Neutrino phenomenology and neutrino oscillations

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I. Neutrinos and the Standard Model

II. Neutrino oscillations in vacuum

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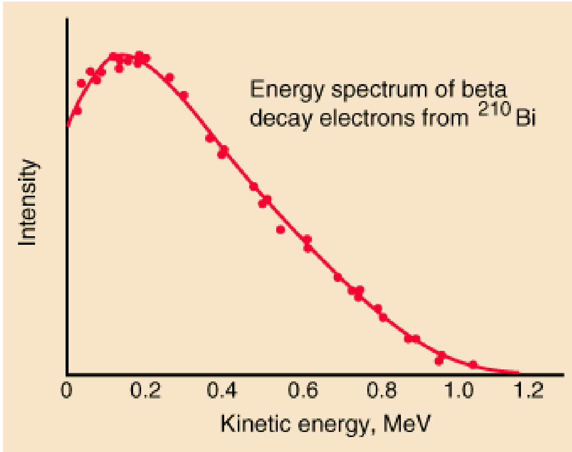
VI. Non-standard neutrino interactions

Discovery of neutrinos

- At end of 1800's radioactivity was discovered and three types of particles were identified: α, β, γ. β: an electron coming out of the radioactive nucleus.
- Energy conservation $\Rightarrow$ e^- should have had a fixed energy

$$(A, Z) \to (A, Z+1) + e^- \quad \Rightarrow \quad E_e = M(A, Z+1) - M(A, Z)$$

- But in 1914 James Chadwick showed that the electron energy spectrum is continuous:



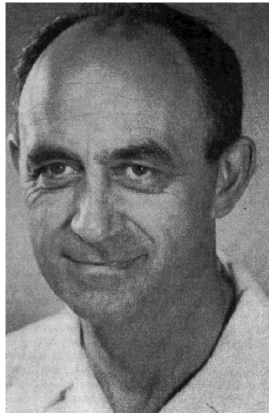
$\Rightarrow$ Do we throw away the energy conservation?

Discovery of neutrinos

- The idea of the neutrino came in 1930, when W. Pauli tried a desperate operation to save the "energy conservation principle".

In his letter addressed to the "Liebe Radioaktive Damen und Herren" (Dear Radioactive Ladies and Gentlemen), the participants of a meeting in Tübingen, he put forward the hypothesis that a new particle exists as "constituent of nuclei", the "neutron" ν, able to explain the continuous spectrum of nuclear beta decay:

$$(A, Z) \to (A, Z+1) + e^- + \nu$$



- The ν is light (in Pauli's words: "the mass of the ν should be of the same order as the e mass"), neutral and has spin 1/2;
- In order to distinguish them from heavy neutrons, Fermi proposed to name them neutrinos.

Discovery of neutrinos

- Electron (anti)neutrinos produced in **nuclear fission reactions** ($E_\nu \sim$ MeV) were firmly observed at Hanford in 1956 [1] through *inverse beta decay*: $\boxed{\bar{\nu}_e + p \to e^+ + n}$;

  ⇒ Nobel prize: Cowan & Reines, 1995

- Muon neutrinos produced in **pion decay** ($E_\nu \sim$ GeV) were detected at Brookhaven in 1962 [2] through *muon appearance*: $\boxed{\nu_\mu + n \to \mu^- + p}$ & $\boxed{\bar{\nu}_\mu + p \to \mu^+ + n}$;

  ⇒ Nobel prize: Lederman, Schwartz & Steinberger, 1988

- Tau neutrinos produced in **charmed meson decay** ($E_\nu \sim 100$ GeV) were detected by the DONUT experiment at Fermilab in 2000 [3] through *tau appearance*. Tau tracks were distinguished from muon tracks due to the fast *tau decay*, which induced a "kink" in the track after ~ 2 mm.

[1] C. L. Cowan Jr. *et al.*, Science **124** (1956) 103.
[2] G. Danby *et al.*, Phys. Rev. Lett. **9** (1962) 36.
[3] K. Kodama *et al.* [DONUT Collaboration], Phys. Lett. B **504** (2001) 218 [hep-ex/0012035].

Neutrino properties: interactions

- Already in 1934, Hans Bethe and Rudolf Peierls showed that the cross section between ν and matter is very small:

$$\sigma^{\nu N} \sim 10^{-38}\ \text{cm}^2\ \frac{E_\nu}{\text{GeV}}$$

- Let's consider for example atmospheric $\nu' s$:

$$\Phi_\nu^{\text{ATM}} = 1\ \nu \text{ per cm}^2 \text{ per second} \qquad \text{and} \qquad \langle E_\nu \rangle = 1\ \text{GeV}$$

- How many interact? In a human body:

$$N_{\text{int}} = \Phi_\nu \times \sigma^{\nu N} \times N_{\text{nucleons}}^{\text{human}} \times T_{\text{life}}^{\text{human}} \qquad (M \times T \equiv \text{Exposure})$$

$$\left.\begin{aligned} N_{\text{nucleons}}^{\text{human}} &= \frac{M^{\text{human}} \approx 80\ \text{kg}}{[\text{gr}]} \times N_A = 5 \times 10^{28}\ \text{nucleons} \\ T_{\text{life}}^{\text{human}} &= 80\ \text{years} = 2 \times 10^9\ \text{sec} \end{aligned}\right\} \begin{aligned} &\text{Exposure}_{\text{human}} \\ &\approx 6\ \text{Ton} \times \text{year} \end{aligned}$$

$$N_{\text{int}} = 1 \times (5 \times 10^{28}) \times (2 \times 10^9) \times 10^{-38} \sim \textbf{1 interaction per lifetime}$$

$\Rightarrow$ Need huge detectors with Exposure $\sim$ KTon $\times$ year

Neutrino properties: mass

- Fermi proposed a kinematic search of ν_e mass from beta spectra in ^3H beta decay:

$$^3H \to ^3He + e^- + \bar{\nu}_e$$

- For "allowed" nuclear transitions, the electron spectrum is given by phase space alone:

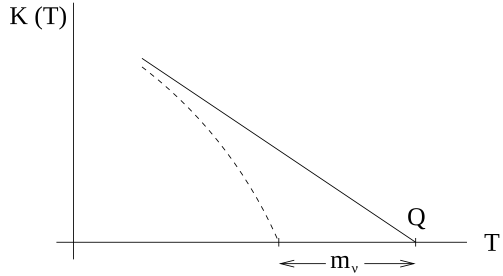
$$K(T) \equiv \sqrt{\frac{dN}{dT}\frac{1}{C p_e E_e F(E_e)}} \propto \sqrt{(Q-T)\sqrt{(Q-T)^2 - m_\nu^2}}$$

where $T = E_e - m_e$, Q = maximum kinetic energy (for ^3H beta decay $Q = 18.6$ KeV)

- $m_\nu \neq 0 \Rightarrow$ distortion from the straight-line at the end point of the spectrum

$$m_\nu = 0 \Rightarrow T_{\text{max}} = Q$$

$$m_\nu \neq 0 \Rightarrow T_{\text{max}} = Q - m_\nu$$



- At present only a bound (Mainz & Troisk experiments):
$m_{\nu_e}^{\text{eff}} \equiv \sum m_j |U_{ej}|^2 < 2.2$ eV (at 95% CL)

- Katrin proposes to improve present sensitivity to $m_{\text{eff}}^{\beta} \sim 0.2$ eV.

Neutrino properties: helicity

- The neutrino helicity was measured in 1957 in a experiment by Goldhaber et al.
- Using the electron capture reaction: (Eu=Europium, Sm=Samarium)

$$e^- + {}^{152}\mathrm{Eu} \to \nu + {}^{152}\mathrm{Sm}^*$$
$${}^{152}\mathrm{Sm}^* \to {}^{152}\mathrm{Sm} + \gamma$$

with $J({}^{152}\mathrm{Eu}) = J({}^{152}\mathrm{Sm}) = 0$, $J({}^{152}\mathrm{Sm}^*) = 1$, $L(e^-) = 0$

- Angular momentum conservation $\Rightarrow$

$$\begin{cases} J_z(e^-) = J_z(\nu) + J_z(\mathrm{Sm}^*) \\ \qquad\quad\; = J_z(\nu) + J_z(\gamma) \\ \pm 1/2 = \mp 1/2 \quad \pm 1 \end{cases} \Rightarrow \boxed{J_z(\nu) = -\frac{1}{2} J_z(\gamma)}$$

- Nuclei are heavy $\Rightarrow \vec{p}({}^{152}\mathrm{Eu}) \simeq \vec{p}({}^{152}\mathrm{Sm}) \simeq \vec{p}({}^{152}\mathrm{Sm}^*) = 0$
  so momentum conservation $\Rightarrow \vec{p}(\nu) = -\vec{p}(\gamma) \Rightarrow$ ν helicity = γ helicity
- Goldhaber et al. found γ had negative helicity $\Rightarrow$ ν has negative helicity

$\Rightarrow$ **Thus so far ν was a particle with $m_\nu = 0$ and left handed.**
(because for massless fermions helicity≡ chirality...)

Neutrinos in the Standard Model

- The SM is a gauge theory based on the symmetry group

$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

- LEP tested this symmetry to 1% precision and the missing particles t, ν_τ were found:

$(1,2)_{-1}$	$(3,2)_{1/3}$	$(1,1)_{-2}$	$(3,1)_{4/3}$	$(3,1)_{-2/3}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

Notice there is no ν_R

$\Rightarrow$ Accidental global symmetry:

$B \times L_e \times L_\mu \times L_\tau$

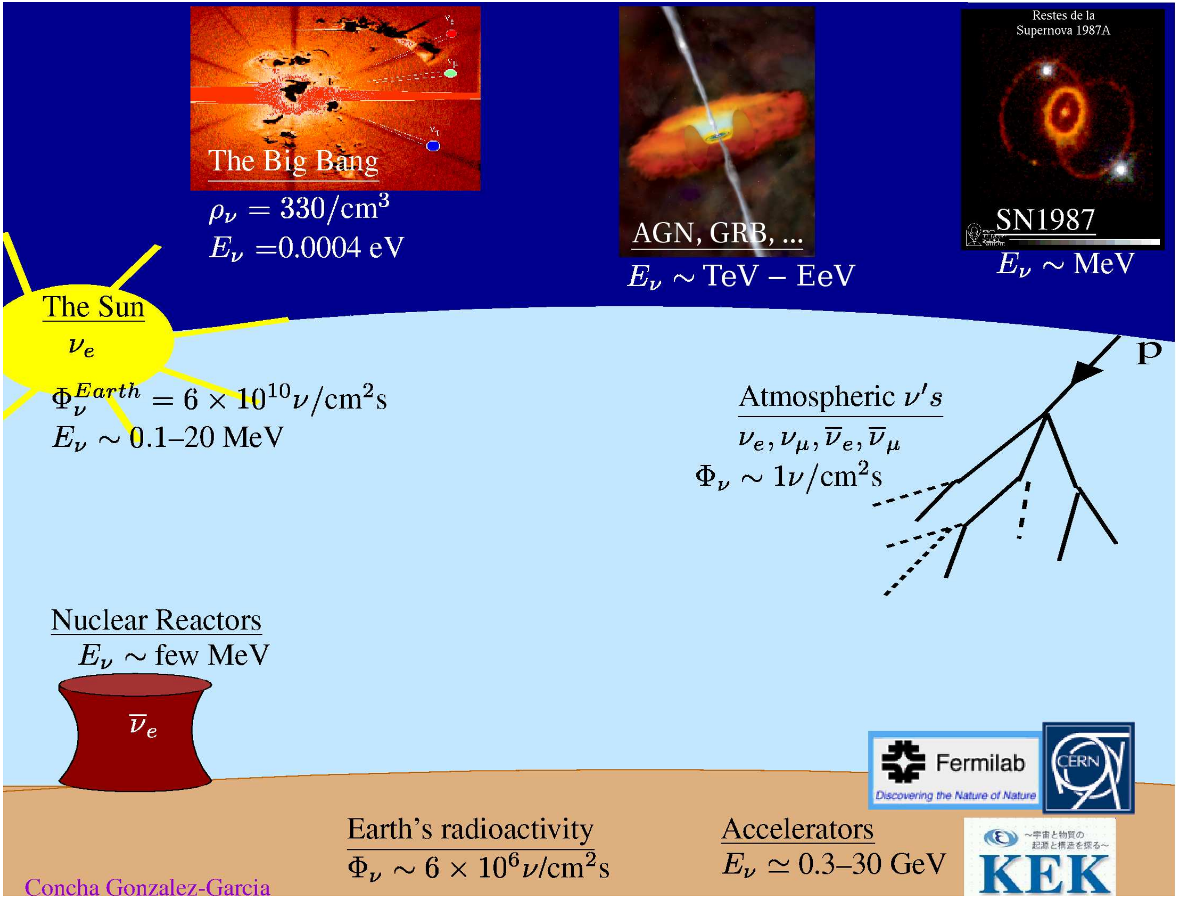
- When SM was invented upper bounds on m_ν:

$m_{\nu_e} < 2.2$ eV $\quad (^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_e)$

$m_{\nu_\mu} < 190$ KeV $\quad (\pi \to \mu + \nu_\mu)$

$m_{\nu_\tau} < 18.2$ MeV $\quad (\tau \to n\pi + \nu_\tau$, with $n > 3)$

$\Rightarrow$ Neutrinos are conjured to be **massless** and **left-handed**.



The Big Bang
$\rho_\nu = 330/\text{cm}^3$
E_ν =0.0004 eV
AGN, GRB, ...
$E_\nu \sim$ TeV – EeV
Restes de la Supernova 1987A
SN1987
$E_\nu \sim$ MeV
The Sun
ν_e
$\Phi_\nu^{Earth} = 6 \times 10^{10} \nu/\text{cm}^2\text{s}$
$E_\nu \sim$ 0.1–20 MeV
p
Atmospheric $\nu's$
$\nu_e, \nu_\mu, \overline{\nu}_e, \overline{\nu}_\mu$
$\Phi_\nu \sim 1\nu/\text{cm}^2\text{s}$
Nuclear Reactors
$E_\nu \sim$ few MeV
$\overline{\nu}_e$
Fermilab
Discovering the Nature of Nature
CERN
Earth's radioactivity
$\Phi_\nu \sim 6 \times 10^6 \nu/\text{cm}^2\text{s}$
Accelerators
$E_\nu \simeq$ 0.3–30 GeV
KEK
Concha Gonzalez-Garcia

Neutrino masses: Dirac or Majorana?

- How to write a mass term for a fermion field? Two possibilities:

Dirac

$$\mathcal{L}^{\text{D}} = -m\,(\overline{\nu_R}\,\nu_L + \overline{\nu_L}\,\nu_R)$$

- can be implemented in the SM via SSB as for up-type quarks:

$$\mathcal{L}^{\text{D}} = -Y^\ell\,\overline{L_L}\,\Phi\,\ell_R - Y^\nu\,\overline{L_L}\,\tilde{\Phi}\,\nu_R + \text{h.c.}$$

- however, it requires **new** field $\nu_R \Rightarrow$ SM extension!

Majorana

$$\mathcal{L}^{\text{M}} = -\frac{1}{2}m\left(\overline{\nu_L^C}\,\nu_L + \overline{\nu_L}\,\nu_L^C\right)$$

- only ν_L used $\Rightarrow$ no new field required;
- breaks gauge simmetries $\Rightarrow$ unthinkable for **charged** particles (Q is conserved);
- can't be written explicitly in the SM $\Rightarrow$ should be generated *effectively* $\Rightarrow$ SM extension!

- both possibilities are phenomenologically viable $\Rightarrow$ most general case is to use both:

$$\mathcal{L} = -Y^\ell\,\overline{L_L}\,\Phi\,\ell_R - Y^\nu\,\overline{L_L}\,\tilde{\Phi}\,\nu_R - \frac{1}{2}M\,\overline{\nu_R^C}\,\nu_R + \text{h.c.}$$

- ν_R is a singlet under SM symmetries $\Rightarrow$ can have an explicit Majorana mass.

Effects of neutrino masses: oscillations

- If neutrinos have mass, a weak eigenstate $|\nu_\alpha\rangle$ produced in $l_\alpha + N \to \nu_\alpha + N'$ is a linear combination of the mass eigenstates ($|\nu_i\rangle$): $|\nu_\alpha\rangle = \sum_{i=1}^{n} U_{\alpha i}\, |\nu_i\rangle$;
- After a distance L (or time t) it evolves $|\nu(t)\rangle = \sum_{i=1}^{n} U_{\alpha i}\, e^{-i\, E_i t}\, |\nu_i\rangle$;
- it can be detected with flavor β with probability $P_{\alpha\beta} = |\langle \nu_\beta | \nu(t)\rangle|^2$:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{j\neq i}^{n} \text{Re}\left[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}\right] \sin^2\left(\frac{\Delta_{ij}}{2}\right) + 2 \sum_{j\neq i}^{n} \text{Im}\left[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}\right] \sin\left(\Delta_{ij}\right) ,$$

$$\frac{\Delta_{ij}}{2} = \frac{(E_i - E_j)L}{2} = 1.27\, \frac{(m_i^2 - m_j^2)}{\text{eV}^2}\, \frac{L/E}{\text{Km/GeV}}$$

- $P_{\alpha\beta}$ depends on *Theoretical* Parameters
  - $\Delta m^2_{ij} = m_i^2 - m_j^2$ The mass differences
  - $U_{\alpha j}$ The mixing angles

  and on Two *Experimental* Parameters:
  - E The neutrino energy
  - L Distance ν source to detector
- no information on mass scale nor Dirac/Majorana nature.

Two-neutrino oscillations in vacuum

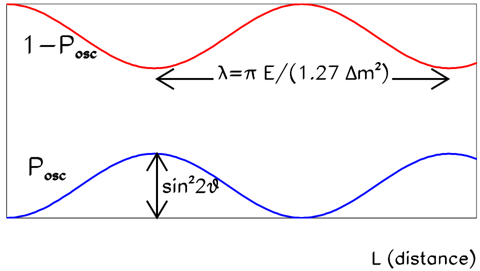
- Equation of motion (**2** parameters): $i\dfrac{d\vec{\nu}}{dt} = \mathbf{H}\,\vec{\nu};\qquad \mathbf{H} = \mathbf{U}\cdot\mathbf{H}_0^d\cdot\mathbf{U}^\dagger;$

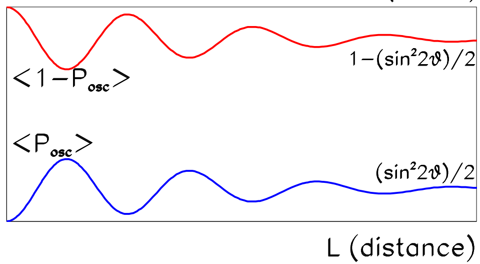
$$\mathbf{O} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \qquad \mathbf{H}_0^d = \frac{1}{2E_\nu}\begin{pmatrix} -\Delta m^2 & 0 \\ 0 & \Delta m^2 \end{pmatrix}, \qquad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_X \end{pmatrix};$$

- $P_{osc} = \sin^2(2\theta)\ \sin^2\left(1.27\,\dfrac{\Delta m^2 L}{E_\nu}\right)$, $P_{\alpha\alpha} = 1 - P_{osc}$;
- In real experiments ν's are not monochromatic:

$$\langle P_{\alpha\beta}\rangle = \frac{1}{\mathcal{N}}\int dE_\nu \frac{d\Phi}{dE_\nu}\sigma_{CC}(E_\nu)P_{\alpha\beta}(E_\nu)$$

- Maximal sensitivity for $\Delta m^2 \sim E_\nu/L$;
- $\Delta m^2 \ll E_\nu/L \Rightarrow$ No time to oscillate $\Rightarrow \langle P_{osc}\rangle \simeq 0$;
- $\Delta m^2 \gg E_\nu/L \Rightarrow$ Averaged osc. $\Rightarrow \langle P_{osc}\rangle \simeq \frac{1}{2}\sin^2(2\theta)$.



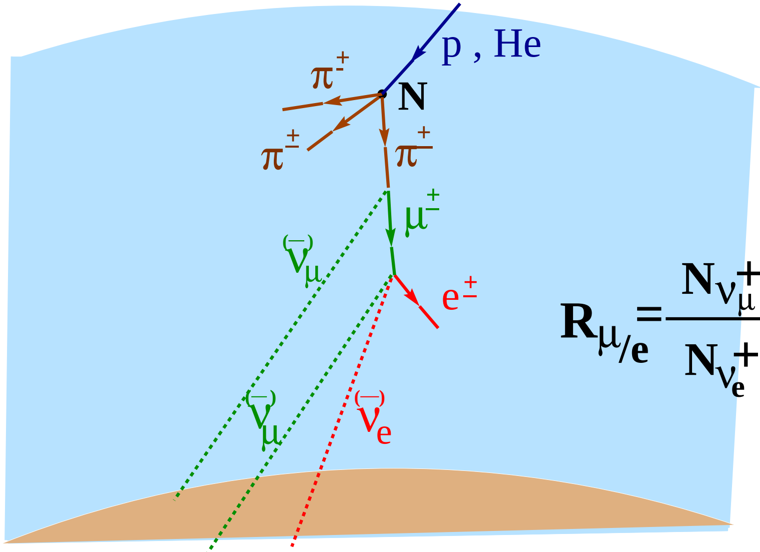


Atmospheric neutrinos

- Atmospheric neutrinos are produced by the interaction of *cosmic rays* (p, He, ...) with the Earth's atmosphere:

1	$A_{cr} + A_{air} \to \pi^\pm, K^\pm, K^0, \dots$
2	$\pi^\pm \to \mu^\pm + \nu_\mu$,
3	$\mu^\pm \to e^\pm + \nu_e + \nu_\mu$;

- at the detector, some ν interacts and produces a **charged lepton**, which is observed.



$$R_{\mu/e} = \frac{N_{\nu_\mu} + N_{\bar\nu_\mu}}{N_{\nu_e} + N_{\bar\nu_e}} \sim 2$$

Physics content of atmospheric data

$$N_{\text{bin}}(\vec{\omega}) = n_t T \sum_{\alpha,\beta,\pm} \int_0^\infty dh \int_{-1}^{+1} dc_\nu \int_{E_{\text{min}}}^\infty dE_\nu \int_{E_{\text{min}}}^{E_\nu} dE_l \int_{-1}^{+1} dc_a \int_0^{2\pi} d\varphi_a$$
$$\frac{d^3\Phi_\alpha^\pm}{dE_\nu\, dc_\nu\, dh}(E_\nu, c_\nu, h)\, P^\pm_{\alpha\to\beta}(E_\nu, c_\nu, h \,|\, \vec{\omega})\, \frac{d^2\sigma_\beta^\pm}{dE_l\, dc_a}(E_\nu, E_l, c_a)\, \varepsilon_\beta^{\text{bin}}(E_l, c_l(c_\nu, c_a, \varphi_a))$$

- Atmospheric neutrino data are a convolution of:
  - neutrino fluxes;
  - neutrino oscillation probabilities: { oscillation parameters $\vec{\omega}$; Earth matter density profile; }
  - neutrino cross-section and details of the detector.

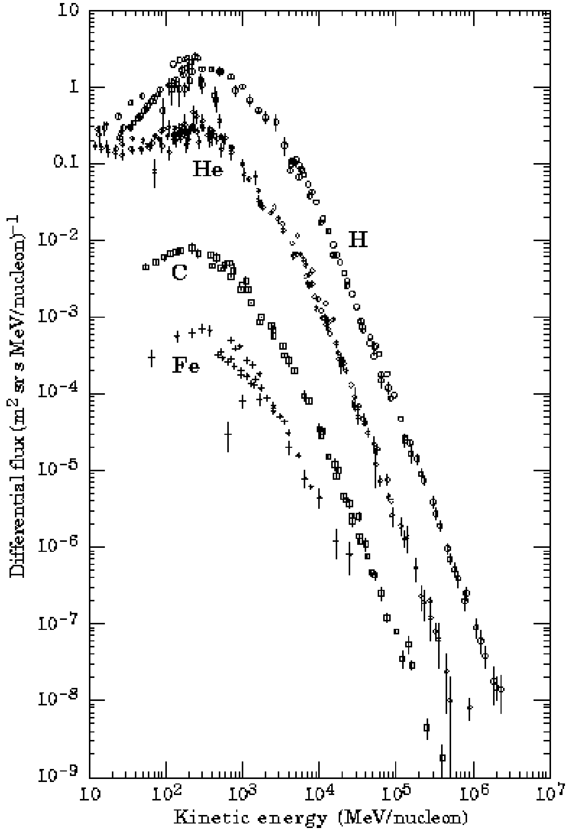
The situation until now:

- ν fluxes, Earth profile and ν cross-sections were known with some accuracy;
- oscillation parameters were **not** known;

$\Rightarrow$ atmospheric data successfully used to extract info on oscillation parameters.

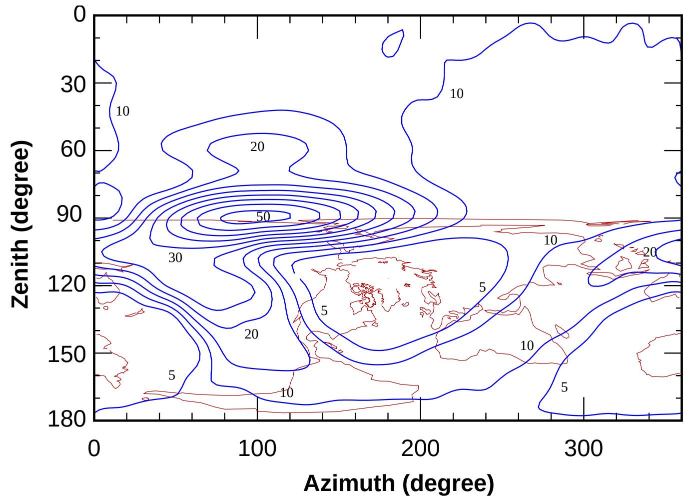
Atmospheric neutrino flux: primary spectrum

- *Composition*:
  - mainly *protons*, however it varies with energy;
  - up to ≈ 100 TeV: 79% protons, 3% helium, ...
- *Energy dependence*: above a few GeV $\frac{d\phi}{dE} \propto E^{-3.7}$;
- *Solar modulation*:
  - solar wind prevents low-energy ($\approx$ 10 GeV) cosmic rays from the inner solar system to reach the Earth;
  - therefore, there is an anticorrelation between the 11-year solar cycle and the intensity of cosmic ray below 10 GeV;
  - MAX–MIN flux diff: $\begin{cases} > 100\% \text{ around 1 GeV;} \\ \approx 10\% \text{ at 10 GeV.} \end{cases}$



Atmospheric neutrino flux: geomagnetic field effects

- lower energy cosmic rays are affected by the *geomagnetic field*;
- near the *geomagnetic pole*, almost all primary particle can reach the atmosphere by moving along the field lines;
- on the other hand, close to the *geomagnetic equator* only particles with high (> a few GeV) energy can penetrate;
- key parameter: **magnetic rigidity** $\mathcal{R} = \frac{pc}{Ze}$.

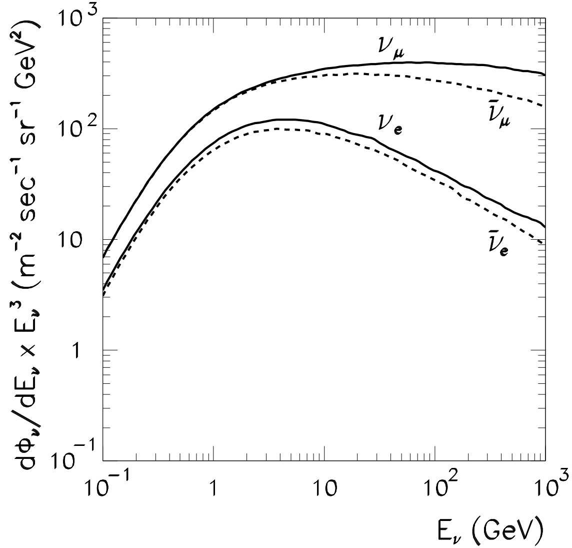


- for fixed azimuth angle, the rigidity cutoff grows from *zero* at the *geomagnetic pole* to its *maximum* at the *geomagnetic equator*;
- the rigidity cutoff is *lower* for particle traveling *eastward* and *higher* for particle travelling *westward*.

Atmospheric neutrino flux: neutrino production

- Interaction of cosmic rays with the air nuclei produces mesons, which decay producing neutrinos:

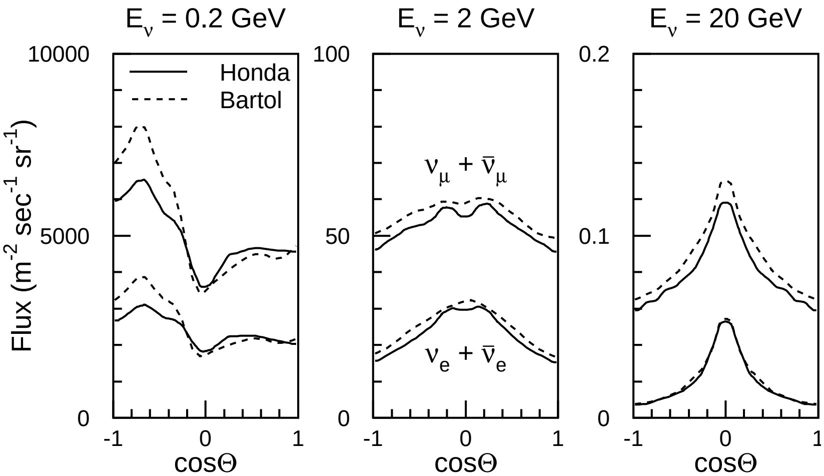
$$\pi^-, K^- \to \mu^- + \bar{\nu}_\mu, \qquad \mu^- \to e^- + \bar{\nu}_e + \nu_\mu;$$
$$\pi^+, K^+ \to \mu^+ + \nu_\mu, \qquad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu;$$



- *approximate power law*:
  - $E \gtrsim 1$ GeV: $\dfrac{d\Phi}{dE} \propto E^{-\gamma}$, $\gamma \sim 3\ (3.5)$ for ν_e (ν_μ);
  - $E \lesssim 1$ GeV: energy dependence weaker due to *solar modulation* and *geomagnetic effects*;
- *$\bar{\nu}/\nu$ ratio*:
  - cosmic rays are p (**not** $\bar{p}$) which produce, on average, more π^+ than π^-;
  - low E: both π and μ decay $\Rightarrow$ we expect $\bar{\nu}_e/\nu_e = \pi^-/\pi^+ < 1$ and $\bar{\nu}_\mu/\nu_\mu = \pi^\pm/\pi^\pm = 1$;
  - high E: secondary μ reach Earth $\Rightarrow$ only $\pi^\pm$ decays give $\nu \Rightarrow \bar{\nu}_\mu/\nu_\mu \simeq \pi^-/\pi^+ < 1$.

