Synergies between atmospheric and long-baseline neutrino data

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I. **Introduction: atmospheric neutrino data**

II. **Water Cerencov: physics reach of electron-like events**

III. **Magnetized Iron: potentialities of muon-like events**

IV. **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 (2881 ton-yr);
  - **Accelerator**: K2K + Minos (2.5×10^{20} p.o.t.);

- best-fit point and 1σ (3σ) ranges:

$$\theta_{12} = 34.5 \pm 1.4 \left(^{+4.8}_{-4.0}\right), \quad \Delta m^2_{21} = 7.67^{+0.22}_{-0.21} \left(^{+0.67}_{-0.61}\right) \times 10^{-5}\ \text{eV}^2,$$

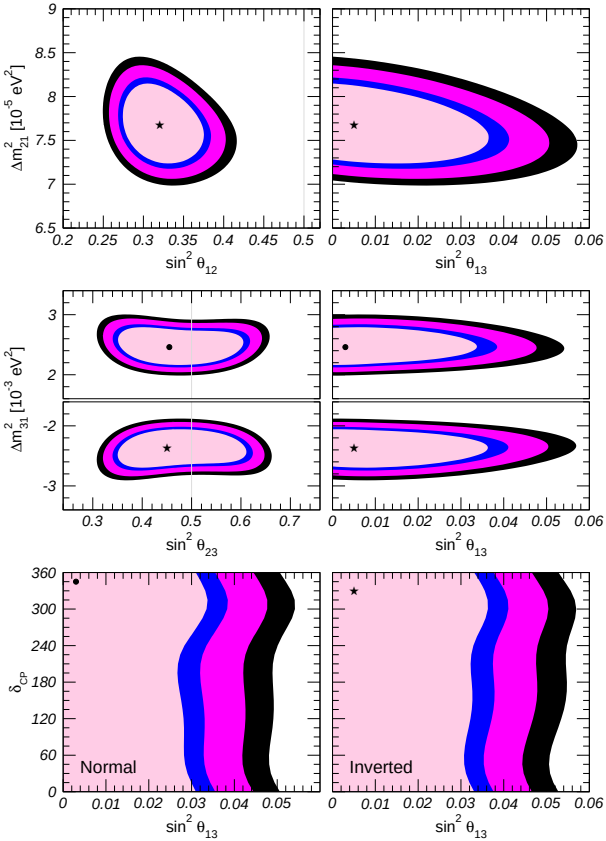
$$\theta_{23} = 42.3^{+5.1}_{-3.3} \left(^{+11.3}_{-7.7}\right), \quad \Delta m^2_{31} = \begin{cases} -2.37 \pm 0.15 \left(^{+0.43}_{-0.46}\right) \times 10^{-3}\ \text{eV}^2, \\ +2.46 \pm 0.15 \left(^{+0.47}_{-0.42}\right) \times 10^{-3}\ \text{eV}^2, \end{cases}$$

$$\theta_{13} = 3.9^{+3.9} \left(^{+9.0}\right), \qquad \delta_{CP} \in [0, 360];$$

- neutrino mixing matrix:

$$|U|_{90\%} = \begin{pmatrix} 0.80 \to 0.84 & 0.53 \to 0.60 & 0.00 \to 0.17 \\ 0.29 \to 0.52 & 0.51 \to 0.69 & 0.61 \to 0.76 \\ 0.26 \to 0.50 & 0.46 \to 0.66 & 0.64 \to 0.79 \end{pmatrix},$$

$$|U|_{3\sigma} = \begin{pmatrix} 0.77 \to 0.86 & 0.50 \to 0.63 & 0.00 \to 0.22 \\ 0.22 \to 0.56 & 0.44 \to 0.73 & 0.57 \to 0.80 \\ 0.21 \to 0.55 & 0.40 \to 0.71 & 0.59 \to 0.82 \end{pmatrix}.$$

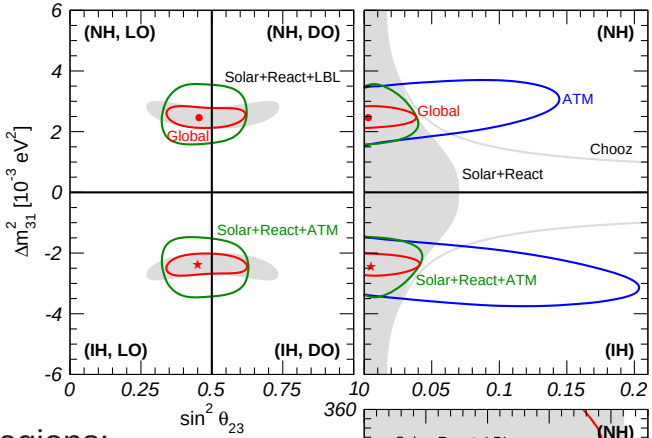


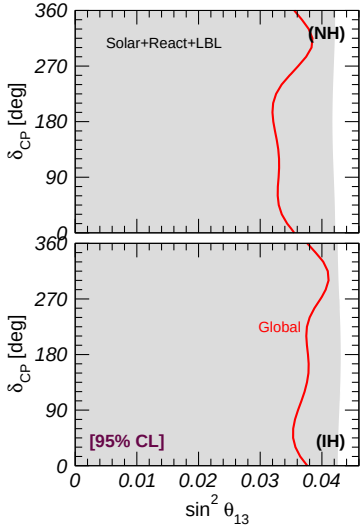
[Gonzalez-Garcia & MM, arXiv:0704.1800.v2]
[KamLAND analysis courtesy of T. Schwetz]

