T2K
Physics Analysis Status
and
Sensitivity Update

* some of the pages are removed from slide for the web version

A.K.Ichikawa, Kyoto university
for the T2K collaboration

ν oscillation, current status

CP phase
KEY to understand the origin of matter dominant universe

Mixing matrix for leptons

Unknown

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$$

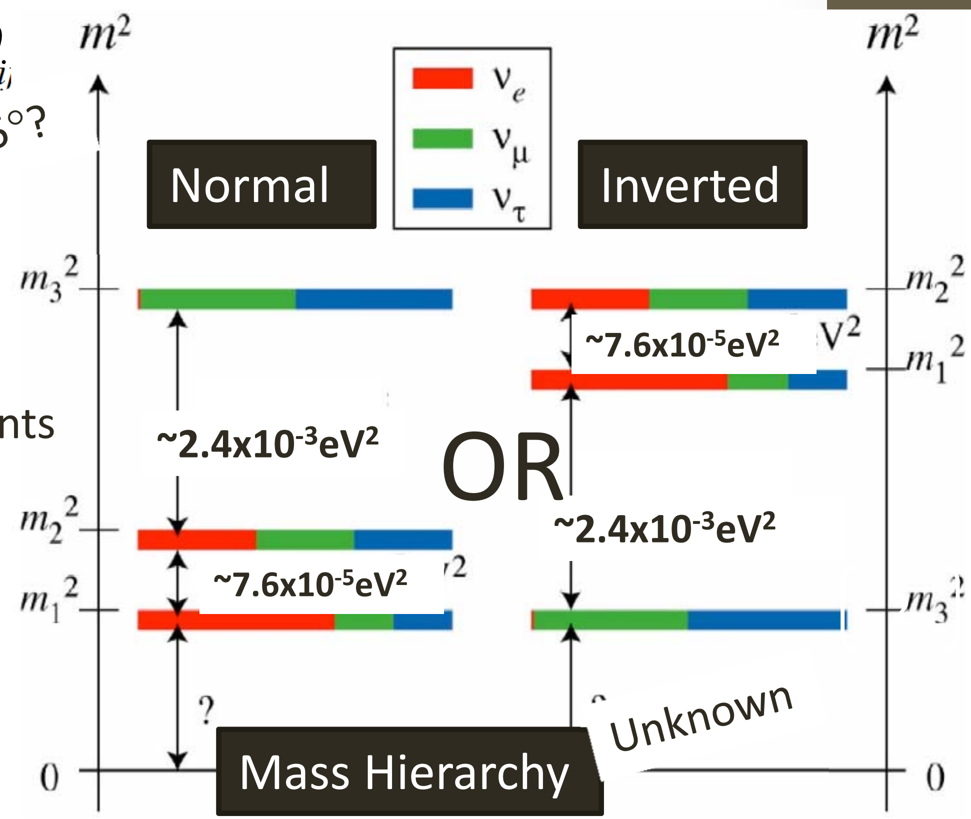
$$\theta_{12} = 33.6° \pm 1.0°$$

How close to 45°?

$$\theta_{23} = 45° \pm 6° \quad (90\%\mathrm{CL})$$

$$\theta_{13} = 9.1° \pm 0.6° !$$

← Reactor experiments



Big Impact
on 0ν double-β decay search
(hence on Majorana ν confirmation)

Suggestive Mixing Matrixes

quarks

$$U_{CKM} \approx \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

$$\delta = 60°$$

leptons

$$U_{PMNS} \approx \begin{pmatrix} 0.8 & 0.55 & 0.15 \\ -0.4 & 0.6 & 0.7 \\ 0.4 & -0.6 & 0.7 \end{pmatrix}$$

$$\delta = ?$$

Example of prediction.
Assuming some symmetry among quarks and leptons,

$$U_{CKM} \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$U_{PMNS} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ \sqrt{1/6} & -\sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

$$= \begin{pmatrix} 0.816 & 0.577 & 0 \\ -0.408 & 0.577 & 0.707 \\ 0.408 & -0.577 & 0.707 \end{pmatrix}$$

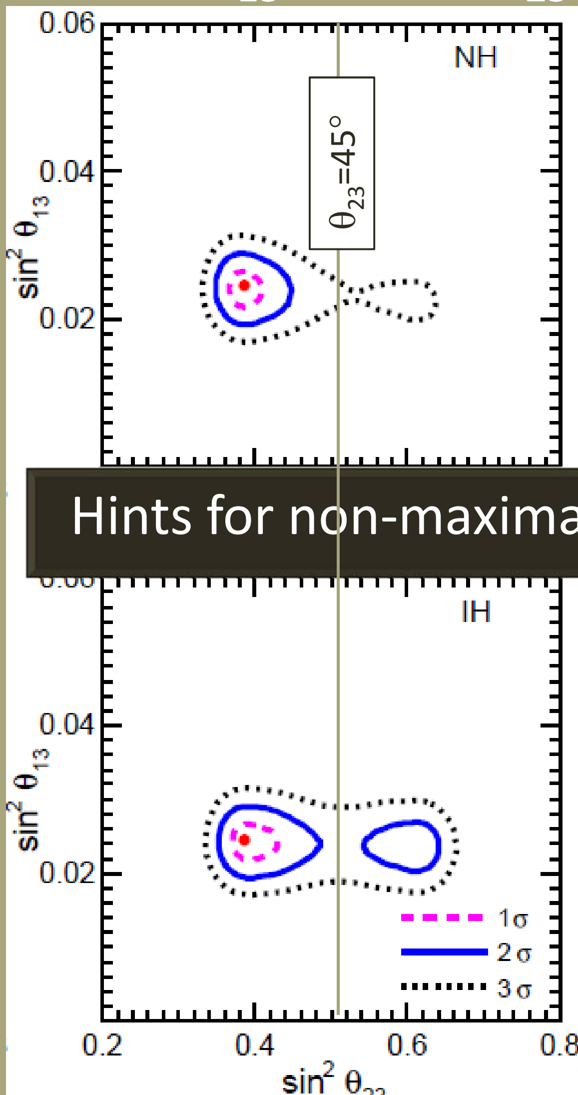
Can be a KEY to understand the origin of quark and lepton

Global Analysis

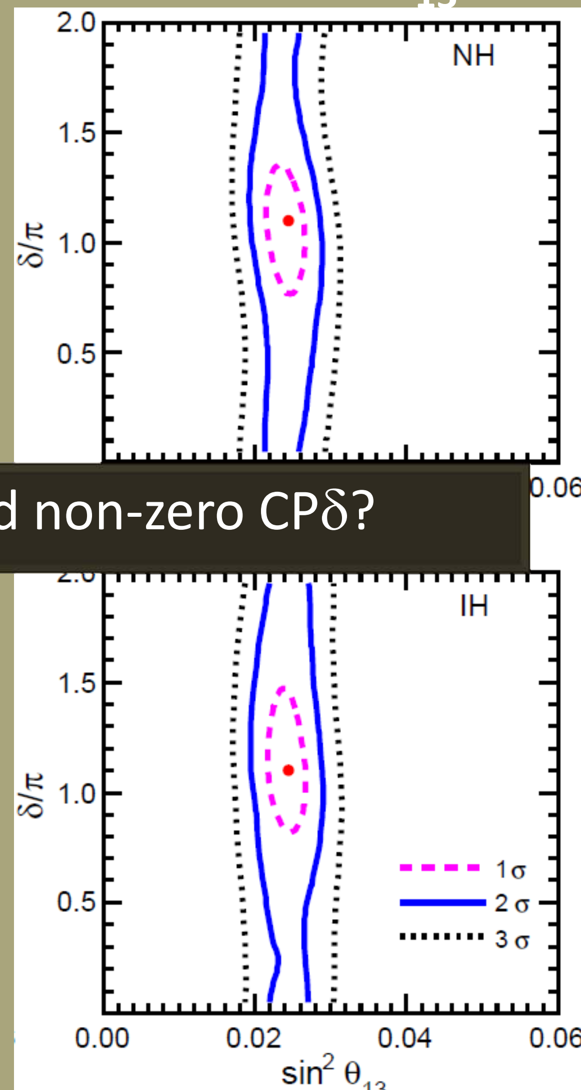
(LBLacc+Solar+KamLAND+SBL reactors+SKAtm)

G.L.Fogli et.al,
Phys.Rev. D86 (2012) 013012

$\sin^2\theta_{13}$ v.s. $\sin^2\theta_{23}$



δ v.s. $\sin^2\theta_{13}$



Hints for non-maximal θ_{23} and non-zero CPδ?