Atmospheric neutrino flux: zenith distribution

- $(\nu_\mu + \bar\nu_\mu) / (\nu_e + \bar\nu_e)$ *ratio*:
  - low E: ratio very close to 2;
  - high E: secondary μ reach Earth $\Rightarrow$ ratio increases;
- *up-down ratio*:
  - low E: *asymmetry* due to geo-magnetic field effects;
  - high E: symmetry restored;



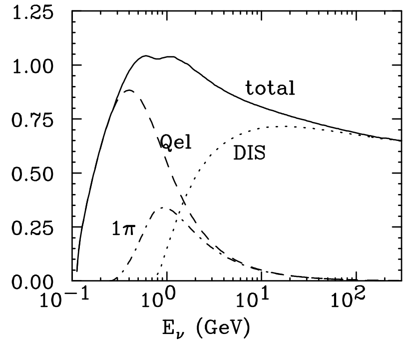
- *horizontal-vertical ratio*:
  - *horizontal* $\pi^\pm$ travel longer in a less dense atmosphere than *vertical* ones;
  - hence horizontal $\pi^\pm$ have higher probability of decaying before interacting with air;
  - therefore, for $E \gtrsim 1$ GeV the fluxes are higher for *horizontal* than for *vertical* ν.

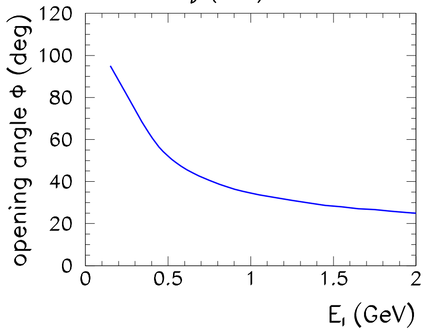
Neutrino-nucleon cross-section

- Charged-current neutrino-nucleon interactions:

	neutrino ν_l	*antineutrino* $\bar\nu_l$
– QE:	$\nu_l + n \to l^- + p$	$\bar\nu_l + p \to l^+ + n$
– 1π:	$\nu_l + p \to l^- + (p + \pi^+)$ $\nu_l + n \to l^- + (p + \pi^0)$ $\nu_l + n \to l^- + (n + \pi^+)$	$\bar\nu_l + n \to l^+ + (n + \pi^-)$ $\bar\nu_l + p \to l^+ + (n + \pi^0)$ $\bar\nu_l + p \to l^+ + (p + \pi^-)$
– DIS:	$\nu + N \to l^- + X$	$\bar\nu + N \to l^+ + X$

- in all these processes a charged lepton is produced;
- the detection occurs *by identifying the produced lepton*;
- QE (DIS) cross-section dominates at low (high) energy.



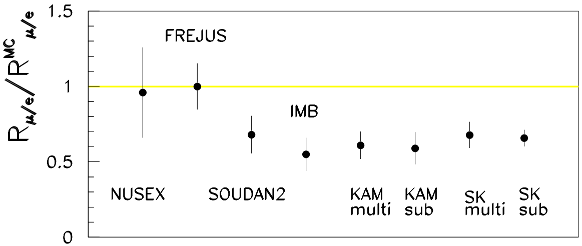


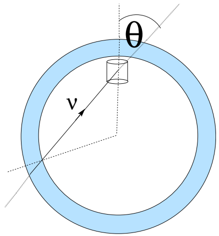
Angular distribution

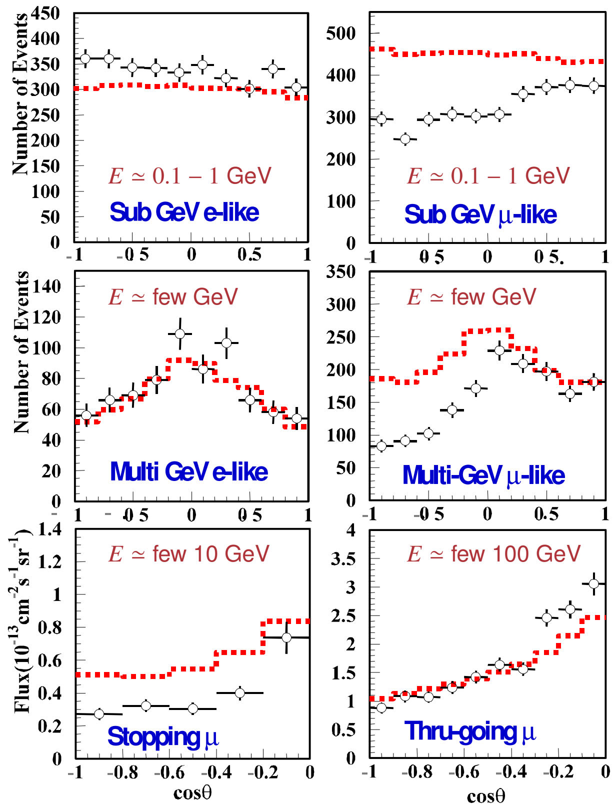
- Low E: the scattering angle between the incoming neutrino and the outgoing lepton is large $\Rightarrow$ the information on the original neutrino direction is lost;
- high E: outgoing lepton almost collinear with the incoming neutrino.

Atmospheric neutrinos: experimental status

- historically:
  - – no deficit in iron calorimeters;
  - – deficit in water Cerenkov;
- possibly a mistake in water Cerenkov?
- ambiguity resolved by Soudan2 and MACRO;
- present data (SK): agreement in ν_e, deficit in ν_μ;
- SK deficit in ν_μ:
  - – grows with L;
  - – decreases with E_ν;
- solution: $\nu_\mu \to \nu_\tau$ two-neutrino oscillations.





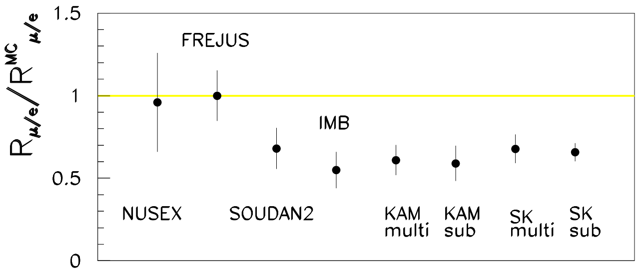


Atmospheric ν Oscillations: Parameter Estimate

- Data: $\begin{cases} \nu_e\text{: good agreement with SM;} \\ \nu_\mu\text{: visible deficit at low energy;} \end{cases}$

$\Rightarrow$ oscillations in the $\nu_\mu \to \nu_X$ channel.

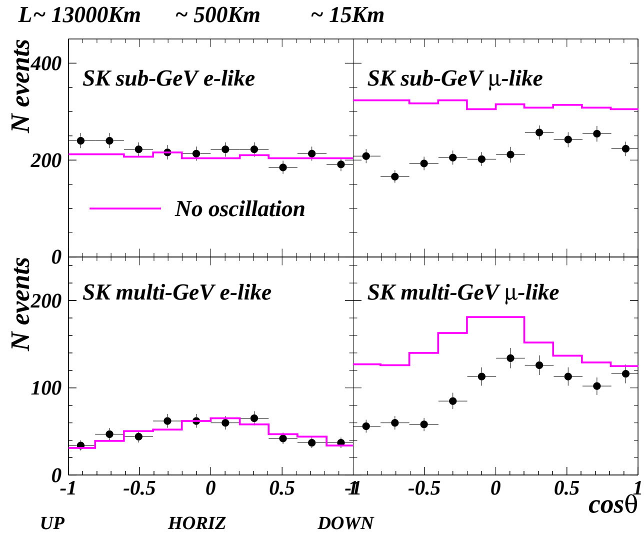
- From Total Contained Event Rates:



- $\langle P_{\mu\mu} \rangle = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{2E}\right)$
  $\sim 0.5 \div 0.7$

$\Rightarrow \sin^2(2\theta) \gtrsim 0.6$;

- From Angular Distribution:



- For $E \sim 1$ GeV:
  deficit at $L \sim 10^2 \div 10^4$ Km:

$$\frac{\Delta m^2(\text{eV}^2) L(\text{km})}{2E(\text{GeV})} \sim 1$$

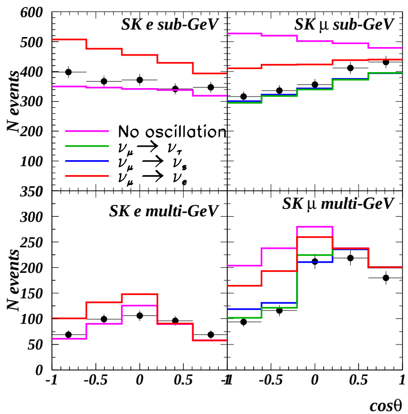
$\Rightarrow \Delta m^2 \sim 10^{-4} \div 10^{-2}$ eV^2.

Atmospheric ν Oscillation Analysis

- Three possible oscillation channels: $\nu_\mu \to \nu_e$, $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_{\text{sterile}}$;

$\nu_\mu \to \nu_e$

- The angular distribution for Contained:

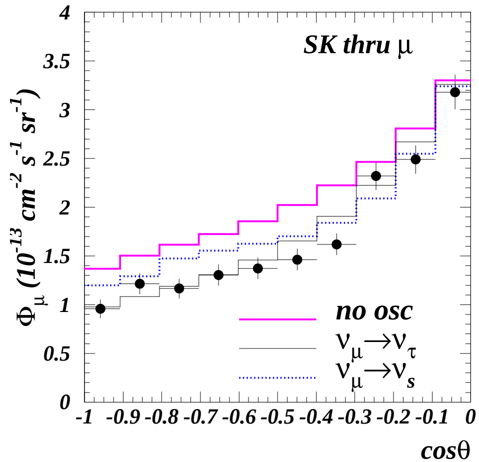


- not enough up-down asymmetry for μ's;
- excess of e-like events;

$\Rightarrow$ **ruled out.**

$\nu_\mu \to \nu_{\text{sterile}}$

- The angular distribution for Thru-Going μ:

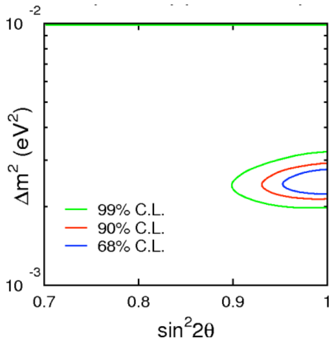


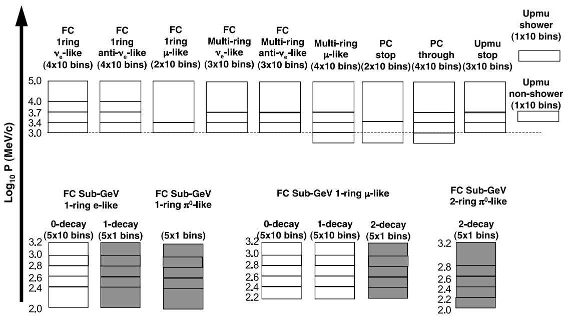
- matter effects $\Rightarrow$ Flatter distribution;

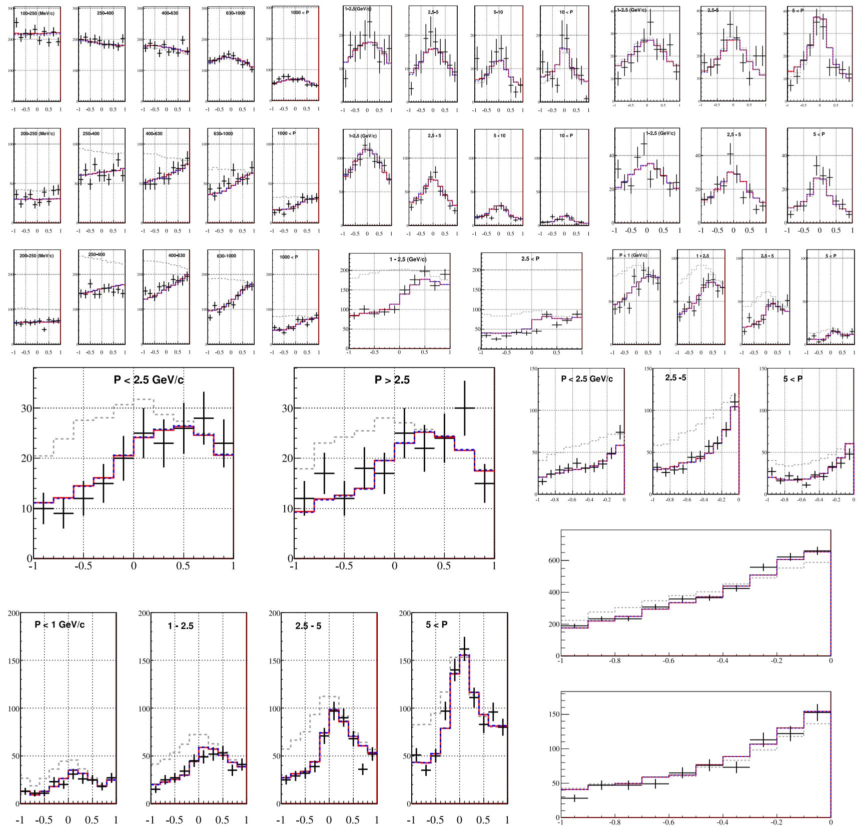
$\Rightarrow$ **ruled out.**

Atmospheric neutrinos: where we are

- SK(1–4) data: 480 bins defined by flavor, charge, topology, momentum, . . . ;
- channel: $\nu_\mu \to \nu_\tau$;
- perfect fit with just 2 params: $(\Delta m^2, \theta)$.





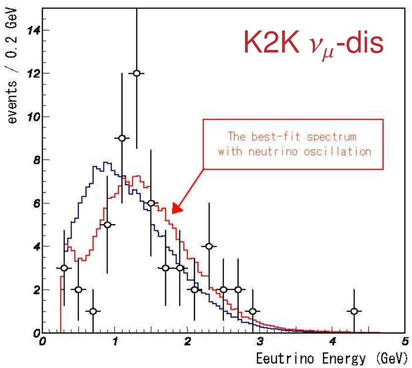


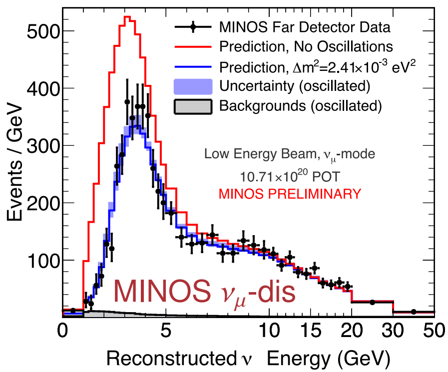
Accelerator neutrino experiments

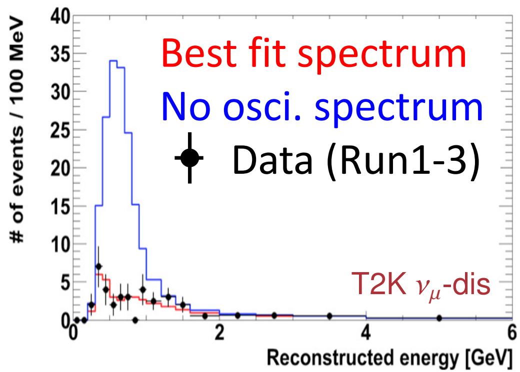
- p + target $\to$ stuff + $\pi^\pm$, then $\pi^\pm \to \mu^\pm + \nu_\mu$ (decay $\mu^\pm \to e^\pm + \nu_e + \nu_\mu$ not exploited);
- detection: focus on ν_μ disappearance and ν_e appearance. For the former:

Exper	Length	Energy	No-osc	Observed	Detector
K2K	250 km	1 GeV	88 (ν_μ)	56 (ν_μ)	single-ring μ-like events in SK
MINOS	735 km	3 GeV	3564 (ν_μ) 464 ($\bar\nu_\mu$)	2894 (ν_μ) 357 ($\bar\nu_\mu$)	dedicated far detector
T2K	295 km	0.6 GeV	196 (ν_μ)	58 (ν_μ)	single-ring μ-like events in SK

- Result: various experiments observed a clear **energy-dependent** ν_μ deficit.

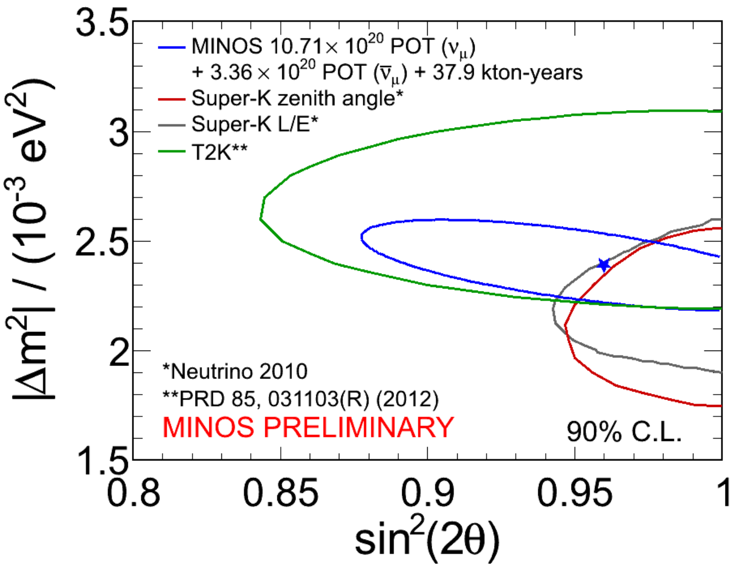


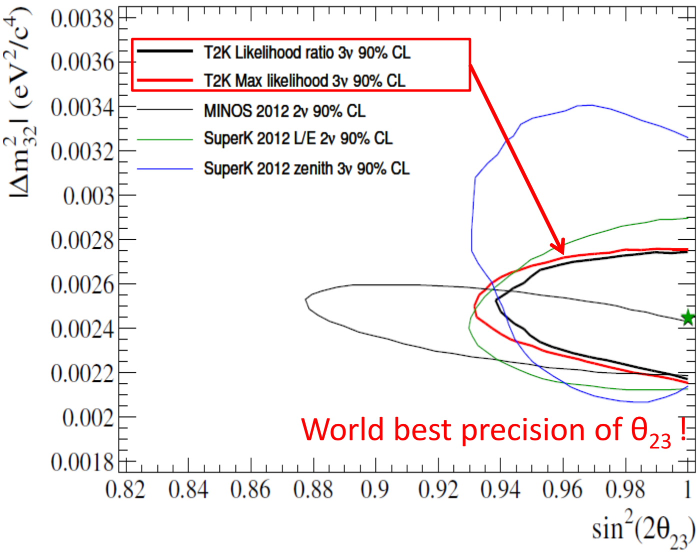




Joint interpretation of atmospheric and accelerator (ν_μ) data

- Hypothesis: $\nu_\mu \to \nu_\tau$ mass-induced oscillations;
- CPT conservation $\Rightarrow$ same behavior of ν and $\bar{\nu}$ in atmospheric and accelerator data;
- model perfectly explains all the data with only two parameters: $(\Delta m^2_{\text{atm}}, \theta_{\text{atm}})$.



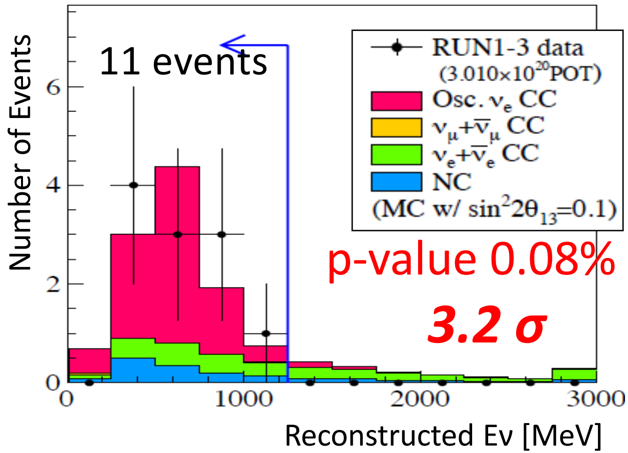


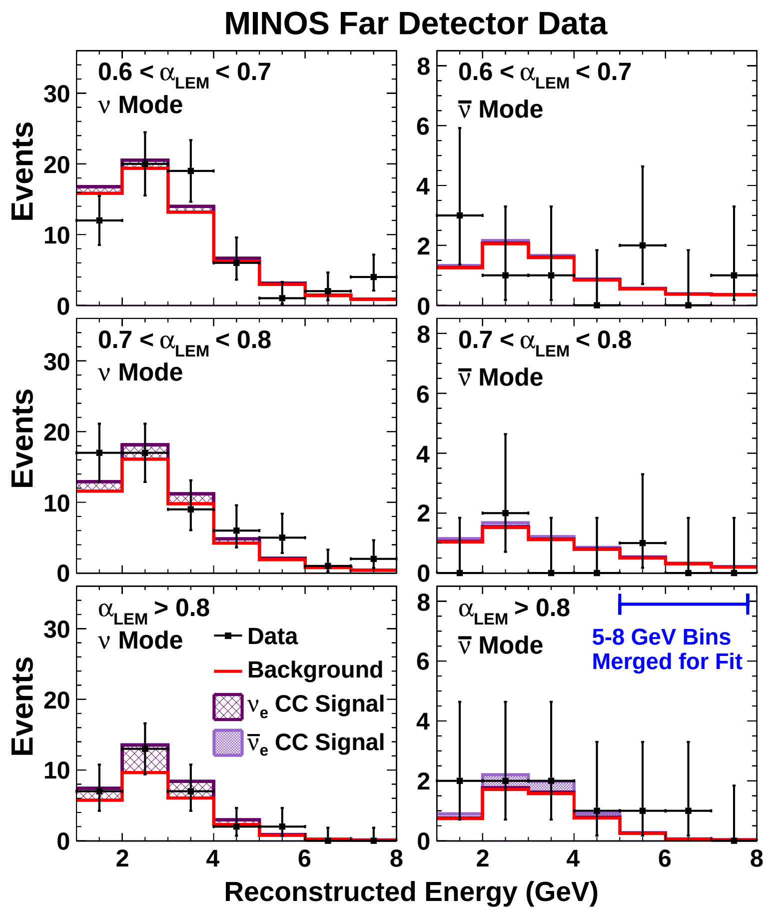
Accelerator experiments: ν_e

- Minos and T2K $\nu_\mu \to \nu_e$ appearance:

Exper	No-osc	Observed
MINOS	69 (ν_e) 10 $(\bar{\nu}_e)$	88 (ν_e) 12 $(\bar{\nu}_e)$
T2K	2.8 (ν_e)	11 (ν_e)

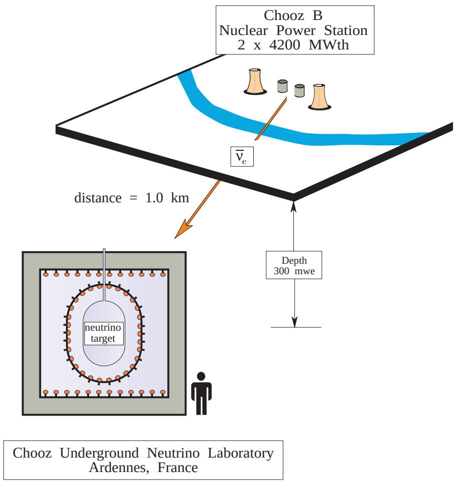
- both observe clear ν_e excess . . .

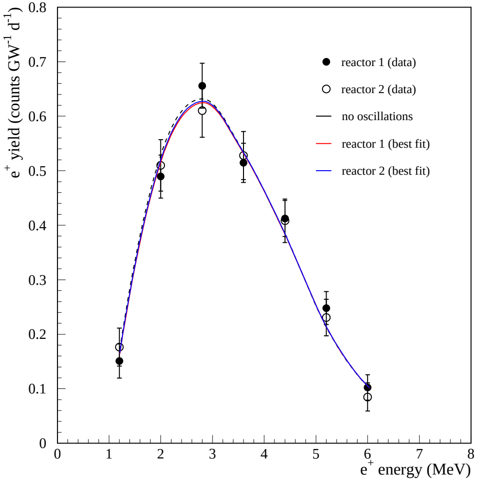


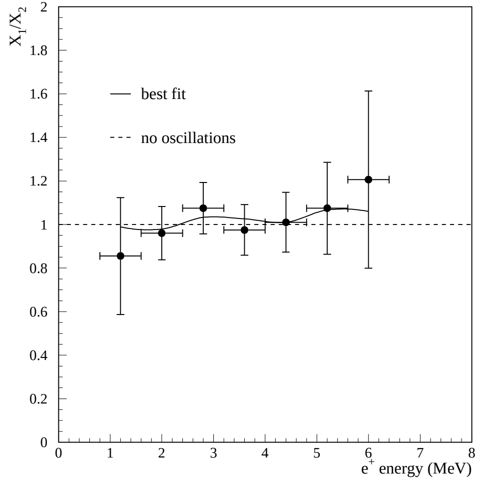


Long-baseline reactor experiments: until 2011

- Electron antineutrinos ($\bar{\nu}_e$) produced by nuclear fission in reactor's core;
- CHOOZ: search for $\bar{\nu}_e$ disappearance, $\langle L \rangle \approx 1$ km; data taken from 04/1997 to 07/1998;
- target: 5 tons liquid scintillator loaded with **gadolinium** (improves neutron capture);
- detection: inverse beta decay ($\bar{\nu}_e + p \to e^+ + n$), both e^+ and n observed;
- result: perfect agreement with theoretical expectations without neutrino conversion.

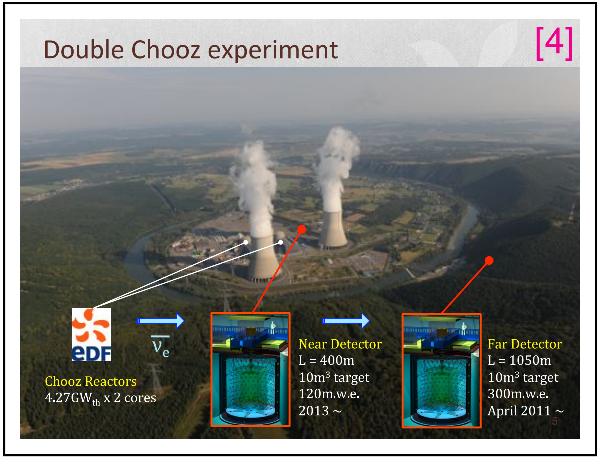


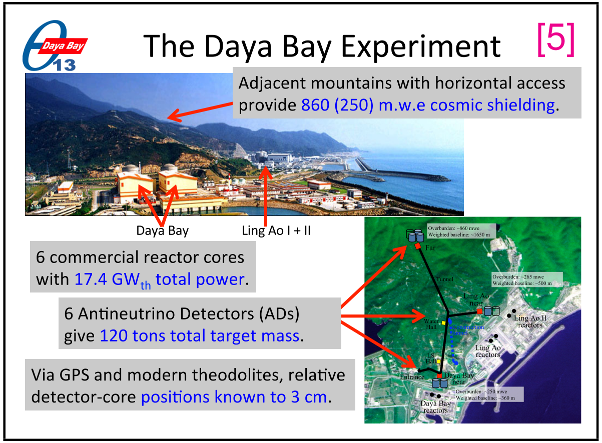


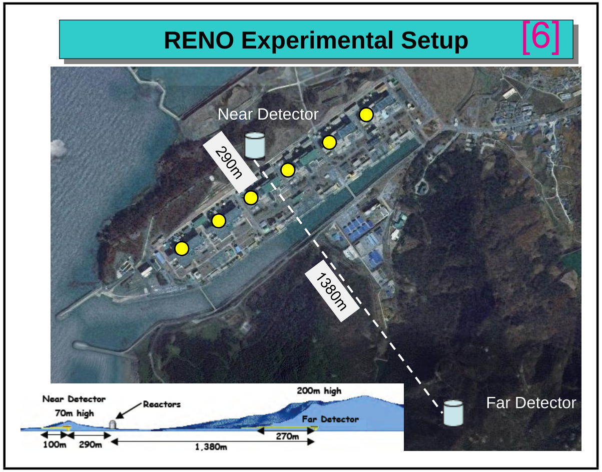


2012: a new generation of reactor exps

- At the end of 2011 – beginning of 2012 **three** new reactor experiments presented their first data;
- sensitivity greatly increased w.r.t. CHOOZ.



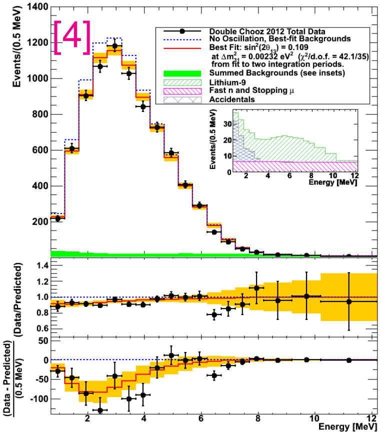


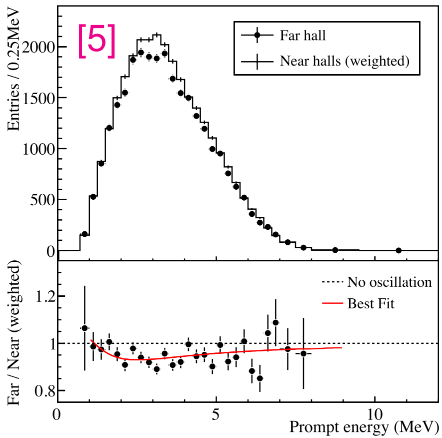


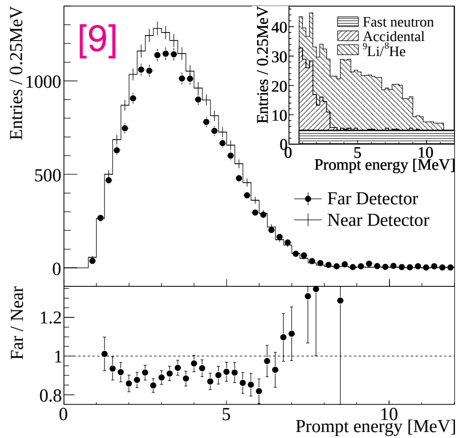
[4] M. Ishitsuka [DOUBLE-CHOOZ], talk at Neutrino 2012.
[5] D. Dwyer [DAYA-BAY], talk presented at Neutrino 2012.
[6] S.B. Kim [RENO], talk presented at Neutrino 2012.

