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RESOLVING DEGENERACIES BETWEEN CP-δ and θ_{13}

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THERE ARE THREE SOURCES OF DEGENERACIES:

INTRINSIC

SIGN Δm^2_{13}-AMBIGUITY

θ_{23},($\pi/2 - \theta_{23}$)-AMBIGUITY (if $\theta_{23} \neq 45°$)

- **ASSUME THAT (θ_{13}, δ) ARE THE TRUE (NATURE) VALUES IN $P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)}$**

- **(θ'_{13}, δ') ARE FAKE SOLUTIONS OF:**

$$\left.\begin{array}{l} P'_{\nu_e \nu_\mu}(\theta'_{13}, \delta') = P_{\nu_e \nu_\mu}(\theta_{13}, \delta) \\ P'_{\bar{\nu}_e \bar{\nu}_\mu}(\theta'_{13}, \delta') = P_{\bar{\nu}_e \bar{\nu}_\mu}(\theta_{13}, \delta) \end{array}\right\}$$

WHERE P' DIFFERS IN EACH CASE

WE EXPAND AT SECOND ORDER IN Δm^2_{12} and θ_{13},

IN VACUUM APPROXIMATION:

$$P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} = s^2_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{13} L}{4E}$$

$$+\ c^2_{23} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L}{4E}$$

$$+\ \tilde{J} \cos\left(\pm\delta - \frac{\Delta m^2_{13} L}{4E}\right) \frac{\Delta m^2_{12} L}{4E} \sin \frac{\Delta m^2_{13} L}{4E}$$

$$\tilde{J} \equiv \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12}.$$

ONE CAN RESOLVE MOST OF THEM

BY EXPLOITING

THE DIFFERENT E_ν, L DEPENDANCE

SUPER BEAMS AND NUFACT

ARE TWO PLANNED STEPS

OF OSCILLATION ν-PHYSICS

NOT TWO DIFFERENT ALTERNATIVES

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NUFACT'S DESIGN REQUIRES A

PROTON ACCELERATOR

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HIGH-INTENSITY ν BEAMS:

A SUPER BEAM FACILITY

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WE SHOULD COMBINE

THEIR EXPECTED RESULTS

χ^2 FITS TO δ AND θ_{13}

3 **baselines** : S-beams(130 Km), Nufact(732 Km,2810 Km)

Nufacts'setup 10^{21} (μ^+,μ^-) of 50 GeV (five bins of 10 GeV)[a]

Realistic efficiencies and backgrounds have been included for a 40 Kton iron magnetized calorimeter detector.[b]

For E_ν's > 10 GeV, efficiencies typically of order 50%.

For E_ν's < 10 GeV, very low efficiencies.

Super Beams'setup CERN SPL 4MW 10^{23} POT/yr of 2.2 GeV, 2 years run with π^+'s and 10 years run with π^-'s [c]

400 Kton Water Cherenkov detector and efficiencies$\sim 70\%$.

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[a] A.Cervera *et al.*,Nucl.Phys. **B579** (2000) 17

[b] A. Cervera, F. Dydak and J. Gomez Cadenas, Nucl. Instrum. Meth. A **451** (2000) 123.

[c] J. J. Gomez-Cadenas *et al.* [CERN working group on Super Beams Collaboration], arXiv:hep-ph/0105297

χ^2 FITS TO δ AND θ_{13}

OSCILLATION PARAMETERS IN THE LMA-MSW SCENARIO:

- $|\Delta m^2_{12}| = 10^{-4}$ eV^2,
  - $|\Delta m^2_{23}| = 3 \times 10^{-3}$ eV^2,
  - $\sin 2\theta_{12} = \sin 2\theta_{23} = 1.$

THE SMALL EXPECTED UNCERTAINTIES IN THESE

PARAMETERS NOT INCLUDED YET.

