CP violations in Lepton Number Violation Process and Neutrino Oscillations

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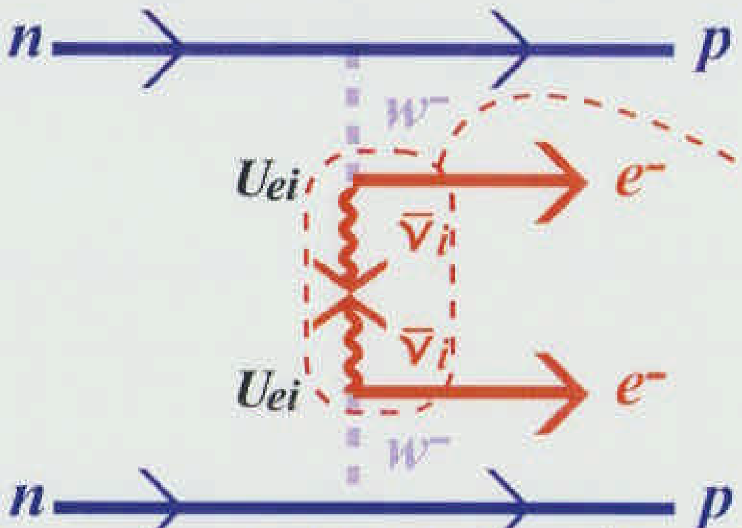
1. Restriction by ○ and △

(1)



Neutrinoless Double Beta Decay ($(\beta\beta)_{0\nu}$)

Complex mass triangle

(1) The decay ratio of $(\beta\beta)_{0\nu}$ is proportional to the averaged mass. The averaged mass is given as follows.

$$\langle m_\nu \rangle \equiv \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{2i\beta} + |U_{e3}|^2 m_3 e^{2i(\rho-\delta)} \right|$$

$$\equiv \left| |U_{e1}|^2 \tilde{m}_1 + |U_{e2}|^2 \tilde{m}_2 + |U_{e3}|^2 \tilde{m}_3 \right|$$

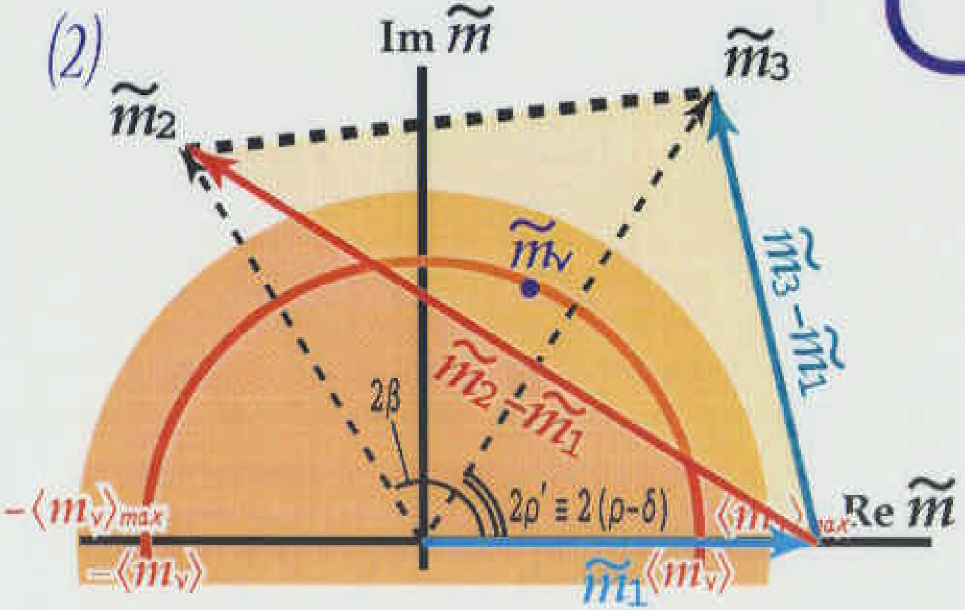
$$= \left| \tilde{m}_1 + |U_{e2}|^2 (\tilde{m}_2 - m_1) + |U_{e3}|^2 (\tilde{m}_3 - m_1) \right|$$