The role of atmospheric data

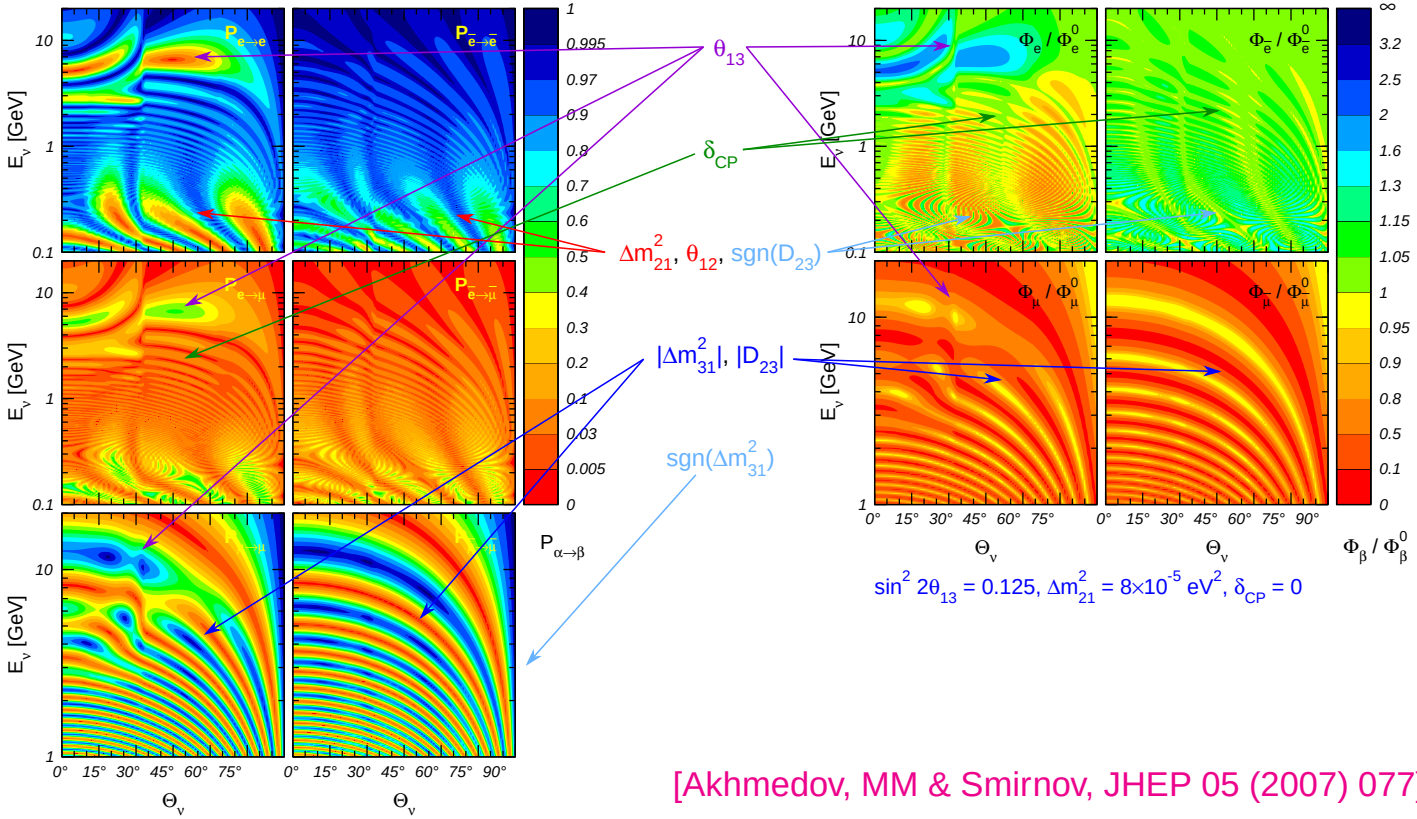
- Present reactor and accelerator data dominate $|\Delta m^2_{31}|$ and θ_{13} but give no info on:
  - the **mass hierarchy** (sign of Δm^2_{31});
  - the **octant** (sign of $\theta_{23} - \pi/4$);
  - the **CP phase**;
- note the high degree of symmetry of the gray regions;
- conversely, regions including 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

