

Neutrino fits

Michele Maltoni

Instituto de Física Teórica UAM/CSIC

Conference on “Interplay between Particle and Astroparticle Physics”

LAL, Orsay, France – September 9th, 2016



General three-neutrino framework

- Equation of motion: **6 parameters** (including **Dirac** and neglecting **Majorana** phases):

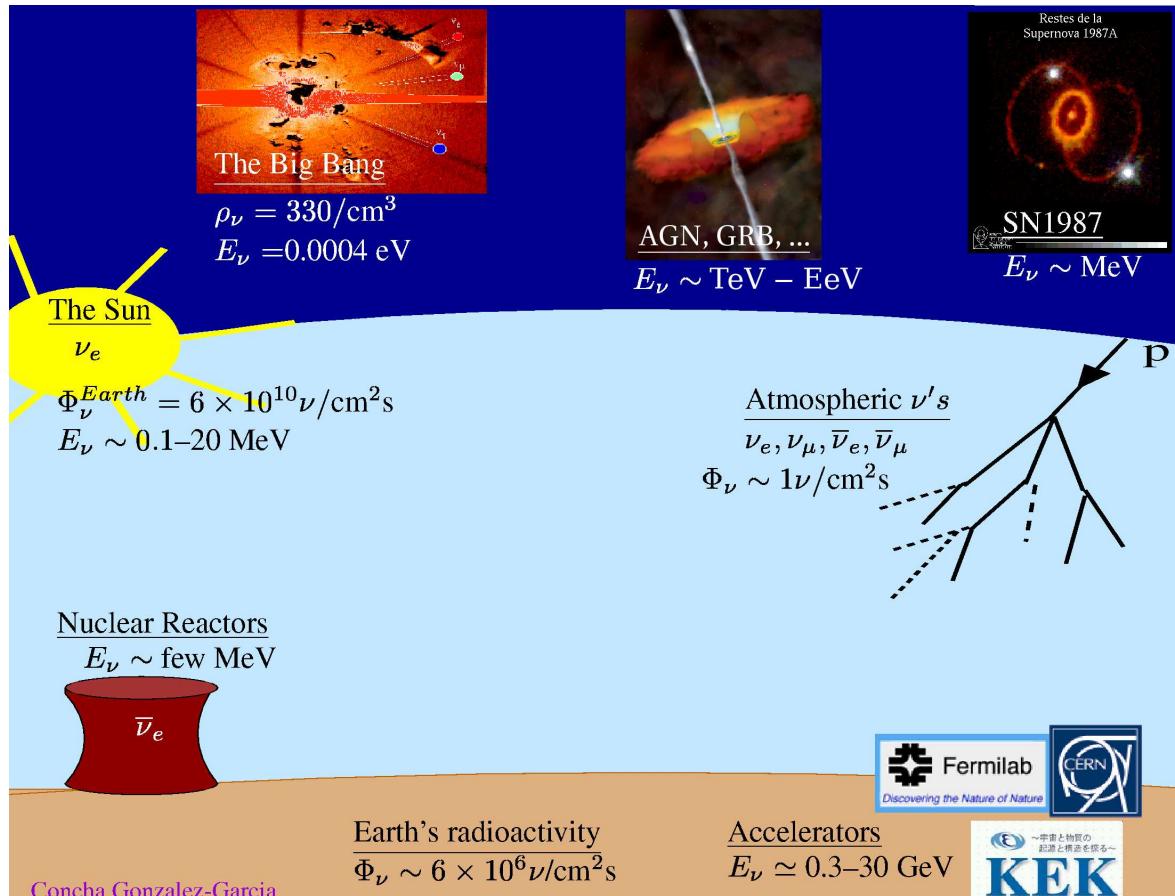
$$i \frac{d\vec{\nu}}{dt} = H \vec{\nu}; \quad H = U_{\text{vac}} \cdot D_{\text{vac}} \cdot U_{\text{vac}}^\dagger \pm V_{\text{mat}};$$

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

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

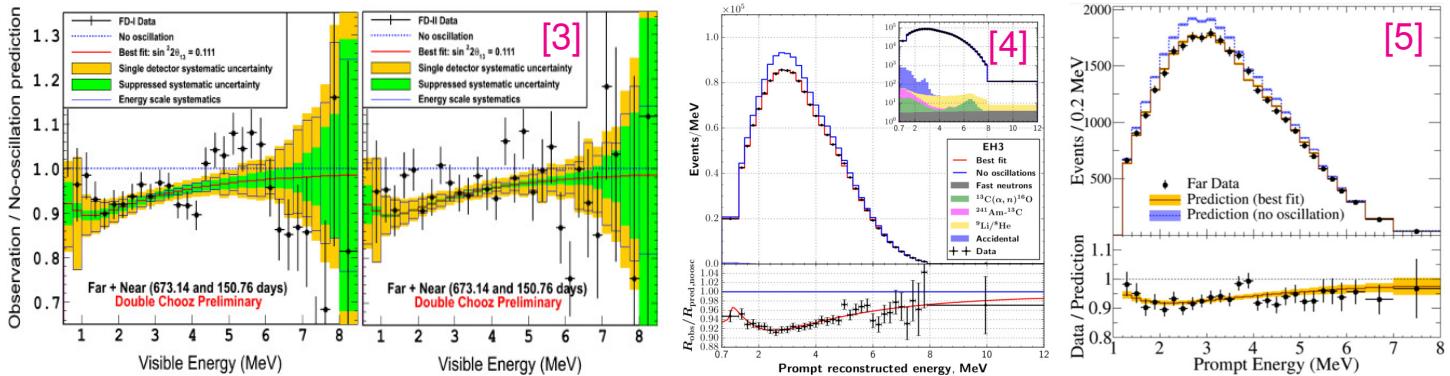
6 parameters \iff 6 types of experiments

- SOLAR** sector: $\begin{cases} \text{– solar experiments (mainly SNO)} & \rightarrow \theta_{12} \\ \text{– reactor VLBL (KamLAND)} & \rightarrow \Delta m_{21}^2 \end{cases}$
- REACT** sector: $\begin{cases} \text{– reactor LBL (Double-Chooz, Daya-Bay, Reno)} & \rightarrow \theta_{13} \end{cases}$
- ATMOS** sector: $\begin{cases} \text{– atmospheric experiments (SK)} & \rightarrow \theta_{23} \\ \text{– accelerator LBL-DIS (Minos } \nu_\mu \rightarrow \nu_\mu\text{)} & \rightarrow \Delta m_{31}^2 \\ \text{– accelerator LBL-APP (Minos } \nu_\mu \rightarrow \nu_e, \text{ T2K)} & \rightarrow \delta_{\text{CP}} \end{cases}$



Reactor neutrinos: the 2012 revolution

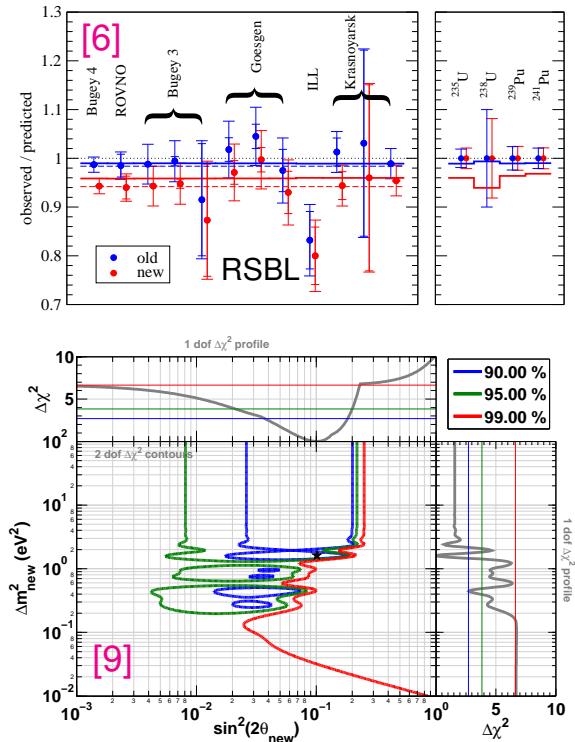
- Until summer 2011, only CHOOZ [1] and PALO-VERDE [2] **upper limits** available;
- since then: **positive signal** from DOUBLE-CHOOZ [3], DAYA-BAY [4], RENO [5];
- it is now a firmly established fact that $\theta_{13} \neq 0 \Rightarrow$ full 3ν oscillation phenomenology.



- [1] M. Apollonio *et al.* [CHOOZ], Eur. Phys. J. C **27** (2003) 331 [[hep-ex/0301017](#)].
- [2] F. Boehm *et al.* [PALO-VERDE], Phys. Rev. D **64** (2001) 112001 [[hep-ex/0107009](#)].
- [3] T. Matsubara [DOUBLE-CHOOZ], talk presented at ICHEP 2016, Chicago, USA, August 3–10, 2016.
- [4] Z. Yu [DAYA-BAY], talk presented at Neutrino 2016, London, UK, July 4–9, 2016.
- [5] K.K. Joo [RENO], talk presented at Neutrino 2016, London, UK, July 4–9, 2016.

The reactor neutrino anomaly

- In [7, 8] 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) finding **no evidence** are actually **observing a deficit**;
 - this deficit **could** be interpreted as being due to neutrino oscillations **but** requires $\Delta m^2 \gtrsim 1 \text{ eV}^2 \Rightarrow$ cannot fully accommodate RSBL data within 3ν ;
 - consistent approach [6]: fit also reactor fluxes (within errors) including **all** reactor data;
- ⇒ **use of near detector** ⇒ **problem avoided.**



[6] T. Schwetz, M. Tortola, J.W.F. Valle, New J. Phys. **13** (2011) 063004 [[arXiv:1103.0734](https://arxiv.org/abs/1103.0734)].