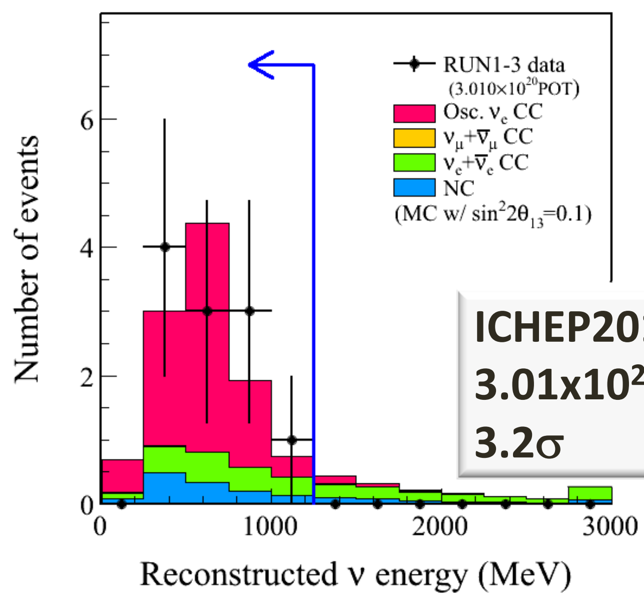
Normal Mass Hierarchy

Inverted Mass Hierarchy

Physics Analysis Status

ν_e appearance

- ✓ PRL 107 (2011) 041801 (Run1+2 result) referred to > 455 times
- ✓ Result w/ Run1-3 (11events) was released at ICHEP2012 in August: 3.2σ
  - Full paper of this analysis is being prepared and will be submitted soon.
- ✓ Aiming to achieve ~5σ significance w/ data up to Summer 2013.
- ✓ Will update results in Summer



ICHEP2012
3.01×10^{20} POT
3.2σ

✖ 2.66

8×10^{20} POT

~5σ sensitivity

ν_μ disappearance

New! w/ Run1-3 data (3.01×10^{20}POT)

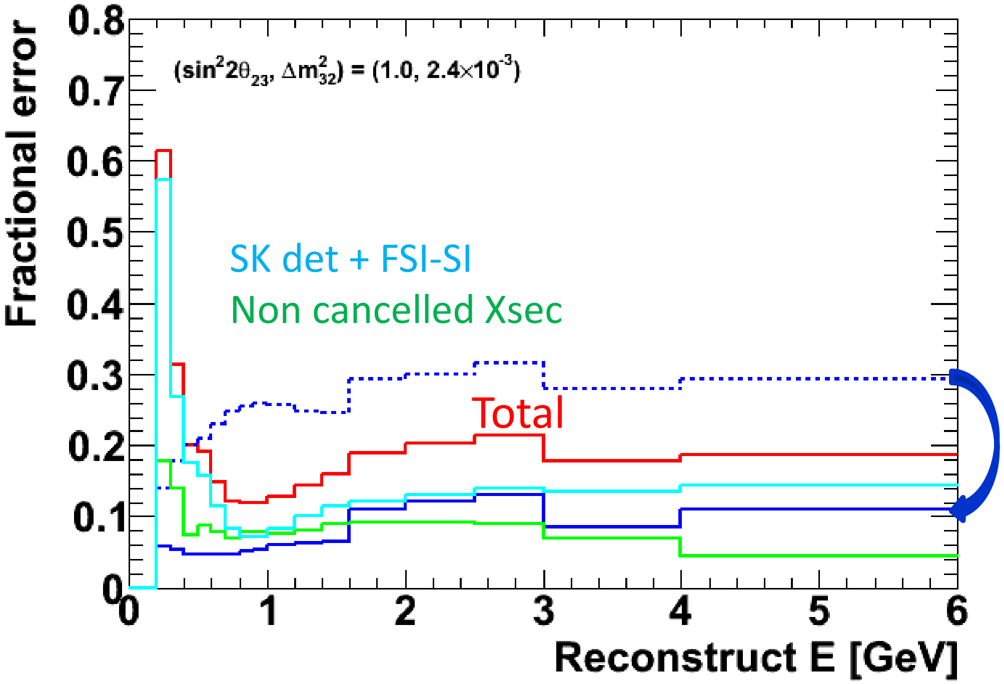
- Update since July 2011(=1.4×10^{20}POT)
- Use event rate and E_{rec} spectrum (Same as before)
- New analysis w/ spectrum constraint by ND280
  - 2 independent analyses
  - Validation w/ RunI+II data and fake data

3.01×10^{20} POT	Data	MC(*) Expectations w/ oscillation				
		MC total	ν_μ CCQE	ν_μ CC non-QE	ν_e CC	NC
FCFV	174	167	34	84	7.9	40
1-ring μ-like	66	68	32	32	0.04	3.5
p_μ>200MeV/c, Ndecay-e<=1	58	58	31	23	0.03	3.2
Efficiency[%]		20	69	21	0.4	2.4

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

Systematic Errors

	ν_e sample	ν_μ sample
Flux & X-section	5.0% (22.6%)	4.1%(21.8%)
X-sec (non-cancel w/ ND280)	7.5%	6.2%
SK detector	3.0%	10.5%
Final-State and Secondary interactions	2.3%	3.5%
total	9.9%(24.2%)	13.2%(25.0%)



() is the case w/o ND280 constraint

(Flux)x(X-sec) constraint by ND280

Reconstructed E_ν spectrum of ν_μ sample

Preliminary

Analysis completed and under internal review, now.

T2K sensitivity update

(All plots are **VERY preliminary**
and **work in progress**.
Plan to show more complete results in Jun. PAC)

T2K sensitivity update

Precise measurement of $\sin^2 2\theta_{13}$ by reactor boosts the T2K sensitivity on CP-δ and θ_{23} octant degeneracy(*).

- $\theta_{12} = 33.6^\circ \pm 1.0^\circ$
- $\theta_{23} = 45^\circ \pm 6^\circ$ (90%CL)
- $\theta_{13} = 9.1^\circ \pm 0.6^\circ$
- mass hierarchy: unknown

* ν_μ disapp. is measuring $\sin^2 2\theta_{23}$ and cannot resolve $\theta_{23}<45^\circ$ or $\theta_{23}>45^\circ$.

