Atmospheric neutrinos
in a megaton-class Water Cerenkov detector

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I. **Introduction: atmospheric neutrino data**

II. **Discussion: sensitivity to oscillation parameters**

III. **Results: synergies with long-baseline experiments**

Conclusions

Atmospheric neutrinos

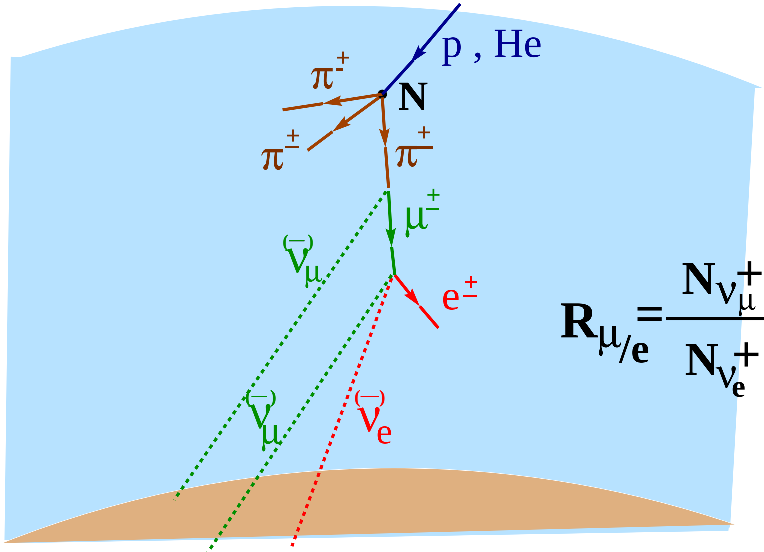
- Atmospheric neutrinos are produced by the interaction of *cosmic rays* (p, He, ...) with the Earth's atmosphere:

1 $A_{\rm cr} + A_{\rm air} \to \pi^\pm, K^\pm, K^0, \ldots$

2 $\pi^\pm \to \mu^\pm + \nu_\mu$,

3 $\mu^\pm \to e^\pm + \nu_e + \nu_\mu$;

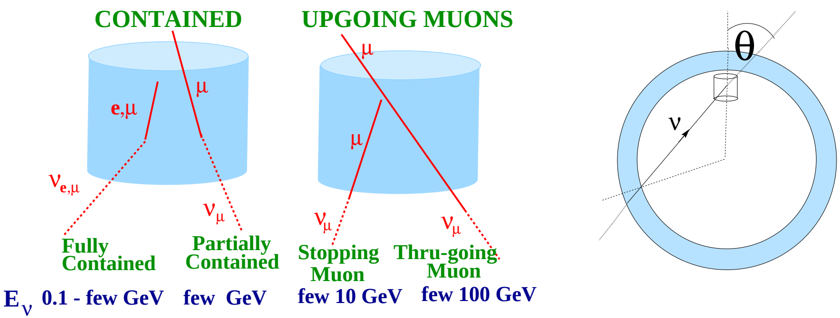
- at the detector, some ν interacts and produces a **charged lepton**, which is observed.

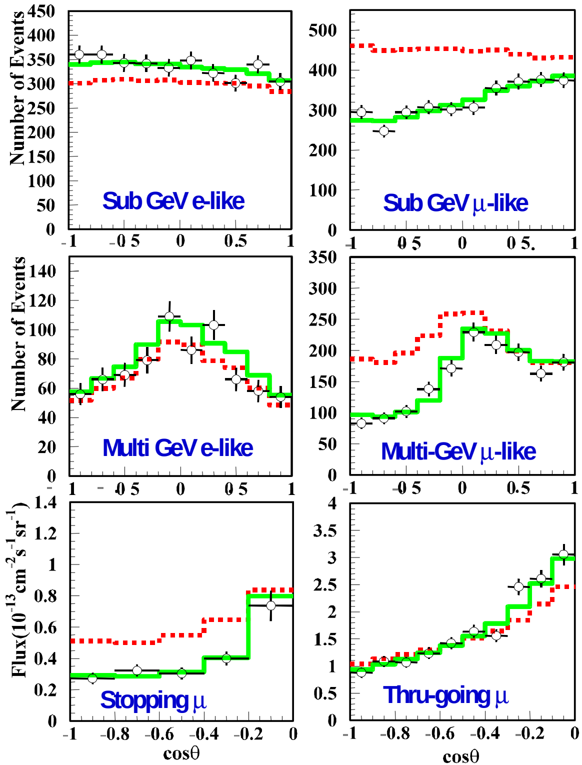


$$R_{\mu/e} = \frac{N_{\nu_\mu} + N_{\bar\nu_\mu}}{N_{\nu_e} + N_{\bar\nu_e}} \sim 2$$

Super-Kamiokande and 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:
  - grows with L;
  - decreases with E_ν;
- data agree with $\nu_\mu \to \nu_\tau$ oscillations (green line).





Physics content of atmospheric data

$$N_{\text{bin}}(\vec{\omega}) = n_t T \sum_{\alpha,\beta,\pm} \int_0^\infty dh \int_{-1}^{+1} dc_\nu \int_{E_{\min}}^\infty dE_\nu \int_{E_{\min}}^{E_\nu} dE_l \int_{-1}^{+1} dc_a \int_0^{2\pi} d\varphi_a$$
$$\frac{d^3\Phi_\alpha^\pm}{dE_\nu\, dc_\nu\, dh}(E_\nu, c_\nu, h)\, P_{\alpha\to\beta}^\pm(E_\nu, c_\nu, h \,|\, \vec{\omega})\, \frac{d^2\sigma_\beta^\pm}{dE_l\, dc_a}(E_\nu, E_l, c_a)\, \varepsilon_\beta^{\text{bin}}(E_l, c_l(c_\nu, c_a, \varphi_a))$$

- Atmospheric ν data are a convolution of neutrino fluxes, oscillation parameters $\vec{\omega}$, Earth matter density profile, cross-sections and details of the detector;
- we want to extract information on the oscillation parameters $\vec{\omega}$;
- ν fluxes, Earth profile, cross-sections and the detector are **source of uncertainties**.