[7] T.A. Mueller *et al.*, Phys. Rev. **C83** (2011) 054615 [[arXiv:1101.2663](https://arxiv.org/abs/1101.2663)].

[8] P. Huber, Phys. Rev. C **84** (2011) 024617 [[arXiv:1106.0687](https://arxiv.org/abs/1106.0687)].

[9] G. Mention *et al.*, Phys. Rev. **D83** (2011) 073006 [[arXiv:1101.2755](https://arxiv.org/abs/1101.2755)].

⇒ Talk: Schwetz

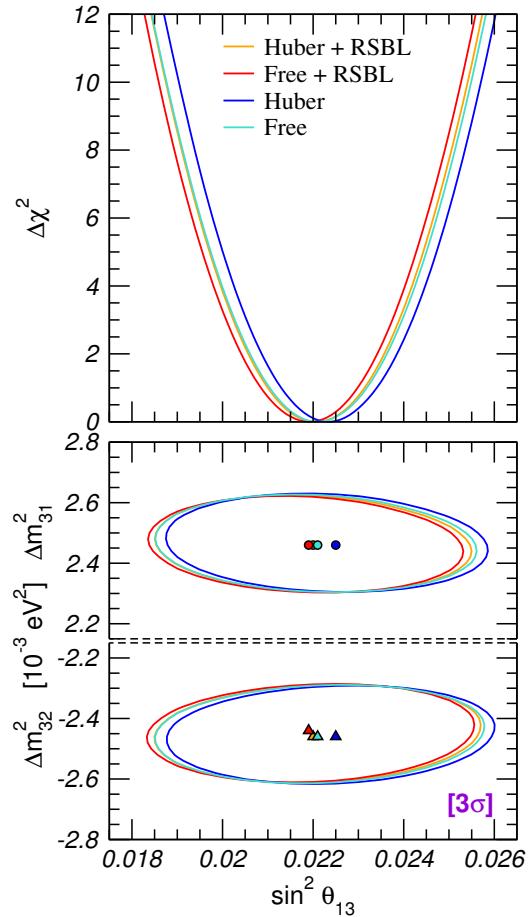
Impact of the reactor anomaly on θ_{13}

- Analysis of reactor data require a precise knowledge of the reactor ν fluxes. We follow two approaches:
 - use the **flux calculations** presented in [8];
 - treat the fluxes as **free parameters** and fit them;
- The **reactor fluxes** in [7, 8] are quite **large**, hence they favor **large** suppression \Rightarrow **larger** θ_{13} ;
- including RSBL experiments in the fit [6] 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: $\delta(\sin^2 \theta_{13}) = \pm 0.0003$.

[6] Schwetz *et al.*, NJP **13** (2011) 063004 [[arXiv:1103.0734](https://arxiv.org/abs/1103.0734)].

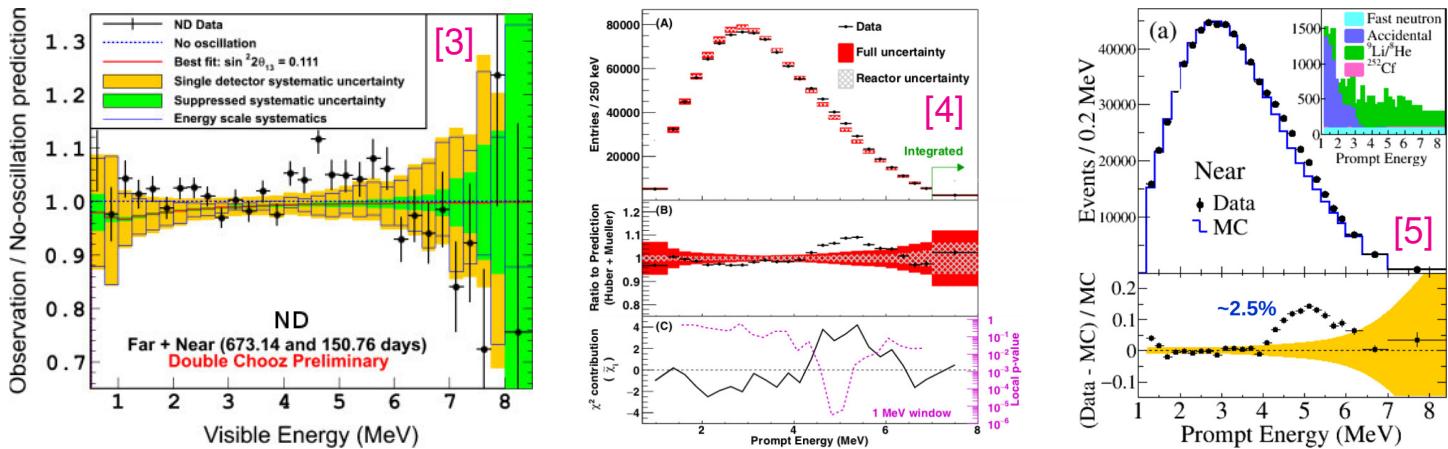
[7] Mueller *et al.*, PRC **83** (2011) 054615 [[arXiv:1101.2663](https://arxiv.org/abs/1101.2663)].

[8] Huber, PRC **84** (2011) 024617 [[arXiv:1106.0687](https://arxiv.org/abs/1106.0687)].



More trouble with the reactor fluxes: the 5 MeV excess

- An unexpected excess of events has been observed around 5 MeV; [⇒ Talk: Hayes](#)
- the excess is present in **all** experiments, even the old ones (with low statistics);
- the excess is independent of distance (visible both at ND and FD) and reactor power;
- the presence of a **near detector** allows to disentangle θ_{13} from flux uncertainties.



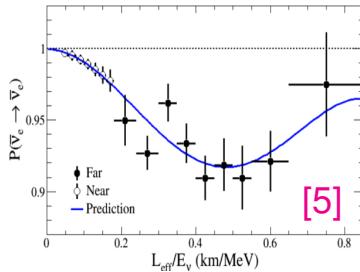
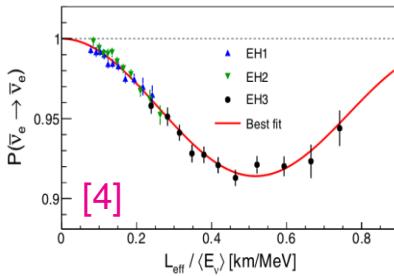
[3] T. Matsubara [DOUBLE-CHOOZ], talk presented at ICHEP 2016, Chicago, USA, August 3–10, 2016.

[4] Z. Yu [DAYA-BAY], talk presented at Neutrino 2016, London, UK, July 4–9, 2016.

[5] K.K. Joo [RENO], talk presented at Neutrino 2016, London, UK, July 4–9, 2016.

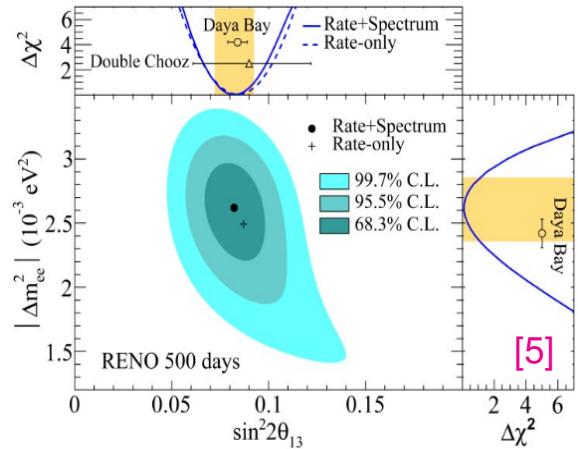
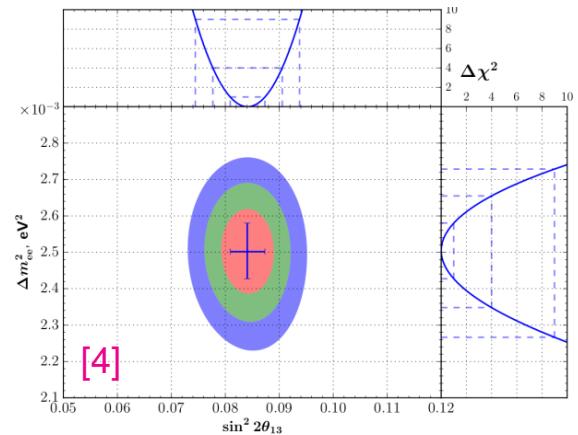
Measuring Δm_{31}^2 with reactors only

- Sizable deficit at the **far** detector \Rightarrow oscillations \Rightarrow lower bound on θ_{13} and Δm_{31}^2 ;
- smaller deficit at the **near** detector \Rightarrow not-too-much oscillations \Rightarrow upper bound on Δm_{31}^2 ;
- Daya-Bay and Reno spectral information \Rightarrow oscillation pattern clearly visible $\Rightarrow \Delta m_{31}^2$ accurately determined.