Max. 27% asymmetry by CP phase for $\theta_{23}=45^\circ$

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}\left(1+\frac{2a}{\Delta m_{31}^2}\left(1-2S_{13}^2\right)\right)$$

Leading including matter effect

$$+8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

CP conserving

$$-8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

CP violating

$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\Phi_{21}$$

Solar

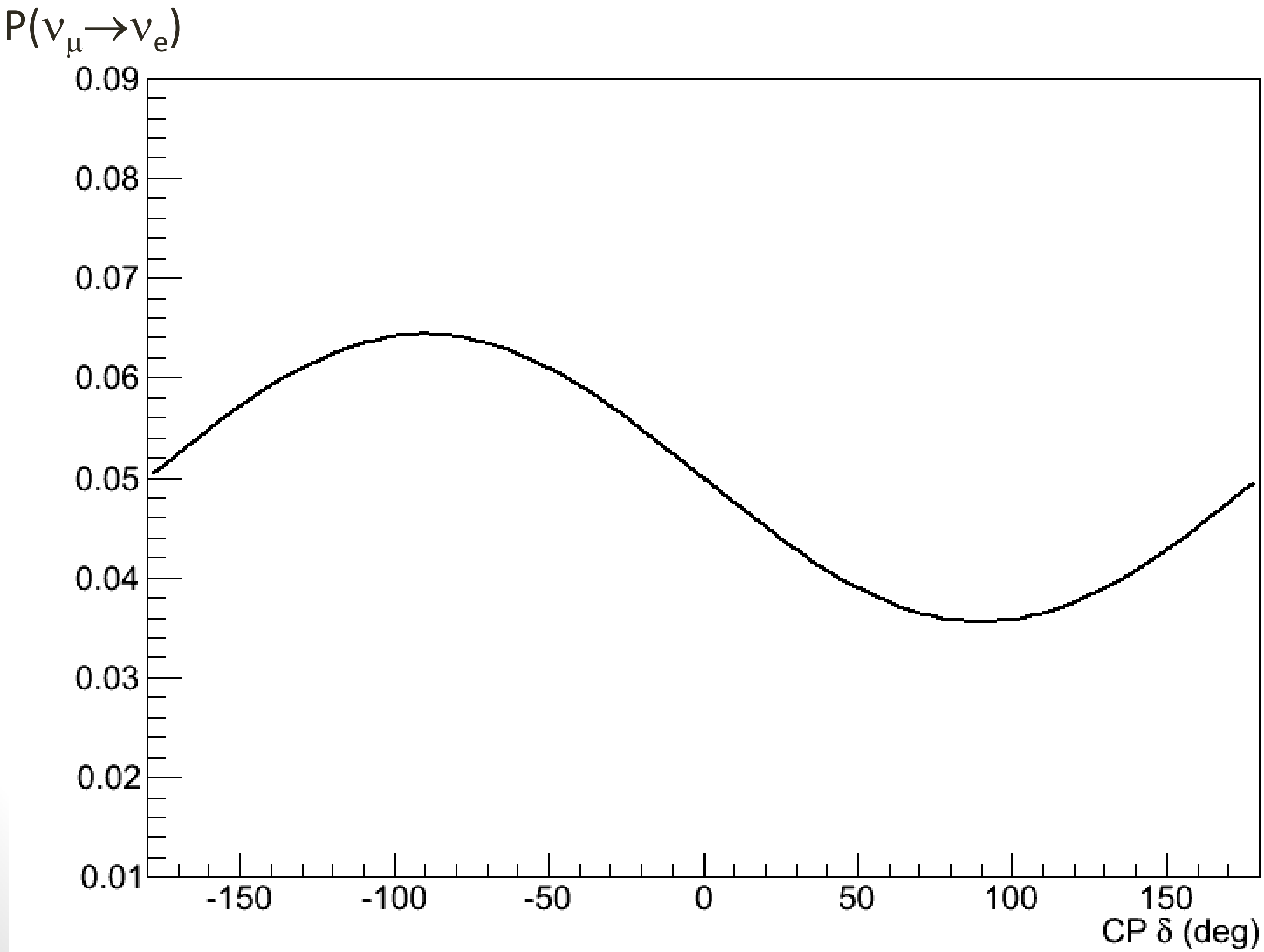
$$-8C_{13}^2 S_{13}^2 S_{23}^2 (1-2S_{13}^2)\frac{aL}{4E}\cos\Phi_{32}\sin\Phi_{31}$$

Matter effect

ν_μ to ν_e oscillation probability

at oscillation maximum

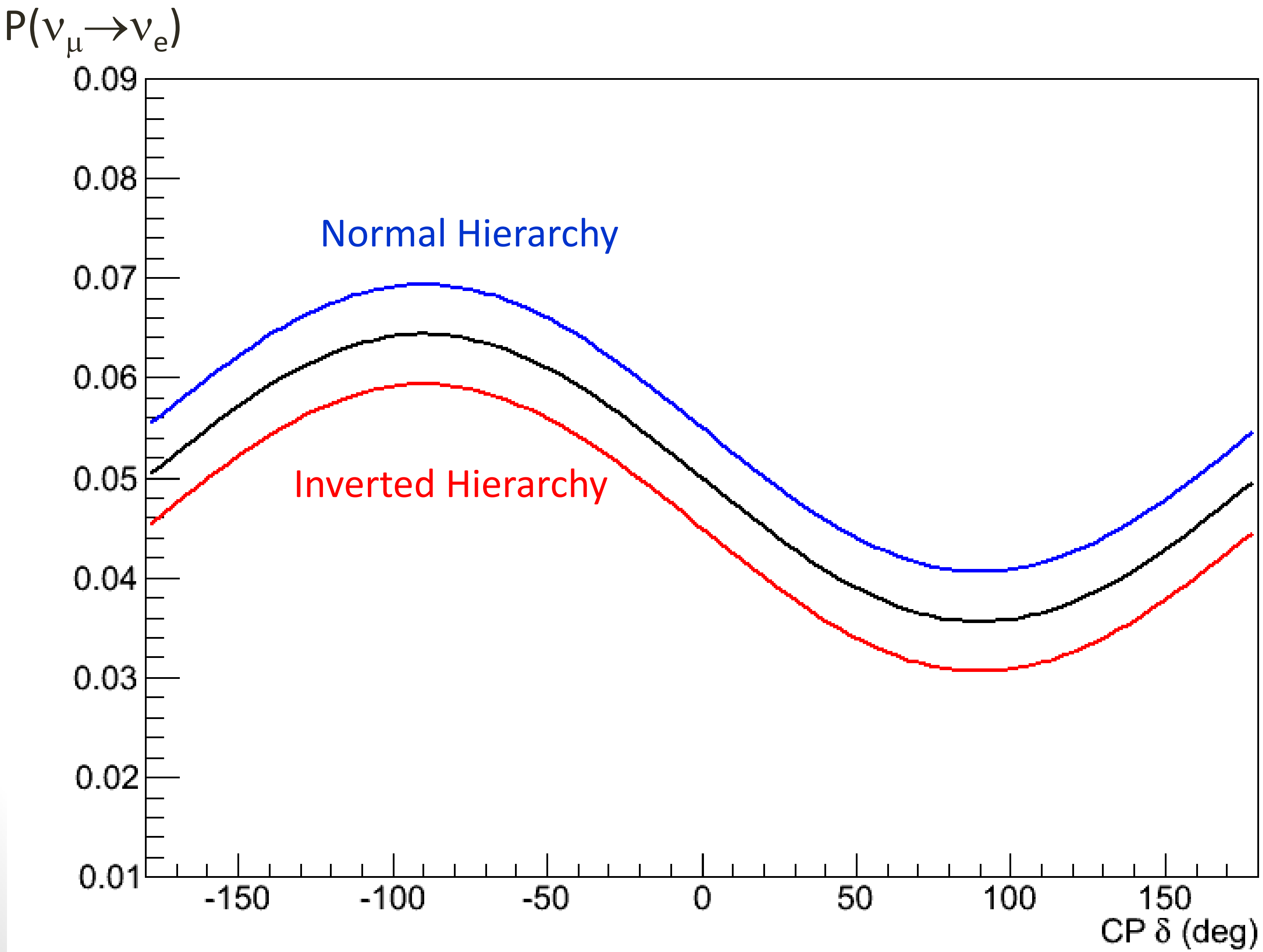
$\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$ in vacuum



