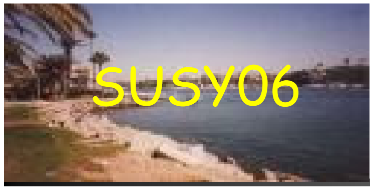

Unitarity of the lepton mixing matrix

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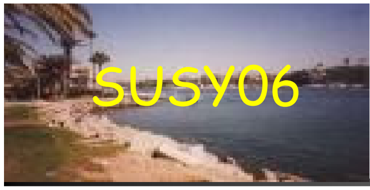
Based on a collaboration with:

S. Antusch, C. Biggio, B. Gavela,

J. López Pavón and C. Peña-Garay

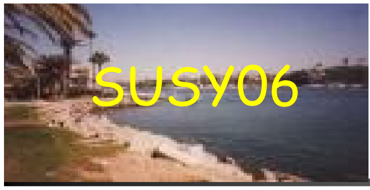


Motivations

- ν masses and mixing $\rightarrow$ evidence of Physics Beyond the SM
- Typical explanations (see-saw) involve NP with $\Lambda > v$
- This NP often induces deviations from unitarity at low energy

↓

We will analyze the present constraints on the mixing matrix *without* assuming unitarity



The general idea…

$$U=\begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23}-s_{23}s_{13}c_{12}e^{-i\delta} & c_{12}c_{23}-s_{23}s_{13}s_{12}e^{-i\delta} & s_{23}c_{13} \\ s_{23}s_{12}-c_{23}s_{13}c_{12}e^{-i\delta} & -s_{23}c_{12}-c_{23}s_{13}s_{12}e^{-i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\downarrow$$

$$N=\begin{pmatrix} N_{e1} & N_{e2} & N_{e3} \\ N_{\mu 1} & N_{\mu 2} & N_{\mu 3} \\ N_{\tau 1} & N_{\tau 2} & N_{\tau 3} \end{pmatrix}$$

Effective Lagrangian

- 3 light ν
- all unitarity violation from NP with $\Lambda > \mathrm{v}$
- flavour universality

$$L = i\,\bar{\nu}_\alpha \partial K_{\alpha\beta} \nu_\beta + \bar{\nu}_\alpha M_{\alpha\beta} \nu_\beta - \frac{g}{\sqrt{2}}\left(W_\mu^+ \bar{l}_\alpha \gamma^\mu P_L \nu_\alpha + h.c.\right) - \frac{g}{\cos\theta_W}\left(Z_\mu \bar{\nu}_\alpha \gamma^\mu P_L \nu_\alpha + h.c.\right) + \ldots$$

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Diagonal mass and canonical kinetic terms

$$L = i\,\bar{\nu}_i \partial \nu_i + \bar{\nu}_i m_{ii} \nu_i - \frac{g}{\sqrt{2}} \left(W_\mu^+ \bar{l}_\alpha \gamma^\mu P_L N_{\alpha i} \nu_i + h.c. \right) - \frac{g}{\cos\theta_W} \left(Z_\mu \bar{\nu}_i \gamma^\mu P_L (N^+ N)_{ij} \nu_j + h.c. \right) + \ldots$$

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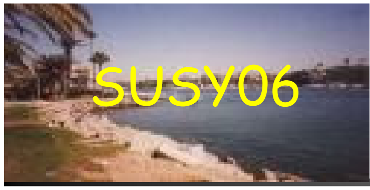
$$\nu_\alpha = N_{\alpha i} \nu_i$$

N is not unitary



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unchanged

$$\nu_\alpha = N_{\alpha i}\nu_i$$

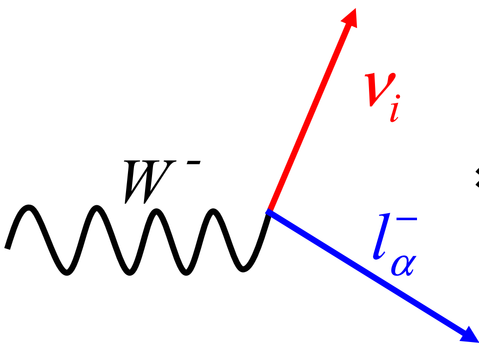
N is not unitary

$$\langle \nu_i | \nu_j \rangle = \delta_{ij}$$

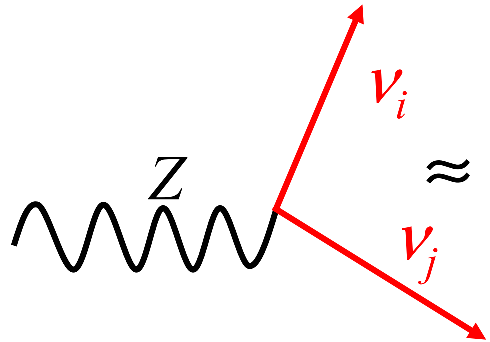
SUSY06

The effects of non-unitarity…

… appear in the interactions



$\approx N_{\alpha i}$

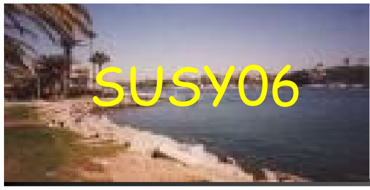


$\approx \left(N^+ N\right)_{ij}$

This affects weak decays…

$$\Gamma = \Gamma_{SM} \sum_i \left|N_{\alpha i}\right|^2 = \Gamma_{SM} \left(N N^+\right)_{\alpha\alpha}$$