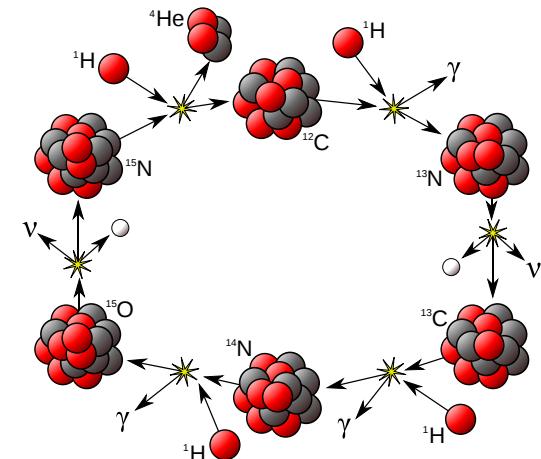
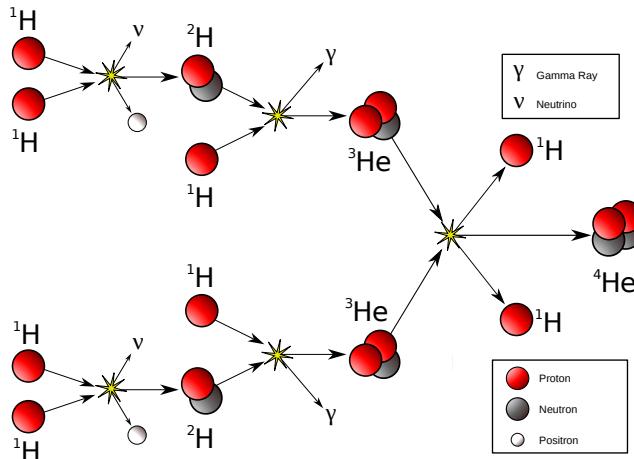
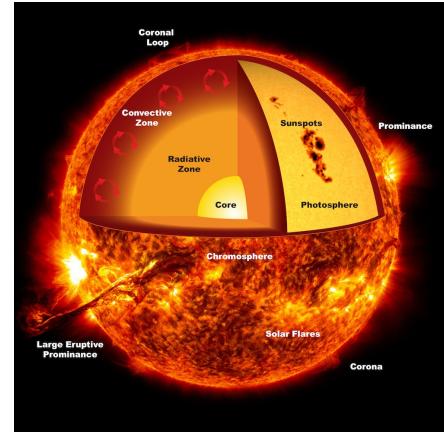
[4] Z. Yu [DAYA-BAY], talk at Neutrino 2016.

[5] K.K. Joo [RENO], talk at Neutrino 2016.



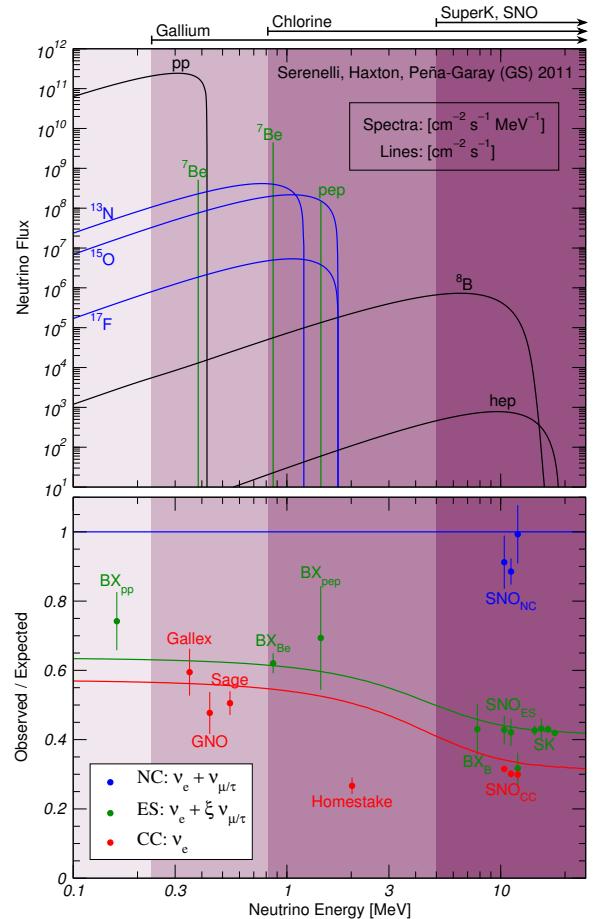
Solar neutrinos

- Solar neutrinos are produced by **nuclear fusion reactions** in the core of the Sun;
- two different mechanisms at work: **proton-proton chain** and **CNO cycle**. Both give $4p \rightarrow {}_2^4\text{He} + 2e^+ + 2\nu_e + \gamma$;
- in this way the Sun produces both **light** and **neutrinos**, in well-defined mutual proportions.



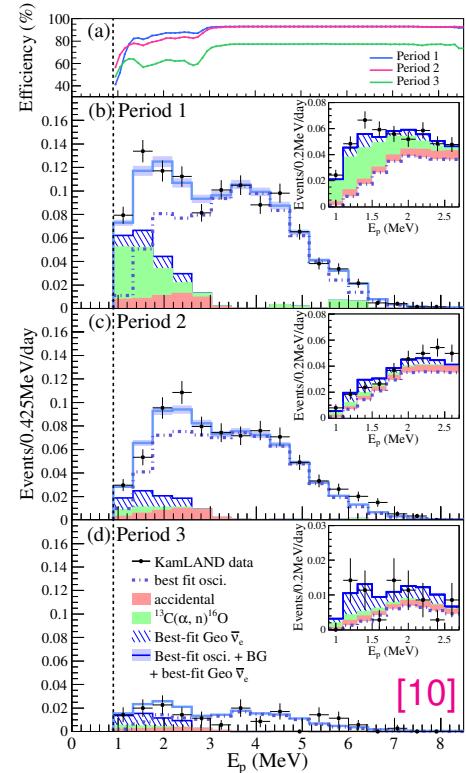
The solar neutrino problem

- Fusion reactions produce ν_e with a characteristic energy (^7Be , pep) or spectrum (pp, CNO, ^8B , hep);
- during the last 40 years, a number of underground experiments has measured their flux in different energy windows;
- it is found that ALL the experiments observe a deficit of about **30 – 60%**;
- the deficit is NOT the same for all the experiments, and shows a clear **energy dependence**;
- it is **not possible** to reconcile the data with the Standard Solar Model (SSM) by simply readjusting the parameters of the model;
- the deficit is **maximum for CC** (ν_e), reduced for ES ($\nu_e + 0.15 \nu_{\mu/\tau}$), and **absent for NC** ($\nu_e + \nu_{\mu/\tau}$).



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.
- solution: $\nu_e \rightarrow \nu_{\text{active}}$ 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 P_{ee} measured, $\Delta m_{31}^2 \approx \infty \Rightarrow$ same relevant parameters as solar: θ_{13} , Δm_{21}^2 and θ_{21} ;
- neutrino oscillation hypothesis provides perfect agreement between **solar** and **KamLAND** data.



[10] A. Gando *et al.* [KamLAND], PRD **88** (2013) 3, 033001 [[arXiv:1303.4667](https://arxiv.org/abs/1303.4667)].

Relevance of solar data in the determination of Δm_{21}^2 and θ_{12}

- $P_{ee} = c_{13}^4 P_{\text{eff}} + s_{13}^4$, $i \frac{d\vec{v}}{dt} = \left[\frac{\Delta m_{21}^2}{4E_\nu} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix} \pm \sqrt{2} G_F N_e \begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} \right] \vec{v}$, $\vec{v} = \begin{pmatrix} v_e \\ v_\mu \\ v_\tau \end{pmatrix}$;
 - $\nu_\mu \equiv \nu_\tau \Rightarrow$ no sensitivity to θ_{23} and δ_{CP} ;
 - $\Delta m_{31}^2 \approx \infty \Rightarrow$ specific Δm_{31}^2 value irrelevant;
 - \Rightarrow data only depend on Δm_{21}^2 , θ_{12} and θ_{13} ;
 - param's: $\begin{cases} \theta_{12} \text{ dominated by SNO;} \\ \Delta m_{21}^2 \text{ dominated by KamLAND;} \end{cases}$
 - solar region determined by high-E data, low-E contribution marginal;
 - SNO-NC measurement confirms SSM;
 - KamLAND precisely determines the oscillation pattern.
-

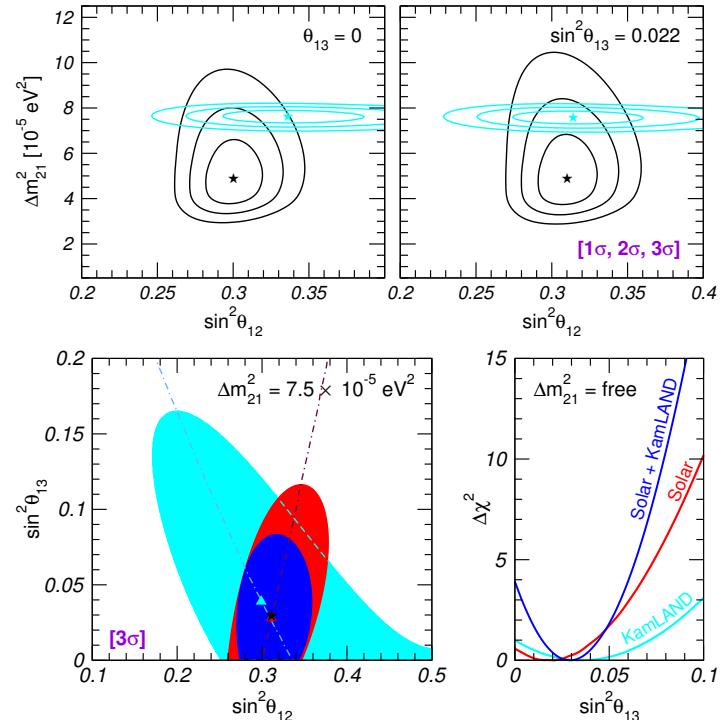
Effect of θ_{13} on solar & KamLAND data

- ν_e survival probability:

$$P_{ee} \approx \begin{cases} \text{Kam: } \cos^4 \theta_{13} (1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}), \\ \text{low-E: } \cos^4 \theta_{13} \left(1 - \frac{1}{2} \sin^2 2\theta_{12}\right), \\ \text{high-E: } \cos^4 \theta_{13} \sin^2 \theta_{12}; \end{cases}$$

- When θ_{13} increases:

- KamLAND region shifts to smaller θ_{12} ;
- solar region moves to larger θ_{12} (high-E data dominate over low-E ones);
- therefore, a non-zero value of θ_{13} reduces the tension between solar and KamLAND data [11, 12];
- however, a small tension in Δm_{21}^2 remains.