LBL reactor experiments: the 2012 revolution

- Until summer 2011, only CHOOZ [7] and PALO-VERDE [8] **upper limits** available;
- since then: **positive signal** from DOUBLE-CHOOZ [4], DAYA-BAY [5], RENO [9];
- present status: $\underline{\theta_{13} \neq 0 \; @ \; 9\sigma}$ after inclusion of the data presented at Neutrino 2012.







[7] M. Apollonio *et al.* [CHOOZ], Eur. Phys. J. C **27** (2003) 331 [hep-ex/0301017].

[8] F. Boehm *et al.* [PALO-VERDE], Phys. Rev. D **64** (2001) 112001 [hep-ex/0107009].

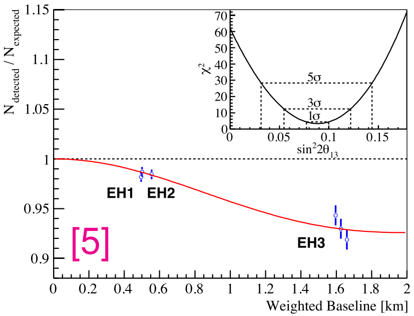
[4] M. Ishitsuka [DOUBLE-CHOOZ], talk presented at Neutrino 2012, Kyoto, Japan, June 3-9, 2012.

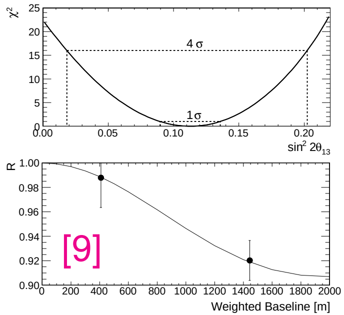
[5] D. Dwyer [DAYA-BAY], talk presented at Neutrino 2012, Kyoto, Japan, June 3-9, 2012.

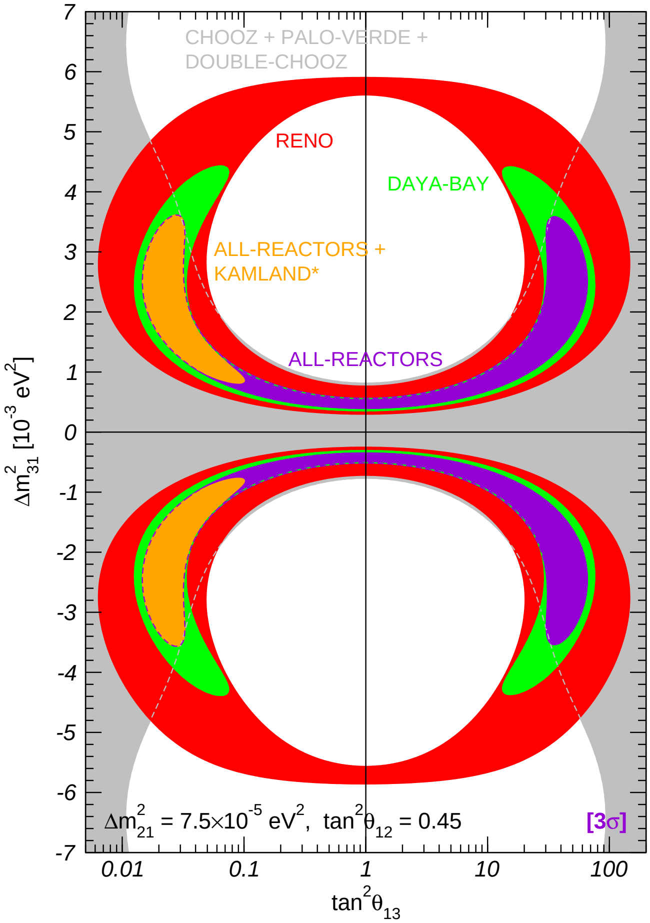
[9] J.K. Ahn *et al.* [RENO], Phys. Rev. Lett. **108** (2012) 191802 [arXiv:1204.0626].

ν oscillations at reactors

- New oscillation channel: $\nu_e \to \nu_e \Rightarrow$ same Δm^2_{atm} as ATM, but different angle θ_{rea};
- sizable deficit at the **far** detector $\Rightarrow$ oscillations $\Rightarrow$ **lower** bound on θ_{rea} and Δm^2_{atm};
- smaller deficit at the **near** detector $\Rightarrow$ not-too-much oscillations $\Rightarrow$ **upper** bound on Δm^2_{atm}.





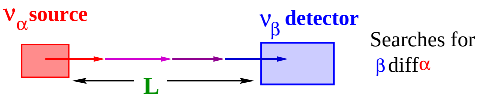


[5] D. Dwyer [DAYA-BAY], talk at Neutrino 2012.
[9] J.K. Ahn *et al.* [RENO], Phys. Rev. Lett. **108** (2012) 191802 [arXiv:1204.0626].

Laboratory Searches at Short Distance

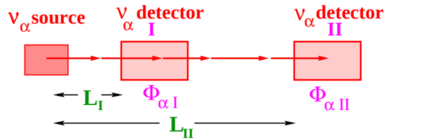
- ν source in laboratory experiments: Accelerator or Nuclear Reactor.

Appearance Experiments



Experiment	$\langle\frac{E/\text{MeV}}{L/\text{m}}\rangle$	Facility	α	β
CCFR	100	FNAL	ν_μ, ν_e	ν_τ
E531	25	FNAL	ν_μ, ν_e	ν_τ
Nomad	13	CERN	ν_μ, ν_e	ν_τ
Chorus	13	CERN	ν_μ, ν_e	ν_τ
E776	2.5	BNL	ν_μ	ν_e
Karmen2	2.5	Rutherford	$\bar{\nu}_\mu$	$\bar{\nu}_e$
LSND	3	Los Alamos	$\bar{\nu}_\mu$	$\bar{\nu}_e$

Disappearance Experiments

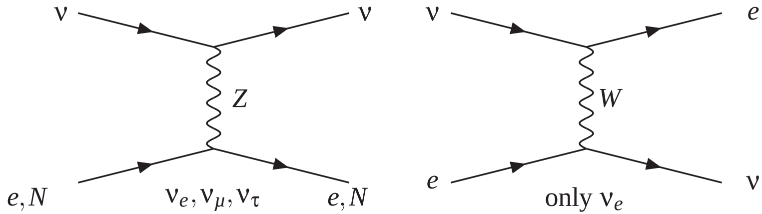


Compares $\Phi_{\alpha\,I}$ and $\Phi_{\alpha\,II}$ to look for loss

Experiment	$\langle\frac{E/\text{MeV}}{L/\text{m}}\rangle$	Facility	α
CDHSW	1.4	CERN	ν_μ
BugeyIII	0.05	Reactor	$\bar{\nu}_e$
Chooz	0.005	Reactor	$\bar{\nu}_e$

Two-neutrino oscillations in matter

- If ν cross matter regions (Sun, Earth...) it interacts *coherently*
- But different flavors have different interactions:



- To include this effect: potential in the evolution equation

$$i\frac{d}{dt}\begin{pmatrix}\nu_e \\ \nu_X\end{pmatrix} = \left[\frac{\Delta m^2}{4E_\nu}\begin{pmatrix}-\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta\end{pmatrix} \pm \begin{pmatrix}V_e & 0 \\ 0 & V_X\end{pmatrix}\right] \cdot \begin{pmatrix}\nu_e \\ \nu_X\end{pmatrix},$$

$$V_e = \sqrt{2}G_F\left(N_e - \frac{1}{2}N_n\right), \qquad V_\mu = V_\tau = \sqrt{2}G_F\left(-\frac{1}{2}N_n\right), \qquad V_s = 0,$$

$N_{e(n)}$ = electron (neutron) density, sign = + (−) for neutrinos (antineutrinos).

⇒ **Modification of mixing angle and oscillation wavelength.**

Matter effects: effective mass and mixing

- For neutrinos (up to an irrelevant multiple of the identity matrix):

$$\mathbf{H} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} -\Delta & 0 \\ 0 & \Delta \end{pmatrix} \cdot \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} + \begin{pmatrix} A & 0 \\ 0 & -A \end{pmatrix}, \quad \Delta \equiv \frac{\Delta m^2}{4E_\nu}, \quad A = \frac{V_e - V_X}{2};$$

- note that the hamiltonian $\mathbf{H}(x)$ depends on the position along the neutrino trajectory;
- in general, for $x_1 \neq x_2$ we have $[\mathbf{H}(x_1), \mathbf{H}(x_2)] \neq 0$;
- however, for any given x we can diagonalyze $\mathbf{H}(x)$:

$$\mathbf{H} = \begin{pmatrix} \cos\theta_m(x) & \sin\theta_m(x) \\ -\sin\theta_m(x) & \cos\theta_m(x) \end{pmatrix} \cdot \begin{pmatrix} -\Delta_m(x) & 0 \\ 0 & \Delta_m(x) \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_m & -\sin\theta_m(x) \\ \sin\theta_m(x) & \cos\theta_m(x) \end{pmatrix}$$

  and comparing with the previous expression:

$$\left.\begin{aligned} \Delta_m \cos(2\theta_m) &= \Delta\cos(2\theta) - A \\ \Delta_m \sin(2\theta_m) &= \Delta\sin(2\theta) \end{aligned}\right\} \Rightarrow \left\{\begin{aligned} \Delta_m &= \sqrt{[\Delta\cos(2\theta) - A]^2 + [\Delta\sin(2\theta)]^2} \\ \tan(2\theta_m) &= \frac{\Delta\sin(2\theta)}{\Delta\cos(2\theta) - A} \end{aligned}\right.$$

- for antineutrinos, just replace $A \to -A$.

Matter effects: level crossing and resonant enhancement

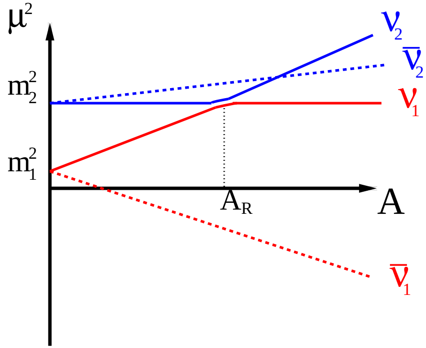
- From the previous transparency:

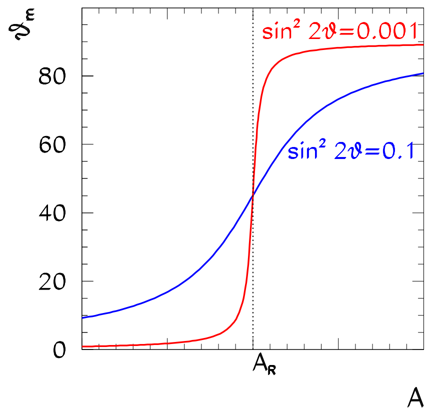
$$\left.\begin{aligned} \Delta_m \cos(2\theta_m) &= \Delta \cos(2\theta) - A \\ \Delta_m \sin(2\theta_m) &= \Delta \sin(2\theta) \end{aligned}\right\} \Rightarrow \quad \tan(2\theta_m) = \frac{\Delta \sin(2\theta)}{\Delta \cos(2\theta) - A};$$

- choosing Δ_m with the same sign as Δ, we see that:
  - $\cos(2\theta_m)$ and $\cos(2\theta)$ have $\frac{\text{the same}}{\text{opposite}}$ sign if $\Delta \cos(2\theta) \frac{<}{>} A$;
  - θ_m is maximal (45°) for $\Delta \cos(2\theta) = A$, even if θ is small;
  - the value $A_R = \Delta \cos(2\theta)$ is called *resonant density*.
- for constant matter density, we can define the oscillation lenght in matter as:

$$L_m^{\text{osc}} = L_0^{\text{osc}} \frac{\Delta}{\Delta_m} \quad \text{with} \quad L_0^{\text{osc}} = \frac{\pi}{\Delta};$$

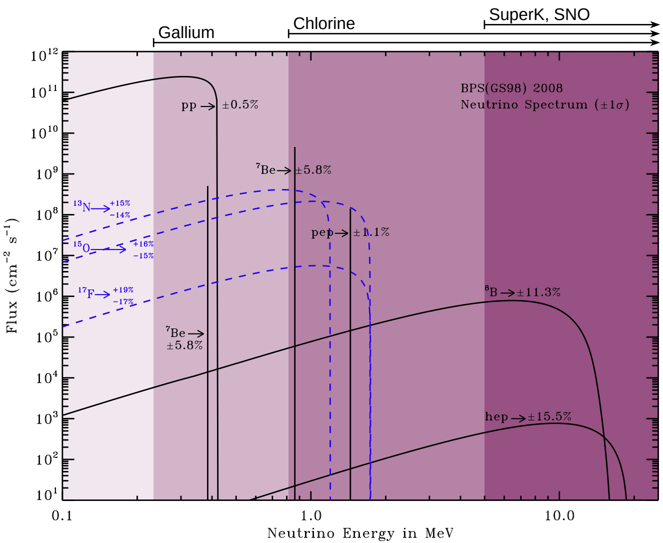
- no level crossing occur if $\Delta \cos(2\theta)$ and A have opposite sign.

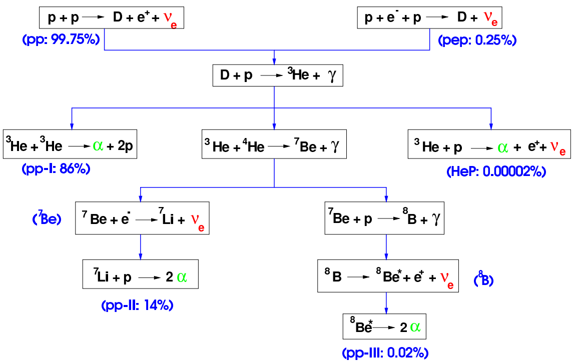


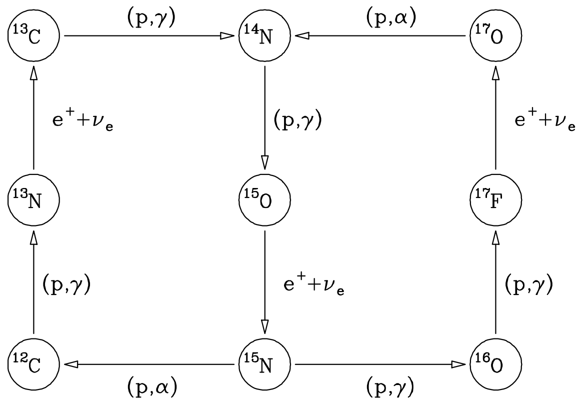


Solar neutrinos

- Neutrinos are by *nuclear reactions* in the core of the Sun;
- 2 mechanisms: pp chain and CNO cycle;
- both give $4p \to {}^4\text{He} + 2e^+ + 2\nu_e + \gamma$.







Radiochemical experiments

⇒ Homestake (South Dakota, USA):
(44.35° N, 615 tons, 1970)

- SSM: $^{7}\text{Be} = 14\%$, $\text{CNO} = 3\%$, $^{8}\text{B} = 80\%$;
- Reaction: $\nu_e + {}^{37}Cl \to {}^{37}Ar + e^-$;
- Threshold: 0.814 MeV;
- Rate: $\langle 8.58 \rangle$ $2.56 \pm 0.16 \pm 0.16$ SNU.

⇒ SAGE (Baksan, Russia):
(43.3° N, 30→60 tons, 1990)

- SSM: $pp = 55\%$, $^{7}\text{Be} = 28\%$, $\text{CNO} = 3\%$, $^{8}\text{B} = 11\%$;
- Reaction: $\nu_e + {}^{71}Ga \to {}^{71}Ge + e^-$;
- Threshold: 0.233 MeV;
- Rate: $\langle 129.0 \rangle$ $65.4^{+3.1}_{-3.0}{}^{+2.6}_{-2.8}$ SNU.

⇒ GALLEX/GNO (LNGS, Italy):
(42.5° N, 30 tons, 1991)

- SSM: $pp = 55\%$, $^{7}\text{Be} = 28\%$, $\text{CNO} = 3\%$, $^{8}\text{B} = 11\%$;
- Reaction: $\nu_e + {}^{71}Ga \to {}^{71}Ge + e^-$;
- Threshold: 0.233 MeV;
- Rate: $\langle 129.0 \rangle$
  - $73.1^{+6.1}_{-6.0}{}^{+3.7}_{-4.1}$ SNU (Gallex),
  - $62.9^{+5.5}_{-5.3}{}^{+2.5}_{-2.5}$ SNU (GNO).

- 1 SNU = 10^{-36} captures/atom/sec.

Cerencov experiments

⇒ Kamiokande (Japan): (36.5° N, 1 kton, 1986–1995)
- Threshold: 7.5 MeV;
- Flux: $\langle 5.88 \pm 0.65 \rangle$ $(2.80 \pm 0.19 \pm 0.33) \times 10^6$ cm^{-2} s^{-1}.

⇒ Super–Kamiokande (Japan): (36.5° N, 45 ktons, 1996)
- Threshold: 6.5 MeV $\to$ 5.0 MeV $\to \dots$;
- Flux: $\langle 5.88 \pm 0.65 \rangle$ $(2.32 \pm 0.03 \pm 0.08) \times 10^6$ cm^{-2} s^{-1}.

⇒ SNO (Sudbury, Canada): (46.5° N, 1 kton, 1999–2006)
- Reactions:
  - CC: $\nu_e + d \to p + p + e^-$,
  - ES: $\nu_x + e^- \to \nu_x + e^-$,
  - NC: $\nu_x + d \to n + p + \nu_x$;
- Flux:

	Phase-I [5.0]	Phase-II [5.5]	Phase-III [6.0]
CC	$1.76^{+0.06\,+0.09}_{-0.05\,-0.09}$	$1.68^{+0.06\,+0.08}_{-0.06\,-0.09}$	$1.67^{+0.05\,+0.07}_{-0.04\,-0.08}$
ES	$2.39^{+0.24\,+0.12}_{-0.23\,-0.12}$	$2.35^{+0.22\,+0.15}_{-0.22\,-0.15}$	$1.77^{+0.24\,+0.09}_{-0.21\,-0.10}$
NC	$5.09^{+0.44\,+0.46}_{-0.43\,-0.43}$	$4.94^{+0.21\,+0.38}_{-0.21\,-0.34}$	$5.54^{+0.33\,+0.36}_{-0.31\,-0.34}$

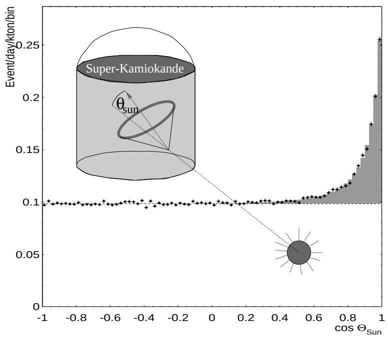
(units: threshold = MeV; flux = 10^6 cm^{-2} s^{-1})

⇒ Borexino (LNGS, Italy): (42.5° N, 280 tons, 2007)
- Threshold: 0.2 MeV;
- Flux (^{7}Be): $\langle 5.08 \pm 0.30 \rangle$ $(3.36 \pm 0.21 \pm 0.24) \times 10^9$ cm^{-2} s^{-1}.

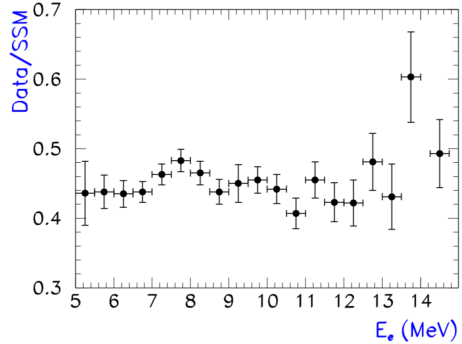
The Super-Kamiokande experiment

- Real-time experiment:
  - allow reconstruction of ν direction, and correlation with Sun position;
  - allow accurate measurement of time variation;
  - can search for energy distortions;
  - measure day-night asymmetry.

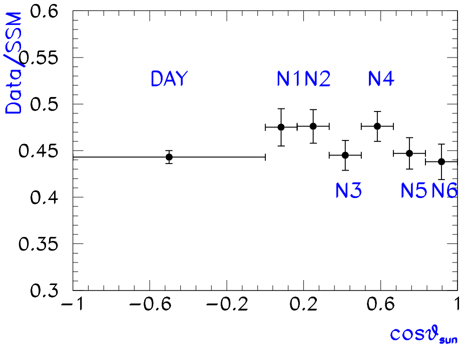
- ν comes from the sun



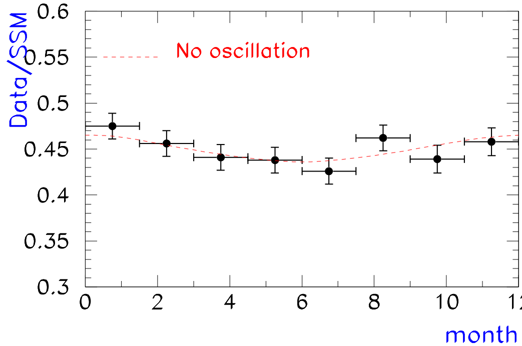
- no E_ν distortion (above 5 MeV)



- small day/night asymmetry



- no seasonal effect beyond $1/R^2$

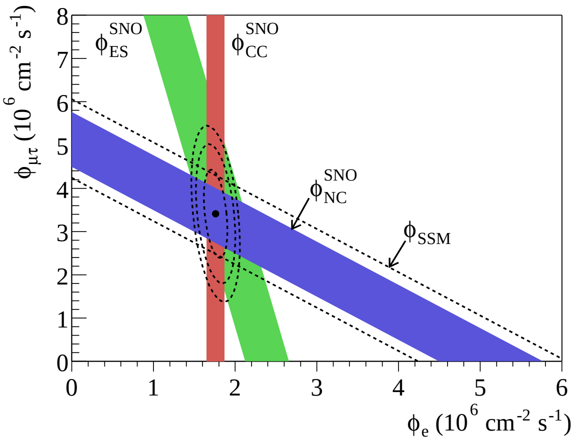


The SNO experiment

- This experiment consists of three phases of about one year duration each:
  1. accurate measurement of CC reaction rate with pure heavy-water;
  2. enhanced sensitivity to NC through the addition of NaCl salt to the heavy-water;
  3. direct measurement of NC signal through the introduction of a network of proportional counters filled with ^{3}He in pure heavy-water.

★ phase-I: $(10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1})$

$$\begin{cases} \phi_{\text{CC}} = 1.76^{+0.06\ +0.09}_{-0.05\ -0.09} = \phi_e, \\ \phi_{\text{ES}} = 2.39^{+0.24\ +0.12}_{-0.23\ -0.12} = \phi_e + r\,\phi_{\mu,\tau}, \\ \phi_{\text{NC}} = 5.09^{+0.44\ +0.46}_{-0.43\ -0.43} = \phi_e + \phi_{\mu,\tau}. \end{cases}$$

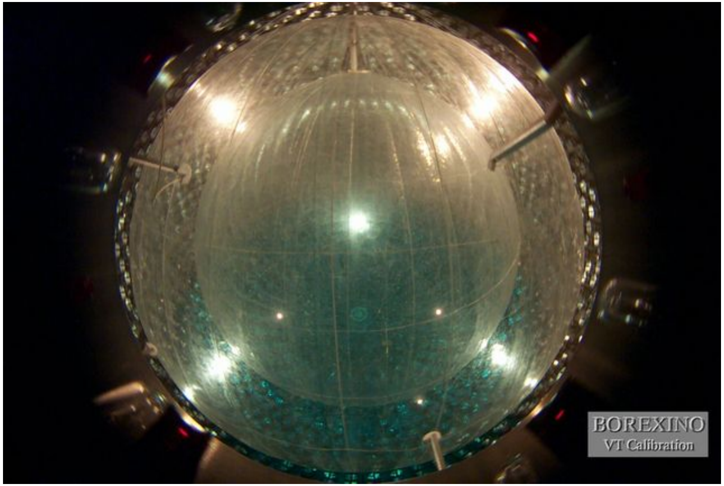


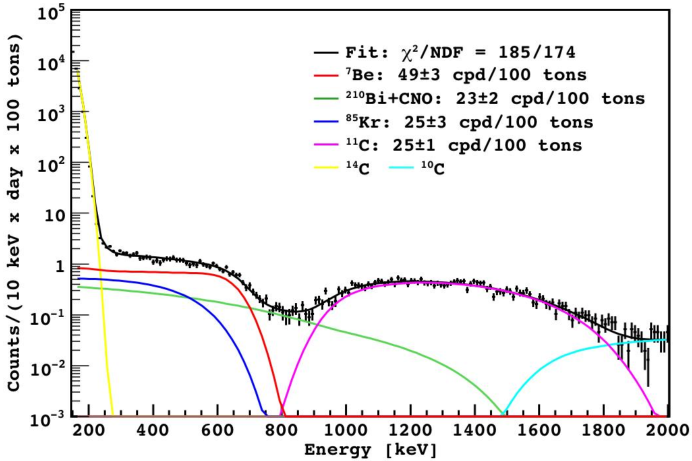
- sum rule: $\phi_{\text{NC}} = [\phi_{\text{ES}} - (1 - r)\phi_{\text{CC}}] / r$; $(r \equiv \sigma^{\text{ES}}_{\nu_{\mu,\tau}} / \sigma^{\text{ES}}_{\nu_e} \simeq 0.15)$
- from these data we derive a *5.3σ evidence of flavor conversion*: $\phi_{\mu,\tau} = 3.41^{+0.45\ +0.48}_{-0.45\ -0.45}$;

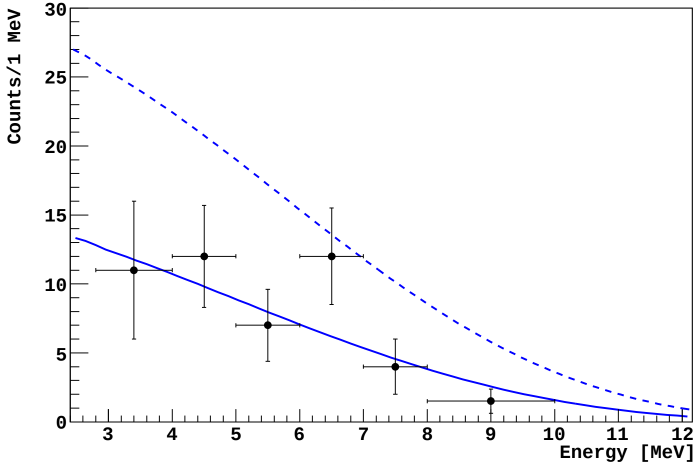
★ phase-II and phase-III in very good agreement (except for phase-III ES result).

The Borexino Experiement

- Target: liquid scintillator (278 tons).
- Reaction: $\nu_x + e^- \to \nu_x + e^-$ (ES).
- Threshold: extremely low (150 keV).
- Challenge: remove background.
- Real time experiment.

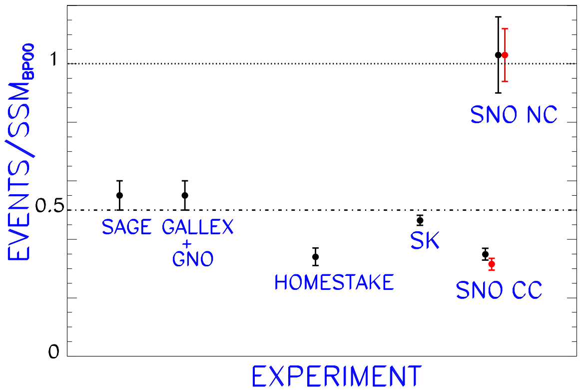






Solar neutrino data: summary

Type	Experiment	Detection	Flavor	$E_{\rm th}$ (MeV)	$\frac{\text{Data}}{\text{BP00}}$
radio-	Homestake	^{37}Cl$(\nu, e^-)^{37}$Ar	ν_e	$E_\nu > 0.81$	0.35 ± 0.06
chemical	Gallium	^{71}Ga$(\nu, e^-)^{71}$Ge	ν_e	$E_\nu > 0.23$	0.55 ± 0.05
real-time	Kam $\Rightarrow$ SK	ES $\nu_x e^- \to \nu_x e^-$	$\nu_e + r\,\nu_{\mu/\tau}$	$E_e > 5$	0.46 ± 0.09
	SNO	CC $\nu_e d \to p p e^-$	ν_e	$T_e > 5$	0.35 ± 0.07
		NC $\nu_x d \to \nu_x d$	$\nu_e + \nu_{\mu,\tau}$	$T_\gamma > 5$	1.01 ± 0.23
		ES $\nu_x e^- \to \nu_x e^-$	$\nu_e + r\,\nu_{\mu/\tau}$	$T_e > 5$	0.46 ± 0.23

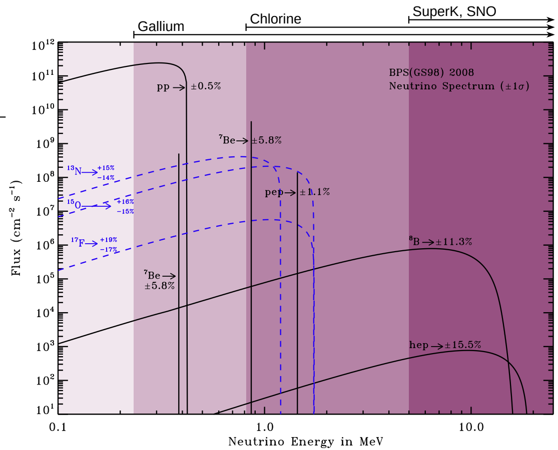


- All experiments measuring mostly ν_e observed a deficit: $P_{ee} \in [0.3 \to 0.6]$;
- deficit is energy dependent;
- Error in calculation of the solar ν fluxes, or new physics in neutrino propagation?
- Answer: **no deficit** in NC $\Rightarrow$ solar model OK.

