NEW TRENDS
IN ν-PHYSICS

MAY 14, 2003

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FERMILAB TH

U_{e3}: EXPERIMENTAL AND THEORETICAL CHALLENGES

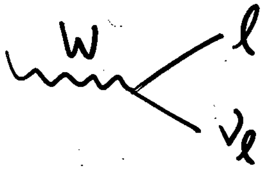
- WHAT IS U_{e3}, AND WHAT DO WE KNOW ABOUT IT ?
- HOW DO WE GO ABOUT MEASURING IT ?
- PREDICTING U_{e3}: THE THEORETICAL CHALLENGE
  - NEUTRINO MASS ANARCHY
- CONCLUSIONS...

3 FLAVOR NEUTRINO OSCILLATIONS

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

FLAVOR EIGENSTATES

MASS EIGENSTATES



$m_{\nu_i} \equiv m_i$

DEFINING THE MASS EIGENSTATES

- $m_1^2 < m_2^2 \qquad \left(\Delta m_{12}^2 \equiv m_2^2 - m_1^2 > 0 \right)$

- $|\Delta m_{13}^2| > \Delta m_{12}^2 \implies$ SIGN(Δm_{13}^2) IS AN "OBSERVABLE"

GIVEN THIS (PECULIAR ?) DEFINITION

IT TURNS OUT:*

$$\frac{|U_{e2}|^2}{|U_{e1}|^2} \equiv tg^2\theta_{12} \text{ "="} \; tg^2\theta_{SOL}$$

$$\Delta m^2_{12} \text{ "="} \; \Delta m^2_{SOL}$$

$$\frac{|U_{\mu 3}|^2}{|U_{23}|^2} \equiv tg^2\theta_{23} \text{ "="} \; tg^2\theta_{ATM}$$

$$|\Delta m^2_{13}| \approx |\Delta m^2_{23}| \text{ "="} \; \Delta m^2_{ATM}$$

$$\sin^2\theta_{13} \equiv |U_{e3}|^2 = \; ?$$ (CONSTRAINED...)

$$J_{CP} \equiv \mathrm{Im}\left[U^*_{e3} U_{\mu 3} U_{e2} U^*_{\mu 2} \right] = \frac{1}{8} \sin 2\theta_{23} \times \sin 2\theta_{12} \times \sin 2\theta_{13} \cos\theta_{13} \times \underline{\sin\delta} = \; ?$$

$\sin\delta$ ← CP-ODD "DIRAC" PHASE

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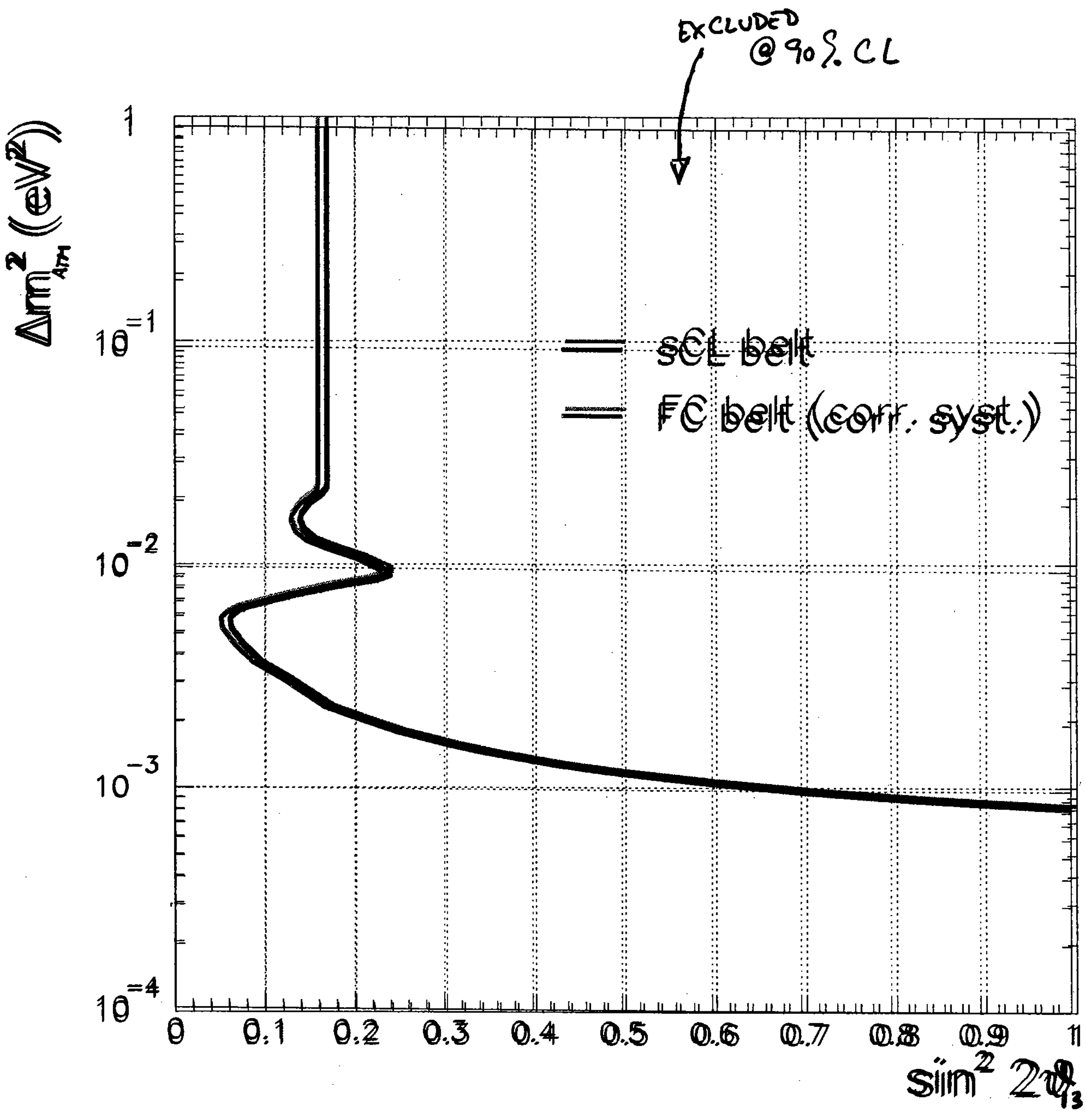
* BECAUSE $|U_{e3}|$ SMALL, $\Delta m^2_{ATM} \gg \Delta m^2_{SOLAR}$

FINAL CHOOZ RESULT

HEP-EX/0301017



ATM + SOLAR DATA TELL YOU THAT $|U_{e3}|$ IS SMALL (NOT CLOSE TO 1)