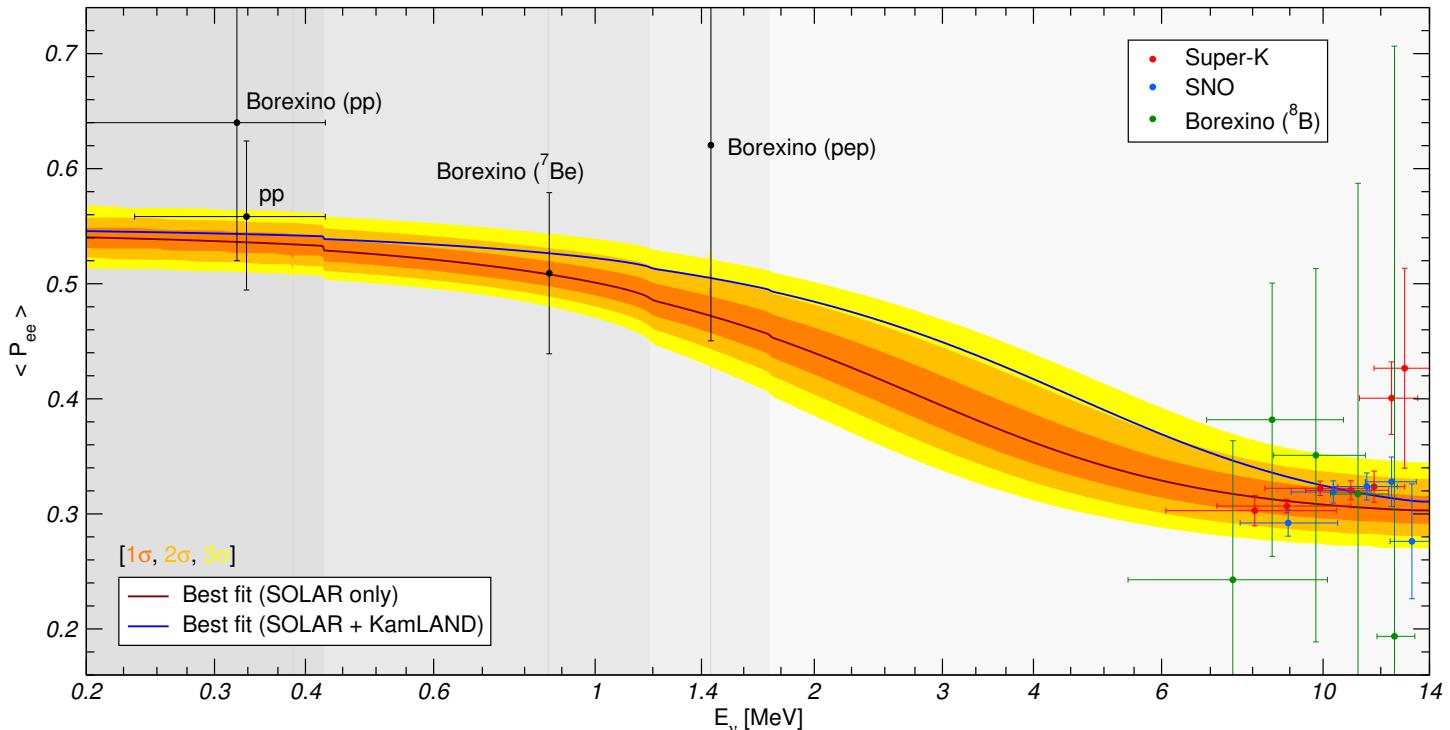


[11] G.L. Fogli *et al.*, Phys. Rev. Lett. **101** (2008) 141801 [[arXiv:0806.2649](https://arxiv.org/abs/0806.2649)].

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

Transition between vacuum and MSW regime in solar data

- Tension between **solar** and **KamLAND** related to non-observation of low-E turn-up.

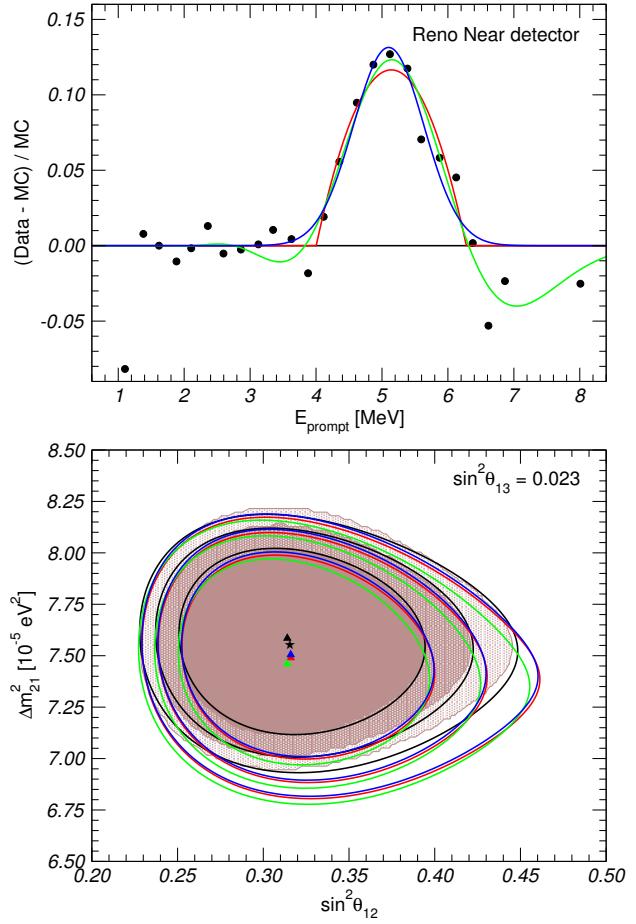


KamLAND and the 5 MeV excess

- KamLAND detects neutrinos from various reactors, and has **no** near detector. Hence, spectral distortions may be potentially relevant;
- the effects of the “5 MeV bump” in KamLAND were discussed briefly in [13], and more in detail in [14]. In both cases the impact on Δm_{21}^2 was found to be small;
- Hence:
 - the determination of Δm_{21}^2 is robust against present uncertainties in the reactor fluxes;
 - the 5 MeV reactor excess does not help in reconciling the observed tension between solar and KamLAND data.

[13] M. Maltoni, A.Yu. Smirnov, arXiv:1507.05287.

[14] F. Capozzi *et al.*, arXiv:1601.07777.