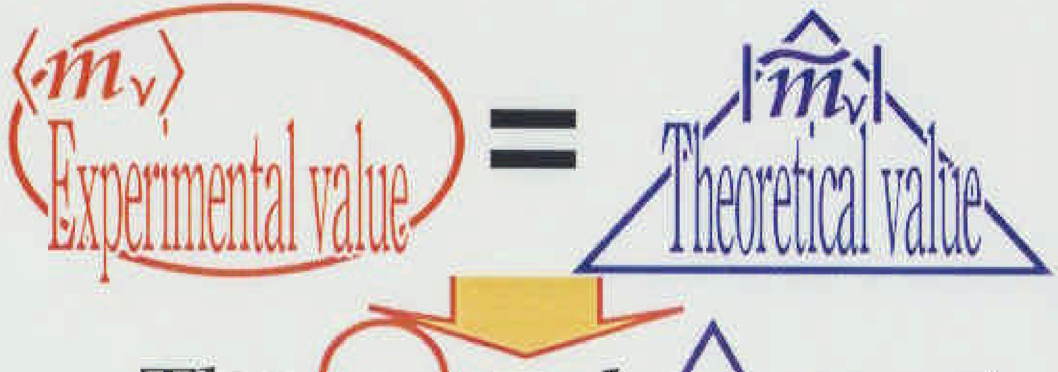
$$\equiv |\tilde{m}_\nu| \lesssim 0.2[\mathrm{eV}] \equiv \langle m_\nu \rangle_{max}$$

$$0 \leqslant |U_{e2}|^2 + |U_{e3}|^2 = 1 - |U_{e1}|^2 \leqslant 1$$

$$(U_{e1} \equiv |U_{e1}|,\ U_{e2} \equiv |U_{e2}| e^{i\beta},\ U_{e3} \equiv |U_{e3}| e^{i(\rho-\delta)} \equiv |U_{e3}| e^{i\rho'})$$

(2)





The ○ and △ must overlap each other!

