Resolving parameter degeneracies in long-baseline experiments by atmospheric neutrino data

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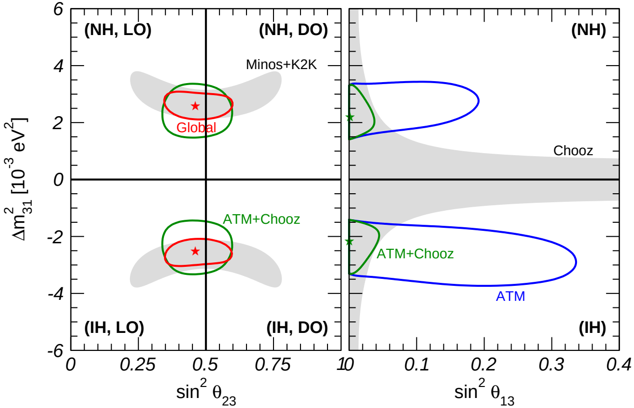
Parameter degeneracies and present data

- Present reactor and accelerator data **fix** $|\Delta m^2_{31}|$ and θ_{13} but give no info on:
  - the **mass hierarchy** (sign of Δm^2_{31});
  - the **octant** (sign of $\theta_{23} - \pi/4$);
- this is reflected by the high degree of symmetry of their allowed regions (gray);



- conversely, regions including also ATM data are visibly **asymmetric**:
  - SK bound on θ_{13} is much stronger for **normal** than for **inverted hierarchy**;
  - the global allowed region is clearly shifted towards the **light side** ($\theta_{23} < 45^\circ$);
- evidence is not statistically relevant but the effect is promising;

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

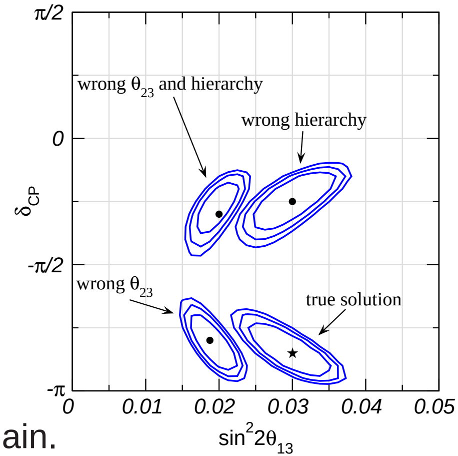
Parameter degeneracies and future experiments

- Precision of forthcoming LBL experiments is challenged by *parameter degeneracies*:
  - *intrinsic* or $(\delta_{CP}, \theta_{13})$: $P_{\nu_\mu\to\nu_e}(\theta_{13}, \delta_{CP}) = P_{\nu_\mu\to\nu_e}(\theta'_{13}, \delta'_{CP})$
  - *hierarchy* or $\mathrm{sgn}(\Delta m^2_{31})$: $P_{\nu_\mu\to\nu_e}(\Delta m^2_{31}, \delta_{CP}) = P_{\nu_\mu\to\nu_e}(-\Delta m^2_{31}, \delta'_{CP})$
  - *octant* or θ_{23}: $P_{\nu_\mu\to\nu_\mu} \propto \sin^2 2\theta_{23}$, $P_{\nu_\mu\to\nu_e}(\theta_{23}, \theta_{13}, \delta_{CP}) = P_{\nu_\mu\to\nu_e}(\pi/2-\theta_{23}, \theta'_{13}, \delta'_{CP})$

$\Rightarrow$ if only total number of $\nu_{e,\mu}$ and $\bar\nu_{e,\mu}$ at a given L/E are measured $\Rightarrow$ 8-fold degeneracy.