$$\Gamma = \Gamma_{SM} \sum_{ij} \left|\left(N^+ N\right)_{ij}\right|^2$$



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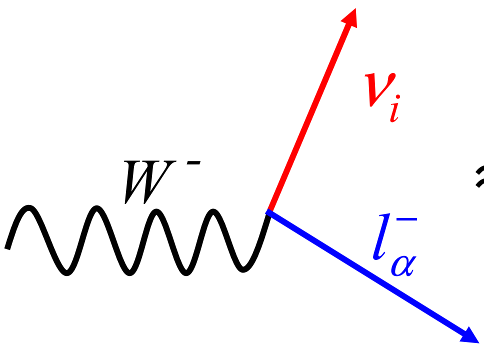
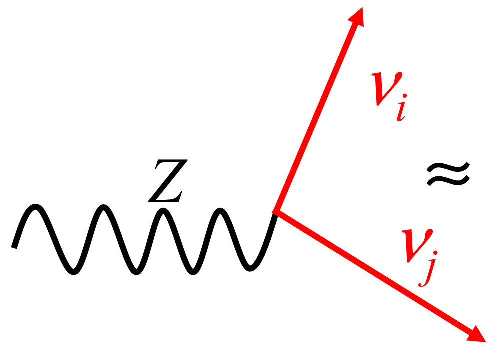


$$\approx N_{\alpha i}$$



$$\approx \left(N^+N\right)_{ij}$$

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$$\Gamma = \Gamma_{SM} \sum_{ij} \left|\left(N^+N\right)_{ij}\right|^2$$

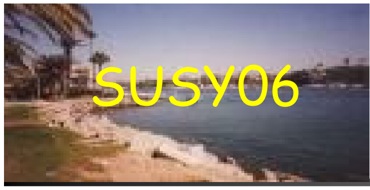
… and oscillation probabilities…

$$\left|\nu_\alpha\right\rangle = \frac{1}{\sqrt{\sum_i \left|N_{\alpha i}\right|^2}} \sum_i N^*_{\alpha i}\left|\nu_i\right\rangle \equiv \sum_i \widetilde{N}^*_{\alpha i}\left|\nu_i\right\rangle$$

$$\left\langle \nu_\beta \middle| \nu_\alpha \right\rangle = \left(\widetilde{N}^*\widetilde{N}^t\right)_{\alpha\beta} \neq \delta_{\alpha\beta}$$

ν oscillation in vacuum

- mass basis $$i\frac{d}{dt}\left|\nu_i\right\rangle = \hat{H}^{free}\left|\nu_i\right\rangle = \sum_j H_{ij}^{free}\left|\nu_j\right\rangle = E_i\left|\nu_i\right\rangle \qquad \left|\nu_i(t)\right\rangle = e^{-iE_it}\left|\nu_i^0\right\rangle$$



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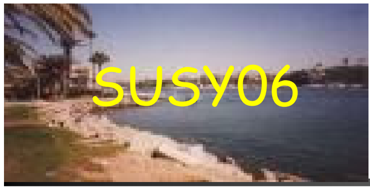
- flavour basis $$i\frac{d}{dt}\left|\nu_\alpha\right\rangle = \hat{H}^{free}\left|\nu_\alpha\right\rangle = \sum_\beta E_{\alpha\beta}^{free}\left|\nu_\beta\right\rangle$$

with $$E_{\alpha\beta}^{free} = \widetilde{N}_{\alpha i}^{*} H_{ij}^{free} \left(\widetilde{N}^{*}\right)_{j\beta}^{-1} \neq H_{\alpha\beta}^{free} = \widetilde{N}_{\alpha i}^{*} H_{ij}^{free} \widetilde{N}_{j\beta}^{t}$$



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- flavour basis $$i\frac{d}{dt}\left|\nu_\alpha\right\rangle = \hat{H}^{free}\left|\nu_\alpha\right\rangle = \sum_\beta E_{\alpha\beta}^{free}\left|\nu_\beta\right\rangle$$

with $$E_{\alpha\beta}^{free} = \tilde{N}_{\alpha i}^{*} H_{ij}^{free}\left(\tilde{N}^{*}\right)_{j\beta}^{-1} \neq H_{\alpha\beta}^{free} = \tilde{N}_{\alpha i}^{*} H_{ij}^{free}\tilde{N}_{j\beta}^{t}$$

$$P(\nu_\alpha \to \nu_\beta; L) = \frac{\left|\sum_i N_{\alpha i}^{*} e^{iP_i L} N_{\beta i}\right|^2}{\sum_j \left|N_{\alpha j}\right|^2 \sum_k \left|N_{\beta k}\right|^2}$$