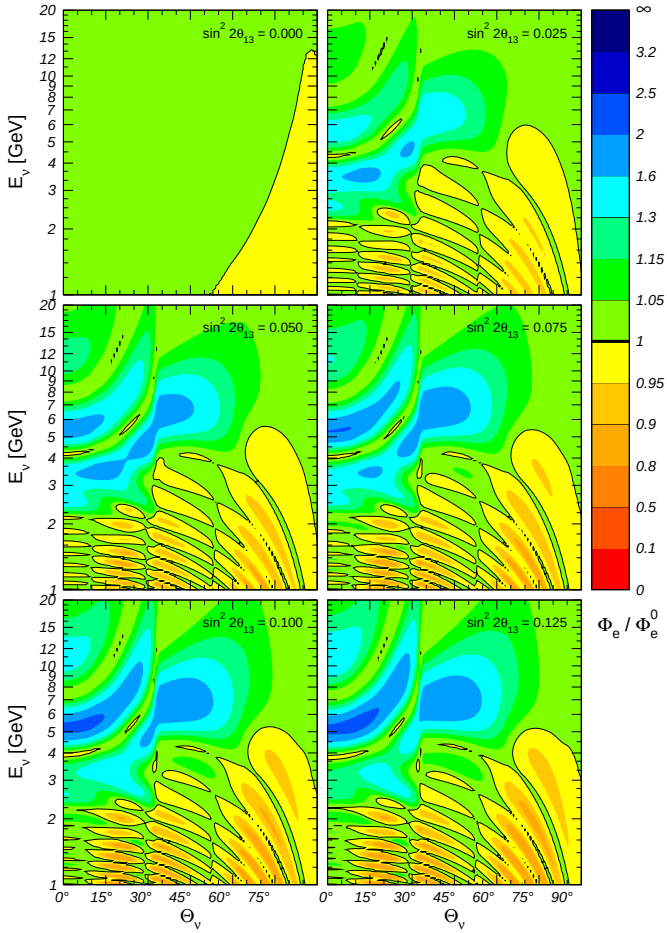


[Akhmedov, MM & Smirnov, JHEP 05 (2007) 077]

Sensitivity to θ_{13}

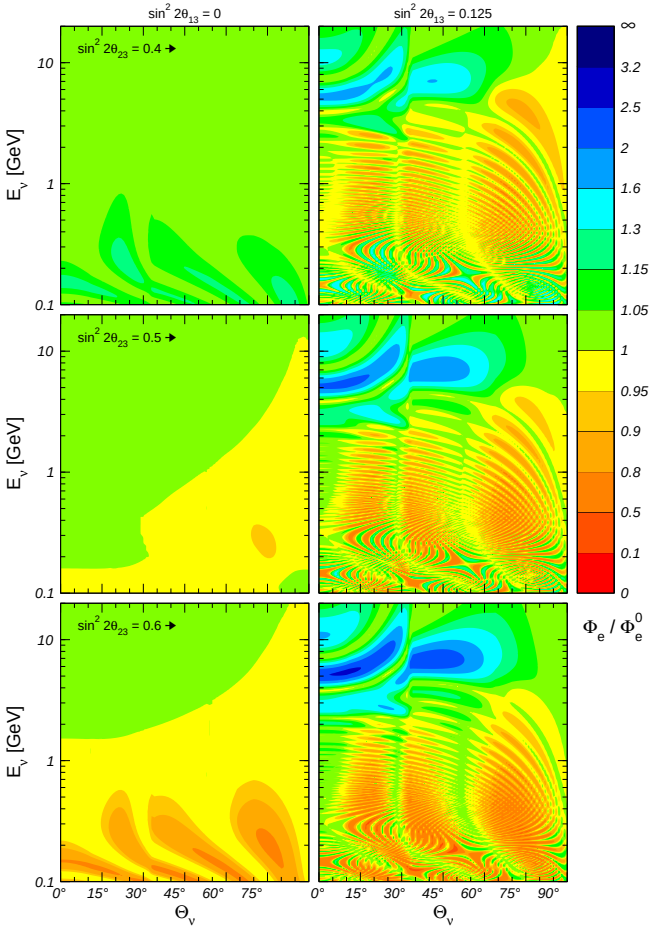
- In principle, θ_{13} can be measured by observing the MSW & parametric resonances;
- in practice, the sensitivity is limited by:
  - *statistics*: at $E_\nu \sim 6$ GeV the ATM flux is already suppressed;
  - *background*: the $\nu_e \longrightarrow \nu_e$ events strongly dilute the $\nu_\mu \longrightarrow \nu_e$ signal; also resonance occur only for ν **OR** $\bar{\nu}$, not both;
  - *resolution*: need **precise determination** of resonance peak to measure θ_{13}, but E_ν reconstruction is usually very poor;

$\Rightarrow$ sensitivity to θ_{13} may not be competitive with **dedicated** LBL and reactor experiments.



