ニュートリノ振動とLFV

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1. ニュートリノ振動

Maki, Nakagawa, Sakata

相互作用の固有状態　≠　質量の固有状態　（実際の粒子）

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\alpha i} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

ニュートリノの生成観測　：　相互作用を必要とする。

荷電レプトンの相方

ニュートリノの伝搬　：　粒子として伝搬。質量の固有状態。

伝搬に複数の経路

複数の状態の量子力学的干渉

＝ニュートリノ振動

Parametrisation of lepton mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\alpha i} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor eigenstates

Mass eigenstates

Atmospheric ν,
Accelerator ν experiments
(K2K, MINOS, T2K..)

θ_{23} ~ 45°
Δm^2_{23} ~ 2.5×10^{-3} (eV^2)

Reactor ν,
Accelerator ν,
Atm. ν

$\sin^2 2\theta_{13}$ ~0.025

Solar ν,
Reactor
ν

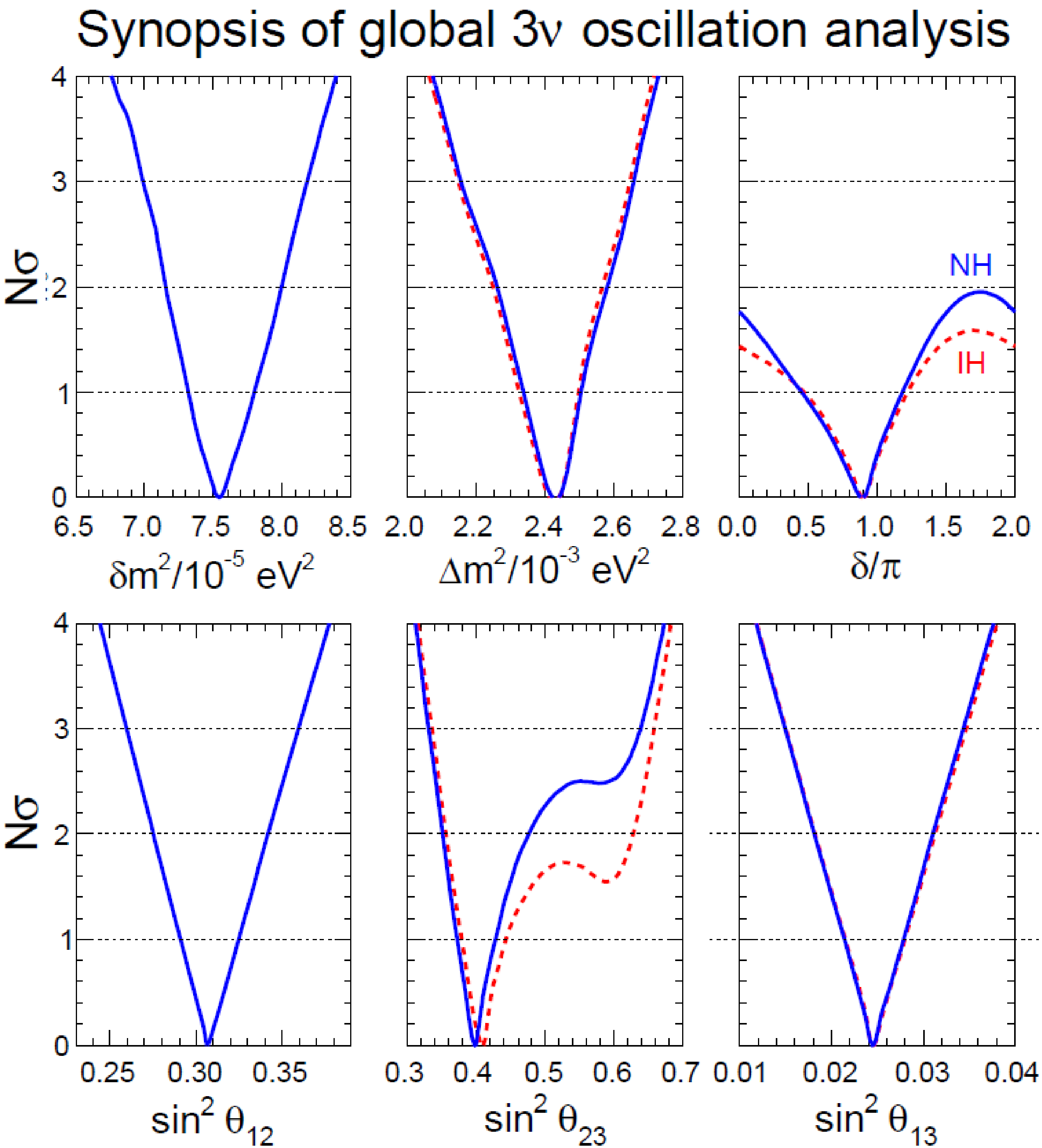
$\sin^2\theta_{12}$ ~ 0.31
Δm^2_{12} ~ 7.5×10^{-5} (eV^2)

$$P(n_a \to n_b)$$

$$= d_{ab} - 4 \cdot \sum_{i>j} \mathrm{Re}\left(U^*_{ai} U_{bi} U_{aj} U^*_{bj}\right) \cdot \sin^2 F_{ij} \pm 2 \cdot \sum_{i>j} \mathrm{Im}\left(U^*_{ai} U_{bi} U_{aj} U^*_{bj}\right) \cdot \sin^2 2F_{ij}$$

$$\sin^2 2F_{ij} = D m^2_{ij} L / 4E = 1.27 \times m^2_{ij} (\mathrm{eV}^2) L(\mathrm{km}) / E(\mathrm{GeV})$$

Lepton SectorではCPは破れているのか？

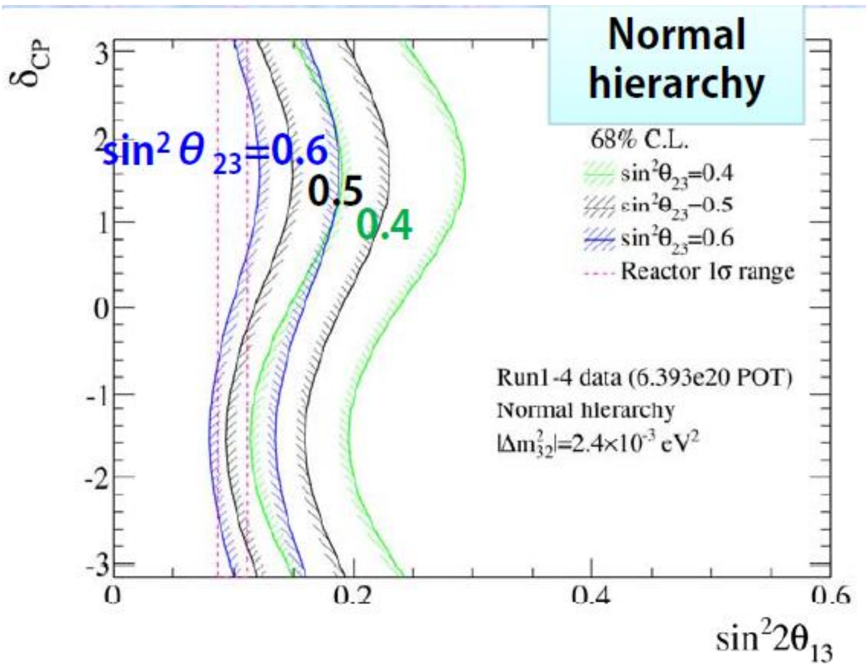


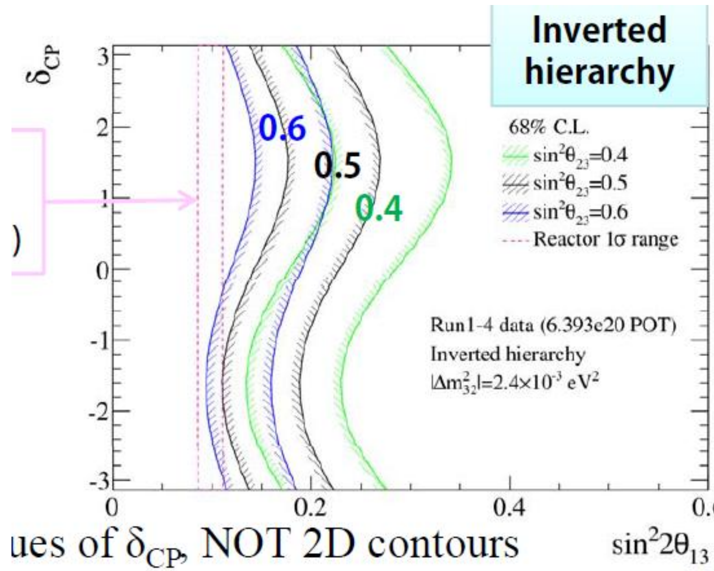
Fogli *et al* 1205.5254

混合角
ほぼ確定
！？

CPは？

KEK Seminar at 7/19





- normal hierarchy

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

- inverted hierarchy:

$$\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}$$

Assuming
$|\Delta m^2_{32}|=2.4\times10^{-3}$ eV^2
$\sin^2 2\theta_{23}=1.0$

PDG2012
reactor average
value (0.098±0.013)

VS

差を埋めるのはCPV?????

2. CPの破れ--- 粒子と反粒子の違いとして

自己紹介もかねて

VOLUME 55, NUMBER 3 1 FEBRUARY 1997

CP and T violation tests in neutrino oscillation

Jiro Arafune* and Joe Sato†

, REVIEW D VOLUME 56, NUMBER 5 1 SEPTEMBER 1997

CP violation and matter effect in long baseline neutrino oscillation experiments

Jiro Arafune,* Masafumi Koike,† and Joe Sato‡

$$\Delta P(\nu_\mu \to \nu_e) \equiv P(\nu_\mu \to \nu_e; L) - P(\overline{\nu_\mu} \to \overline{\nu_e}; L)$$
$$= \Delta P_1(\nu_\mu \to \nu_e) + \Delta P_2(\nu_\mu \to \nu_e)$$
$$+ \Delta P_3(\nu_\mu \to \nu_e),$$

「CPV」

$$\Delta P_3(\nu_\mu \to \nu_e) = -8 \frac{\delta m_{21}^2 L}{2E} \sin^2 \frac{\delta m_{31}^2 L}{4E} s_\delta c_\phi^2 s_\phi c_\psi s_\psi c_\omega s_\omega$$

本当のCPV

VS

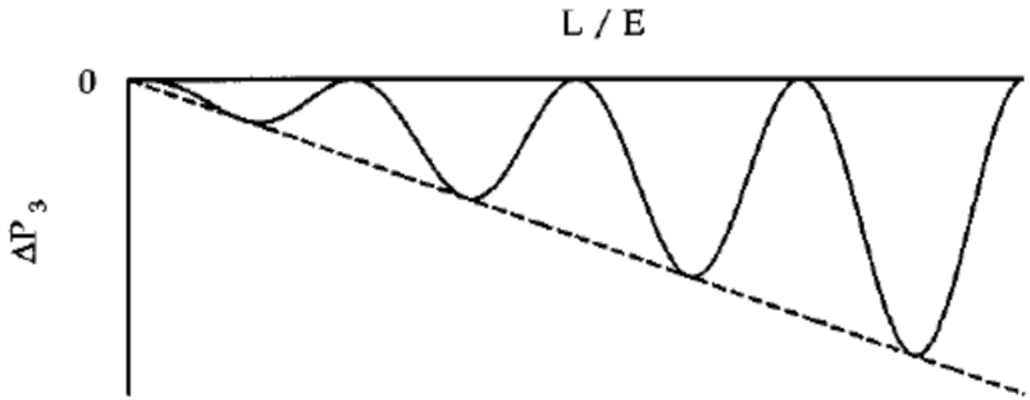
$$\Delta P_1(\nu_\mu \to \nu_e) = 16 \frac{a}{\delta m_{31}^2} \sin^2 \frac{\delta m_{31}^2 L}{4E} c_\phi^2 s_\phi^2 s_\psi^2 (1 - 2 s_\phi^2)$$

$$\Delta P_2(\nu_\mu \to \nu_e) = -4 \frac{aL}{2E} \sin \frac{\delta m_{31}^2 L}{2E} c_\phi^2 s_\phi^2 s_\psi^2 (1 - 2 s_\phi^2)$$

偽のCPV
＝
物質効果

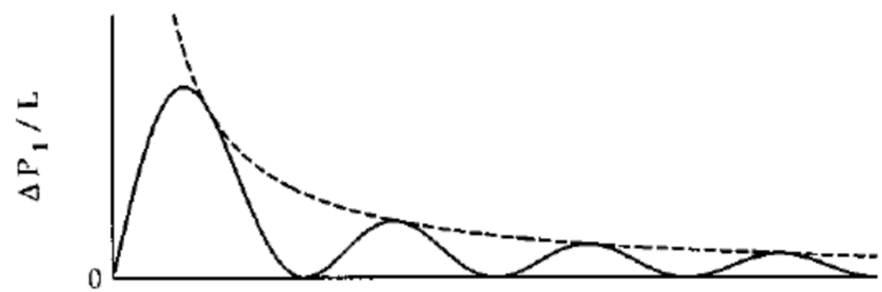
2. CPの破れ

$$\Delta P_3(\nu_\mu \to \nu_e) = -8\frac{\delta m_{21}^2 L}{2E}\sin^2\frac{\delta m_{31}^2 L}{4E} s_\delta c_\phi^2 s_\phi c_\psi s_\psi c_\omega s_\omega$$