Example: T2K-II

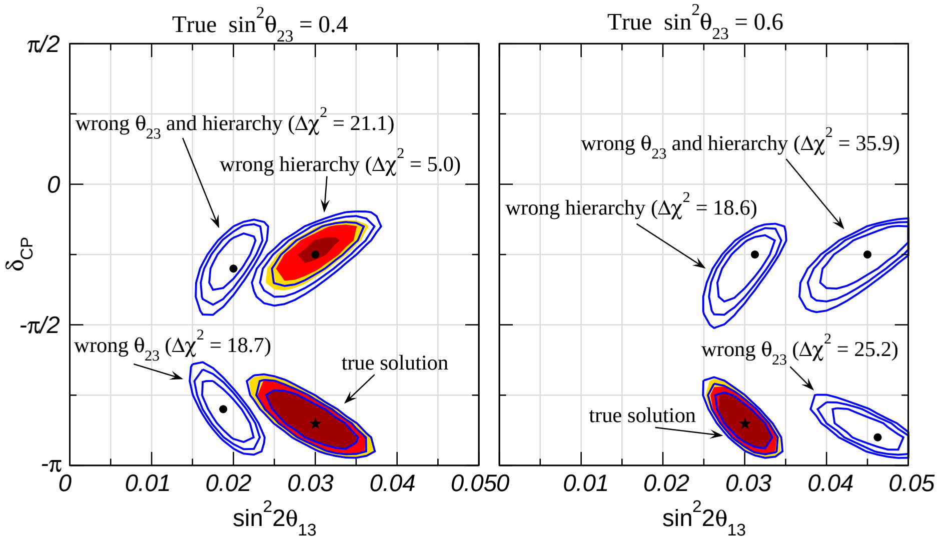
- **Beam**: 4 MW at JPARC, $\langle E_\nu \rangle \approx 0.76$ GeV, 2° off-axis;
- **Baseline**: 295 km;
- **Detector**: 1 Mton Cerenkov at Kamioka (HK);
- **Runtime**: 2 yr (ν) + 6 yr ($\bar\nu$), all channels;



$\Rightarrow$ *intrinsic* degeneracy solved by E_ν spectrum, but others remain.

Solving parameter degeneracies with atmospheric data

- The HK detector of T2K-II will also record ATM events. We assume 9 yr of data. When these events are combined with the LBL ones:
  - the **octant degeneracy** is completely solved regardless of the **true octant**;
  - the **hierarchy degeneracy** is solved if **true octant** is the dark one.
- **solid**: LBL only;
- **colored**: LBL + ATM;
- regions at 2σ, 99%, 3σ CL (2 dof);
- true values:
  $\delta_{CP} = -0.85\pi$,
  $\sin^2\theta_{13} = 0.03$,
  $\Delta m^2_{31} = 2.2 \times 10^{-3}$ eV^2,
  $\Delta m^2_{21} = 7.9 \times 10^{-5}$ eV^2.



[Huber, MM, Schwetz, PRD 71 (2005) 053006, hep-ph/0501037]

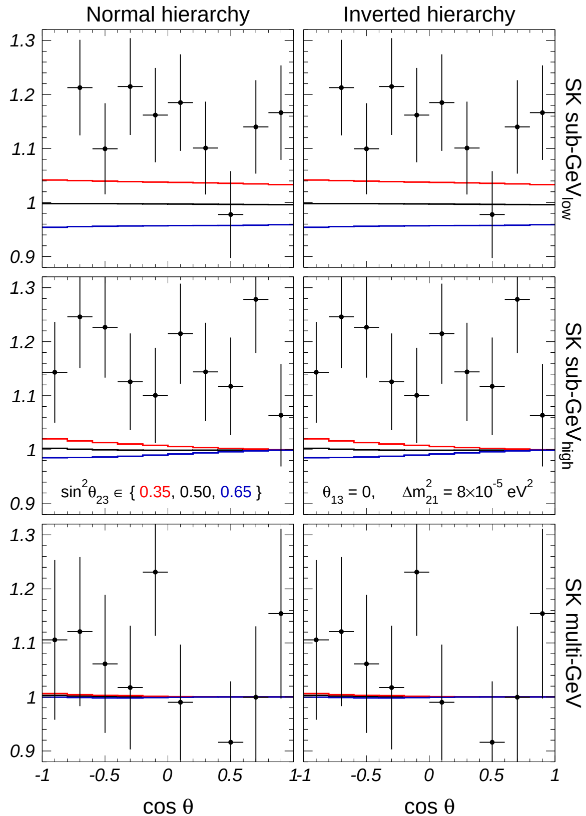
Pure Δm^2_{21} effects and octant discrimination

- 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**.