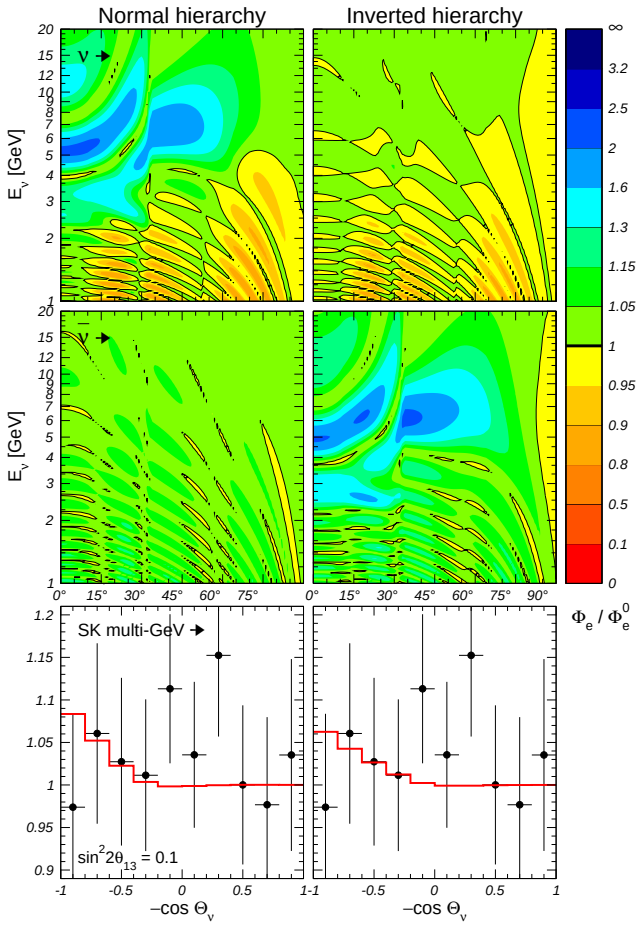
Sensitivity to the octant

- 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** $\bar{\nu}$.



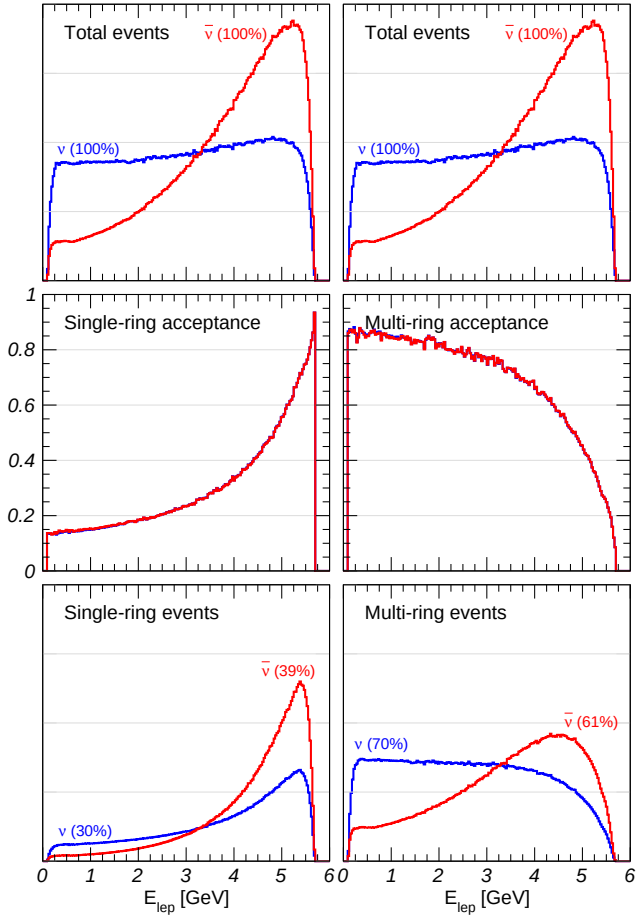
Sensitivity to the hierarchy

- $\theta_{13} \neq 0 \Rightarrow$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 Water Cerenkov, at *multi-GeV* energies, we have $N^{\text{tot}}_{\nu_e}/N^{\text{tot}}_{\bar{\nu}_e} \approx 2.5$ for *all CC interactions*;
- however, in *single-ring* sample this ratio can be considerably reduced: $N^{\text{1-ring}}_{\nu_e}/N^{\text{1-ring}}_{\bar{\nu}_e} \approx 1.7 \Rightarrow$ **sensitivity is decreased**.



Single-ring versus multi-ring events

- **Single-ring:**
  - only one track $\Rightarrow$ event is "clean";
  - small scattering angle;
  - final lepton carry most of the ν energy;
  - final hadronic system has little energy;
  - enriched in $\bar{\nu} \Rightarrow N_{\nu_e}/N_{\bar{\nu}_e}$ decreased.
- **Multi-ring:**
  - many tracks $\Rightarrow$ event is "messy".
  - the scattering angle tend to be large;
  - final lepton carry only a fraction of ν energy;
  - final hadronic system has a lot of energy;
  - enriched in $\nu \Rightarrow N_{\nu_e}/N_{\bar{\nu}_e}$ increased.
- Use of <u>both</u> sets $\Rightarrow$ statistical $\nu/\bar{\nu}$ separation.