ν_μ to ν_e oscillation probability

at oscillation maximum

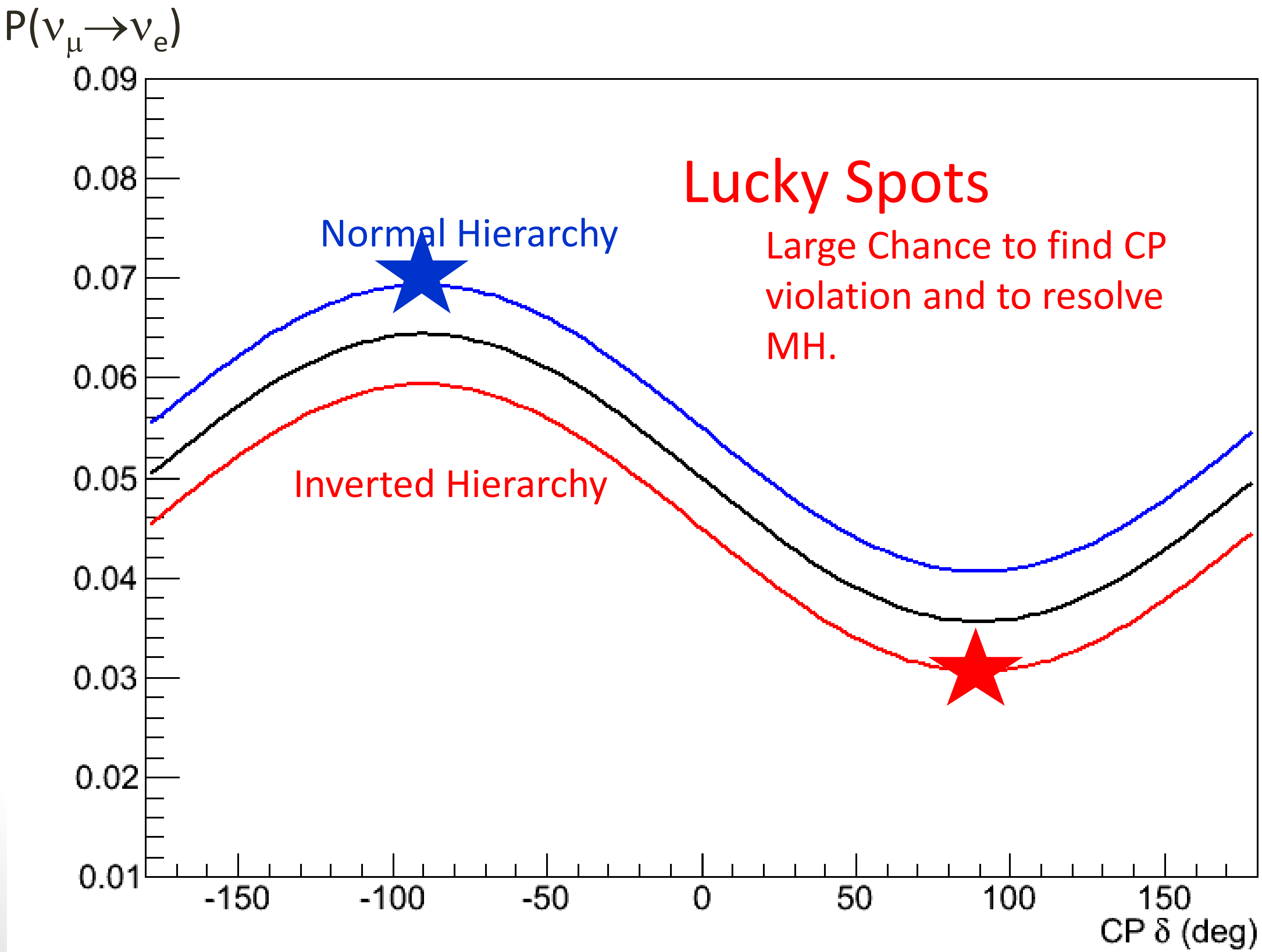
$\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, w/ matter effect



ν_μ to ν_e oscillation probability

at oscillation maximum

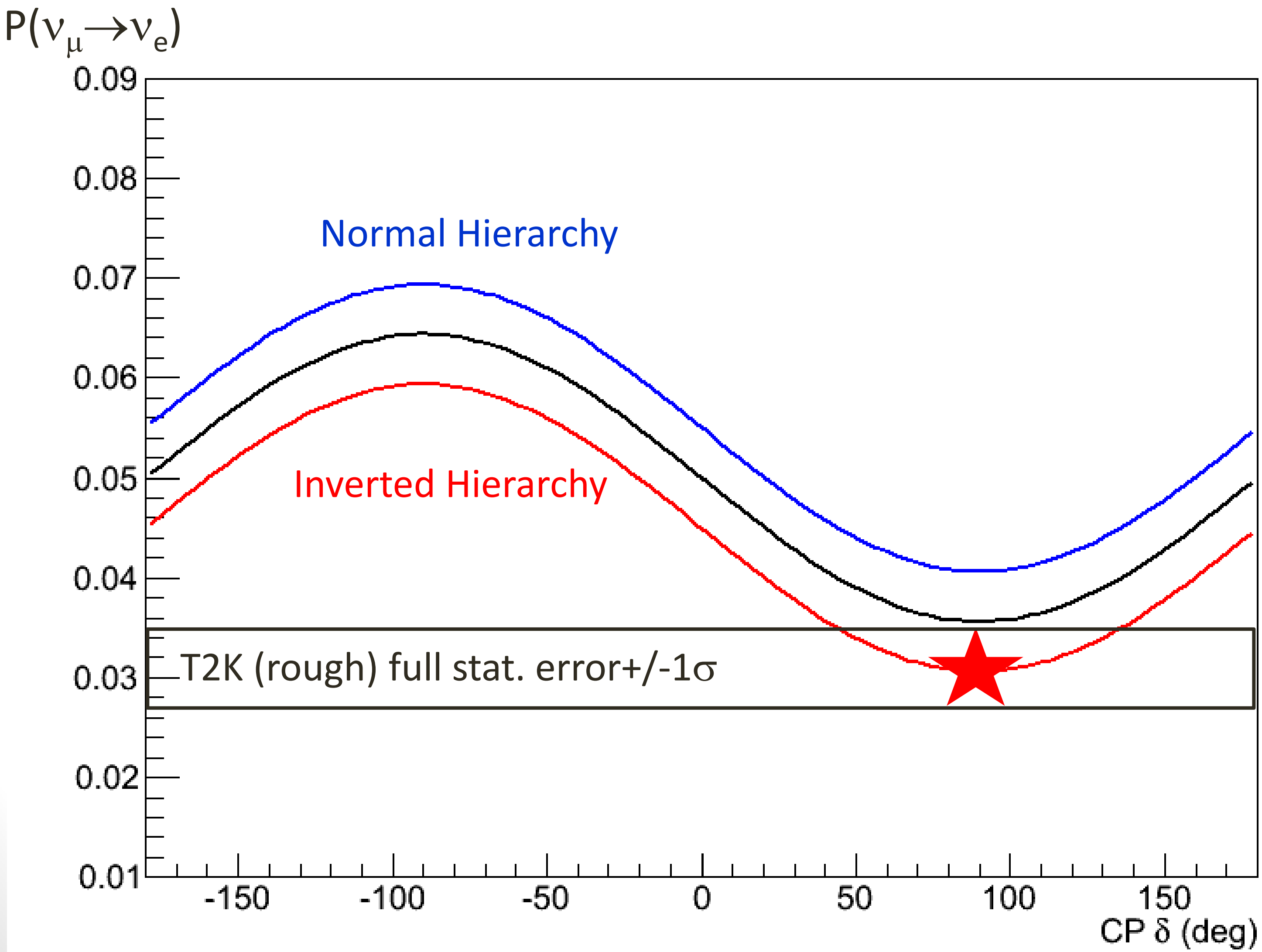
$\sin^2 2\theta_{13}$=0.1, $\sin^2 2\theta_{23}$=1, w/ matter effect