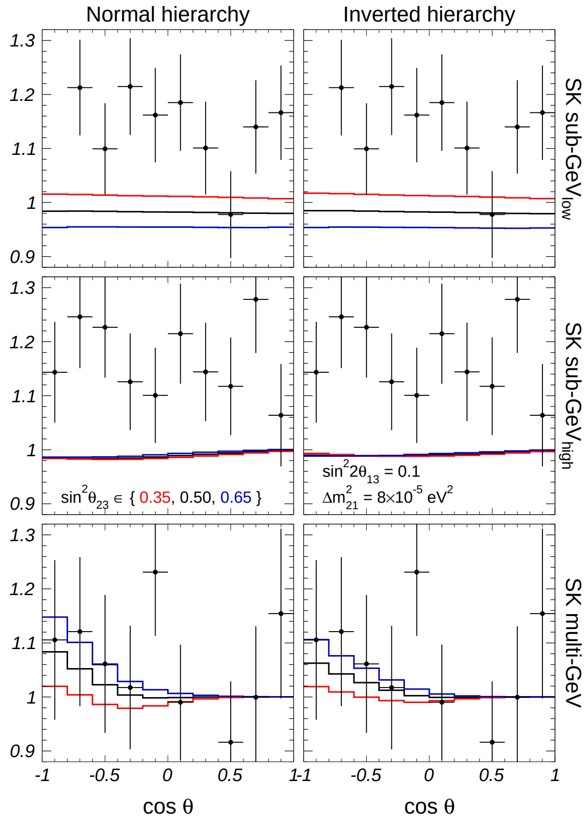


θ_{13} effects and hierarchy discrimination

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

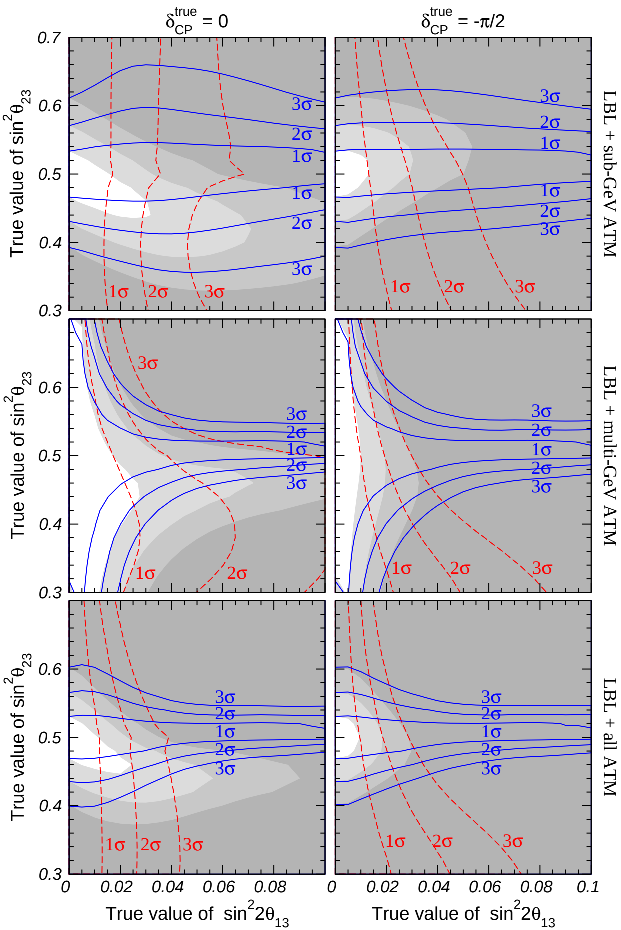
$$\begin{aligned}\delta_e \simeq\; & (\bar r \cos^2\theta_{23} - 1)\, P_{2\nu}(\Delta m^2_{21}, \theta_{12}) && [\Delta m^2_{21} \text{ term}] \\ & + (\bar r \sin^2\theta_{23} - 1)\, P_{2\nu}(\Delta m^2_{31}, \theta_{13}) && [\theta_{13} \text{ term}] \\ & - \bar r \sin\theta_{13} \sin 2\theta_{23}\,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

- 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;
- fluxes and cross-sections different for ν and $\bar\nu \Rightarrow$ multi-GeV events **sensitive to mass hierarchy**;
- sensitivity is larger for θ_{23} in the **dark side**.



Resolving parameter degeneracies

- 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.