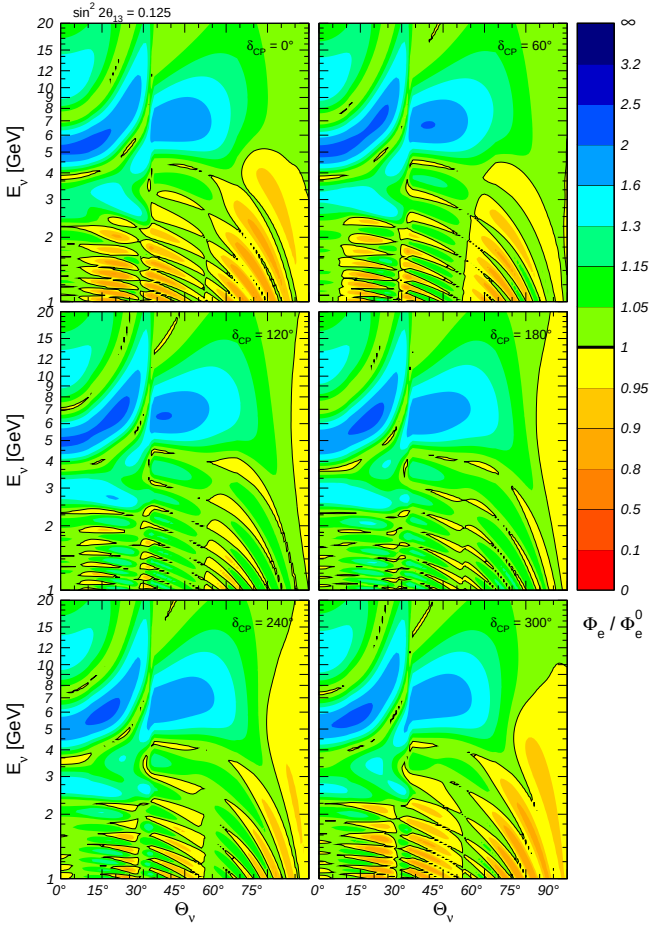


Sensitivity to the CP phase

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

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

- mainly visible in the **intermediate-energy** region: $1\ \mathrm{GeV} < E_\nu < 3\ \mathrm{GeV}$;
- present for both ν **AND** $\bar{\nu}$;
- affected by **everything**: θ_{13}, θ_{23}, octant, mass hierarchy, ... $\Rightarrow$ effects hard to disentangle;
- **present analysis**: effects of δ_{CP} on other parameters properly included.



Eventograms

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

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

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

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

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

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

- the function ξ shows which regions in the (Θ_ν, E_ν) plane mostly contribute to the total χ^2:

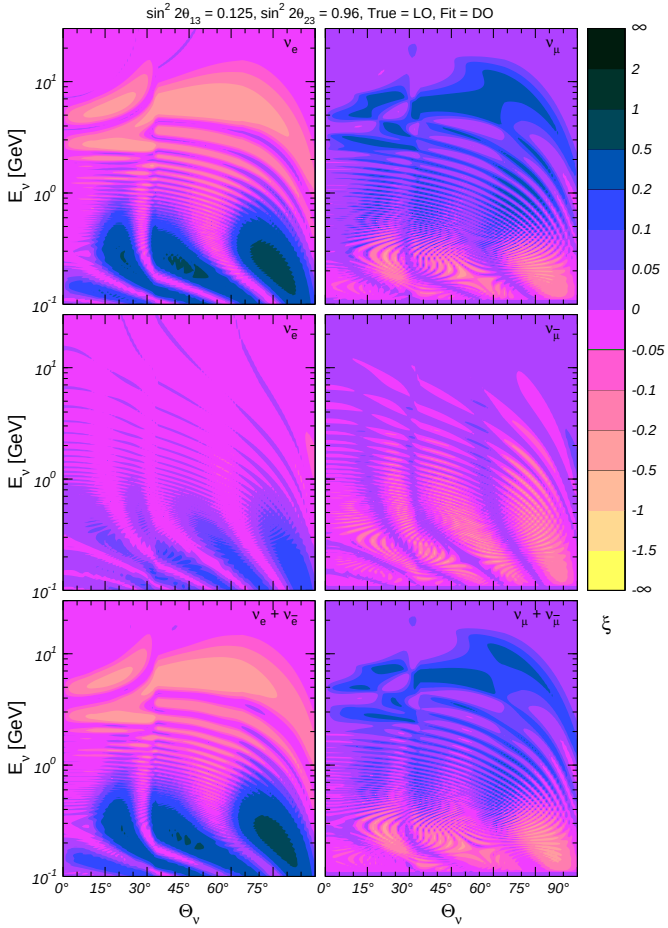
$$\chi^2 = \iint \xi^2(\Theta_\nu, E_\nu)\, d\Theta_\nu\, d\ln E_\nu\,;$$

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

Sensitivity to the octant

- 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 $\theta_{13} \Rightarrow$ 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.**