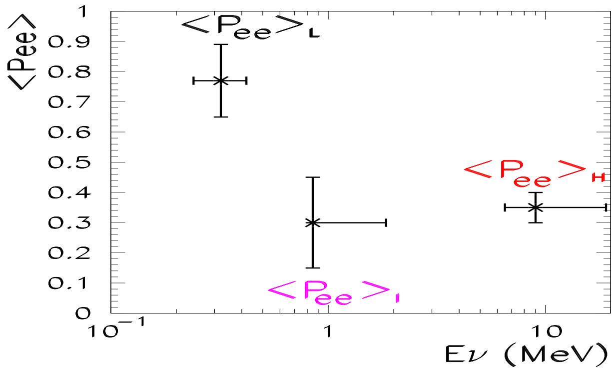
Solar Neutrinos: Flavor Conversion Probabilities

- Fitting the observed rates:

		Data/SSM	R_{th}
Cl		0.35 ± 0.06	$0.76\, f_B \langle P_{ee}\rangle_H + 0.24 \langle P_{ee}\rangle_I$
Ga		0.55 ± 0.05	$0.1\, f_B \langle P_{ee}\rangle_H + 0.36 \langle P_{ee}\rangle_I + 0.54 \langle P_{ee}\rangle_L$
SK		0.46 ± 0.09	$f_B[\langle P_{ee}\rangle_H + 0.15\,(1 - \langle P_{ee}\rangle_H)]$
SNO	CC	0.35 ± 0.07	$f_B \langle P_{ee}\rangle_H$
	NC	1.01 ± 0.23	f_B

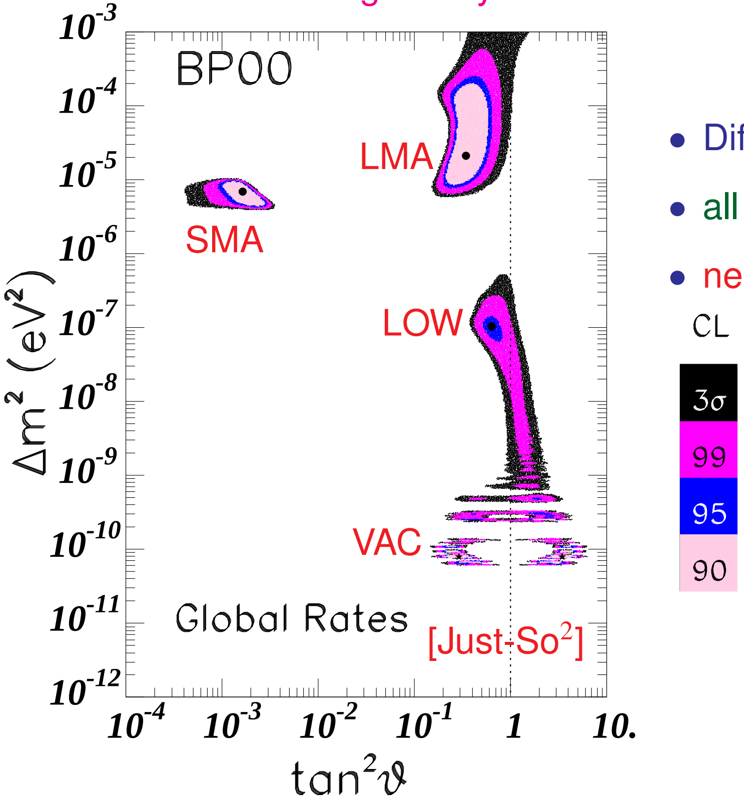


- Oscillation channel: $\nu_e \to \nu_X$;
- The ν_e survival probability:



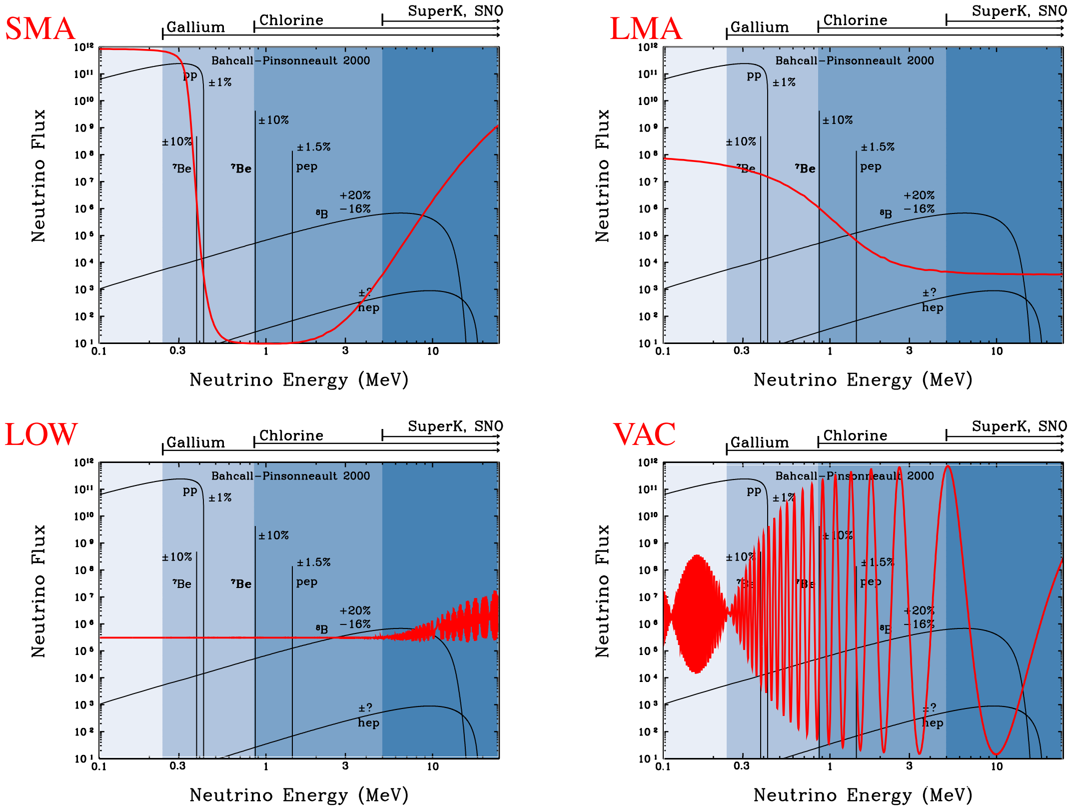
Solar neutrinos: oscillation solutions (year: 2001)

Allowed regions by fit to **TOTAL RATES**: Cl, Ga, SK and SNO CC



- Different regimes can explain the Total Rates;
- all give similar $\langle P_{ee}\rangle_L$, $\langle P_{ee}\rangle_I$, $\langle P_{ee}\rangle_H$;
- need more observables to discriminate.

Energy Dependence of P_{ee} for Different Solutions



Solar ν oscillations (year: 2005)

- exp. data: **84**

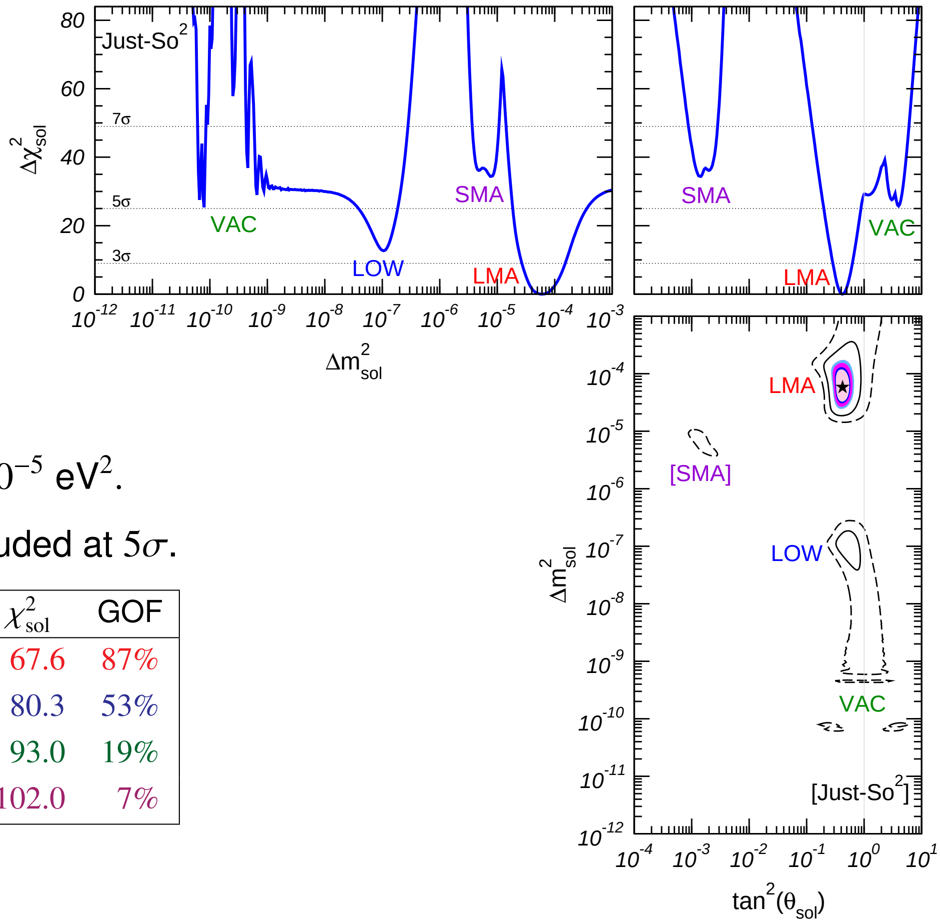
  $3_{\text{rates}} + 44_{\text{SK}} + 37_{\text{SNO}}$;

- parameters: **2** (Δm^2, θ);

- 5σ: $\begin{cases} \tan^2\theta_{\text{sol}} \in [0.20,\ 0.88], \\ \Delta m^2_{\text{sol}} \in [1.9,\ 36] \times 10^{-5}\ \text{eV}^2. \end{cases}$

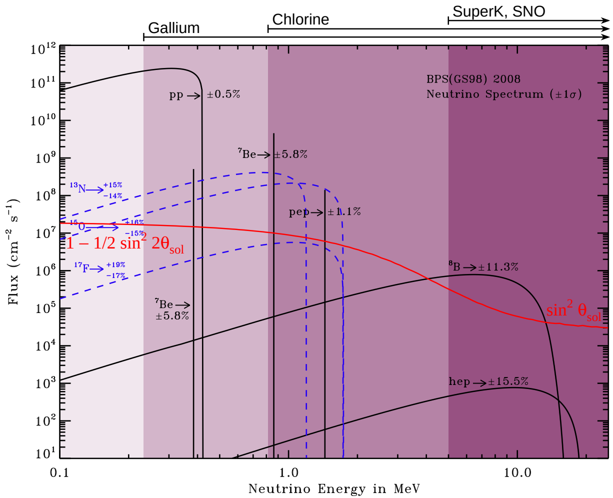
- maximal mixing $\theta \approx 45°$ excluded at 5σ.

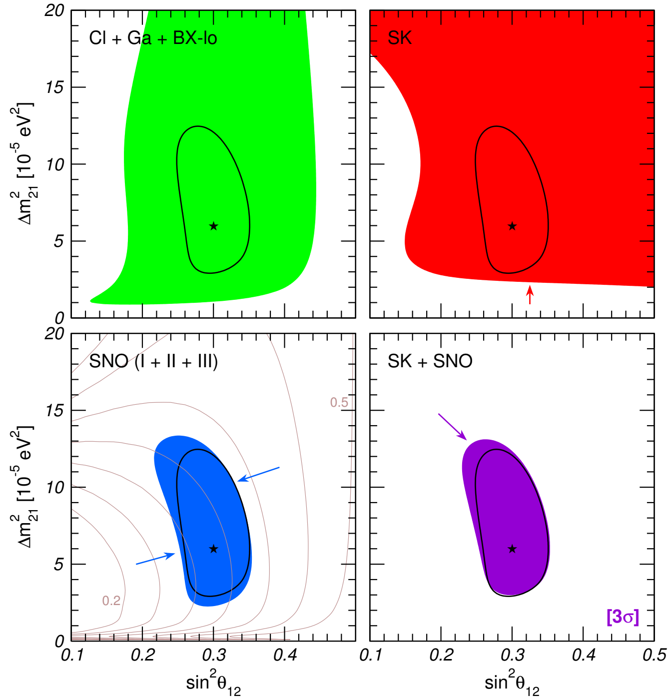
Region	$\tan^2\theta\text{sol}$	Δm^2_{sol} [eV^2]	χ^2_{sol}	GOF
LMA	0.42	6.0×10^{-5}	67.6	87%
LOW	0.50	1.0×10^{-7}	80.3	53%
VAC	0.25	7.9×10^{-11}	93.0	19%
SMA	1.4×10^{-3}	7.6×10^{-6}	102.0	7%



Solar neutrinos (2012): anatomy of the oscillation solution

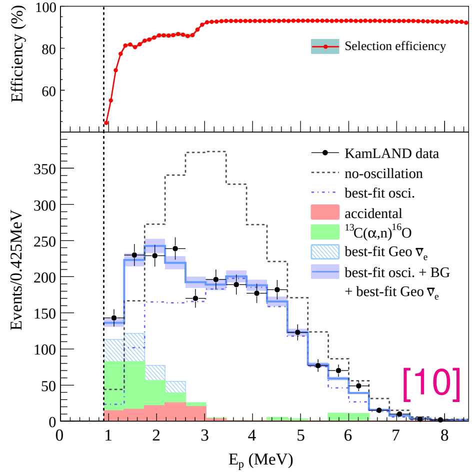
- $\theta_{13} = 0 \;\Rightarrow\; i\dfrac{d\vec{\nu}}{dt} = \left[\dfrac{\Delta m^2_{21}}{4E_\nu}\begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12}\end{pmatrix} \pm \sqrt{2}\,G_F \begin{pmatrix} N_e & 0 \\ 0 & 0\end{pmatrix}\right]\vec{\nu}$, with $\vec{\nu} = \begin{pmatrix}\nu_e \\ \nu_a\end{pmatrix}$;
- Data: low-E (Cl, Ga): $P_{ee} \approx 1 - \frac{1}{2}\sin^2 2\theta_{12}$, high-E (SK, SNO): $P_{ee} \approx \sin^2\theta_{12}$;
- fit presently dominated by high-E.





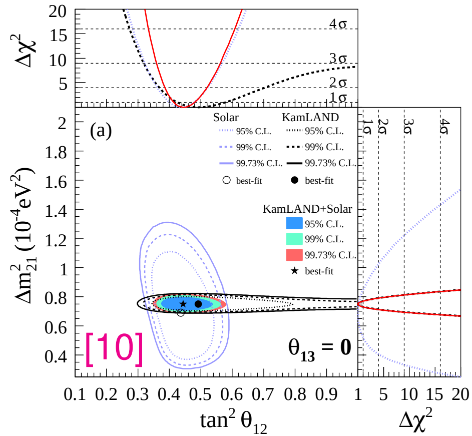
The KamLAND reactor experiment

- Nuclear fission reactions in nuclear power plants produce *electron anti-neutrinos*;
- neutrino flux from many plants in Japan measured by KamLAND (average baseline: ≈ 180 km);
- an energy-dependent deficit of $\bar{\nu}_e$ is observed.



Combining solar & KamLAND data

- Hypothesis: $\nu_e \to \nu_{\text{active}}$ conversion due to **non-zero neutrino masses** and **flavor mixing**;
- CPT conservation $\Rightarrow$ physics of solar (ν) and KamLAND ($\bar{\nu}$) neutrino conversion must be the same;
- only two parameters: Δm^2_{sol} and θ_{sol};
- this model perfectly explains both effects.



[10] A. Gando *et al.*, PRD **83** (2011) 052002 [arXiv:1009.4771].

Three neutrino oscillations

- Equation of motion: **6** parameters (including CP violating effects):

$$i\frac{d\vec{\nu}}{dt} = H\,\vec{\nu}; \qquad H = U_{\text{vac}} \cdot D_{\text{vac}} \cdot U_{\text{vac}}^{\dagger} \pm V_{\text{mat}};$$

$$U_{\text{vac}} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \cancel{\begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}, \qquad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix};$$

$$D_{\text{vac}} = \frac{1}{2E_\nu}\left[\operatorname{diag}(0,\ \Delta m^2_{21},\ \Delta m^2_{31}) + \cancel{m_1^2 I}\right]; \qquad V_{\text{mat}} = \sqrt{2} G_F N_e \operatorname{diag}(1,\ 0,\ 0)\,.$$

Connection with two-neutrino oscillations

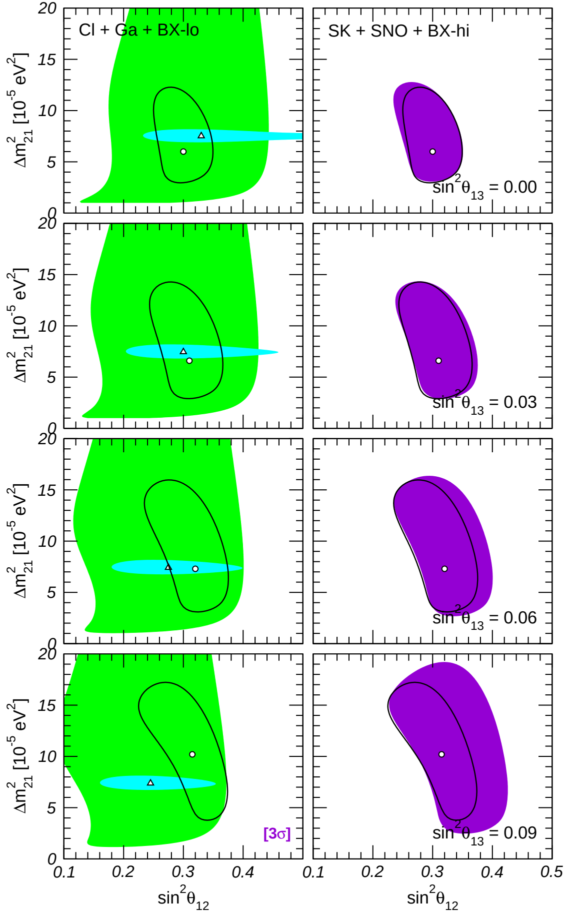
- **Solar** parameters Δm^2_{sol} and θ_{sol} are identified with Δm^2_{21} and θ_{12};
- **atmospheric** parameters Δm^2_{atm} and θ_{atm} are identified with Δm^2_{31} and θ_{23};
- **reactor** angle θ_{rea} constrained by Chooz corresponds to θ_{13};
- **CP-violating** phase δ_{CP} is a genuine 3ν feature, with no two-neutrino counterpart;
- smallness of θ_{13} and $\Delta m^2_{21}/\Delta m^2_{31}$ implies that solar and atm sectors are decoupled.

Impact of θ_{13} on solar & KamLAND

- $\nu_\mu \equiv \nu_\tau \Rightarrow$ no sensitivity to θ_{23} and δ_{CP};
- $\Delta m^2_{31} \approx \infty \Rightarrow$ specific Δm^2_{31} value irrelevant;

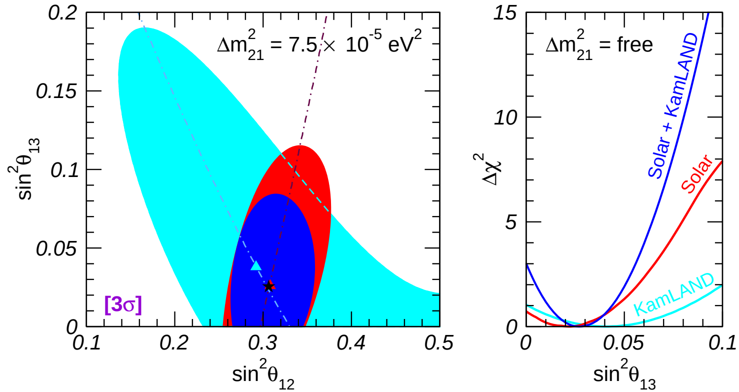
$\Rightarrow$ data only depend on Δm^2_{21}, θ_{12} and θ_{13};

- $$P_{ee} \approx \begin{cases} \text{Kam: } \cos^4\theta_{13}\left(1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E}\right), \\ \text{low-E: } \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2 2\theta_{12}\right), \\ \text{high-E: } \cos^4\theta_{13}\sin^2\theta_{12}; \end{cases}$$
- as θ_{13} increases, $\cos^4\theta_{13}$ decreases and:
  - KamLAND and low-E data favor **smaller** θ_{12};
  - high-E data favor **larger** θ_{12} and Δm^2_{21};
- synergy between solar and KamLAND data: as θ_{13} increases, Δm^2_{21}: $\begin{cases} \text{increases in solar data;} \\ \text{remains stable in KamLAND;} \end{cases}$
- hence: $\begin{cases} \theta_{13} \text{ small (but } \neq 0) \Rightarrow \text{better agreement;} \\ \theta_{13} \text{ large} \Rightarrow \text{a tension appear.} \end{cases}$



Preference for non-zero θ_{13} from solar + KamLAND data

- For $\theta_{13} = 0$, we have $\sin^2\theta_{12} = \begin{cases} 0.30 \text{ from Solar data} \\ 0.33 \text{ from KamLAND data} \end{cases} \Rightarrow$ a tension appear;
- as we have just seen, when θ_{13} increases:
  - solar region slightly moves to larger θ_{12} (high-E data dominate over low-E ones);
  - KamLAND region definitely shifts to smaller θ_{12};
- therefore, a non-zero value of θ_{13} reduces the tension between solar and KamLAND data [11, 12];
- new SNO (I+II+III) analysis favor smaller $\phi_{CC}/\phi_{NC} \Rightarrow$ smaller θ_{12} from solar $\Rightarrow$ tension with KamLAND is increased $\Rightarrow$ larger θ_{13} is preferred.

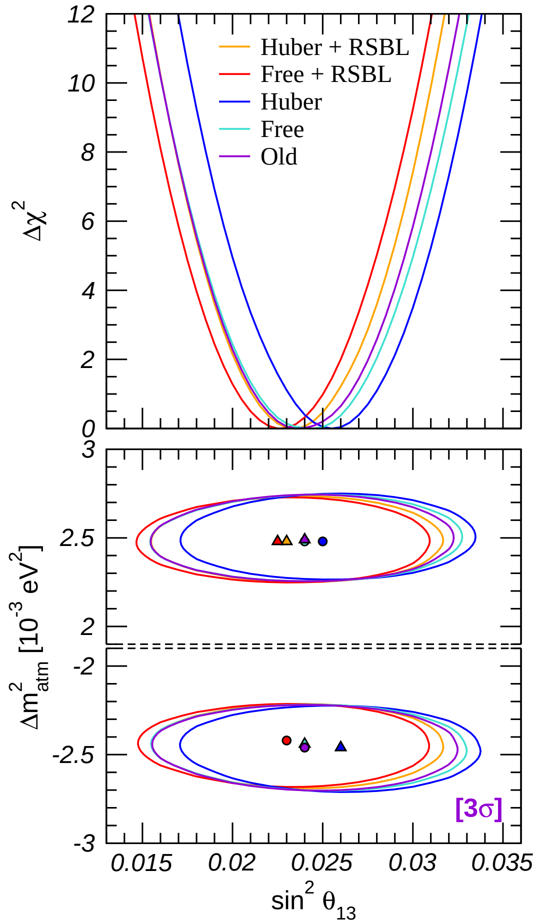


[11] G.L. Fogli *et al.*, Phys. Rev. Lett. **101** (2008) 141801 [arXiv:0806.2649].

[12] T. Schwetz, M.A. Tortola, J.W.F. Valle, New J. Phys. **10** (2008) 113011 [arXiv:0808.2016].

Impact of the reactor neutrino fluxes

- Analysis of reactor data require a precise knowledge of the reactor ν fluxes. We follow two approaches:
  - use the flux calculations presented in [15];
  - treat the fluxes as free parameters and fit them;
- The reactor fluxes in [14, 15] are quite **large**, hence they favor **large** suppression $\Rightarrow$ **larger** θ_{13};
- including reactor short-baseline (RSBL) experiments in the fit [13] results in **smaller** fluxes $\Rightarrow$ **smaller** θ_{13};
- once RSBL data are included, the specific prior on the reactor fluxes (fixed or free) has little impact;
- θ_{13} uncertainty from fluxes: $\delta(\sin^2\theta_{13}) = \pm 0.002$.

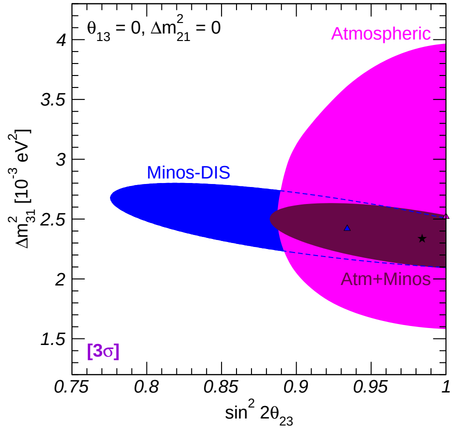


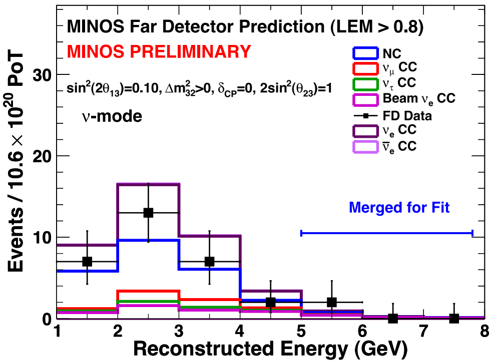
[13] Schwetz *et al.*, NJP **13** (2011) 063004 [arXiv:1103.0734].
[14] Mueller *et al.*, PRC **83** (2011) 054615 [arXiv:1101.2663].
[15] Huber, PRC **84** (2011) 024617 [arXiv:1106.0687].

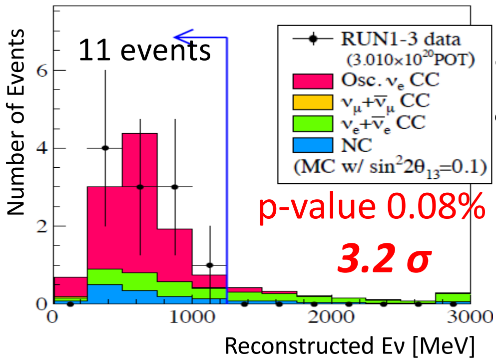
Atmospheric sector: general overview

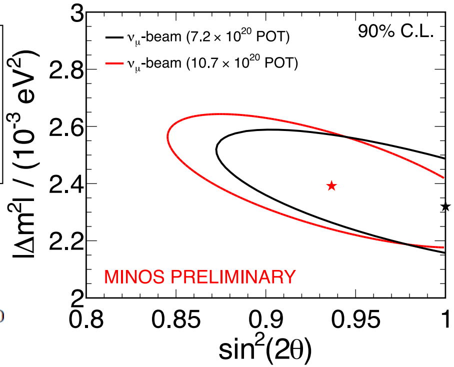
- Δm^2_{31} is now determined by Minos-DIS ($\nu_\mu \to \nu_\mu$) data;
- θ_{23} still dominated by SK atmospheric data;
- θ_{13} & δ_{CP} mostly visible in appearance ($\nu_\mu \to \nu_e$) data; hints of $\theta_{13} \neq 0$ from Minos-APP (2.1σ) and T2K (3.2σ);
- Δm^2_{21} effects visible but only at subleading level;

★ **new result**: Minos disappearance data now slightly favor non-maximal θ_{23} mixing.



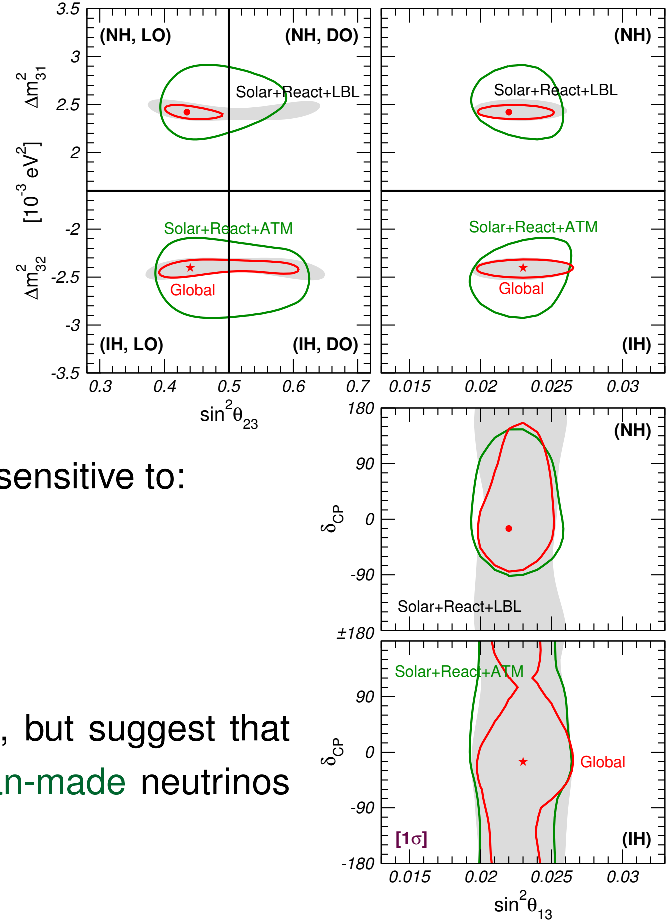






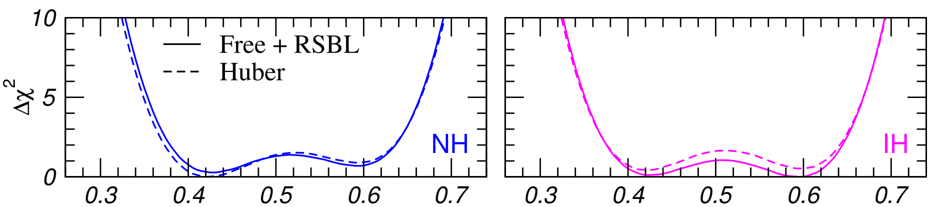
The role of atmospheric data

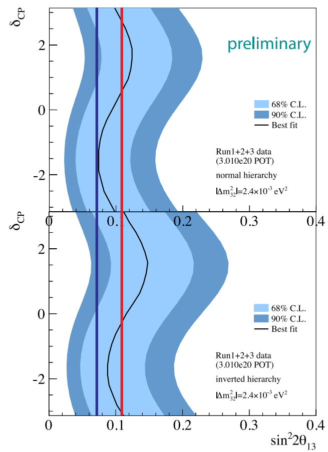
- Present reactor and accelerator data dominate $|\Delta m^2_{31}|$ and θ_{13} but give poor info on:
  - the **mass hierarchy** (sign of Δm^2_{31});
  - the **octant** (sign of $\theta_{23} - \pi/4$);
- note the high degree of symmetry of the gray regions;
- conversely, regions including ATM are visibly sensitive to:
  - **octant**: definite shift from maximal mixing;
  - **hierarchy**: size & shape vary considerably;
  - **CP phase**: non-trivial dependence on δ_{CP};
- these features are not statistically significant, but suggest that atmospheric data and experiments using man-made neutrinos may provide complementary information;
- let's now consider this in more detail...