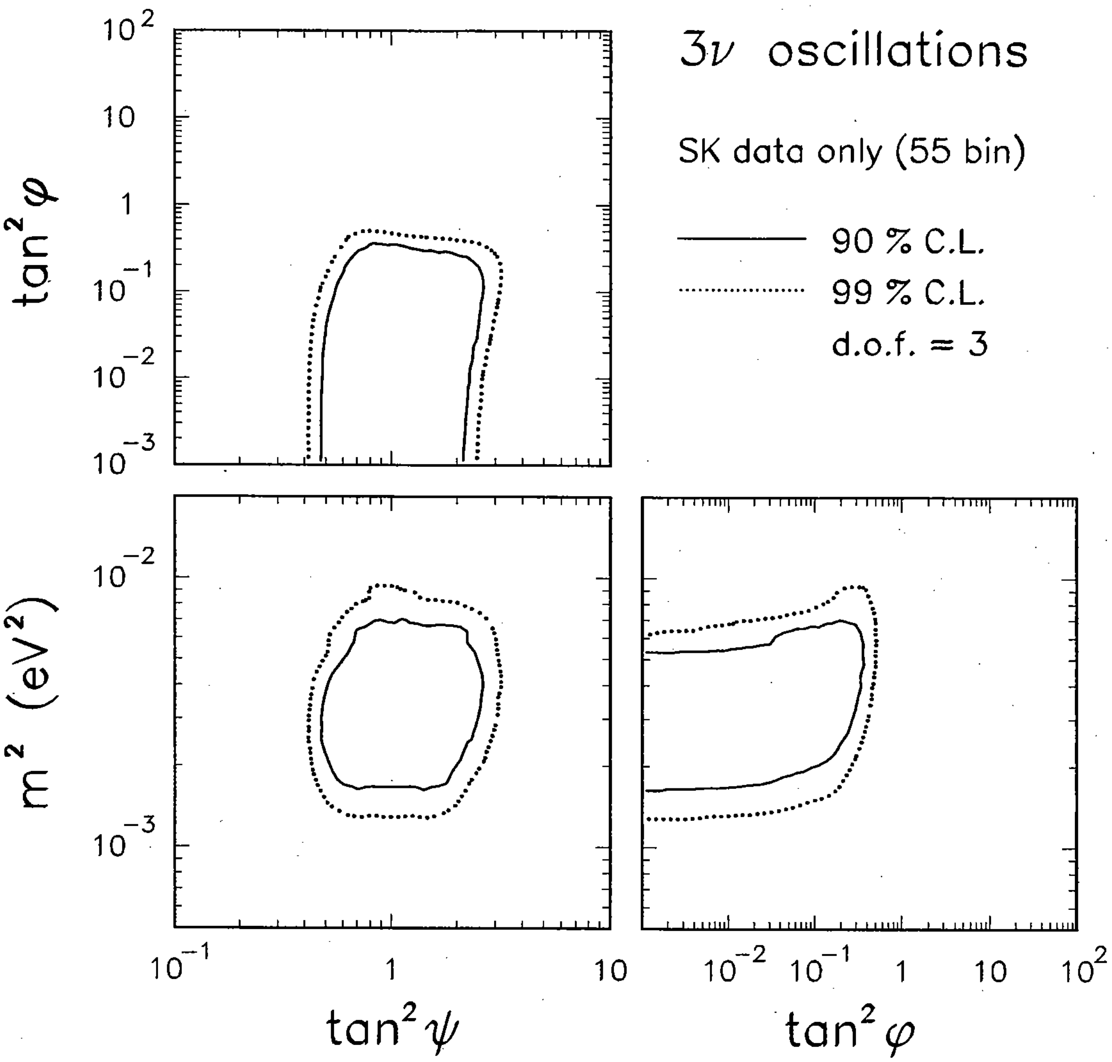


Fig. 3. Projections of the regions allowed in the 3ν parameter space $(m^2, \tan^2\psi, \tan^2\phi)$ at 90% and 99% C.L. ($\Delta\chi^2 = 6.25$ and 11.36 for $N_{\rm DF} = 3$) onto the coordinate planes. The fit includes SK data only (79.5 kTy). The pure 2ν case of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations is recovered for $\tan^2\phi \to 0$. Nonzero values of ϕ parametrize ν_e mixing.