Good

- baseline: $10 \to 10^4$ km;
- energy: $0.1 \to 10^4$ GeV;
- *huge statistics* and *large matter effects*.

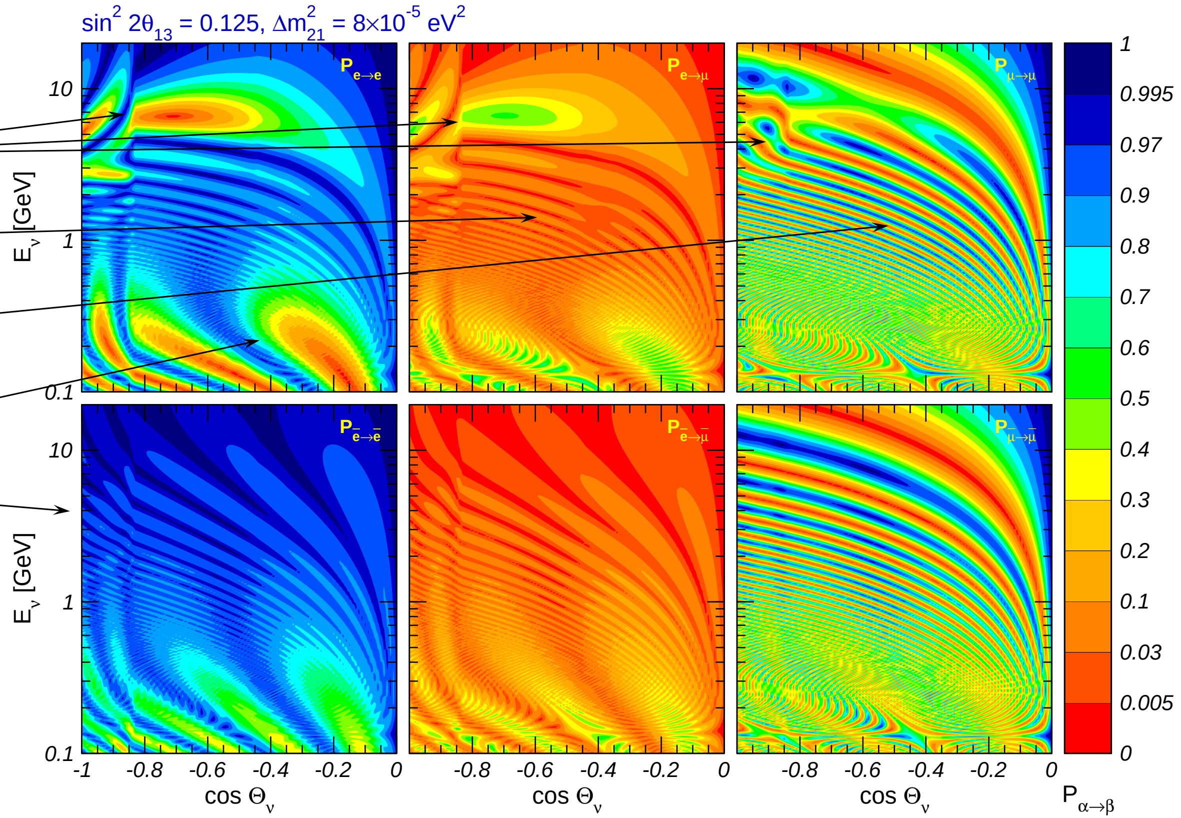
Bad

- no “front detector” $\Rightarrow$ *huge systematics*;
- poor accuracy in ν *energy and direction*;
- only $\nu + \bar{\nu}$ without magnetized detector.

Atmospheric neutrinos: a laboratory for neutrino oscillations

Sensitivity to:

- θ_{13}
- δ_{CP}
- $|\Delta m^2_{31}|$, $|D_{23}|$
- Δm^2_{21}, θ_{12}, sgn(D_{23})
- sgn(Δm^2_{31})

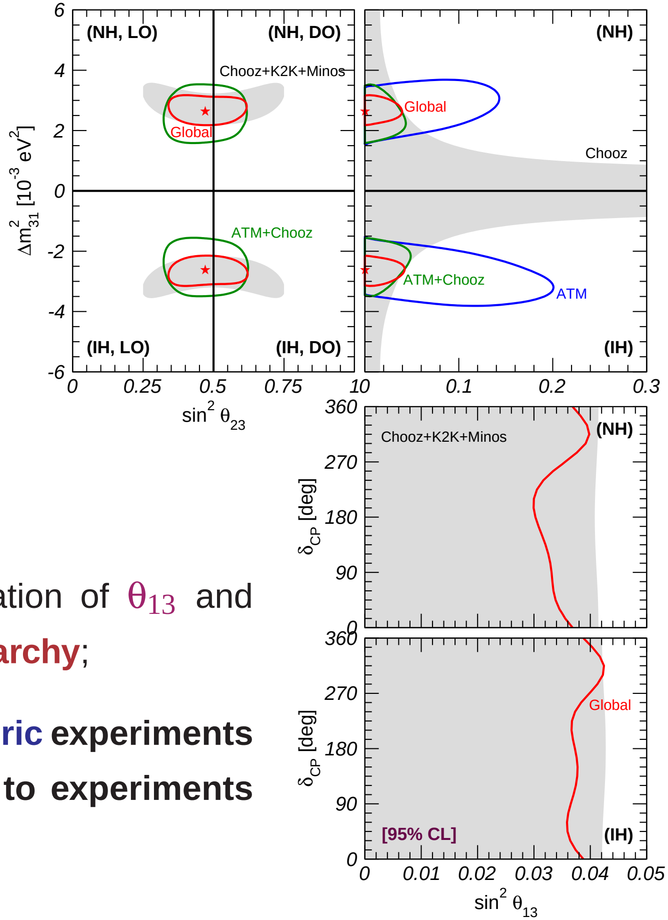


In principle, each ν oscillation parameter leaves its signature in ATM probabilities

