Synergies between Future Atmospheric and Long Baseline Neutrino Experiments

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I. Introduction: atmospheric neutrino data

II. Discussion: sensitivity to oscillation parameters

III. Results: synergies with long-baseline experiments

Conclusions

Neutrino oscillations: where we are

- Global six-parameter fit (including δ_{CP}):
  - **Solar**: Cl + Ga + SK + SNO-I + SNO-II;
  - **Atmospheric**: SK-I + SK-II;
  - **Reactor**: Chooz + KamLAND;
  - **Accelerator**: K2K + Minos (3.4×10^{20} p.o.t.);

- best-fit point and 1σ (3σ) ranges:

$$\theta_{12} = 34.5 \pm 1.4 \left({}^{+4.8}_{-4.0}\right), \quad \Delta m^2_{21} = 7.67\,{}^{+0.22}_{-0.21} \left({}^{+0.67}_{-0.60}\right) \times 10^{-5}\ \text{eV}^2,$$

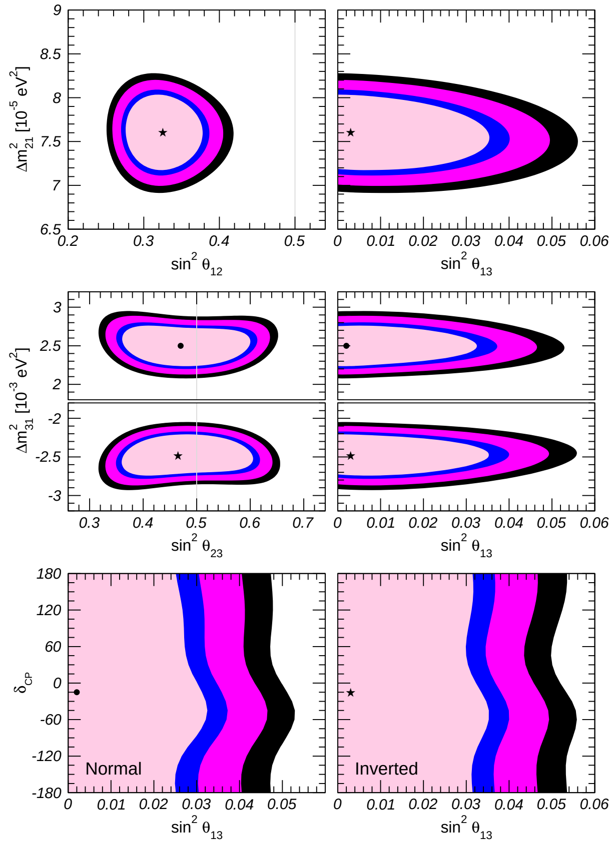
$$\theta_{23} = 43.1\,{}^{+4.4}_{-3.5} \left({}^{+10.1}_{-8.0}\right), \quad \Delta m^2_{31} = \begin{cases} -2.39 \pm 0.12 \left({}^{+0.37}_{-0.40}\right) \times 10^{-3}\ \text{eV}^2, \\ +2.49 \pm 0.12 \left({}^{+0.39}_{-0.36}\right) \times 10^{-3}\ \text{eV}^2, \end{cases}$$

$$\theta_{13} = 3.2\,{}^{+4.5} \left({}^{+9.6}\right), \qquad \delta_{CP} \in [0,\ 360];$$

- neutrino mixing matrix:

$$|U|_{90\%} = \begin{pmatrix} 0.80 \to 0.84 & 0.53 \to 0.60 & 0.00 \to 0.17 \\ 0.29 \to 0.52 & 0.51 \to 0.69 & 0.61 \to 0.76 \\ 0.26 \to 0.50 & 0.47 \to 0.66 & 0.64 \to 0.79 \end{pmatrix},$$

$$|U|_{3\sigma} = \begin{pmatrix} 0.77 \to 0.86 & 0.50 \to 0.63 & 0.00 \to 0.22 \\ 0.22 \to 0.55 & 0.45 \to 0.73 & 0.57 \to 0.80 \\ 0.21 \to 0.55 & 0.41 \to 0.70 & 0.59 \to 0.82 \end{pmatrix}.$$

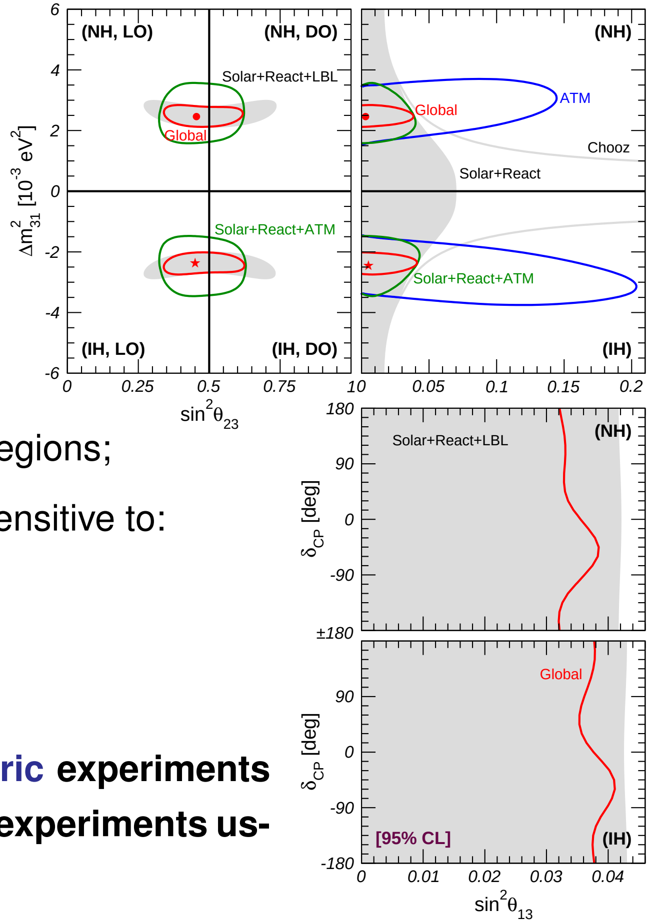


[Gonzalez-Garcia & MM, PREP 460 (2008) 1]