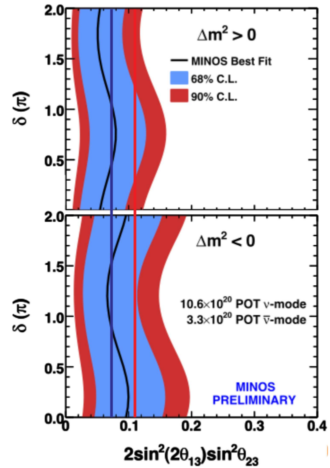


Octant discrimination with REA+LBL data

- In principle, REA + LBL-APP + LBL-DIS can fix the octant [16]:
  - REACTORS: measure $\sin^2(2\theta_{\text{rea}}) \equiv \sin^2(2\theta_{13})$;
  - LBL-DIS: measure $\sin^2(2\theta_{\text{dis}})$, with $\sin^2\theta_{\text{dis}} \equiv \cos^2\theta_{13}\sin^2\theta_{23}$;
  - LBL-APP: measure $\sin^2(2\theta_{\text{app}}) \equiv \sin^2(2\theta_{13})\, 2\sin^2\theta_{23}$ and δ_{CP};
- in practice, putting explicit numbers:
  - from REACTORS: $\sin^2(2\theta_{13}) \simeq 0.09$;
  - from LBL-DIS: $\sin^2(2\theta_{\text{dis}}) \simeq 0.96$ implies $\sin^2\theta_{23} = 0.41$ or 0.61;
  - hence, REA + LBL-DIS imply $\sin^2(2\theta_{\text{app}}) = 0.074$ or 0.110;
- both values of $\sin^2(2\theta_{\text{app}})$ are in similar agreement with LBL-APP.







[16] G.L. Fogli *et al.*, Phys. Rev. D **86** (2012) 013012 [arXiv:1205.5254].

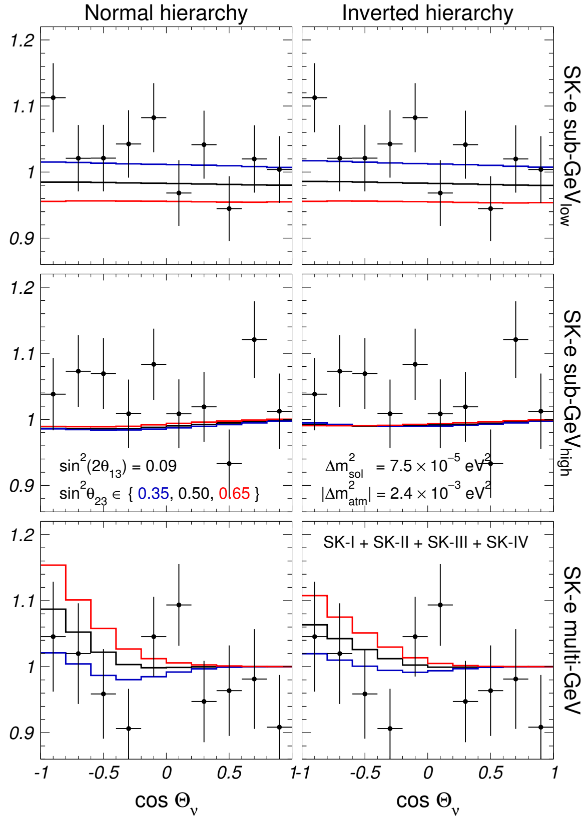
Octant and hierarchy discrimination in atmospheric data

- Excess of e-like events, $\delta_e \equiv N_e/N_e^0 - 1$:

$$\delta_e \simeq (\bar{r}\cos^2\theta_{23} - 1)\, P_{2\nu}(\Delta m^2_{21},\, \theta_{12}) \quad [\Delta m^2_{21} \text{ term}]$$
$$+ (\bar{r}\sin^2\theta_{23} - 1)\, P_{2\nu}(\Delta m^2_{31},\, \theta_{13}) \quad [\theta_{13} \text{ term}]$$
$$- \bar{r}\sin\theta_{13}\sin 2\theta_{23}\ \mathrm{Re}(A^*_{ee} A_{\mu e})\,; \quad [\delta_{\text{CP}} \text{ term}]$$

  with $\bar{r} \equiv \Phi^0_\mu/\Phi^0_e$;

- similar but less pronounced effects also appear in μ-like events (not discussed here);
- resonance in $P_{2\nu}(\Delta m^2_{31},\, \theta_{13}) \Rightarrow$ enhancement of ν ($\bar{\nu}$) oscillations for normal (inverted) hierarchy $\Rightarrow$ **hierarchy discrimination**;
- δ_e distinguishes between light and dark side $\Rightarrow$ **octant discrimination**;
- **present data**: excess in e-like sub-GeV events $\Rightarrow$ preference for light side.



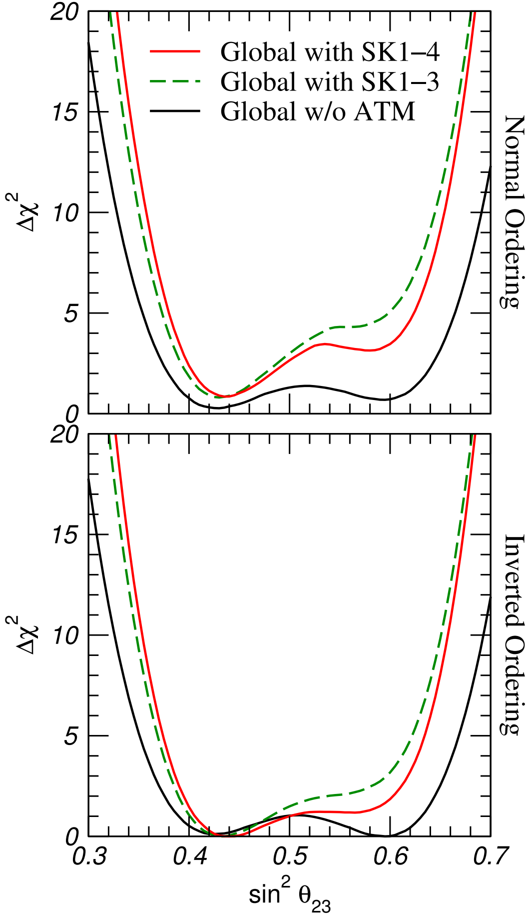
Octant and hierarchy: present status

θ_{23} octant

- Deviation of θ_{23} from maximal mixing **is a physical effect**, which follows from:
  - excess of events in sub-GeV e-like data;
  - zenith distortion in multi-GeV e-like data;
- the effect is not statistically significant, but it is well understood and clearly visible;
- found also by other Fogli *et al.* [16], but **not** by SK.

Mass hierarchy

- Matter effects enhanced for larger θ_{13} $\Rightarrow$ sensitive to specific range of θ_{13};
- no meaningful preference for NH or for IH.



[16] G.L. Fogli *et al.*, PRD **86** (2012) 013012 [arXiv:1205.5254].

Neutrino oscillations: where we are

- Global 6-parameter fit (including δ_{CP}):
  - **Solar**: Cl + Ga + SK(1–4) + SNO-full (I+II+III) + Borexino;
  - **Atmospheric**: SK-1 + SK-2 + SK-3 + SK-4;
  - **Reactor**: KamLAND + Chooz + Palo-Verde + Double-Chooz + Daya-Bay + Reno;
  - **Accelerator**: Minos (DIS+APP) + T2K (DIS+APP);
- best-fit point and 1σ (3σ) ranges:

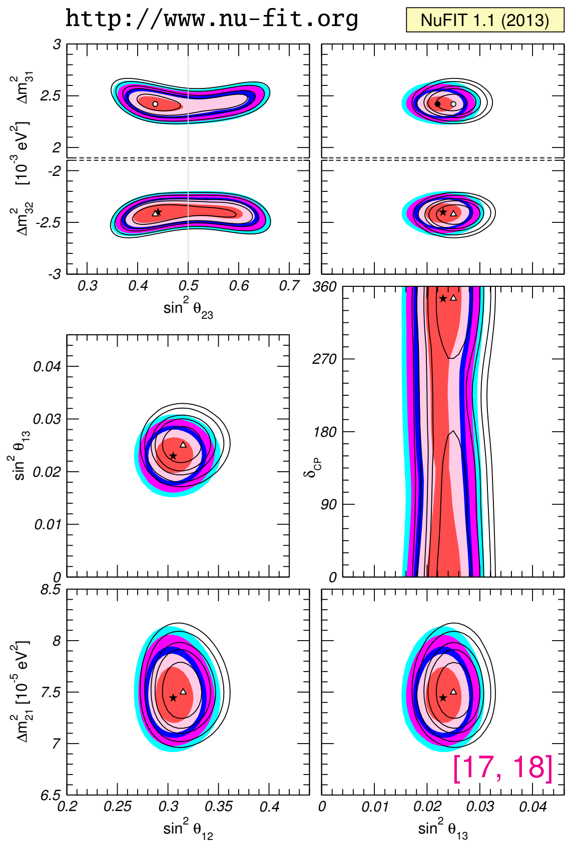
$$\theta_{12} = 33.57\,^{+0.77}_{-0.75}\left(^{+2.44}_{-2.19}\right), \quad \Delta m^2_{21} = 7.45\,^{+0.19}_{-0.16}\left(^{+0.60}_{-0.47}\right)\times 10^{-5}\ \text{eV}^2,$$

$$\theta_{23} = 41.4\,^{+3.5}_{-1.8}\left(^{+12.6}_{-4.7}\right), \quad \Delta m^2_{31} = \begin{cases} -2.403\,^{+0.062}_{-0.063}\left(^{+0.184}_{-0.193}\right)\times 10^{-3}\ \text{eV}^2, \\ +2.421\,^{+0.022}_{-0.023}\left(^{+0.191}_{-0.173}\right)\times 10^{-3}\ \text{eV}^2, \end{cases}$$

$$\theta_{13} = 8.75\,^{+0.42}_{-0.44}\left(^{+1.21}_{-1.46}\right), \quad \delta_{CP} = 341\,^{+58}_{-46}\ (\text{any});$$

- neutrino mixing matrix:

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.515 \to 0.581 & 0.127 \to 0.173 \\ 0.218 \to 0.533 & 0.430 \to 0.719 & 0.591 \to 0.800 \\ 0.222 \to 0.534 & 0.431 \to 0.720 & 0.582 \to 0.793 \end{pmatrix}.$$



[17] M.C. Gonzalez-Garcia *et al.*, JHEP **12** (2012) 123 [arXiv:1209.3023].
[18] M.C. Gonzalez-Garcia *et al.*, NuFIT 1.1 (2013), http://www.nu-fit.org.

What's still missing?

- Neutrino oscillation parameters still to be measured:
  - **value** of δ_{CP}, and whether it differs from 0 and π (CP violation);
  - **size** and **sign** of $\sin^2\theta_{23} - 1/2$ (the θ_{23} octant);
  - **sign** of Δm^2_{31} (neutrino mass hierarchy);
- data that we will almost certainly have (taken from Table 1 of Ref. [19]):

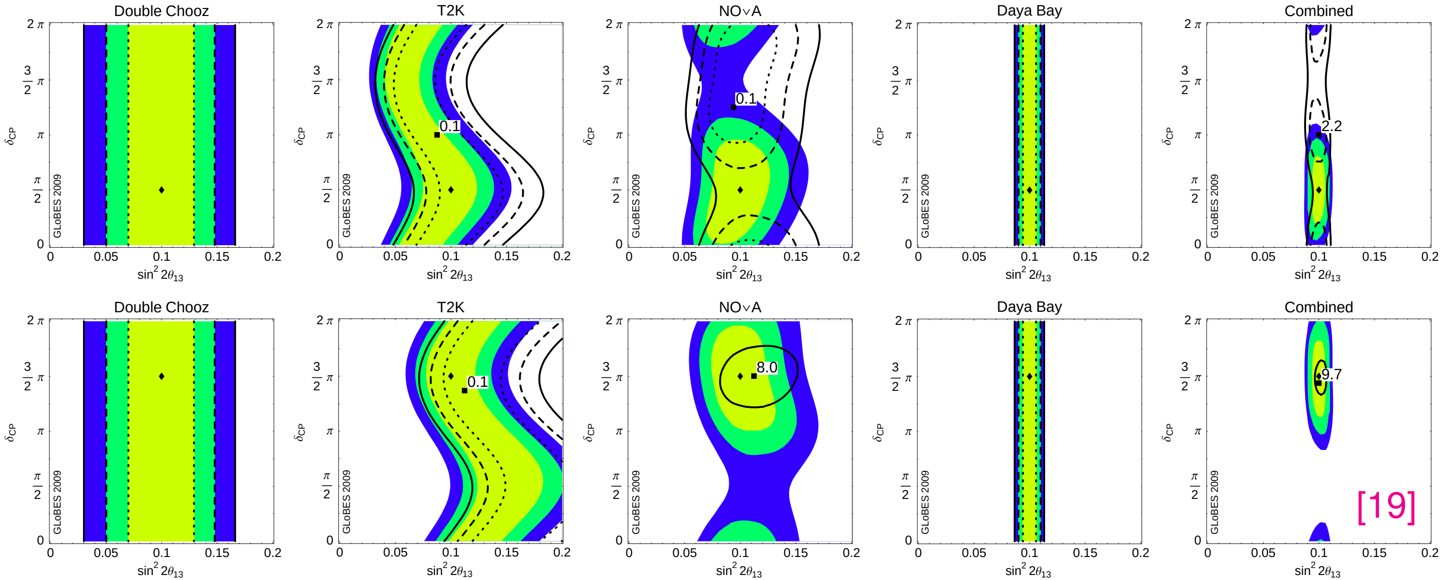
Setup	t_ν [yr]	$t_{\bar\nu}$ [yr]	P_{Th} or P_{Target}	L [km]	Detector technology	m_{Det}
Double Chooz	-	3	8.6 GW	1.05	Liquid scintillator	8.3 t
Daya Bay	-	3	17.4 GW	1.7	Liquid scintillator	80 t
RENO	-	3	16.4 GW	1.4	Liquid scintillator	15.4 t
T2K	5	-	0.75 MW	295	Water Cerenkov	22.5 kt
NOνA	3	3	0.7 MW	810	TASD	15 kt

  plus two atmospheric neutrino detectors: ICECUBE Deep-Core and INO;
- can we answer the remaining questions with this?

[19] P. Huber, M. Lindner, T. Schwetz, W. Winter, JHEP **0911** (2009) 044 [arXiv:0907.1896].

CP Violation and mass hierarchy: hard tasks

- Ability to determine the mass hierarchy and CP violation depend on the true value of δ_{CP};
- 90% discovery chances [19]: $\lesssim 50\%$ for hierarchy and $\lesssim 30\%$ for CPV $\Rightarrow$ **we need luck!**

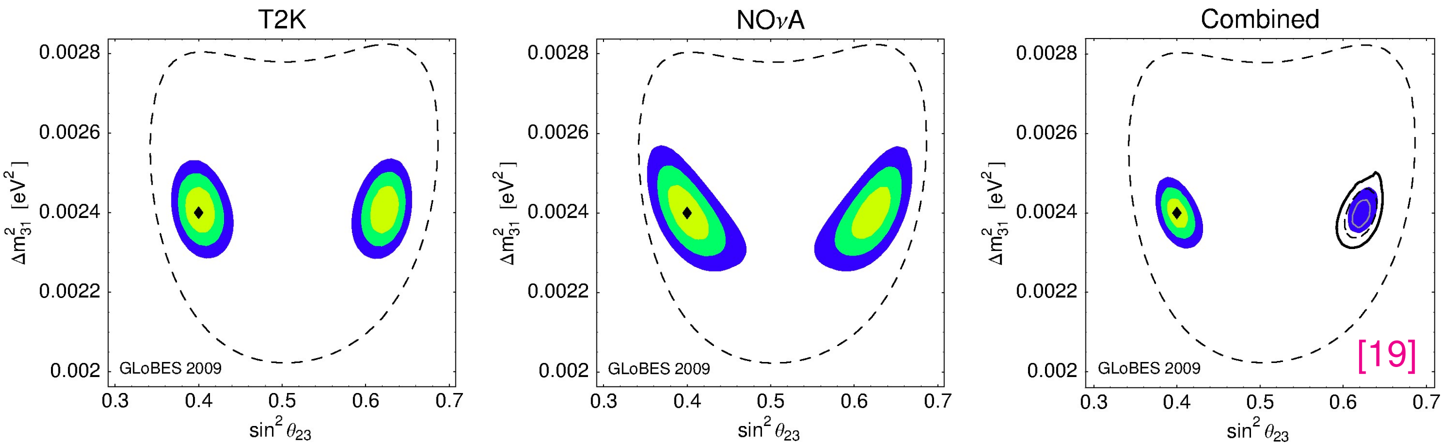


simulated values: NH, $\sin^2(2\bar{\theta}_{13}) = 0.1$, $\sin^2\bar{\theta}_{23} = 0.5$, $\bar{\delta}_{CP} = 90°$ (upper) and $270°$ (lower).

[19] P. Huber, M. Lindner, T. Schwetz, W. Winter, JHEP **0911** (2009) 044 [arXiv:0907.1896].

θ_{23} octant: another hard task for accelerators

- Good news: precision on the leading atmospheric parameters ($|\Delta m^2_{31}|$, θ_{23}) will increase considerably in the next few years;
- however, even for large deviation of θ_{23} from maximal mixing it will still be non-trivial to resolve the octant with forthcoming accelerator experiments (*i.e.*, T2K and Noνa) [19].

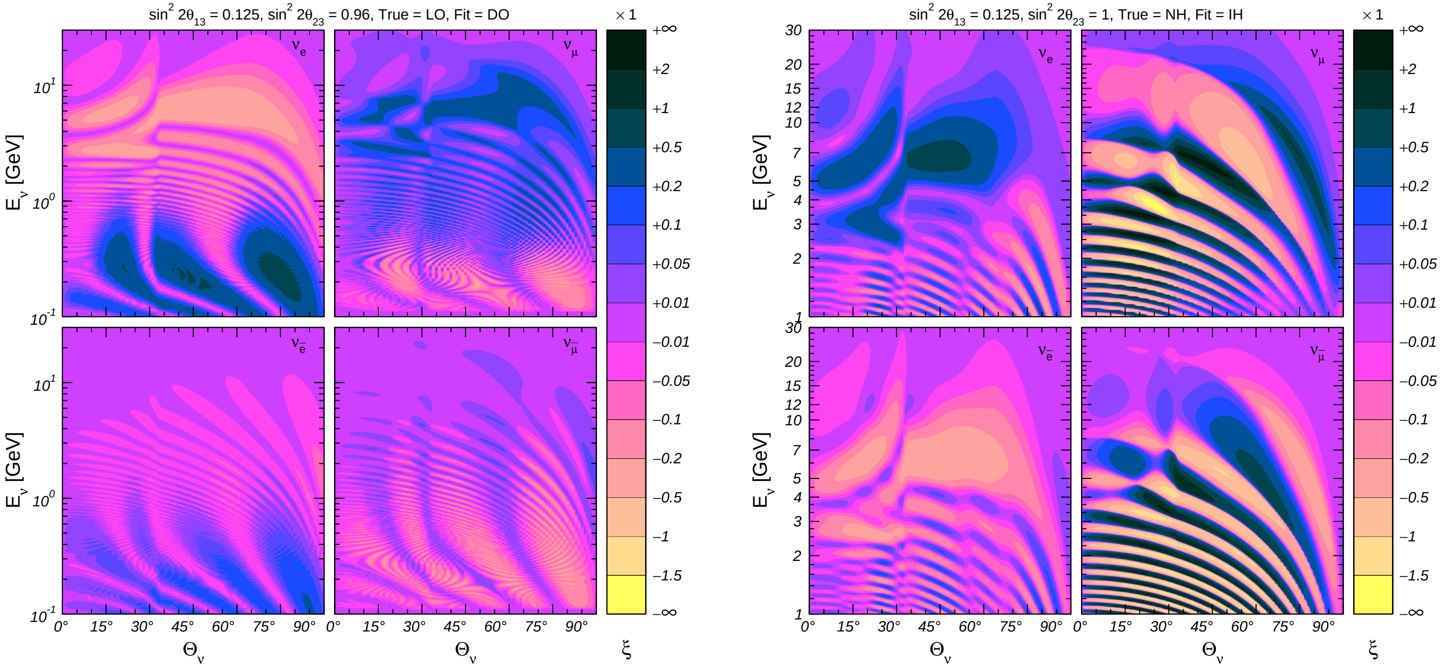


simulated values: NH, $\sin^2(2\bar\theta_{13}) = 0.1$, $\sin^2\bar\theta_{23} = 0.4$, $\bar\delta_{\text{CP}} = 0$.

[19] P. Huber, M. Lindner, T. Schwetz, W. Winter, JHEP **0911** (2009) 044 [arXiv:0907.1896].

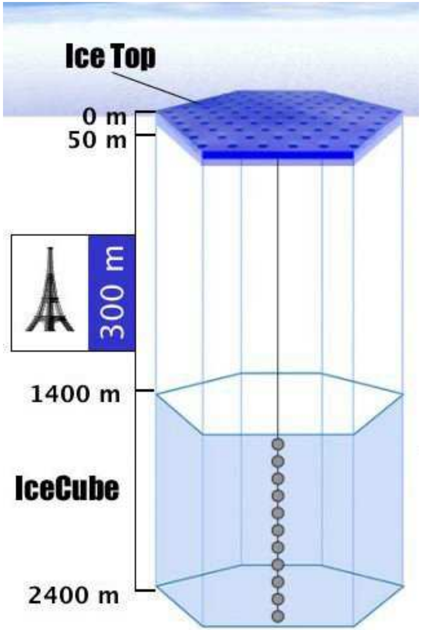
Can atmospheric data help?

- Signatures from matter resonance with Δm^2_{21} (~ 200 MeV) and with Δm^2_{31} (~ 6 GeV);
- if detectable with enough resolution, can help resolving octant and hierarchy.



Neutrino telescopes: the IceCUBE detector and Deep-Core

- Geometry: hexagon of 80 strings (separation: 125 m), each carrying 60 photo-multipliers (distance: 17 m). Total size: ~ 1 km^3 (20000 times bigger than SK).



[http://icecube.wisc.edu/gallery/]

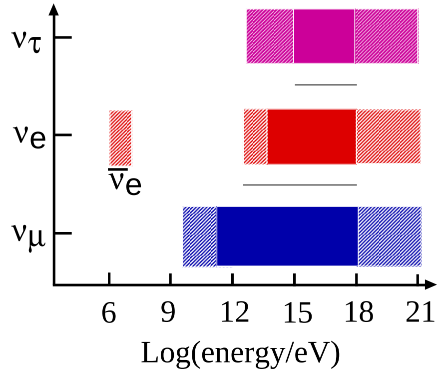
- Detection technique: observation of *Cerenkov light*;
- Threshold: ~ 80 GeV for ν_μ, ~ 10 TeV for ν_e and ν_τ; [Halzen & Hooper, Rept. Prog. Phys. 65 (2002) 1025]
- Resolution (μ): angular $\lesssim 1^\circ$, energy $\lesssim 30\%$ in logarithm; [Astropart. Phys. 20 (2004) 507]

IceCUBE Deep-Core

- 6 more strings in the core $\Rightarrow$ ν_μ threshold to ~ 15 GeV.

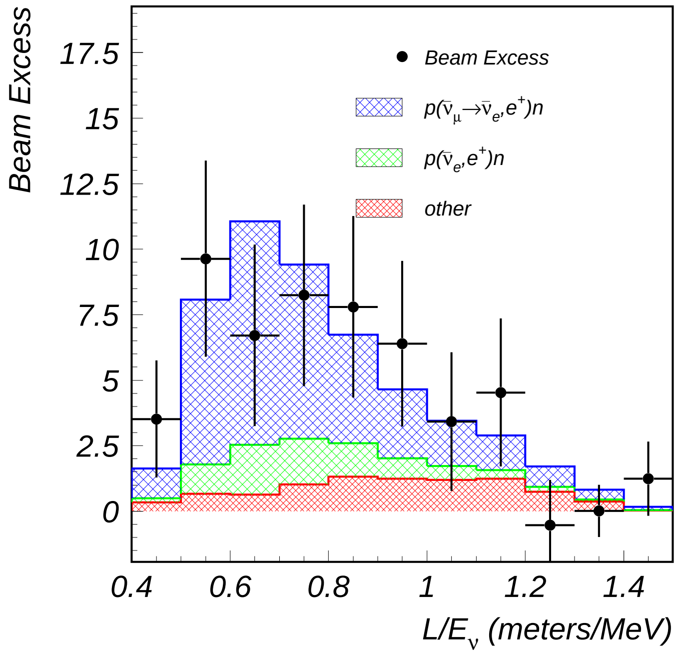
PINGU (proposed)

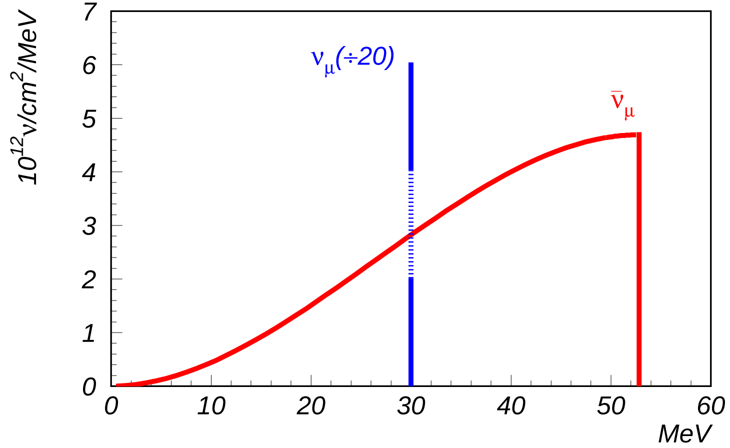
- Further increase string density in the core $\Rightarrow$ lower ν_μ threshold below 6 GeV.

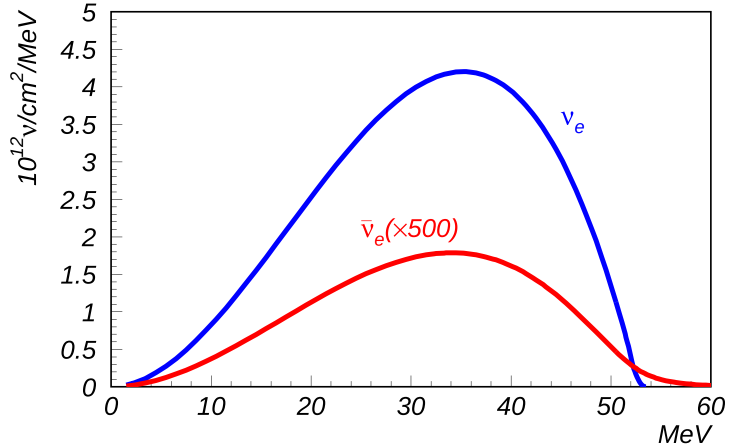


The LSND experiment

- Source: $\pi^+ \to \mu^+ \nu_\mu$ at rest, $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$;
- Signal: $\bar{\nu}_e$ appearance, $\langle L \rangle \simeq 35$ m;
- Karmen: **no evidence** at $\langle L \rangle \simeq 17$ m.



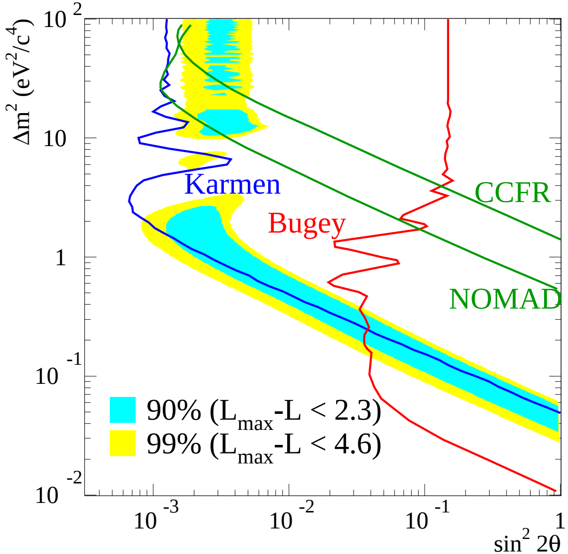




The LSND problem

- LSND observed $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam ($E_\nu \sim$ 30 MeV, $L \simeq 35$ m);
- Karmen did not confirm the claim, but couldn't fully exclude it either;
- the signal is compatible with $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations provided that $\Delta m^2 \gtrsim 0.1$ eV^2;
- on the other hand, other data give (at 3σ):

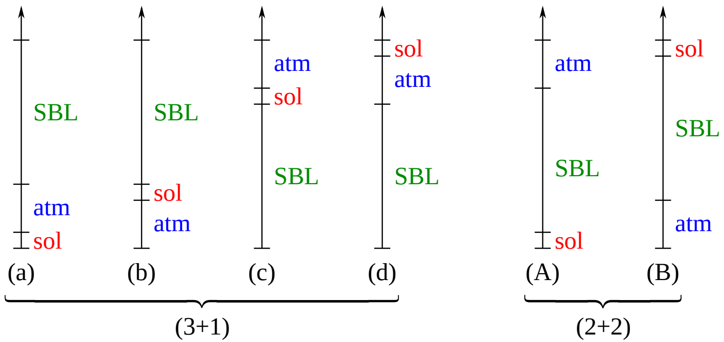
$$\Delta m^2_{\text{SOL}} \simeq 7.5 \pm 0.6 \times 10^{-5} \text{ eV}^2 ,$$
$$\left|\Delta m^2_{\text{ATM}}\right| \simeq 2.4 \pm 0.3 \times 10^{-3} \text{ eV}^2 ;$$



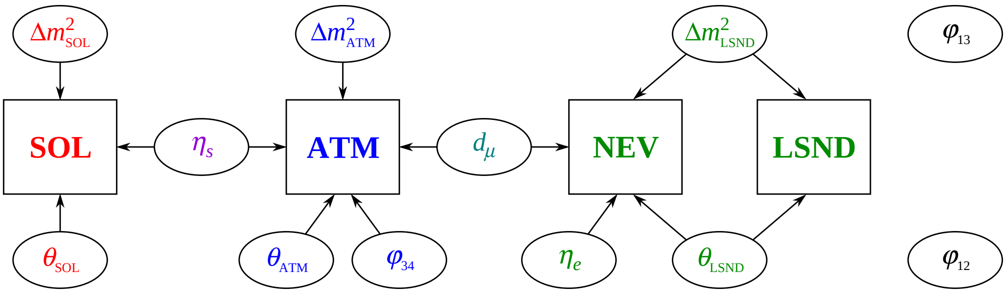
- in order to explain LSND with <u>mass-induced neutrino oscillations</u> one needs *at least one more* neutrino mass eigenstate;
- **WARNING: having enough Δm^2 is not enough. To make sure that the model works, one has to check explicitly that all the experiments can be fitted <u>simultaneously</u>.**

Four neutrino mass models

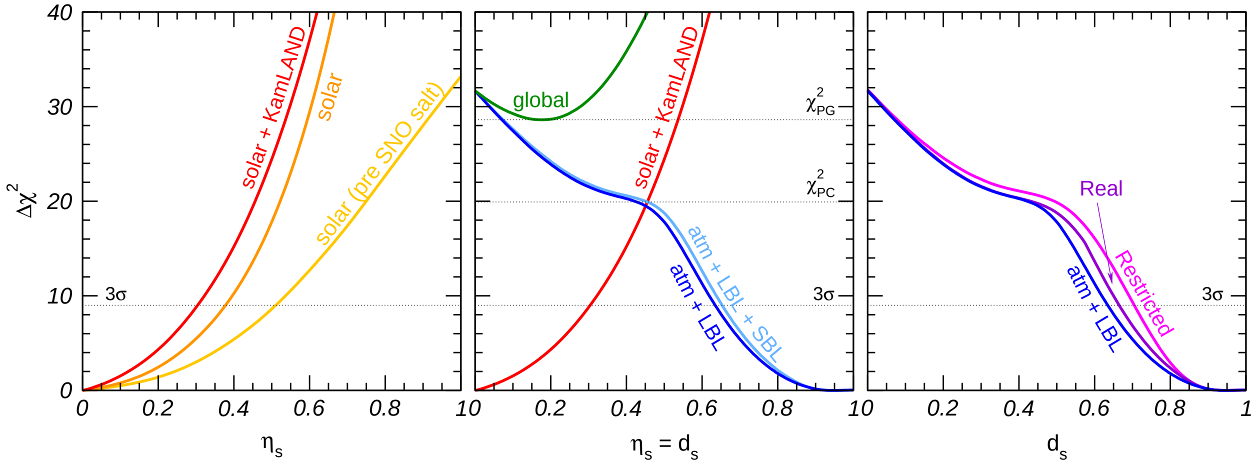
- Approximation: $\Delta m^2_{\text{SOL}} \ll \Delta m^2_{\text{ATM}} \ll \Delta m^2_{\text{LSND}} \Rightarrow$ 6 different mass schemes:



- Total: 3 Δm^2, 6 angles, 3 phases. Different set of experimental data *partially decouple*:



(2+2): ruled out by solar and atmospheric data



- in (2+2) models, fractions of ν_s in solar (η_s) and atmos ($1 - d_s$) add to one $\Rightarrow$ $\boxed{\eta_s = d_s}$;
- 3σ allowed regions $\eta_s \le 0.31$ (solar) and $d_s \ge 0.63$ (atmos) do not overlap; superposition occurs only above 4.5σ ($\chi^2_{\text{PC}} = 19.9$);
- the χ^2 increase from the combination of solar and atmos data is $\chi^2_{\text{PG}} = 28.6$ (1 dof), corresponding to a PG $= 9 \times 10^{-8}$ [20].

