Octant degeneracy with neutrino oscillation experiments

(T2KK+RENO/KASKA)

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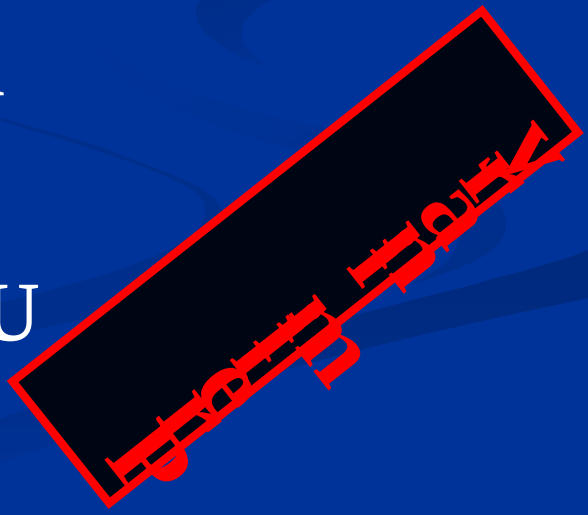
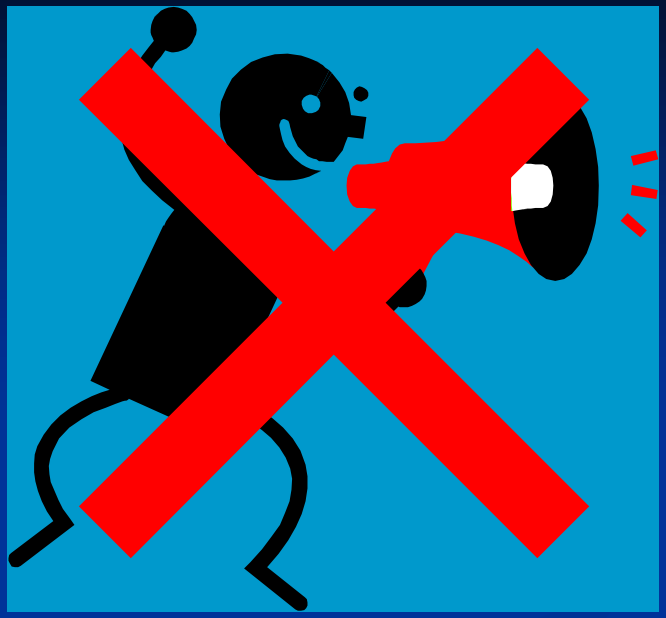
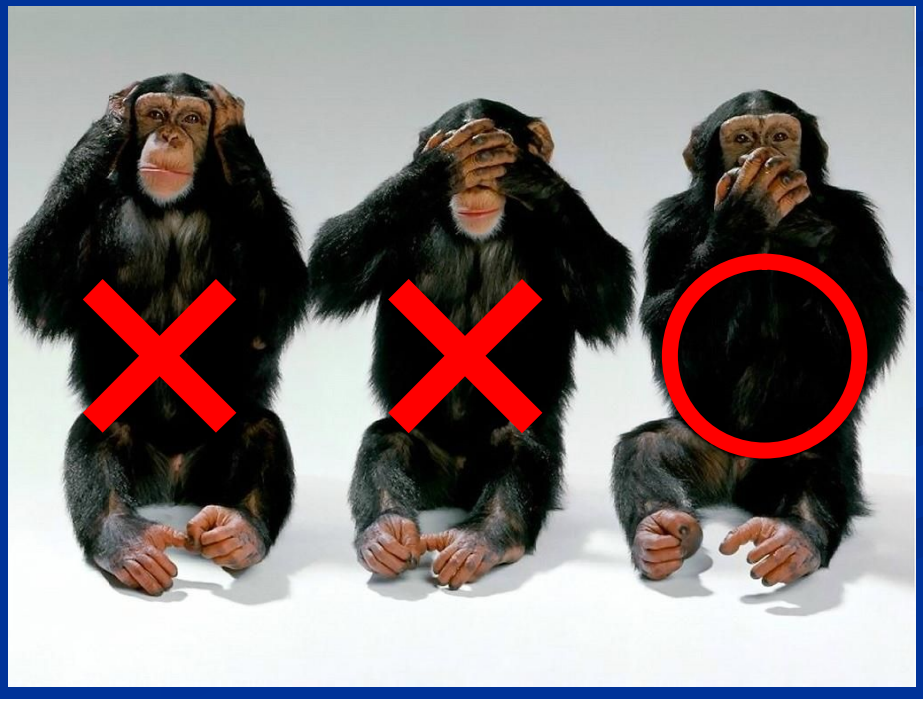
now under writing







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  - **effect of reactor exp.**
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Short Review

Three ambiguity

1

$\delta m^2_{atm} = \delta m^2_{13}$

sign of this mass hierarchy

normal	**inverted**
	2
3	1
$\delta m^2_{13}>0$	$\delta m^2_{13}<0$
2	
1	3

2

$\sin^2 2\theta_{rct}, \delta_{MNS}$

no measured CP Violation

reactor (ν_e ! ν_e)

will measure θ_{rct} unknown CP phase

3

$\sin^2 2\theta_{atm}$

value of θ_{atm} (octant)

best fit : θ_{atm}=45^o no octant ambiguity

matter effect

$$P(\nu_\mu \to \nu_e) = 4\sin^2\theta_{\rm atm}\,\sin^2\theta_{\rm rct}\left(1 + A^e\right)\sin^2\left(\frac{\Delta_{13}}{2} + B^e\right)$$

$$A^e = \frac{aL}{\Delta_{13}E}\cos^2 2\theta_{\rm rct} - \frac{\Delta_{12}}{2}\frac{\sin 2\theta_{\rm sun}}{\tan\theta_{\rm atm}\sin\theta_{\rm rct}}\sin\delta_{\rm MNS}$$

$$\Delta_{ij} \equiv \frac{\delta m^2_{ij}}{2E_\nu}L$$

$$\approx 0.11\frac{\pi}{\Delta_{13}}\frac{L}{295\text{km}} - \left[0.49\left(\frac{0.10}{\sin^2 2\theta_{\rm rct}}\right)^{1/2}\sin\delta_{\rm MNS}\right]\frac{|\Delta_{13}|}{\pi}$$

$$B^e = -\frac{aL}{4E}\cos^2 2\theta_{\rm rct} + \frac{\Delta_{12}}{2}\left(\frac{\sin 2\theta_{\rm sun}}{2\tan\theta_{\rm atm}\sin\theta_{\rm rct}}\cos\delta_{\rm MNS} - \sin^2\theta_{\rm sun}\right)$$

$$\approx -0.08\frac{L}{295\text{km}} + \left[0.24\left(\frac{0.10}{\sin^2 2\theta_{\rm rct}}\right)^{1/2}\cos\delta_{\rm MNS} - 0.016\right]\frac{|\Delta_{13}|}{\pi}$$

“matter effect” : “base-line length”

hep-ph/0602115

Basic Strategy

- transition probability

$$P\left(\nu_\mu \to \nu_e\right) = 4\sin^2\theta_{\text{atm}}\sin^2\theta_{\text{rct}}\left(1+A^e\right)\sin^2\left(\frac{\Delta_{13}}{2}+B^e\right)$$

- "transition probability" sensitive to the $\sin^2\theta_{\text{atm}}$
- When $\sin^2\theta_{\text{rct}}$ is measured by the reactor experiments, $\sin^2\theta_{\text{atm}}$ will be determined from transition probability

- "Long" base-line enhance the matter effect.
- guess "T2KK is better than T2K for octant."