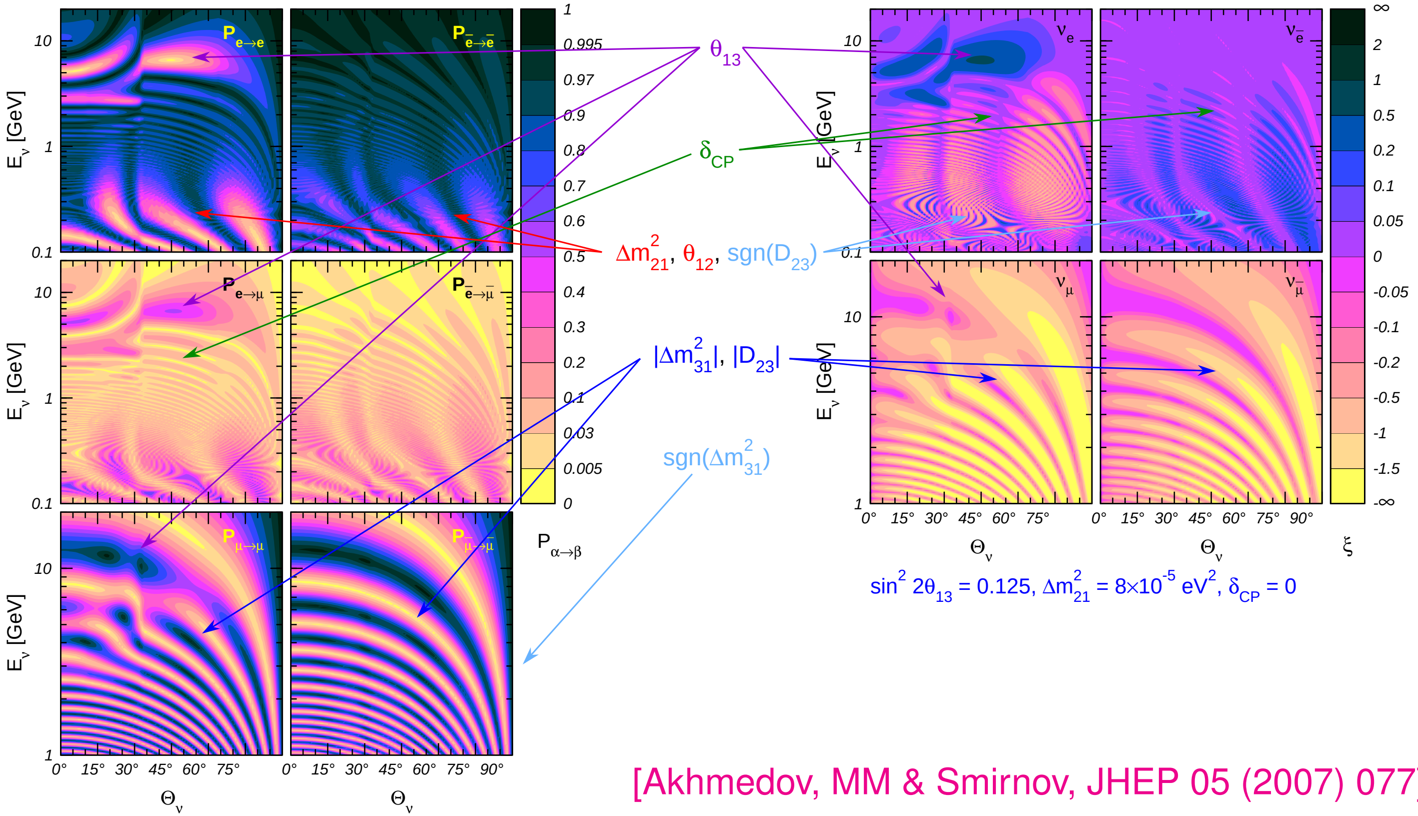
The role of atmospheric data

- Present reactor and accelerator data dominate $|\Delta m^2_{31}|$ and θ_{13} but give no info on:
  - the **mass hierarchy** (sign of Δm^2_{31});
  - the **octant** (sign of $\theta_{23} - \pi/4$);
  - the **CP phase**;
- 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**: relevant for the bound on θ_{13};
  - **CP phase**: impact on θ_{13} bound;

⇒ **present data suggest that future atmospheric experiments may provide complementary information to experiments using man-made neutrinos.**



Atmospheric neutrinos: a laboratory for neutrino oscillations

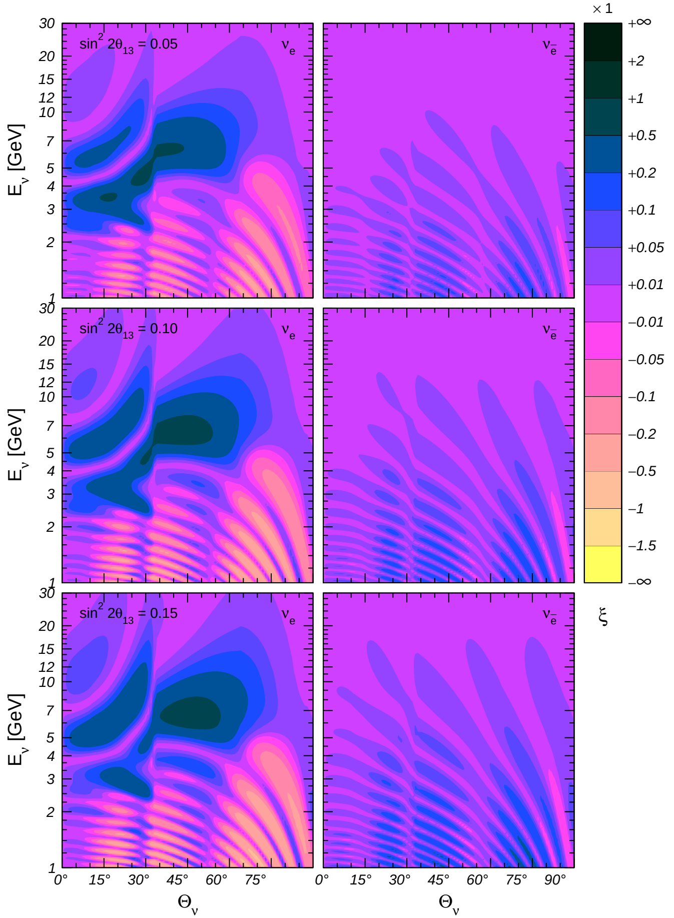


[Akhmedov, MM & Smirnov, JHEP 05 (2007) 077]