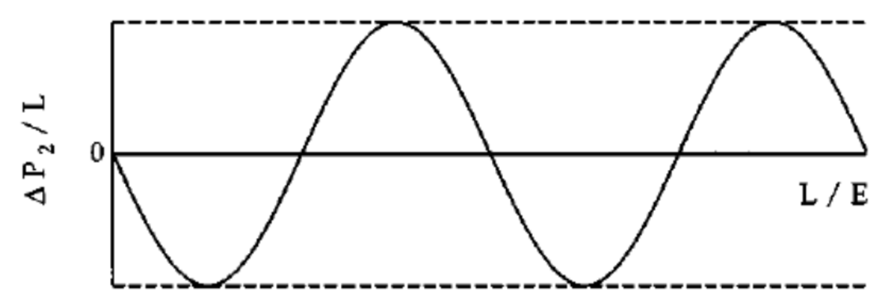


(c)

本当のCPV



(a)



(b)

$$\Delta P_1(\nu_\mu \to \nu_e) = 16\frac{a}{\delta m_{31}^2}\sin^2\frac{\delta m_{31}^2 L}{4E} c_\phi^2 s_\phi^2 s_\psi^2 (1-2s_\phi^2)$$

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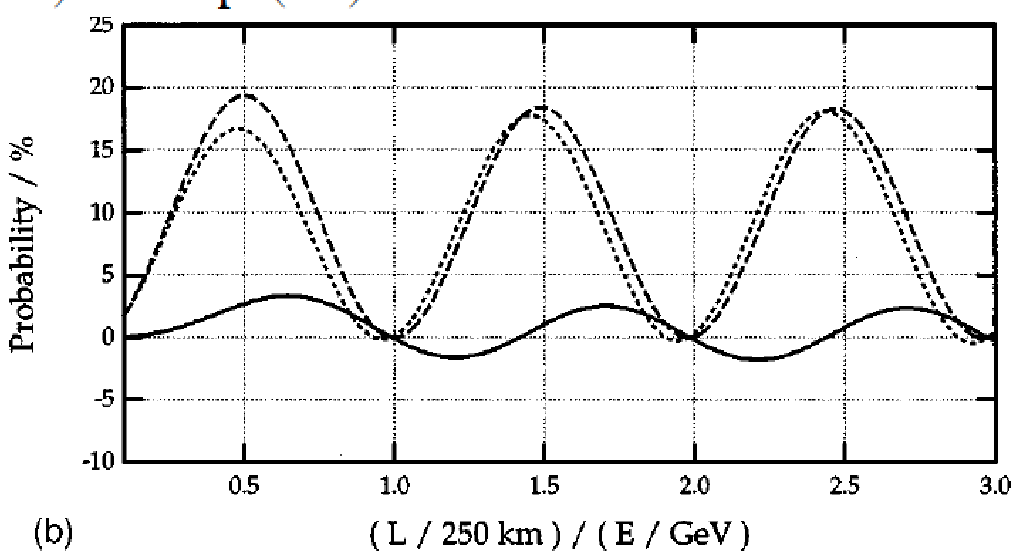
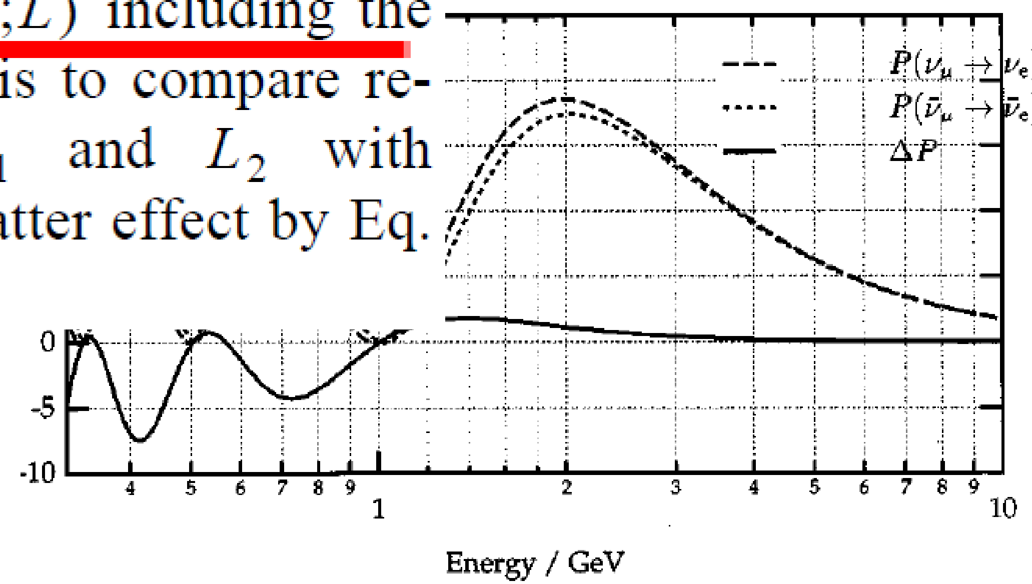
物質効果

We have shown with the aid of these formulas two methods to distinguish pure CP violation from matter effect. The dependence of pure CP-violation effect on the energy E and the distance L is different from that of matter effect: The former depends on L/E alone and has a form $f(L/E)$, while the latter has a form $L \times g(L/E) \equiv E \times \tilde{g}(L/E)$. One method to distinguish is to observe closely the energy dependence of the difference $P(\nu_\mu \to \nu_e; L) - P(\nu_\mu \to \nu_e; L)$ including the envelope of oscillation bumps. The other is to compare results from two different distances L_1 and L_2 with $L_1/E_1 = L_2/E_2$ and then to subtract the matter effect by Eq. (38) or Eq. (39).





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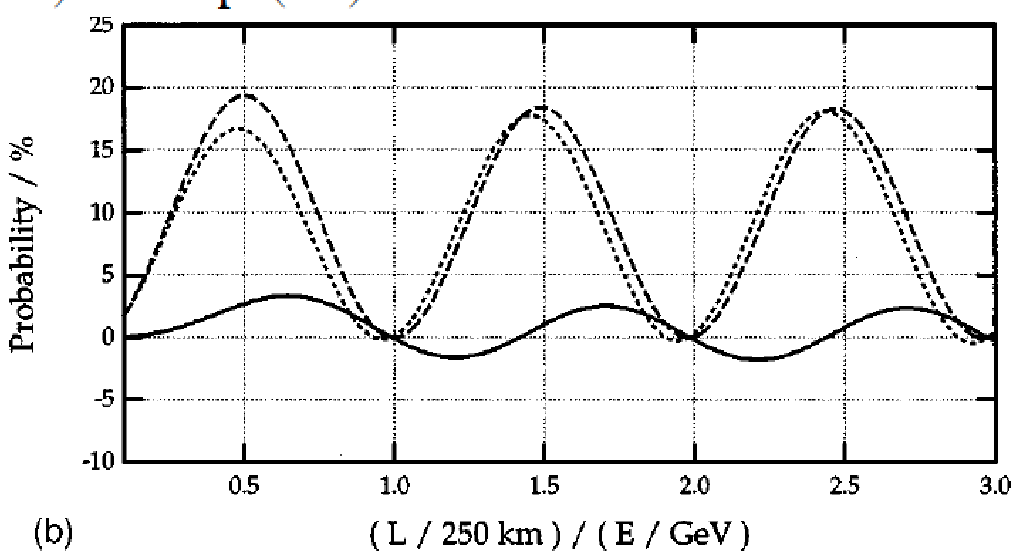
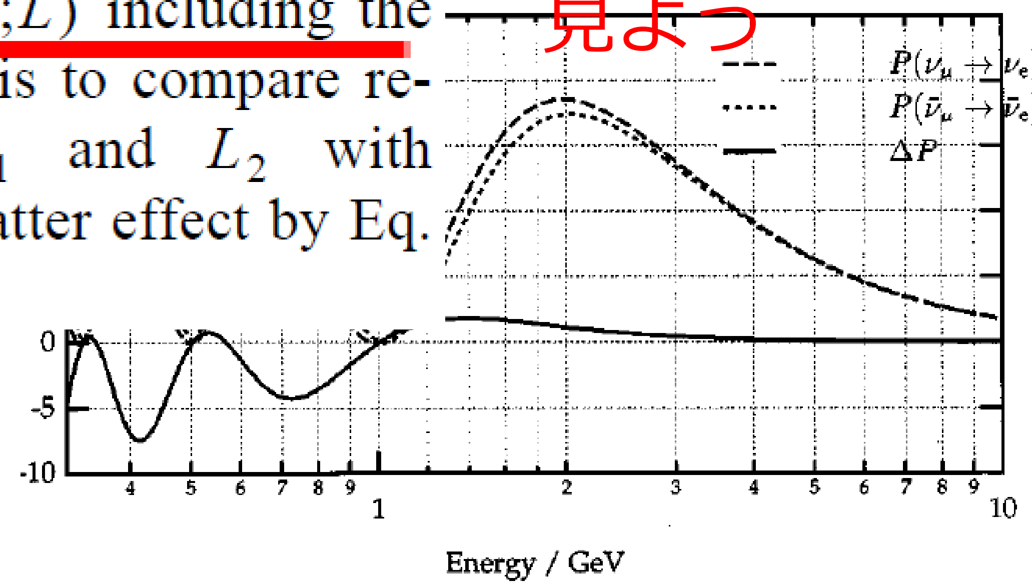
2nd ,3rd
∵
Maximum
を
見よう



(b)



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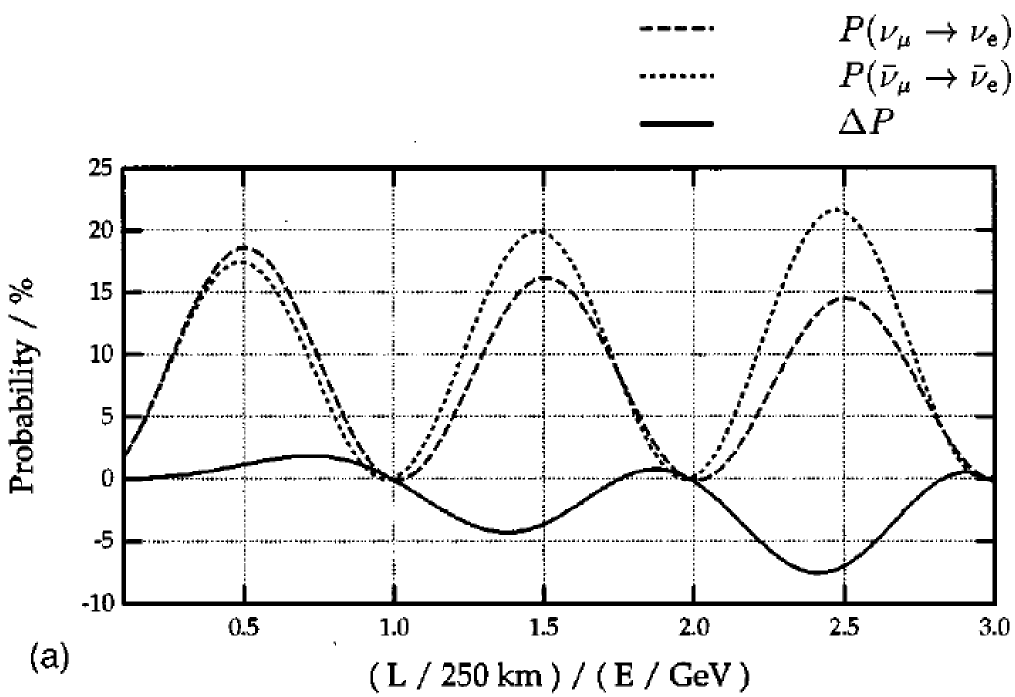
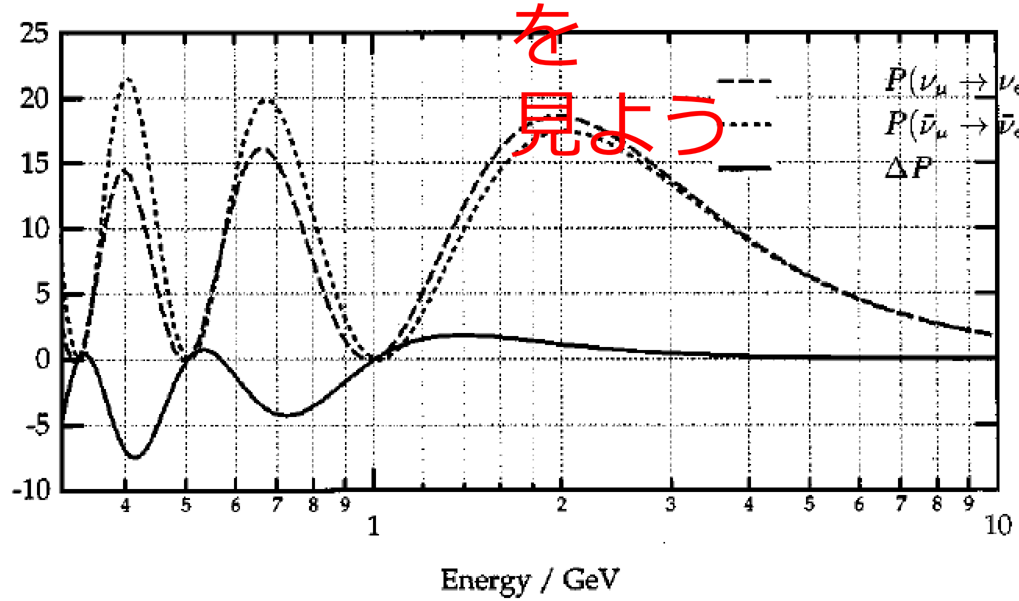
m ?(L/E), while