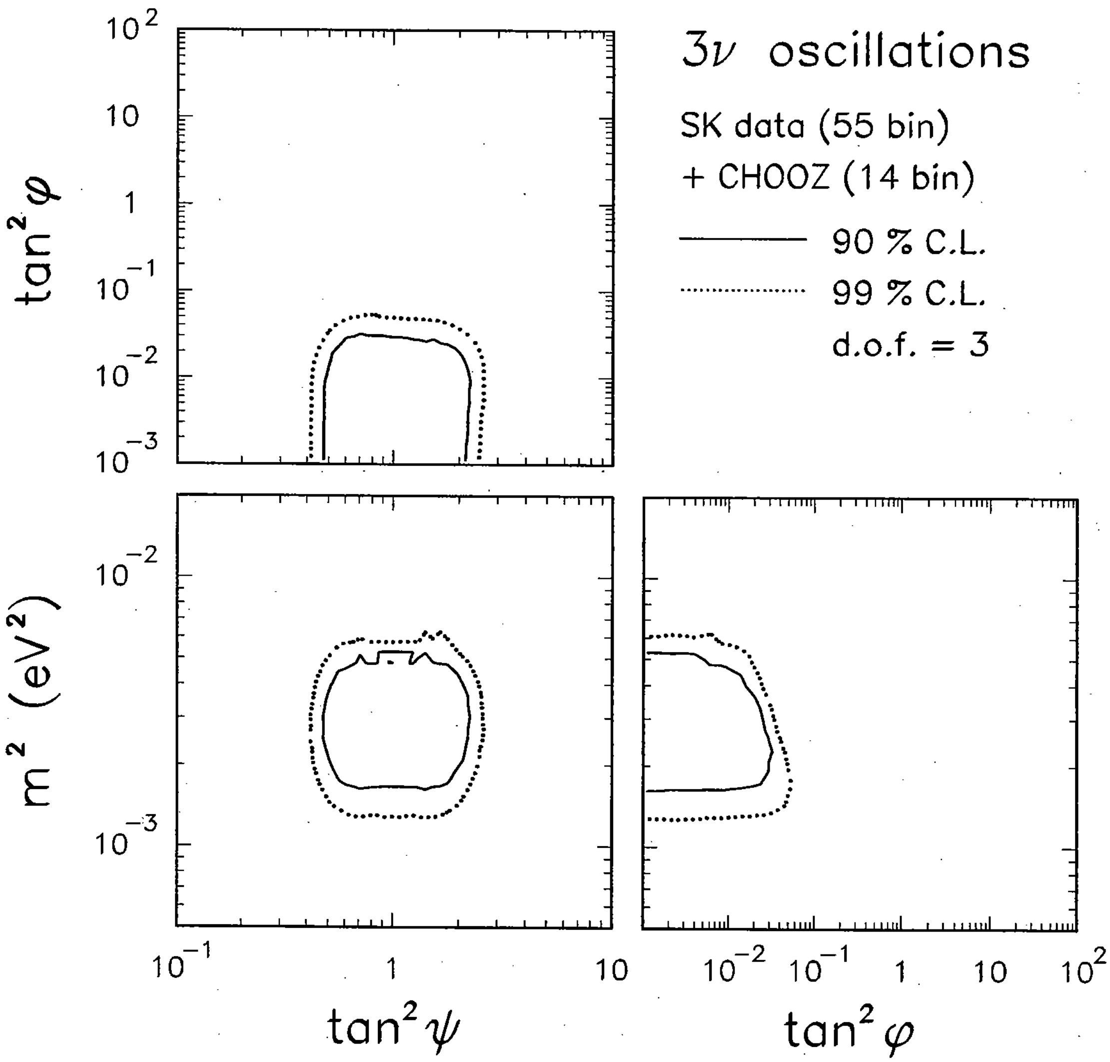


Fig. 4. As in Fig. 3, but including final CHOOZ positron spectra [5] (14 data points minus one adjustable normalization factor).

FoGLi ET AL

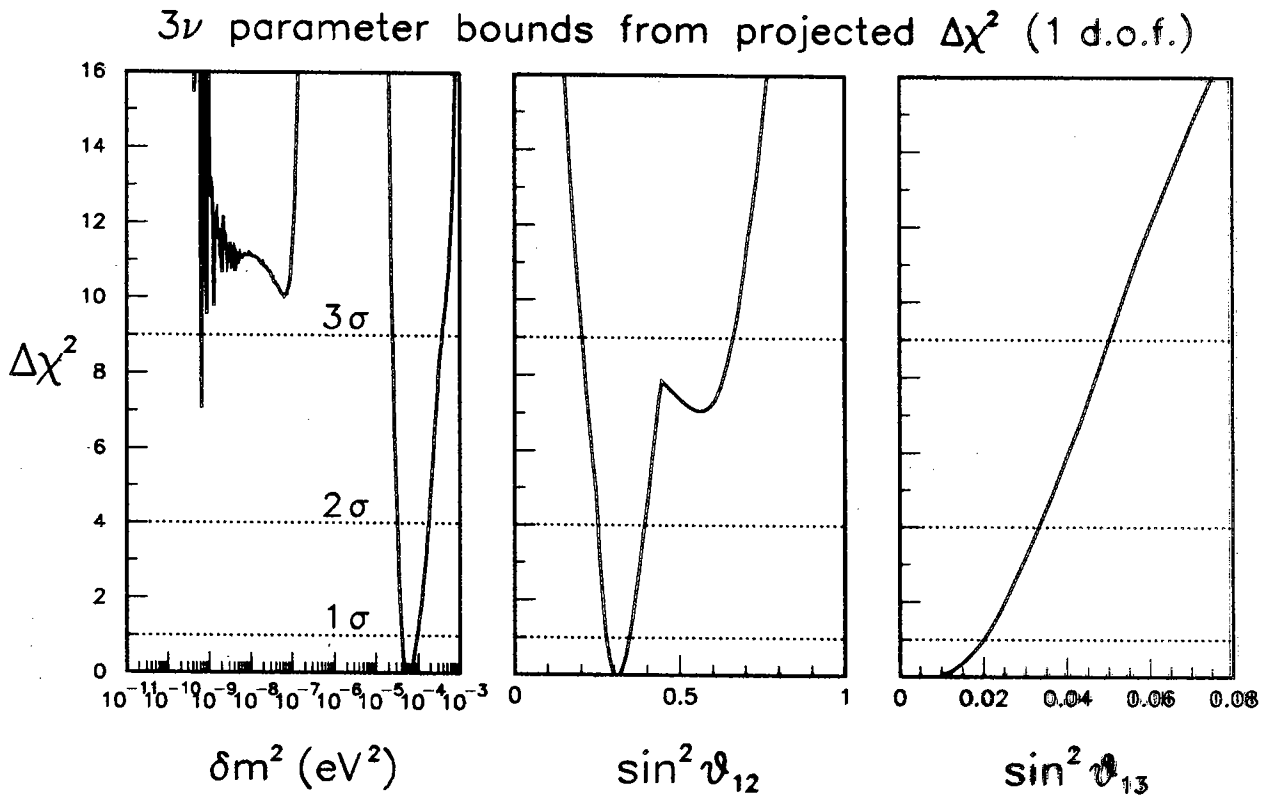
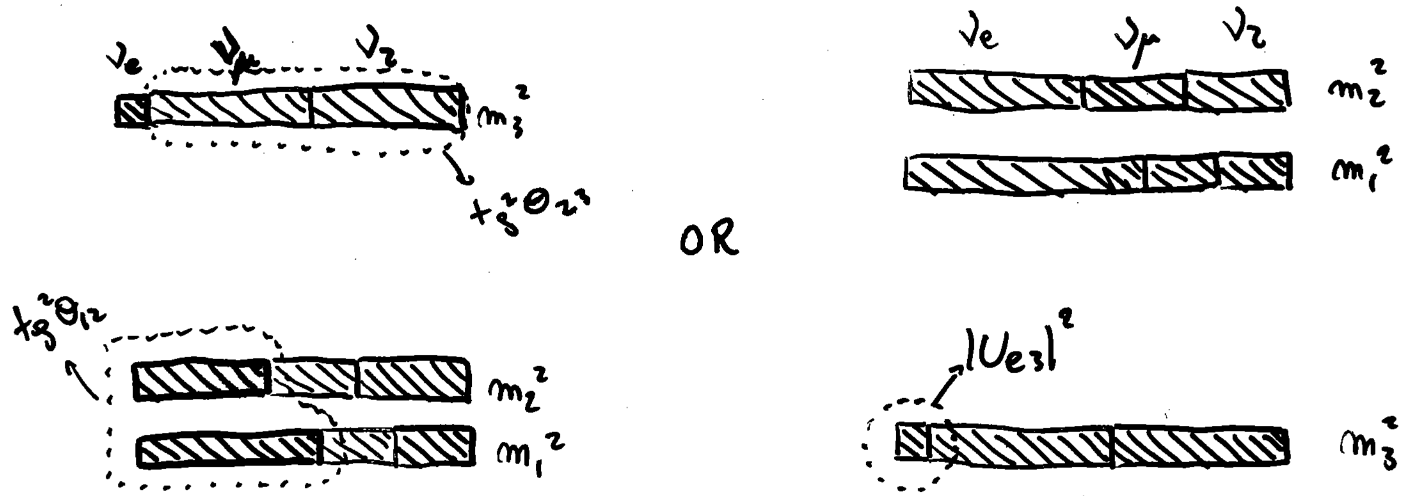