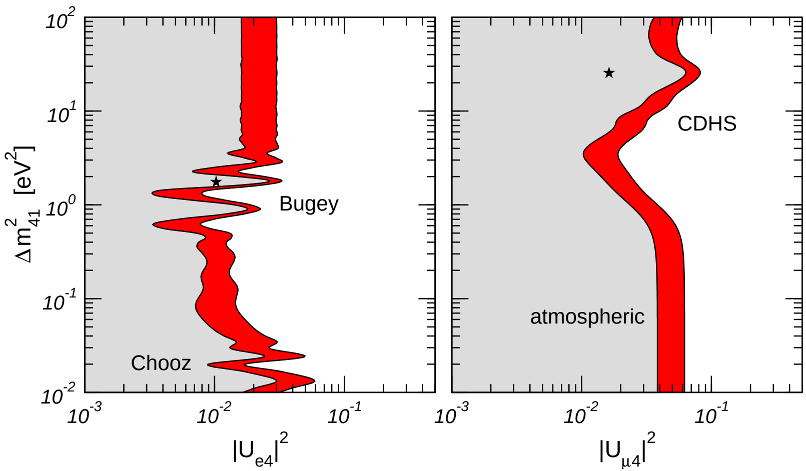
[20] M. Maltoni, T. Schwetz, M.A. Tortola, J.W.F. Valle, Nucl. Phys. **B643** (2002) 321 [hep-ph/0207157].

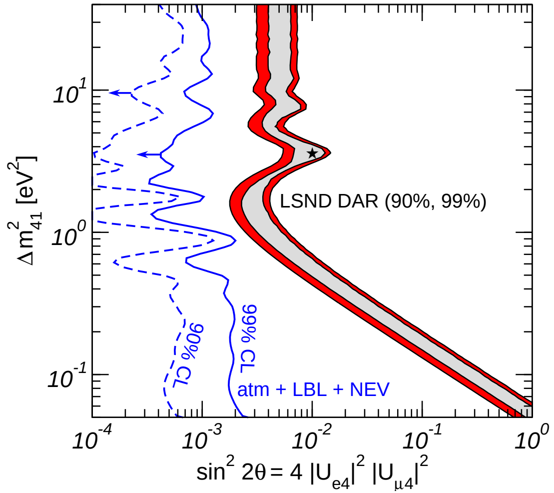
(3+1): tension between LSND and short-baseline data

- In (3+1) schemes the SBL *appearance* probability is effectively 2ν oscillations:

$$P_{\mu e} = \sin^2 2\theta \, \sin^2 \frac{\Delta m^2_{41} L}{4E}, \quad \sin^2 2\theta = 4\,|U_{e4}|^2\,|U_{\mu4}|^2 ;$$

- *disappearance* experiments bound $|U_{e4}|^2$ and $|U_{\mu4}|^2$;



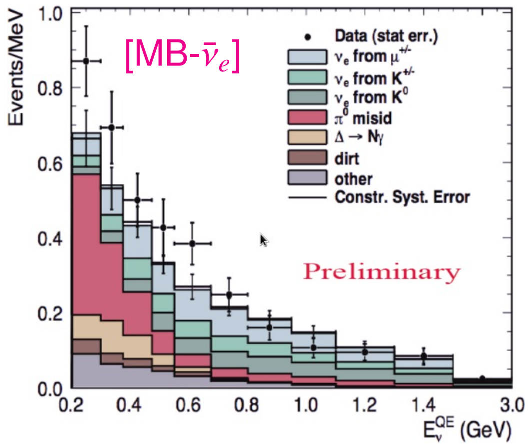


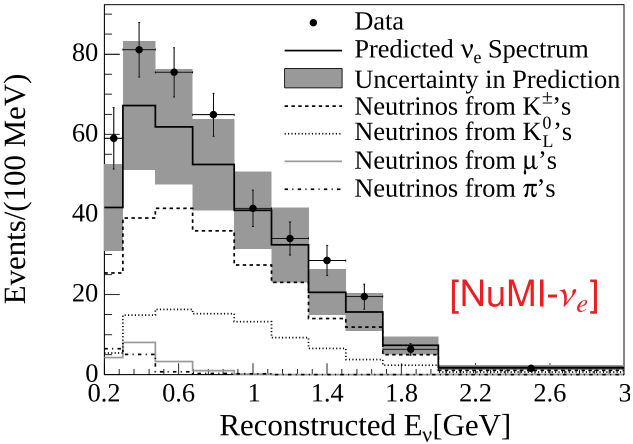
- LSND is in conflict [20]:
  - with other *appearance* experiments (Karmen & Nomad);
  - with all *disappearance* exp's.

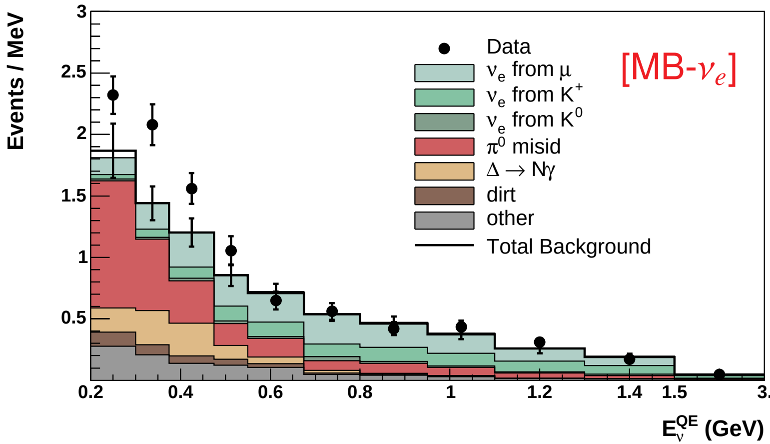
[20] M. Maltoni, T. Schwetz, M.A. Tortola, J.W.F. Valle, Nucl. Phys. **B643** (2002) 321 [hep-ph/0207157].

The MiniBooNE experiment ($\leq$ 5/2012)

- E_ν and L very different from LSND (but similar L/E_ν) $\Rightarrow$ can check **the oscillation solution** of the LSND problem, **not** the signal itself;
- very peculiar results:
  - strong low-energy excess in ν_e, mild in $\bar{\nu}_e$;
  - mild mid-energy excess in $\bar{\nu}_e$, but not in ν_e.

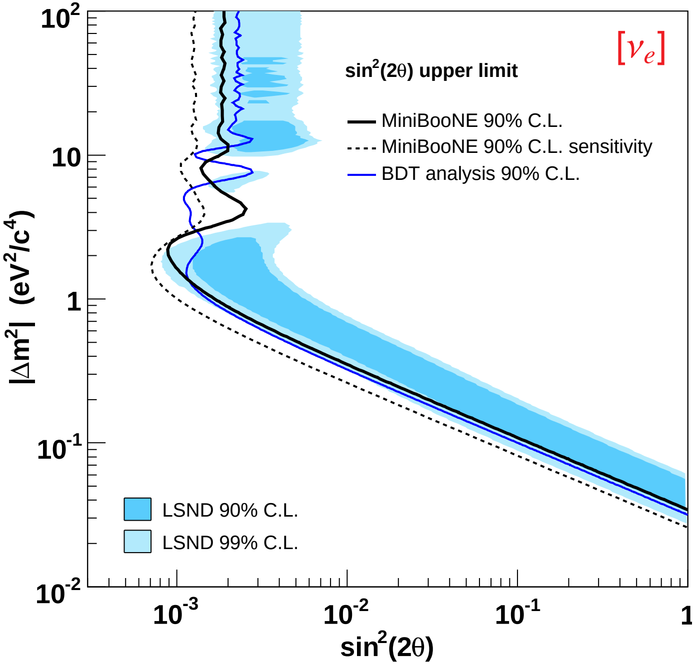


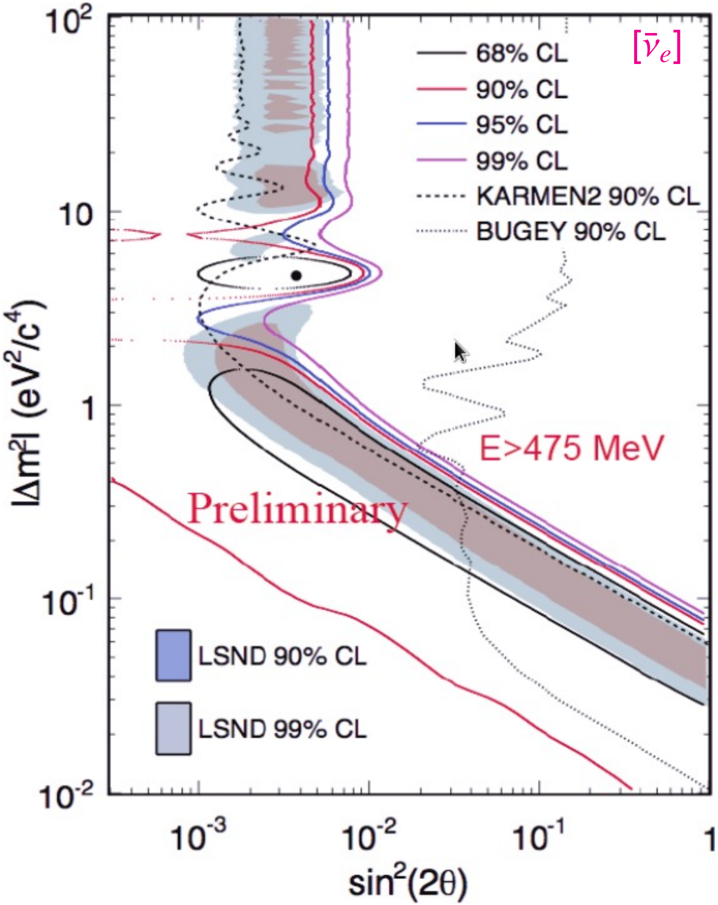




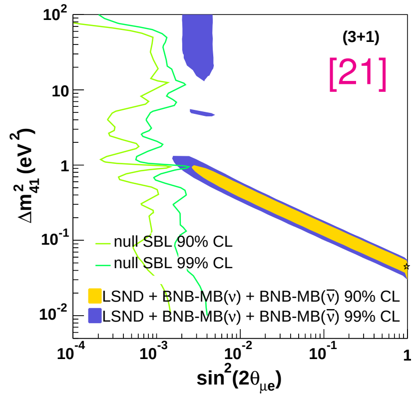
LSND vs MiniBooNE in (3+1)

- ν_e: no signal ⇒ **excludes** LSND;
- $\bar{\nu}_e$: signal ⇒ **mildly confirms** LSND.





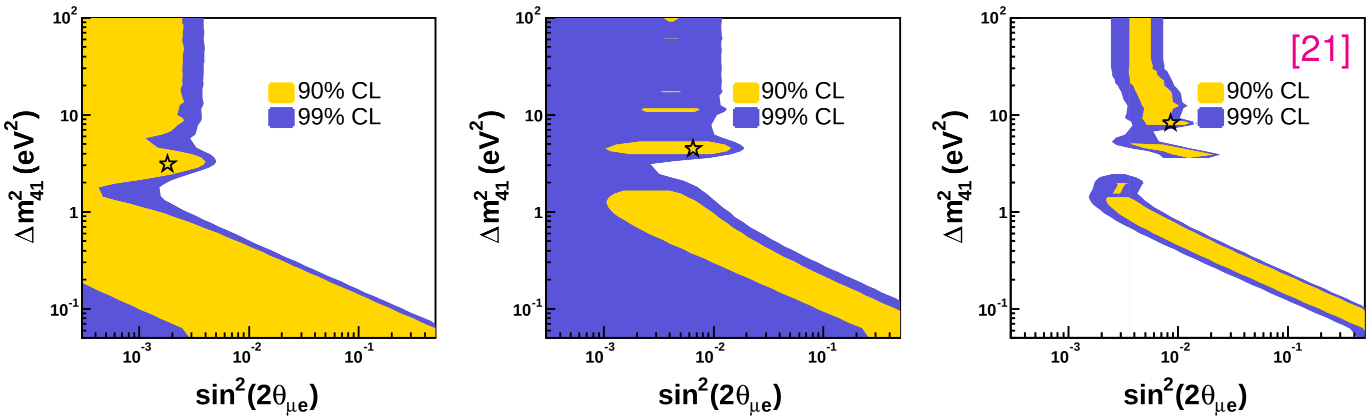
Status of (3+1) models after MiniBooNE



- (3+1) four-neutrino schemes fail because:
  - can't reconcile *appearance* and *disappearance* data;
  - can't explain the different ν_e (MB) and $\bar{\nu}_e$ (LSND) results;
  - can't account for the low-energy ν_e event excess in MB.

⇒ **(3+1) models are ruled out as explanation of SBL data.**

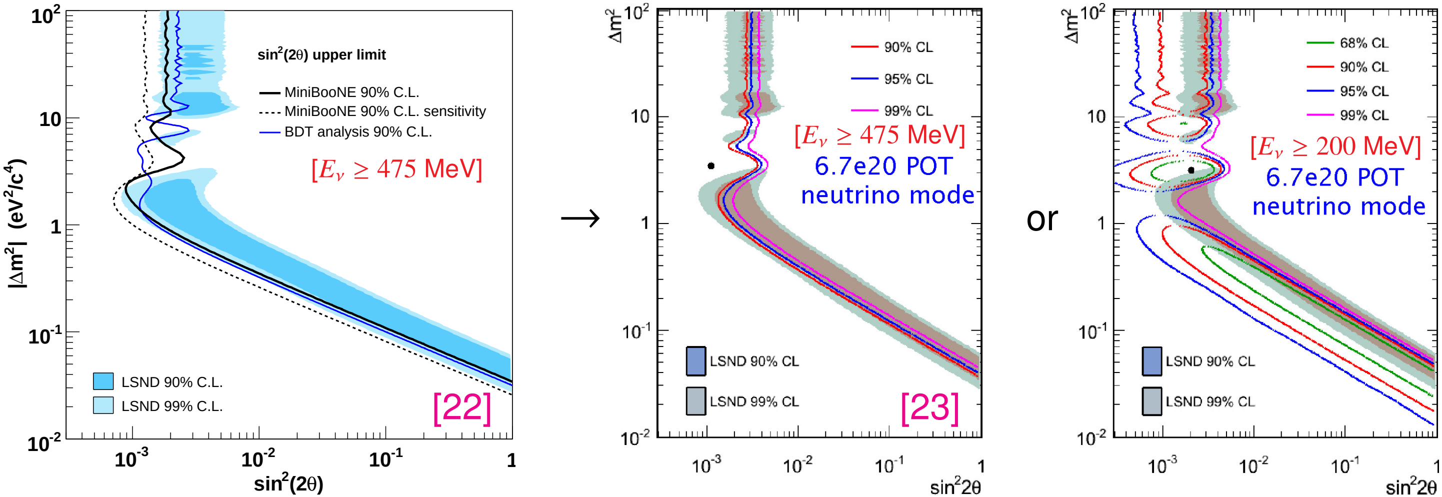
BNB-MB(ν) | BNB-MB($\bar{\nu}$) [OLD] | LSND



[21] G. Karagiorgi *et al.*, Phys. Rev. **D80** (2009) 073001 [arXiv:0906.1997].

Latest MiniBooNE results ($\geq$ 6/2012): neutrino data

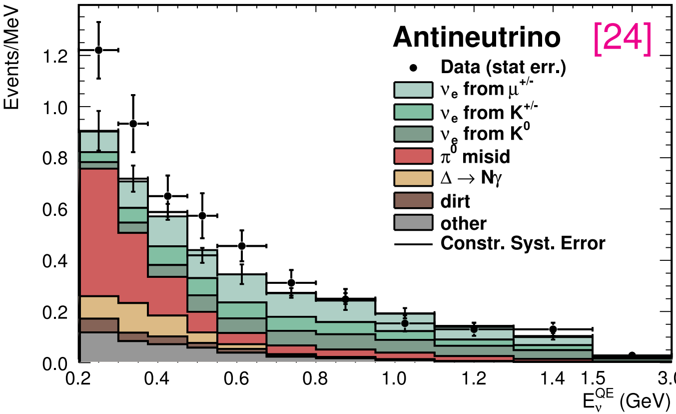
- Statisics: 5.58 (2007) $\to$ 6.46 (2008) $\times 10^{20}$ POT, then just improved analysis;
- is ν signal compatible with 2ν oscillations? $\begin{cases} \text{2007: } P_\text{osc} \simeq 1\% \Rightarrow \text{no it isn't [22];} \\ \text{2012: } P_\text{osc} \simeq 6\% \Rightarrow \text{maybe it is [23];} \end{cases}$
- do MB ν data rule out LSND $\bar\nu$ signal in (3+1)? 2007: yes [22]; 2012: not really [23].



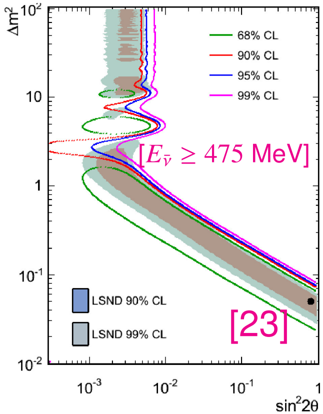
[22] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], Phys. Rev. Lett. **98** (2007) 231801 [arXiv:0704.1500].
[23] C. Polly, talk at Neutrino 2012, Kyoto, Japan, June 3-9, 2012.

Latest MiniBooNE results ($\geq$ 6/2012): antineutrino data

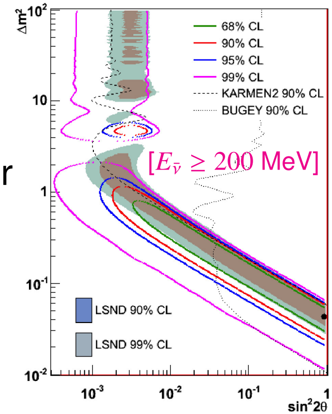
- New data presented at Neutrino 2012, statistics doubled [23];
- compatibility with ν data: { low-energy excess increased $\Rightarrow$ better agreement; mid-energy excess reduced $\Rightarrow$ better agreement;
- is $\bar{\nu}$ signal compatible with 2ν oscillations? $P_{\text{osc}} = 67.5\%$ $\Rightarrow$ definitely yes [23, 24];
- is MB-$\bar{\nu}$ signal compatible with LSND? Yes, irrespective of the energy threshold.



$\Rightarrow$



or

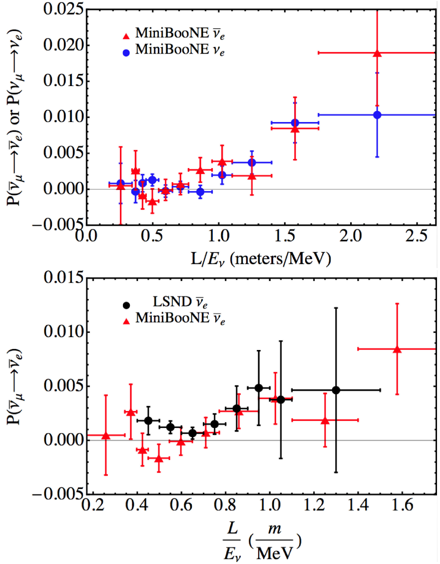


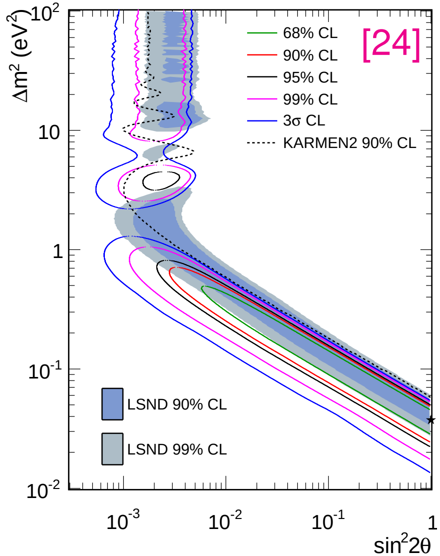
[23] C. Polly, talk at Neutrino 2012, Kyoto, Japan, June 3-9, 2012.

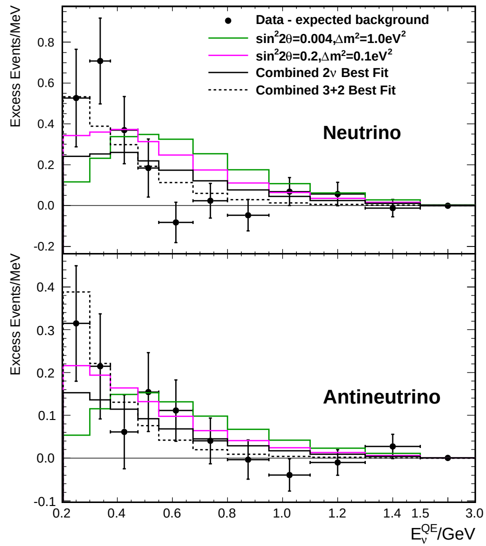
[24] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], arXiv:1207.4809.

MiniBooNE ($\geq$ 6/2012): global $\nu + \bar{\nu}$ appearance in (3+1)

- MiniBooNE ν and $\bar{\nu}$ no longer in open disagreement with LSND within (3+1) models;
- however, dramatic change in interpretation **not** linked to dramatic change in data;
- problems still there ($P_{\text{osc}} \simeq 6.7\%$ [24]) $\Rightarrow$ no great change expected in our conclusions.







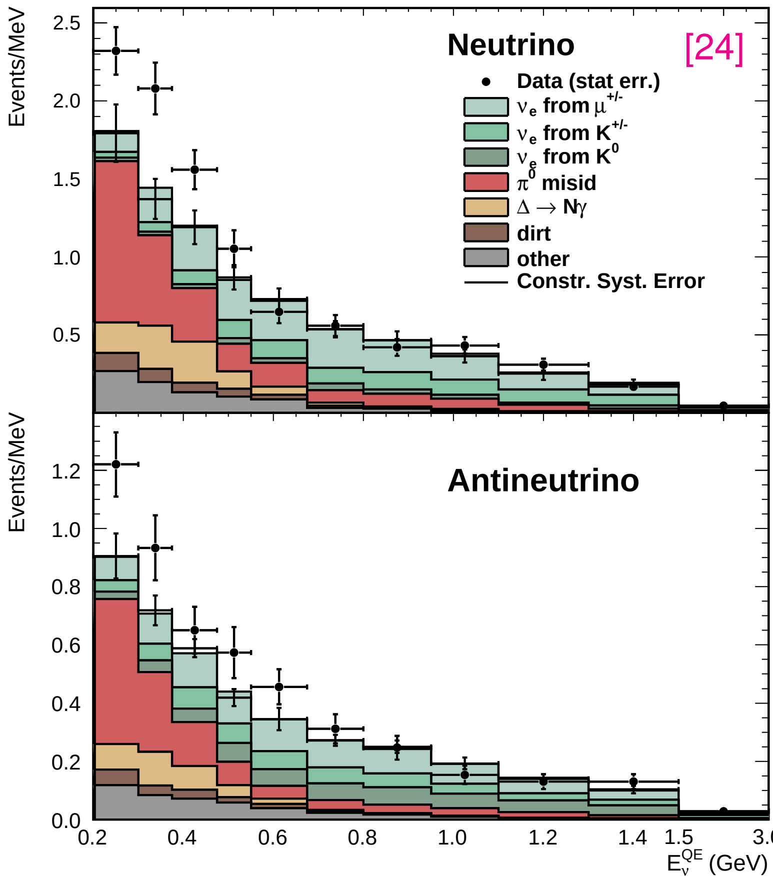
[24] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], arXiv:1207.4809.

The MiniBooNE excess

- MiniBooNE observed an overall 3.8σ excess, mostly at low energy [24];
- although no longer *"in open disagreement"*, ν and $\bar{\nu}$ signals are not really equivalent either. For example:

$$P_{2\nu} = \begin{cases} 6.1\% & \text{for } \nu; \\ 67.5\% & \text{for } \bar{\nu}; \end{cases}$$

- former omission of low-energy ν bins ($E_\nu^{\text{QE}} < 475$ MeV) based on the hypothesis of **two-flavor oscillations**;
- is it possible to do something better about low-energy data in **more sophisticated** models?



[24] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], arXiv:1207.4809.

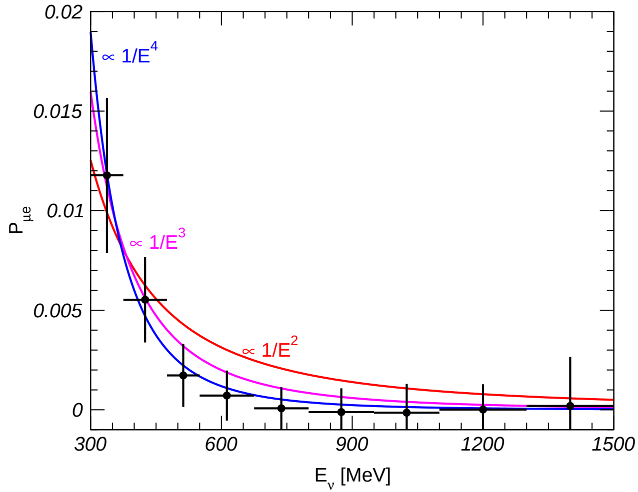
Explaining the MiniBooNE excess with two sterile neutrinos

- With *one* extra sterile neutrino, m_4:

$$P^{4\nu}_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\phi_{41} \quad \text{with} \quad \phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E};$$

- for large energy $P^{4\nu}_{\mu e}$ drops as $1/E^2$;
- however, the low-energy MB excess is much sharper ($\sim 1/E^4$);

⇒ **it is very hard to account for the MB excess with only one extra sterile neutrino.**



- On the other hand, with *two* extra neutrinos, m_4 and m_5:

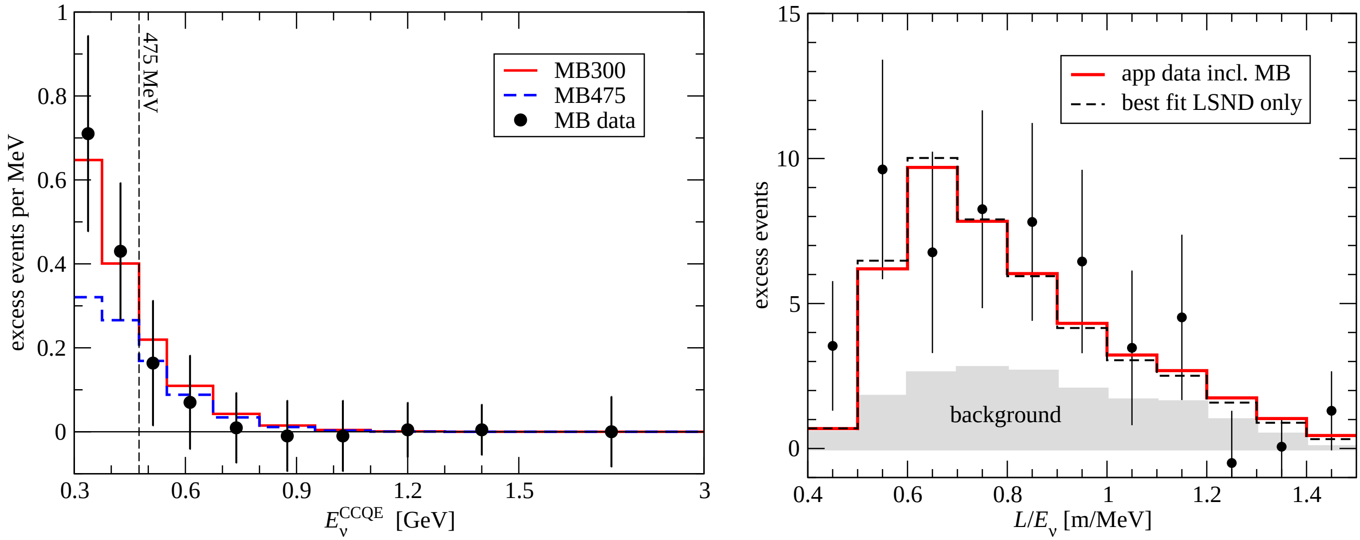
$$P^{5\nu}_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2\phi_{51} + 8|U_{e4}U_{e5}U_{\mu 4}U_{\mu 5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} - \delta);$$

- terms of order $1/E^2$ cancel if $\delta = \pi$ and $|U_{e4}\,U_{\mu 4}|\Delta m^2_{41} = |U_{e5}\,U_{\mu 5}|\Delta m^2_{51}$;

⇒ **with two extra sterile states it is possible to fit the MB low-energy excess** [25].