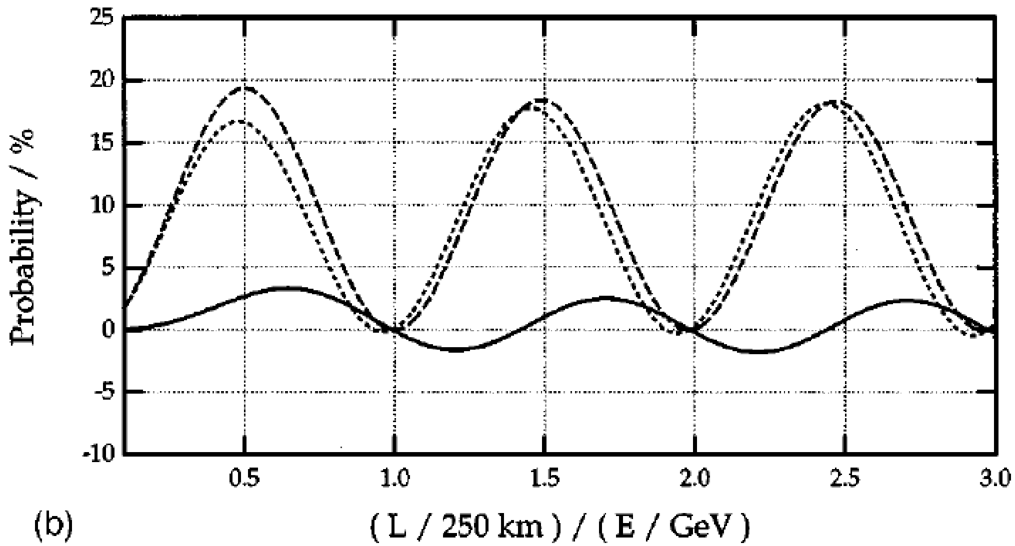
CPV有り

2nd ,3rd ‥ Maximumを見よう





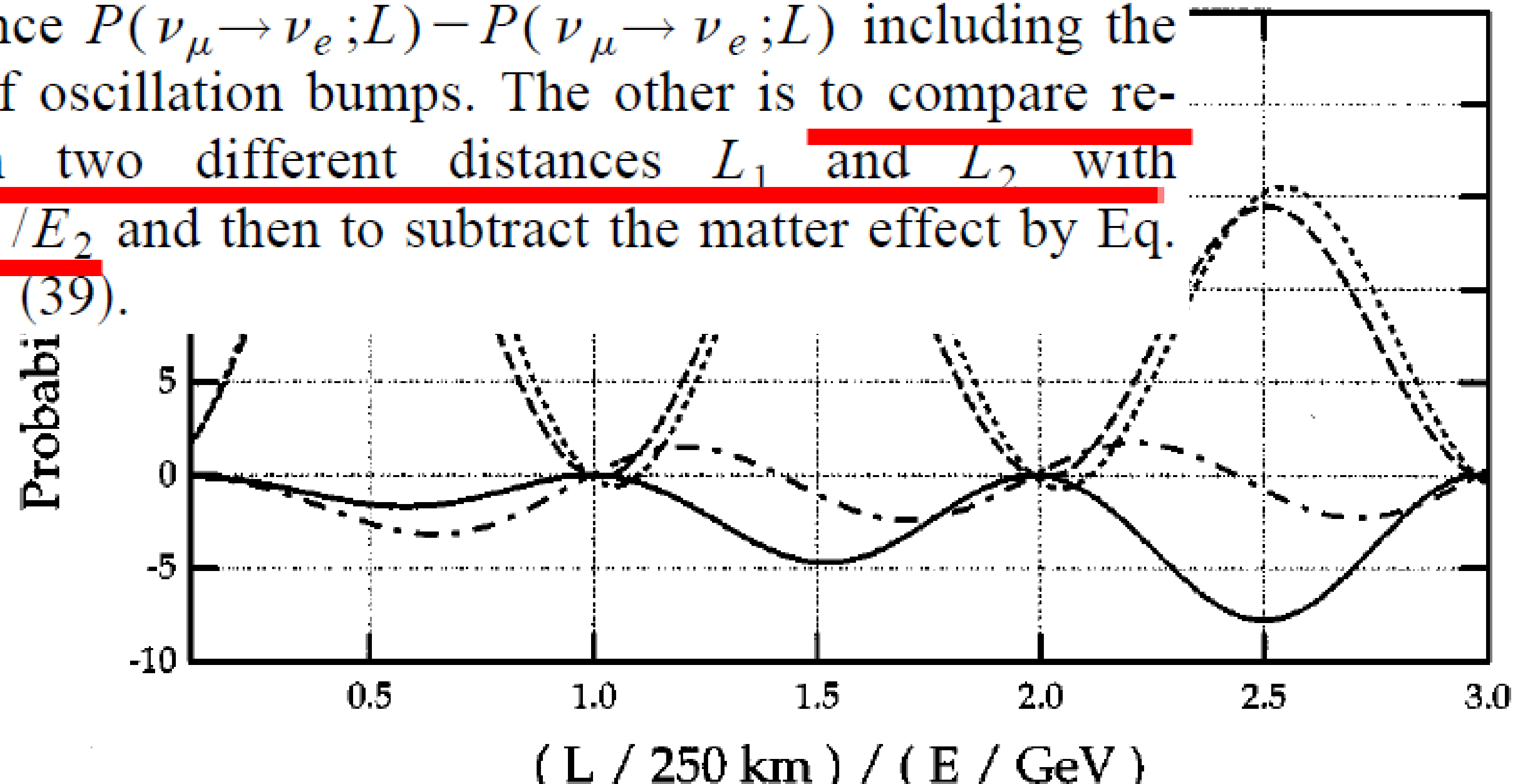
L/E



CPVなし

L/E

We have shown with the aid of these formulas two methods to distinguish pure CP violation from matter effect. The dependence of pure CP-violation effect on the energy E and the distance L is different from that of matter effect: The former depends on L/E alone and has a form $f(L/E)$, while the latter has a form $L \times g(L/E) \equiv E \times \tilde{g}(L/E)$. One method to distinguish is to observe closely the energy dependence of the difference $P(\nu_\mu \to \nu_e; L) - P(\overline{\nu_\mu} \to \overline{\nu_e}; L)$ including the envelope of oscillation bumps. The other is to compare results from two different distances L_1 and L_2 with $L_1/E_1 = L_2/E_2$ and then to subtract the matter effect by Eq. (38) or Eq. (39).



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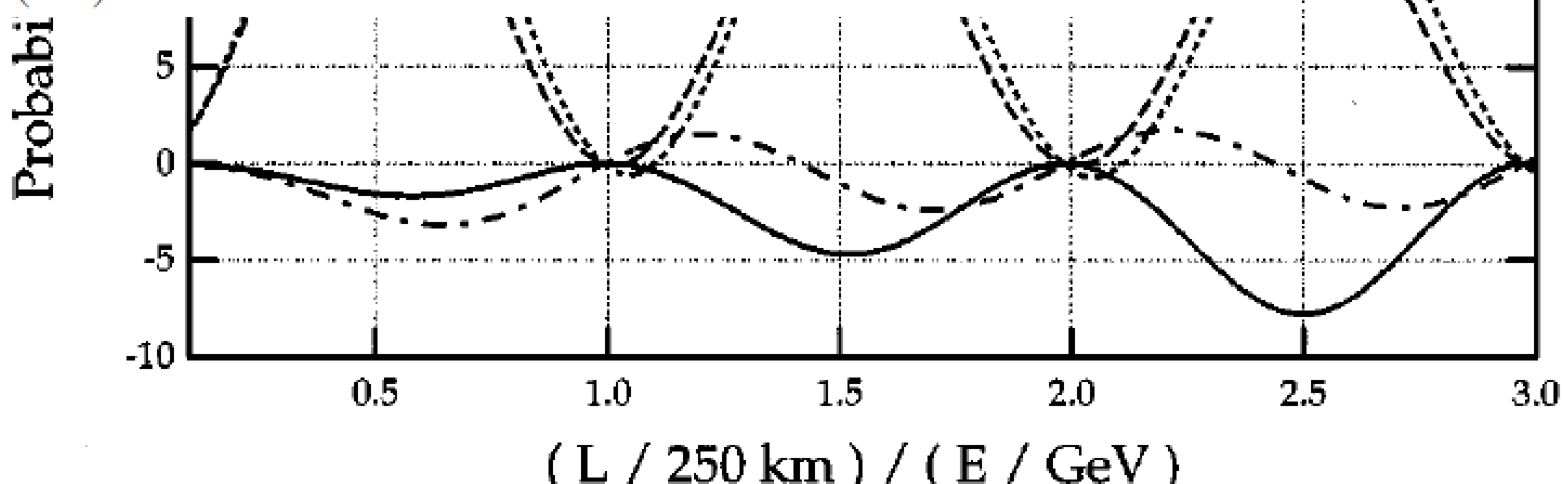

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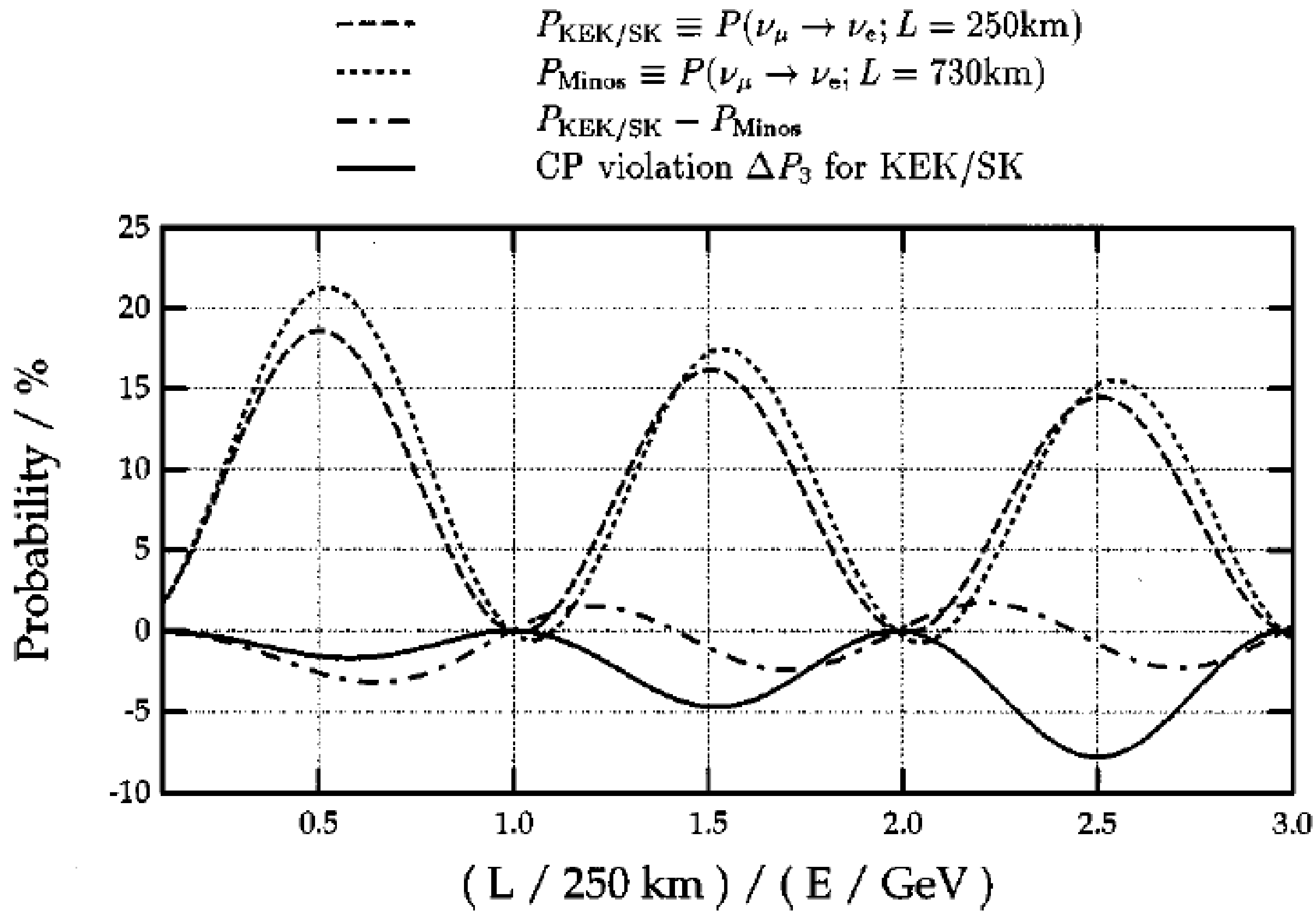
$L_1/E_1 = L$
(38) or Eq



2. CPの破れ

Each method has both its merits and demerits. The first one has the merit that we need experiments with only a single detector. A merit of the second is that we do not need wide range of energy (many bumps) to survey the neutrino oscillation.

とはいうものの、同じ実験（グループ）の方がいいような気がしますがどうでしょう？

Second Maximum !?