FIG. 4: Projections of the global (solar+terrestrial) $\Delta\chi^2$ function onto each of the $(\delta m^2, \sin^2\theta_{12}, \sin^2\theta_{13})$ parameters. The n-sigma bounds on each parameter (the others being unconstrained) correspond to $\Delta\chi^2 = n^2$.

WHAT IS LEFT?



$\Delta m^2_{13} > 0$ $\Delta m^2_{13} < 0$

1 - $|U_{e3}|^2$

2 - WHAT IS THE MASS HIERARCHY?

3 - WHAT IS THE CP-ODD PHASE?

[2] CAN BE ADDRESSED WITHIN OSCILLATIONS IF $|U_{e3}|^2$ is BIG

[3] CAN BE ADDRESSED WITHIN OSCILLATIONS IF LMA + $|U_{e3}|^2$ BIG

LOOKING FOR $|U_{e3}|^2$ EFFECTS (EXPERIMENTALLY)

$\nu_\mu \leftrightarrow \nu_e$ TRASITIONS "DOMINATED BY Δm^2_{13} - TERM"

MAXIMIZE BY CHOOSING L, E

$$P^{VAC}_{\bar{\mu}\bar{e}} = 4\,|U_{\mu 3}|^2 |U_{e3}|^2 \sin^2\Delta_{13} -$$

"$(\Delta_{12})^2$ TERM"

$$4\,\mathrm{Re}\left[U_{\mu 1} U^*_{e1} U^*_{\mu 2} U_{e2}\right] \sin^2\Delta_{12} +$$

"$U_{e3}\Delta_{12}$ TERM"

$$2\,\mathrm{Re}\left[U_{\mu 2} U^*_{e2} U^*_{\mu 3} U_{e3}\right]\left(\cos 2(\Delta_{12}-\Delta_{13}) - \cos 2\Delta_{13}\right) -$$

$$\pm 8\,\mathrm{Im}\left[U_{\mu 2} U^*_{e2} U^*_{\mu 3} U_{e3}\right] \sin\Delta_{12} \sin\Delta_{13} \sin(\Delta_{13}-\Delta_{12})$$

"$U_{e3}\,\Delta_{12}$ CP-ODD TERM"

$$\boxed{\Delta_{ij} \equiv \Delta m^2_{ij}\,\frac{L}{4E}}$$

TO BE STUDIED EITHER WITH INTENSE

ν_μ OR $\underbrace{\nu_e \text{ BEAM}}$ "NEUTRINO FACTORY"

A FEW WORDS ON NEXT GENERATION ν_μ-BEAMS

[SUPERBEAMS OFF-AXIS EXPERIMENTS, ETC..]

(SEE TALKS BY PARKE, LINDNER LATER THIS WEEK...

- THESE SEEM TO BE THE "BEST BET" FOR NEXT GENERATION NEUTRINO OSCILLATION EXPT (EXCEPT SEE NEXT TOPIC) [NUMI OFFAXIS, JHF-SUPERK]

  - IT IS "EASY" TO PRODUCE INTENSE ν_μ BEAMS ($\pi \to \mu\nu_\mu$) OF APPROPRIATE ENERGIES

  - NAIVELY, APPEARANCE IS THE "RIGHT WAY" TO REACH (VERY) SMALL ANGLES (VERSUS DISAPPEARANCE)

  - SUCH A SETUP WILL ALSO PROVIDE THE (REQUIRED) PRECISE KNOWLEDGE OF ATMOSPHERIC PARAMETERS

  - ONE CAN LOOK FOR CP-PHASE + SIGN(Δm^2_{13})

MATTER EFFECTS MATTER! (DEPENDING ON BASELINE)

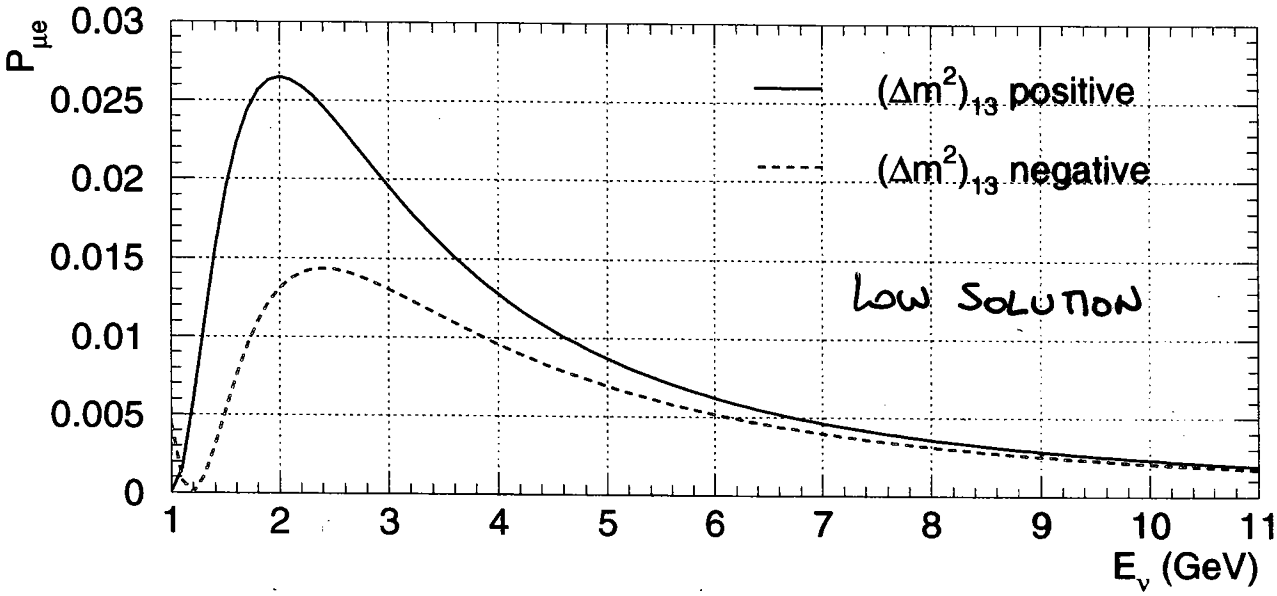


Figure 1: $\nu_\mu \to \nu_e$ oscillation probability for $\Delta m^2_{13} > 0$ (solid line) and $\Delta m^2_{13} < 0$ (dashed line). $|\Delta m^2_{13}| = 3 \cdot 10^{-3}$ eV^2, $\theta_{\rm atm} = \pi/4$, $\Delta m^2_\odot = 1 \times 10^{-7}$ eV^2, $\theta_\odot = \pi/6$, $|U_{e3}|^2 = 0.01$, and $\delta = 0$. $L = 900$ km