Sensitivity to θ_{13}

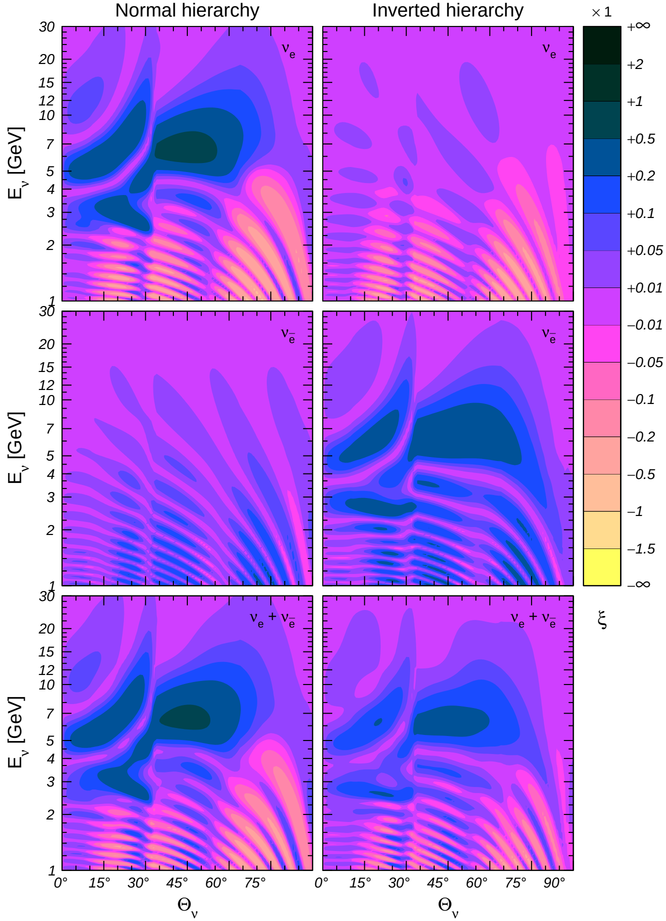
- In principle, θ_{13} can be measured by observing the MSW & parametric resonances;
- in practice, the sensitivity is limited by:
  - *statistics*: at $E_\nu \sim 6$ GeV the ATM flux is already suppressed;
  - *background*: the $\nu_e \to \nu_e$ events strongly dilute the $\nu_\mu \to \nu_e$ signal; also resonance occur only for ν **OR** $\bar{\nu}$, not both;
  - *resolution*: need **precise determination** of resonance peak to measure θ_{13};
  - *timing*: Mton detectors still far in the future, but LBL experiments are starting **now**!

⇒ sensitivity to θ_{13} not competitive with dedicated LBL and reactor experiments.



Sensitivity to the hierarchy: ν_e

- $\theta_{13} \neq 0 \Rightarrow$ resonant enhancement of ν ($\bar{\nu}$) oscillations for normal (inverted) hierarchy;
- mainly visible for high-energy: $E_\nu > 6$ GeV;
- effect can be observed if:
  - detector has **charge discrimination**;
  - detector has **no** charge discrimination but number ν and $\bar{\nu}$ events **is different**;
- in WCD, at *multi-GeV* energies, we have $N_{\nu_e}^{\text{tot}}/N_{\bar{\nu}_e}^{\text{tot}} \approx 2.5$ for *all CC interactions*;
- however, this ratio is reduced in *single-ring*: $N_{\nu_e}^{\text{1-ring}}/N_{\bar{\nu}_e}^{\text{1-ring}} \approx 1.7 \Rightarrow$ sensitivity decreased;
- note that the ratio is enhanced in *multi-ring* $\Rightarrow$ provide complementary information.

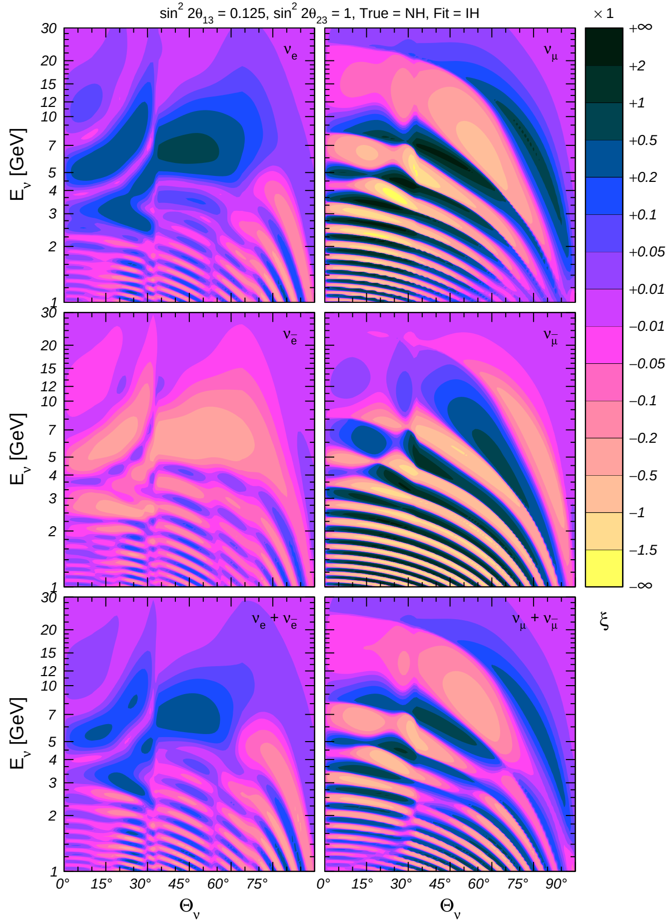


Sensitivity to the hierarchy: ν_μ

- ν_e channel (WCD only):
  - visible signal at high-energy;
  - wide region ⇒ no need for high-res;
- ν_μ channel (both WCD and MIND):
  - very strong signal at high-energy;
  - fast-oscillations ⇒ high-res **crucial**;
- opposite sign between ν and $\bar{\nu}$ ⇒ charge discrimination **essential**. However, for WCD multi-ring events can help;