χ^2 FITS TO δ AND θ_{13}

- The χ^2 for a fixed baseline is:

$$\chi^2_\lambda = \sum_{i,j} \sum_{p,p'} (n^\lambda_{i,p} - N^\lambda_{i,p}) C^{-1}_{i,p:,j,p'} (n^\lambda_{j,p'} - N^\lambda_{j,p'}) \, ,$$

- $N^\lambda_{i,\pm}$ is the number of wrong–sign muons in five bins of energy for both beam polarities.

  $n^\lambda_{i,p}$ are the simulated "data" from a Gaussian or Poisson smearing including backgrounds and efficiencies.

  C is the $2N_{bin} \times 2N_{bin}$ covariance matrix, that contained only statistical errors.

INTRINSIC ($\theta_{13}^{'}$, $\delta^{'}$) DEGENERACIES

IN VACUUM APPROXIMATION,

$$\theta_{13} \text{ large} \begin{cases} \delta^{'} = \pi - \delta, \\ \theta_{13}^{'} \sim \theta_{13} + \cos\delta \ \cot\theta_{23} \ \sin 2\theta_{12} \ \cot \frac{\Delta m_{13}^2 L}{4E} \ \frac{\Delta m_{12}^2 L}{4E} \ . \end{cases}$$

$$\theta_{13} \to 0^\circ \begin{cases} \delta^{'} \sim \pi \text{ or } 0, \\ \theta_{13}^{'} \sim |\cot\theta_{23} \ \sin 2\theta_{12} \ \cot \frac{\Delta m_{13}^2 L}{4E} \ \frac{\Delta m_{12}^2 L}{4E}| \end{cases}$$

INTRINSIC DEGENERACIES ARE $< E_\nu >$, L DEPENDENT

INTRINSIC (θ'_{13}, δ') DEGENERACIES

	$< E_\nu > (GeV)$	$L(km)$	$\cot \frac{\Delta m^2_{13} L}{4E}$
SUPERBEAMS CERN-SPL	0.25	130	-0.43
JHF/off-axis beam	0.7	295	-0.03
NUFACT@732	50	732	$+10.7$
NUFACT@2810	50	2810	$+2.68$
BETABEAMS	0.35	130	$+0.17$

FAKE SOLUTIONS FOR SUPER BEAMS AND NUFACTS GET DIFFERENT DISPLACEMENTS

DEGENERACIES DISAPPEAR IN THE COMBINATIONS!

SIGN OF Δm^2_{13} DEGENERACIES

NATURE HAS CHOSEN A GIVEN SIGN FOR Δm^2_{13}

BUT DATA ANALYSIS PERFORMED WITH THE OPPOSITE SIGN:

$$P'_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s^2_{23}\ \sin^2 2\theta'_{13}\ \sin^2 \frac{\Delta m^2_{13} L}{4}$$

$$+\ c^2_{23}\ \sin^2 2\theta_{12}\ \sin^2 \frac{\Delta m^2_{12} L}{4E}$$

$$-\ \tilde{J}'\ \cos\left(\pm\delta' + \frac{\Delta m^2_{13} L}{4E}\right)\ \frac{\Delta m^2_{12} L}{4E} \sin \frac{\Delta m^2_{13} L}{4E}$$

SIGN of Δm^2_{13} DEGENERACIES

IN VACUUM, APPROXIMATE SYMMETRY: $P^{'} \sim P(\delta \to \pi - \delta)$

$$\begin{cases} \delta^{'} = \delta, \\ \theta^{'}_{13} \sim \theta_{13} + \cos\delta \;\; \cot\theta_{23} \;\sin 2\theta_{12} \;\cot \frac{\Delta m^2_{13} L}{4E} \frac{\Delta m^2_{12} L}{4E} \;, \end{cases}$$

$$\begin{cases} \delta^{'} = \pi - \delta, \\ \theta^{'}_{13} \sim \theta_{13} \;, \end{cases}$$

$$\begin{cases} \delta^{'} \sim 0 \text{ or } \pi, \\ \theta^{'}_{13} \sim \left| \cot\theta_{23} \;\sin 2\theta_{12} \;\cot \frac{\Delta m^2_{13} L}{4E} \frac{\Delta m^2_{12} L}{4E} \right|. \end{cases}$$

- THE SURVIVAL OF ANY OF THESE SOLUTIONS IMPLIES THAT THE SIGN CAN NOT BE MEASURED.
- THE SURVIVAL OF 1 DOES NOT AFFECT THE MEASUREMENT OF θ_{13} AND CP VIOLATION.
- SOLUTION 2 IS $< E_\nu >, L$ DEPENDENT.