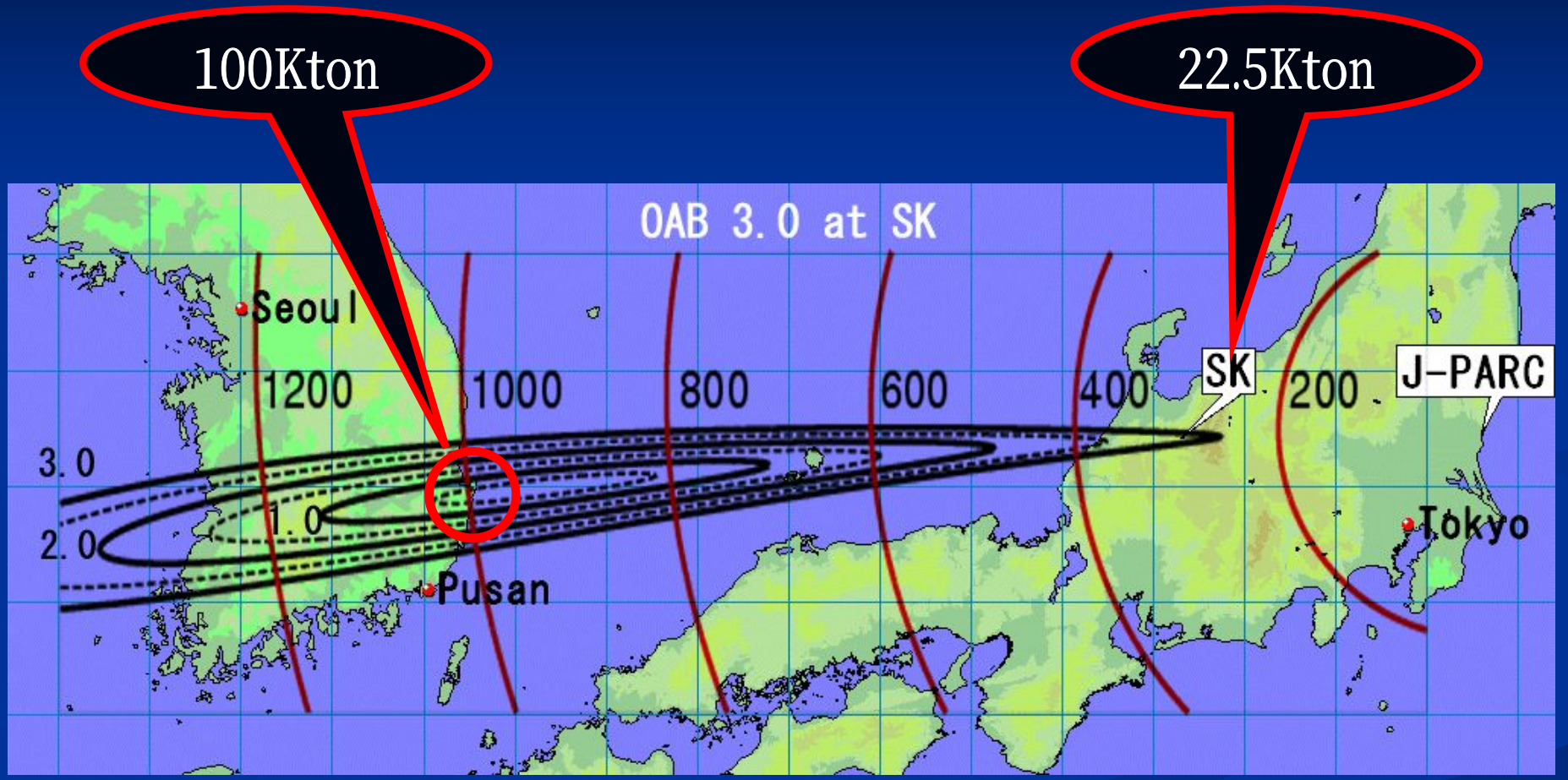
- T2KK can solve the mass hierarchy.

Numerical Analysis

Condition

- **fiducial volume (100% efficiency)**
  - SK : 22.5 kton
  - Korea : 100 kton
- **exposure time**
  - 5 years with 10^{21} POT/year (0.8MW)
  - T2K-I running time
- **base-line and off-axis**
  - SK L=295km OA angle $\theta=3.0^{o}$
  - Korea L=1000km OA angle $\theta=0.5^{o}$

place and OAB



maps are in

http://www2.yukawa.kyoto-u.ac.jp/~okamura/T2KK

input parameters

- **Solar**
  - $\sin^2 2\theta = 0.84 \pm 0.07$, $\delta m^2 = (8.3 \pm 0.6) \times 10^{-5}$ eV^2
- **Atmospheric**
  - $\sin^2 2\theta =$ 0.99,0.96,0.91 $\delta m^2 = (2.5 \pm 0.5) \times 10^{-3}$ eV^2
- **matter density** (uncertainty : ±3%)
  - $\rho = 2.8 / 3.0$ (g/cm^3) (SK/Korea)
- **others** (uncertainty : ±3%)
  - flux normalization (each species)
  - CCQE cross section (ν / anti-ν)
  - fiducial volume (SK / Korea)

#total parameters:16

Event Number

- **CCQE event**
  - easy reconstruct the neutrino energy
  - easy distinguish, *e*-like, μ-like
- **Binning**
  - bin width : 200MeV
  - summation region (#event > 10)
    - 0.4 – 5.0 GeV for μ-like (SK/Korea)
    - 0.4 – 1.2 GeV for e-like (SK)
    - 0.4 – 2.8 GeV for e-like (Korea)
- **BG**
  - beam contamination
  - NOT include NC background (π^0 ! $\gamma\gamma$, $\Leftrightarrow$ *e*-shower)

Systematic errors

event number $(\nu_\beta \to \nu_\alpha)$

δE_ν:200MeV

$$N_\alpha^i(\nu_\beta) = \int_{E_\nu^i}^{E_\nu^i+\delta E_\nu} \Phi_{\nu_\beta}(E) P_{\nu_\beta \to \nu_\alpha}(E) \sigma_\alpha^{QE}(E) dE$$

depends on the matter density: $f_\rho(L)$

true : $$\left(N_\alpha^i\right)^{true} = \sum_{\nu_\beta:\text{all}} N_\alpha^i(\nu_\beta)$$

fit : $$\left(N_\alpha^i\right)^{fit} = f_V^{SK/Kr} \sum_{\nu_\beta:\text{all}} f_{\nu_\beta}^{flux} f_{\nu_\alpha}^{QE} N_\alpha^i(\nu_\beta)$$

all systematic error : 3%

$f_{\nu_\beta}^{flux}$: flux normalization

$f_{\nu_\alpha}^{QE}$: cross section

$f_V^{SK/Kr}$: fiducial volume

χ^2

$$\chi^2 = \sum_{\substack{i:\text{bin} \\ \alpha:e,\mu}} \left(\frac{\left(N_\alpha^i\right)^{fit} - \left(N_\alpha^i\right)^{true}}{\sqrt{\left(N_\alpha^i\right)^{true}}} \right)^2$$

event number

sys. error

$$+ \sum_{\text{all flavor}} \left(\frac{f_{\nu_\beta}^{flux} - 1.0}{0.03} \right)^2 + \sum_{\nu,\bar{\nu}} \left(\frac{f_{\nu_\alpha}^{QE} - 1.0}{0.03} \right)^2 + \sum_{SK,Kr} \left\{ \left(\frac{f_\rho - 1.0}{0.03} \right)^2 + \left(\frac{f_V^{SK/Kr} - 1.0}{0.03} \right)^2 \right\}$$

$$+ \sum_{\text{ATM,SOL}} \left(\frac{\left(\delta m^2_{\text{ATM,SOL}}\right)^{fit} - \left(\delta m^2_{\text{ATM,SOL}}\right)^{true}}{\Delta\left(\delta m^2_{\text{ATM,SOL}}\right)} \right)^2$$

$$+ \sum_{\text{ATM,SOL}} \left(\frac{\left(\sin^2 2\theta_{\text{ATM,SOL}}\right)^{fit} - \left(\sin^2 2\theta_{\text{ATM,SOL}}\right)^{true}}{\Delta\left(\sin^2 2\theta_{\text{ATM,SOL}}\right)} \right)^2$$