2. Examples

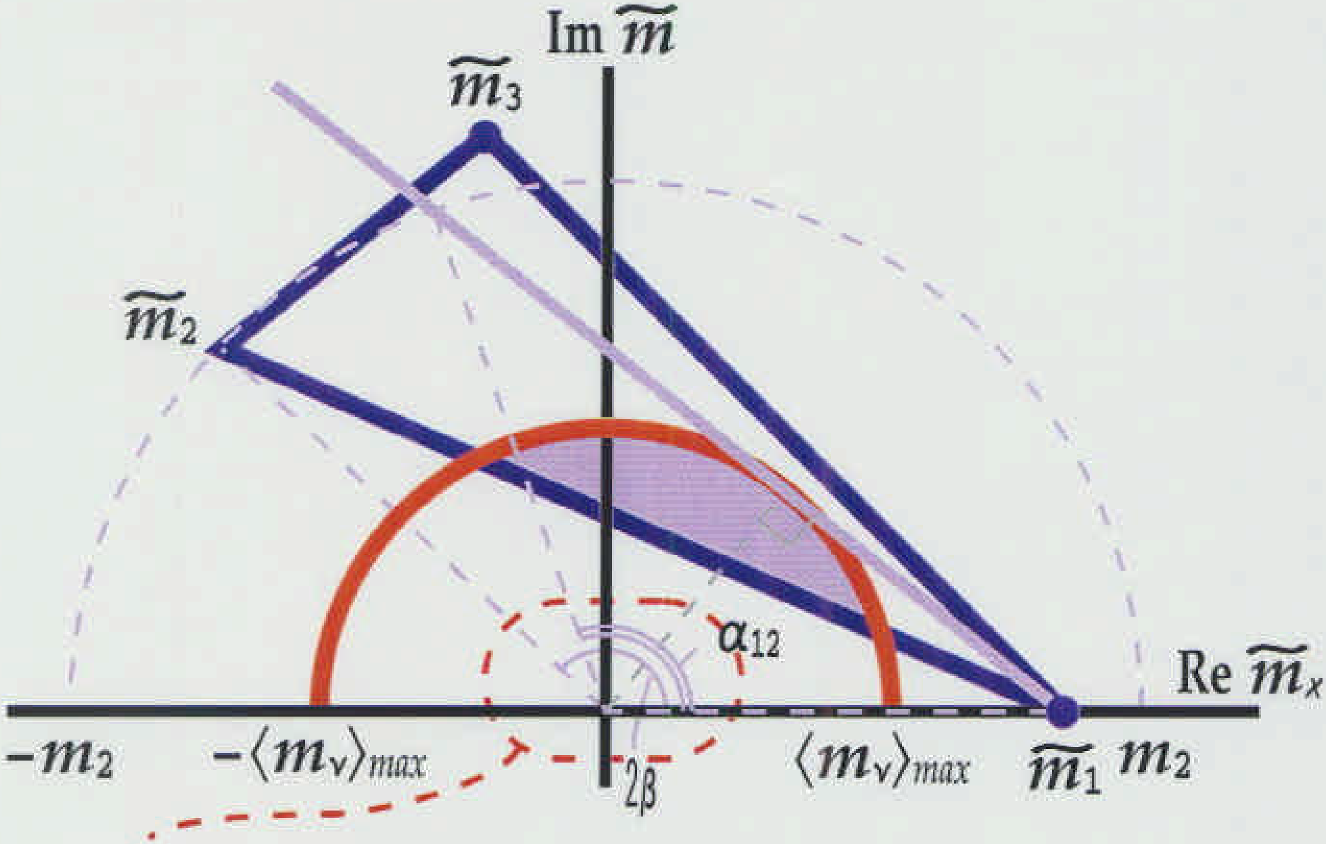
Constraints on CP phases

(2) Using the graphical representation, even if the upper limit, $\langle m_\nu \rangle_{max}$, is only obtained, we can easily derive constraints on the CP phases.

(3) In order that the triangle can overlap with the circle whose radius is $\langle m_\nu \rangle_{max}$, the CP phases must satisfy the following condition.

$$|\arg(\tilde{m}_j/\tilde{m}_i)| \geq \alpha_{ij}$$

which is independent of the mixing elements.



$$2\beta \geq \alpha_{12} \equiv \cos^{-1}(m_1/\langle m_\nu \rangle_{max}) + \cos^{-1}(m_2/\langle m_\nu \rangle_{max})$$

The allowed condition

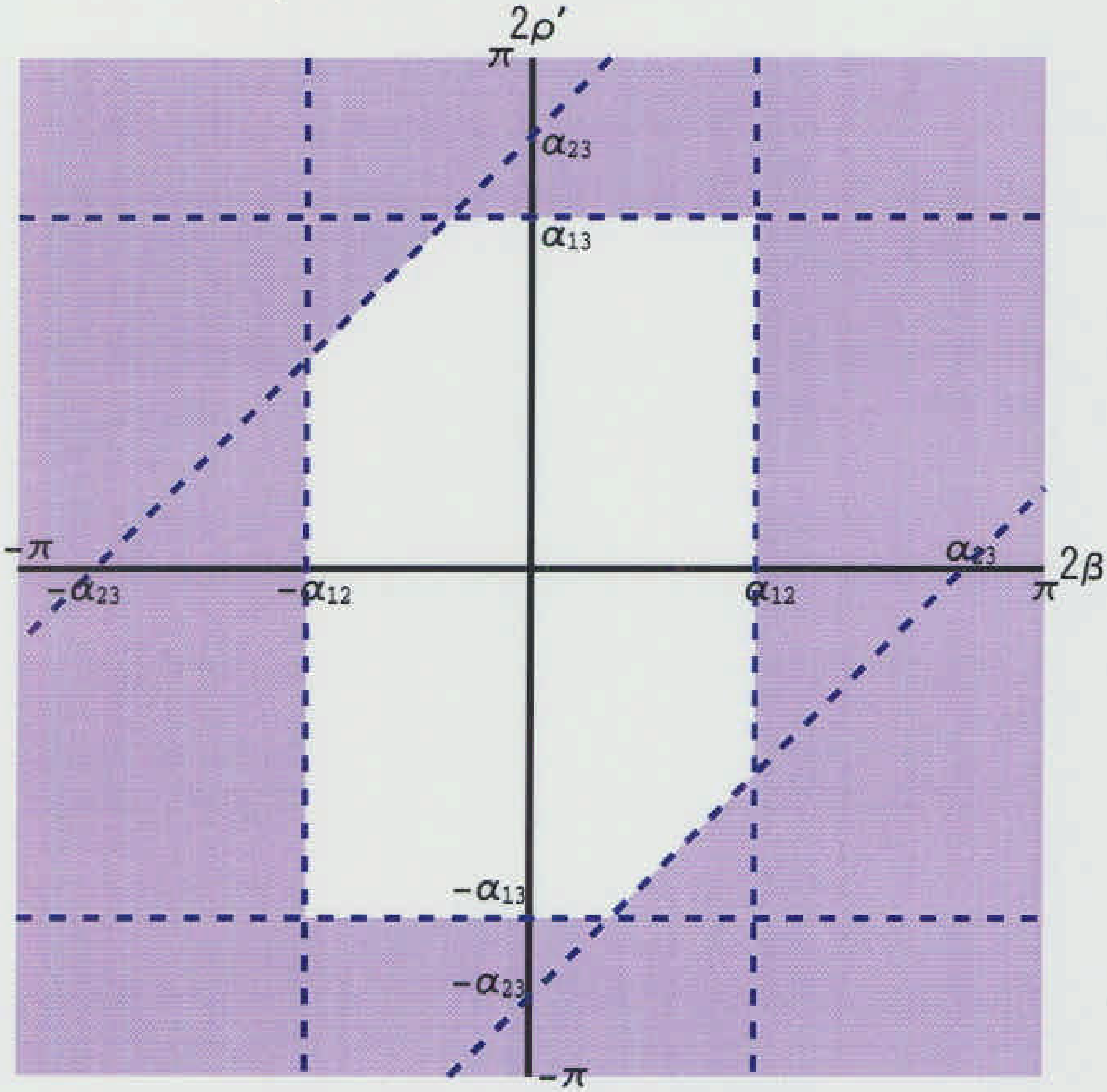
(4) *In order that the triangle can overlap with the circle whose radius is $\langle m_\nu \rangle_{max}$, the CP phases must satisfy the following condition.*