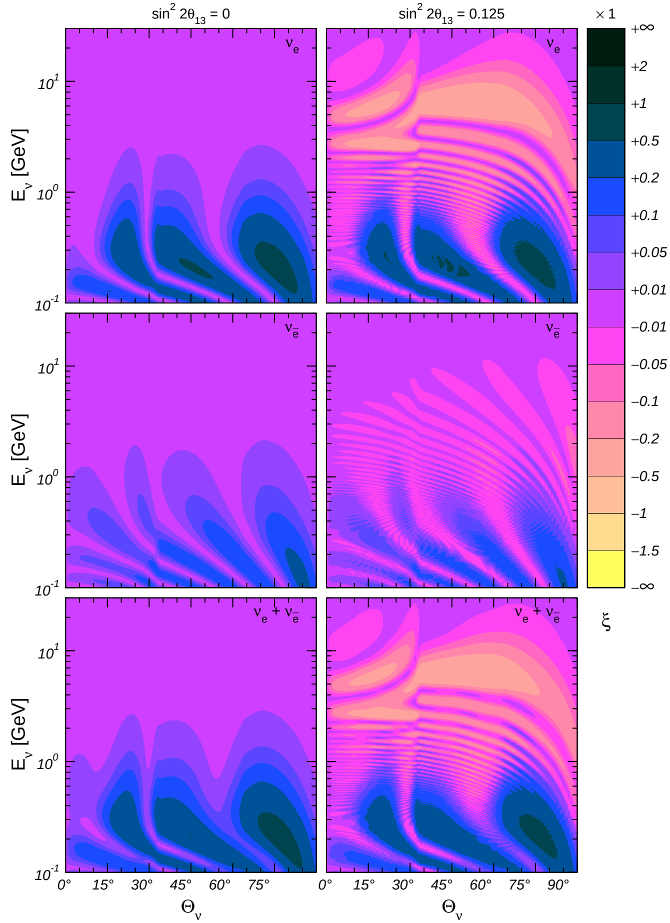
⇒ **Hierarchy**: **MIND better than WCD, but need very high resolution.**

[Petcov & Schwetz, NPB 740 (2006) 1]



Sensitivity to the octant: ν_e

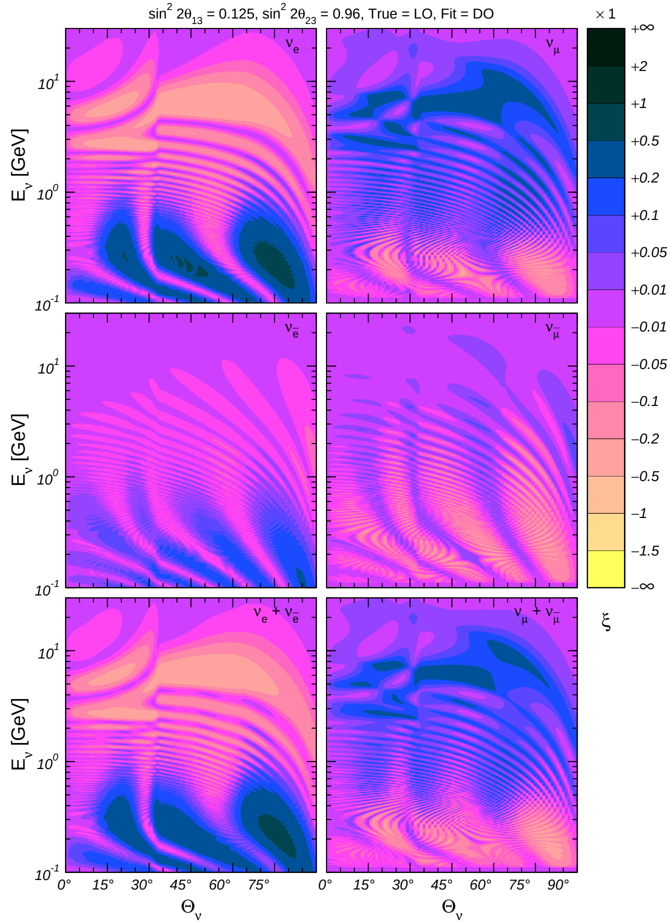
- low-energy ($E_\nu < 1$ GeV) region:
  - $\theta_{13} = 0$: excess (deficit) of ν_e flux for θ_{23} in the light (dark) side;
  - $\theta_{13} \neq 0$: lots of oscillations, but effect persist **on average**;
  - effect present for both ν **AND** $\bar{\nu}$;
- high-energy ($E_\nu > 3$ GeV) region:
  - $\theta_{13} = 0$: no effect;
  - $\theta_{13} \neq 0$: MSW resonance produces an excess of ν_e events; effect is smaller (larger) for θ_{23} in the light (dark) side;
  - resonance occurs only for ν **OR** $\bar{\nu}$.