CP Violationの物理は世代が「３」であることが本質としてある。

➡ 振動現象においても三世代全てが関与していることが重要。

➡ ニュートリノのエネルギーは高過ぎもせず低過ぎもせず

振動現象に於けるエネルギースケールは本質的に二つ

$$E \sim \begin{cases} \delta m_{31}^2 L \\ \delta m_{21}^2 L \end{cases}$$

○ エネルギーが高い ➡ 軽い状態が「縮退」

➡ 「二世代」 ➡ CPの破れ「なし」

振動の式の上では

$$\Longleftrightarrow \delta m_{21}^2 \sim 0$$

$$\begin{aligned} &\sin \Delta_{21} + \sin \Delta_{32} + \sin \Delta_{13} \\ \sim \ &\sin \Delta_{31} + \sin \Delta_{13} \Longrightarrow 0 \end{aligned}$$

○ エネルギーが低い ➡ 重い状態が「decouple」

➡ 「二世代」 ➡ CPの破れ「なし」

振動の式の上では

$$\Longleftrightarrow \Delta m^{2\prime} s \sim \infty$$

$$\begin{array}{ccccc} \sin\Delta_{21} & + & \sin\Delta_{32} & + & \sin\Delta_{13} \\ \downarrow & & \downarrow & & \downarrow \\ 0 & & 0 & & 0 \end{array}$$

いずれの場合もCPの破れの寄与は相対的に小さくなる。

したがって、

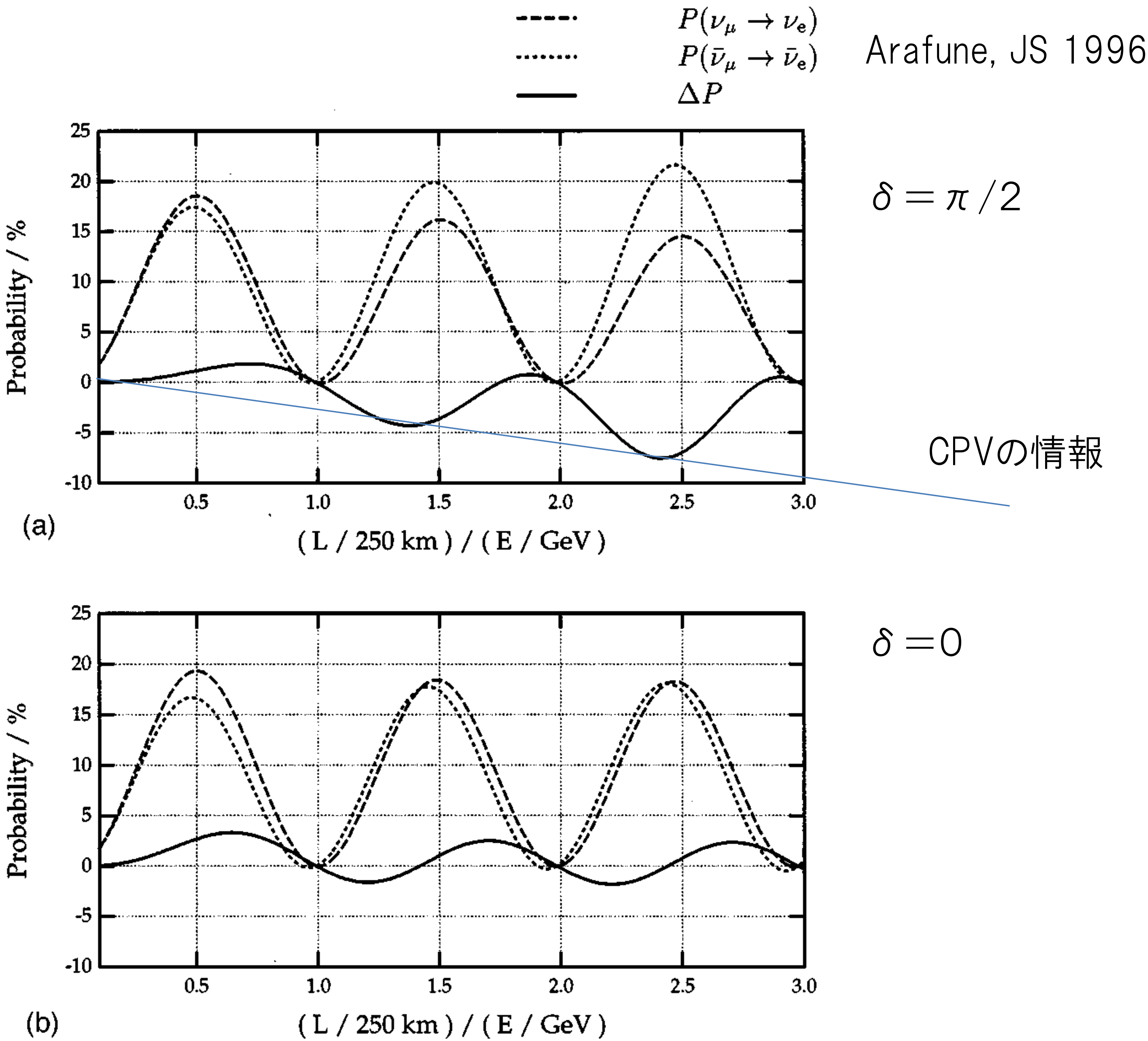
$$\delta m^2_{21} L \ \leq \ E \ \leq \ \delta m^2_{31} L$$

が最適なニュートリノのエネルギー

First Maximum 700MeV

Second 250MeV

……


$P(\nu_\mu \to \nu_e)$
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
ΔP
Arafune, JS 1996
$\delta = \pi/2$
CPVの情報
Probability / %
25
20
15
10
5
0
-5
-10
0.5
1.0
1.5
2.0
2.5
3.0
(a)
(L / 250 km) / (E / GeV)
$\delta = 0$
(b)
(L / 250 km) / (E / GeV)

3．LFV --- New Physics in Oscillation Experiments

Lepton Flavor Violation を内包するように標準理論は拡張されなければならない
しかも、レプトンの混合は大きい

大きなLepton Flavor Violationがニュートリノ振動以外でも見えるはず！！

（おそらく）もっとも調べられた例

MSSM with RH neutrino (Seesaw Model)　Borzumati, Masiero; Hisano et al

Large Flavor Changing Slepton Mass through renormalization

$$W = f_\nu^{i\beta} \bar{N}_i L_\beta H_u$$

$$\mu \frac{d(m_{\tilde{L}}^2)_\alpha^{\ \beta}}{d\mu} = \left(\mu \frac{d(m_{\tilde{L}}^2)_\alpha^{\ \beta}}{d\mu} \right)_{\rm MSSM} (=0)$$
$$+ \frac{1}{16\pi^2} \left[m_{\tilde{L}}^2 f_\nu^\dagger f_\nu + f_\nu^\dagger f_\nu m_{\tilde{L}}^2 + 2 (f_\nu^\dagger m_{\tilde{\nu}}^2 f_\nu + \tilde{m}_{H_u}^2 f_\nu^\dagger f_\nu + A_\nu^\dagger A_\nu) \right]_\alpha^{\ \beta}$$

SUSY breaking　$m_{\tilde{L}}^2$　scalor lepton doublet

$m_{\tilde{\nu}}^2$　right-handed sneutrino

$\tilde{m}_{H_u}^2$　doublet Higgs

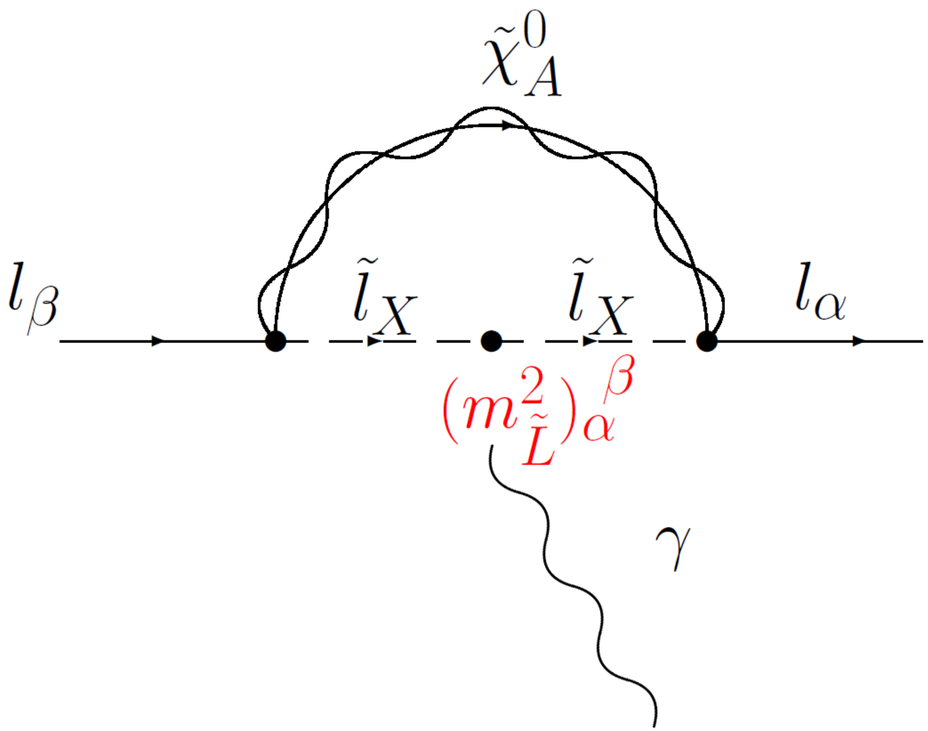
$$V^{Dirac\dagger} f_\nu^{i\beta} U^{Dirac} = {\rm diag}(f_{\nu 1}, f_{\nu 2}, f_{\nu 3})$$

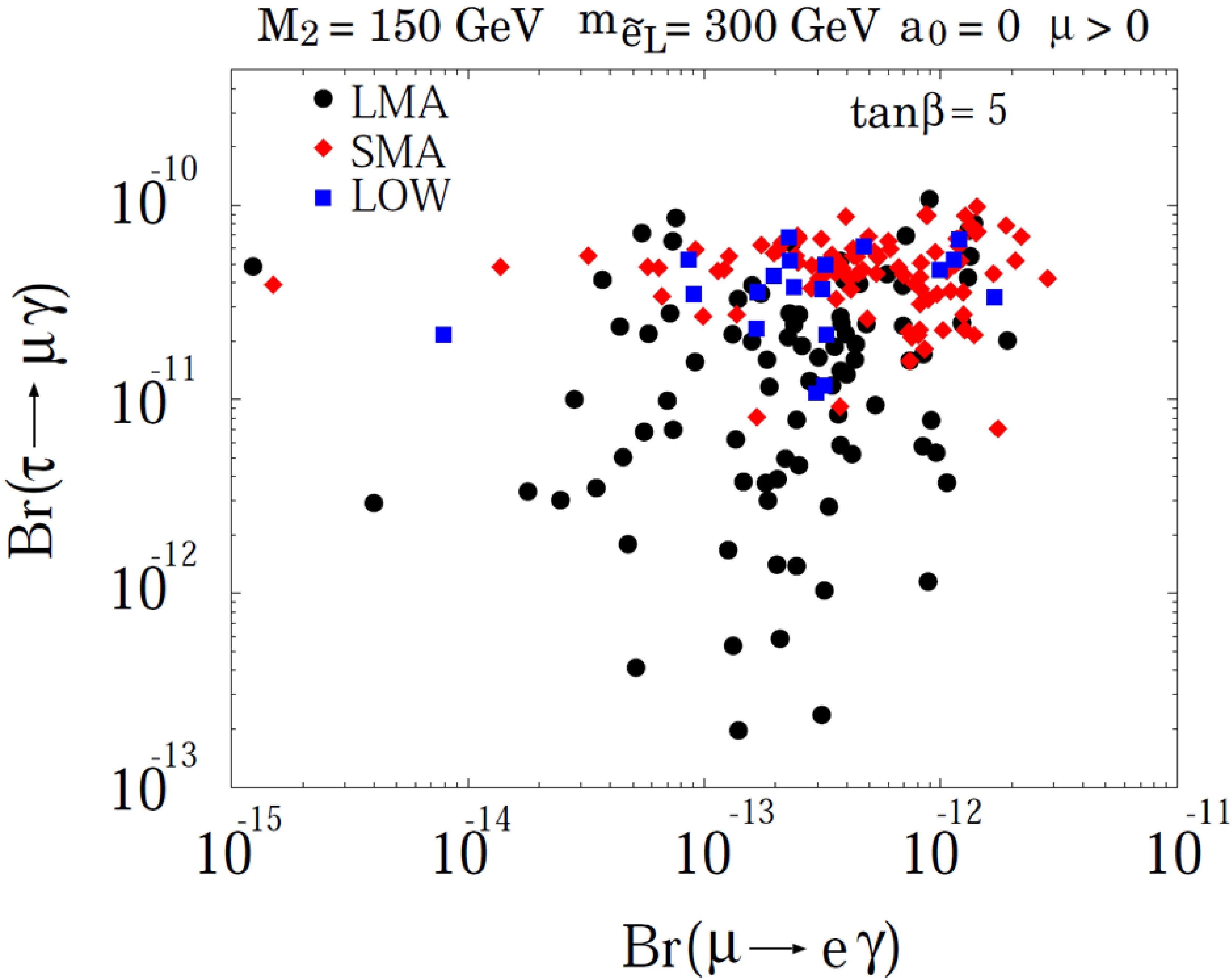
Lepton mixing SUSY Breaking Mass

a_0:: universal A term

$$(m^2_{\tilde{L}})_\alpha^{\ \beta} \simeq -\frac{(6+a_0^2)m_0^2}{16\pi^2}(f_\nu^\dagger f_\nu)_\alpha^{\ \beta}\log\frac{M_G}{M_R}$$

$$\simeq -\frac{(6+a_0^2)m_0^2}{16\pi^2}U^{Dirac}_{\alpha k}(U^{Dirac*})^{\beta k}|f_{\nu k}|^2\log\frac{M_G}{M_R}$$





Sato,Tobe

Charged Lepton Flavor Violation (cLFV)

もうすぐ見える！？

Neutral Lepton Flavor Violation, nLFV, 例えば

$$\pi \longrightarrow \mu + \nu_e$$

も存在する！？

Weak Interaction に対する結合定数の比をε として

$$\frac{\mathrm{Br}(\pi \to \mu\nu_e)}{\mathrm{Br}(\pi \to \mu\nu_\mu)} = \varepsilon^2$$