[25] M. Maltoni, T. Schwetz, Phys. Rev. **D76** (2007) 093005 [arXiv:0705.0107].

Reconciling MiniBooNE and LSND in (3+2) models



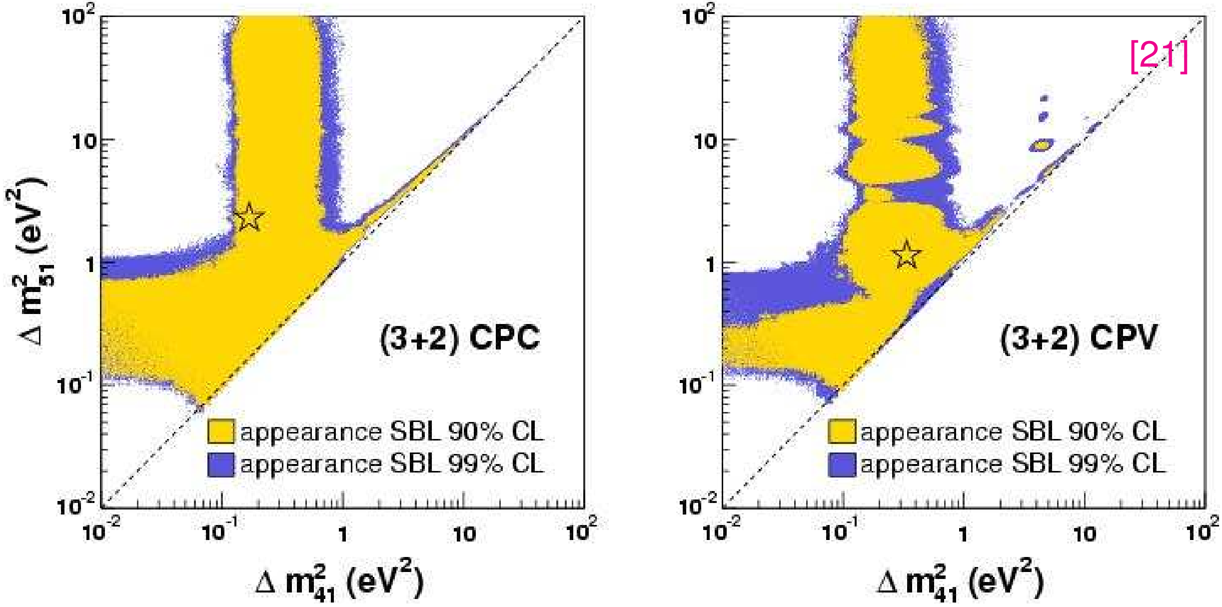
- **Trick**: use the CP phase $\delta = \arg(U_{e4}^* U_{\mu 4} U_{e5} U_{\mu 5}^*)$ to differentiate ν (MB) from $\bar{\nu}$ (LSND):

$$P_{\mu e}^{5\nu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2\phi_{51} + 8|U_{e4}U_{e5}U_{\mu 4}U_{\mu 5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} - \delta);$$

- note that $\delta = \pi + \epsilon$ and $|U_{e4}\, U_{\mu 4}|\Delta m_{41}^2 \approx |U_{e5}\, U_{\mu 5}|\Delta m_{51}^2$ to suppress MB probability [25].

[25] M. Maltoni, T. Schwetz, Phys. Rev. **D76** (2007) 093005 [arXiv:0705.0107].

Fitting all appearance data in (3+2) models



data set	$\lvert U_{e4}U_{\mu4}\rvert$	Δm^2_{41}	$\lvert U_{e5}U_{\mu5}\rvert$	Δm^2_{51}	δ	χ^2_{min}/dof	gof
appearance (CPC)	0.12	0.18	0.006	2.31	–	$95.8/86$	22%
appearance (CPV)	0.080	0.39	0.029	1.10	1.1π	$82.5/85$	56%

NOTE: data taken from Ref. [21], which uses **old** MB-$\bar{\nu}$ data.

[21] G. Karagiorgi *et al.*, Phys. Rev. **D80** (2009) 073001 [arXiv:0906.1997].

The doom of disappearance data

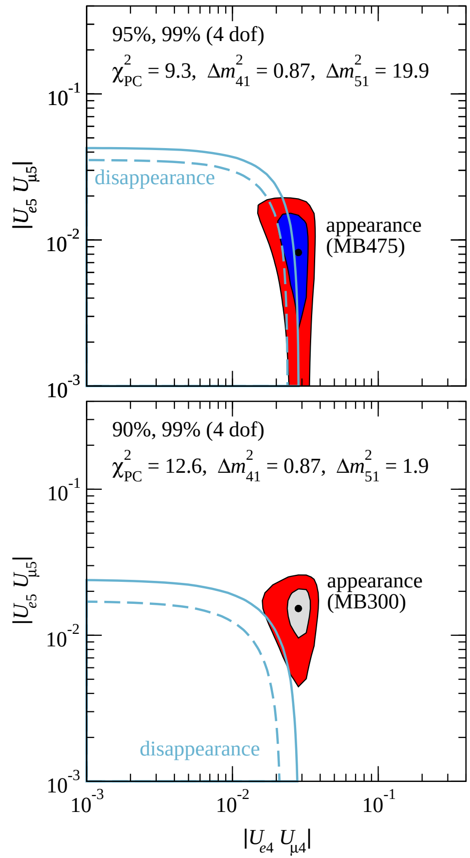
- As for (3+1) models, disappearance data imply bounds on $|U_{ei}|^2$ and $|U_{\mu i}|^2$ ($i = 4, 5$);
- these bounds are in conflict with the large values of $|U_{ei} U_{\mu i}|$ required by appearance data;
- again, a tension between APP and DIS arises:

$$\chi^2_{\text{PG}} = 17.5 \text{ (4 dof)} \Rightarrow \text{PG} = 1.5 \times 10^{-3} \quad \text{[no MB]};$$
$$\chi^2_{\text{PG}} = 17.2 \text{ (4 dof)} \Rightarrow \text{PG} = 1.8 \times 10^{-3} \quad \text{[MB475]};$$
$$\chi^2_{\text{PG}} = 25.1 \text{ (4 dof)} \Rightarrow \text{PG} = 4.8 \times 10^{-5} \quad \text{[MB300]};$$

- alternatively, compare LSND and NEV as in (3+1):

$$\chi^2_{\text{PG}} = 19.6 \text{ (5 dof)} \Rightarrow \text{PG} = 1.5 \times 10^{-3} \quad \text{[before MB]};$$
$$\chi^2_{\text{PG}} = 21.2 \text{ (5 dof)} \Rightarrow \text{PG} = 7.4 \times 10^{-4} \quad \text{[after MB]}.$$

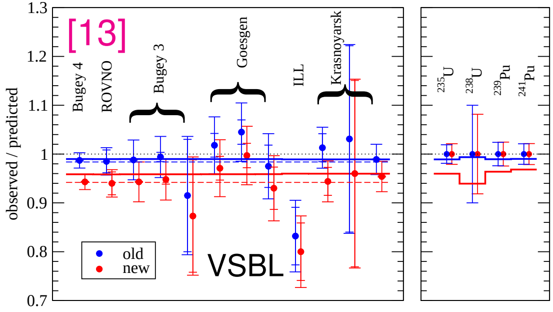
⇒ **Conclusion: (3+2) models fail exactly as (3+1) [25].**

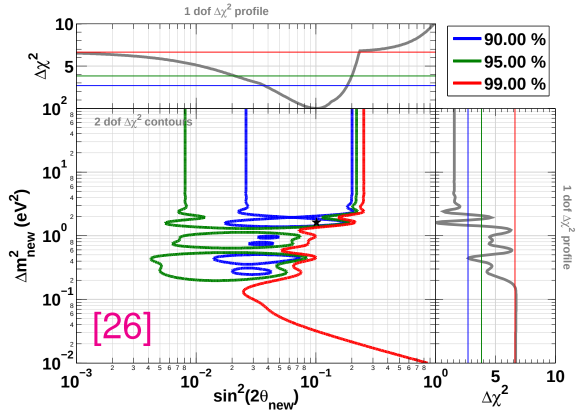


[25] M. Maltoni, T. Schwetz, Phys. Rev. **D76** (2007) 093005 [arXiv:0705.0107].

The reactor neutrino anomaly

- In [14, 15] the reactor $\bar{\nu}$ fluxes was reevaluated;
- the new calculations result in a small increase of the flux by about **3.5%**;
- hence, **all** reactor short-baseline (RSBL) exp. finding no evidence are actually observing a deficit;
- this deficit **could** be interpreted as being due to SBL neutrino oscillations;
- deficit independent of $L \Rightarrow \Delta m^2 \gtrsim 1$ eV^2;
- impact on previous results:
  - 4ν: small (4ν dead anyway);
  - 5ν: important.





[13] T. Schwetz, M. Tortola, J.W.F. Valle, New J. Phys. **13** (2011) 063004 [arXiv:1103.0734].

[14] T.A. Mueller *et al.*, Phys. Rev. **C83** (2011) 054615 [arXiv:1101.2663].

[15] P. Huber, Phys. Rev. C **84** (2011) 024617 [arXiv:1106.0687].

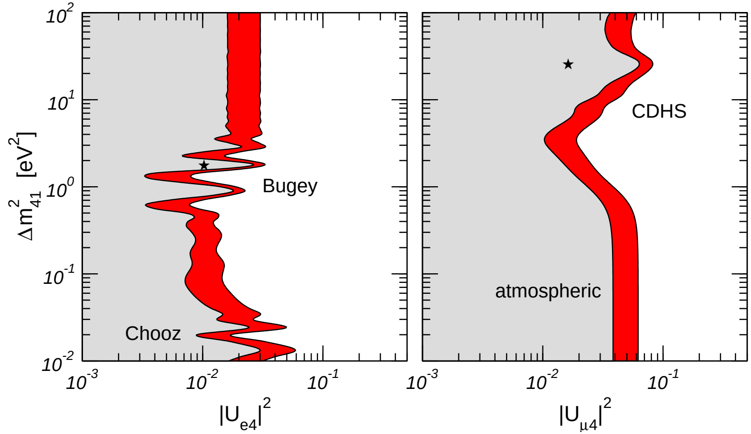
[26] G. Mention *et al.*, Phys. Rev. **D83** (2011) 073006 [arXiv:1101.2755].

Can the reactor neutrino anomaly save the day?

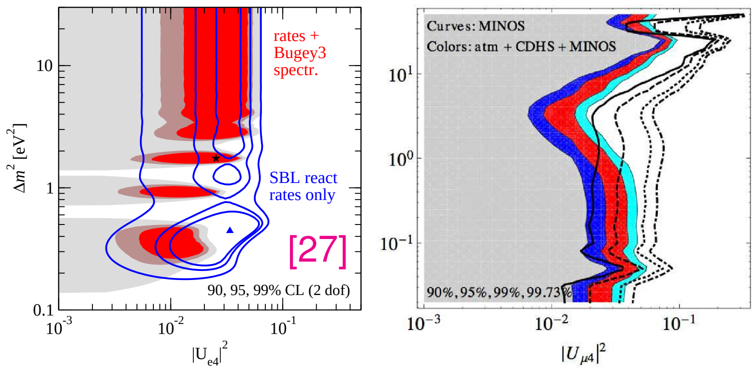
- As expected, the new reactor fluxes lead to a clear preference for $|U_{e4}|^2 \neq 0$;
- however, the <u>upper bound</u> on $|U_{e4}|^2$ is **not** dramatically reduced;
- morever, the bound on $|U_{\mu4}|^2$ from atmospheric data is now independently confirmed by MINOS;
- all together, there is **no** reason to expect an impressive weakening of the disappearance bound.

[27] T. Schwetz, talk at Neutrino 2012, Kyoto, Japan, June 3-9, 2012.

Old reactor fluxes

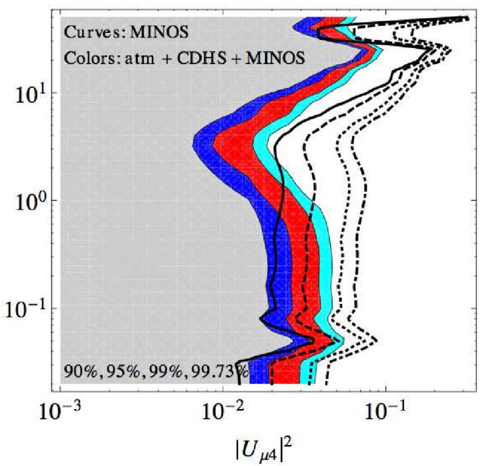


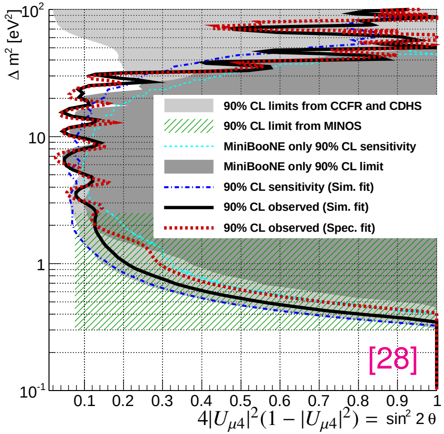
New reactor fluxes & MINOS

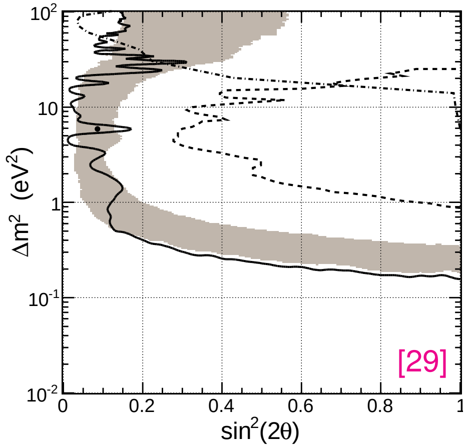


Muon disappearance: combined MiniBooNE & SciBooNE analysis

- In addition to the already mentioned atmospheric and MINOS data, a combined analisys of MiniBooNE & SciBooNE data has recently been presented, for both ν [28] and $\bar{\nu}$ [29];
- No hint of ν_μ disappearance has been found in either case, thus strenghtening the bound in the large-Δm^2 region ($\Delta m^2_{41} \gtrsim 1$ eV^2).





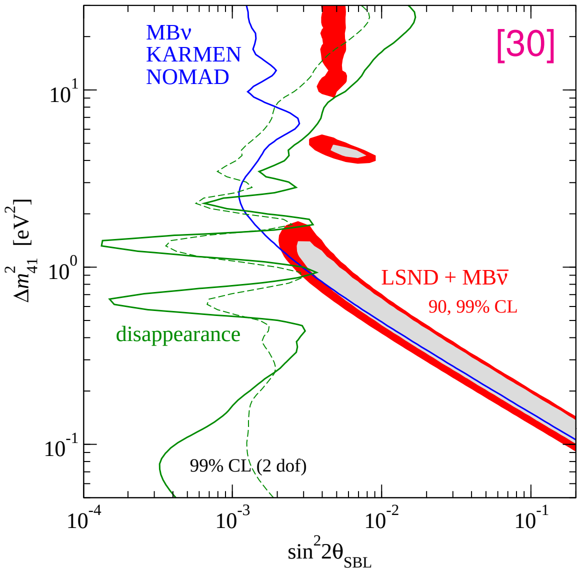


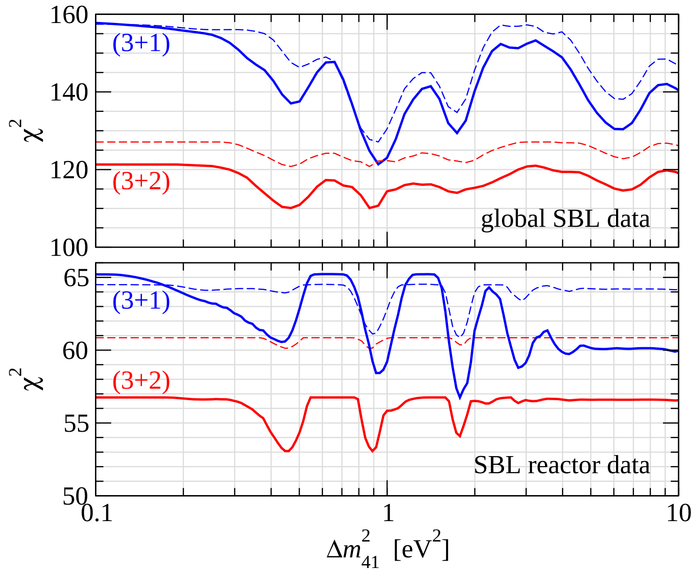
[28] K.B.M. Mahn *et al.* [SciBooNE & MiniBooNE collab], Phys. Rev. D **85** (2012) 032007 [arXiv:1106.5685].

[29] G. Cheng *et al.* [MiniBooNE & SciBooNE collab], Phys. Rev. D **86** (2012) 052009 [arXiv:1208.0322].

Impact of the new reactor fluxes

- (3+1) models: $\chi^2_{\text{PG}}/\text{dof} = 24.2/2 \to 21.5/2$ for LSND + MB($\bar\nu$) vs NEV ($\Delta\chi^2_{\text{PG}} = 2.7$);
- (3+2) models: $\begin{cases} \chi^2_{\text{PG}}/\text{dof} = 25.1/5 \to 19.9/5 \text{ for LSND + MB}(\bar\nu) \text{ vs NEV } (\Delta\chi^2_{\text{PG}} = 5.2); \\ \chi^2_{\text{PG}}/\text{dof} = 19.4/4 \to 14.7/4 \text{ for APP vs DIS } (\Delta\chi^2_{\text{PG}} = 4.7). \end{cases}$

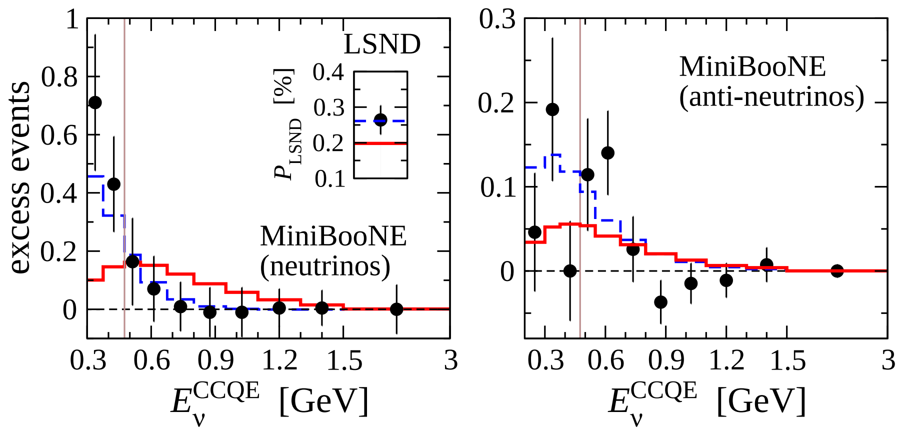


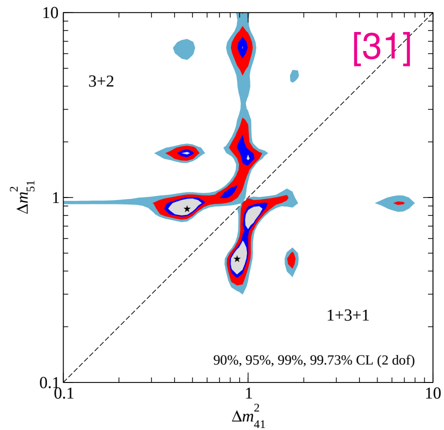


[30] J. Kopp, M. Maltoni and T. Schwetz, Phys. Rev. Lett. **107** (2011) 091801 [arXiv:1103.4570].

Status of (3+2) models with the new reactor fluxes

- (3+2) models experience substantial improvement, but tension with disappearance data remains considerably strong: PG=0.53%;
- situation becomes more critical if the MiniBooNE low-E excess is included, since larger mixing angles are required;
- (1+3+1) works slightly better, but has stronger problems with cosmology since the sum of neutrino masses ($\sum m_\nu$) is larger.





[31] J. Kopp, P.A.N. Machado, M. Maltoni and T. Schwetz, JHEP **1305** (2013) 050 [arXiv:1303.3011].

Non-standard neutrino interactions: formalism

- Effective low-energy Lagrangian for **standard** neutrino interactions with matter:

$$\mathcal{L}_{\text{SM}}^{\text{eff}} = -2\sqrt{2}G_F \sum_{\beta} \left([\bar{\nu}_\beta \gamma_\mu L \ell_\beta][\bar{f}\gamma^\mu L f'] + \text{h.c.} \right) - 2\sqrt{2}G_F \sum_{P,\beta} g_P^f [\bar{\nu}_\beta \gamma_\mu L \nu_\beta][\bar{f}\gamma^\mu P f]$$

  where $P \in \{L, R\}$, (f, f') form an SU(2) doublet, and g_P^f is the Z coupling to fermion f:

$$g_L^\nu = \frac{1}{2}\,, \qquad g_L^\ell = \sin^2\theta_W - \frac{1}{2}\,, \qquad g_L^u = -\frac{2}{3}\sin^2\theta_W + \frac{1}{2}\,, \qquad g_L^d = \frac{1}{3}\sin^2\theta_W - \frac{1}{2}\,,$$

$$g_R^\nu = 0\,, \qquad g_R^\ell = \sin^2\theta_W\,, \qquad g_R^u = -\frac{2}{3}\sin^2\theta_W\,, \qquad g_R^d = \frac{1}{3}\sin^2\theta_W\,;$$

- here we consider NC-like **non-standard** neutrino-matter described by:

$$\mathcal{L}_{\text{NSI}}^{\text{eff}} = -2\sqrt{2}G_F \sum_{P,\alpha,\beta} \varepsilon_{\alpha\beta}^{fP} [\bar{\nu}_\alpha \gamma_\mu L \nu_\beta][\bar{f}\gamma^\mu P f]\,;$$

  note that $\varepsilon_{\alpha\beta}^{fP}$ is Hermitian;

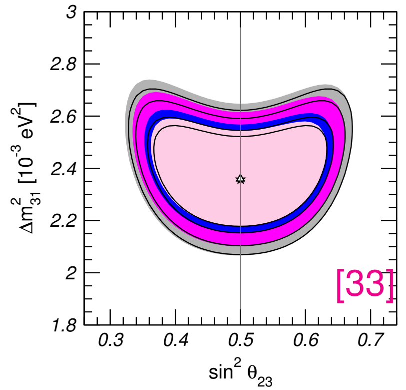
- neutrino **propagation** is only sensitive to the vector couplings $\varepsilon_{\alpha\beta}^{f} = \varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR}$;
- note that NC-like NSI's do **not** affect CC processes such as lepton appearance.

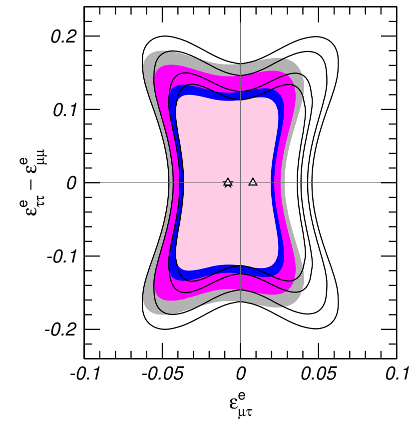
NSI in the $\mu - \tau$ sector: atmospheric neutrinos

- Let's begin from NSI in the $\mu - \tau$ sector [32]: $\vec{\nu} = (\nu_\mu, \nu_\tau)^T$

$$i\frac{d\vec{\nu}}{dt} = \left[\frac{\Delta m^2_{31}}{4E_\nu}\begin{pmatrix} -\cos 2\theta_{23} & \sin 2\theta_{23} \\ \sin 2\theta_{23} & \cos 2\theta_{23}\end{pmatrix} \pm \sqrt{2}\, G_F N_f(r) \begin{pmatrix} \varepsilon^f_{\mu\mu} & \varepsilon^f_{\mu\tau} \\ \varepsilon^{f\star}_{\mu\tau} & \varepsilon^f_{\tau\tau}\end{pmatrix}\right] \vec{\nu},$$

- determination of oscillation parameters is very stable;
- 90% (3σ) bounds on NSI: [33] $\begin{cases} |\varepsilon^e_{\mu\tau}| \le 0.035\ (0.055)\,, \\ |\varepsilon^e_{\tau\tau} - \varepsilon^e_{\mu\mu}| \le 0.11\ (0.18)\,, \\ |\varepsilon^u_{\alpha\beta}|,\ |\varepsilon^d_{\alpha\beta}| : \text{ approx } |\varepsilon^e_{\alpha\beta}|/3\,; \end{cases}$
- bounds on $|\varepsilon^f_{\tau\tau} - \varepsilon^f_{\mu\mu}|$ considerably stronger than LAB ones;
- OSC+NSI bound possible because of **large energy window**:
  - low-energy data constrain oscillations (drop as $1/E$);
  - high-energy data constrain NSI (**no drop** with E).

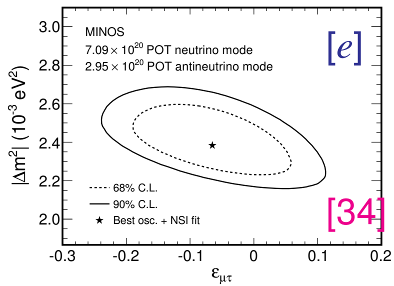


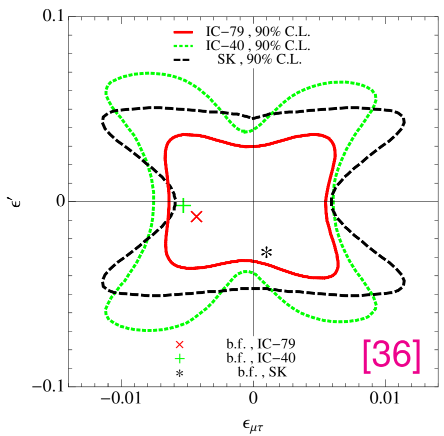


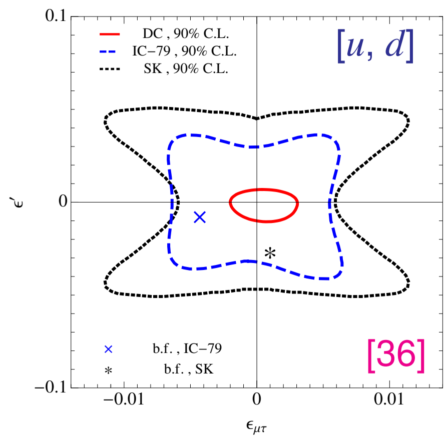
[32] N. Fornengo *et al.*, Phys. Rev. **D65** (2002) 013010 [hep-ph/0108043].
[33] M.C. Gonzalez-Garcia, M. Maltoni and J. Salvado, JHEP **05** (2011) 075 [arXiv:1103.4365].

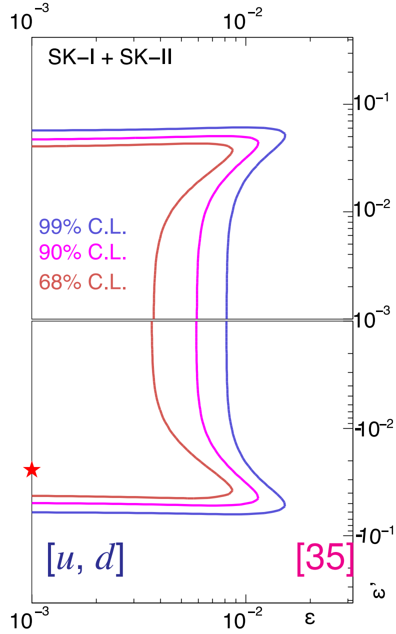
NSI in the $\mu - \tau$ sector: recent analyses

- Similar analysis presented by MINOS [34] and SK [35];
- huge **statistics** and **energy window** from the combined ICECUBE and DEEPCORE projects can boost sensitivity by one order of magnitude [36].









[34] P. Adamson *et al.* [MINOS], arXiv:1303.5314.
[35] G. Mitsuka *et al.* [SK], PRD **84** (2011) 113008 [arXiv:1109.1889].
[36] A. Esmaili and A.Yu. Smirnov, arXiv:1304.1042.