$$\alpha_{ij} \leq |\arg(\tilde{m}_j/\tilde{m}_i)|$$

$$\rightarrow \alpha_{12} \leq |2\beta| \quad \alpha_{13} \leq |2\rho'| \quad \alpha_{23} \leq |2\beta - 2\rho'|$$

$$\left(\alpha_{ij} \equiv \cos^{-1}\frac{\langle m_\nu \rangle}{m_i} + \cos^{-1}\frac{\langle m_\nu \rangle}{m_j} \right)$$

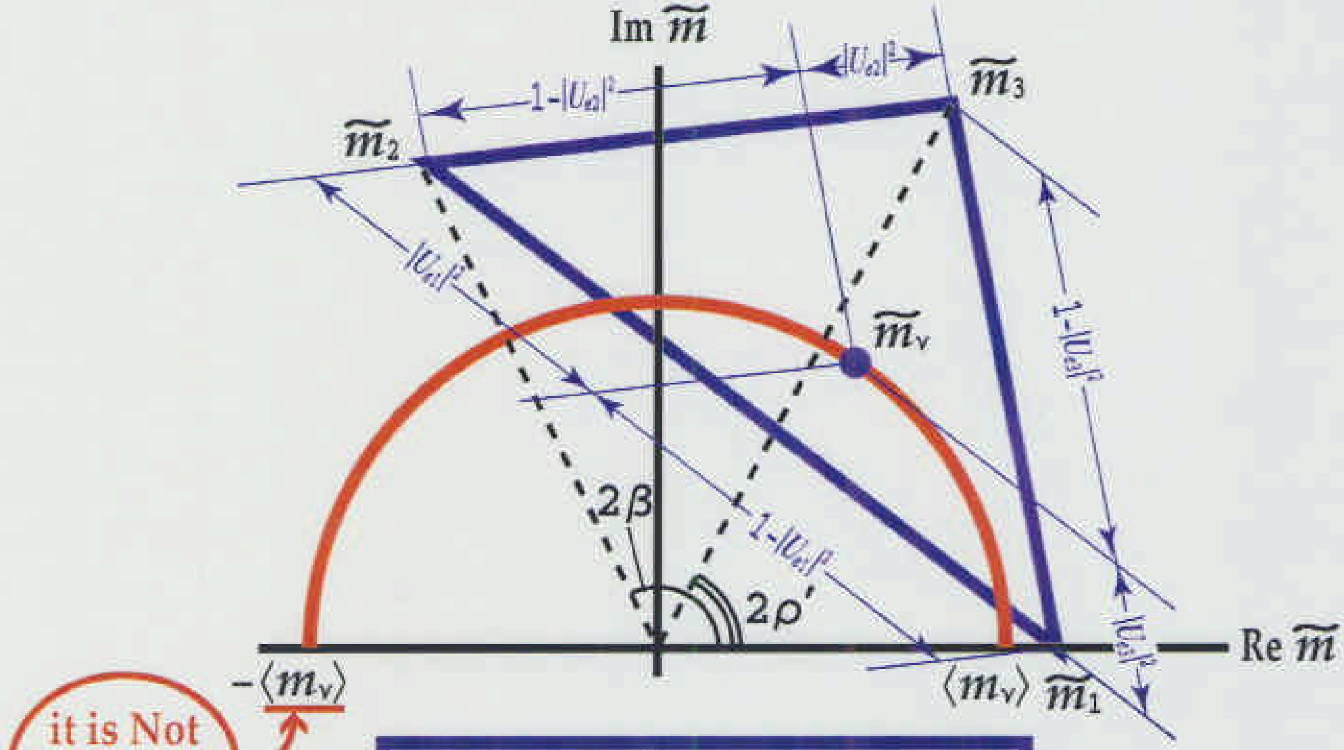
which is independent of the mixing elements.