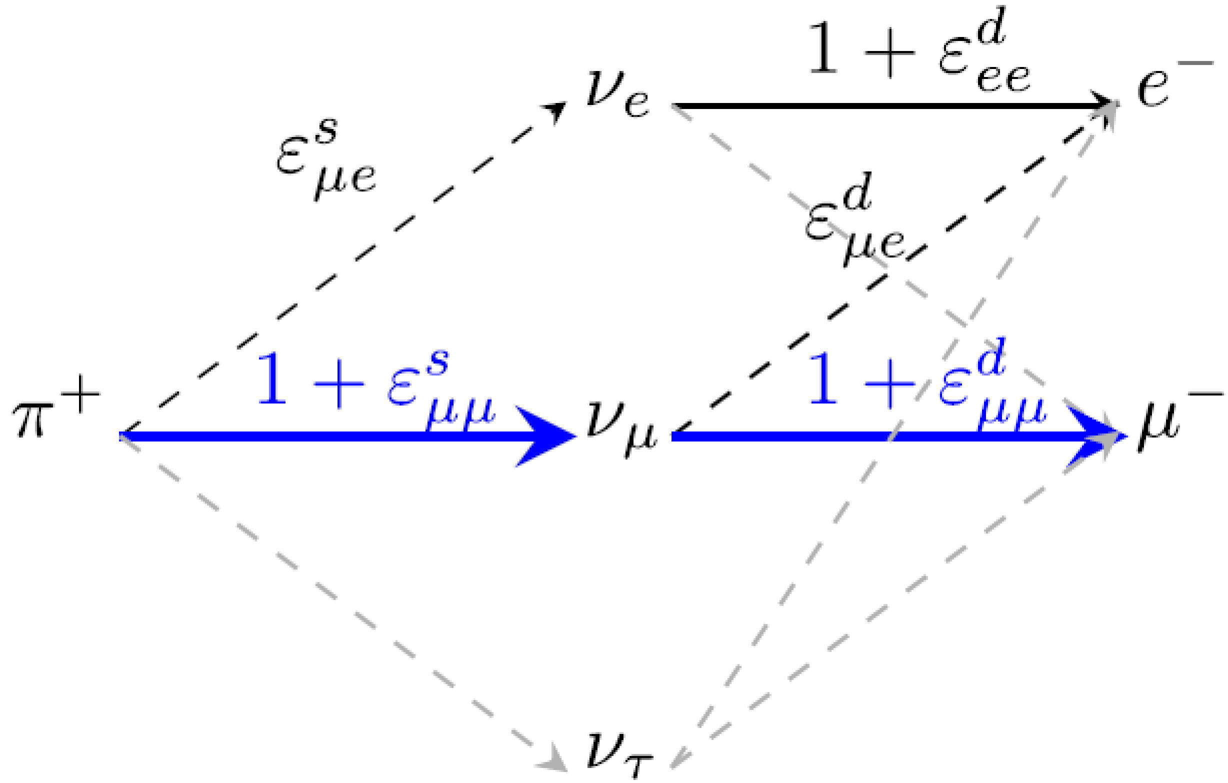
Universalityに影響する。が、ε^2の寄与なのでそれほど強い制限はかからない。

しかし、

$$\nu_\mu \longrightarrow \nu_e$$

振動実験への寄与は ε で効く。

ニュートリノは中間状態であって物理的状態ではない



振動を見ているわけでなく

π が崩壊し遠方で電子を作る

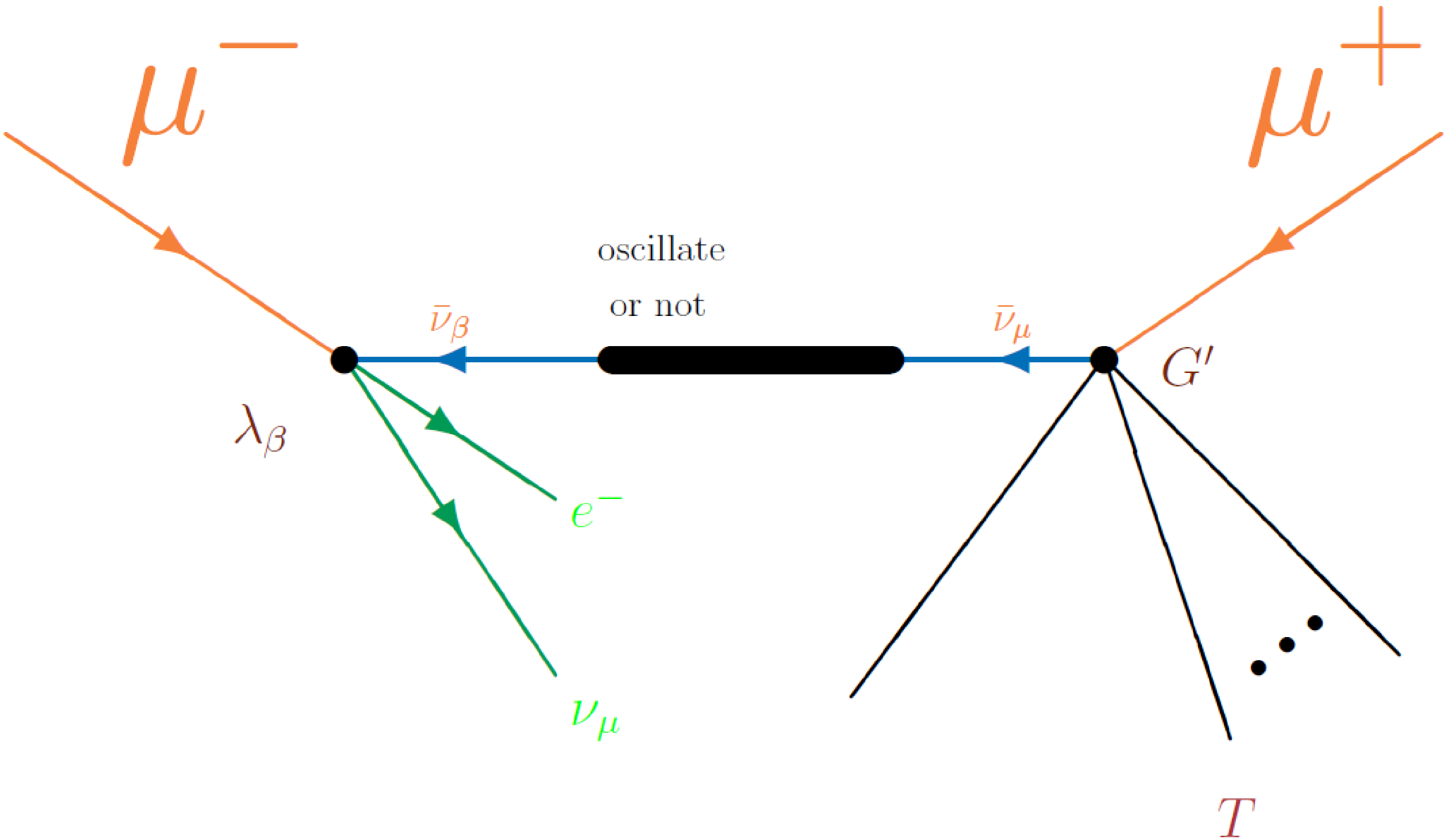
という現象を見ている。よって、振動確率は ε に比例

$$|\mathcal{A}(\nu_\mu \to \nu_e) + \mathcal{A}(\nu_e \to \nu_e)|^2 \sim (1 + 2\varepsilon))|\mathcal{A}(\nu_\mu \to \nu_e)|^2$$

ニュートリノは中間状態！！

厳密には、干渉するのはこの現象に関わる全ての粒子が同じ状態を与える過程

Neutrino Factoryの例だと



$$\nu_e \longrightarrow \nu_\mu$$

と解釈する

干渉があるので、結合定数に比例して寄与がある。

定式化

初期状態　s:source

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon_{\alpha\beta}^s |\nu_\beta\rangle$$

$$\sum_{\alpha=e,\mu,\tau} |\nu_\alpha^s\rangle\langle\nu_\alpha^s| \neq 1, \qquad \sum_{\beta=e,\mu,\tau} |\nu_\beta^d\rangle\langle\nu_\beta^d| \neq 1,$$

終状態　d:detection

$$\langle\nu_\alpha^s|\nu_\beta^s\rangle \neq \delta_{\alpha\beta}, \qquad \langle\nu_\alpha^d|\nu_\beta^d\rangle \neq \delta_{\alpha\beta}.$$

$$\langle\nu_\beta^d| = \langle\nu_\beta| + \sum_{\alpha=e,\mu,\tau} \varepsilon_{\alpha\beta}^d \langle\nu_\alpha|$$

直交しない

Hamiltonian

$$\tilde{V}_{\mathrm{MSW}} = a_{\mathrm{CC}} \begin{pmatrix} 1+\varepsilon_{ee}^m & \varepsilon_{e\mu}^m & \varepsilon_{e\tau}^m \\ \varepsilon_{e\mu}^{m*} & \varepsilon_{\mu\mu}^m & \varepsilon_{\mu\tau}^m \\ \varepsilon_{e\tau}^{m*} & \varepsilon_{\mu\tau}^{m*} & \varepsilon_{\tau\tau}^m \end{pmatrix}$$

$$H_{\alpha\beta} = \frac{1}{2E}\left[U_{\alpha j} \begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 & \\ & & \Delta m_{31}^2 \end{pmatrix}_{jk} (U^\dagger)_{k\beta} + (\tilde{V}_{\mathrm{MSW}})_{\alpha\beta} \right]$$

物質効果に変化

遷移確率

$$\begin{aligned} P_{\nu_\alpha^s \to \nu_\beta^d} &= |\langle\nu_\beta^d|e^{-iHL}|\nu_\alpha^s\rangle|^2 \\ &= |(1+\varepsilon^d)_{\gamma\beta}(e^{-iHL})_{\gamma\delta}(1+\varepsilon^s)_{\alpha\delta}|^2 \\ &= |[(1+\varepsilon^d)^T e^{-iHL}(1+\varepsilon^s)^T]_{\beta\alpha}|^2, \end{aligned}$$

ε の上限

Universalityから　$< \mathcal{O}(10^{-3})$

ε の上限になる場合(Weak Interactionに同じ過程がある場合）と、

ε^2 の上限になる場合(Weak Interactionに同じ過程がない場合）とが存在

c LFVから　　SU(2)　で関係がつく！？

$\mu \to e\gamma$ ⇒ $\nu_\mu \leftrightarrow eW$　(+$W\bar{e}\nu_e$で 物質効果 $\varepsilon^m_{e\mu}$)

$\nu_e \leftrightarrow \mu W$ (+$W\bar{u}d$で $\pi \to \mu + \nu_e$)