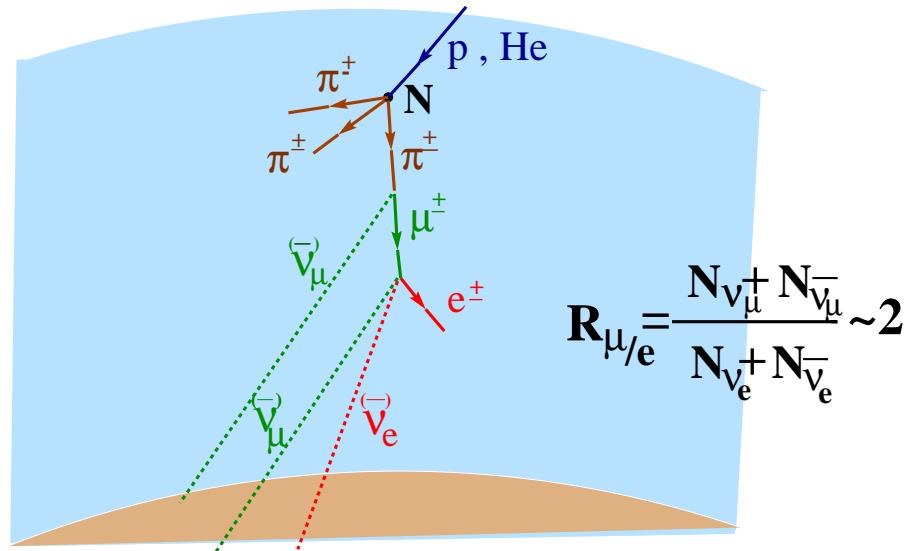


Atmospheric neutrinos

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

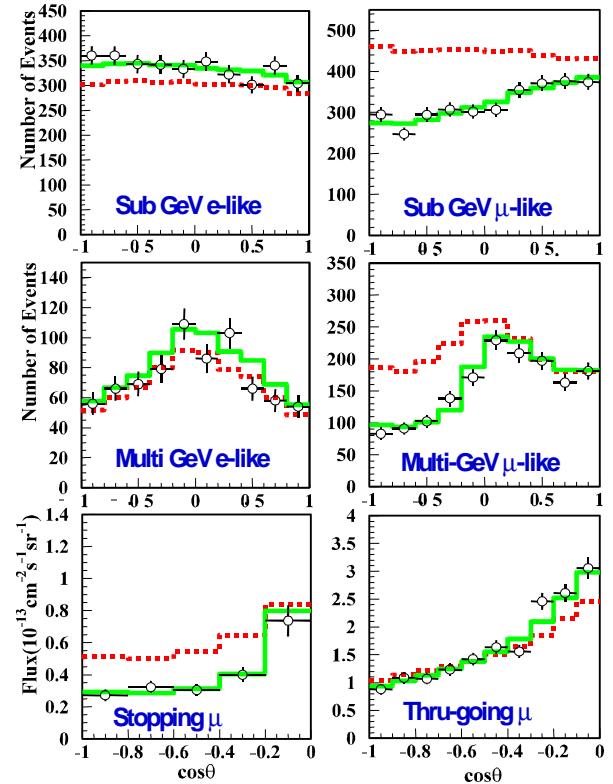
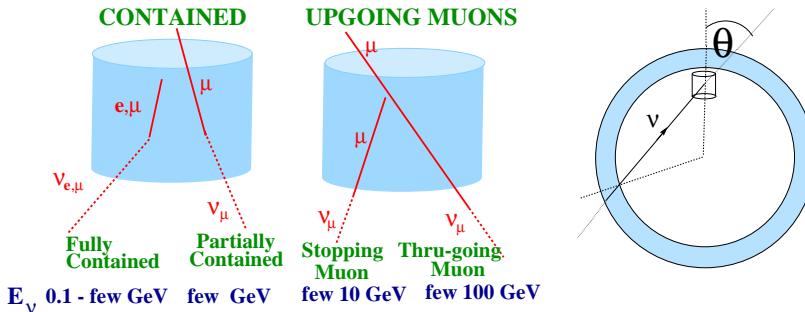
- 1 $A_{\text{cr}} + A_{\text{air}} \rightarrow \pi^\pm, K^\pm, K^0, \dots$
- 2 $\pi^\pm \rightarrow \mu^\pm + \nu_\mu,$
- 3 $\mu^\pm \rightarrow e^\pm + \nu_e + \bar{\nu}_\mu;$

- at the detector, some ν interacts and produces a **charged lepton**, which is observed;
- ν_μ and ν_e fluxes have large ($\approx 20\%$) uncertainties;
- however, the ν_μ/ν_e ratio is predicted with quite good accuracy ($\approx 5\%$).

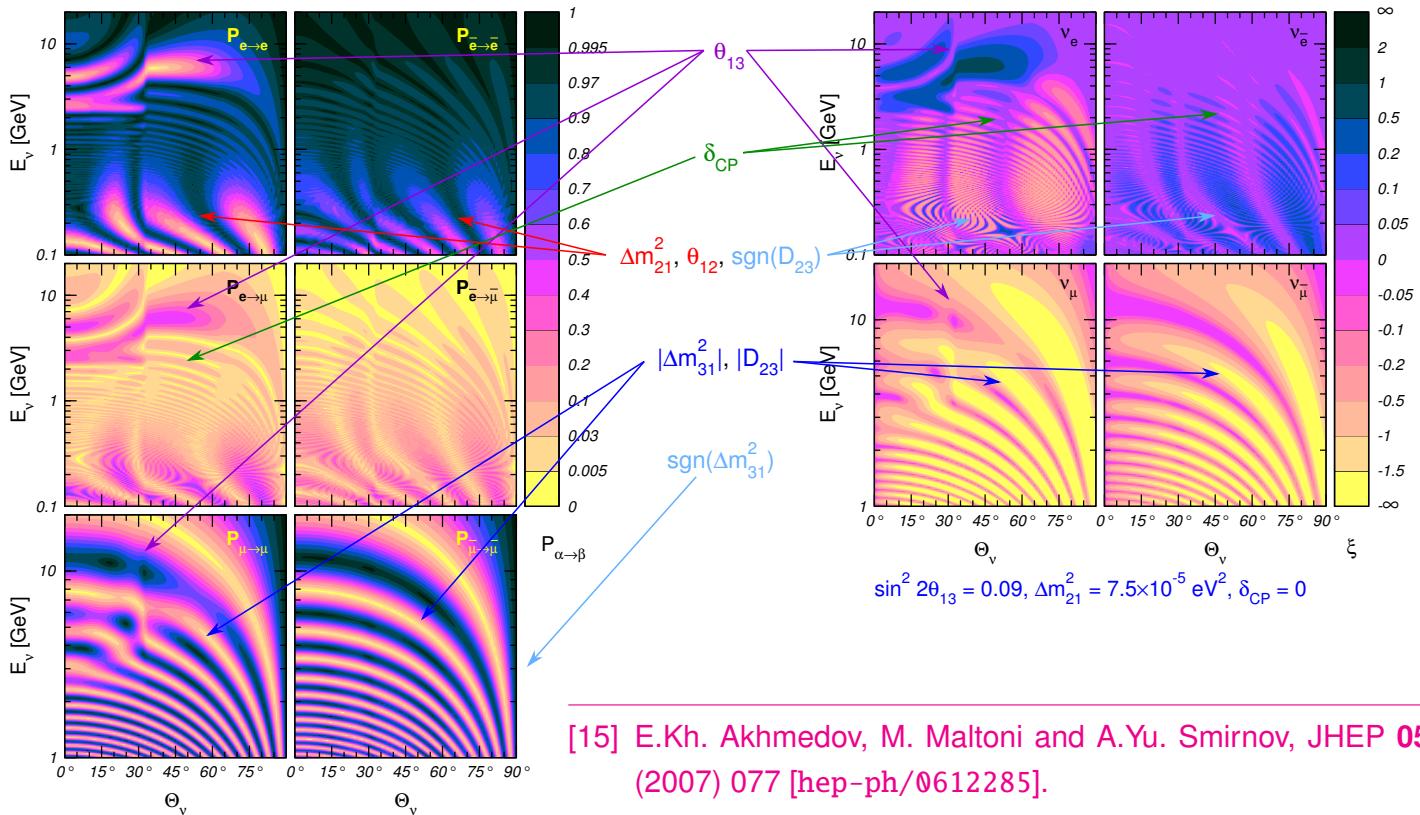


Atmospheric neutrino oscillations

- Data (dots) vs. Monte-Carlo (red dashed line):
 - *small excess* in sub-GeV ν_e ;
 - *no problem* in multi-GeV ν_e ;
 - *zenith-dependent deficit* in all ν_μ samples;
- deficit in ν_μ : $\left\{ \begin{array}{l} \text{– grows with } L; \\ \text{– decreases with } E_\nu; \end{array} \right.$
- deficit cannot be explained by flux uncertainties;
- solution: $\nu_\mu \rightarrow \nu_\tau$ oscillations (green solid line).



Atmospheric neutrinos: a laboratory for neutrino oscillations



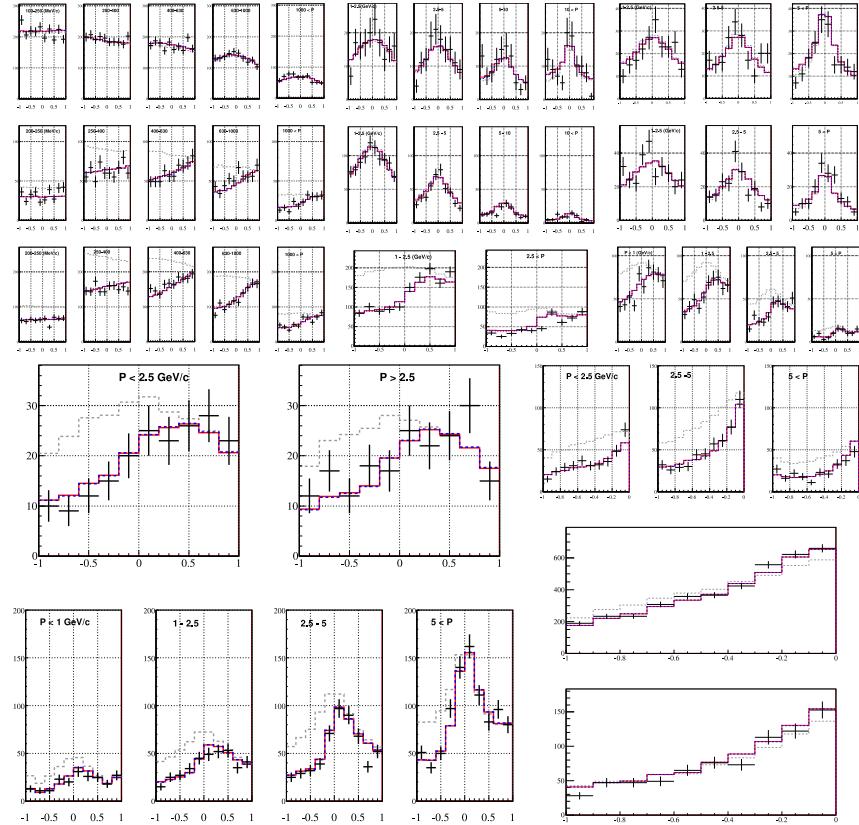
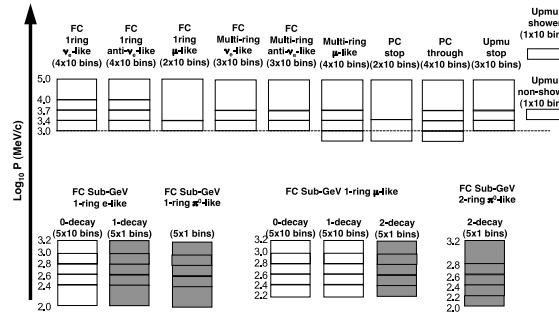
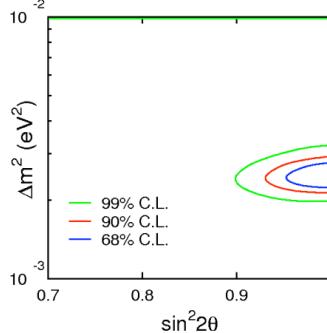
Atmospheric neutrinos: getting the most from SK data