SIGN of Δm^2_{13} DEGENERACIES

MATTER EFFECTS ARE VERY IMPORTANT!

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NO SOLUTIONS SURVIVE AT NUFACT@2810 km

FOR LARGE θ_{13}

$\theta_{23},\ \pi/2-\theta_{23}$ DEGENERACIES

DISAPPEARANCE EXP.: $\sin^2 2\theta_{23} \rightarrow$ ¿ $\theta_{23} \leftrightarrow \pi/2-\theta_{23}$?

SK results (90% C.L) $\sin^2 2\theta_{23} > 0.88 \rightarrow 35^\circ \lesssim \theta_{23} \lesssim 55^\circ$

$$P'_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = c_{23}^2 \sin^2 2\theta'_{13} \sin^2 \frac{\Delta m^2_{13} L}{4}$$

$$+\ s_{23}^2 \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L}{4E}$$

$$+\ \tilde{J}' \cos\left(\pm\delta' - \frac{\Delta m^2_{13} L}{4E}\right) \frac{\Delta m^2_{12} L}{4E} \sin \frac{\Delta m^2_{13} L}{4E}$$

$\theta_{23},\ \pi/2-\theta_{23}$ DEGENERACIES

IN VACUUM

$$\theta_{13}\ \text{large}\ \begin{cases} \sin\delta' = \cot\theta_{23}\ \sin\delta, \\ \theta'_{13} \sim \tan\theta_{23}\ \theta_{13}. \end{cases}$$

$$\theta_{13}\to 0^\circ \begin{cases} \left.\begin{cases} \text{if }\cot 2\theta_{23} > 0 \text{ then } \delta' \sim 0 \\ \text{if }\cot 2\theta_{23} < 0 \text{ then } \delta' \sim \pi \end{cases}\right\} \theta'_{13} \sim |\cot 2\theta_{23}|\ \sin 2\theta_{12}\ \dfrac{\frac{\Delta m^2_{12} L}{4E}}{\sin 2\frac{\Delta m^2_{13} L}{4E}}. \\ \begin{cases} \delta' \sim \pi, \\ \theta'_{13} \sim \tan\theta_{23}\ \sin 2\theta_{12}\ \cot\frac{\Delta m^2_{13} L}{4E}\ \frac{\Delta m^2_{12} L}{4E}. \end{cases} \end{cases}$$

IN SUMMARY

SUPER BEAMS AND NEUTRINO FACTORIES , ARE SUCESIVE STEPS $\rightarrow$ COMBINE RESULTS.

COMBINATION OF NUFACTS + SBEAMS IS PARTICULARLY USEFUL TO RESOLVE DEGENERACIES: different L/E_ν.

INTRINSIC DEGENERACIES disappear down to the sensitivity limit even for NUFACT@ 732 km + SBEAMS. The combination of two SBEAMS with different $E_\nu/L \sim \Delta m^2_{13}$ should also get rid of them.

SIGN Δm^2_{13} • The sign can be resolved in a NUFACT-2810+SBEAM for $\theta_{13} \geq 1^\circ$

- NUFACT-732+SBEAM can resolve the sign for larger θ_{13}.
- At very small θ_{13} the sign remains an ambiguity, but does not interfere with the determination of θ_{13} and δ.

$\theta_{23}, \pi/2 - \theta_{23}$ DEGENERACIES • The ambiguity is difficult to resolve and can interfere with the measurement of θ_{13} and δ if θ_{23} is very far from maximal mixing.

- The combination helps enourmously in minimizing the bias in the extraction of θ_{13} and δ.