Resolving parameter degeneracies with atmospheric neutrinos

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We show that for long-baseline experiments using a Mton water Cherencov detector atmospheric neutrino data provide a powerful method to resolve parameter degeneracies. In particular, the combination of long-baseline and atmospheric data increases significantly the sensitivity to the neutrino mass hierarchy.

The aims of future neutrino experiments are the determination of the mixing angle θ_{13}, the CP-phase $\delta_{\rm CP}$, and the type of the neutrino mass hierarchy (normal or inverted). It is well known that parameter degeneracies are a severe problem on the way towards these goals. In Ref. [1] it was demonstrated that for LBL experiments based on Mton scale water Cherencov detectors data from atmospheric neutrinos (ATM) provide an attractive method to resolve degeneracies (for alternative possibilities see, e.g. [2]).

Atmospheric neutrinos are sensitive to the neutrino mass hierarchy if θ_{13} is sufficiently large due to Earth matter effects, mainly in multi-GeV e-like events [3]. Moreover, sub-GeV e-like events provide sensitivity to the octant of θ_{23} [4,5] due to oscillations with Δm^2_{21}. (See also [6] for a discussion of atmospheric neutrinos.) However, these effects can be explored efficiently only if LBL data provide a very precise determination of $|\Delta m^2_{31}|$ and $\sin^2 2\theta_{23}$, as well as some information on θ_{13} [1].

Here we illustrate the synergies from a combined LBL+ATM analysis at the examples of the T2K phase II experiment [7] with the HK detector of 450 kton fiducial mass, and two experiments with beams from CERN to a 450 kton detector at Frejus, namely the SPL super beam [8] and a beta beam [9]. The LBL experiments are simulated with the GLoBES software [10], and a general three-flavour analysis of ATM data is performed based on [5] and references therein. For each experiment we assume a running time of 10 years, where the neutrino/antineutrino time is chosen as 2+8 years for SPL and T2K, and 5+5 years for the beta beam.

The effect of degeneracies becomes apparent in Fig. 1. For given true parameter values the data can be fitted with the wrong hierarchy and/or with the wrong octant of θ_{23}. Hence, from LBL data alone the hierarchy and the octant cannot be determined. Moreover, as visible from the solid lines in Fig. 1 the degenerate solutions appear at parameter values different from the true ones, an hence, ambiguities exist in the determination of θ_{13} and $\delta_{\rm CP}$. If the LBL data are combined with ATM data only the colored regions in Fig. 1 survive, i.e., in this particular example for all three experiments the degeneracies are completely lifted at 95% CL, the mass hierarchy and the octant of θ_{23} can be identified, and the ambiguities in θ_{13} and $\delta_{\rm CP}$ are resolved. Let us note that here we have chosen a favourable value of $\sin^2\theta_{23} = 0.6$; for values $\sin^2\theta_{23} < 0.5$ in general the sensitivity of ATM data is weaker [1].

In Fig. 2 we discuss the sensitivity to the neutrino mass hierarchy. For LBL data alone (solid lines) there is practically no sensitivity for the CERN-Frejus experiments (because of the very small matter effects due to the relatively short baseline), and the sensitivity of T2K depends strongly on the true value of $\delta_{\rm CP}$. Also ATM-only (dashed lines) has a very poor sensitivity. However, with the LBL+ATM combination (shaded regions) all experiments can identify the mass hierarchy at 2σ CL provided $\sin^2 2\theta_{13} \gtrsim 0.03-0.05$, where for the CERN experiments the sensitivity shows somewhat more dependence on the true value of $\delta_{\rm CP}$.

*T.S. is supported by the VI Framework Programme of the EC under a Marie Curie Intra-European Fellowship.

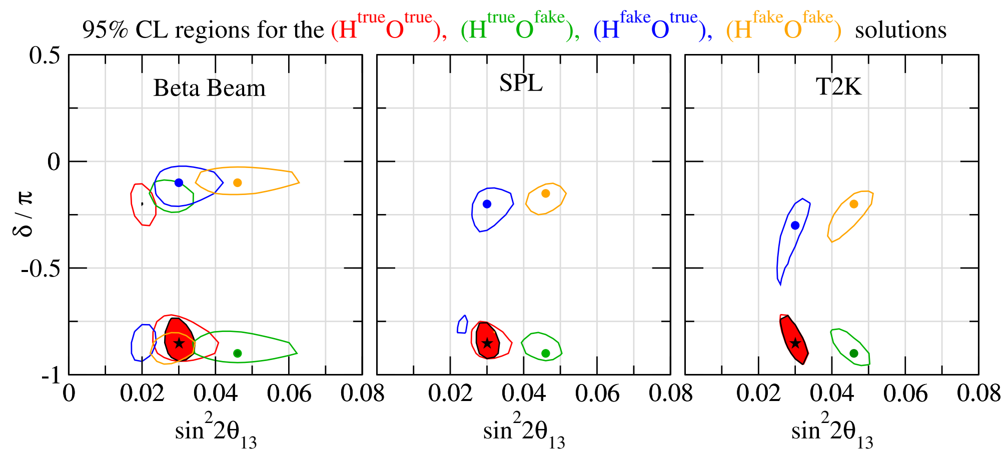

Figure 1. Allowed regions in $\sin^2 2\theta_{13}$ and $\delta_{\rm CP}$ for LBL data alone (contour lines) and LBL+ATM data combined (colored regions). The true parameter values are $\delta_{\rm CP} = -0.85\pi$, $\sin^2 2\theta_{13} = 0.03$, $\sin^2\theta_{23} = 0.6$. $\rm H^{true/fake}(O^{true/fake})$ refers to solutions with the true/fake mass hierarchy (octant of θ_{23}).

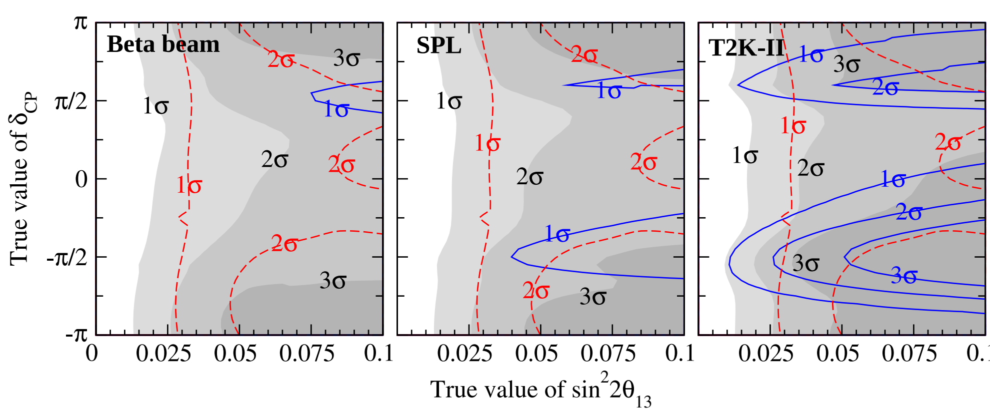

Figure 2. Sensitivity to the mass hierarchy as a function of the true values of $\sin^2 2\theta_{13}$ and $\delta_{\rm CP}$ for $\theta_{23}^{\rm true} = \pi/4$ and a true normal hierarchy. Shown are the contours corresponding to a rejection of the wrong hierarchy at the 1, 2, and 3σ CL (from light to dark shading). The shaded regions correspond to LBL+ATM data combined, solid curves correspond to LBL-only, and dashed curves to ATM-only.

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