Zero-distance effect:

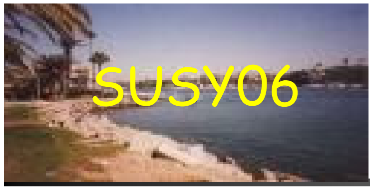
$$P(\nu_\alpha \to \nu_\beta; 0) \propto \left|\sum_i N_{\alpha i}^{*} N_{\beta i}\right|^2 \neq \delta_{\alpha\beta}$$

ν oscillation in matter

$$-L^{\text{int}} = \underbrace{\sqrt{2}G_F n_e}_{V_{CC}} \bar{\nu}_e \gamma^0 \nu_e - \underbrace{\frac{1}{\sqrt{2}} G_F n_n}_{V_{NC}} \sum_\alpha \bar{\nu}_\alpha \gamma^0 \nu_\alpha$$

2 families

$$i\frac{d}{dt}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \left[U^*\begin{pmatrix}E_1 & 0 \\ 0 & E_2\end{pmatrix}U^t + \begin{pmatrix}V_{CC} \cancel{-V_{NC}} & 0 \\ 0 & \cancel{-V_{NC}}\end{pmatrix}\right]\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix}$$



ν oscillation in matter

$$-L^{\text{int}} = \sqrt{2} G_F n_e \bar{\nu}_e \gamma^0 \nu_e - \frac{1}{\sqrt{2}} G_F n_n \sum_\alpha \bar{\nu}_\alpha \gamma^0 \nu_\alpha$$

$\sqrt{2} G_F n_e \rightarrow V_{CC}$ $\qquad$ $\frac{1}{\sqrt{2}} G_F n_n \rightarrow V_{NC}$

2 families

$$i\frac{d}{dt}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \left[U^* \begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix} U^t + \begin{pmatrix} V_{CC} - V_{NC} & 0 \\ 0 & -V_{NC} \end{pmatrix} \right] \begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix}$$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \left[N^* \begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix} (N^*)^{-1} + \begin{pmatrix} (V_{CC} - V_{NC}) \sum_i |N_{ei}|^2 & -V_{NC} \sqrt{\frac{\sum_i |N_{\mu i}|^2}{\sum_i |N_{ei}|^2}} \sum_i N^*_{ei} N_{\mu i} \\ (V_{CC} - V_{NC}) \sqrt{\frac{\sum_i |N_{ei}|^2}{\sum_i |N_{\mu i}|^2}} \sum_i N^*_{ei} N_{\mu i} & -V_{NC} \sum_i |N_{\mu i}|^2 \end{pmatrix} \right] \begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix}$$

1. non-diagonal elements
2. NC effects do not disappear

N elements from oscillations: e-row

- Only disappearance exps $\rightarrow$ informations only on $|N_{\alpha i}|^2$

CHOOZ: $\Delta_{12} \approx 0$

$$\Delta_{ij} = \Delta m^2_{ij} L / 2E$$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong \left(|N_{e1}|^2 + |N_{e2}|^2\right)^2 + |N_{e3}|^4 + 2\left(|N_{e1}|^2 + |N_{e2}|^2\right)|N_{e3}|^2 \cos(\Delta_{23})$$

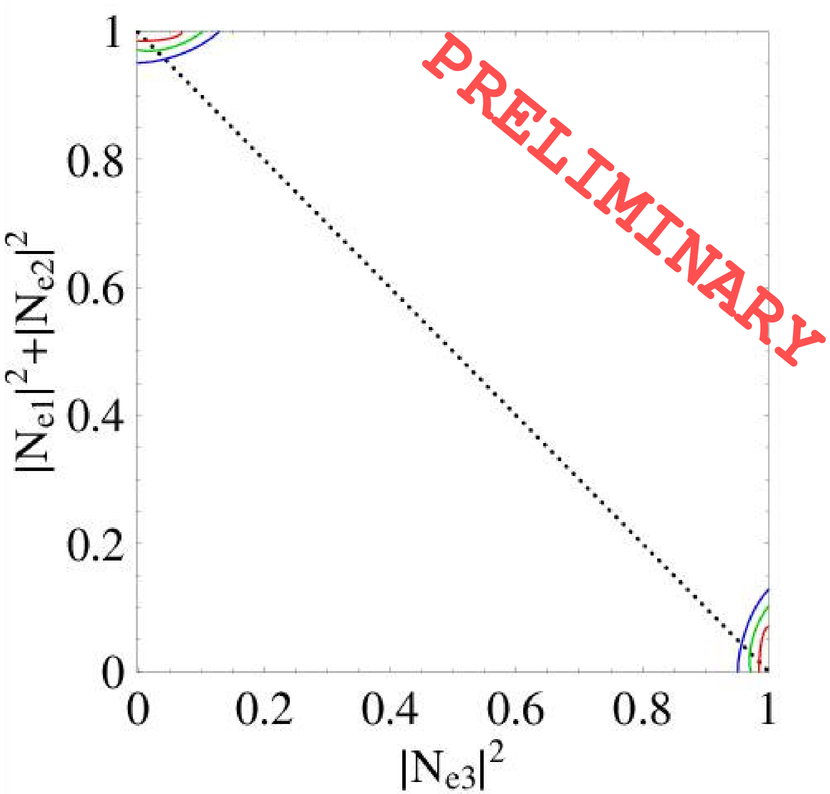
K2K ($\nu_\mu \rightarrow \nu_\mu$): Δ_{23}