[BARENBOIM, AdG, SZLEPER, VELASCO, HEP-PH/0204208]

$$\frac{\Delta m^2}{2E} \times \sqrt{2} G_F N_e \approx 1.4 \times 10^{-4} \frac{eV^2}{GeV}$$

AS LONG AS $E \lesssim 10$ GeV, MATTER EFFECTS ARE AN IMPORTANT PERTURBATION. NOTE THAT FOR $E > 10$ GeV, WE NEED DISTANCES BIGGER THAN $\gtrsim 5000$ km TO AIM AT $\Delta_{13} \sim \pi/2$ ...

HOW ABOUT A "SUPER BUGEY" EXPERIMENT?

[SEE TALK BY LINDNER]

$$P_{\bar{e}\bar{e}} = 1 - 4|U_{e3}|^2(1-|U_{e3}|^2)\sin^2\Delta_{13}$$
$$- 4|U_{e1}|^2|U_{e2}|^2\sin^2\Delta_{12} \rightsquigarrow \text{"SOLAR TERM"}$$
$$+ 2|U_{e2}|^2|U_{e3}|^2\left[\cos 2(\Delta_{13}-\Delta_{12}) - \cos 2\Delta_{13}\right]$$

↳ "INTERFERENCE TERM" (SMALL)

- MATTER EFFECTS ARE IRRELEVANT
- THERE ARE LOTS OF NUCLEAR REACTORS AROUND (PLUS, THEIR NEUTRINOS ARE FREE...)
- NO $\cancel{CP}$ OR SIGN OF Δm^2_{13} SENSITIVITY...

⇒ MUST HAVE INCREDIBLY SMALL SYSTEMATIC UNCERTAINTIES TO BE "COMPETITIVE"!

SUBJECT OF (INTENSE?) RESEARCH RIGHT NOW...

INTERLUDE: WHY DO WE CARE ABOUT $|U_{e3}|$ ET AL ?

- NEUTRINO MIXING PARAMETERS ARE FUNDAMENTAL CONSTANTS OF THE (NOW EXTENDED) S.M., JUST LIKE THE CABIBBO ANGLE, THE FINE STRUCTURE CONSTANT OR THE top MASS.

- WITH FUTURE OSCILLATION EXPERIMENTS, WE HAVE THE OPPORTUNITY OF PROBING WHETHER CP-INVARIANCE HOLDS IN THE LEPTONIC SECTOR. DOES A "CKM-LIKE" PICTURE DESCRIBES $\not{CP}$ IN LEPTONS AS WELL ?

- "PRECISE" MEASUREMENTS OF THE NEUTRINO MIXING PARAMETERS WILL SHED LIGHT [HOPEFULLY...] INTO OUR UNDERSTANDING OF FLAVOR [+ MORE...]

THEORETICAL CHALLENGES

- "NEUTRINO FLAVOR CONVERSION" IS THE ONLY EVIDENCE WE HAVE FOR PHYSICS BEYOND THE STANDARD MODEL.

- EVEN THE SIMPLEST (MOST LIKELY FROM EXPERIMENTS) SOLUTION REQUIRES A QUALITATIVE MODIFICATION OF WHAT WE MEAN BY "S.M."

- FURTHERMORE, LEPTONIC MIXING SEEMS TO BE "DIFFERENT". BY THAT WE MEAN:

$$V_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \qquad \boldsymbol{\times} \qquad V_{MNS} \sim \begin{pmatrix} 1 & 1 & \delta \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

$$\lambda \sim 0.2 \qquad\qquad\qquad \delta \lesssim 0.2$$

WHILE SOME MIGHT CLAIM THAT THEORIST "PREDICTED" VERY SMALL NEUTRINO MASS, NOONE CAN CLAIM THAT WE ANTICIPATED IN ANY WAY THE LARGE NEUTRINO MIXING ANGLES...

ONE REASON FOR THIS IS THAT WE BELIEVE (VIA GUT'S OF ALL KINDS) THAT QUARKS AND LEPTONS ARE CONNECTED AT SOME VERY HIGH SCALE: (NAIVELY $V_{CKM} \sim V_{MNS}$ AT M_{GUT})

[OF COURSE, WE LEARNED (SEE TALKS BY ALBRIGHT, MOHAPATRA, FOR EXAMPLE) THAT GUTS CAN BE MADE TO PROPERLY FIT V_{CKM} AND V_{MNS}...]

THE FACT THAT WE DON'T KNOW THE "PHYSICS" BEHIND MASSES + MIXING DOES NOT STOP US FROM TRYING – QUITE THE CONTRARY.

WE DRAW "INSPIRATION" FROM THE QUARK SECTOR. THERE, THE PECULIAR VALUES OF THE MASSES + MIXING ANGLES HAVE LED PEOPLE TO BELIEVE THAT NATURE IS TRYING TO TELL US SOMETHING...

WHAT WE AIM AT IS THE PRESENCE OF SOME NEW FUNDAMENTAL PRINCIPLE (SYMMETRY) THAT DINAMICALLY EXPLAINS WHY MASSES + MIXING ANGLES COME OUT AS THEY DO...

$\boxed{\text{FLAVOR SYMMETRIES}}$

STARTING POINT: WHAT DO THE MASS MATRICES "ROUGHLY" LOOK LIKE?

(EXPLAINING ALL DATA WITH "SMALLEST" AMOUNT OF INPUT)

Table 1
Leading order low energy neutrino Majorana mass matrices m_{LL} consistent with large atmospheric and solar mixing angles, classified according to the rate of neutrinoless double beta decay and the pattern of neutrino masses.