ν_μ to ν_e oscillation probability

at oscillation maximum

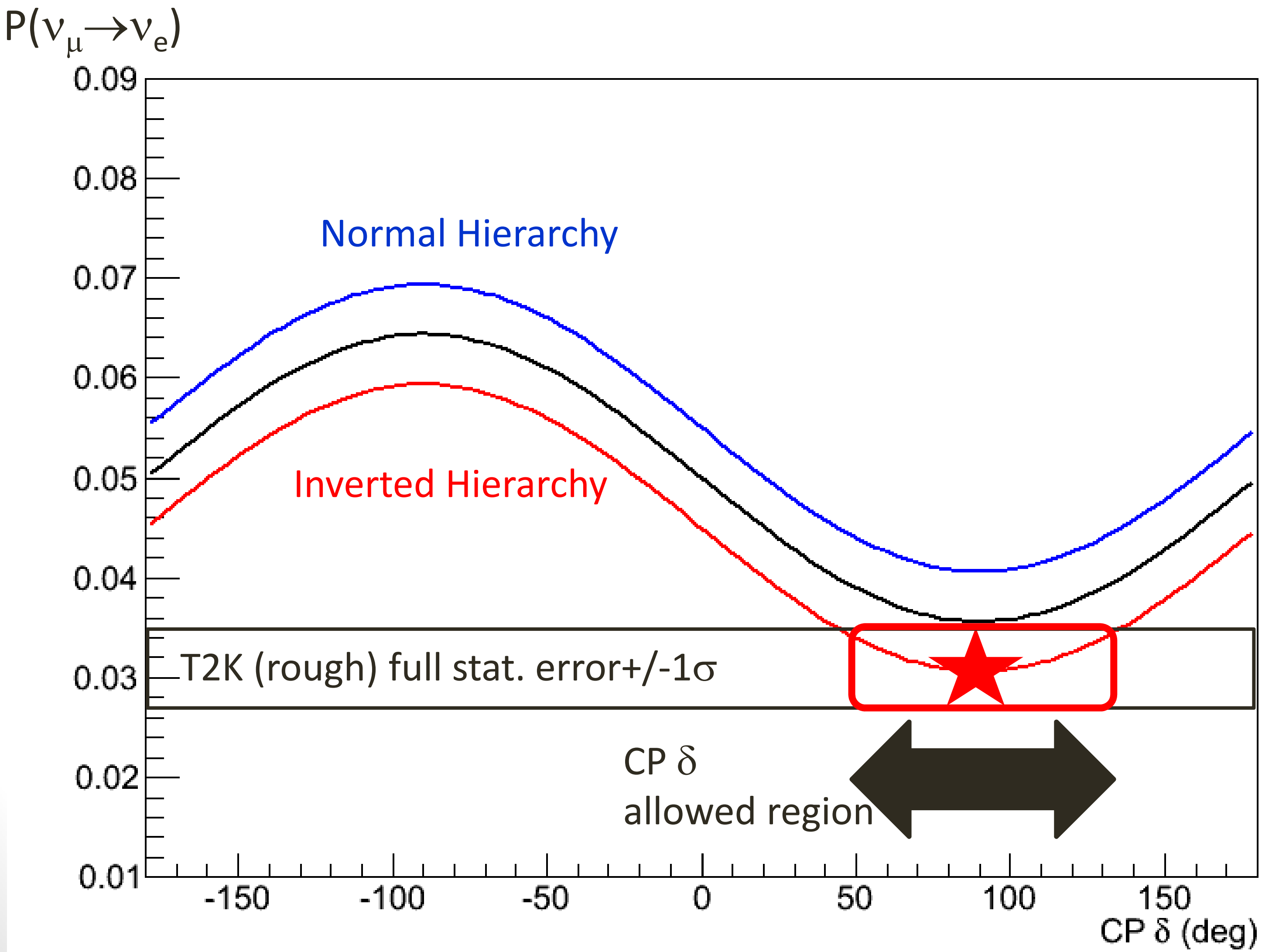
$\sin^2 2\theta_{13}$=0.1, $\sin^2 2\theta_{23}$=1, w/ matter effect



ν_μ to ν_e oscillation probability

at oscillation maximum

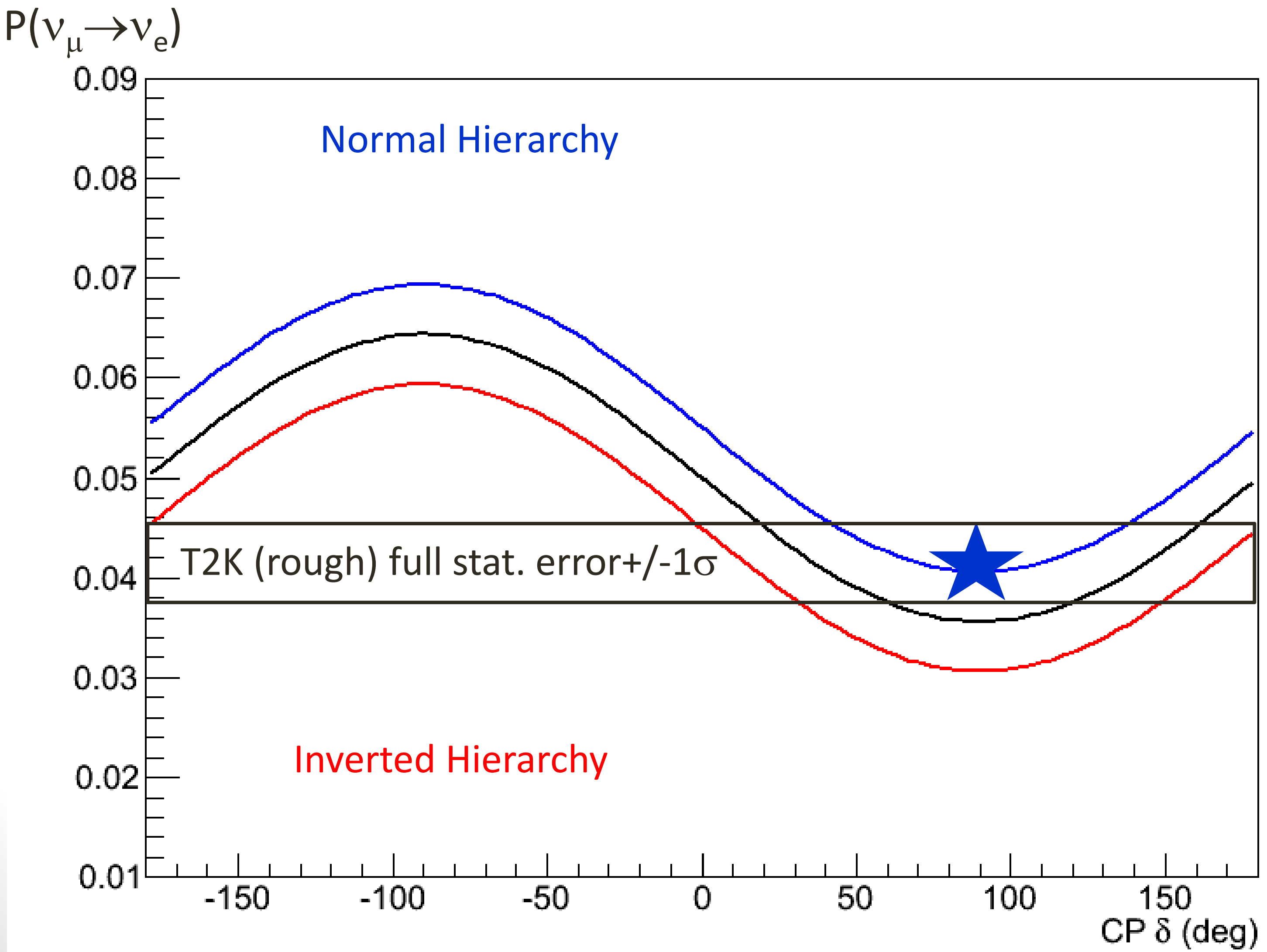
$\sin^2 2\theta_{13}$=0.1, $\sin^2 2\theta_{23}$=1, w/ matter effect