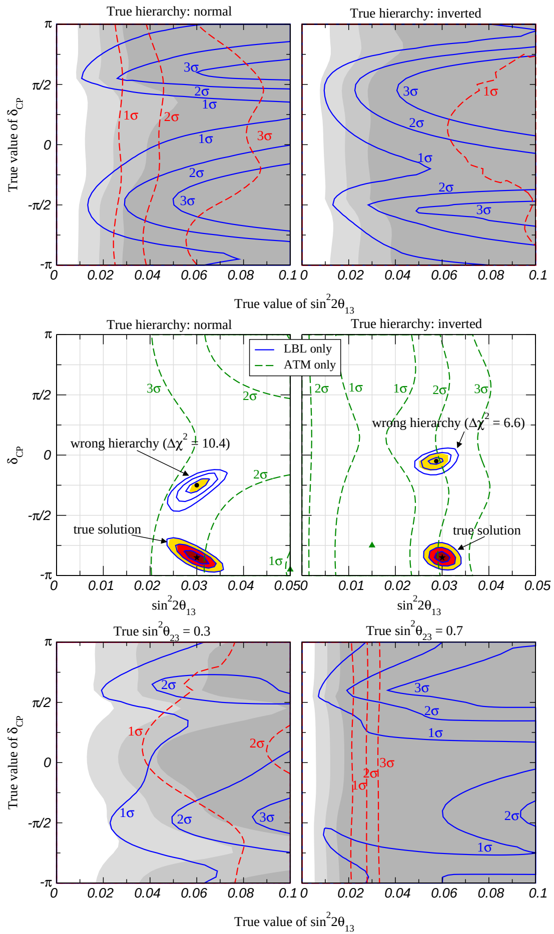
Determining the mass hierarchy

- solid: LBL, dashed: ATM, **shaded**: ATM+LBL;
- sensitivity of LBL alone strongly depend on δ_{CP};
- ATM data: more ν than $\bar{\nu}$ $\Rightarrow$ sensitivity is stronger for **normal** than for **inverted** hierarchy;
- fake **ATM** solution: $\begin{cases} \theta_{13}^{\text{wrong}} > \theta_{13}^{\text{true}} & \text{for \textbf{normal}}; \\ \theta_{13}^{\text{wrong}} < \theta_{13}^{\text{true}} & \text{for \textbf{inverted}}; \end{cases}$
- fake **LBL** solution: different δ_{CP} but same θ_{13};

$\Rightarrow$ bound from **LBL+ATM** data considerably stronger than the sum of the two;

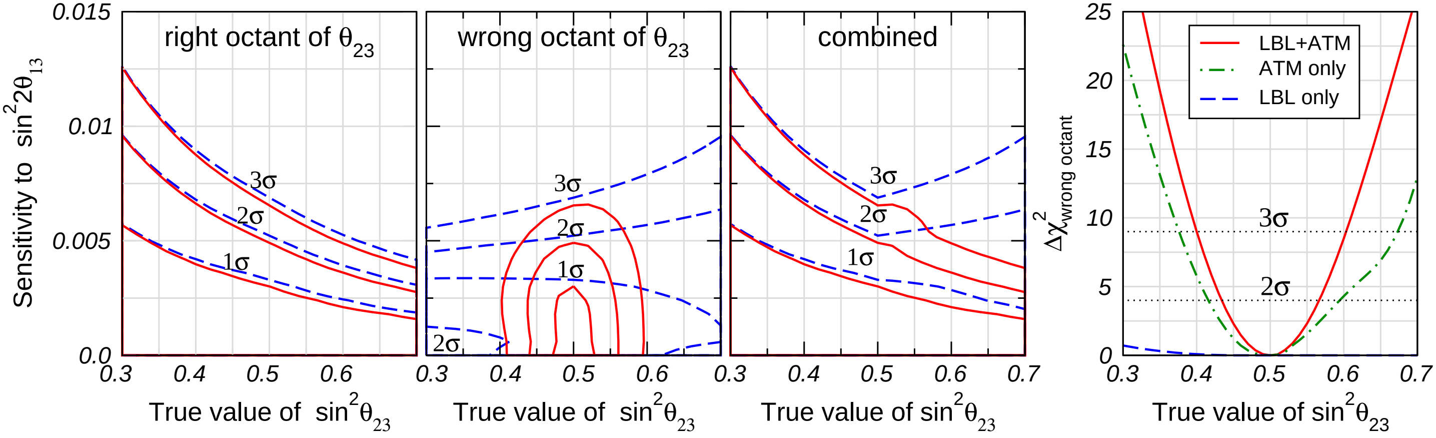
Non-maximal θ_{23}

- sensitivity to the hierarchy is much stronger for $\theta_{23} > 45^\circ$ than for $\theta_{23} < 45^\circ$.