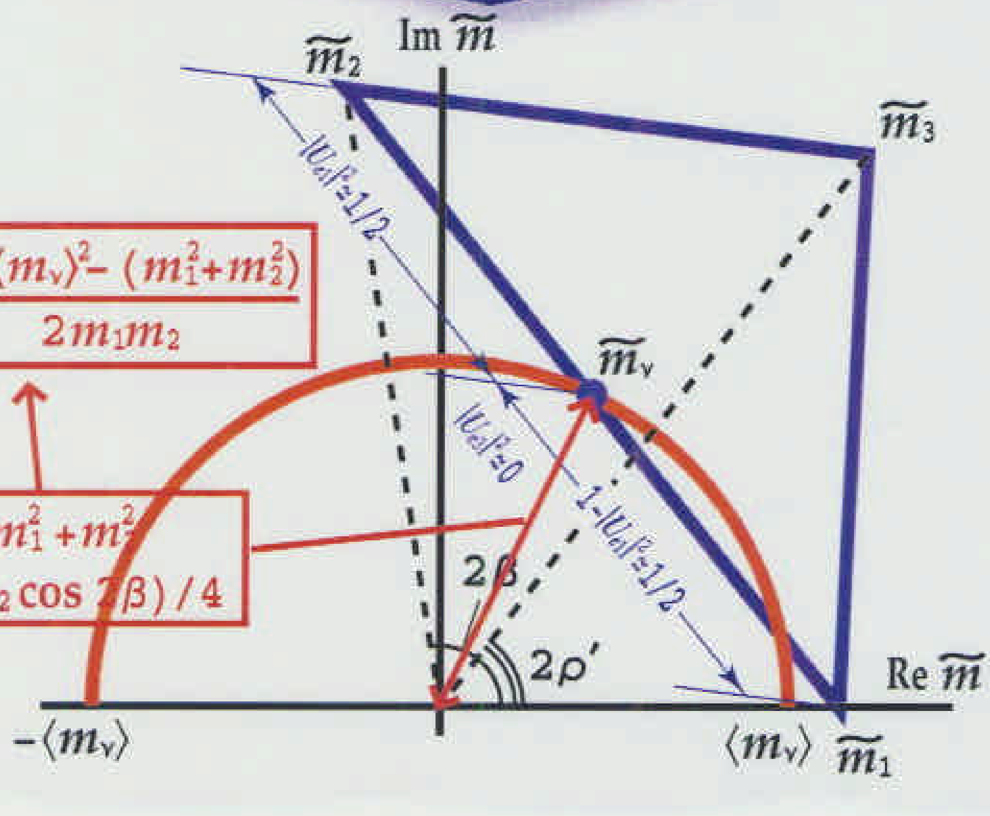
In the white area, the triangle can not overlap with the circle.

Relation between the triangle and $\langle m_\nu \rangle$

(5) The mixing elements $|U_{ei}|$ are expressed as the ratios of the heights from vertices $\widetilde{m}_i$ separeated by $\widetilde{m}_\nu$.



$|U_{e1}|^2 = |U_{e2}|^2 = 1/2$, $|U_{e3}|^2 = 0$
(Solar MSW LMA or Just So) (CHOOZ)