ν_μ to ν_e oscillation probability

at oscillation maximum

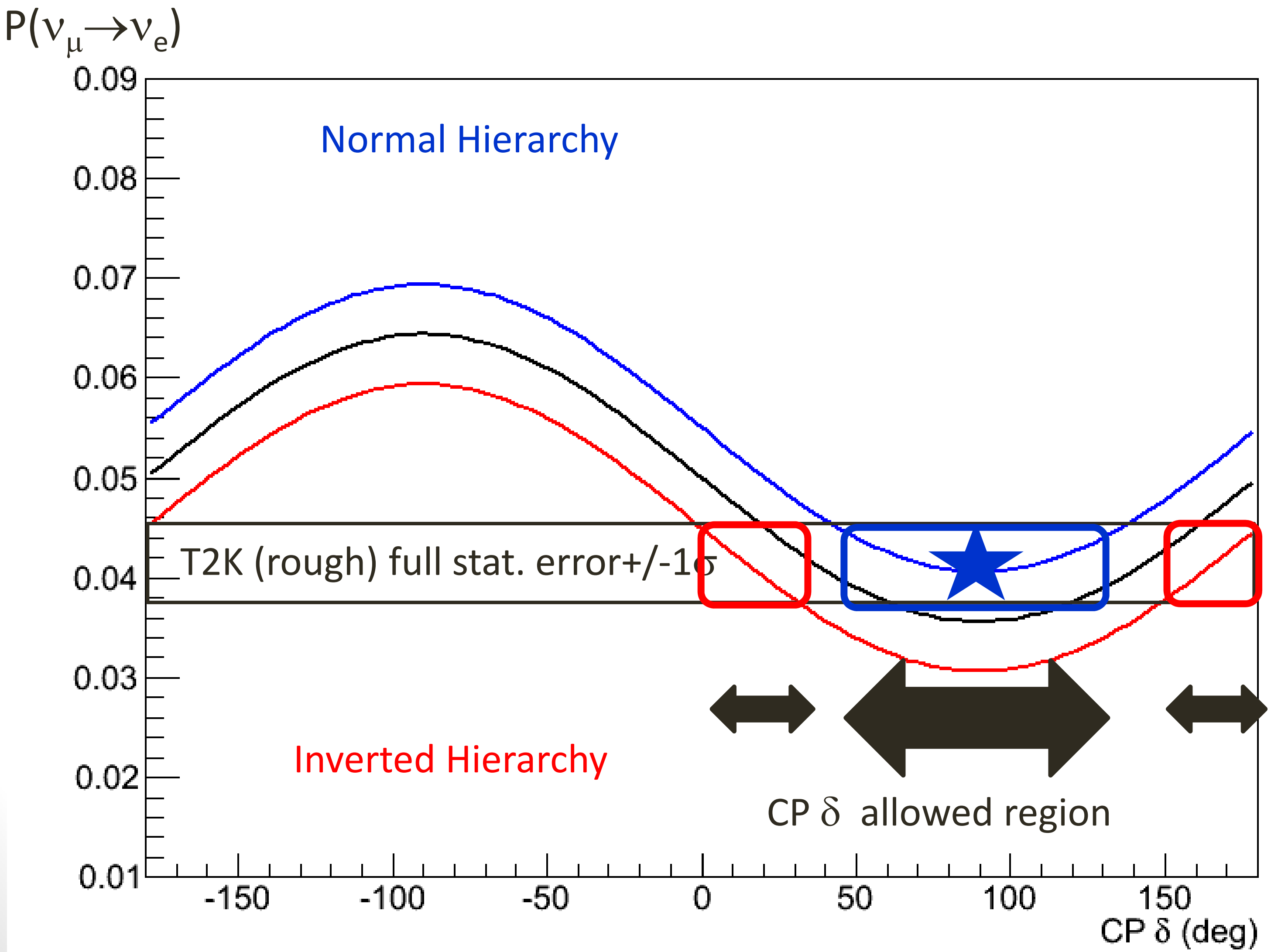
$\sin^2 2\theta_{13}$=0.1, $\sin^2 2\theta_{23}$=1, w/ matter effect