$\varepsilon^{s,d}_{\mu e}$

単純には同じくらいの制限？ ε^2 の上限？

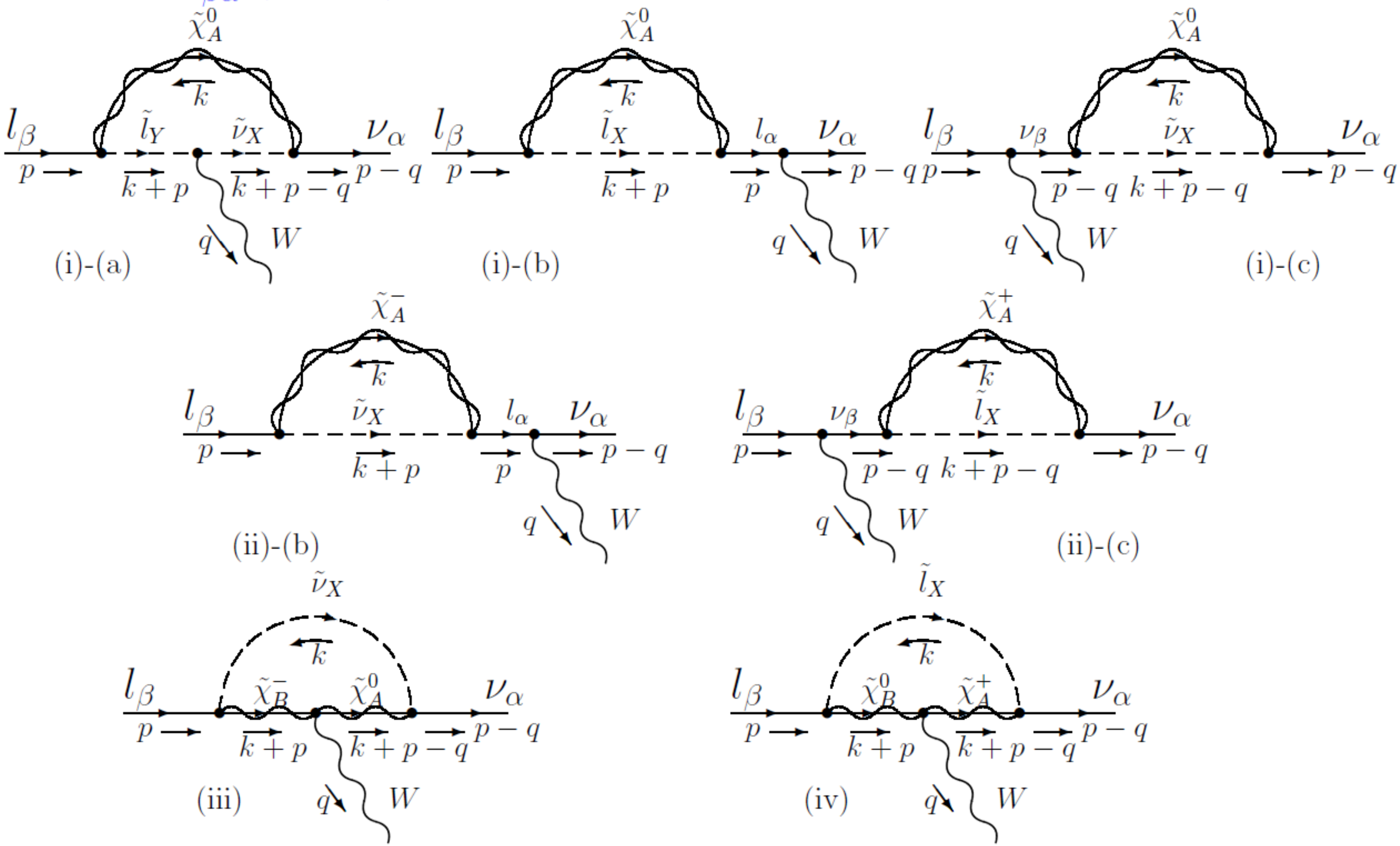
しかしBoxやtreeからの寄与もある

⇒ 模型による

MSSM with RH neutrino (Seesaw Model)の例

Ota,Sato

Example of $\epsilon^{s}_{\beta\alpha}$ (Source): W-penguin diagrams



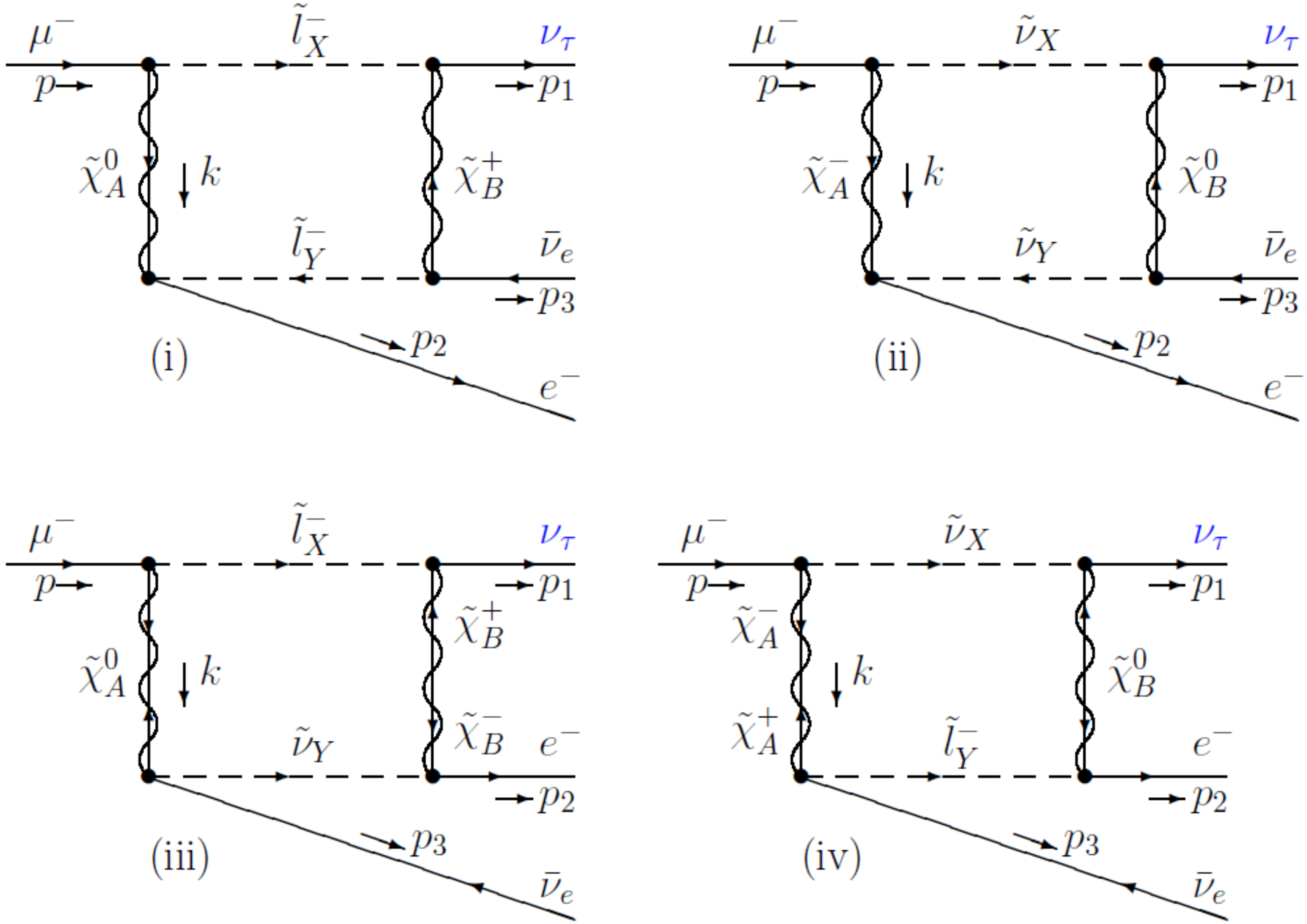
○ $\bar{\nu}_\gamma$ l^-_γ attaced.

○SU(2) limit, Divergence cansels among them

MSSM with RH neutrino (Seesaw Model)の例

Ota,Sato

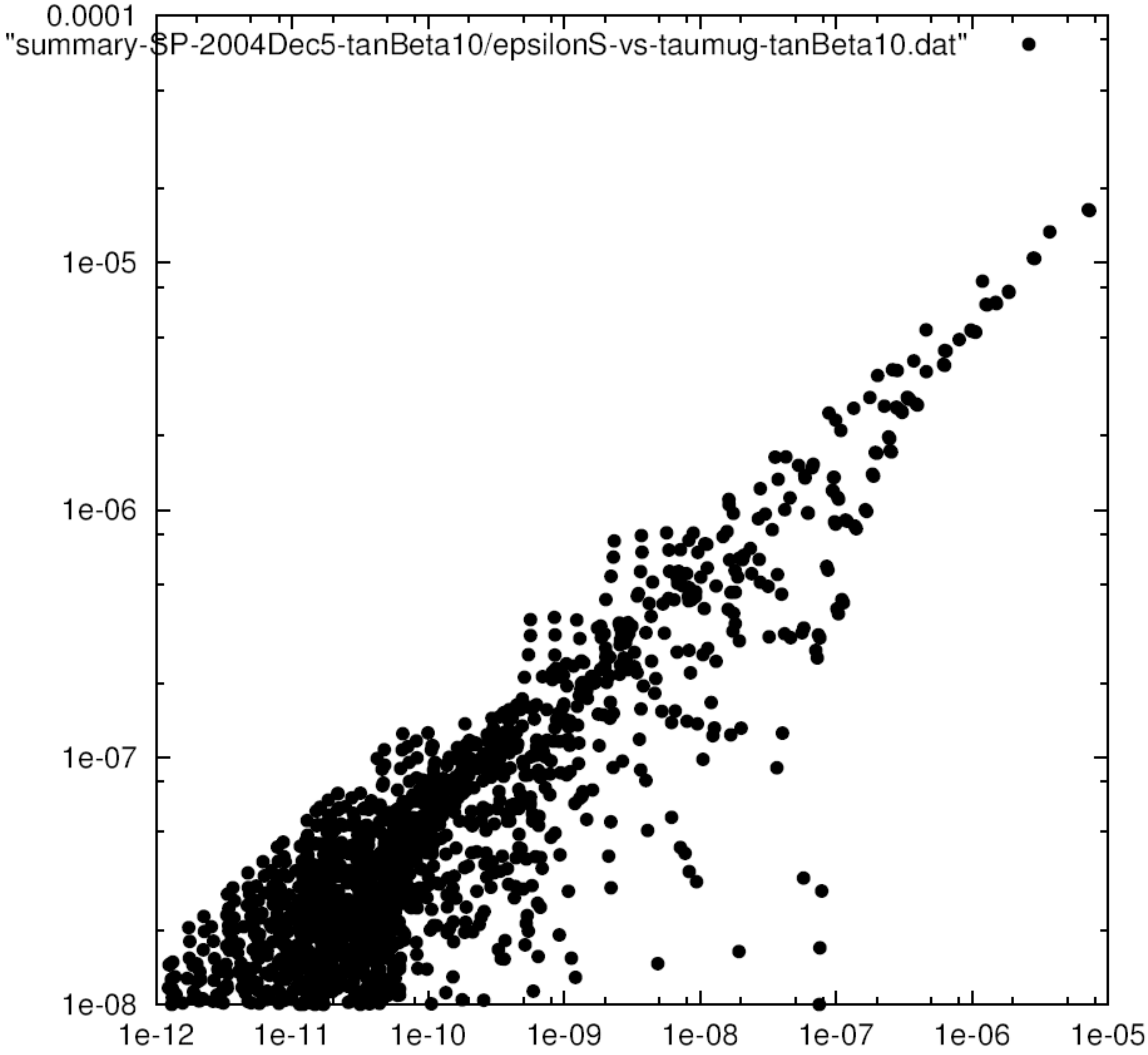
Box diagrams for $\epsilon^s_{\mu\tau}$



- Calculation straightforwad
- For $\epsilon^s_{\mu e}$ there are other graphs.