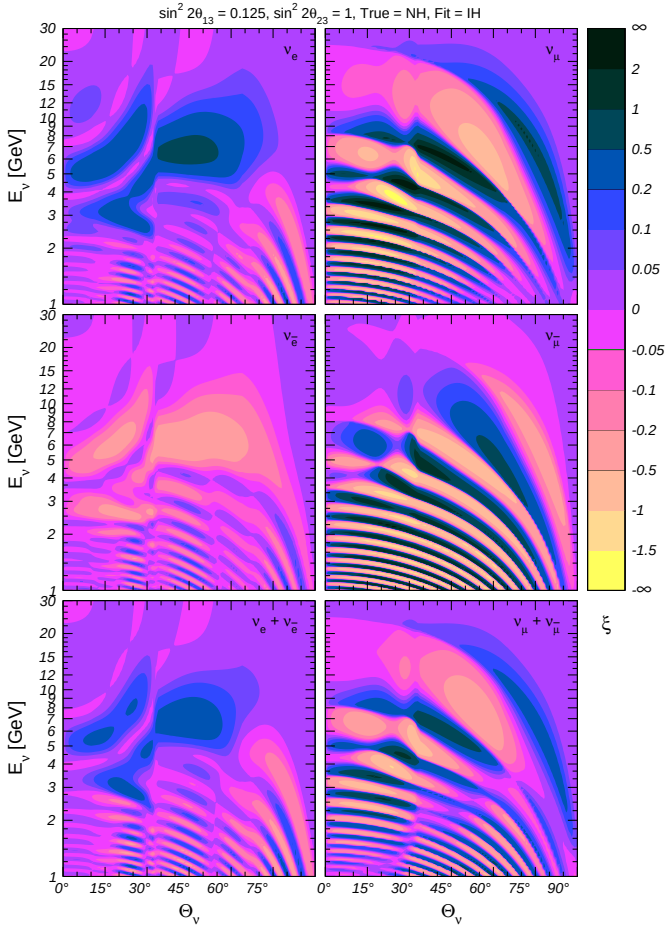


Sensitivity to the hierarchy

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

$\Rightarrow$ **Hierarchy: MIND better than WCD, but need very high resolution**.

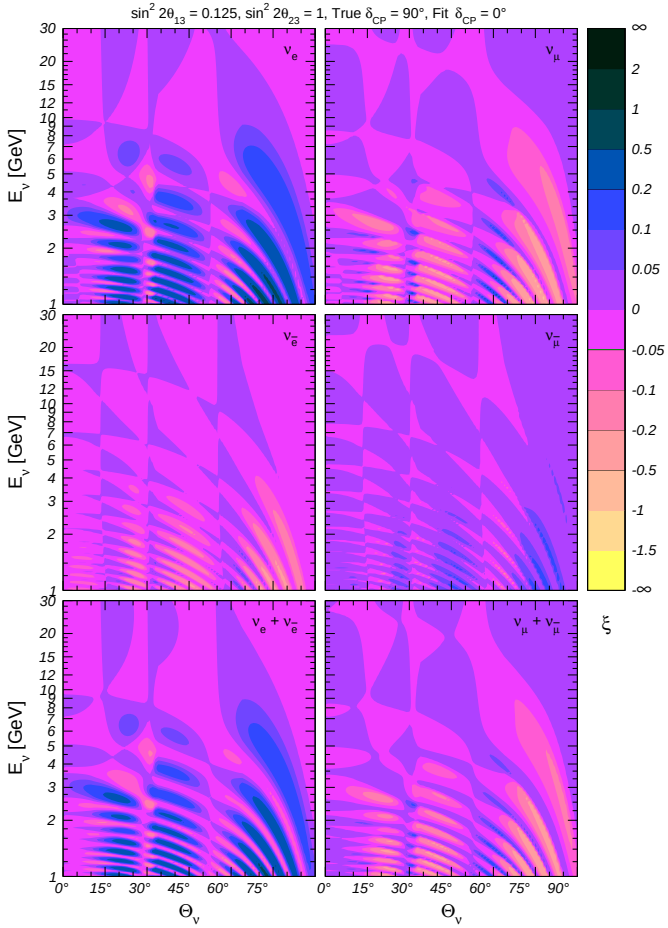
[Petcov & Schwetz, NPB 740 (2006) 1]



Sensitivity to the CP phase

- effect stronger for ν_e, but present also for ν_μ;
- opposite sign between ν and $\bar{\nu}$ $\Rightarrow$ charge discrimination **important** $\Rightarrow$ bad for WCD;
- only at intermediate energy $\Rightarrow$ bad for MIND;
- small-size structures $\Rightarrow$ need good resolution to avoid dilution (but no danger of cancellation);

$\star$ in summary: need ν_e, at low energy, with charge discrimination and good detector resolution $\Rightarrow$ **very hard to achieve**!



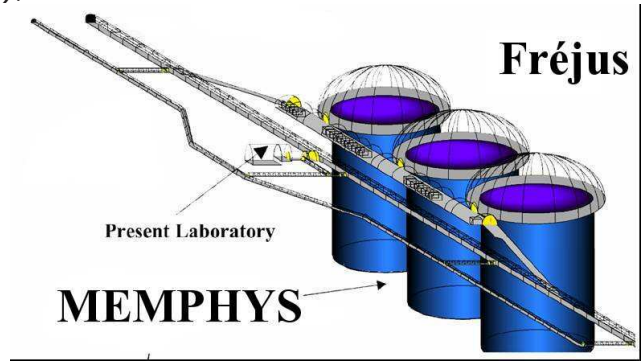
Comparison of the CERN-MEMPHYS and T2HK neutrino projects

- **Beam**:
  - **βB**: 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**:
  - **βB** & **SPL**: 3×145 Kton water Cerenkov at Fréjus (MEMPHYS);
  - **T2HK**: 440 Kton water Cerenkov at Kamioka (HK);
- **Baseline**:
  - **βB** & **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]