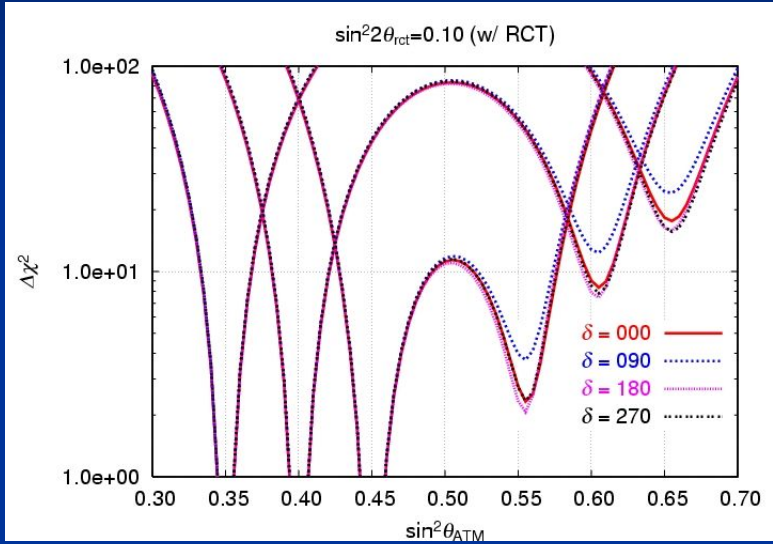
$$+ \left(\frac{\left(\sin^2 2\theta_{\text{RCT}}\right)^{fit} - \left(\sin^2 2\theta_{\text{RCT}}\right)^{true}}{\Delta\left(\sin^2 2\theta_{\text{RCT}}\right)} \right)^2$$

parameter error

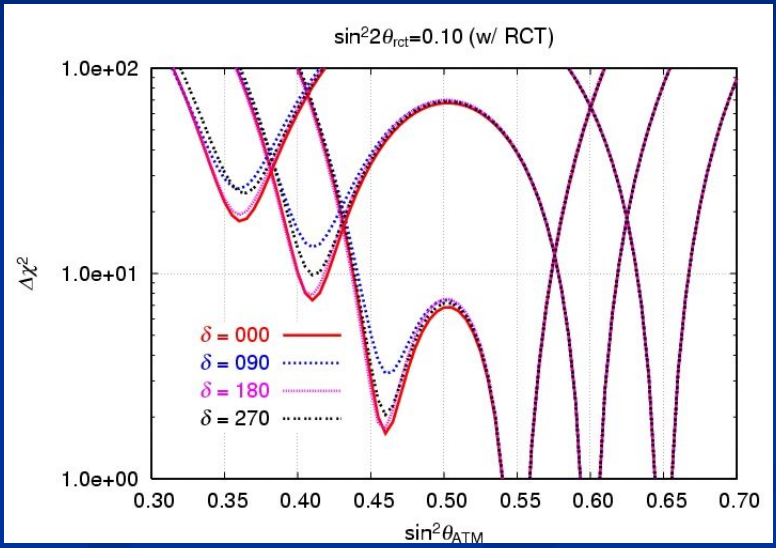
new term (θ_{13}) from RCT exp.

octant in T2KK

input:$\theta<\pi/4$



input:$\theta>\pi/4$

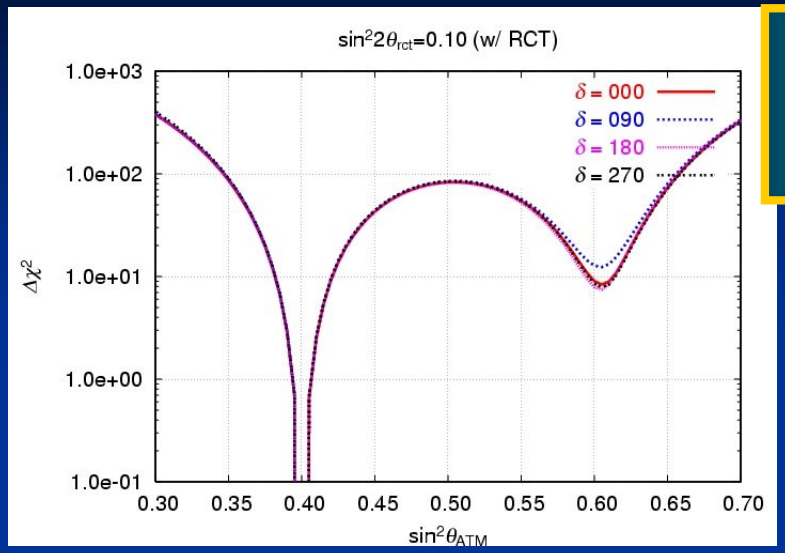


input : $\sin^2 2\theta_{rct} = 0.10 \pm 0.01$
δ $= 0, 90, 180, 270$
normal hierarchy

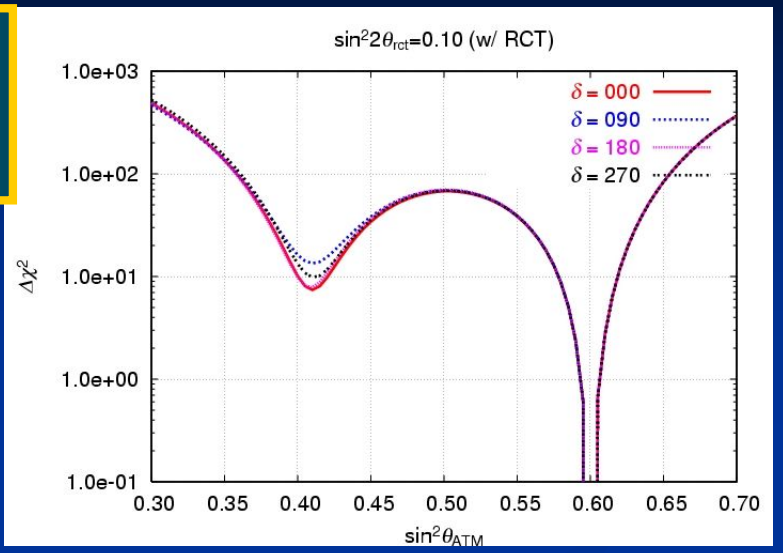
$\sin^2 2\theta$	0.99	0.96	0.91
sig.	1σ	3σ	4σ

$\sin^2 2\theta$	$\sin^2\theta$	$\sin^2\theta$
	$\theta<\pi/4$	$\theta>\pi/4$
0.99	0.45	0.55
0.96	0.40	0.60
0.91	0.35	0.65

Reactor experiment



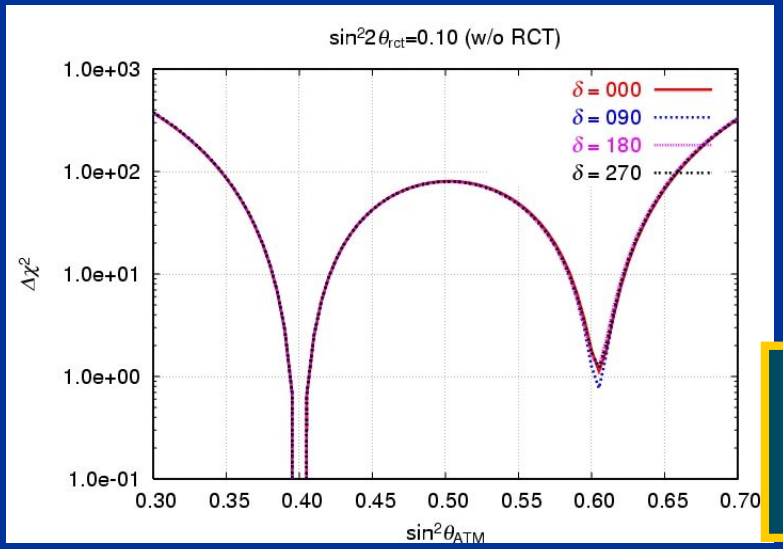
with RCT.