	Type I Small $\beta\beta_{0\nu}$	Type II Large $\beta\beta_{0\nu}$
A Normal hierarchy $m_1^2, m_2^2 \ll m_3^2$	$\beta\beta_{0\nu} \lesssim 0.0082$ eV $\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} \frac{m}{2}$	–
B Inverted hierarchy $m_1^2 \approx m_2^2 \gg m_3^2$	$\beta\beta_{0\nu} \lesssim 0.0082$ eV $\begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \frac{m}{\sqrt{2}}$	$\beta\beta_{0\nu} \gtrsim 0.0085$ eV $\begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & \frac{1}{2} \\ 0 & \frac{1}{2} & \frac{1}{2} \end{pmatrix} m$
C Approximate degeneracy $m_1^2 \approx m_2^2 \approx m_3^2$	$\begin{pmatrix} 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \end{pmatrix} m$	$\beta\beta_{0\nu} \gtrsim 0.035$ eV diag(1,1,1)m $\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} m$

Table 2
Some candidate GUT and Family symmetry groups.

G_{GUT}	G_{Family}
E_6	$SU(3)$
$SO(10)$	$SU(2)$
$SU(5)$	$U(1)$
$SU(5) \times U(1)$	Z_N
$SU(3)^3$	$O(3) \times O(3)$
$SU(4) \times SU(2) \times SU(2)$	$SO(3)$
$SU(3) \times SU(2) \times SU(2) \times U(1)$	$S(3) \times S(3)$
$SU(3) \times SU(2) \times U(1) \times U(1)$	$S(3)$
$SU(3) \times SU(2) \times U(1)$	Nothing

"GOOD" FLAVOR MODELS SOLVE MANY PROBLEMS AT ONCE + LEAD TO NEW EXPERIMENTAL CONSEQUENCES?

Table 2: Order-of-magnitude estimates for θ_{13}.

Texture	θ_{12}	θ_{13}	Perturbations
$m_\nu^{\rm D1} = m \begin{pmatrix} \delta & -\frac{1}{\sqrt{2}} & \frac{(1-\epsilon)}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} & \frac{(1+\eta)}{2} & \frac{(1+\eta-\epsilon)}{2} \\ \frac{(1-\epsilon)}{\sqrt{2}} & \frac{(1+\eta-\epsilon)}{2} & \frac{(1+\eta-2\epsilon)}{2} \end{pmatrix}$	$\approx \pi/4$	$\approx \left(\frac{\Delta m^2_{sun}}{\Delta m^2_{atm}}\right)^{1/2}$	$\epsilon \gg \delta$
		≈ 0	$\epsilon \ll \delta$
$m_\nu^{\rm D2} = m \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + r \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \right] + \delta m_\nu$	$\approx \pi/4$	$\approx \left(\frac{m_e}{m_\mu}\right)^{1/2}$	
$m_\nu^{\rm I} = m \begin{pmatrix} \delta & -1 & 1 \\ -1 & \eta & \eta \\ 1 & \eta & \eta \end{pmatrix}$	$\approx \pi/4$	$\approx \frac{\Delta m^2_{sun}}{\Delta m^2_{atm}}$	$\eta \gg \delta$
		$\ll \frac{\Delta m^2_{sun}}{\Delta m^2_{atm}}$	$\eta \ll \delta$
$m_\nu^{\rm N} = m \begin{pmatrix} \delta & \epsilon & \epsilon \\ \epsilon & 1+\eta & 1+\eta \\ \epsilon & 1+\eta & 1+\eta \end{pmatrix}$			$\eta < \delta \approx \epsilon$
	$O(1)$	$\approx \left(\frac{\Delta m^2_{sun}}{\Delta m^2_{atm}}\right)^{1/2}$	
			$\delta \approx \epsilon^2 \approx \eta^2$
	$\approx \pi/4$	$\approx \left(\frac{\Delta m^2_{sun}}{\Delta m^2_{atm}}\right)^{1/3}$	$\delta \approx \epsilon^2 \quad \eta = 0$

~~a) Degenerate case. If $|m|$ is the common mass, apart from a phase, and taking $s_{13} = 0$, which, as already observed, is a safe approximation in this case, we have $m_{ee} = |m|(c_{12}^2 \pm s_{12}^2)$. Here the phase ambiguity has been reduced to a sign ambiguity~~

OF COURSE, WE SAY THAT NEUTRINO MIXING IS STRANGE BECAUSE WE HAVE GROWN ACCUSTOMED TO QUARK MIXING.

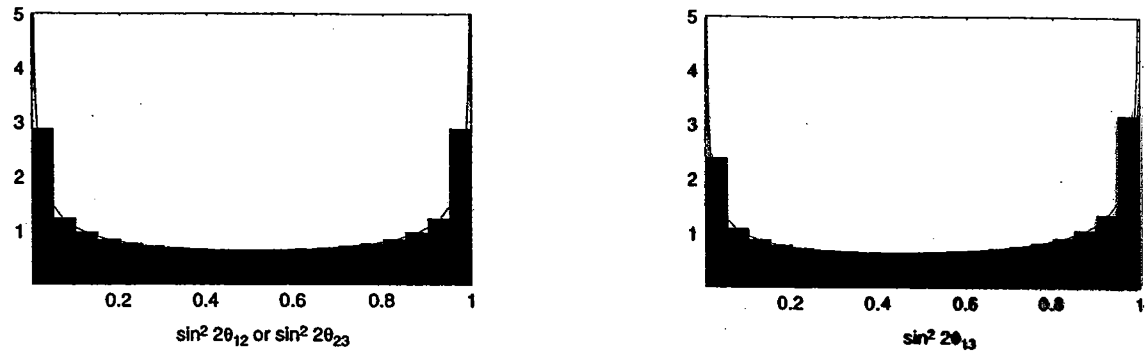
PERHAPS WE SHOULD BACKUP AND RE-EXAMINE THIS:

AFTER ALL QUARK MIXING IS STRANGE, WHILE NEUTRINO MIXING MIGHT BE QUITE "COMMON".
CAN ONE QUANTIFY THIS STATEMENT?