Sensitivity to the octant: ν_μ

- low-energy region (only WCD):
  - visible signal for both ν_e and ν_μ events, but ν_e signal four times stronger;
  - same sign between ν and $\bar{\nu}$ $\Rightarrow$ no need for charge discrimination;
  - good resolution helps but not crucial;
  - signal independent of θ_{13} $\Rightarrow$ guaranteed;
- high-energy region (both WCD and MIND):
  - again, ν_e signal stronger than ν_μ;
  - signal present only for ν or $\bar{\nu}$ $\Rightarrow$ charge-blind signal *diluted* but *not canceled*;
  - visible signal only for large θ_{13};

$\Rightarrow$ **Octant: WCD better than MIND.**

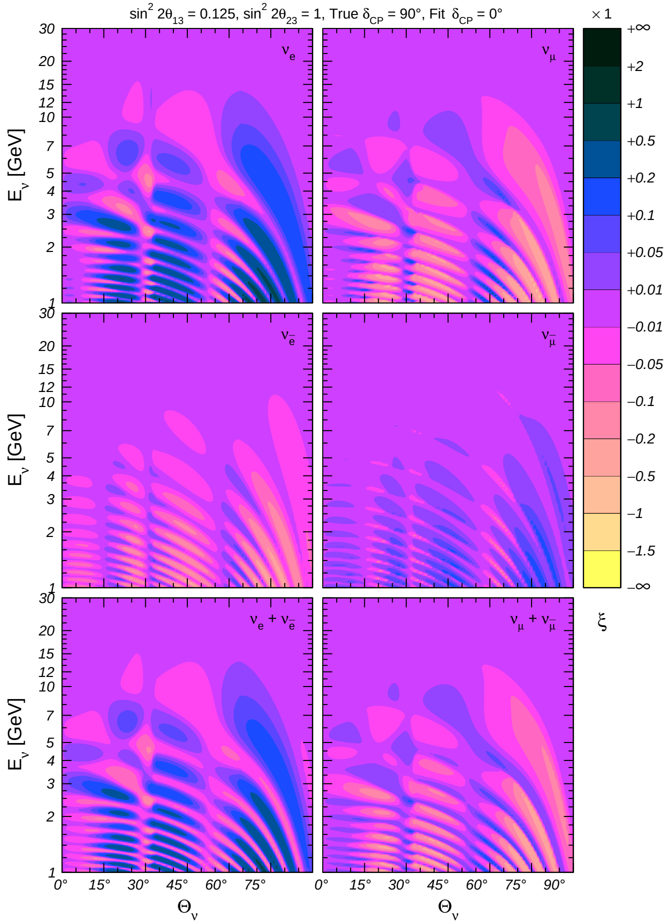


Sensitivity to the CP phase

- $\theta_{13} \neq 0 \Rightarrow$ interference of Δm^2_{21} and Δm^2_{31} osc:

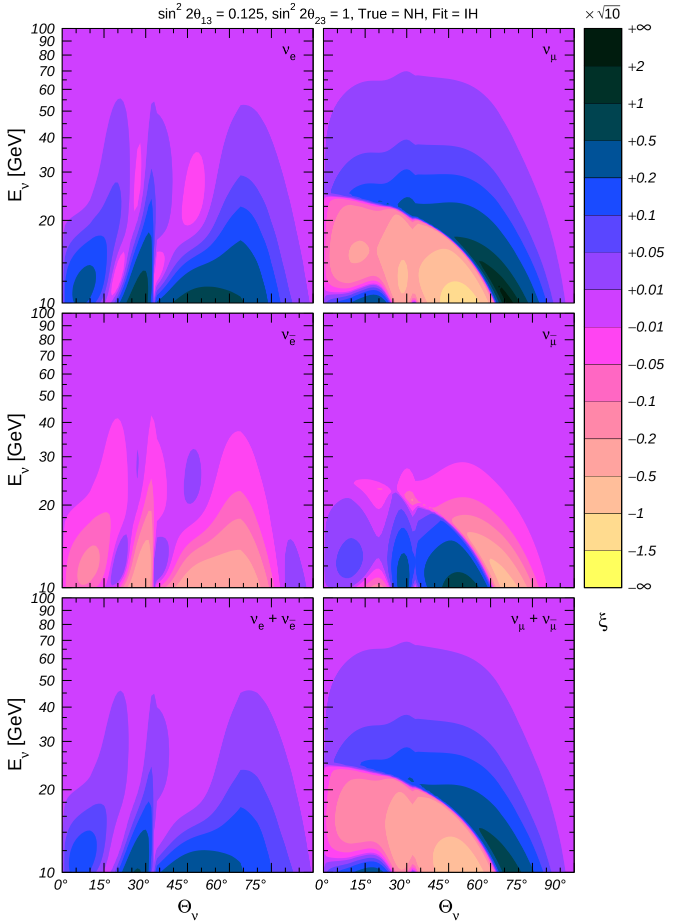
$$\delta_e \simeq (\bar r \cos^2\theta_{23} - 1)\, P_{2\nu}(\Delta m^2_{21}, \theta_{12}) \quad [\Delta m^2_{21} \text{ term}]$$
$$+ (\bar r \sin^2\theta_{23} - 1)\, P_{2\nu}(\Delta m^2_{31}, \theta_{13}) \quad [\theta_{13} \text{ term}]$$
$$- \bar r \sin\theta_{13} \sin 2\theta_{23}\, \mathrm{Re}(A^*_{ee}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

- effect stronger for ν_e, but present also for ν_μ;
- visible in the **intermediate-energy** region $1\text{ GeV} < E_\nu < 3\text{ GeV} \Rightarrow$ bad for MIND;
- opposite sign between ν and $\bar\nu \Rightarrow$ charge discrimination **important** $\Rightarrow$ bad for WCD;
- small structures $\Rightarrow$ need good resolution to avoid dilution (but no danger of cancellation);
- affected by **everything**: θ_{13}, θ_{23}, octant, hierarchy, ... $\Rightarrow$ effects hard to disentangle.



The high-energy region

- Structures in the oscillograms extend to very large energies (virually infinite);
- however, transition probabilities decrease as $1/E^2 \Rightarrow$ need very large detectors to see oscillations;
- these signatures can provide information on hiearchy and octant, however a large θ_{13} is crucial;
- regions are quite large $\Rightarrow$ no need for extremely good resolution;
- ν_μ signal suitable for investigation by neutrino telescopes, provided that energy threshold should be lowered to ~ 10 GeV or so.