- SK(1–4) data: 480 580 bins defined by flavor, charge, topology, momentum, . . . ;

- channel:

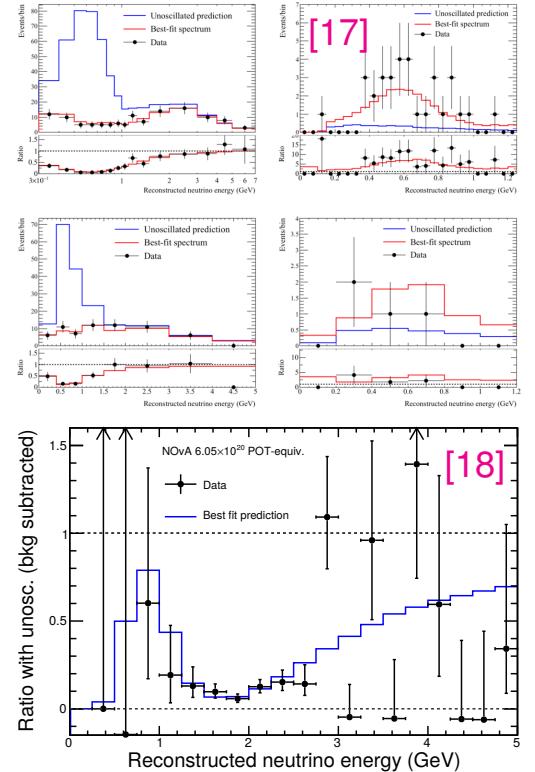
$$\nu_\mu \rightarrow \nu_\tau;$$

- perfect fit with just 2 params: $(\Delta m^2, \theta)$.



Long-baseline accelerator experiments

- ν_μ 's are produced at accelerators through π decay, with mean energy ~ 3 GeV (Minos) ~ 7 GeV (Minos+), ~ 2 GeV (NOvA), ~ 0.6 GeV (T2K);
- flux measured at 735 km (Minos & Minos+), 810 km (NOvA), 295 km (T2K);
- all experiments observe a clear deficit of ν_μ 's at low energy [16, 17, 18], as well as an excess of ν_e events;
- solution: leading $\nu_\mu \rightarrow \nu_\tau$ mass-induced oscillations, together with sub-leading $\nu_\mu \rightarrow \nu_e$ conversion;
- MINOS and T2K also measured $\bar{\nu}_\mu$ disappearance and $\bar{\nu}_e$ appearance, finding agreement with the $\bar{\nu}_\mu$ and $\bar{\nu}_e$ neutrino channel (as implied by CPT).



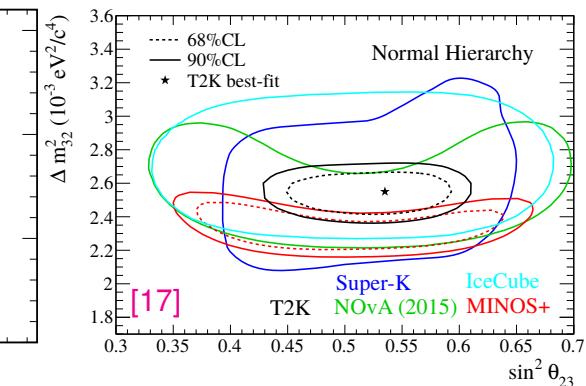
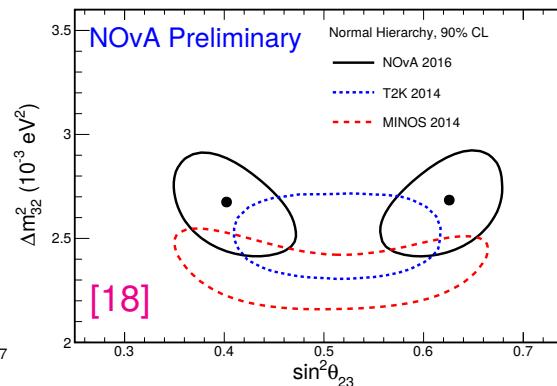
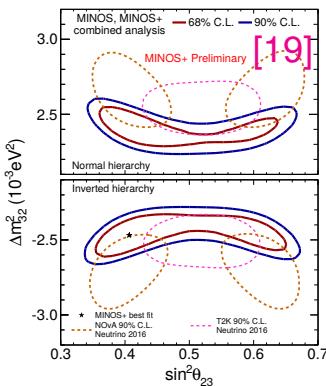
[16] R. Nichol [MINOS], talk at Neutrino 2012, Kyoto, Japan, June 3–9, 2012.

[17] H.A. Tanaka [T2K], talk at Neutrino 2016, London, UK, 4–9 July 2016.

[18] P. Vahle [NOvA], talk at Neutrino 2016, London, UK, 4–9 July 2016.

Atmospheric oscillations: Δm_{32}^2 and θ_{23}

- Δm_{31}^2 & θ_{23} dominated by LBL disappearance ($\nu_\mu \rightarrow \nu_\mu$) data;
- Δm_{21}^2 effects contribute only at subleading level.
- reasonably good agreement between all experiments in the allowed regions. However, some differences are visible...



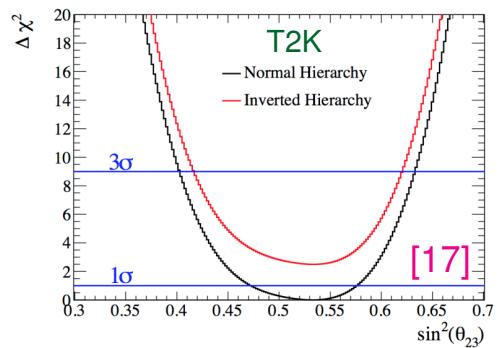
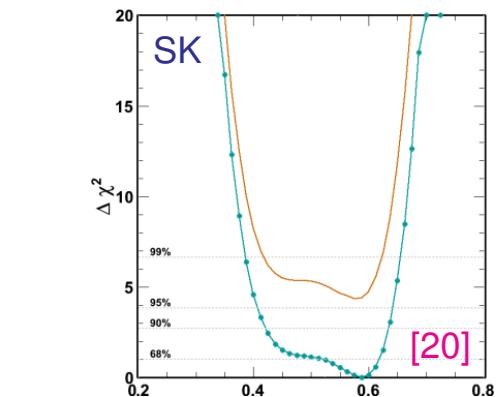
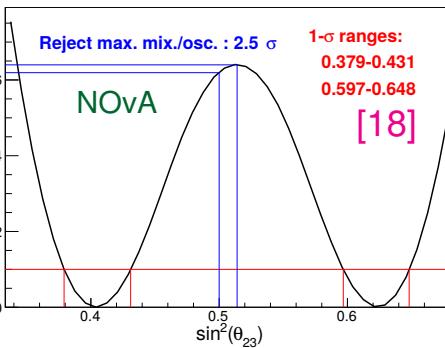
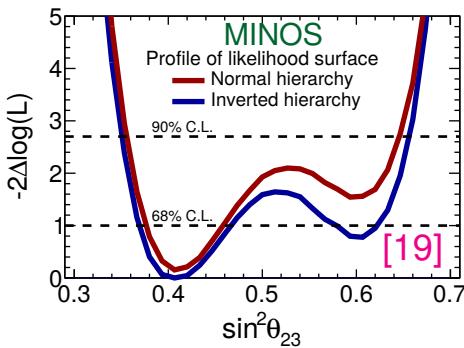
[17] H.A. Tanaka [T2K], talk at Neutrino 2016, London, UK, 4–9 July 2016.

[18] P. Vahle [NOvA], talk at Neutrino 2016, London, UK, 4–9 July 2016.

[19] J. Evans [MINOS], talk at Neutrino 2016, London, UK, 4–9 July 2016.

Atmospheric oscillations: θ_{23} mixing

- Some discrepancy observed on the determination of θ_{23} :
 - NOvA: 2.5σ deviation but no octant preference [18];
 - Minos: 1.5σ deviation, LO preferred [19];
 - SK: 0.5σ preference for DO [20];
 - T2K: no preference, maximal mixing selected [17].



[17] H.A. Tanaka [T2K], talk at Neutrino 2016, London, UK, 4–9 July 2016.