ν_μ to ν_e oscillation probability

at oscillation maximum

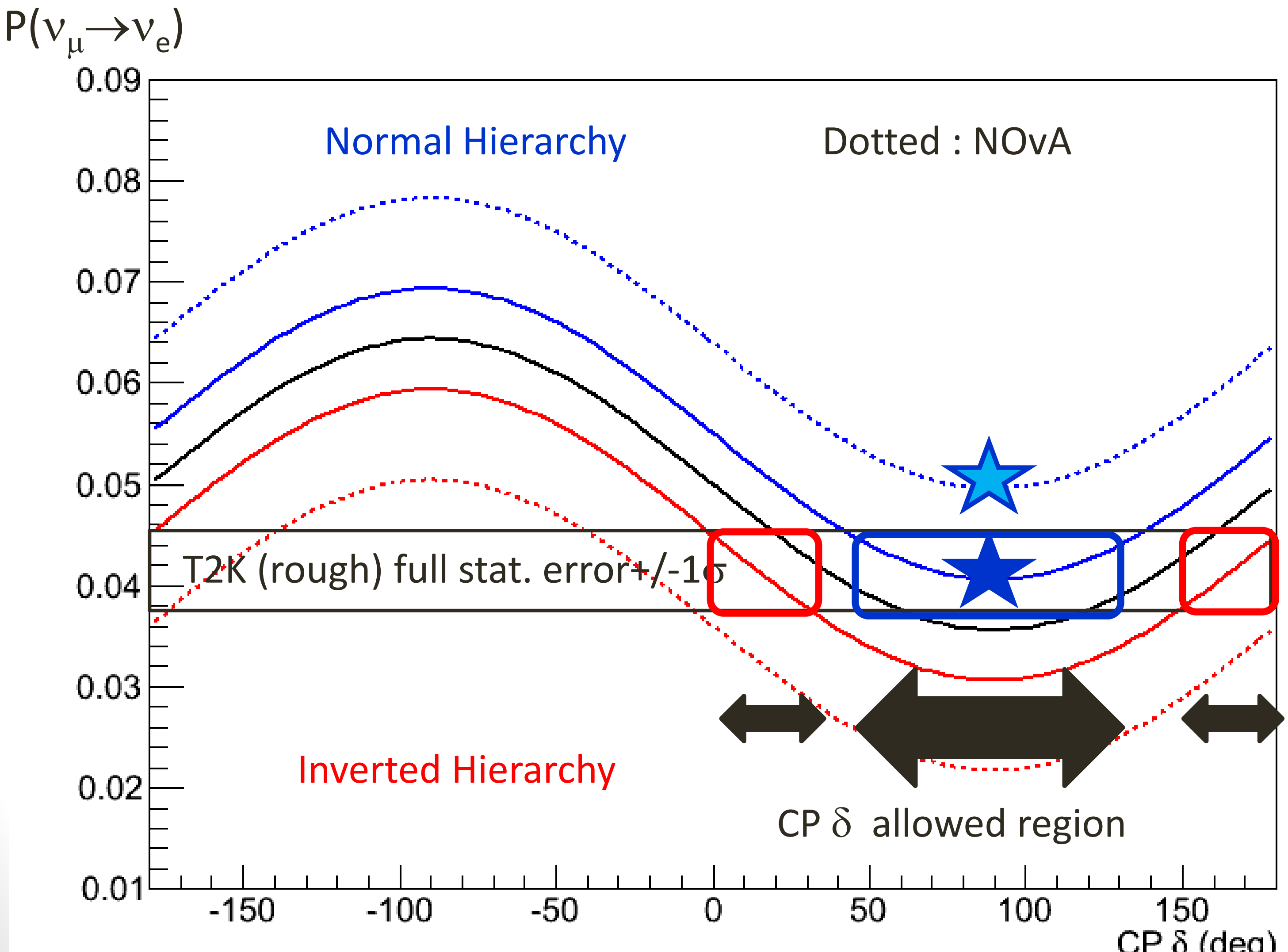
$\sin^2 2\theta_{13}$=0.1, $\sin^2 2\theta_{23}$=1, w/ matter effect



ν_μ to ν_e oscillation probability

at oscillation maximum

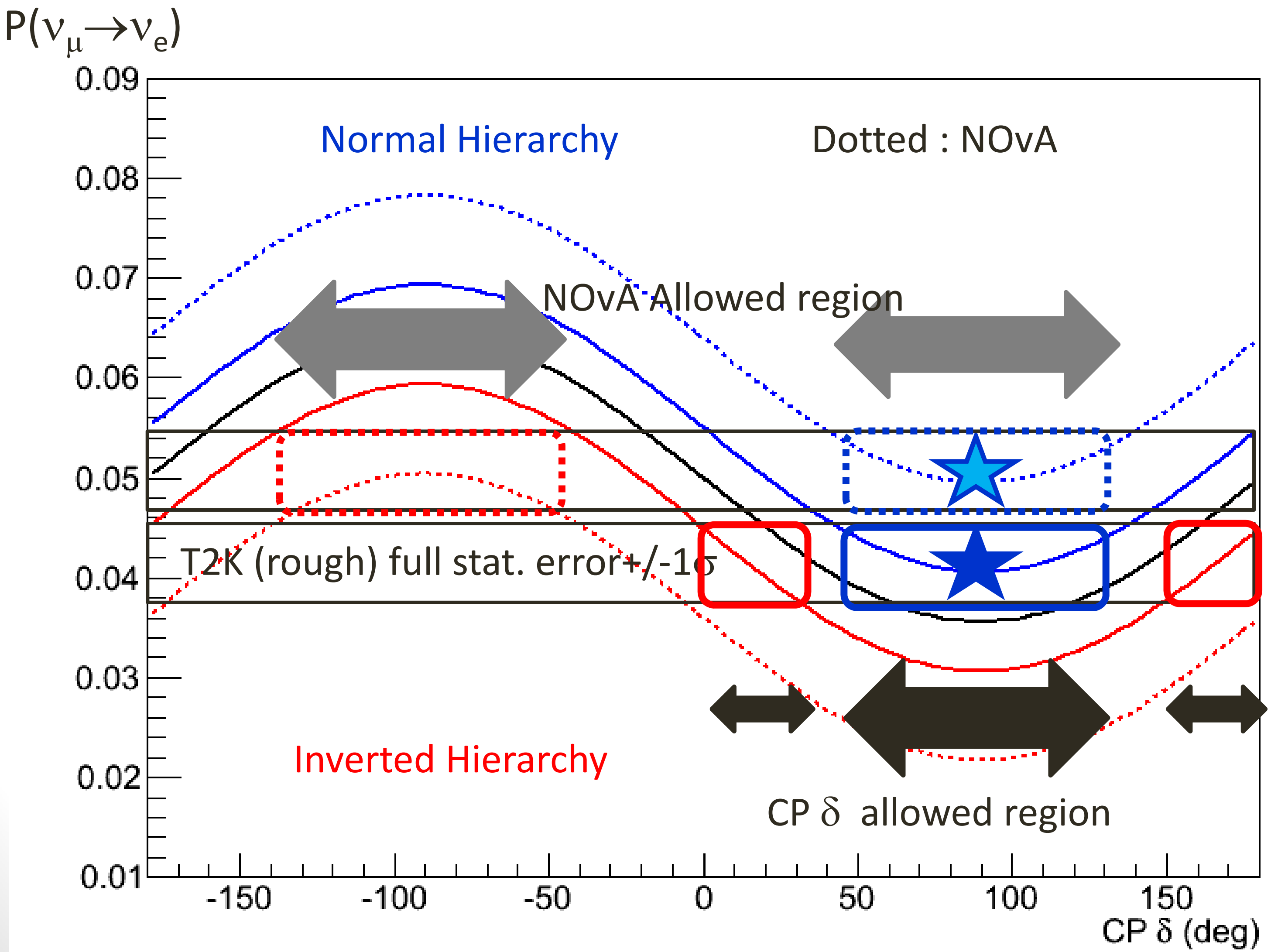
$\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, w/ matter effect