1. Degeneracy

$$|N_{e1}|^2 + |N_{e2}|^2 \leftrightarrow |N_{e3}|^2$$

2. $|N_{e1}|^2$, $|N_{e2}|^2$

cannot be disentangled



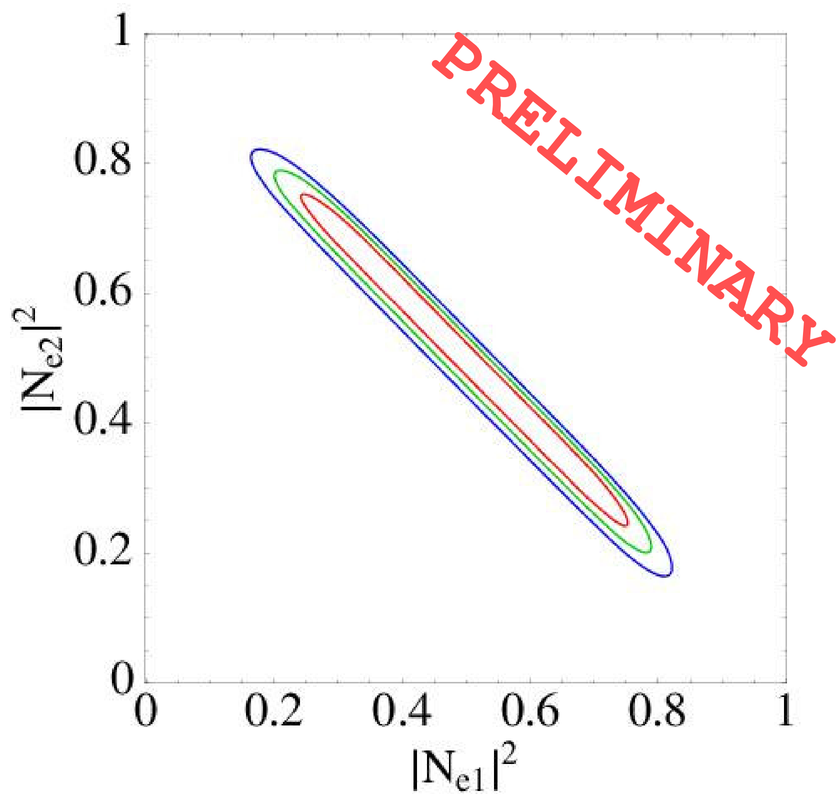
N elements from oscillations: e -row

KamLAND: $\Delta_{23} >> 1$

$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong |N_{e1}|^4 + |N_{e2}|^4 + |N_{e3}|^4 + 2|N_{e1}|^2 |N_{e2}|^2 \cos(\Delta_{12})$$

$$\begin{cases} |N_{e1}|^2 + |N_{e2}|^2 \approx 1 \\ |N_{e3}|^2 \approx 0 \end{cases}$$

$\rightarrow$ first degeneracy solved



$\mathcal{N}$ elements from oscillations: *e* -row

KamLAND: $\Delta_{23} >> 1$

$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong |N_{e1}|^4 + |N_{e2}|^4 + |N_{e3}|^4 + 2|N_{e1}|^2|N_{e2}|^2 \cos(\Delta_{12})$$