HABA + MURAYAMA

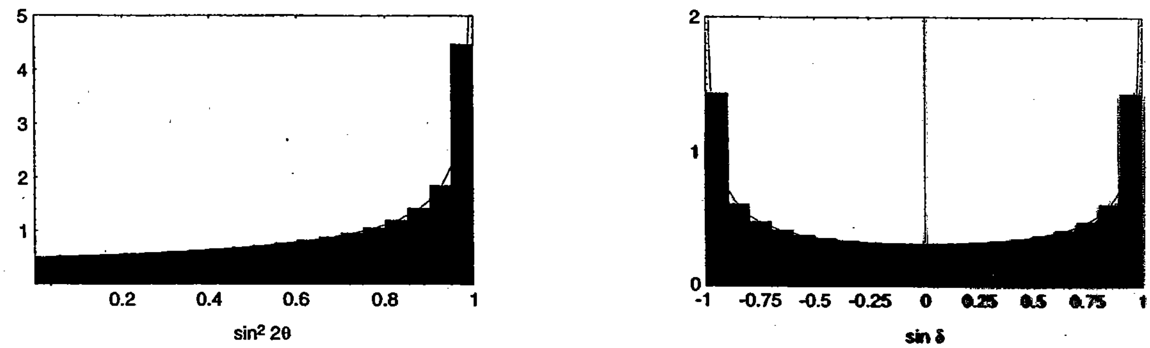
PRD 63, 053011

(2001)



O(3)

Figure 1: Distributions in (a) $\sin^2 2\theta_{12}$ or $\sin^2 2\theta_{13}$ and (b) $\sin^2 2\theta_{13}$ for the case of real mass matrices.



U(3)

Figure 2: Distributions in (a) $\sin^2 2\theta_{12}$ or $\sin^2 2\theta_{13}$ or $\sin^2 2\theta_{23}$ and (b) $\sin\delta$ for the case of complex mass matrices.

NEUTRINO FLAVOR WITHOUT FLAVOR?

⇒ SIMPLEST BOTTOM-UP APPROACH ! ⇐

IS THE MNS MATRIX "TYPICAL" OF WHAT YOU WOULD EXPECT IF THERE WAS NO FUNDAMENTAL DISTINCTION AMONG THE 3 NEUTRINOS, I.E., IS THE MNS MATRIX "ANY OLD" 3x3 UNITARY MATRIX ?

TABLE I: $\sin^2\theta_{ij}$ in the MNS and CKM mixing matrices, according to the PDG parametrization [1]. In square barckets we quote the currently allowed experimental values for the CKM (MNS) entries at the 90% (three sigma) confidence level.

"angle"	CKM [90% expt.]	MNS [3σ expt.]
$\sin^2\theta_{13}$	$\lvert V_{ub}\rvert^2$ $[(6.2-23)\times 10^{-6}]$	$\lvert U_{e3}\rvert^2$ $[0-0.05]$
$\sin^2\theta_{12}$	$\sin^2\theta_C$ $[0.048-0.051]$	$\sin^2\theta_{\rm sol}$ $[0.2-0.5]$
$\sin^2\theta_{23}$	$\lvert V_{cb}\rvert^2$ $[(1.4-1.9)\times 10^{-3}]$	$\sin^2\theta_{\rm atm}$ $[0.35-0.65]$

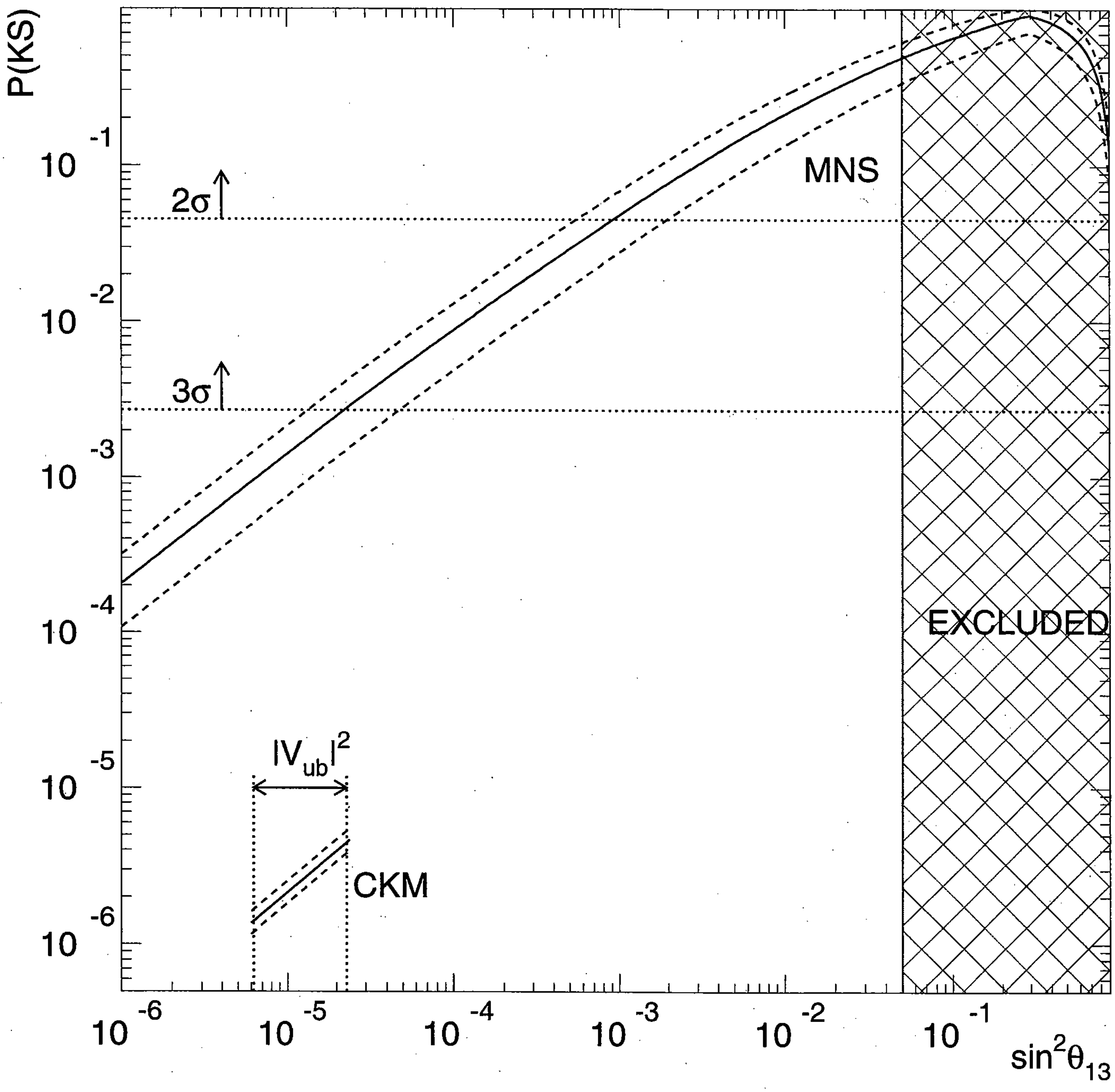
"ANARCHY"* IN THE MIXING MATRIX MIGHT BE EXPRESSED AS THE FOLLOWING "MODEL":

WE PREDICT THAT THE MIXING MATRIX IS A "RANDOM VARIABLE" DRAWN FROM A FLAT DISTRIBUTION OF UNITARY 3X3 MATRIX.