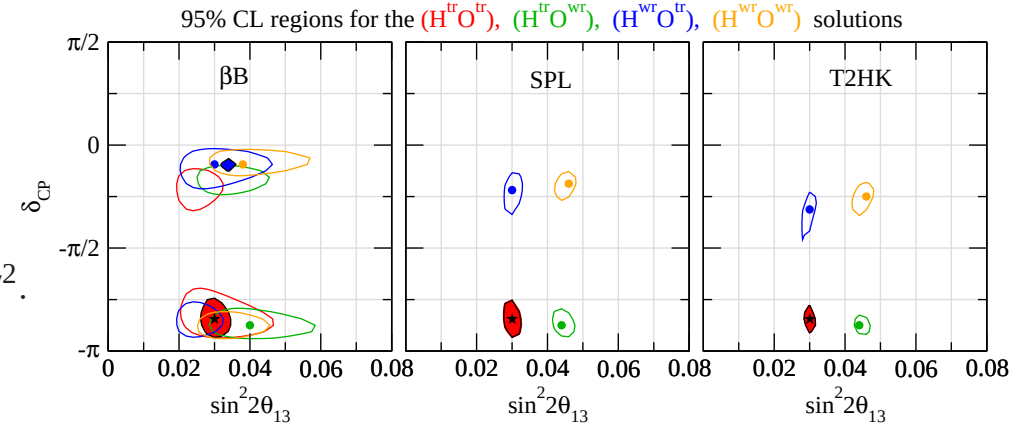
Solving parameter degeneracies with atmospheric data

- **βB**: 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;

⇒ all degeneracies disappear after inclusion of ATM data.

- true values:

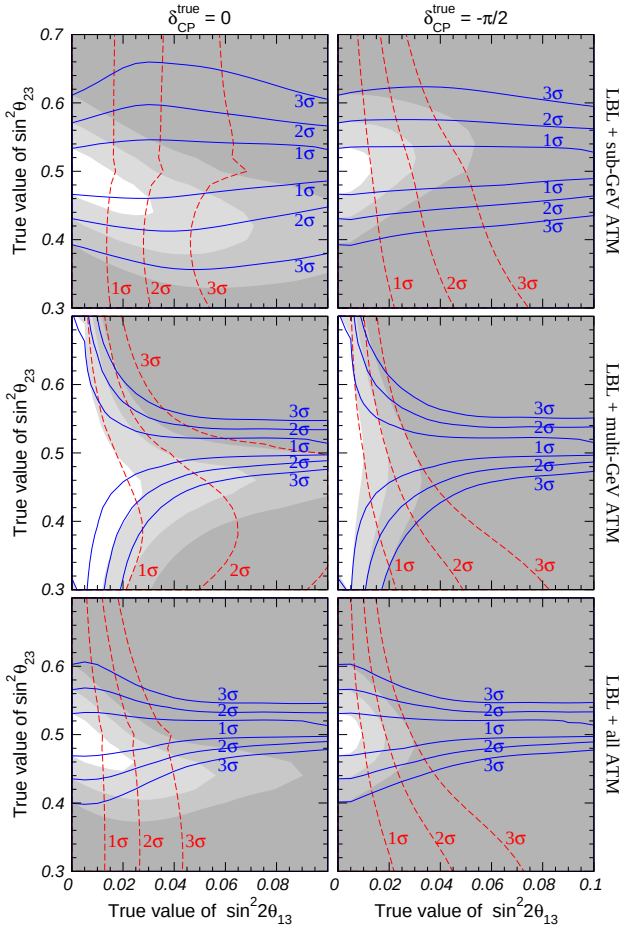
$$\delta_{CP} = -0.85\pi,$$
$$\sin^2 2\theta_{13} = 0.03,$$
$$\sin^2 \theta_{23} = 0.6,$$
$$\Delta m^2_{31} = +2.4 \times 10^{-3}\ \text{eV}^2.$$



Resolving degeneracies in T2HK

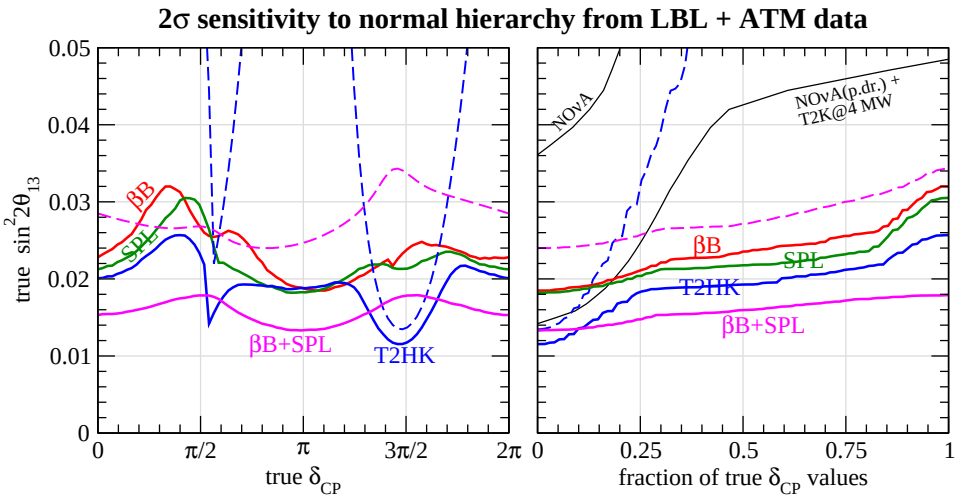
- sensitivity to the **octant** (blue lines):
  - given by **sub-GeV** events for $\theta_{13} \approx 0$;
  - given by **multi-GeV** events for $\theta_{13} \gtrsim 0.04$;
  - only mildly dependent on δ_{CP};
- sensitivity to the **hierarchy** (red lines):
  - dominated by **multi-GeV** for $\theta_{23}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

