RESOLVING DEGENERACIES BETWEEN CP-δ and θ_{13}

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LEPTONIC CP VIOLATION IN ν OSCILLATIONS

$$\mathbf{U_{MNS}}: \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

THE MAIN GOAL OF NEUTRINO FACTORY [ab]

IS TO MEASURE SIMULTANEOUSLY

δ**-CP and** θ_{13}

through

$P(\nu_e \to \nu_\mu)$ **and** $P(\bar{\nu}_e \to \bar{\nu}_\mu)$

by searching for

WRONG SIGN MUONS FOR BOTH POLARITIES

Exploring the full range of δ-CP and θ_{13}...

At fixed E_ν, L

WE COULD NOT DETERMINE THEM UNAMBIGOUSLY

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WE DISCOVERED

EXISTENCE OF DEGENERATE SOLUTIONS

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

THESE DEGENERACIES COULD BE RESOLVED WITH

SIGNIFICANT E_ν , L DEPENDANCE

BUT IF WE INCLUDED

REALISTIC EFFICIENCIES AND BACKGROUNDS

IT WAS NECESSARY TO COMBINE BASELINES.

IF DETECTOR THRESHOLD IS LOWER

DEGENERACIES ARE RESOLVED AT ONLY ONE BASELINE

(M. Freund, P. Huber and M. Lindner, Nucl. Phys. B 615 (2001))

RECENTLY, V. Barger *et. al* [a] HAVE POINTED THAT NEW DEGENERACIES MAY APPEAR

[a] V. Barger, D. Marfatia and K. Whisnant,Phys. Rev. D **65** (2002)

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

$$P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} = P^{\text{large}\,\theta_{13}} + P^{\text{small}\,\theta_{13}} + P^{\text{inter}}_{\nu(\bar{\nu})}$$

Which value of θ_{13} is "small"?

If $\Delta m^2_{12} = 1 \times 10^{-4}$**eV**^{2} $\quad (\theta_{13})_{\nu\textbf{fact}} \sim 1^\circ$,

$(\theta_{13})_{\textbf{sbeams}} \sim 2^\circ$

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

[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.

π^-'s [c]

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

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[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 (θ'_{13}, δ') DEGENERACIES

IN VACUUM APPROXIMATION,

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

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

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: $P^{'} \sim P(\delta \to \pi - \delta)$

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

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

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

- 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}

NOT THE COMMON ONE, BUT

FOR LARGE θ_{13} MATTER EFFECTS ARE IMPORTANT

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FAKE SOLUTIONS DISAPPEAR AT NUFACT@2810 km

FOR LARGE θ_{13}

FOR $\theta_{13} \longrightarrow 0^\circ$ THE FAKE SOLUTION $< E_\nu >, L$ INDEPENDENT SURVIVES IN COMBINATIONS

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

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

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

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

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

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

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

DEGENERACIES

BUT we have seen that

frontier between LARGE and SMALL θ_{13} regimes

depends on θ_{23}

Then, in a given SETUP

Nature could have chosen θ_{23} $\longrightarrow$ Large θ_{13} is dominant

Data analysis with ($\pi/2 - \theta_{23}$)$\longrightarrow$ Small θ_{13} is dominant

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HELP TO SOLVE SOME SCENARIOS

$\theta_{23},\ \pi/2-\theta_{23}$ 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 $\longrightarrow$ 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.