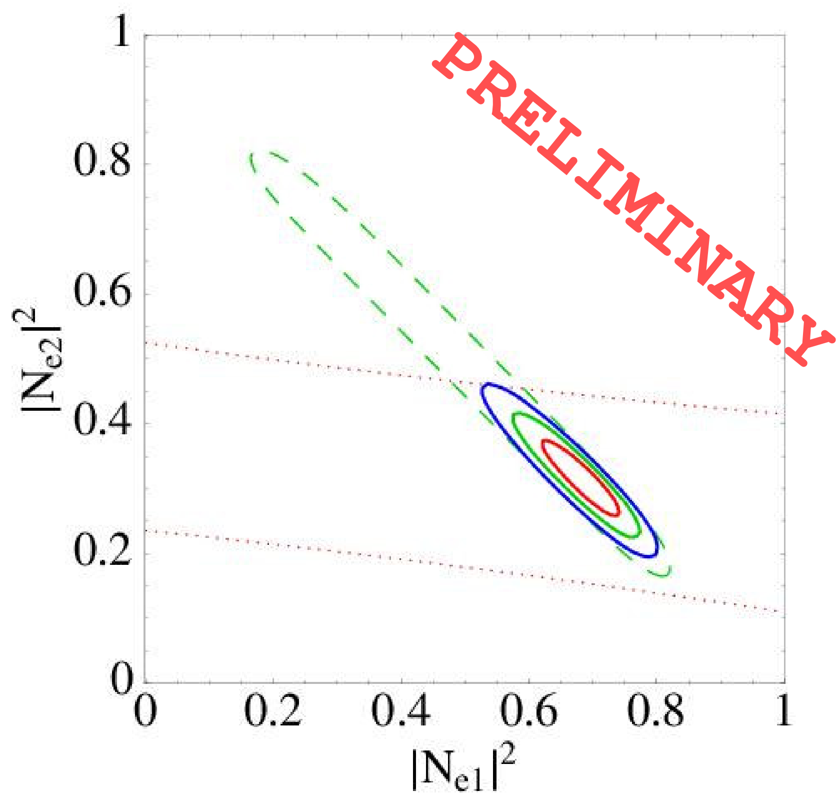
$$\begin{cases} |N_{e1}|^2 + |N_{e2}|^2 \approx 1 \\ |N_{e3}|^2 \approx 0 \end{cases}$$

$\rightarrow$ first degeneracy solved

SNO:

$$P(\nu_e \to \nu_e) \cong 0.1|N_{e1}|^2 + 0.9|N_{e2}|^2$$

$\rightarrow$ all $|N_{ei}|^2$ determined



N elements from oscillations: μ -row

Atmospheric + K2K: $\Delta_{12} \approx 0$

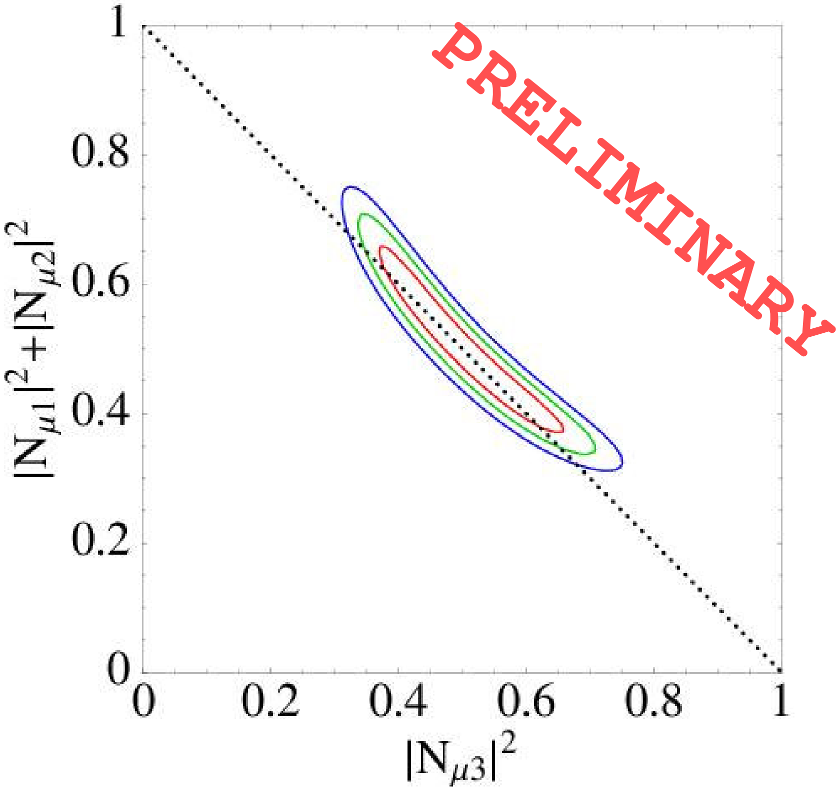
$$P(\nu_\mu \to \nu_\mu) \cong \left(|N_{\mu 1}|^2 + |N_{\mu 2}|^2\right)^2 + |N_{\mu 3}|^4 + 2\left(|N_{\mu 1}|^2 + |N_{\mu 2}|^2\right)|N_{\mu 3}|^2 \cos(\Delta_{23})$$