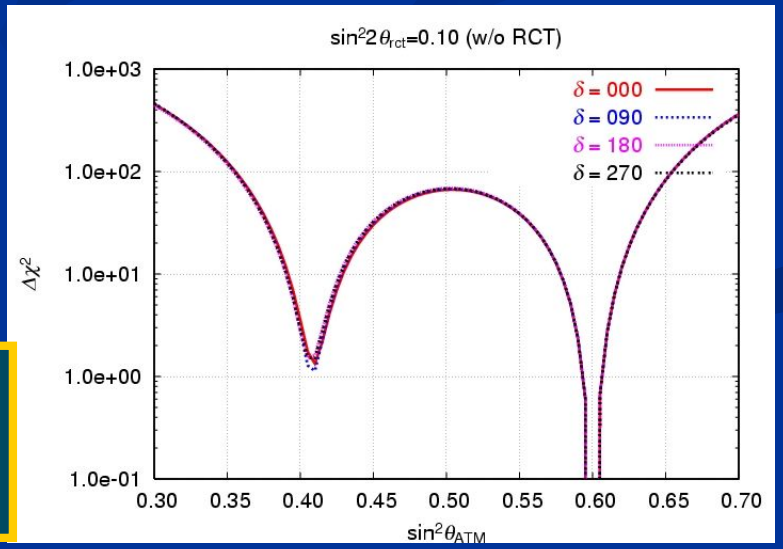
input:θ<π/4

0.96

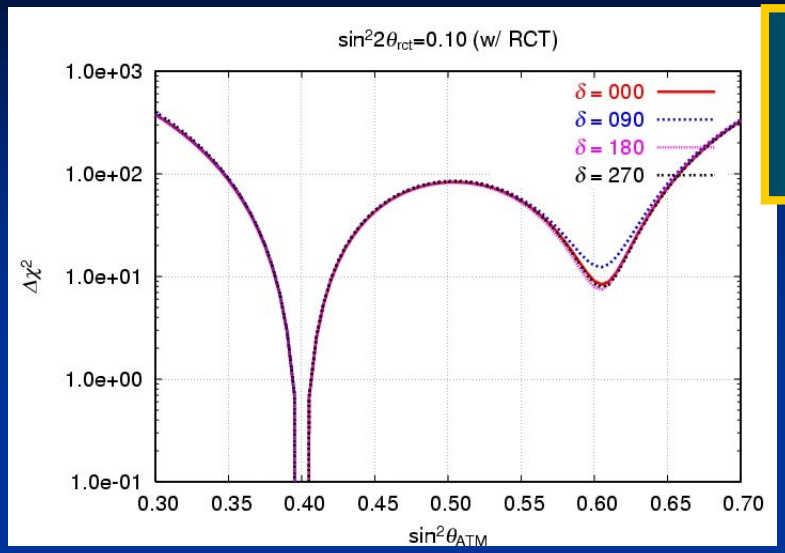
input:θ>π/4



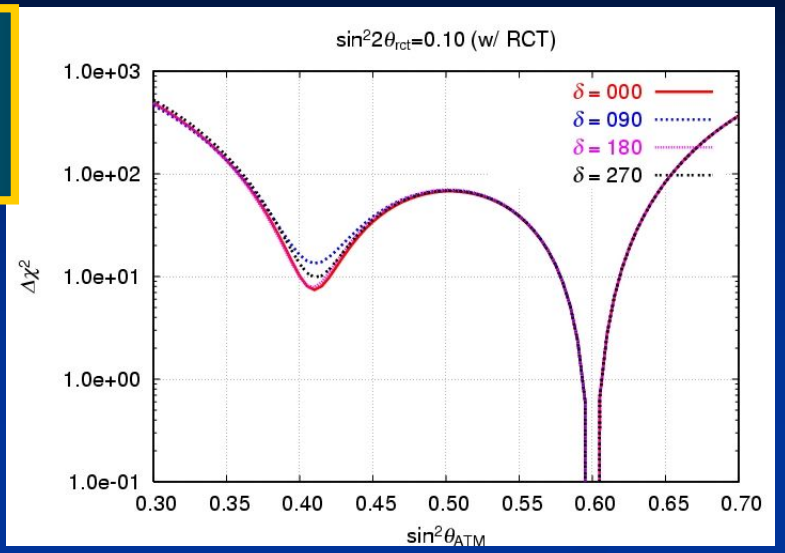
without RCT.



Far detector



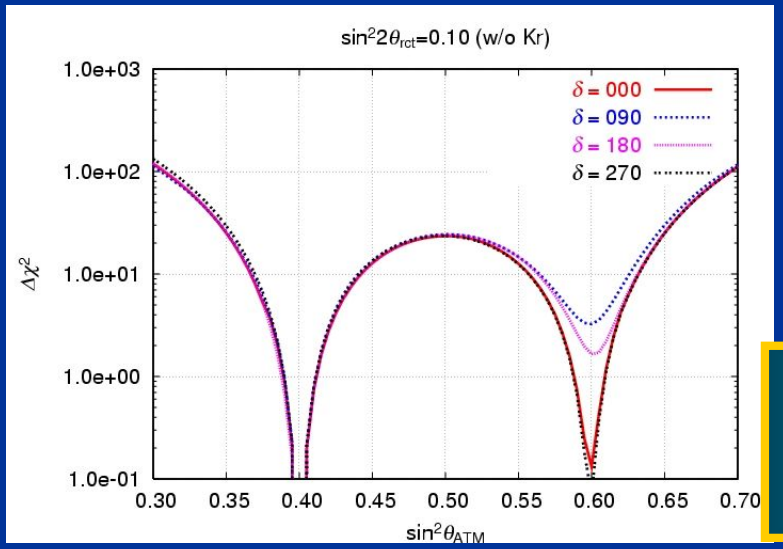
T2KK (w/ FD)



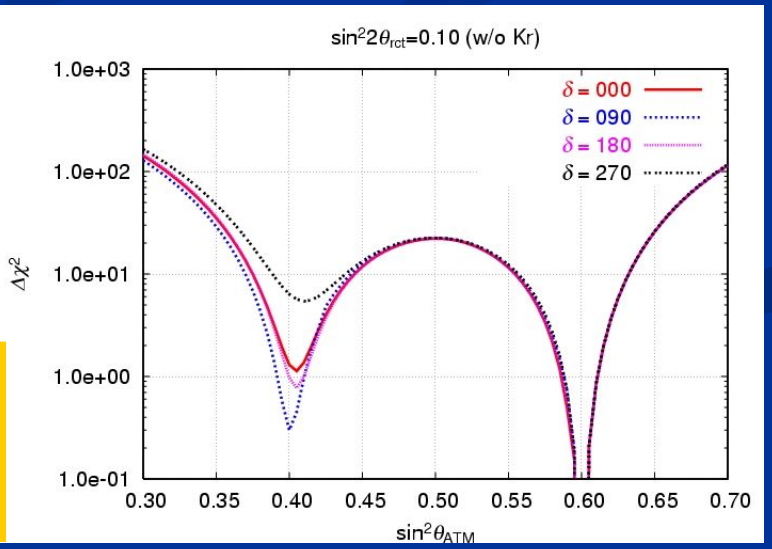
input:θ<π/4

0.96

input:θ>π/4

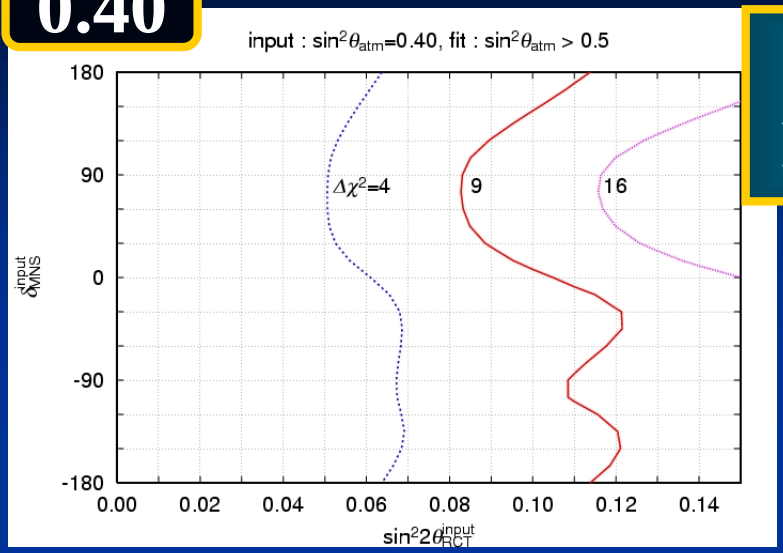


T2K (w/o FD)