Sensitivity of present data

- The potentialities of ATM experiments are already visible in **present** data:
  - θ_{13}: weak but definite bound;
  - **octant**: shift from maximal mixing;
  - **hierarchy**: impact on θ_{13} bound;
  - **CP phase**: impact on θ_{13} bound;
- LBL (grey regions) dominate the determination of θ_{13} and $|\Delta m^2_{31}|$ but are insensitive to **octant** and **hierarchy**;

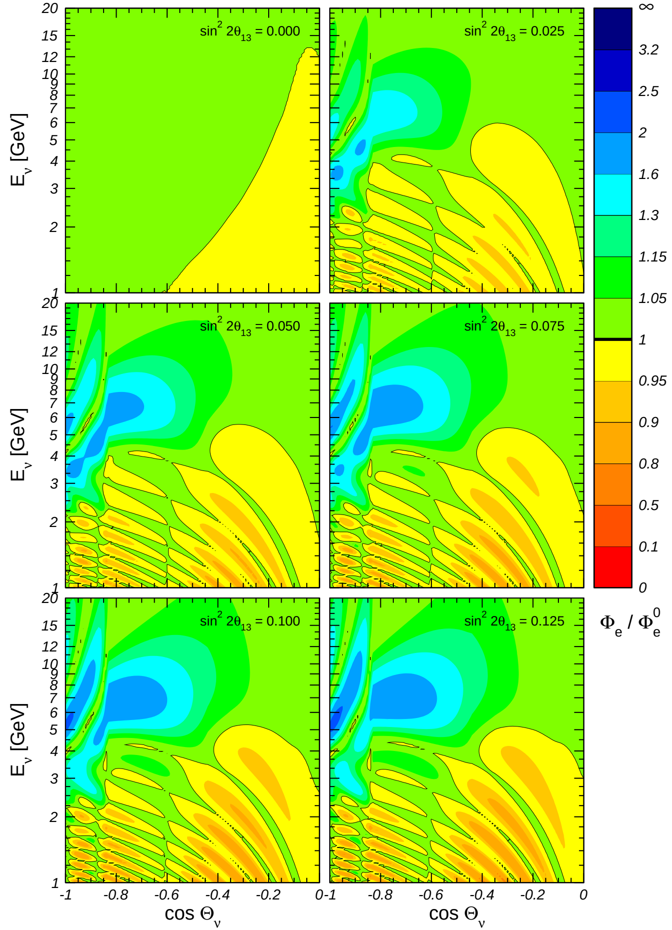
⇒ **present data suggest that future atmospheric experiments may provide complementary information to experiments using man-made neutrinos.**



Sensitivity to θ_{13}

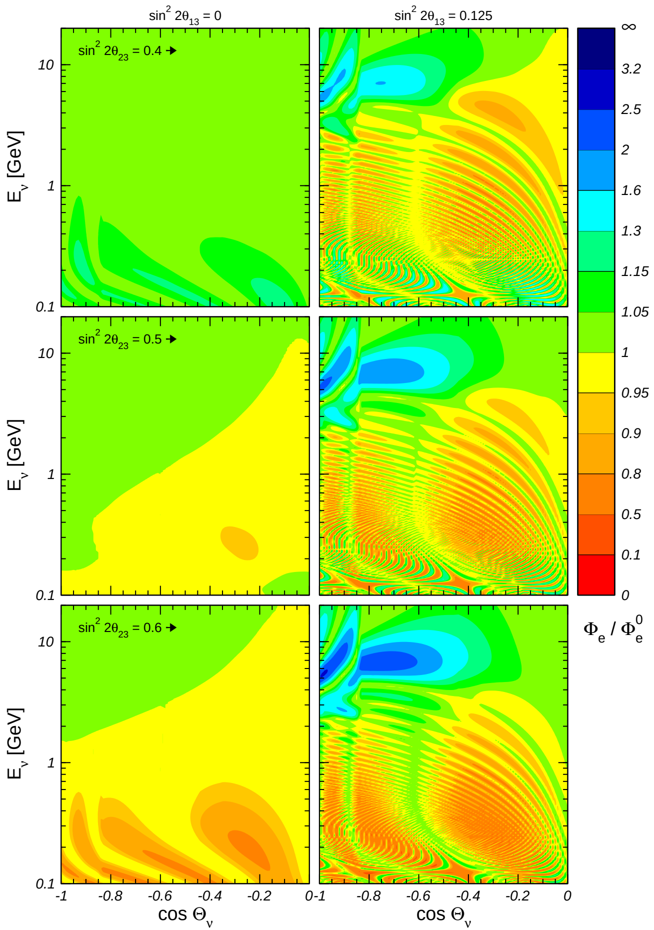
- In principle, θ_{13} can be measured by observing the MSW & parametric resonances;
- in practice, the sensitivity is limited by:
  - *statistics*: at $E_\nu \sim 6$ GeV the ATM flux is already suppressed;
  - *background*: the $\nu_e \to \nu_e$ events strongly dilute the $\nu_\mu \to \nu_e$ signal;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

⇒ sensitivity to θ_{13} will **not** be competitive with dedicated LBL 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** $\bar{\nu}$.