1. Degeneracy

$$|N_{\mu 1}|^2 + |N_{\mu 2}|^2 \leftrightarrow |N_{\mu 3}|^2$$

2. $|N_{\mu 1}|^2$, $|N_{\mu 2}|^2$

cannot be disentangled



N elements from oscillations only

with unitarity
OSCILLATIONS

$$|U|^2 = \begin{pmatrix} 0.62-0.77 & 0.22-0.37 & <0.04 \\ 0.04-0.27 & 0.18-0.53 & 0.34-0.67 \\ 0.04-0.28 & 0.19-0.55 & 0.31-0.66 \end{pmatrix}$$

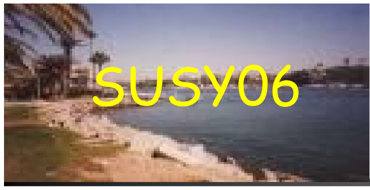
M. C. Gonzalez Garcia hep-ph/0410030

3σ

without unitarity
OSCILLATIONS

$$|N|^2 = \begin{pmatrix} 0.58-0.80 & 0.20-0.44 & <0.13 \\ \left[|N_{\mu 1}|^2 + |N_{\mu 2}|^2 \right. & \left. = \quad 0.32-0.73 \right] & 0.32-0.73 \\ ? & ? & ? \end{pmatrix}$$

PRELIMINARY



(NN^{+}) from decays

- W decays $\rightarrow \dfrac{(NN^{+})_{\alpha\alpha}}{\sqrt{(NN^{+})_{ee}}\sqrt{(NN^{+})_{\mu\mu}}}$
- Invisible Z $\rightarrow \dfrac{\sum_{ij}(N^{+}N)_{ij}}{\sqrt{(NN^{+})_{ee}}\sqrt{(NN^{+})_{\mu\mu}}}$
- Universality tests $\rightarrow \dfrac{(NN^{+})_{\alpha\alpha}}{(NN^{+})_{\beta\beta}}$
- Rare leptons decays $\rightarrow \dfrac{\left|(NN^{+})_{\beta\alpha}\right|^{2}}{(NN^{+})_{\alpha\alpha}(NN^{+})_{\beta\beta}}$

(NN^{+}) from decays

- W decays $\rightarrow \dfrac{(NN^{+})_{\alpha\alpha}}{\sqrt{(NN^{+})_{ee}}\sqrt{(NN^{+})_{\mu\mu}}}$
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- Rare leptons decays $\rightarrow \dfrac{\left|(NN^{+})_{\beta\alpha}\right|^{2}}{(NN^{+})_{\alpha\alpha}(NN^{+})_{\beta\beta}}$

$\rightarrow$ Global fit

90% cl $$\left|NN^{+}\right| \approx \begin{pmatrix} 1.002 \pm 0.005 & < 7.2\cdot 10^{-5} & < 1.6\cdot 10^{-2} \\ < 7.2\cdot 10^{-5} & 1.003 \pm 0.005 & < 1.3\cdot 10^{-2} \\ < 1.6\cdot 10^{-2} & < 1.3\cdot 10^{-2} & 1.003 \pm 0.005 \end{pmatrix}$$

PRELIMINARY

$\rightarrow$ N is unitary at % level

N elements from oscillations & decays

with unitarity
OSCILLATIONS

$$|U|^2 = \begin{pmatrix} 0.62-0.77 & 0.22-0.37 & <0.04 \\ 0.04-0.27 & 0.18-0.53 & 0.34-0.67 \\ 0.04-0.28 & 0.19-0.55 & 0.31-0.66 \end{pmatrix}$$

M. C. Gonzalez Garcia hep-ph/0410030

3σ

without unitarity
OSCILLATIONS
+DECAYS

$$|N|^2 = \begin{pmatrix} 0.57-0.79 & 0.21-0.43 & <0.04 \\ 0.04-0.30 & 0.17-0.54 & 0.33-0.67 \\ 0.01-0.33 & 0.10-0.58 & 0.29-0.70 \end{pmatrix}$$

PRELIMINARY

In the future…

MEASUREMENT OF MATRIX ELEMENTS

- $|N_{e3}|^2$, μ-row → MINOS, T2K, Super-Beams, ν Factories…
- τ-row → high energies: ν Factories
- phases → *appearance* experiments: Super-Beams, ν Factories, β-beams

TESTS OF UNITARITY

Rare leptons decays (present)

- $\mu \to e\gamma$ $\quad |\sum_i N_{ei} N^*_{\mu i}|^2 < 7.2 \cdot 10^{-5}$
- $\tau \to e\gamma$ $\quad |\sum_i N_{ei} N^*_{\tau i}|^2 < 0.016$
- $\tau \to \mu\gamma$ $\quad |\sum_i N_{\mu i} N^*_{\tau i}|^2 < 0.013$