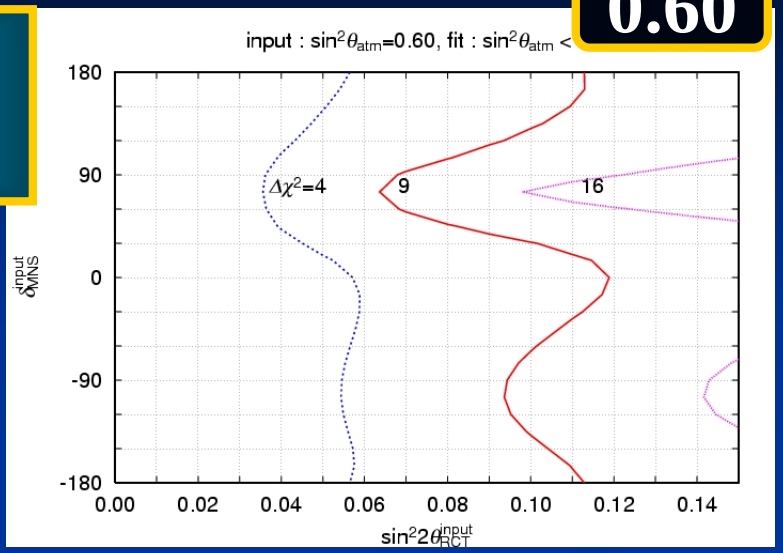
CP vs RCT plain

0.40



normal hierarchy

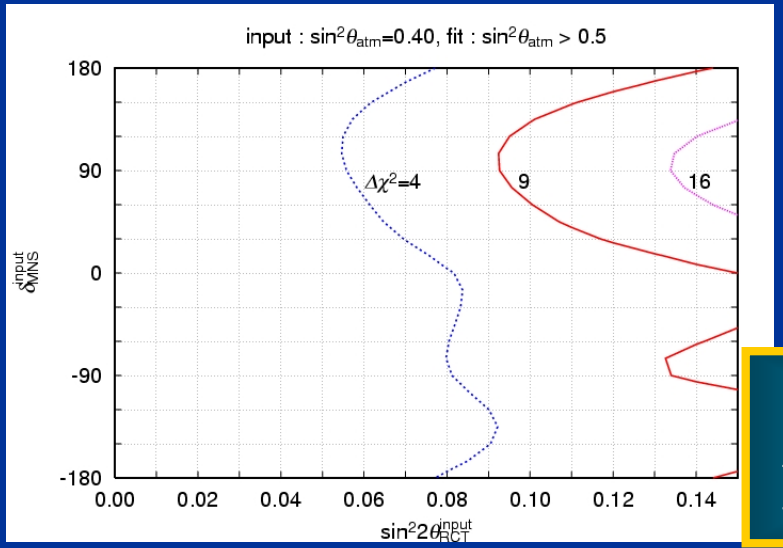
0.60



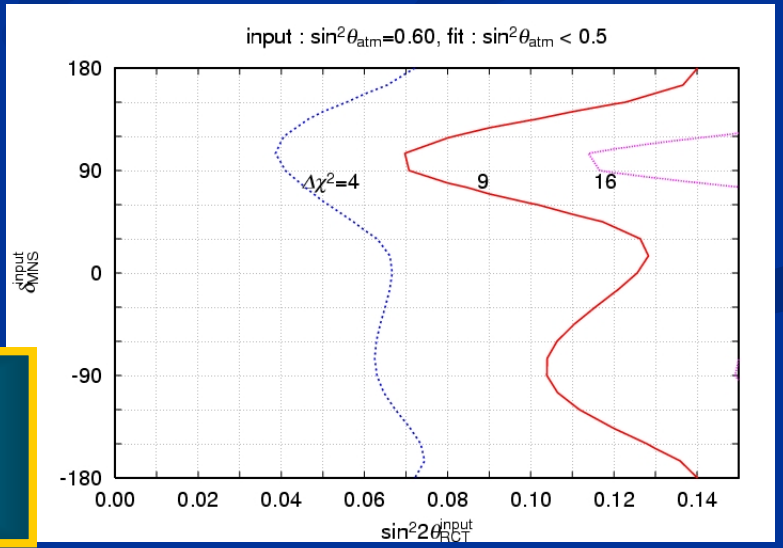
input:θ<π/4

0.96

input:θ>π/4

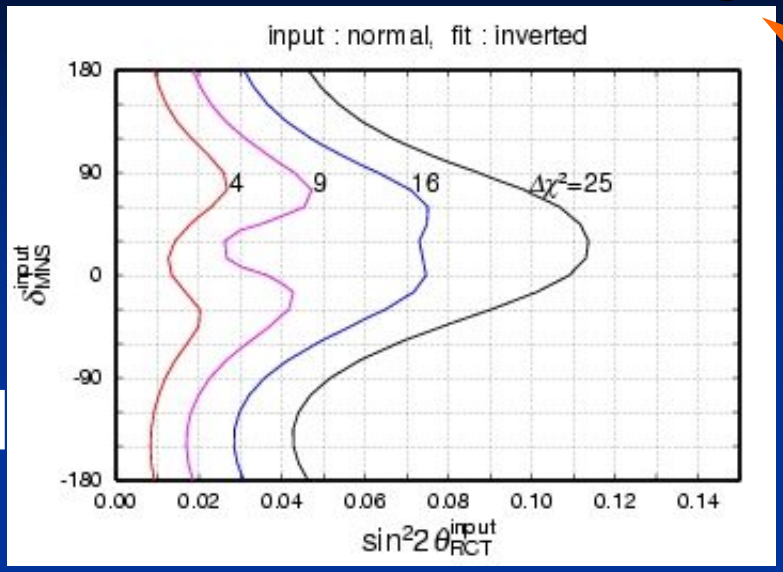


inverted hierarchy



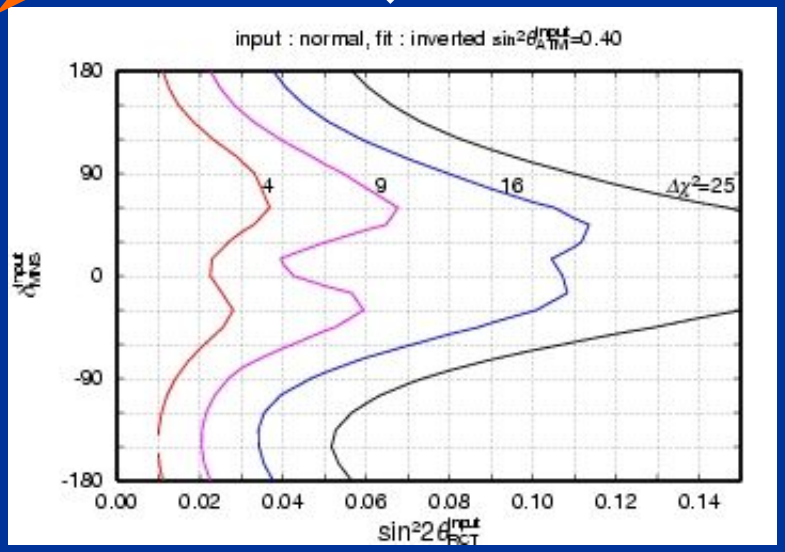