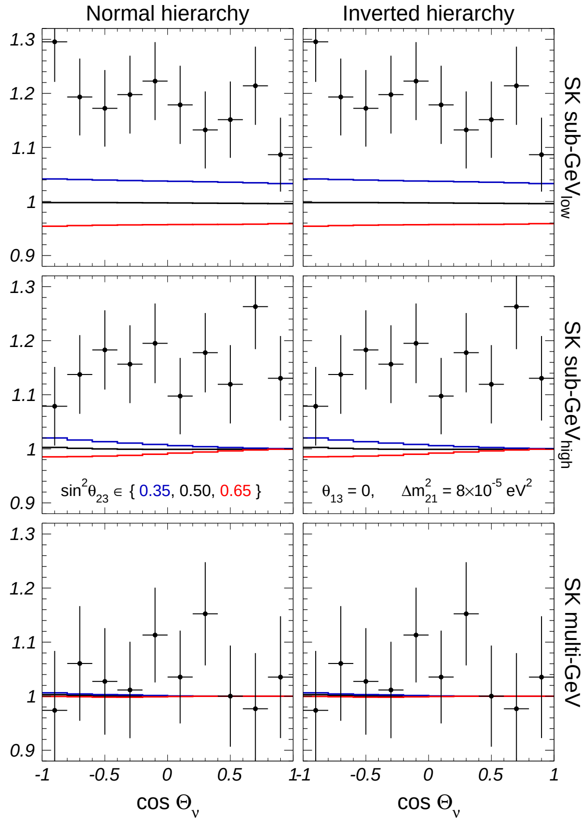
Octant discrimination: pure Δm^2_{21} effects

- 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.



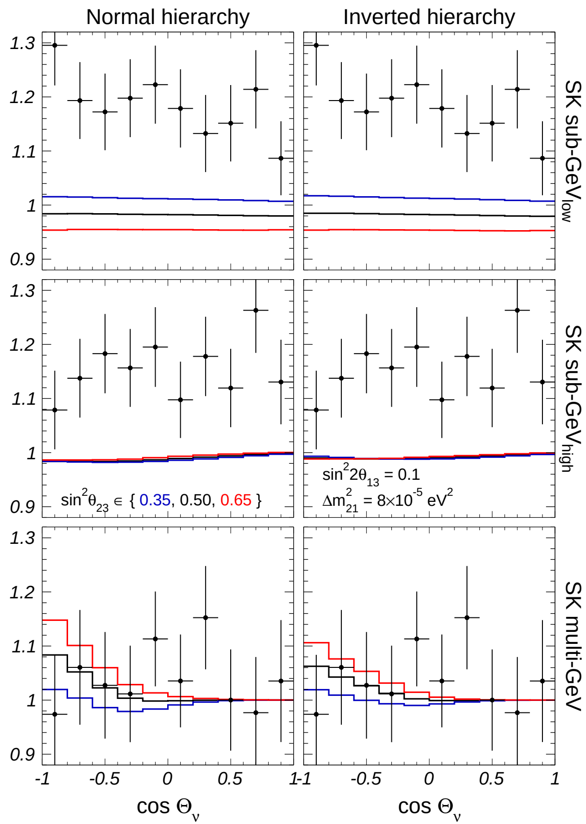
Octant discrimination: θ_{13} effects

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

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

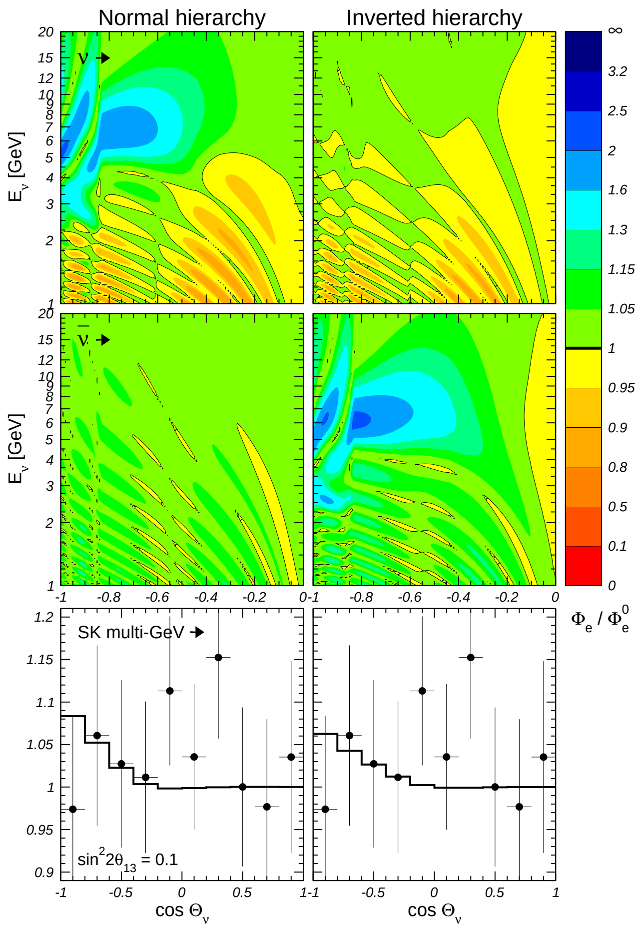
- for **sub-GeV** effect of Δm^2_{21} is diluted by θ_{13};
- for **multi-GeV** resonance in $P_{2\nu}(\Delta m^2_{31}, \theta_{13}) \Rightarrow$ enhancement of ν ($\bar{\nu}$) oscillations for normal (inverted) hierarchy;
- more ν than $\bar{\nu}$ events $\Rightarrow$ sensitivity enhancement is larger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

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



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 poor**.