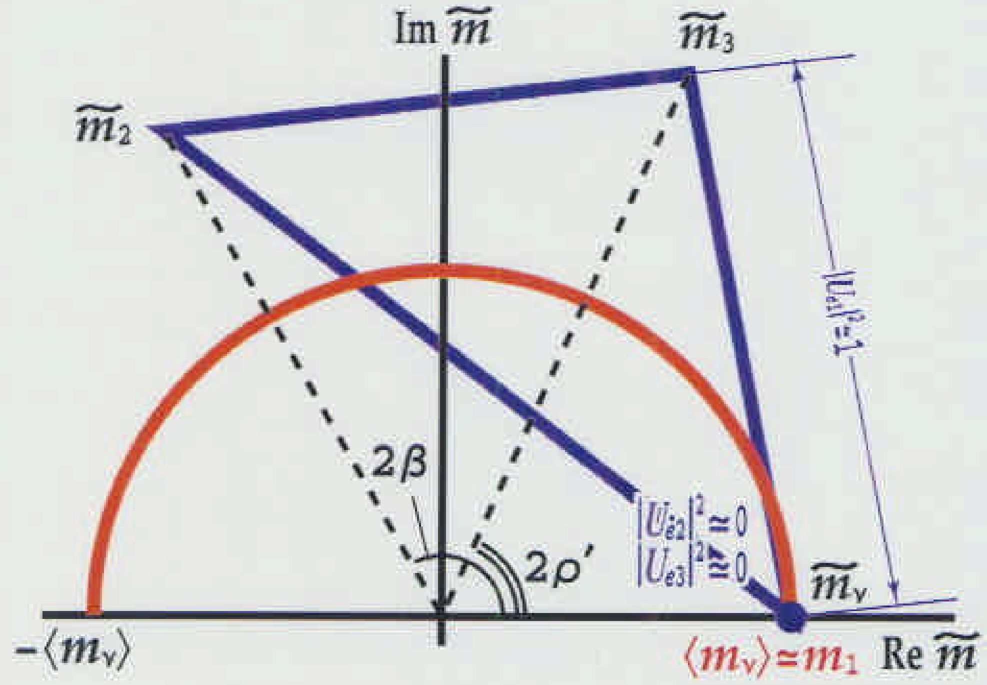


$$\cos 2\beta = \frac{4\langle m_\nu \rangle^2 - (m_1^2 + m_2^2)}{2 m_1 m_2}$$

$$\langle m_\nu \rangle^2 = (m_1^2 + m_2^2 + 2 m_1 m_2 \cos 2\beta)/4$$

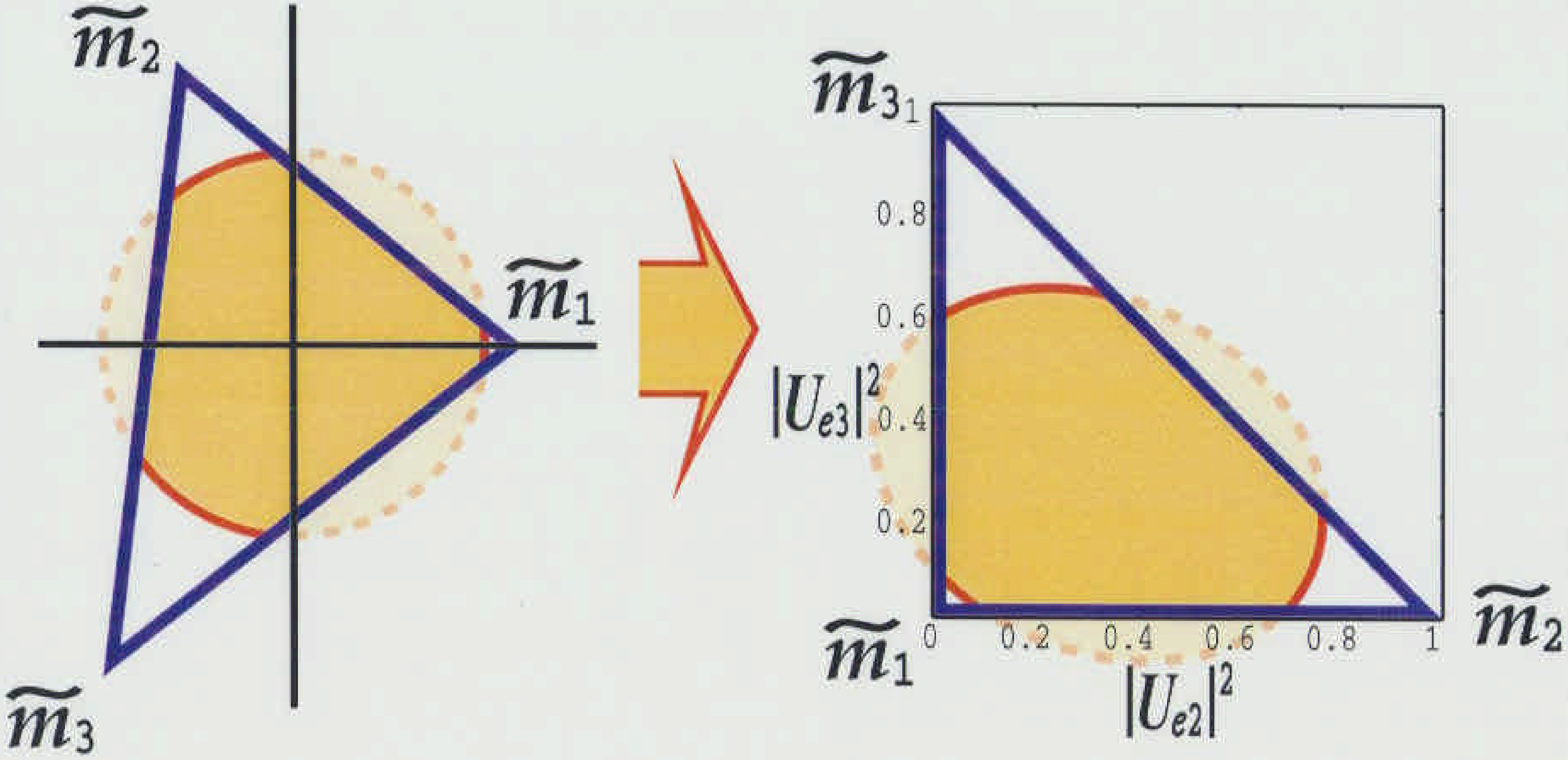
$|U_{e1}|^2 = 1, |U_{e2}|^2 = 0, \quad |U_{e3}|^2 = 0$