ZERO-DISTANCE EFFECT

Near detector at a ν factory

- $\nu_e \to \nu_\mu$ $\quad |\sum_i N_{ei} N^*_{\mu i}|^2 < 2.3 \cdot 10^{-4}$
- $\nu_e \to \nu_\tau$ $\quad |\sum_i N_{ei} N^*_{\tau i}|^2 < 2.9 \cdot 10^{-3}$
- $\nu_\mu \to \nu_\tau$ $\quad |\sum_i N_{\mu i} N^*_{\tau i}|^2 < 2.6 \cdot 10^{-3}$

Conclusions

If we don’t assume unitarity for the lepton mixing matrix

- Present oscillation experiments can only measure half the elements
- EW decays confirms unitarity at % level
- Combining oscillations and decays, bounds for all the elements can be found comparable with the ones obtained with the unitary analysis

Future experiments can:

- improve the present measurements on the e - and μ - rows
- give information on the τ-row and on phases (appearance exps)
- test unitarity by constraining the zero-distance effect with a near detector
- discriminate among different NP scenarios

Non-unitarity from see-saw

$$L = L_{SM} + i\bar{N}_R \partial N_R - Y_\nu \left(\bar{l}_L \tilde{H} N_R + \bar{N}_R \tilde{H}^+ l_L\right) - \frac{1}{2} M \left(\bar{N}_R^c N_R + \bar{N}_R N_R^c\right)$$

Integrate out N_R

$$L^{eff} = L_{SM} + \frac{1}{\Lambda} L^{d=5} + \frac{1}{\Lambda^2} L^{d=6} + \ldots$$

$$-\frac{1}{4}\left(\bar{\tilde{l}}_{L\alpha} \vec{\tau} \left[Y_\nu^* \frac{\eta}{M} Y_\nu^+\right]_{\alpha\beta} l_{L\beta}\right)\left(\tilde{H}^+ \vec{\tau} H\right)$$

d=5 operator
it gives mass to ν

$$\left(\bar{l}_{L\alpha} \tilde{H}\right) i\partial \left[Y_\nu \frac{1}{M^2} Y_\nu^+\right]_{\alpha\beta} \left(\tilde{H}^+ l_{L\beta}\right)$$

d=6 operator
it renormalises kinetic energy

Broncano, Gavela, Jenkins 02

SUSY06

In a real experiment…

$$n_{ev} \sim \int dE \frac{d\Phi_\alpha}{dE} P_{\alpha\beta}(E)\sigma_\beta(E)\varepsilon(E)$$

ν produced in CC $\quad \dfrac{d\Phi_\alpha}{dE} \sim \sum_i |N_{\alpha i}|^2 \dfrac{d\Phi_\alpha^{SM}}{dE}$

ν detected in CC $\quad \sigma_\beta \sim \sum_i |N_{\beta i}|^2 \sigma_\beta^{SM}$

$$n_{ev} \sim \int dE \frac{d\Phi_\alpha^{SM}}{dE} \underbrace{\sum_i |N_{\alpha i}|^2 P_{\alpha\beta}(E) \sum_i |N_{\beta i}|^2}\sigma_\beta^{SM}(E)\varepsilon(E)$$

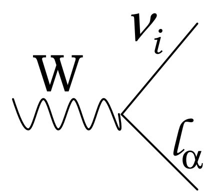
$$\rightarrow \hat{P}(\nu_\alpha \to \nu_\beta; L) = \left| \sum_i N_{\alpha i}^* e^{iP_i L} N_{\beta i} \right|^2$$

Exceptions:

- flux measured: no $\sum_i |N_{\alpha i}|^2$
- detection via NC: $\sum_i |N_{\beta i}|^2$ replaced by $\sum_{i,j} |N_{\alpha i}^* N_{\alpha j}|^2$
- production via μ or τ decay: flux corrected by 2 factors $\sum_i |N_{\alpha i}|^2 \sum_j |N_{\beta j}|^2$

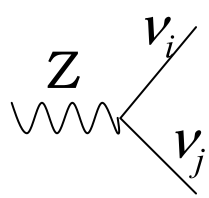
$(NN^\dagger)$ from decays: G_F

- W decays



$$\rightarrow \frac{(NN^+)_{\alpha\alpha}}{\sqrt{(NN^+)_{ee}}\sqrt{(NN^+)_{\mu\mu}}}$$

- Invisible Z



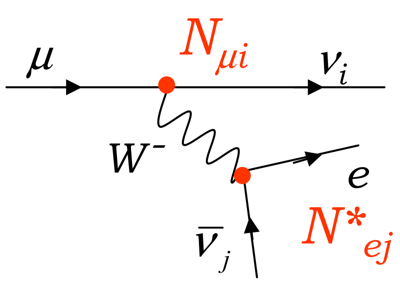
$$\rightarrow \frac{\sum_{ij} (N^+N)_{ij}}{\sqrt{(NN^+)_{ee}}\sqrt{(NN^+)_{\mu\mu}}}$$