Single-ring versus multi-ring events

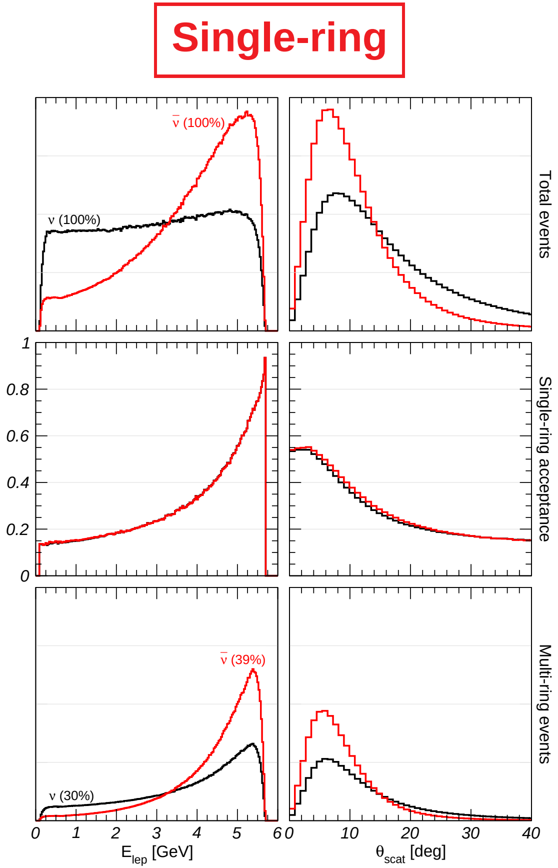
- Qualitatively, a neutrino scattering off a nucleon can transfer **a little** or **a lot** of its momentum to the nucleon. This lead to different signatures in the detector:

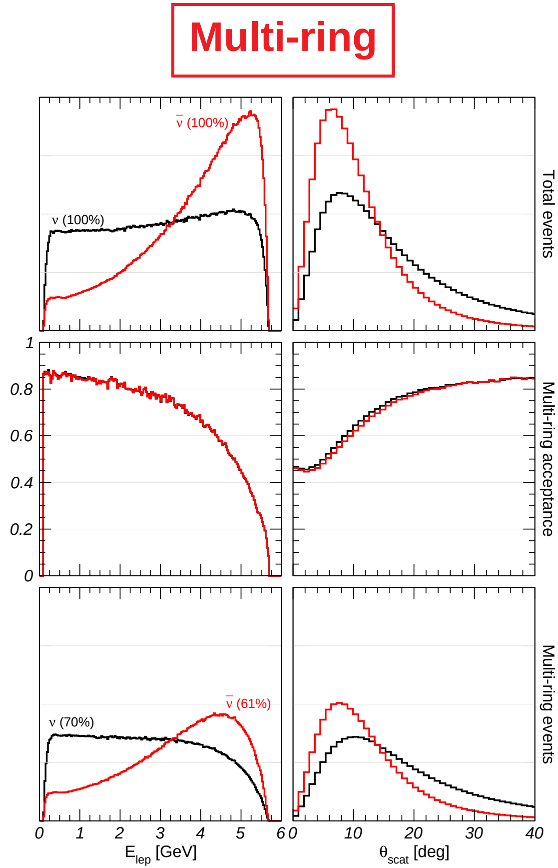
Small momentum transfer

- the scattering angle will be small;
- the final lepton will carry most of the incoming ν energy;
- the final hadronic system will have little energy & particles $\Rightarrow$ has higher chances to escape the ring-detection algorithm;
- this type of events has higher probability of being tagged as *single-ring*;
- only one track $\Rightarrow$ event is relatively clean.

Large momentum transfer

- the scattering angle tend to be large;
- the final lepton will carry only a fraction of the incoming ν energy;
- the final hadronic system will have a lot of energy & particles $\Rightarrow$ will probably produce a visible signature;
- this type of events has higher probability of being tagged as *multi-ring*;
- many tracks $\Rightarrow$ event is “messy”.





- Different $\nu/\bar{\nu}$ content $\Rightarrow$ combination allow **charge separation** at statistical level.

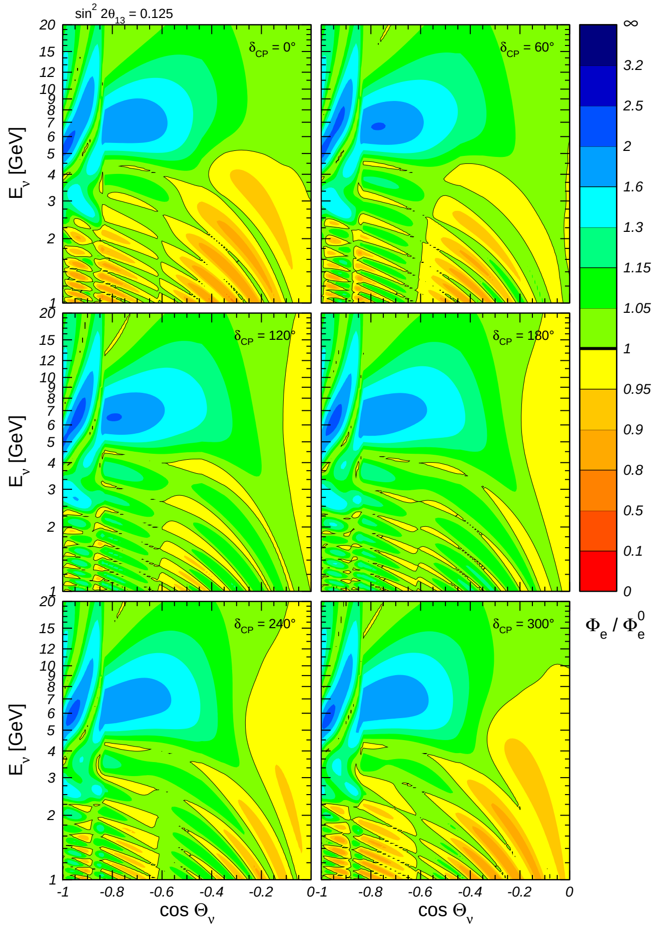
Sensitivity to the CP phase

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

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

- mainly visible in the **intermediate-energy** region: $1\text{ GeV} < E_\nu < 3\text{ GeV}$;
- present for both ν **AND** $\bar{\nu}$;
- affected by **everything**: θ_{13}, θ_{23}, octant, mass hierarchy, … $\Rightarrow$ effects hard to disentangle;