MSSM with RH neutrino (Seesaw Model)の例

Ota,Sato



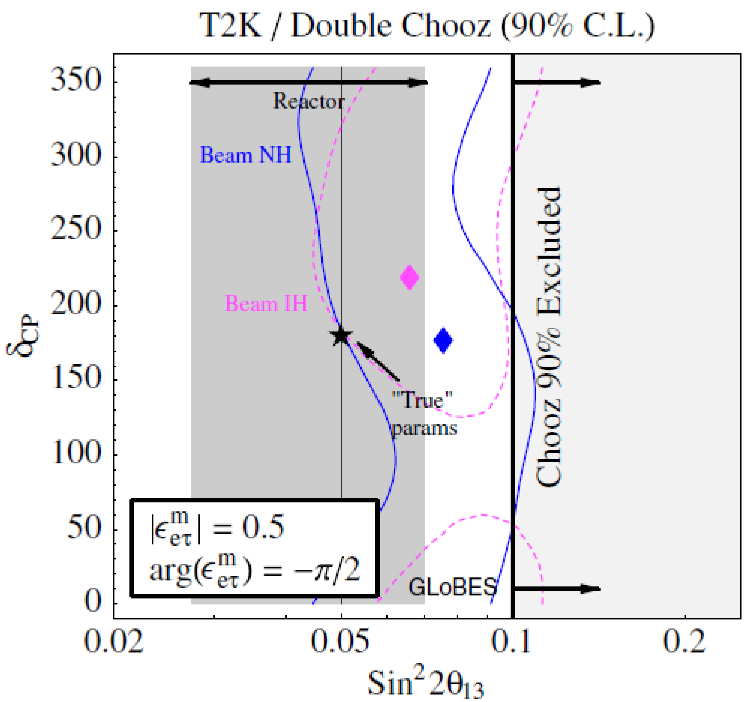
強い相関

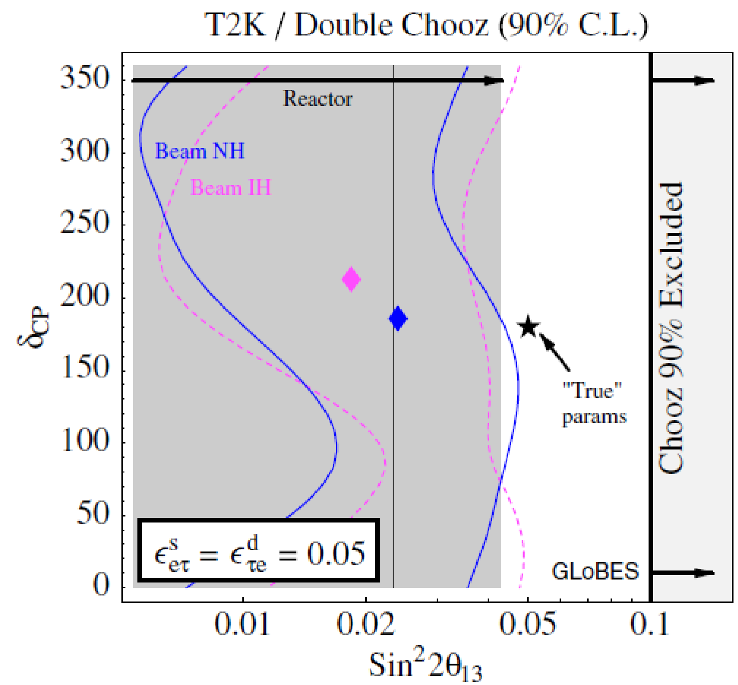
$\mathrm{Br}(\tau \to \mu\gamma)$

一方、Treeが寄与する場合は大きくなることもある

もし大きいとすると、三世代決めうちのフィットだと実験結果に矛盾？
極端な例

KOPP, LINDNER, OTA, AND SATO

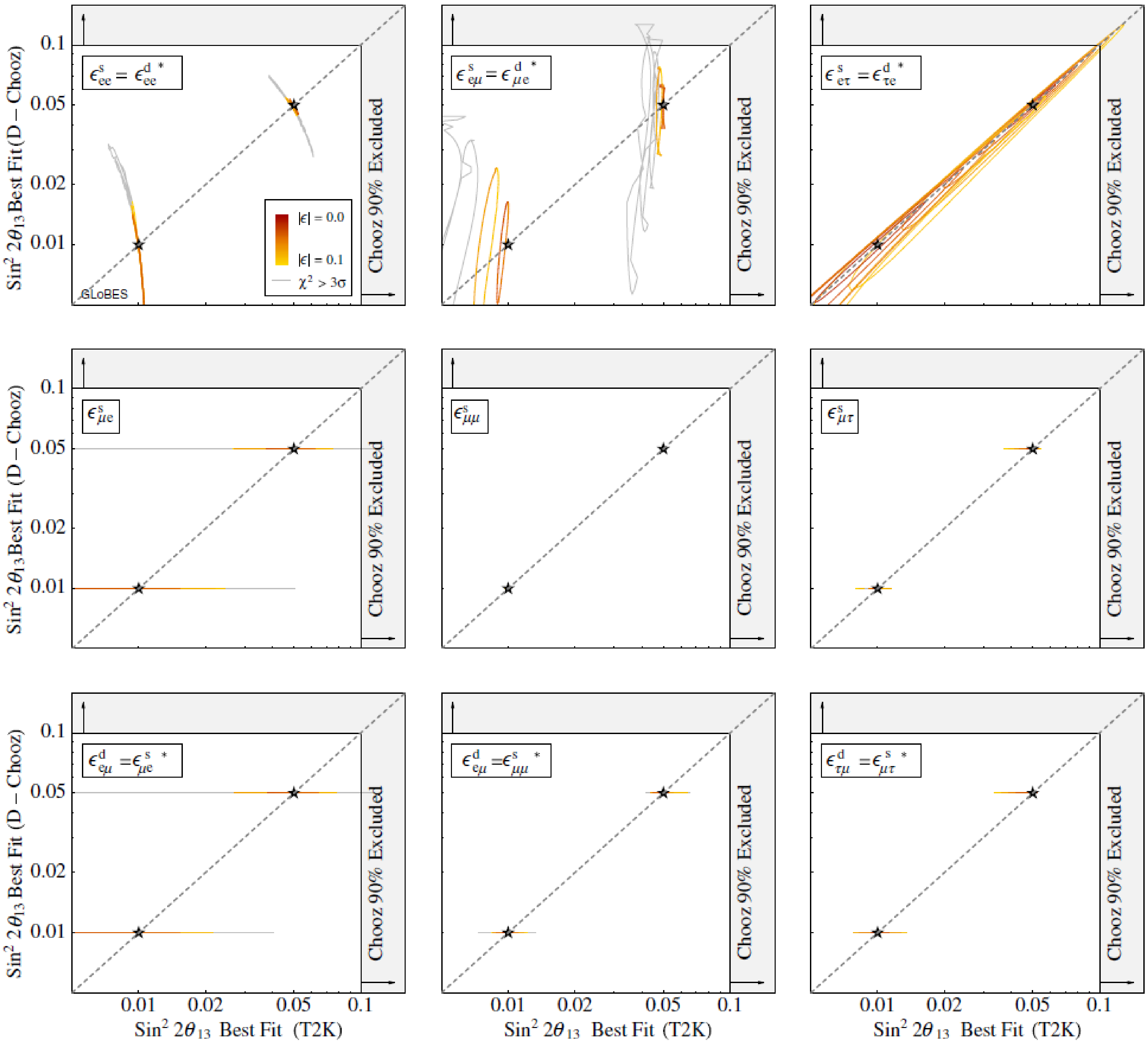




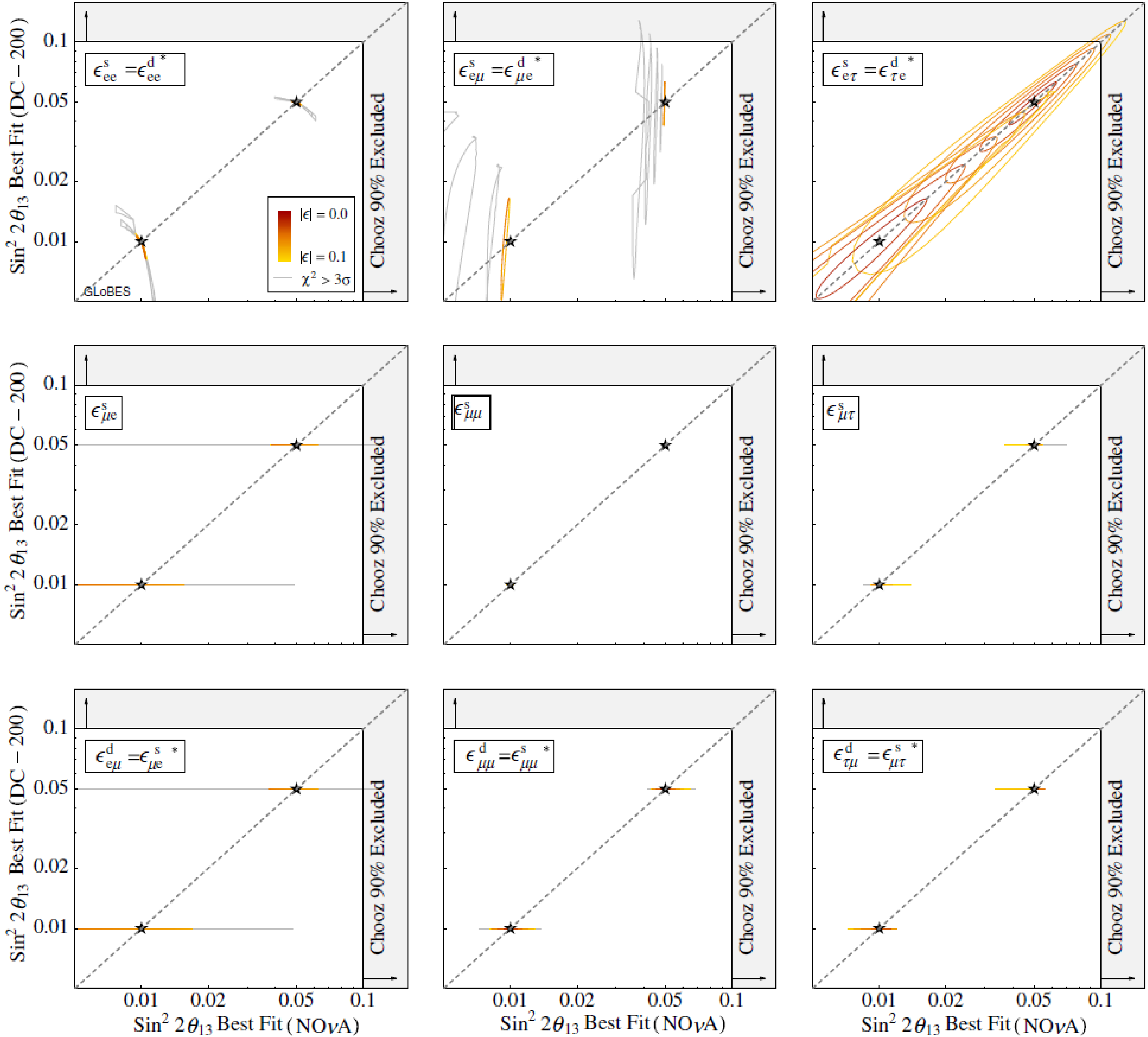
物質効果のみ
長基線実験に影響

初期状態と終状態
両方に影響。ともに正しい値を外す

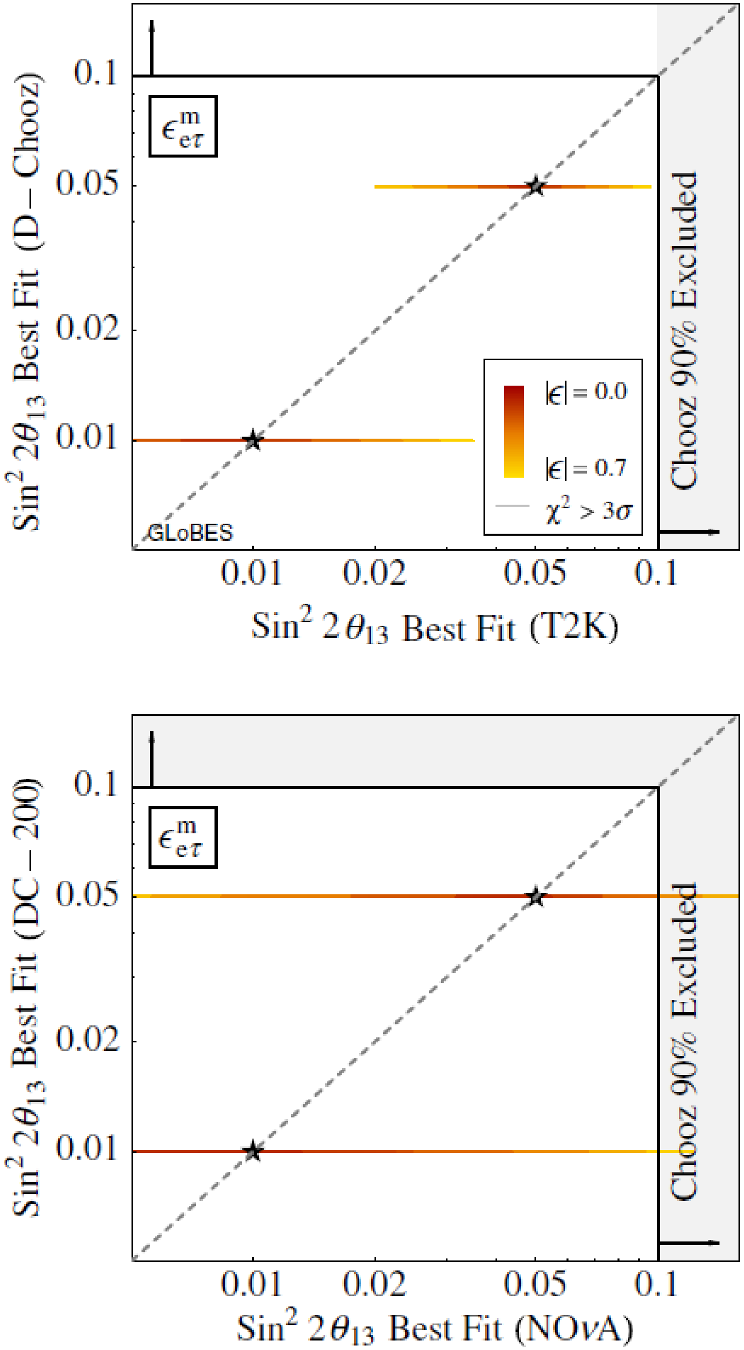
T2K vs Double Chooooz



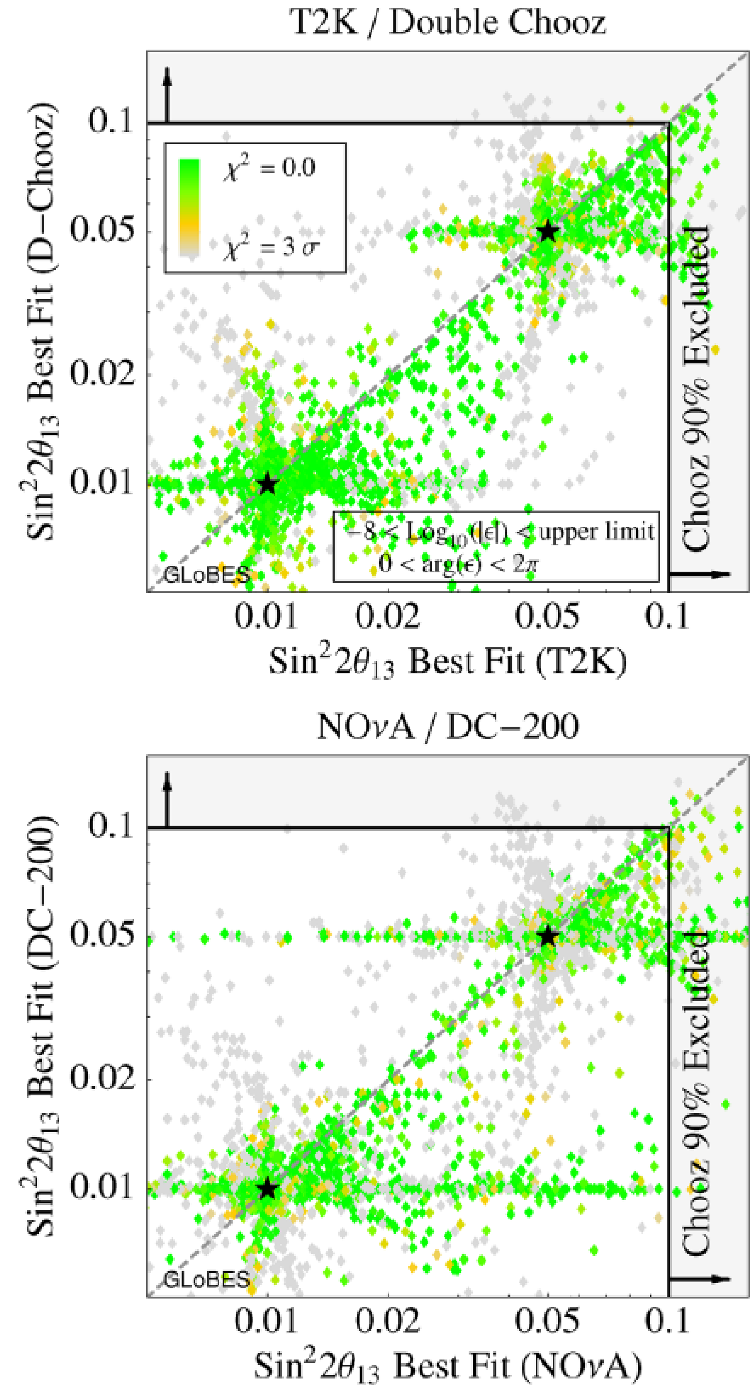
T2K vs NO ν A



$\epsilon^s_{ee} = \epsilon^{d\,*}_{ee}$
$\epsilon^s_{e\mu} = \epsilon^{d\,*}_{\mu e}$
$\epsilon^s_{e\tau} = \epsilon^{d\,*}_{\tau e}$
$\epsilon^s_{\mu e}$
$\epsilon^s_{\mu\mu}$
$\epsilon^s_{\mu\tau}$
$\epsilon^d_{e\mu} = \epsilon^{s\,*}_{\mu e}$
$\epsilon^d_{\mu\mu} = \epsilon^{s\,*}_{\mu\mu}$
$\epsilon^d_{\tau\mu} = \epsilon^{s\,*}_{\mu\tau}$
$|\epsilon| = 0.0$
$|\epsilon| = 0.1$
$\chi^2 > 3\sigma$
GLoBES
Chooz 90% Excluded
$\sin^2 2\theta_{13}$ Best Fit (DC − 200)
$\sin^2 2\theta_{13}$ Best Fit (NOνA)
0.01
0.02
0.05
0.1