(Solar MSW SMA) (CHOOZ)



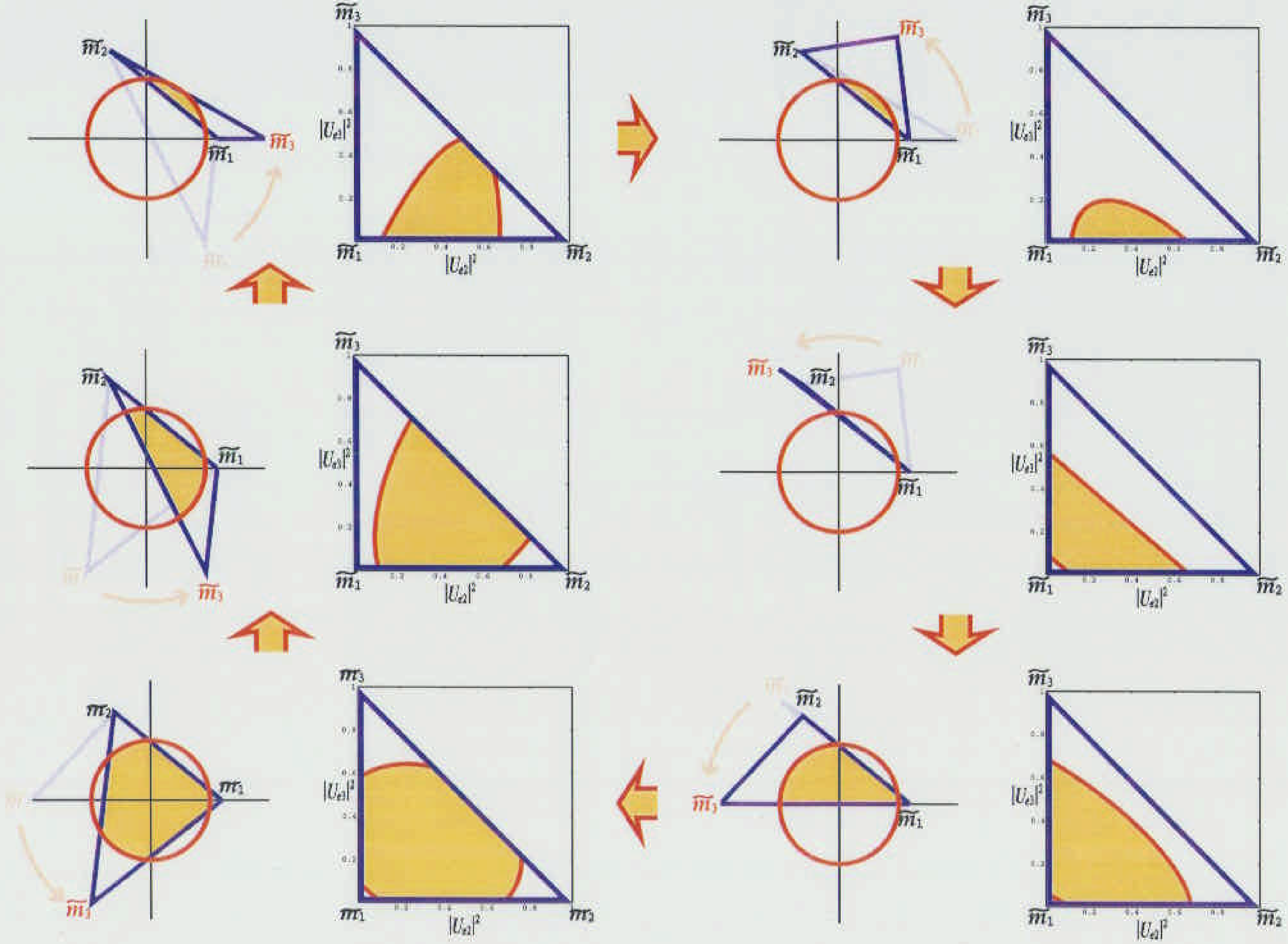
Constraints on mixing angles for fixed CP phases