impact from octant
to the others

mass hierarchy

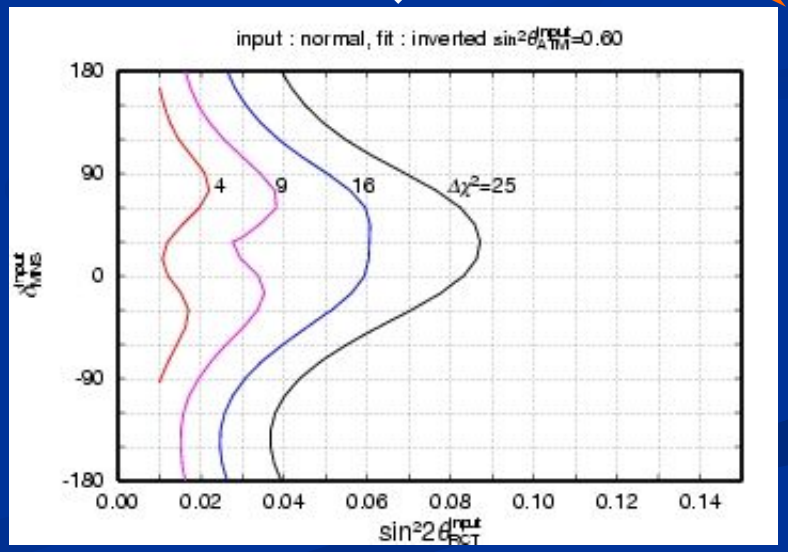


0.50 (1.00)

0.40 (0.96)



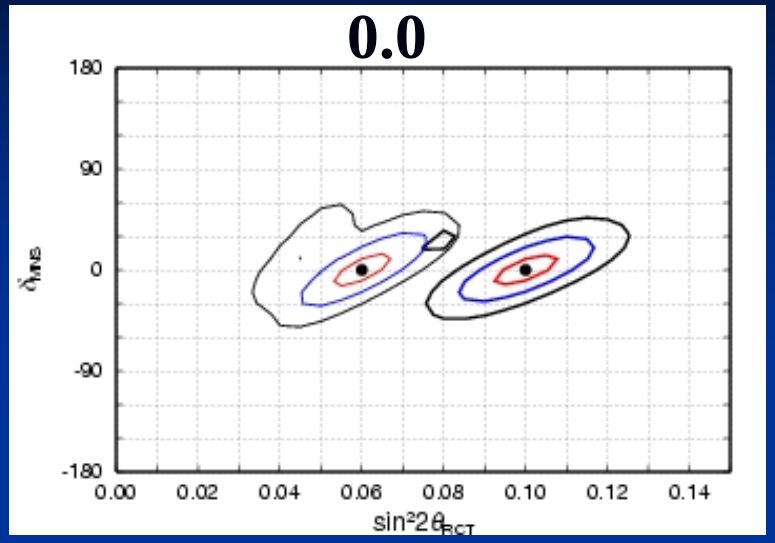
0.60 (0.96)



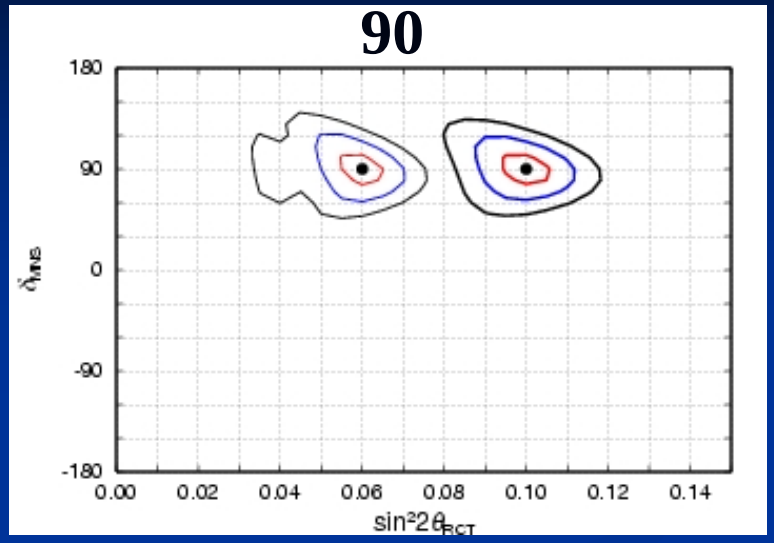
event number mainly determine the hierarchy

CP phase ($\sin^2\theta_{atm}$=0.40)