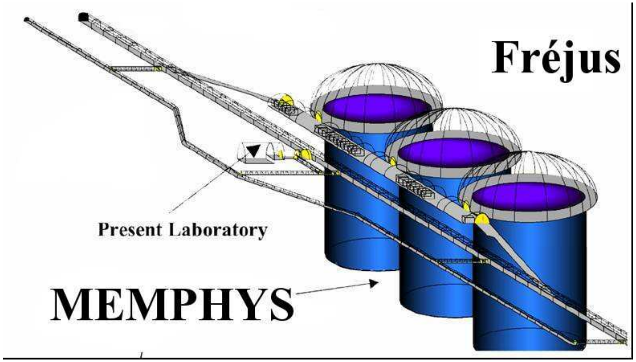
Comparison of the CERN-MEMPHYS and T2HK neutrino projects

- **Beam**:
  - β**B**: ν_e from ^{18}Ne (5 yr) + $\bar{\nu}_e$ from ^{6}He (5 yr) @ $\gamma = 100$, $\langle E_\nu \rangle = 400$ MeV;
  - **SPL**: 4 MW SPL at CERN, ν_μ (2 yr) + $\bar{\nu}_\mu$ (8 yr), $\langle E_\nu \rangle = 300$ MeV;
  - **T2HK**: 4 MW Super Beam from Tokai, ν_μ (2 yr) + $\bar{\nu}_\mu$ (8 yr);
- **Detector**:
  - β**B** & **SPL**: 3×145 Kton water Cerenkov at Fréjus (MEMPHYS);
  - **T2HK**: 440 Kton water Cerenkov at Kamioka (HK);
- **Baseline**:
  - β**B** & **SPL**: 130 km (CERN → Fréjus);
  - **T2HK**: 295 km (Tokai → Kamioka);

★ simulation of LBL data: **GLoBES** software;

★ simulation of ATM data: same as SK, but with real detectors geometry.

[Campagne, MM, Mezzetto & Schwetz, JHEP 04 (2007) 003]



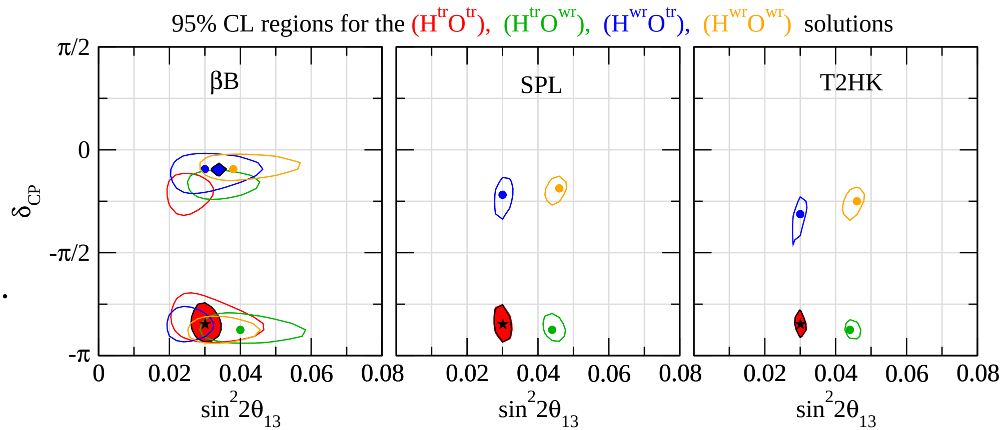
Solving parameter degeneracies with atmospheric data

- β**B**: complete 8-fold degeneracy due to:
  - lack of precise information on Δm^2_{31} and θ_{23} (usually provided by ν_μ disappearance);
  - spectral information not efficient enough to resolve the *intrinsic* degeneracy;
- **SPL** & **T2HK**: only 4-fold degeneracy appears if spectrum information is used;

$\Rightarrow$ all degeneracies disappear after inclusion of ATM data.

- true values:

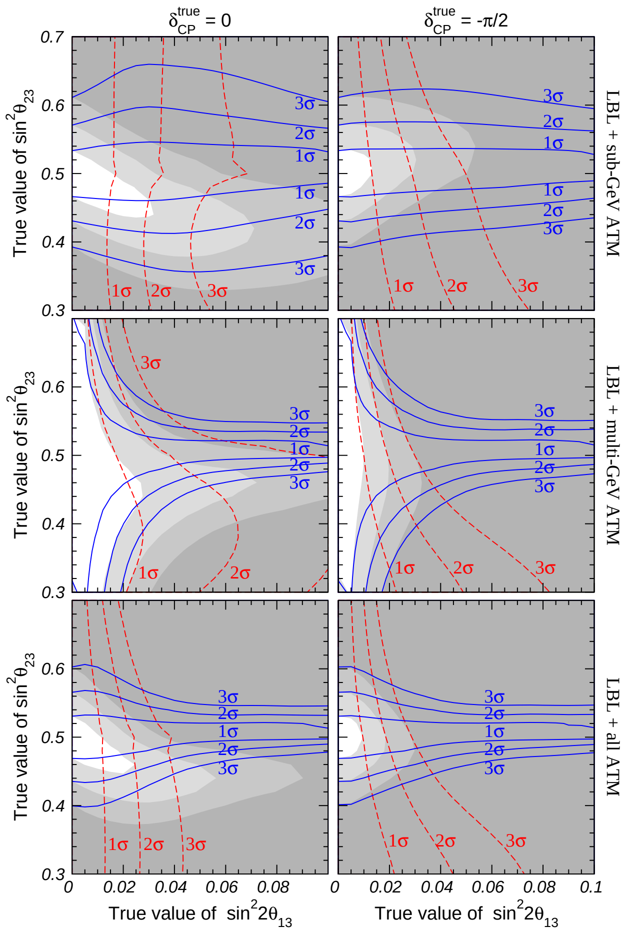
$$\delta_{CP} = -0.85\pi,$$
$$\sin^2 2\theta_{13} = 0.03,$$
$$\sin^2 \theta_{23} = 0.6,$$
$$\Delta m^2_{31} = +2.4 \times 10^{-3}\ \text{eV}^2.$$