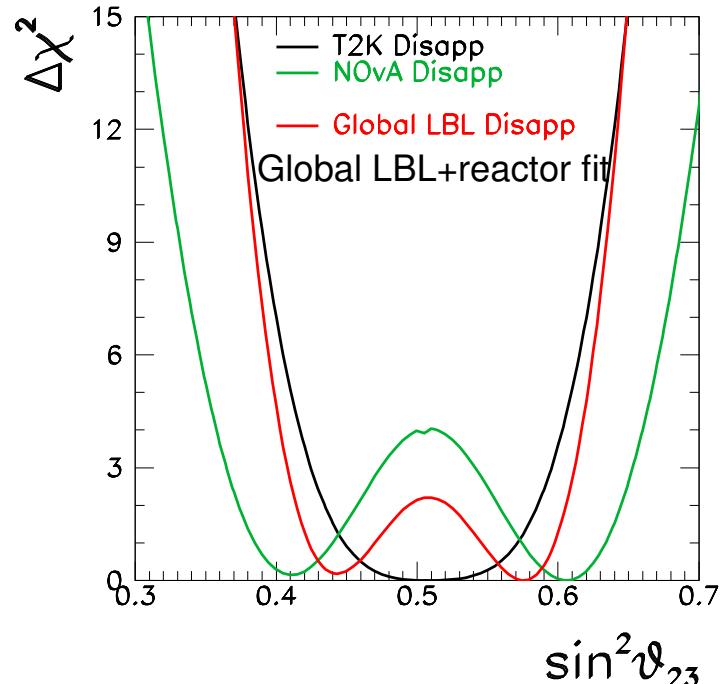
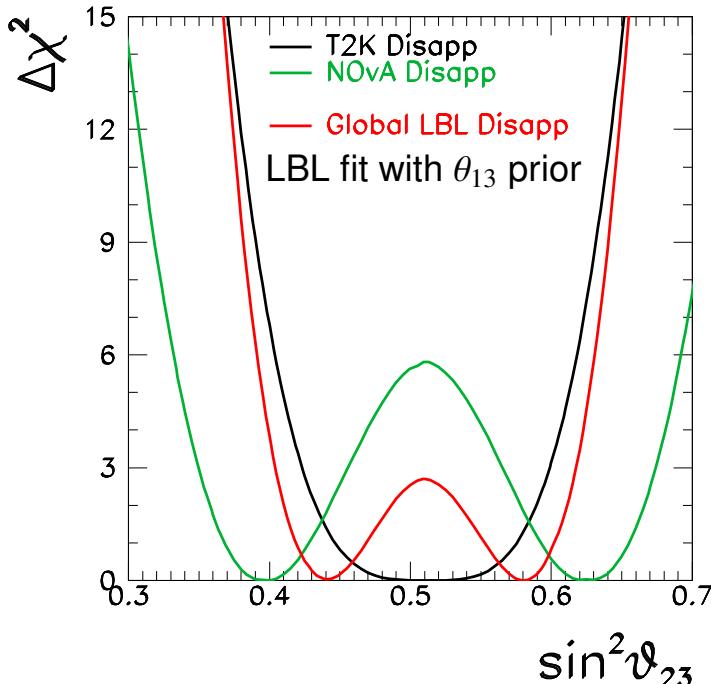
[18] P. Vahle [NOvA], talk at Neutrino 2016, London, UK, 4–9 July 2016.

[19] J. Evans [MINOS], talk at Neutrino 2016, London, UK, 4–9 July 2016.

[20] S. Moriyama [SK], talk at Neutrino 2016, London, UK, 4–9 July 2016.

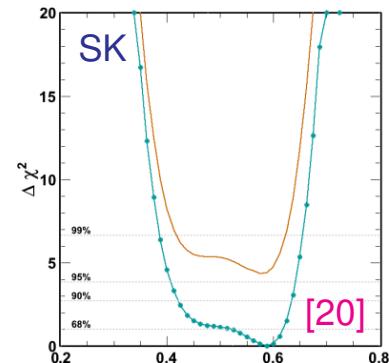
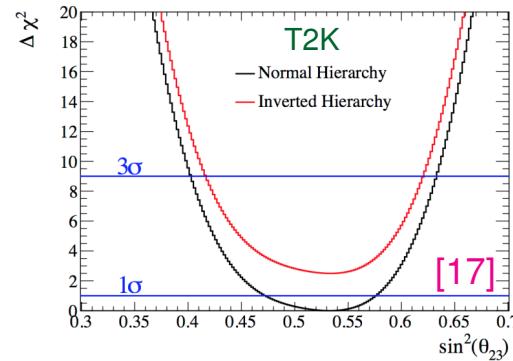
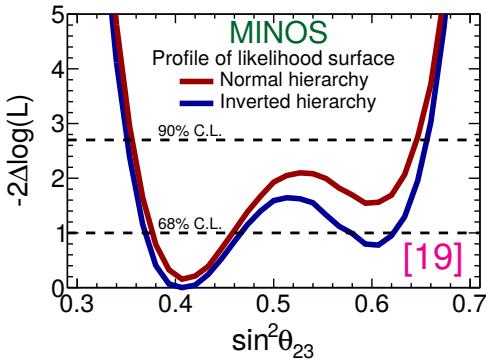
Maximal θ_{23} mixing: comparison of NOvA and T2K data

- As just seen, NOvA rejects maximal mixing whereas T2K favors it;
- the tension is reduced if LBL and reactor data are properly combined in a 3ν scenario.



Atmospheric oscillations: mass hierarchy

- SK (SK+T2K): NH favored, $\Delta\chi^2_{\text{IH}} = +4.3$ ($\Delta\chi^2_{\text{IH}} = +5.2$) [20];
 - Minos: no indication ($\Delta\chi^2_{\text{IH}} = -0.2$, negligible) [19];
 - NOvA: very weak preference ($\Delta\chi^2_{\text{IH}} = +0.47$) [18].
- ⇒ preference for NH dominated by SK/T2K.



[17] H.A. Tanaka [T2K], talk at Neutrino 2016, London, UK, 4–9 July 2016.

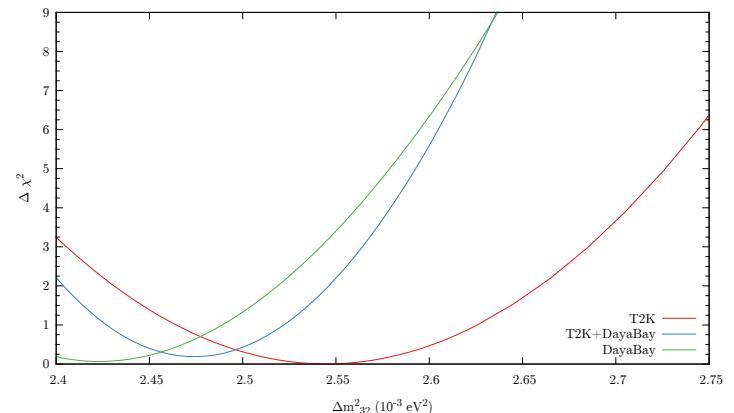
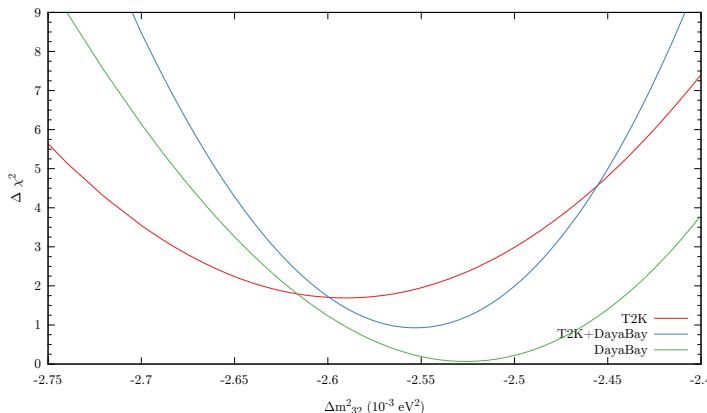
[18] P. Vahle [NOvA], talk at Neutrino 2016, London, UK, 4–9 July 2016.

[19] J. Evans [MINOS], talk at Neutrino 2016, London, UK, 4–9 July 2016.

[20] S. Moriyama [SK], talk at Neutrino 2016, London, UK, 4–9 July 2016.

Hierarchy determination: T2K versus reactor data

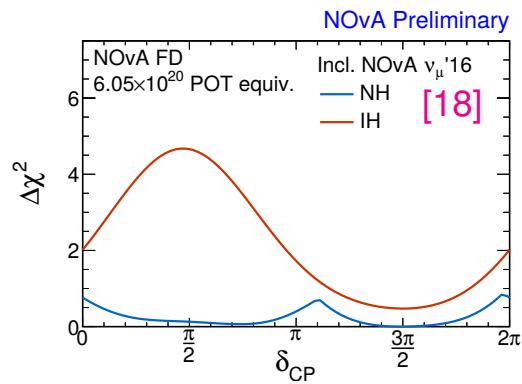
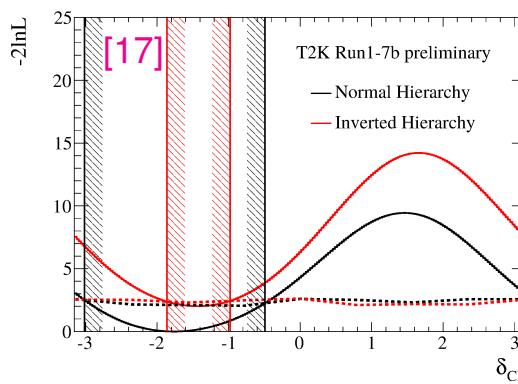
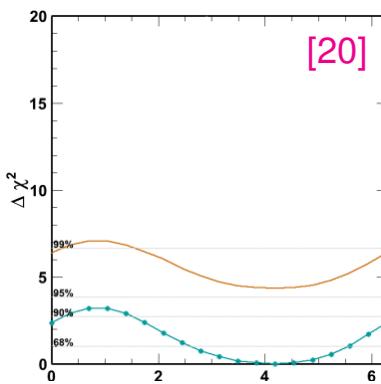
- T2K favor NH over IH by $\Delta\chi^2_{\text{IH}} \approx 2$. This result was derived assuming the θ_{13} prior implied by reactor data [17];
- however, both T2K and reactor data also depend on Δm_{31}^2 ;
- there is a small tension between the Δm_{31}^2 value favored by T2K and reactor data. Such tension is somewhat stronger for NH than for IH;
- hence, T2K + reactor favor NH over IH only by $\Delta\chi^2_{\text{IH}} \approx 1$.



[17] H.A. Tanaka [T2K], talk at Neutrino 2016, London, UK, 4–9 July 2016.