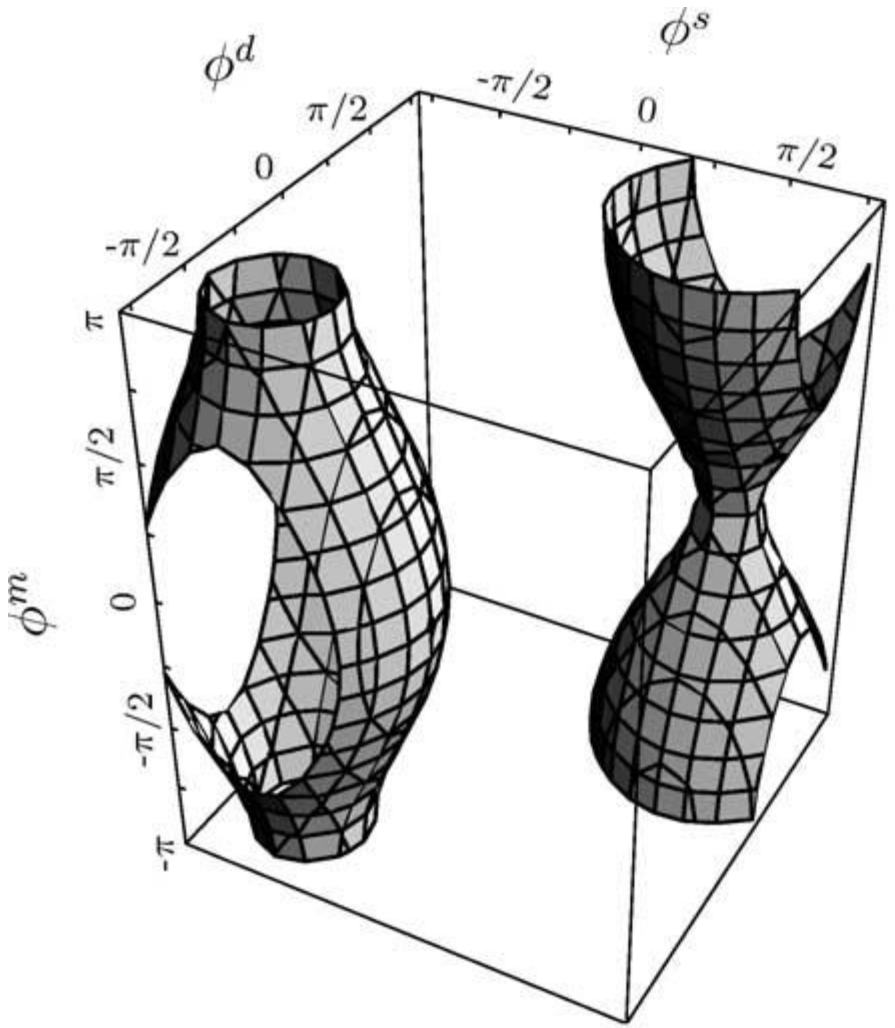
物質効果

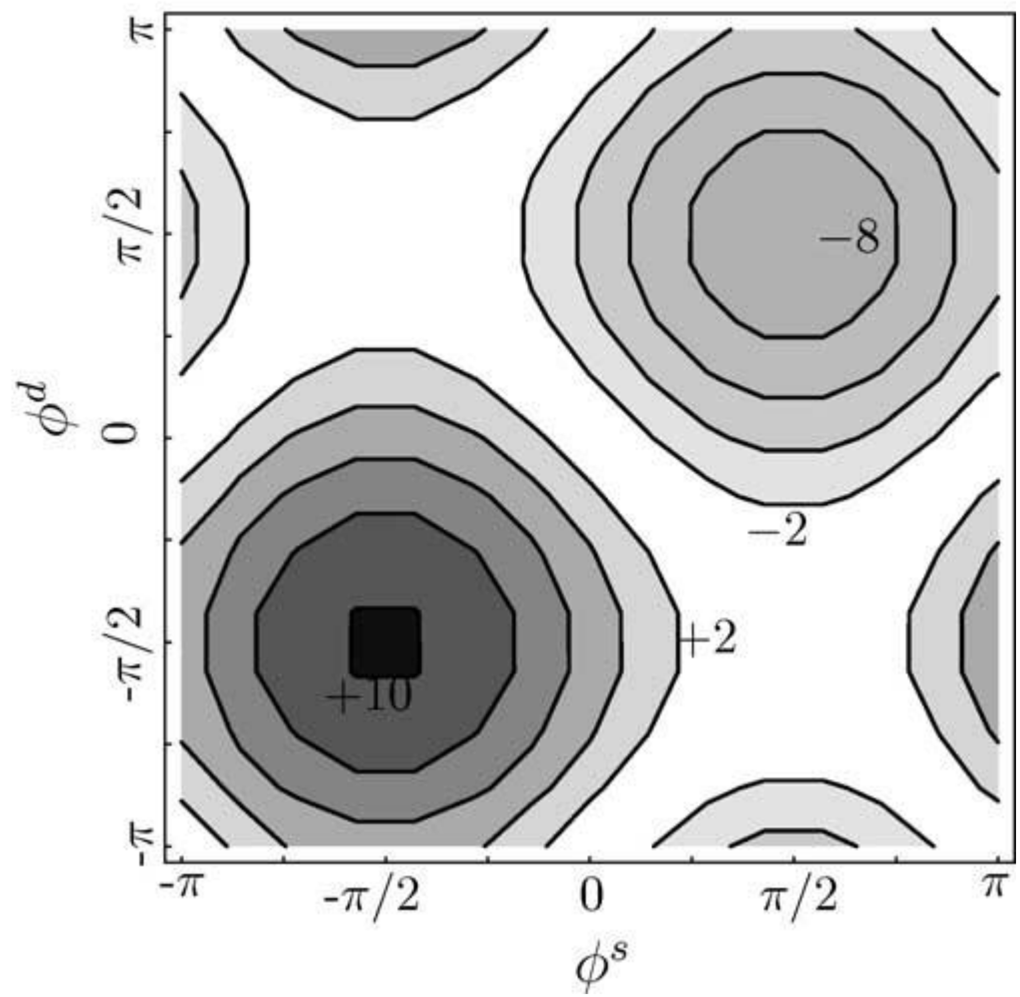


ランダムに振った場合

OPERAでも多少は見えるかも

T. Ota, J. Sato





壺の中にパラメタがあれば期待されるappearance
より有意にずれる。

⟺ 他の実験と「矛盾」

$|\epsilon^{s,m,d}_{\mu\tau}|$ are assumed to be 0.01

もう一つの見方

NSIを特徴つけるパラメタはいっぱい

⇒　どれが本当に必要なのか、フィットの良さの基準は？

三世代決めうちのフィットが悪いと言うこと

⇔　MNS行列はユニタリ？
本当は12（=18－1－3－2）パラメタ

混合行列がユニタリであるかをチェックすることで
新しい物理の存在の示唆を得られる。

かも！？

Oscillation probability $P(\nu_\alpha \to \nu_\beta)$ for $E \sim O(100)$ MeV and $L \sim O(100)$ Km

$\delta m_{ij}^2 = m_i^2 - m_j^2$	mass square difference
E	Neutrino energy
L	Distance
$\Delta_{ij} = \frac{\delta m_{ij}^2}{2E} L$	phase of oscillation
$J \equiv \mathrm{Im}(U_{e3}^* U_{\mu 3} U_{e2} U_{\mu 2}^*)$	Jarlskog Parameter (CP measure)

$$
\begin{aligned}
& P(\nu_\mu \to \nu_e) \\
&= 4|U_{e3}U_{\mu 3}|^2 \sin^2 \frac{\Delta_{31}}{2} \\
&+ 4\mathrm{Re}(U_{e3}^* U_{\mu 3} U_{e2} U_{\mu 2}^*) + \frac{\delta m_{21}^2}{\delta m_{31}^2} \Delta_{31} \sin \Delta_{31} \\
&- 4\mathrm{Im}(U_{e3}^* U_{\mu 3} U_{e2} U_{\mu 2}^*) + \frac{\delta m_{21}^2}{\delta m_{31}^2} \Delta_{31} \sin^2 \frac{\Delta_{31}}{2} \\
&- 4\mathrm{Re}(U_{e2}^* U_{\mu 2} U_{e1} U_{\mu 1}^*) \left(\frac{\delta m_{21}^2}{\delta m_{31}^2}\right)^2 \left(\frac{\Delta_{31}^2}{2}\right)^2 \\
&\equiv A \sin^2 \frac{\Delta_{31}}{2} \\
&+ \frac{B}{2} \Delta_{31} \sin \Delta_{31} \\
&+ C \Delta_{31} \sin^2 \frac{\Delta_{31}}{2} \\
&+ D \left(\frac{\Delta_{31}^2}{2}\right)^2
\end{aligned}
$$

CPV

Up to the leading(second) order of small values,

U_{e3} and $\frac{\delta m_{21}^2}{\delta m_{31}^2}$.

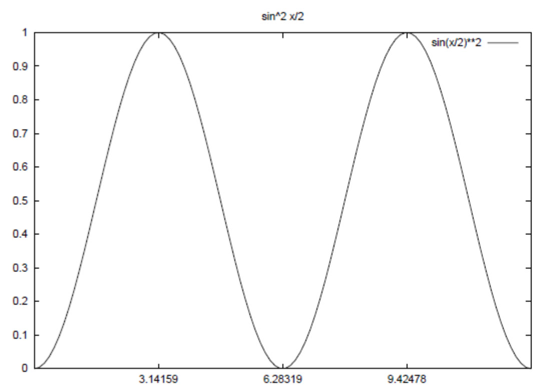
必要に応じて物質効果も取り入れる

基底

$$\sin^2\frac{\Delta_{31}}{2},\ \ \Delta_{31}\sin\Delta_{31},\ \ \Delta_{31}\sin^2\frac{\Delta_{31}}{2},\ \ \Delta_{31}^2$$

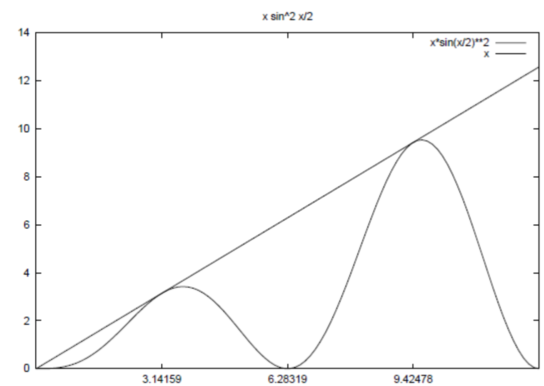
直交してないが独立(なはず)

$\sin^2\frac{\Delta_{31}}{2}$



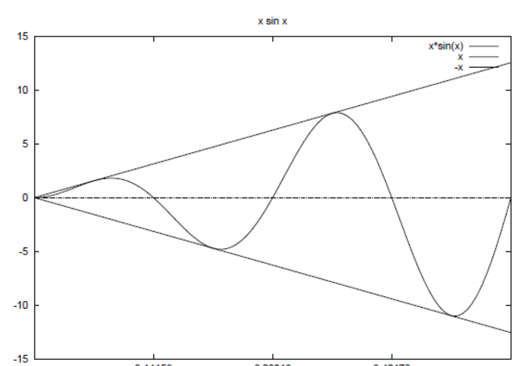
Δ_{31}

$\Delta_{31}\sin^2\frac{\Delta_{31}}{2}$



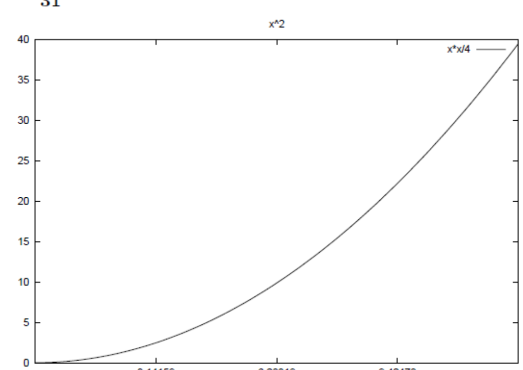
Δ_{31}

$\sin^2\Delta_{31}$



Δ_{31}

Δ_{31}^2



Δ_{31}

基底の係数を、三世代・ユニタリ、などを忘れて取り出す

もし三世代でかつ新しい物理がなければユニタリティから要求される

$$4AD = B^2 + C^2$$

が、成立。これを見ればdegeneracyは明らか

成立していなければNSIがある証拠となる。

⇒ NSIを議論するためにはCPをまず測る必要がある

4.まとめ

CPの破れはもうすぐ測れる！？

T2Kで閉じるといいですね。

昨日の友は今日の敵？

CPの破れが背景事象になる日が来る？

是非、LFVも測れますように。

nLFVはどれくらいの大きさか？

模型ごと？

模型によらず？＜－SU(2)の縛り

振動をUnitarity　Checkという観点から見直せるか？