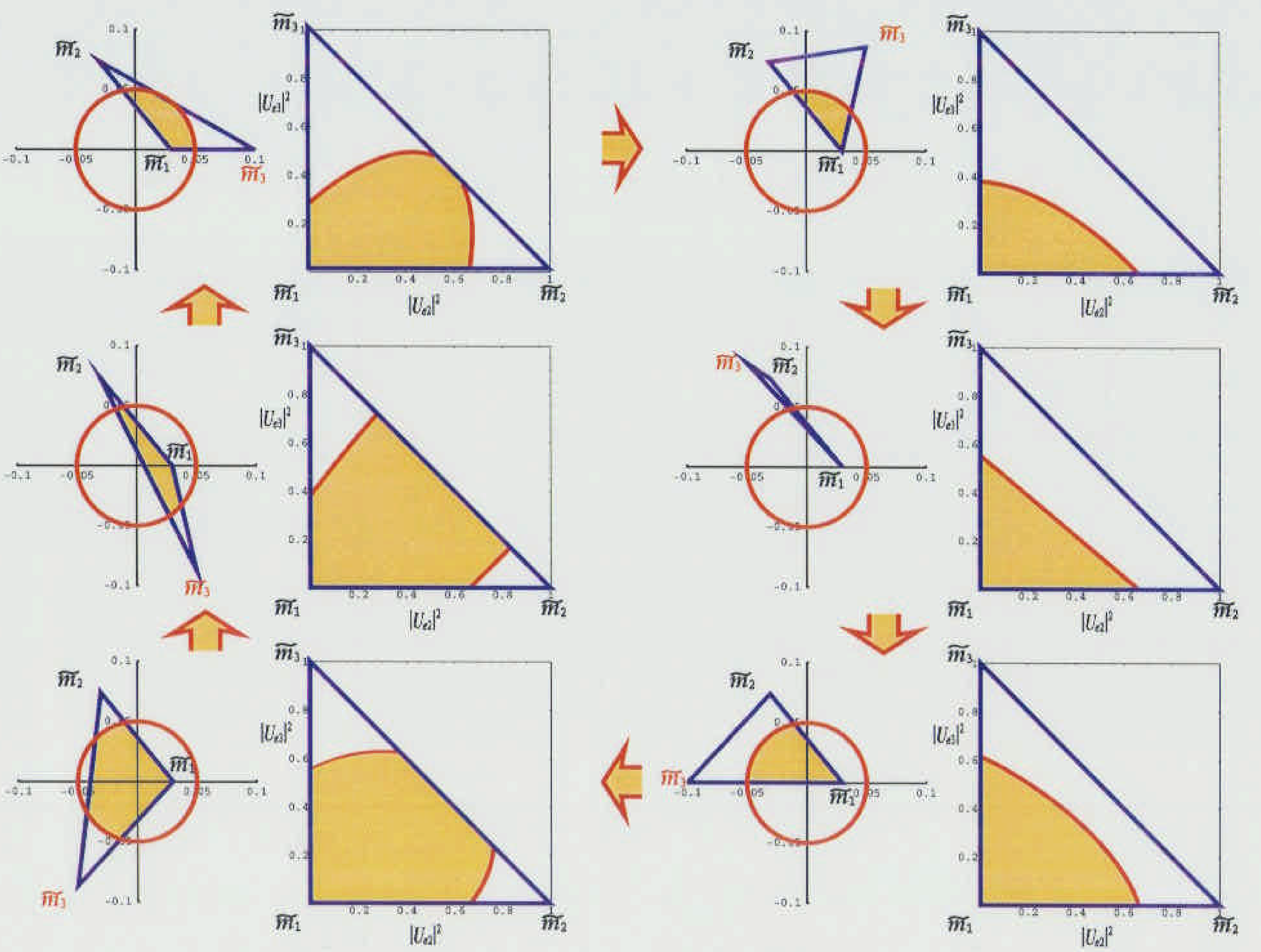
(6) *Using the isosceles right triangle deformed from an arbitrary triangle,*



we can also derive constraints on the mixing element, easily.

As taking $2\rho'$ every $\pi/3$, the allowed region of mixing elements change as follows.




$\tilde{m}_1$
$\tilde{m}_2$
$\tilde{m}_3$
$|U_{e2}|^2$
$|U_{e3}|^2$

3. Summary

(i) We have introduced the graphical representation of $\not{CP}$ effects in the lepton # violation process.

(ii) By using our graphical representation, $\not{CP}$ phases can be constrained, easily.

(iii) By combining the data of ν oscillation, the constraint becomes more severe.