Resolving degeneracies in T2HK

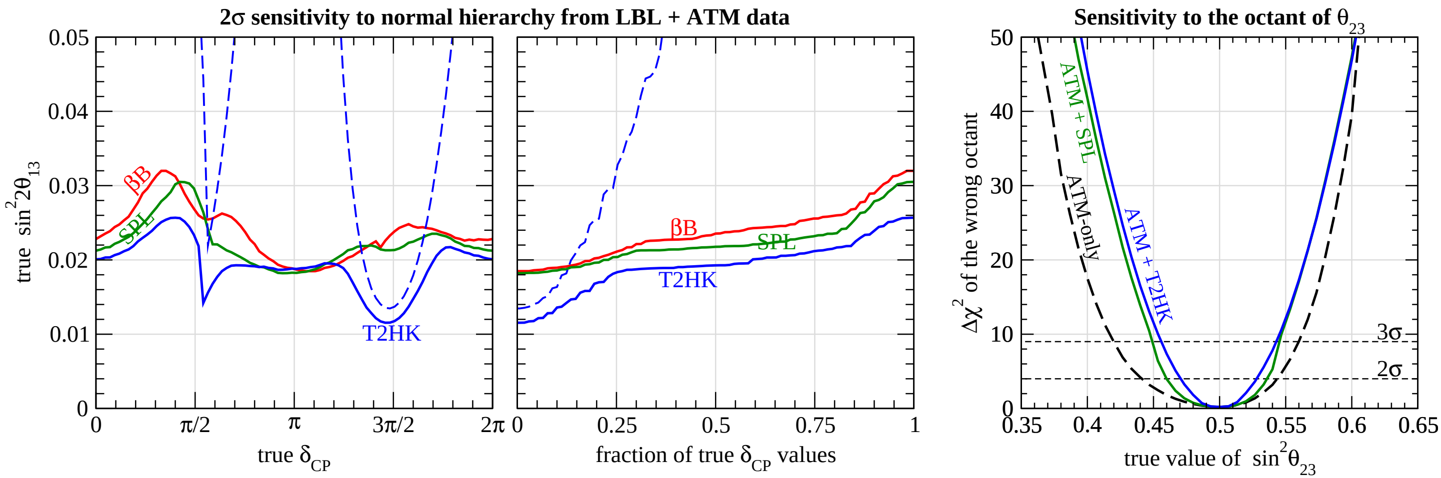
- sensitivity to the **octant** (blue lines):
  - given by **sub-GeV** events for $\theta_{13} \approx 0$;
  - given by **multi-GeV** events for $\theta_{13} \gtrsim 0.04$;
  - only mildly dependent on δ_{CP};
- sensitivity to the **hierarchy** (red lines):
  - dominated by **multi-GeV** for $\theta_{23} > 45°$;
  - **sub-GeV** events relevant if $\theta_{23} < 45°$;
  - strongly depends on δ_{CP} in the latter case;
- sensitivity to **octant+hierarchy** (gray areas):
  - mostly given by "sum" of blue and red lines;
  - δ_{CP} interference terms may be relevant.

[Huber, MM & Schwetz, PRD 71 (2005) 053006]



Determining the mass hierarchy and the octant

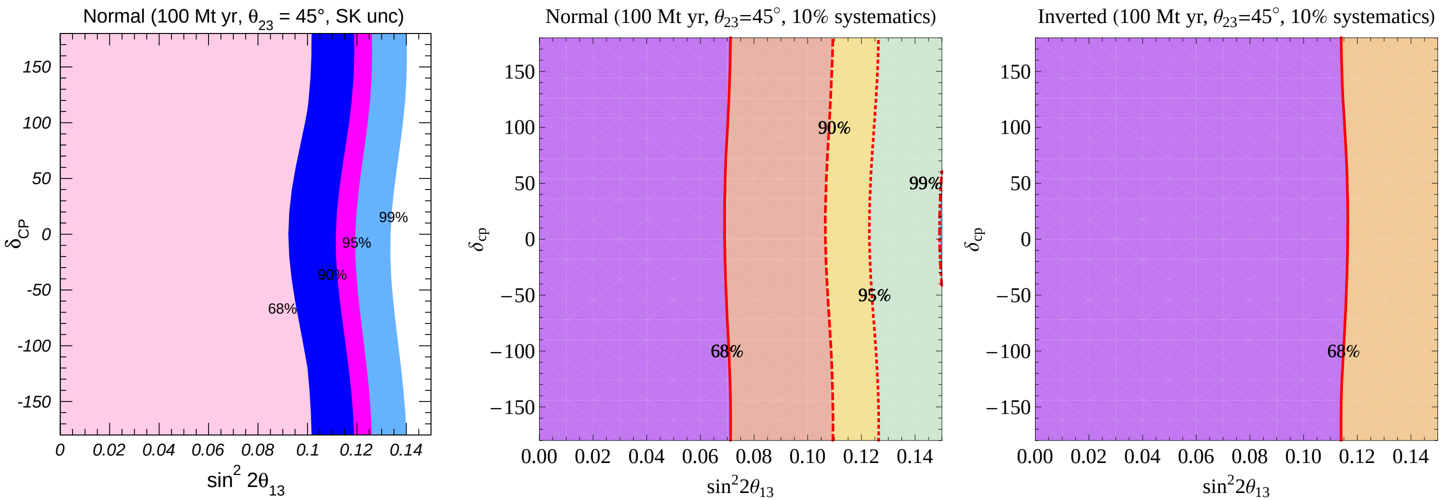
- Sensitivity to hierarchy of LBL data alone is quite poor due to parameter degeneracies;
- with ATM data included, the sensitivity to the hierarchy for the MEMPHYS project (both β**B** and **SPL** setup) is comparable to that of **T2HK**;
- sensitivity to the octant almost completely dominated by ATM data, with only minor contributions from LBL.



Neutrino telescopes: mass hierarchy @ IceCUBE Deep-Core

- **Idea**: have part of the detector with incresed photo-coverage, and use the rest as veto;
- **Goal**: lower the energy threshold as much as possible;
- **Why**: gain sensitivity to neutrino parameters (*e.g.*, mass hierarchy), with huge statistics.

⇒ Result promising, but needs careful study. What about other telescopes (*e.g.*, ANTARES)?