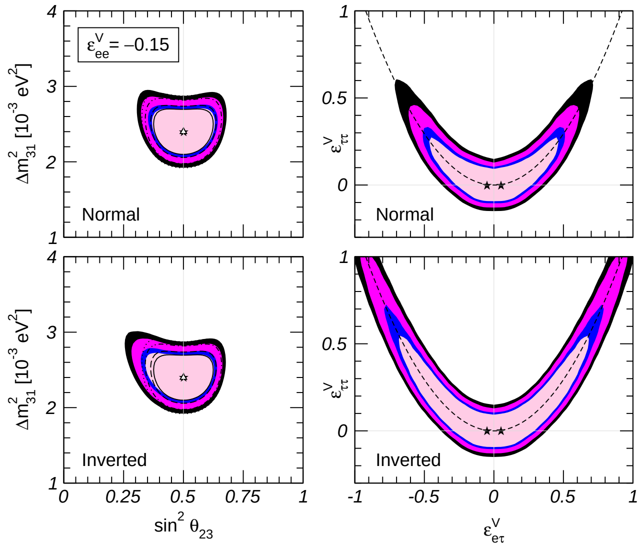
Atmospheric ν: the $\nu_e - \nu_\tau$ channel

$$\oplus \begin{cases} N_u/N_e = 3.137\ \text{(core)}, 3.012\ \text{(mantle)} \\ N_d/N_e = 3.274\ \text{(core)}, 3.024\ \text{(mantle)} \end{cases}$$

- Let us now turn to the $e - \tau$ sector [37, 38, 39]:

$$V_{\text{NSI}} \propto \begin{pmatrix} \varepsilon_{ee} & 0 & \varepsilon_{e\tau} \\ 0 & \varepsilon_{\mu\mu} & 0 \\ \varepsilon_{e\tau}^\star & 0 & \varepsilon_{\tau\tau} \end{pmatrix} \qquad \varepsilon_{\alpha\beta} \equiv \sum_f \frac{N_f}{N_e} \varepsilon_{\alpha\beta}^f \approx \varepsilon_{\alpha\beta}^e + 3\,\varepsilon_{\alpha\beta}^u + 3\,\varepsilon_{\alpha\beta}^d$$

- a dramatic cancellation [37] occurs along the parabola $(1 + \varepsilon_{ee} - \varepsilon_{\mu\mu})(\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}) = |\varepsilon_{e\tau}|^2$;
- determination of osc. parameters **still stable**;
- **but** bound on $|\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}|$ no longer applies;
- however, the $\perp$ bound is still strong [35, 37];



$\Rightarrow$ **Correlations among different $\varepsilon_{\alpha\beta}$ can have very important consequences!**

[35] G. Mitsuka *et al.* [SK], Phys. Rev. **D84** (2011) 113008 [arXiv:1109.1889].

[37] A. Friedland, C. Lunardini, and M. Maltoni, Phys. Rev. **D70** (2004) 111301 [hep-ph/0408264].

[38] A. Friedland and C. Lunardini, Phys. Rev. **D72** (2005) 053009 [hep-ph/0506143].

[39] A. Friedland and C. Lunardini, Phys. Rev. **D74** (2006) 033012 [hep-ph/0606101].

Bounds from non-oscillation experiments

- Present bounds on $\varepsilon_{\alpha\beta} = \varepsilon^e_{\alpha\beta} + 3\,\varepsilon^u_{\alpha\beta} + 3\,\varepsilon^d_{\alpha\beta}$ [45]:

$\|\varepsilon_{ee}\| \lesssim \mathcal{O}(1)$	poor	LSND, Reactors, CHARM	[40, 41, 42]
$\|\varepsilon_{\mu\mu}\| \lesssim \mathcal{O}(0.01)$	good	CHARM II, NuTeV	[40, 42]
$\|\varepsilon_{\tau\tau}\| \lesssim \mathcal{O}(10)$	poor	LEP, τ decay	[40, 42, 43]
$\|\varepsilon_{e\mu}\| \lesssim$ ~~$\mathcal{O}(0.001)$~~	~~strong~~	~~radiative corrections~~	~~[42]~~
$\|\varepsilon_{e\mu}\| \lesssim \mathcal{O}(0.1)$	mild	CHARM II, NuTeV	[44, 45]
$\|\varepsilon_{e\tau}\| \lesssim \mathcal{O}(1)$	poor	LEP+LSND+Reactors, CHARM	[40, 42, 43]
$\|\varepsilon_{\mu\tau}\| \lesssim \mathcal{O}(0.1)$	mild	CHARM II, NuTeV	[40, 42]

- no strong bound (other than $\varepsilon_{\mu\mu}$) appear;
- in particular, the common assumption $\varepsilon_{e\mu} = 0$ is not justified.

[40] J. Barranco *et al.*, arXiv:0711.0698.

[41] J. Barranco *et al.*, Phys. Rev. **D73** (2006) 113001 [hep-ph/0512195].

[42] S. Davidson *et al.*, JHEP **03** (2003) 011 [hep-ph/0302093].

[43] Z. Berezhiani and A. Rossi, Phys. Lett. **B535** (2002) 207 [hep-ph/0111137].

[44] C. Biggio, M. Blennow, E. Fernandez-Martinez, JHEP **03** (2009) 139 [arXiv:0902.0607].

[45] C. Biggio, M. Blennow, E. Fernandez-Martinez, JHEP **08** (2009) 090 [arXiv:0907.0097].

Non-standard interactions and 3ν oscillations

- Equation of motion: **6** (vac) + **8** (NSI) = **14** parameters:

$$i\frac{d\vec{\nu}}{dt} = H\,\vec{\nu}; \qquad H = U_{\text{vac}} \cdot D_{\text{vac}} \cdot U_{\text{vac}}^{\dagger} \pm V_{\text{mat}}; \qquad D_{\text{vac}} = \frac{1}{2E_\nu}\,\text{diag}\left(0,\ \Delta m^2_{21},\ \Delta m^2_{31}\right);$$

$$U_{\text{vac}} = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{\text{CP}}} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\text{CP}}} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\text{CP}}} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\text{CP}}} & -c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\text{CP}}} & c_{13}\,c_{23} \end{pmatrix}, \qquad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix},$$

$$\varepsilon_{\alpha\beta} \equiv \sum_f \frac{N_f}{N_e}\varepsilon^f_{\alpha\beta}, \qquad V_{\text{mat}} \equiv V_{\text{SM}} + V_{\text{NSI}} = \sqrt{2}G_F N_e \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^\star_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^\star_{e\tau} & \varepsilon^\star_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix};$$

- too much parameters ⇒ only partial analyses technically possible;
- so far, most numerical studies assumed some specific $\varepsilon_{\alpha\beta}$ to be zero;
- in what follows we will try to simplify the problem while being as conservative as possible, based on the results of partial analyses presented in the previous slides [33].

[33] M.C. Gonzalez-Garcia, M. Maltoni and J. Salvado, JHEP **05** (2011) 075 [arXiv:1103.4365].

The degenerate matter-eigenvalues approximation

- So far we have learned that:
  - from $\mu-\tau$: NSI spoil the vacuum oscillation patterns favored by data $\Rightarrow$ strong bounds;
  - from $e-\tau$: bounds become very weak when two eigenvalues of V_{mat} coincide;
- hence, the limit of two coinciding V_{mat} eigenvalues is the most conservative one.
- general parametrization:

$$V_{\text{mat}} = P_{\text{rel}} U_{\text{mat}} D_{\text{mat}} U_{\text{mat}}^\dagger P_{\text{rel}}^\dagger ,$$

$$\begin{cases} P_{\text{rel}} = \text{diag}\left(e^{i\alpha_1}, e^{i\alpha_2}, e^{-i\alpha_1 - i\alpha_2}\right), \\ U_{\text{mat}} = R_{12}(\varphi_{12}) R_{13}(\varphi_{13}), \\ D_{\text{mat}} = \sqrt{2} G_F N_e(r)\, \text{diag}(\varepsilon, 0, 0); \end{cases}$$

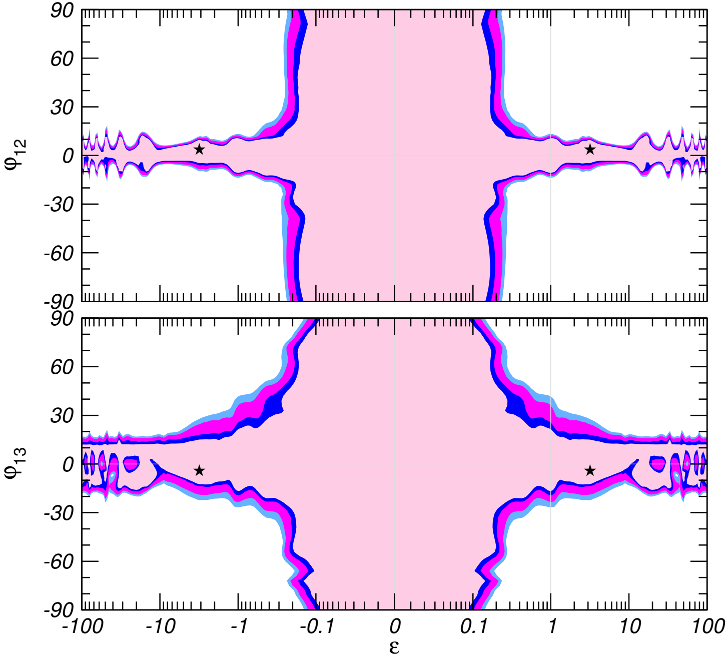
$$\begin{aligned} 1 + \varepsilon_{ee} - \varepsilon_{\mu\mu} &= \varepsilon\,(\cos^2\varphi_{12} - \sin^2\varphi_{12}) \cos^2\varphi_{13}, \\ \varepsilon_{\tau\tau} - \varepsilon_{\mu\mu} &= \varepsilon\,(\sin^2\varphi_{13} - \sin^2\varphi_{12}\cos^2\varphi_{13}), \\ \varepsilon_{e\mu} &= -\varepsilon \cos\varphi_{12} \sin\varphi_{12} \cos^2\varphi_{13}\, e^{i(\alpha_1 - \alpha_2)}, \\ \varepsilon_{e\tau} &= -\varepsilon \cos\varphi_{12} \cos\varphi_{13} \sin\varphi_{13}\, e^{i(2\alpha_1 + \alpha_2)}, \\ \varepsilon_{\mu\tau} &= \varepsilon \sin\varphi_{12} \cos\varphi_{13} \sin\varphi_{13}\, e^{i(\alpha_1 + 2\alpha_2)}. \end{aligned}$$

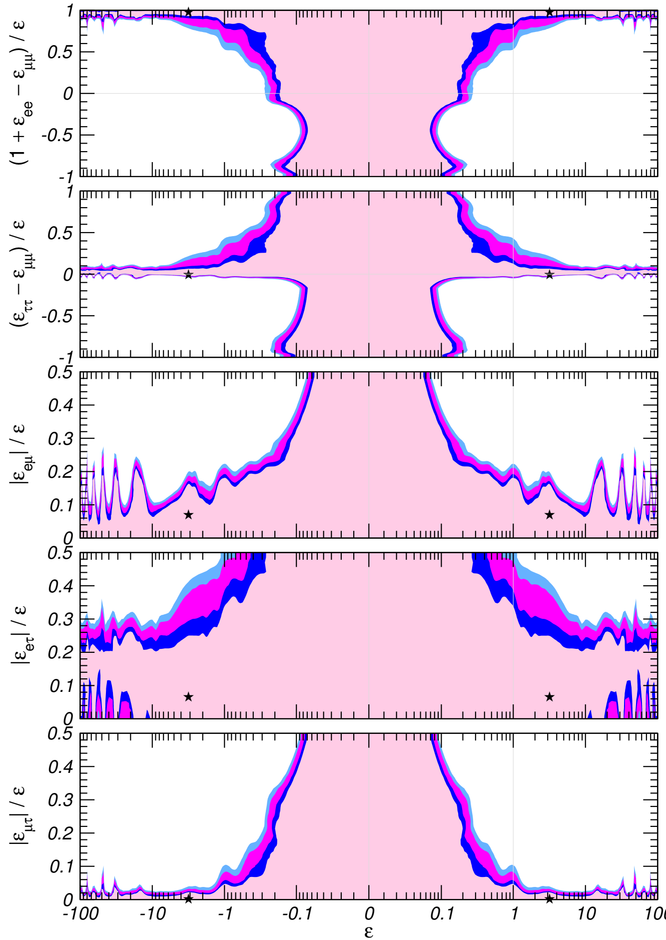
- set $\Delta m^2_{21} = 0 \Rightarrow \theta_{12}$ and δ_{CP} disappear $\Rightarrow$ **3** (vac) + **2** (rel) + **3** (mat) = **8** parameters;
- SM is recovered for $\varphi_{12} = \varphi_{13} = 0$ and $\varepsilon = \pm 1$, with $\text{sgn}(\varepsilon) \cdot \text{sgn}(\Delta m^2_{31}) \Leftrightarrow$ mass hierarchy;
- it can be shown that neutrino evolution reduces to an effective $(1\nu + 2\nu)$ scenario [46].

[46] M. Blennow and T. Ohlsson, Phys. Rev. D **78** (2008) 093002 [arXiv:0805.2301].

General bounds on NSI

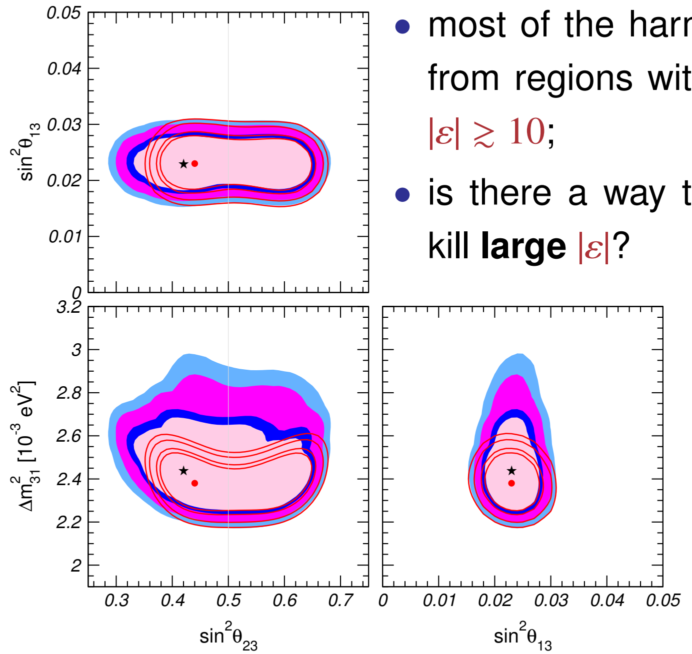
- No bound on $|\varepsilon|$ available from osc. data;
- $|\varepsilon| \gtrsim 1$ implies $|\varphi_{12}| \lesssim 15^\circ$ and $|\varphi_{13}| \lesssim 30^\circ$;
- is there a way to kill **small** $|\varepsilon|$?



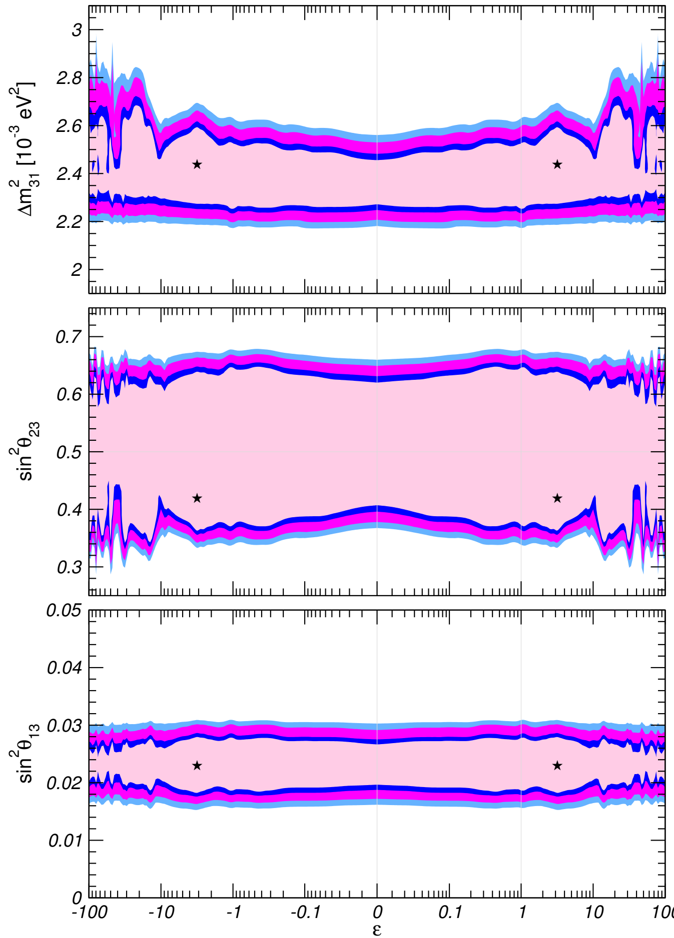


Stability of the oscillation solution

- ATM data partially stabilize the determination of the oscillation parameters;
- however, MINOS bound on Δm^2_{31} spoiled;



- most of the harm from regions with $|\varepsilon| \gtrsim 10$;
- is there a way to kill **large** $|\varepsilon|$?



Combining solar and atmospheric neutrinos

- As in the SM case, solar neutrinos can be reduced to an effective 2ν problem:

$$i\frac{d\vec{\nu}}{dt} = \left[\frac{\Delta m^2_{21}}{4E_\nu}\begin{pmatrix}-\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12}\end{pmatrix} + \sqrt{2}\,G_F N_e(r)\begin{pmatrix}c^2_{13} & 0 \\ 0 & 0\end{pmatrix} + \sqrt{2}\,G_F N_f(r)\begin{pmatrix}-\varepsilon^f_D & \varepsilon^f_N \\ \varepsilon^{f\star}_N & \varepsilon^f_D\end{pmatrix}\right]\vec{\nu},$$

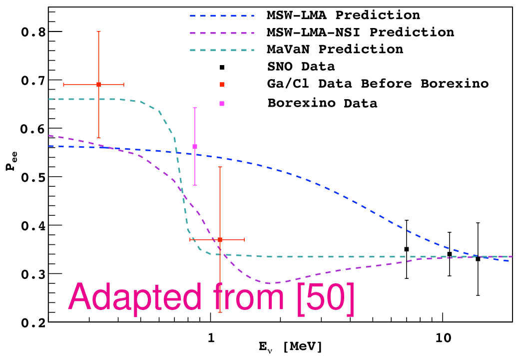
$$\vec{\nu} = \begin{pmatrix}\nu_e \\ \nu_a\end{pmatrix}, \qquad \begin{cases} \varepsilon^f_D = c_{13}s_{13}\Re\left[e^{i\delta_{\text{CP}}}(s_{23}\,\varepsilon^f_{e\mu} + c_{23}\,\varepsilon^f_{e\tau})\right] - (1+s^2_{13})c_{23}s_{23}\Re(\varepsilon^f_{\mu\tau}) \\ \qquad - c^2_{13}(\varepsilon^f_{ee} - \varepsilon^f_{\mu\mu})/2 + (s^2_{23} - s^2_{13}c^2_{23})(\varepsilon^f_{\tau\tau} - \varepsilon^f_{\mu\mu})/2\,, \\ \varepsilon^f_N = c_{13}(c_{23}\,\varepsilon^f_{e\mu} - s_{23}\,\varepsilon^f_{e\tau}) + s_{13}e^{-i\delta_{\text{CP}}}\left[s^2_{23}\,\varepsilon^f_{\mu\tau} - c^2_{23}\,\varepsilon^{f\star}_{\mu\tau} + c_{23}s_{23}(\varepsilon^f_{\tau\tau} - \varepsilon^f_{\mu\mu})\right]; \end{cases}$$

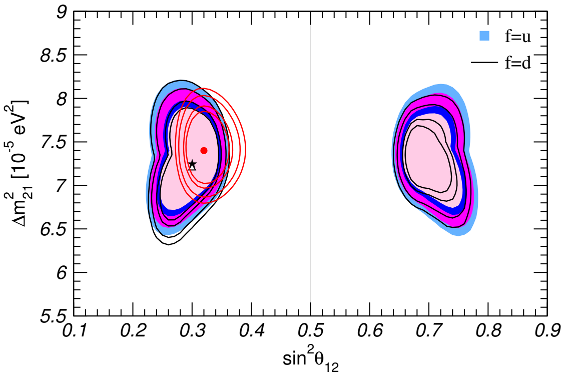
- pre-Borexino solar data *can be perfectly fitted* by NSI only $\Rightarrow$ solar LMA solution **is unstable** with respect to the introduction of NSI [47, 48, 49];
- KamLAND **requires** Δm^2_{21} but is insensitive to NSI $\Rightarrow$ it **determines** Δm^2_{21};
- Solar+KamLAND bounds on NSI very weak [47], but **not** be affected by the ATM cancellation $\Rightarrow$ potential for **synergy**! Example: $1 + \varepsilon_{ee} = 0 \Rightarrow$ no MSW $\Rightarrow$ excluded.

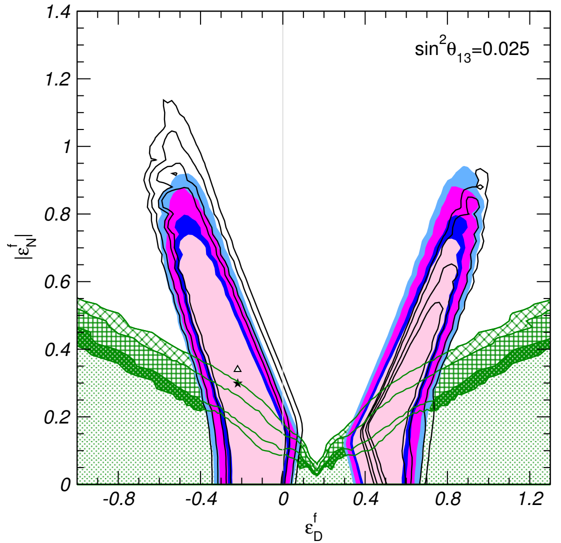
[47] O. G. Miranda, M. A. Tortola, and J. W. F. Valle, JHEP **10** (2006) 008 [hep-ph/0406280].
[48] M. M. Guzzo, P. C. de Holanda, and O. L. G. Peres, Phys. Lett. **B591** (2004) 1 [hep-ph/0403134].
[49] A. Friedland, C. Lunardini, and C. Pena-Garay, Phys. Lett. **B594** (2004) 347 [hep-ph/0402266].

Solar neutrino data and NSI

- Elastic scattering cross-section affected by $\varepsilon^e_{\alpha\beta}$ ⇒ focus only on $f = u$ and $f = d$ for simplicity;
- solar chemical composition varies with radius ⇒ $f = u$ and $f = d$ not trivially related;
- strong negative NSI can flip the sign of the matter term ⇒ θ_{12} flips into the dark side [47];
- non-observation of MSW turn-up slightly favor a bit of NSI since they can produce a flatter solar spectrum.



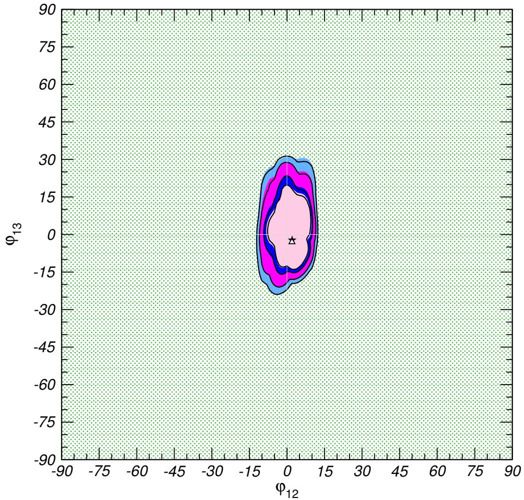


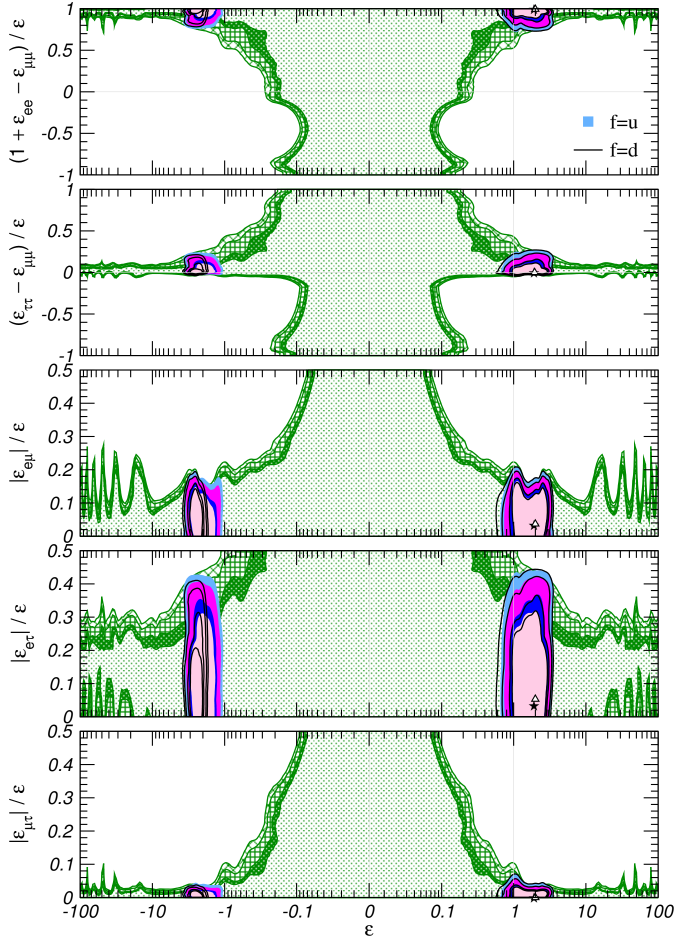


[47] O. Miranda *et al.*, JHEP **10** (2006) 008 [hep-ph/0406280].
[50] C. Galbiati, talk at Neutrino 2008 Conference.

Impact of solar data

- Allowed regions dramatically reduced;
- the bounds $|\varphi_{12}| \lesssim 15^\circ$ and $|\varphi_{13}| \lesssim 30^\circ$ are now independent of ε;
- general bounds on $\varepsilon^f_{\alpha\beta}$ can be derived.

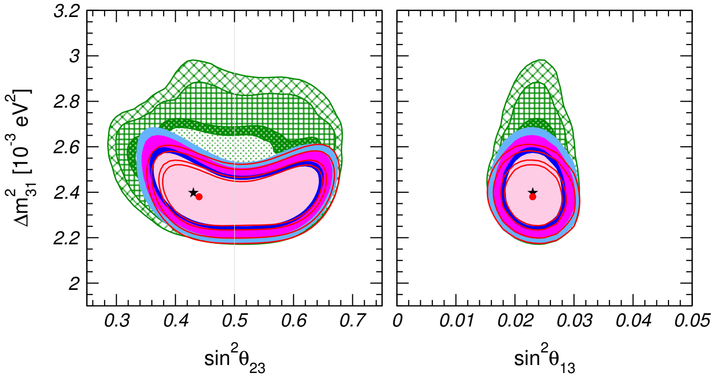


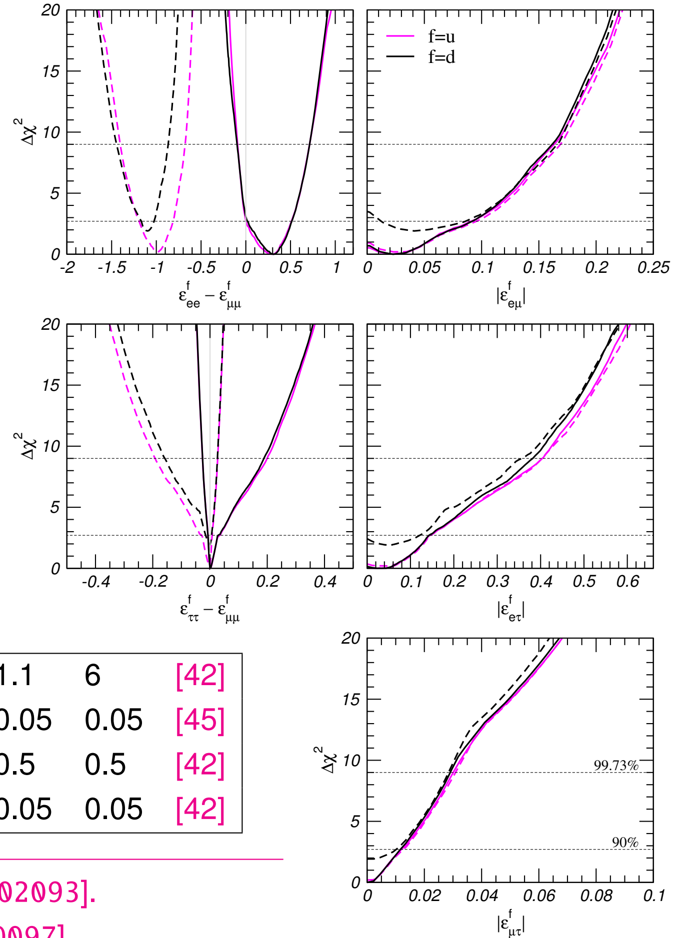


[51] M.C. Gonzalez-Garcia *et al.*, in preparation.

Bounds on NSI parameters

- Oscillation parameters fully stabilized;





- most oscil. bounds stronger than lab ones.

$\lvert\varepsilon^u_{\tau\tau}\rvert$	0.034	1.4	3	[42]
$\lvert\varepsilon^u_{e\mu}\rvert$	0.096	0.05	0.05	[45]
$\lvert\varepsilon^u_{e\tau}\rvert$	0.15	0.5	0.5	[42]
$\lvert\varepsilon^u_{\mu\tau}\rvert$	0.013	0.05	0.05	[42]

$\lvert\varepsilon^d_{\tau\tau}\rvert$	0.029	1.1	6	[42]
$\lvert\varepsilon^d_{e\mu}\rvert$	0.092	0.05	0.05	[45]
$\lvert\varepsilon^d_{e\tau}\rvert$	0.14	0.5	0.5	[42]
$\lvert\varepsilon^d_{\mu\tau}\rvert$	0.012	0.05	0.05	[42]

[42] S. Davidson *et al.*, JHEP **03** (2003) 011 [hep-ph/0302093].
[45] C. Biggio *et al.*, JHEP **08** (2009) 090 [arXiv:0907.0097].

Three-neutrino oscillations

- Most of the present data from solar, atmospheric, reactor and accelerator experiments are well explained by the 3ν oscillation hypothesis. **The 3ν scenario is robust**;
- the discovery of **large** θ_{13} marks the beginning of a new phase in ν phenomenology;
- the next step involve searching for CP violation, for non-maximal θ_{23} mixing and for the neutrino mass hierarchy. **With present / approved facilities it may not be easy**.

Sterile neutrinos

- A few experiments (LSND, MiniBOONE, RSBL) deviate from the “standard” 3ν scenario;
- however, these “hints” for sterile neutrinos are **not** in agreement among them:
  - MiniBooNE asymmetry in $\nu/\bar{\nu}$ requires CP violation, hence at least **two sterile ν’s**;
  - (3+2) models reconcile APP data, but DIS ones still show strong tension;
  - attempts to include the low-E excess in the game further increase such tension;
  - new reactor fluxes reduce tension with DIS data only marginally;
- **we are still quite far from the solution of the LSND puzzle.**

Non-standard neutrino-matter interactions

- Present atmospheric & accelerator data allow to put stringent bounds on NSI in the $\mu-\tau$ sector, but these bounds are lost in the general 3ν framework;
- however, in combination with solar & reactor data most of these bounds are recovered;
- the determination of the oscillation parameters from the global analysis is stable under the presence of NSI (with some exception for θ_{12}).