Sensitivity to the octant and bound on θ_{13}

- For $\theta_{13} = 0$:
  - octant discrimination is ensured only by ATM (sub-GeV) data;
  - bound on θ_{13} is completely determined by LBL data;
- however, synergy between the two data sets is clearly visible:
  - ATM sensitivity to octant is enhanced by accurate determination of other ν pars;
  - LBL bound on θ_{13} strongly benefit from octant determination.

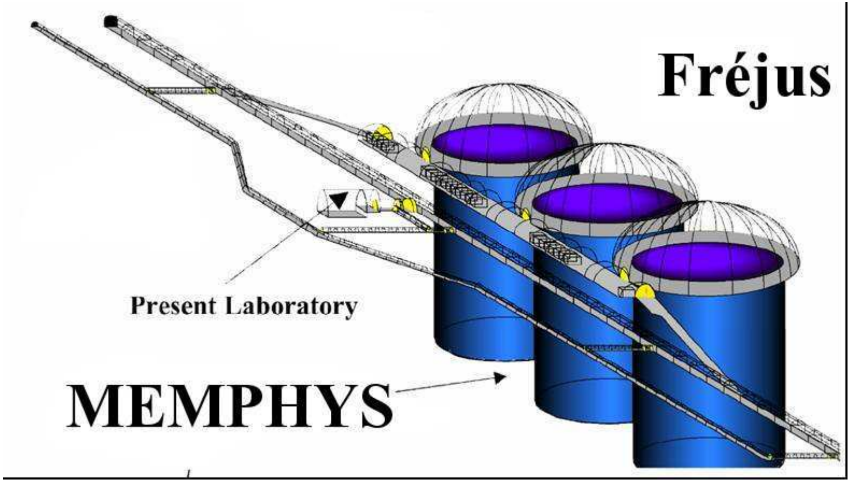


The CERN-MEMPHYS neutrino project

- **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;
- **Baseline**: 130 km (CERN $\longrightarrow$ Fréjus);
- **Detector**: 3×145 Kton water Cerenkov at Fréjus.

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

⋆ simulation of ATM data: same as SK, but with real detector geometry.



[Campagne, MM, Mezzetto, Schwetz, hep-ph/0603172]

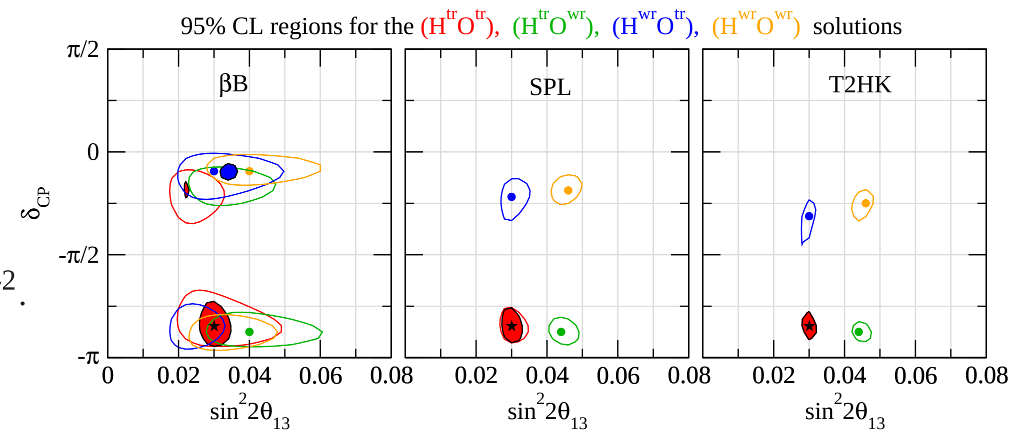
Resolving MEMPHYS degeneracies with ATM data

- **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**: only 4-fold degeneracy appears if spectrum information is used;

⇒ all degeneracies disappear after inclusion of ATM data.