[Mena, Mocioiu & Razzaque, PRD 78 (2008) 093003, arXiv:0803.3044]

- **Atmospheric** data are always present in any **long-baseline** neutrino detector;
- ATM and LBL data provide **complementary** information on neutrino parameters:
  - LBL data will accurately determine $|\Delta m^2_{31}|$ and θ_{23}, and measure/bound θ_{13};
  - ATM data will provide information on the mass hierarchy and on the octant.
- sensitivity to the octant: WCD better than MIND (do not rely on size of θ_{13});
- sensitivity to the hierarchy:
  - MIND very promising but need high detector resolution;
  - charge discrimination very important, however combination of *different detectors types* (charge-blind but with different $\nu/\bar{\nu}$ composition) may do the job;
- ν telescopes: compensate low-$P_{\alpha\beta}$ at high-E_ν with huge statistics ⇒ worth a look.

⇒ [Gonzalez-Garcia, MM & Smirnov, PRD 70 (2004) 093005, hep-ph/0408170]
[Huber, MM & Schwetz, PRD 71 (2005) 053006, hep-ph/0501037]
[Campagne, MM, Mezzetto & Schwetz, JHEP 04 (2007) 003, hep-ph/0603172]
[Akhmedov, MM & Smirnov, JHEP 05 (2007) 077, hep-ph/0612285]
[Gonzalez-Garcia & MM, PREP 460 (2008) 1, arXiv:0704.1800]

Eventograms

- Consider a bin centered at $(\Theta_\nu,\, E_\nu)$ with size $\Delta\Theta_\nu$ and $\Delta \ln E_\nu$. We can write:

$$N_{\text{ex}} \simeq \rho_{\text{ex}}(\Theta_\nu,\, E_\nu)\,\Delta S\,, \qquad N_{\text{th}} \simeq \rho_{\text{th}}(\Theta_\nu,\, E_\nu)\,\Delta S\,, \qquad \Delta S \equiv \Delta\Theta_\nu \cdot \Delta \ln E_\nu\,;$$

- the contribution of this bin to the total χ^2 is:

$$\Delta\chi^2 = (N_{\text{th}} - N_{\text{ex}})^2/N_{\text{ex}} = (\rho_{\text{th}} - \rho_{\text{ex}})^2/\rho_{\text{ex}}\,\Delta S \qquad \text{[Gauss]}\,,$$

$$\Delta\chi^2 = 2[N_{\text{th}} - N_{\text{ex}} + N_{\text{ex}} \ln(N_{\text{ex}}/N_{\text{th}})] = [\rho_{\text{th}} - \rho_{\text{ex}} + \rho_{\text{ex}} \ln(\rho_{\text{ex}}/\rho_{\text{th}})]\,\Delta S \qquad \text{[Poisson]}\,;$$

- in both cases we can define a χ^2 *density function*:

$$\xi^2(\Theta_\nu,\, E_\nu) \equiv \lim_{\Delta S \to 0} \frac{\Delta\chi^2}{\Delta S} \qquad \text{and} \qquad \xi \equiv \text{sgn}(\rho_{\text{ex}} - \rho_{\text{th}})\,\sqrt{\xi^2}\,;$$

- the function ξ shows which regions in the $(\Theta_\nu,\, E_\nu)$ plane mostly contribute to the χ^2:

$$\chi^2 = \iint \xi^2(\Theta_\nu,\, E_\nu)\, d\Theta_\nu\, d\ln E_\nu\,;$$

- in the following we will present isocontours of ξ ("*eventograms*").

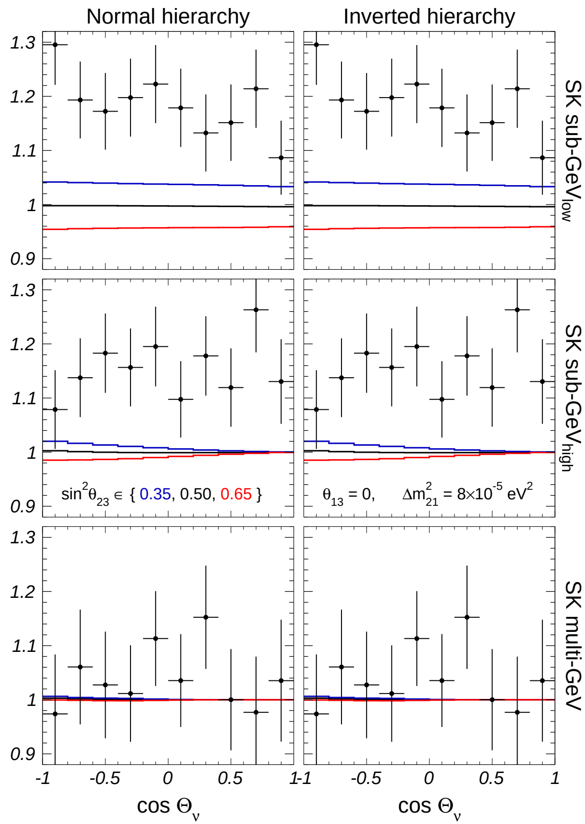
Octant discrimination: pure Δm^2_{21} effects

- Excess of e-like events for $\theta_{13} = 0$:

$$\delta_e \equiv \frac{N_e}{N_e^0} - 1 = \left(\bar{r}\cos^2\theta_{23} - 1\right) P_{2\nu}(\Delta m^2_{21},\, \theta_{12})$$

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

- for **sub-GeV** we have $\bar{r} \approx 2$ so that:
  - for $\theta_{23} \approx 45^\circ$ δ_e vanish;
  - δ_e change sign between light and dark side $\Rightarrow$ **octant discrimination**;
- for **multi-GeV** effects suppressed by $\Delta m^2_{21}/E_\nu$;
- **present data**: excess in e-like sub-GeV events $\Rightarrow$ preference for light side.



Octant discrimination: θ_{13} effects

- For $\theta_{13} \neq 0$:

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

- for **sub-GeV** effect of Δm^2_{21} is diluted by θ_{13};
- for **multi-GeV** resonance in $P_{2\nu}(\Delta m^2_{31},\, \theta_{13}) \Rightarrow$ enhancement of ν ($\bar{\nu}$) oscillations for normal (inverted) hierarchy;
- more ν than $\bar{\nu}$ events $\Rightarrow$ sensitivity enhancement is larger for normal hierarchy;

$\Rightarrow$ for small (large) θ_{13} the sensitivity to the **octant** is worse (better) than for $\theta_{13} = 0$.