- Universality tests

$$\rightarrow \frac{(NN^+)_{\alpha\alpha}}{(NN^+)_{\beta\beta}}$$

Infos on $(NN^\dagger)_{\alpha\alpha}$

G_F is measured in μ-decay



$$\Gamma = \frac{G_F^2 m_\mu^5}{192\pi^3} \sum_i |N_{\mu i}|^2 \sum_j |N_{ej}|^2$$

$$G_F^2 = \frac{G_{F,\exp}^2}{\sum_i |N_{\mu i}|^2 \sum_j |N_{ej}|^2}$$

SUSY06

$(NN^\dagger)$ and $(N^\dagger N)$ from decays

PRELIMINARY

$$|NN^+| \approx \begin{pmatrix} 1.002 \pm 0.005 & < 7.2\cdot 10^{-5} & < 1.6\cdot 10^{-2} \\ < 7.2\cdot 10^{-5} & 1.003 \pm 0.005 & < 1.3\cdot 10^{-2} \\ < 1.6\cdot 10^{-2} & < 1.3\cdot 10^{-2} & 1.003 \pm 0.005 \end{pmatrix}$$

Experimentally

$$N = HV \qquad NN^+ = H^2 = 1 + \varepsilon \quad \text{with } \varepsilon = \varepsilon^+$$

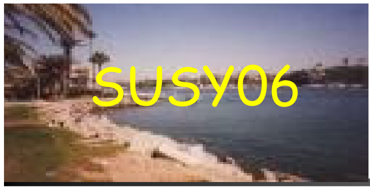
$$N^+N = 1 + V^+\varepsilon V = 1 + \varepsilon'$$

$$|\varepsilon'_{ij}| \le \sqrt{\sum_{\alpha\beta} |\varepsilon_{\alpha\beta}|^2} \approx 0.03$$

$$|N^+N| \approx \begin{pmatrix} 1.00 \pm 0.032 & < 0.032 & < 0.032 \\ < 0.032 & 1.00 \pm 0.032 & < 0.032 \\ < 0.032 & < 0.032 & 1.00 \pm 0.032 \end{pmatrix}$$

Estimation
(the most conservative)

→ N is unitary at % level

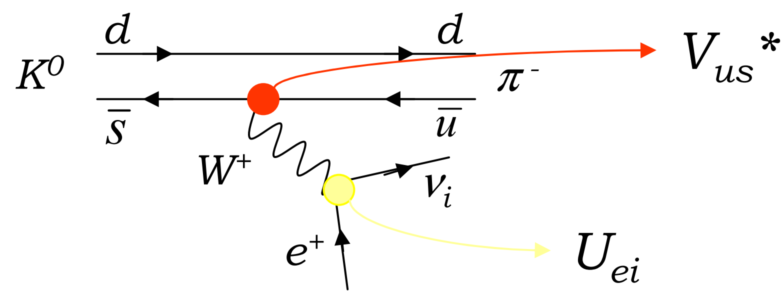


Unitarity in the quark sector

Quarks are detected as mass eigenstates

$\rightarrow$ we can directly measure $|V_{ab}|$

ex: $|V_{us}|$ from $K^0 \rightarrow \pi^- e^+ \nu_e$

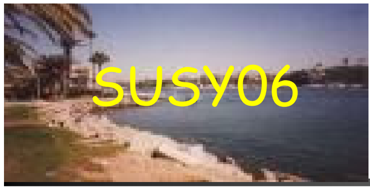


$\rightarrow \quad \sum_i |U_{ei}|^2 = 1$ if U unitary

With V_{ab} we check unitarity conditions:

ex: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0008 \pm 0.0011$

$\rightarrow$ *Measurements of V_{CKM} elements relies on U_{PMNS} unitarity*



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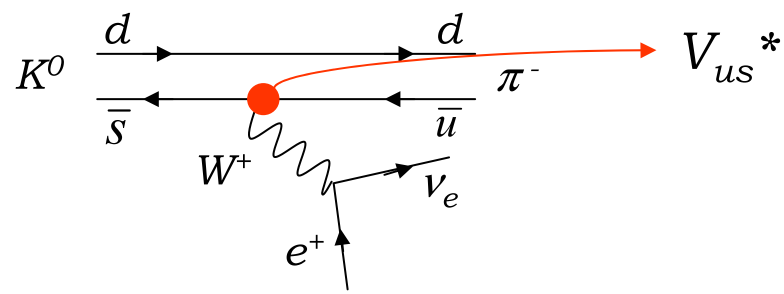

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With leptons:

- decays $\rightarrow$ only $(NN^\dagger)$ and $(N^\dagger N)$
- N elements $\rightarrow$ we need oscillations
- to study the unitarity of N: no assumptions on V_{CKM}