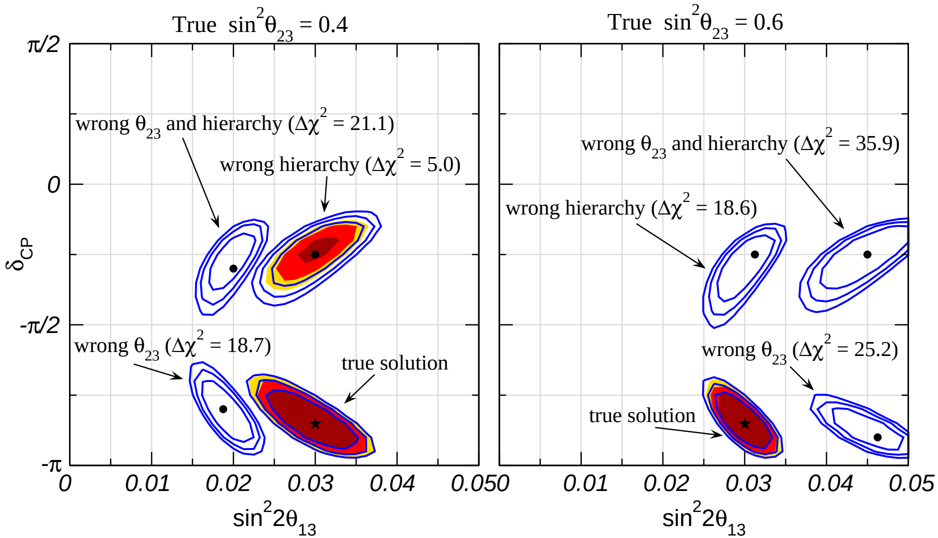
⋆ **present talk**: effects of $\delta_{\rm CP}$ on other parameters included, **BUT** no systematic study of ATM sensitivity to $\delta_{\rm CP}$ itself (left for future work).



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.

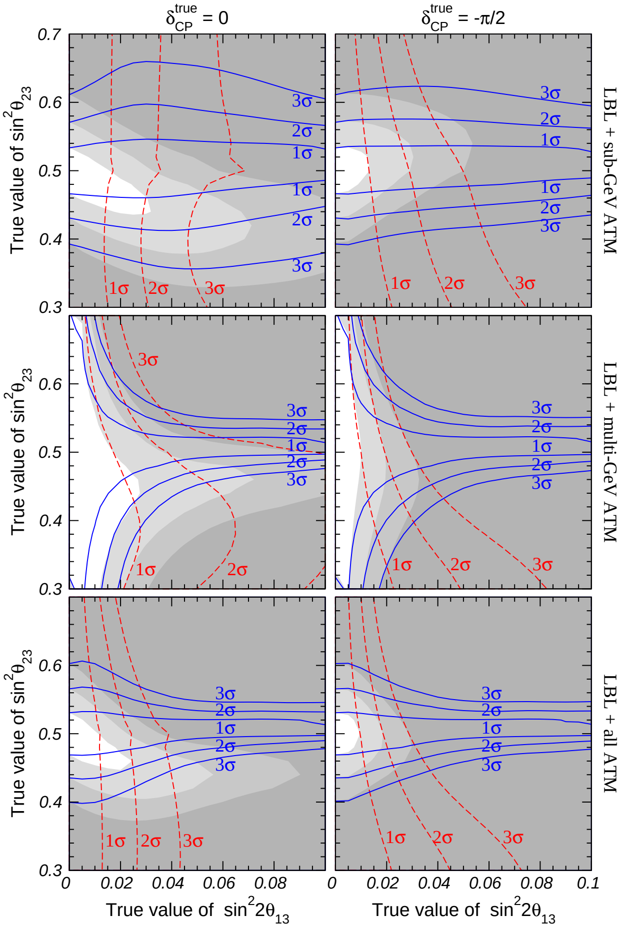
- **solid**: LBL only;
- **colored**: LBL + ATM;
- regions at 2σ, 99%, 3σ CL (2 dof);
- true values:
  $\delta_{CP} = -0.85\pi$,
  $\sin^2\theta_{13} = 0.03$,
  $\Delta m^2_{31} = 2.2 \times 10^{-3}\ \mathrm{eV}^2$,
  $\Delta m^2_{21} = 7.9 \times 10^{-5}\ \mathrm{eV}^2$.



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

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.



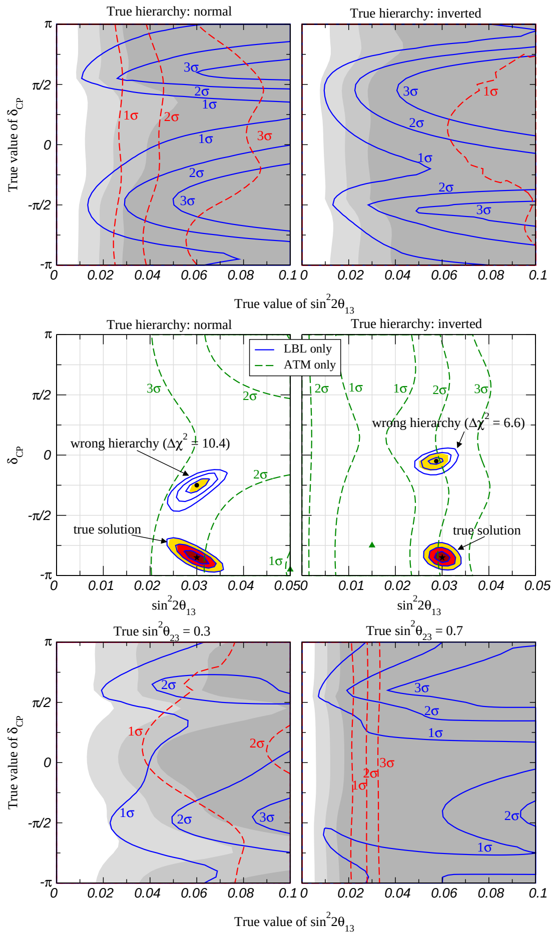
Determining the mass hierarchy

- 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;