- true values:

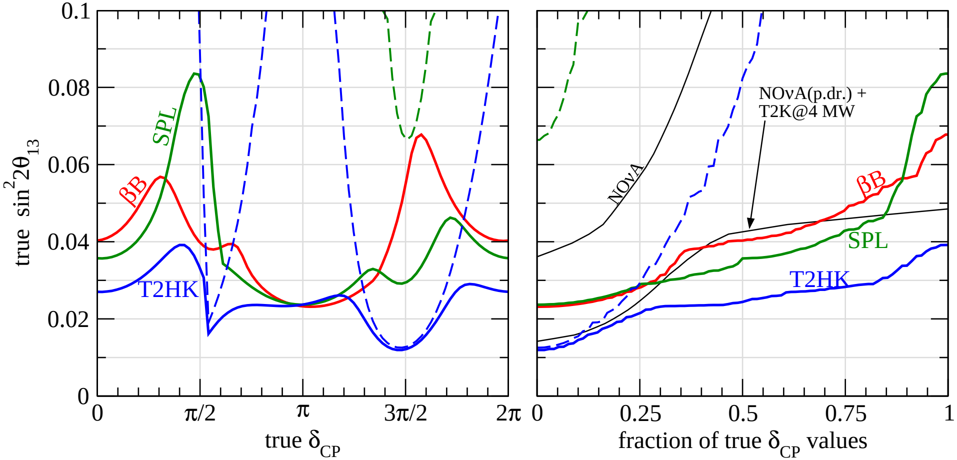
$$\delta_{CP} = -0.85\pi,$$
$$\sin^2 2\theta_{13} = 0.03,$$
$$\sin^2 \theta_{23} = 0.6,$$
$$\Delta m^2_{31} = +2.4\times 10^{-3}\ \mathrm{eV}^2.$$

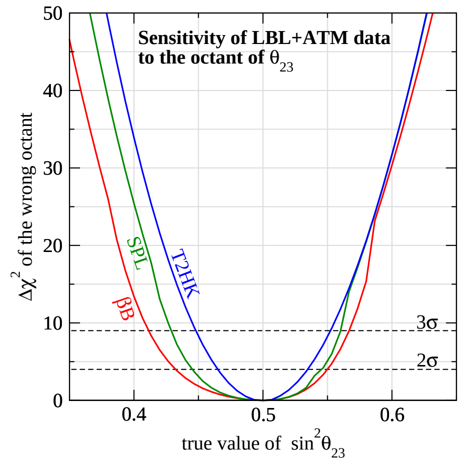


Determining the mass hierarchy and the octant with MEMPHYS

- With ATM data included, the sensitivity to the hierarchy for the MEMPHYS project (both βB and SPL setup) is comparable to that of T2HK;
- note 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 (preliminary).