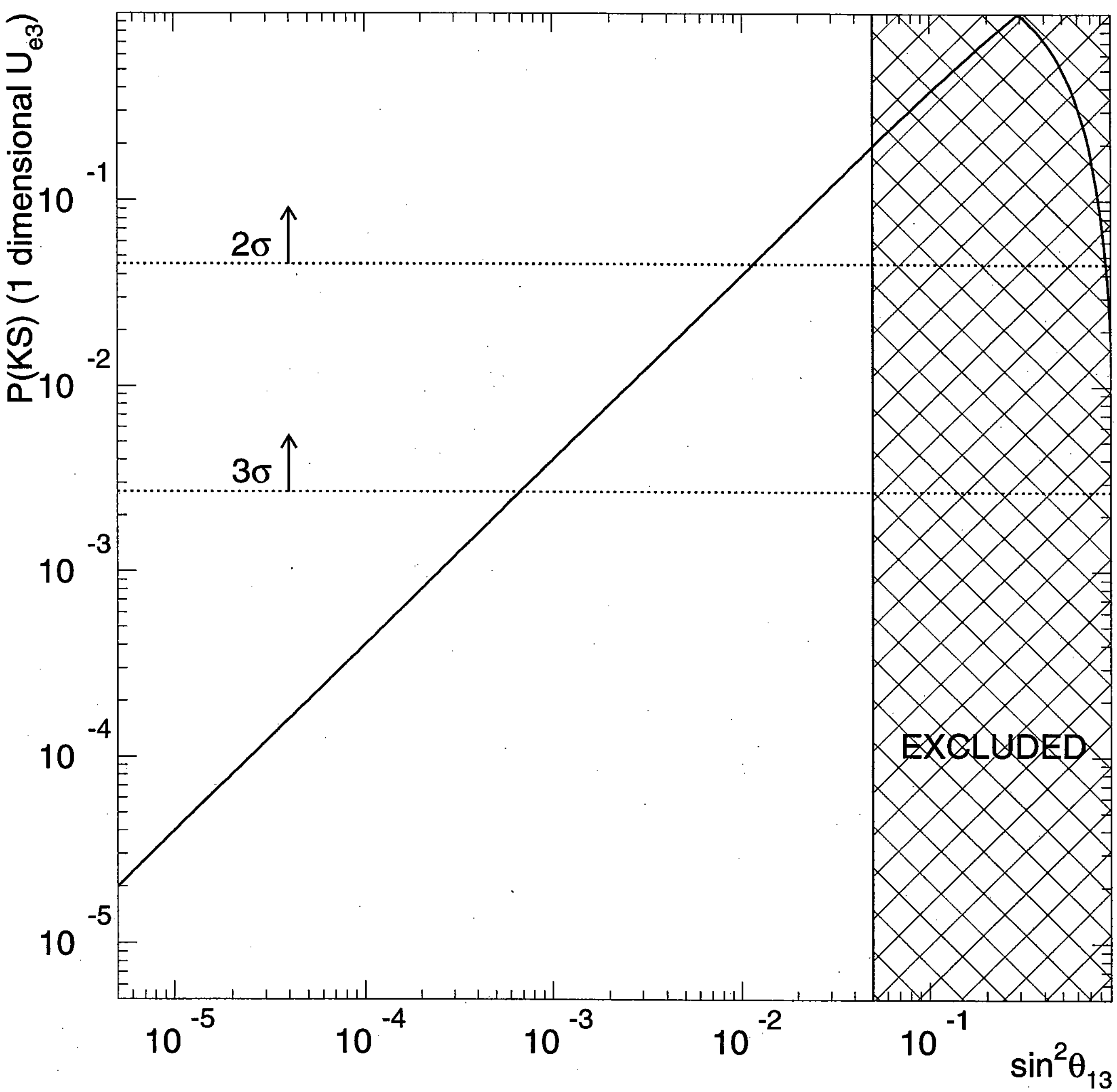
GIVEN NATURE'S "DRAW", HOW LIKELY IS IT THAT THIS HYPOTHESIS IS CORRECT?

SEE A&G, MURAYAMA
HEP-PH/0301050

* HALL, MURAYAMA, WEINER
PRL 84, 2572 (2000)



P(KS)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
2σ
3σ
MNS
EXCLUDED
$|V_{ub}|^2$
CKM
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$\sin^2\theta_{13}$


P(KS) (1 dimensional U_{e3})
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
2σ
3σ
EXCLUDED
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$\sin^2\theta_{13}$

COMMENTS ON ANARCHY:

- THE FACT THAT THIS MODEL WORKS DOES NOT MEAN THAT FLAVOR MODELS DO NOT WORK OR ARE DISFAVORED. THEY DO, HOWEVER, HAVE THE "BURDEN OF PROOF".

- WE NEED NOT (INDEED, DO NOT) SAY ANYTHING ABOUT MASS EIGENVALUES...

- IS THERE SOME "DEEP SIGNIFICANCE" BEHIND NEUTRINO MASS ANARCHY?

  → MAYBE IT MEANS THAT THERE ARE SEVERAL "COMPETING" CONTRIBUTIONS TO THE NEUTRINO MASS-MATRIX...

SUMMARIZING

- IN THE MOST BORING EXTENSION TO THE S.M THERE ARE A FEW, NEW "FUNDAMENTAL PARAMETERS" OF OUR UNDERSTANDING OF NATURE THAT REMAIN COMPLETELY UNKNOWN

- WE NEED NEW EXPERIMENTS! FINDING $|U_{e3}|$ IS ESSENTIAL BECAUSE, IF FOR NO OTHER REASON, LEARNING THE VALUE OF $|U_{e3}|$ WILL TELL US IF WE CAN PROBE $\cancel{CP}$ + $\text{SIGN}(\Delta m^2_{13})$ VIA OSCILLATION EXPERIMENTS.

- THEORY DOES NOT "KNOW" THE VALUE OF $|U_{e3}|$.

THERE ARE SEVERAL DIFFERENT PREDICTIONS IN THE MARKET

$$\boxed{|U_{e3}|_{\text{THEORY}} \in [\,0,\ \text{CHOOZ BOUND}\,]}$$

"DATA DRIVEN FIELD"!

- MAYBE EXPLAINING MIXING IN THE LEPTON SECTOR IS VERY (TOO?) SIMPLE: WOULDN'T THAT BE SURPRISING?