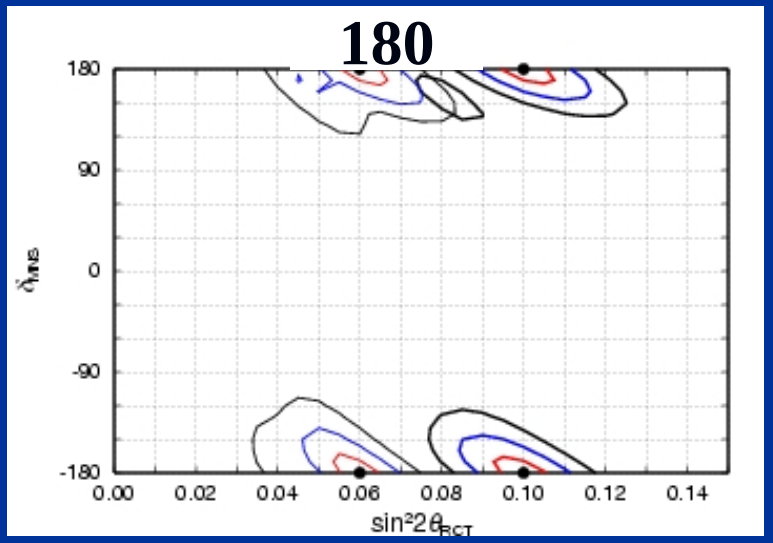
0.0



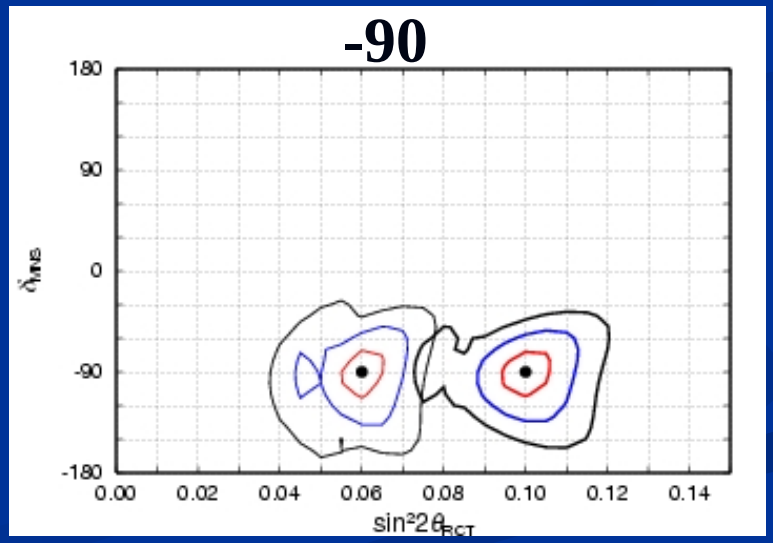
90



180

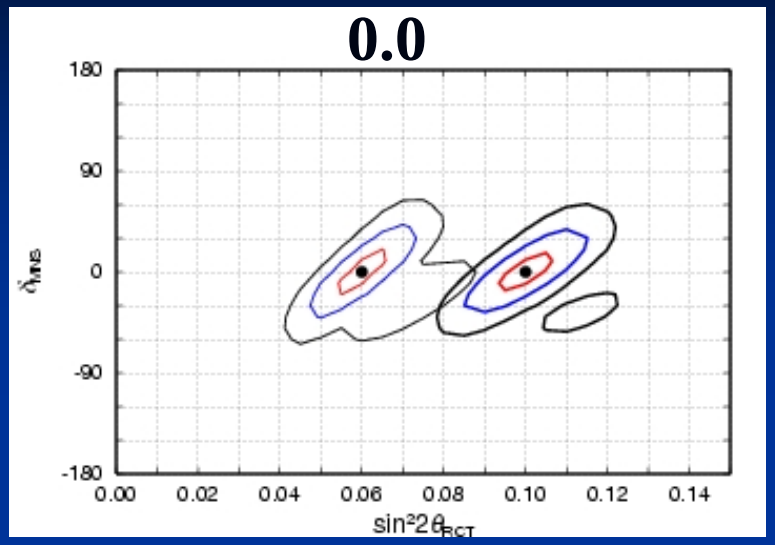


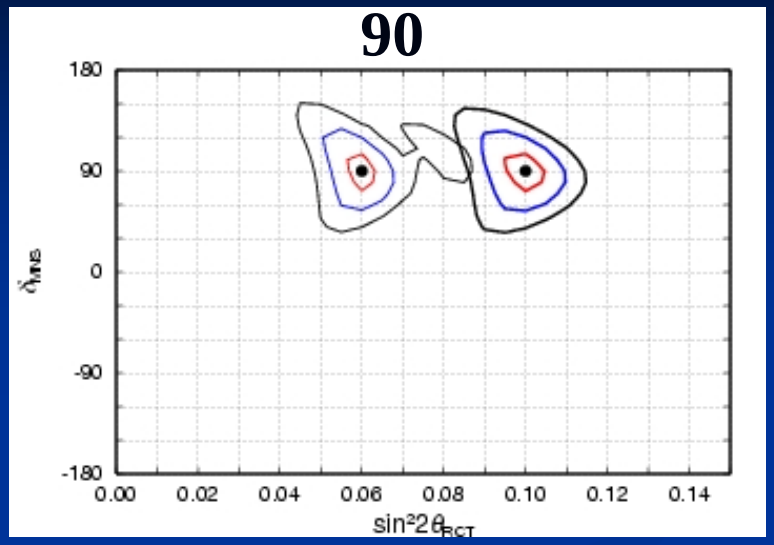
-90

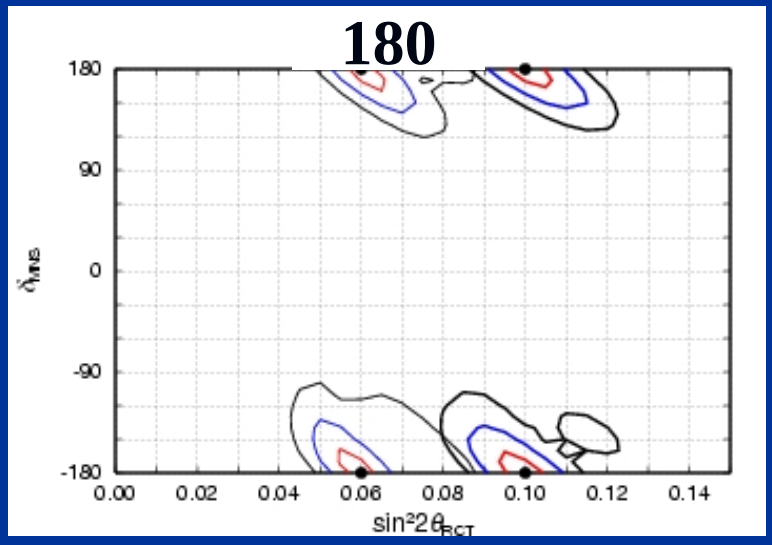


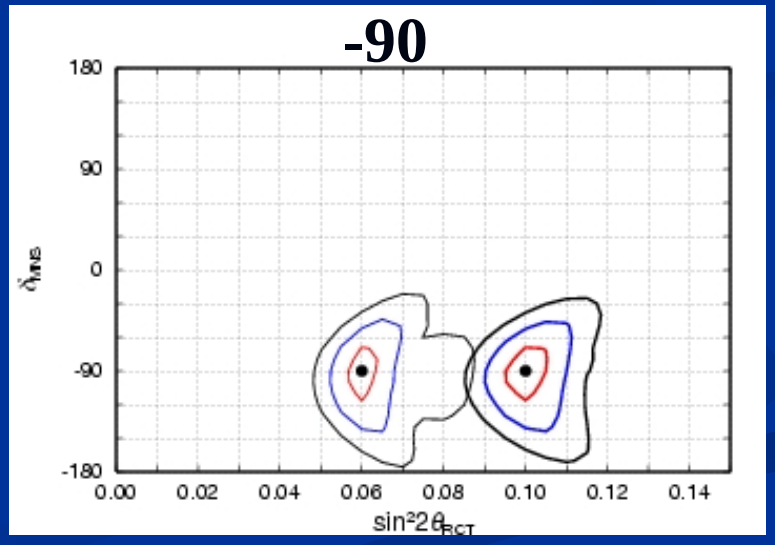
error of CP phase is not drastically changed

CP phase ($\sin^2\theta_{atm}$=0.60)









error of CP phase is not drastically changed

summary

- Need “reactor experiments”
  - transition probability proportional to

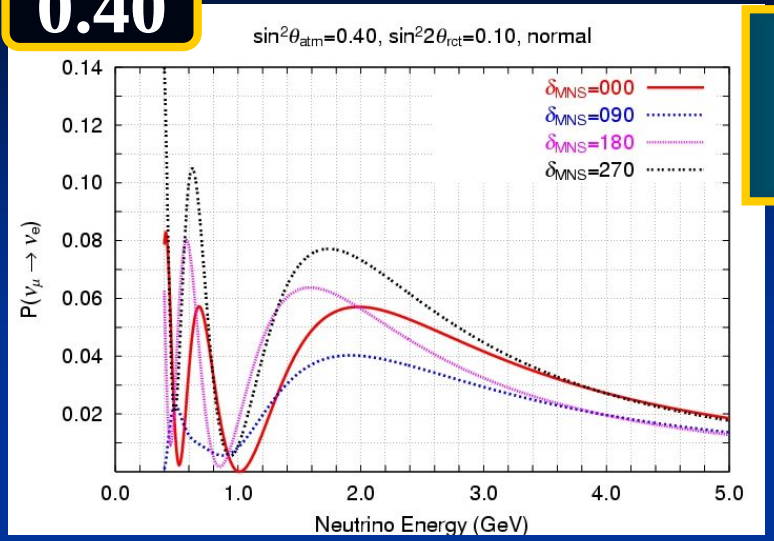
    $\sin^2\theta_{rct}\ \sin^2\theta_{atm}$
- Need “Far detector”
  - matter effect enhance the transition probability
  - mass hierarchy can be solved
- impact from the octant degeneracy to…
  - mass hierarchy : large $\sin^2\theta_{atm}$: good!!
  - CP phase : there is additional region

    error of CP phase not so different


Get It ??