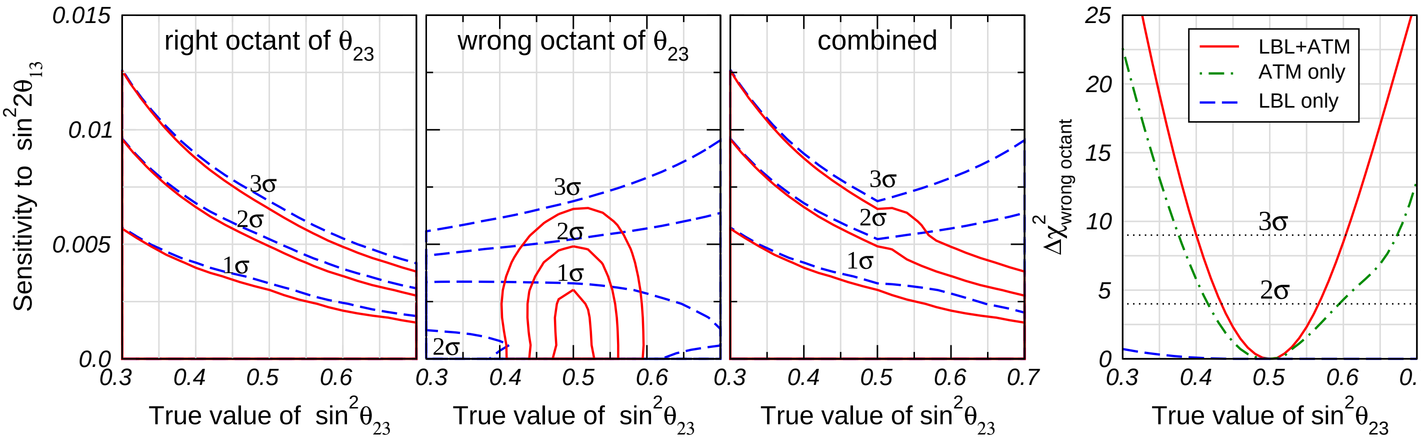
Non-maximal θ_{23}

- 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.



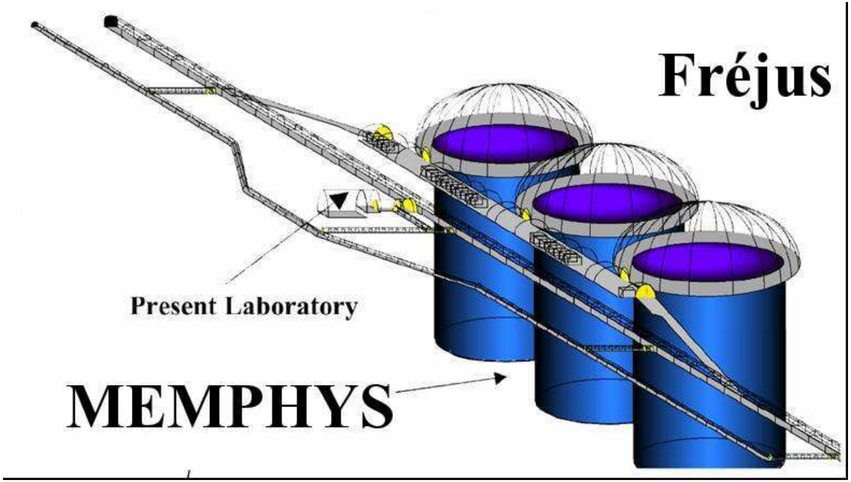
The CERN-MEMPHYS neutrino project

- **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]



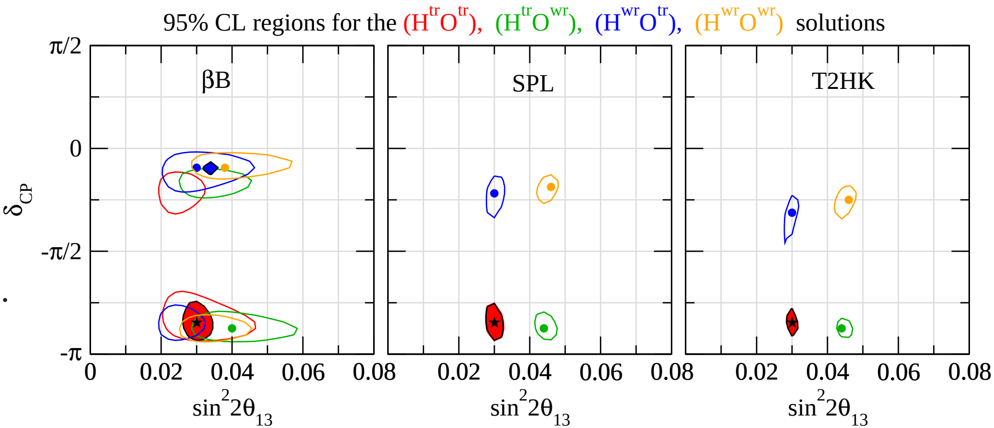
Resolving MEMPHYS degeneracies with ATM data

- **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;

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

- true values:

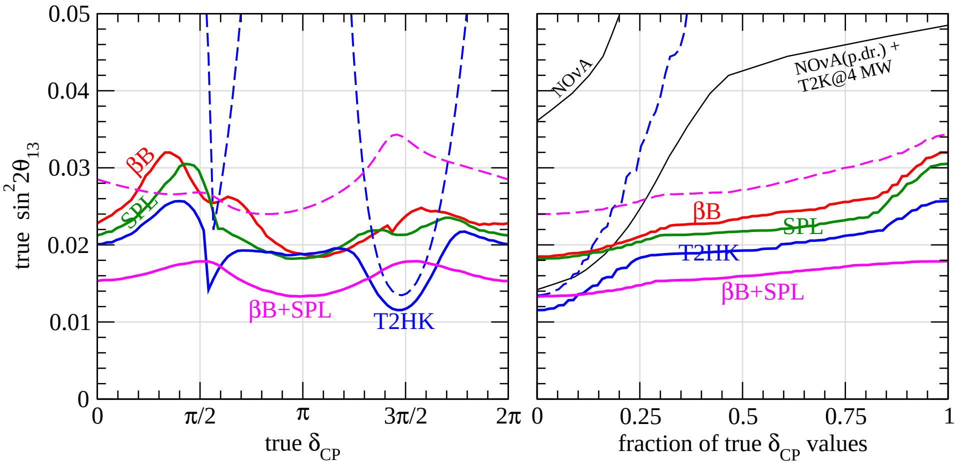
$$\delta_{CP} = -0.85\pi,$$
$$\sin^2 2\theta_{13} = 0.03,$$
$$\sin^2\theta_{23} = 0.6,$$
$$\Delta m^2_{31} = +2.4 \times 10^{-3}\ \text{eV}^2.$$

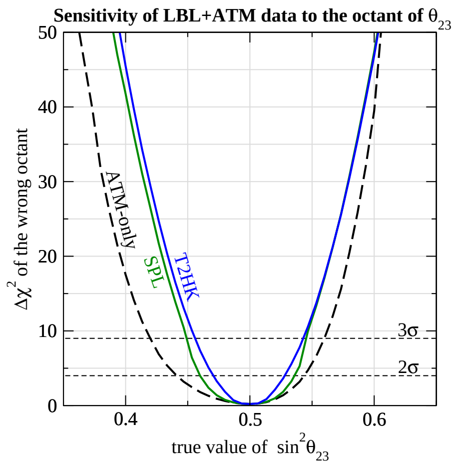


Determining the mass hierarchy and the octant with MEMPHYS

- 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).

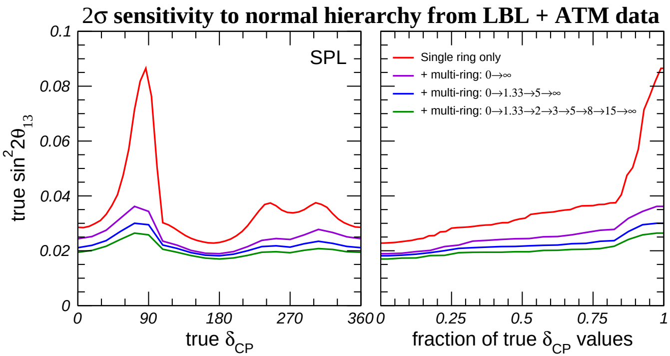
2σ sensitivity to normal hierarchy from LBL + ATM data

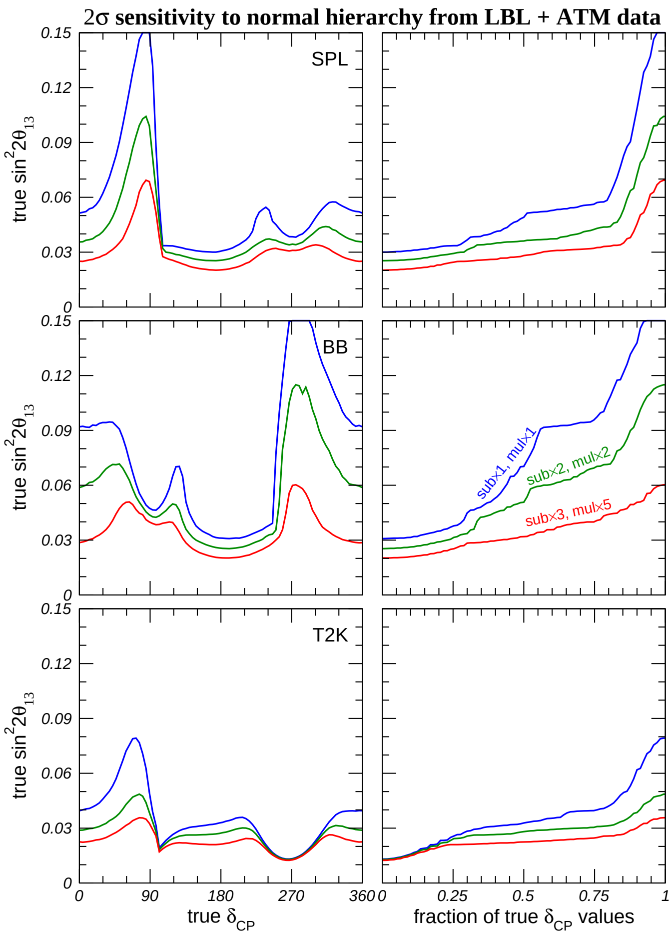




Energy binning and multi-ring

- 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.





- 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]
[Akhmedov, MM, Smirnov, in preparation]

Three-flavor effects in neutrino oscillations

Long-baseline experiments

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

$$P_{\nu_\mu \to \nu_e} \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta + \alpha^2 \Delta^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \qquad \alpha = \Delta m^2_{21}/\Delta m^2_{31},$$
$$+ \alpha \Delta \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin\Delta \cos(\Delta \pm \delta_{CP}) \; ; \qquad \Delta = \Delta m^2_{31} L/(4E_\nu)$$

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

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

Atmospheric neutrinos

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

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

Resolving parameter degeneracies

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