2σ sensitivity to normal hierarchy from LBL + ATM data



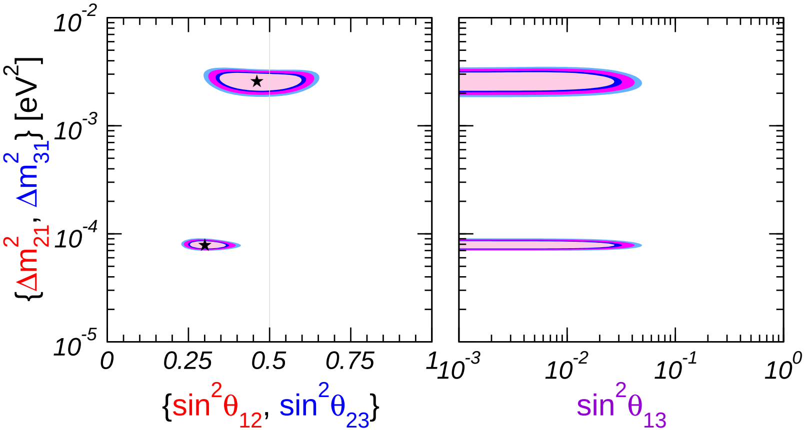


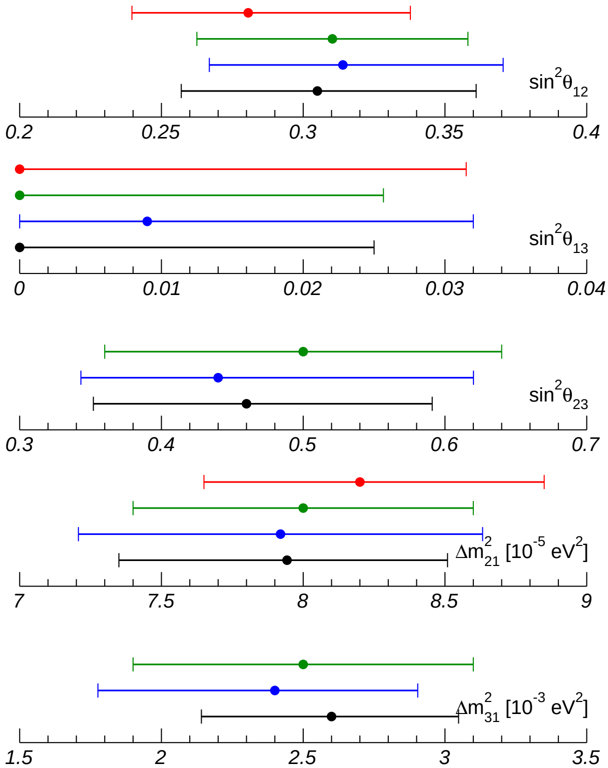
- Many proposals for future long-baseline neutrino experiments demand the construction of megaton detectors;
- these detectors will naturally be sensitive to atmospheric neutrinos as well;
- we have shown that ATM and LBL data will provide complementary information on the neutrino oscillation parameters. In particular:
  - LBL data will accurately determine $|\Delta m^2_{31}|$ and θ_{23}, and measure/bound θ_{13};
  - ATM data will provide unique information on the mass hierarchy and on the octant.
- the sensitivity to neutrino parameters achievable with combined ATM+LBL is considerably stronger than that of ATM and LBL data taken separately.

$\Rightarrow$ [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, hep-ph/0603172]

Present status of neutrino oscillations

- Experiments: solar, atmospheric (SK), reactor (Chooz+KamLAND), accelerator (K2K+Minos);
- ν pars: $\begin{cases} \theta_{12}, \Delta m^2_{21}, |\Delta m^2_{31}|: \textbf{measured}; \\ \theta_{13}, |\theta_{23} - \pi/4|: \textbf{bounded}; \\ \delta_{CP}, \text{hier}, \text{oct}, m_1, \phi_i: \textbf{unknown}. \end{cases}$
- each data set is relevant.





- Bahcall *et al.*, JHEP 0408 (2004) 016
- Strumia & Vissani, NPB 726 (2005) 294
- Fogli *et al.*, hep-ph/0506083
- this talk [see also NJP 6 (2004) 122]

Three-flavor effects in neutrino oscillations

Long-baseline experiments

- Appearance probability (in vacuum): $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ and $\Delta \equiv \Delta m^2_{31} L/(4E_\nu)$

$$P_{\nu_\mu \to \nu_e} \simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\Delta + \alpha^2 \Delta^2 \sin^2 2\theta_{12} \cos^2\theta_{23} + \alpha\Delta \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin\Delta \cos(\Delta \pm \delta_{CP}) ;$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31}, \quad \Delta = \Delta m^2_{31} L/(4E_\nu)$$

- for T2K, assume $|\Delta| \approx \pi/2$ and neglect α^2 term:

Octant: $\begin{cases} \sin^2 2\theta'_{13} \approx \sin^2 2\theta_{13} \tan^2\theta_{23}, \\ \sin\delta'_{CP} \approx \sin\delta_{CP} \tan\theta_{23}; \end{cases}$ **Hierarchy:** $\begin{cases} \theta'_{13} \approx \theta_{13}, \\ \delta'_{CP} \approx \pi - \delta_{CP}. \end{cases}$

Atmospheric neutrinos

- Excess of electron events: $\bar{r} \equiv \Phi^0_\mu / \Phi^0_e$

$$\begin{aligned} \delta_e \equiv N_e/N_e^0 - 1 \simeq & (\bar{r}\cos^2\theta_{23} - 1) P_{2\nu}(\Delta m^2_{21}, \theta_{12}) && [\Delta m^2_{21} \text{ term}] \\ & + (\bar{r}\sin^2\theta_{23} - 1) P_{2\nu}(\Delta m^2_{31}, \theta_{13}) && [\theta_{13} \text{ term}] \\ & - \bar{r} \sin\theta_{13} \sin 2\theta_{23} \, \mathrm{Re}(A^*_{ee} A_{\mu e}) . && [\delta_{CP} \text{ term}] \end{aligned}$$

Resolving parameter degeneracies

- **Octant** discrimination for $\theta_{13} \gtrsim 0.04$ is stronger for **true normal hierarchy**.