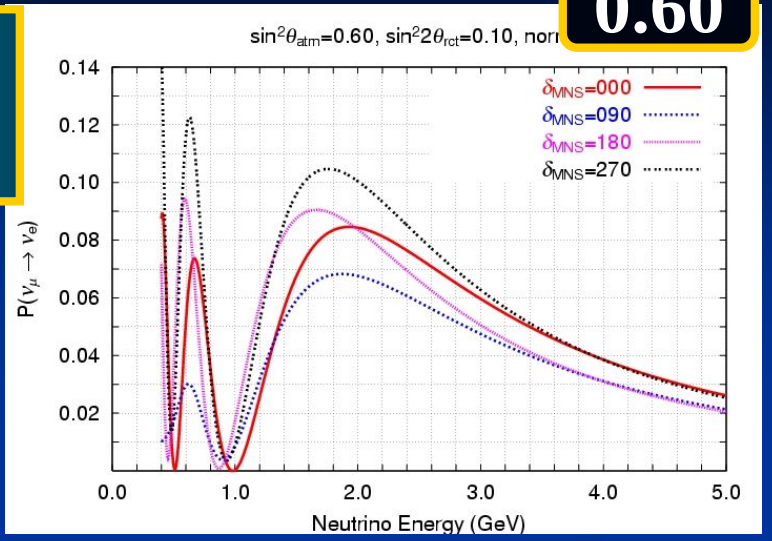
probability

0.40



normal hierarchy

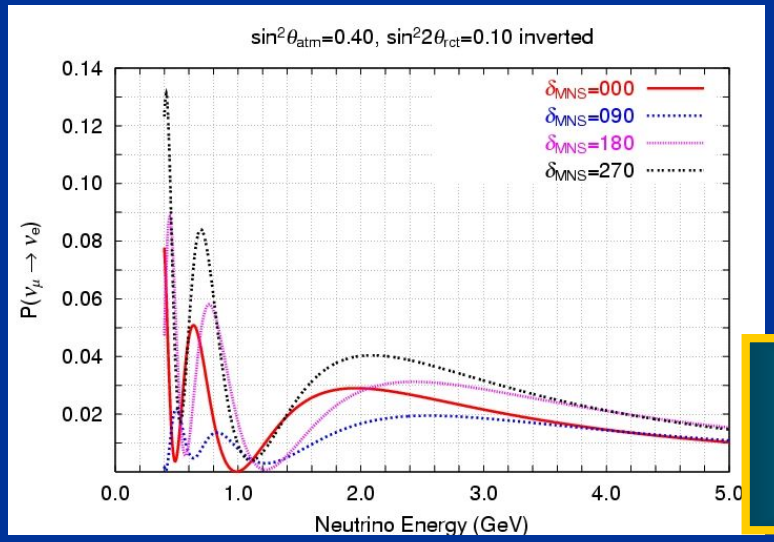
0.60



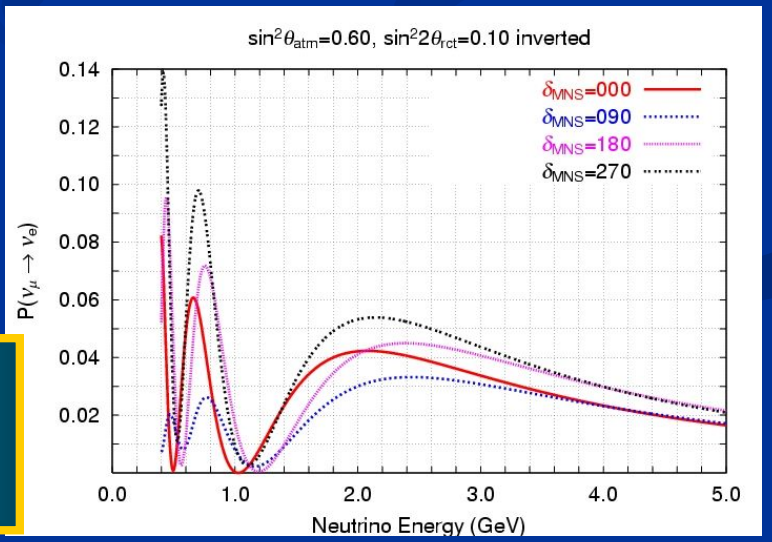
input:θ<π/4

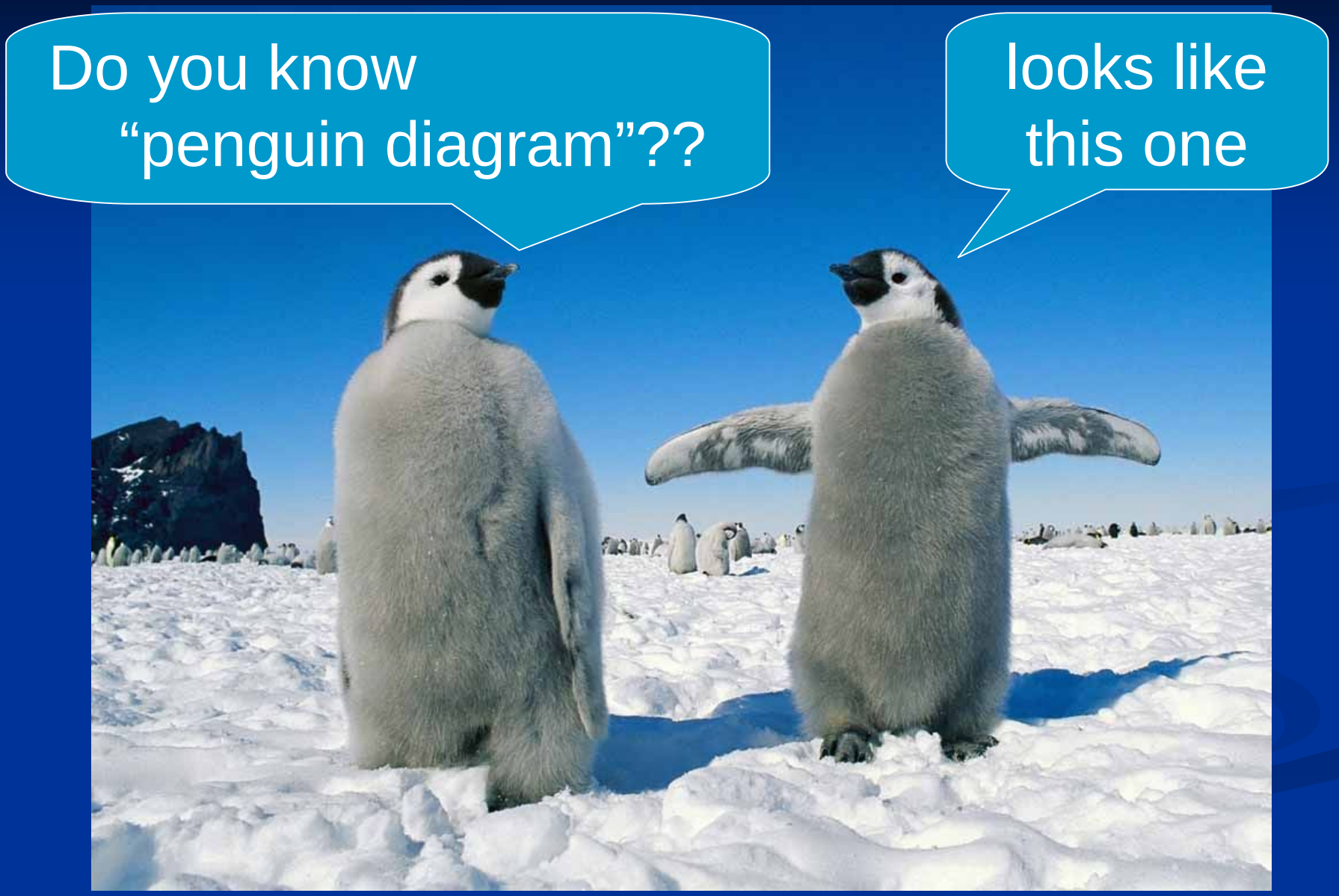
0.96

input:θ>π/4



inverted hierarchy




Do you know
“penguin diagram”??
looks like
this one