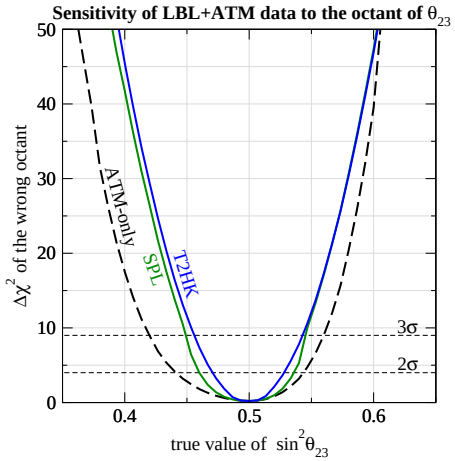
[Huber, MM & Schwetz, PRD 71 (2005) 053006]



Determining the mass hierarchy and the octant

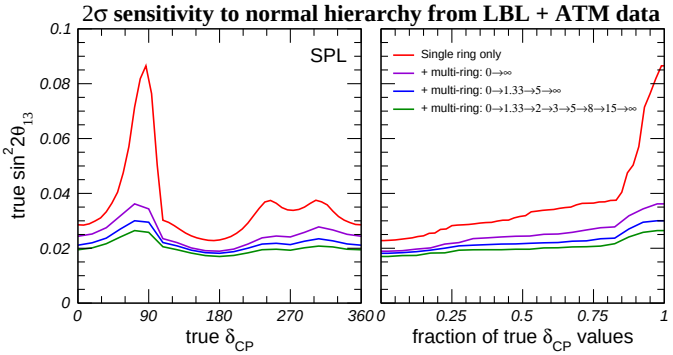
- With ATM data included, the sensitivity to the hierarchy for the MEMPHYS project (both **βB** and **SPL** setup) is comparable to that of **T2HK**;
- complementarity between **βB** and **SPL** ⇒ maximum gain if **combined**;
- ATM sensitivity to the octant strongly enhanced by splitting of sub-GeV data into *low* and *high* momentum subsamples.

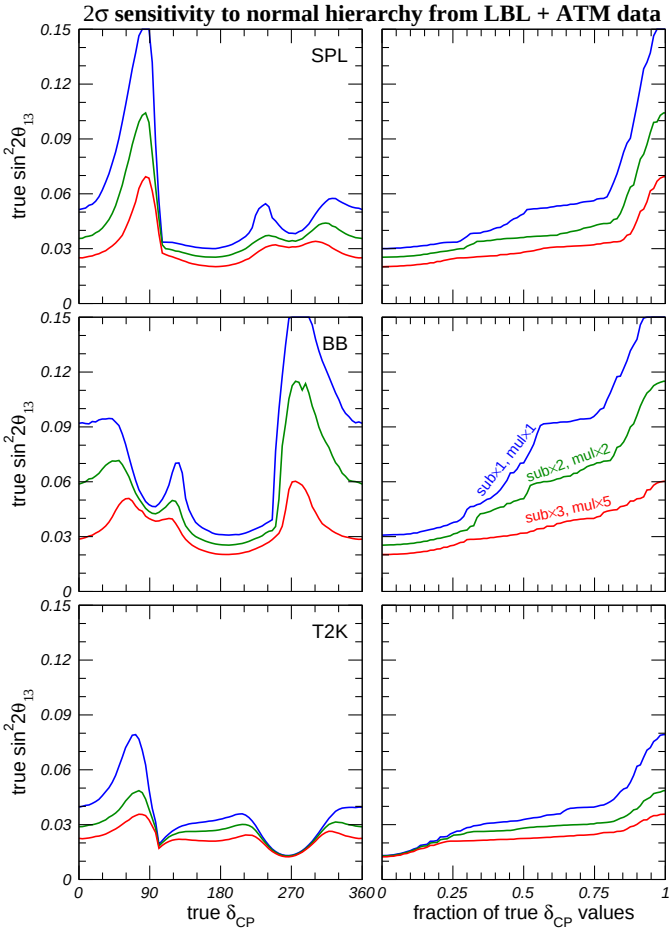




Energy binning and multi-ring

- The sensitivity to octant, hierarchy, CP-phase etc. proceeds from oscillation effects at different ν energy;
- splitting data into different energy regions is crucial to improve the sensitivity;
- multi-ring events are essential for the determination of the mass hierarchy.





Conclusions

- **GREAT SALE**: buy a **LBL** neutrino detector and get **ATM** data **FOR FREE**!
- 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.

$\Rightarrow$ [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, arXiv:0704.1800, submitted to Phys. Rept.]