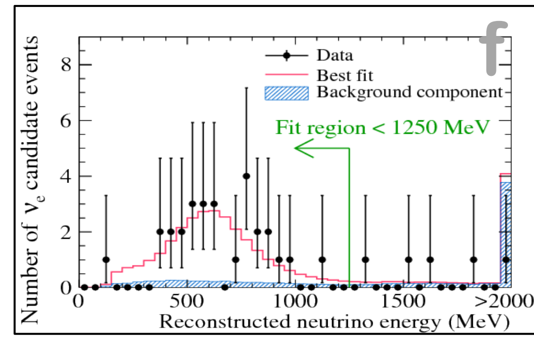
$e \rightarrow e$ (δm^2 , θ_{12})



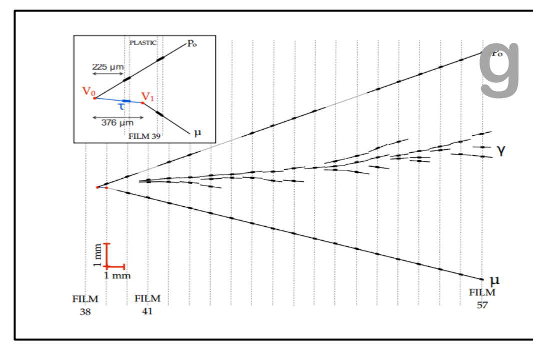
$\mu \rightarrow \mu$ (Δm^2 , θ_{23})



$\mu \rightarrow e$ (Δm^2 , θ_{13} , θ_{23})



$\mu \rightarrow \tau$ (Δm^2 , θ_{23})



δm^2 $|\Delta m^2|$ θ_{12} θ_{23} θ_{13}

+ 3ν unknowns: sign(Δm^2), sign(θ_{23}-π/4), δ

Thank you for your attention!