Atmospheric oscillations: CP phase

- Indication in favor of maximal CP violation, $\delta_{CP} = -90^\circ$;
- ν_e excess in T2K- ν matches $\bar{\nu}_e$ deficit in T2K- $\bar{\nu}$;
- NOvA and SK also indicate preference for $\delta_{CP} = -90^\circ$.



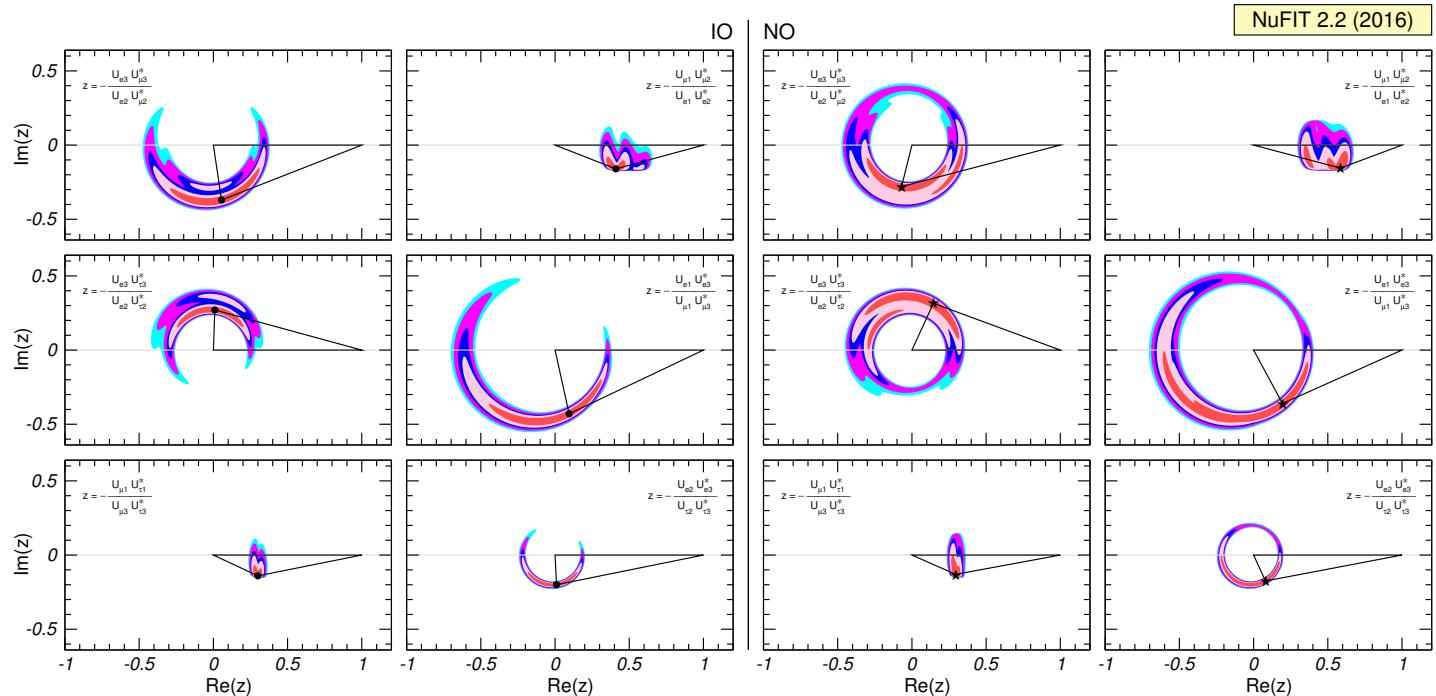
[17] H.A. Tanaka [T2K], talk at Neutrino 2016, London, UK, 4–9 July 2016.

[18] P. Vahle [NOvA], talk at Neutrino 2016, London, UK, 4–9 July 2016.

[20] S. Moriyama [SK], talk at Neutrino 2016, London, UK, 4–9 July 2016.

CP violation: present status

- Indications in favor of maximal CP violation are still weak;
- however, some combination of hierarchy and δ_{CP} can already be excluded.



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 + DeepCore;
 - **Reactor**: KamLAND + Chooz + Palo-Verde
+ Double-Chooz + Daya-Bay + Reno;
 - **Accelerator**: Minos + T2K + NOvA;
- best-fit point and 1σ ranges:

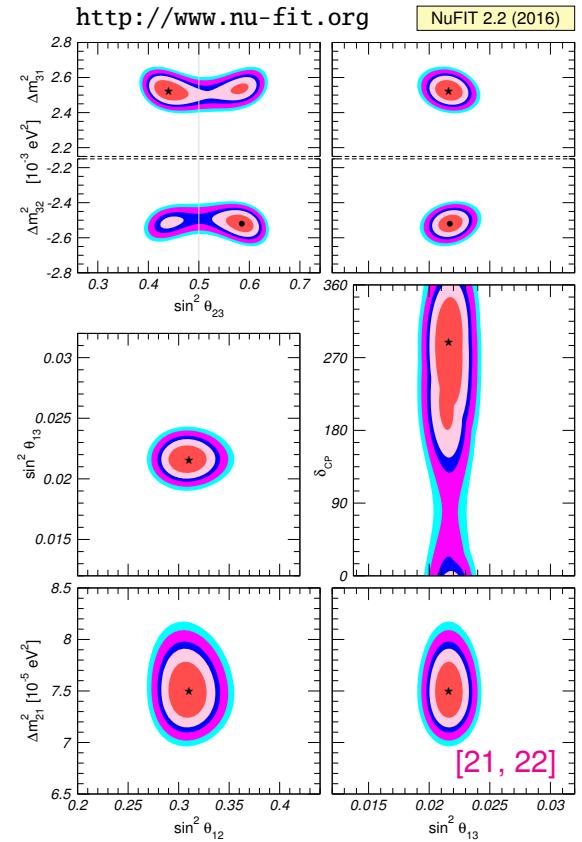
$$\theta_{12} = 33.72^{+0.79}_{-0.76}, \quad \Delta m_{21}^2 = 7.49^{+0.19}_{-0.17} \times 10^{-5} \text{ eV}^2,$$

$$\theta_{23} = \begin{cases} 41.5^{+1.3}_{-1.1}, \\ 49.9^{+1.1}_{-1.3}, \end{cases} \quad \Delta m_{3\ell}^2 = \begin{cases} +2.526^{+0.039}_{-0.037} \times 10^{-3} \text{ eV}^2, \\ -2.518^{+0.038}_{-0.037} \times 10^{-3} \text{ eV}^2, \end{cases}$$

$$\theta_{13} = 8.46^{+0.14}_{-0.15}, \quad \delta_{\text{CP}} = 289^{+38}_{-51};$$

- neutrino mixing matrix:

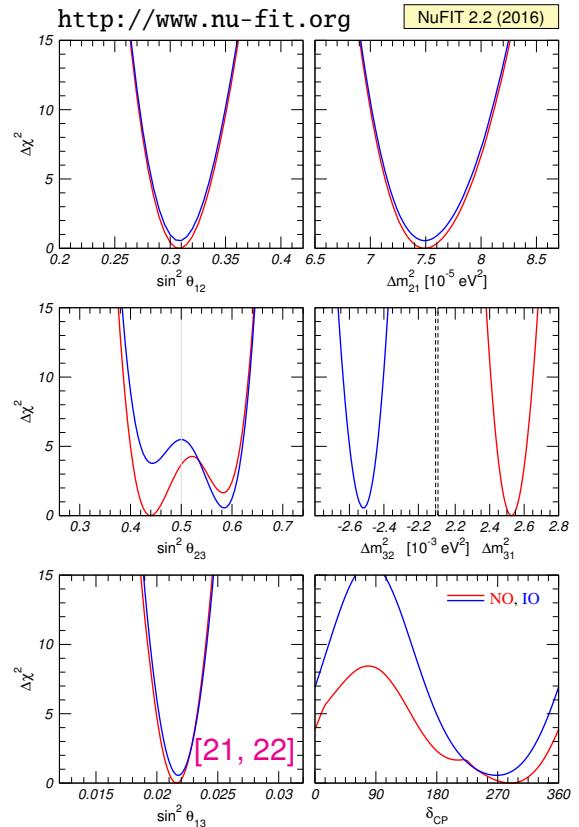
$$|U|_{3\sigma} = \begin{pmatrix} 0.798 \rightarrow 0.843 & 0.517 \rightarrow 0.584 & 0.139 \rightarrow 0.155 \\ 0.234 \rightarrow 0.518 & 0.449 \rightarrow 0.696 & 0.617 \rightarrow 0.787 \\ 0.251 \rightarrow 0.528 & 0.463 \rightarrow 0.706 & 0.600 \rightarrow 0.774 \end{pmatrix}.$$



[21] M.C. Gonzalez-Garcia *et al.*, JHEP **11** (2014) 052 [[arXiv:1409.5439](https://arxiv.org/abs/1409.5439)].

[22] M.C. Gonzalez-Garcia *et al.*, NuFIT 2.2 (2016), <http://www.nu-fit.org>.

- Most of the present data from **solar**, **atmospheric**, **reactor** and **accelerator** experiments are well explained by the 3ν oscillation hypothesis. **The three-neutrino scenario is robust**;
- the discovery of **large θ_{13}** is a major breakthrough, and marks the beginning of a new phase in neutrino 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, although some interesting “hints” seem to be emerging;
- synergies between different experiments will be very important to increase the sensitivity.



[21] M.C. Gonzalez-Garcia *et al.*, JHEP **11** (2014) 052 [[arXiv:1409.5439](https://arxiv.org/abs/1409.5439)].

[22] M.C. Gonzalez-Garcia *et al.*, NuFIT 2.2 (2016), <http://www.nu-fit.org>.