ν_μ to ν_e oscillation probability

at oscillation maximum

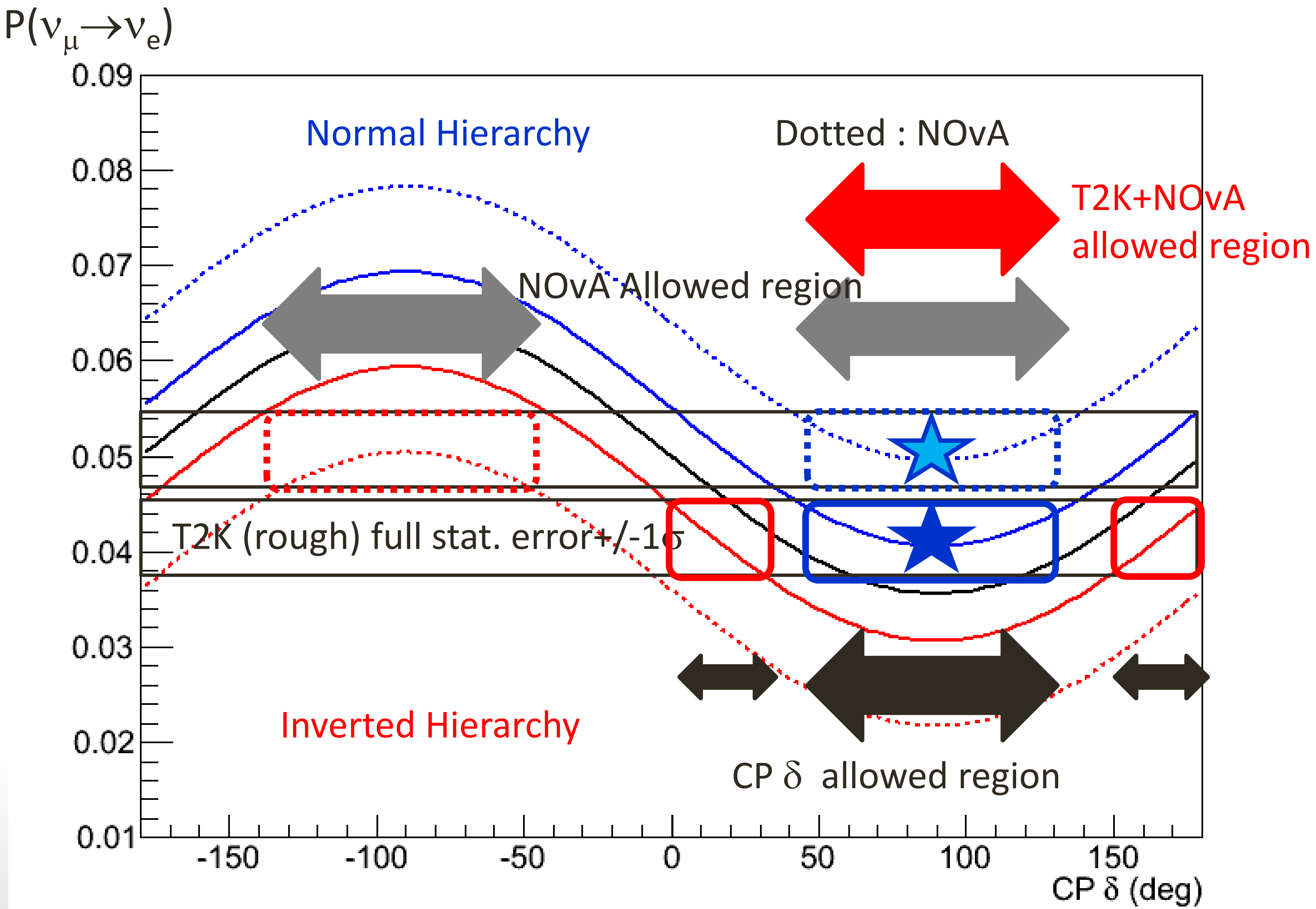
$\sin^2 2\theta_{13}$=0.1, $\sin^2 2\theta_{23}$=1, w/ matter effect



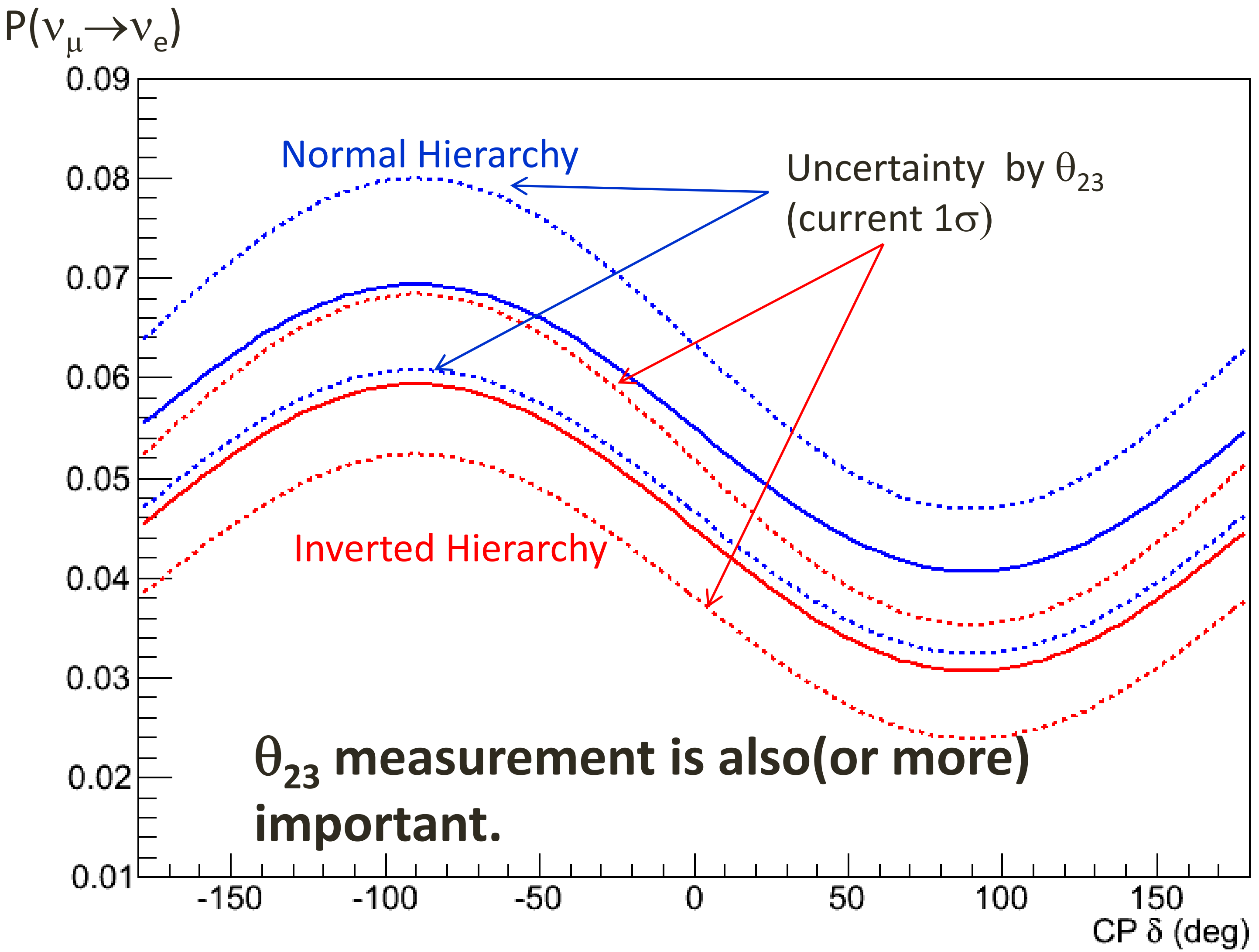
ν_μ to ν_e oscillation probability

at oscillation maximum

$\sin^2 2\theta_{13}$=0.1, $\sin^2 2\theta_{23}$=1, w/ matter effect



Actually, w/ θ_{23} uncertainty



θ_{23} measurement is also(or more) important.

T2K sensitivity
@7.8E21 POT(750kW x 5e7sec @ 30GeV)

- ✓ Combined 3 Flavor Appearance and Disappearance Fit
- ✓ Reconstructed E_ν spectrum for ν_e and ν_μ samples
- ✓ w/ and w/o reactor results
  - $\sin^2 2\theta_{13}=0.1\pm0.005$: marginalize by error(=reactor sys. error)
- ✓ w/ and w/o current systematic error
  - Full covariance matrix on reconstructed E_ν spectrum
  - Assume same error for anti-ν mode. +10% overall normalization error.
- ✓ Uncertainties for other oscillation parameters are taken into account
  - e.g. δ.vs.$\sin^2 2\theta_{13}$ plot is made by marginalizing the effect from θ_{23} and Δm^2_{32} uncertainties.
  - Results w/ normal mass hierarchy case. Sensitivities w/ two assumptions (NH and IH): MH unknown in analysis.
- ✓ Many combinations of ν-mode:anti-ν mode running ratio

Case Study

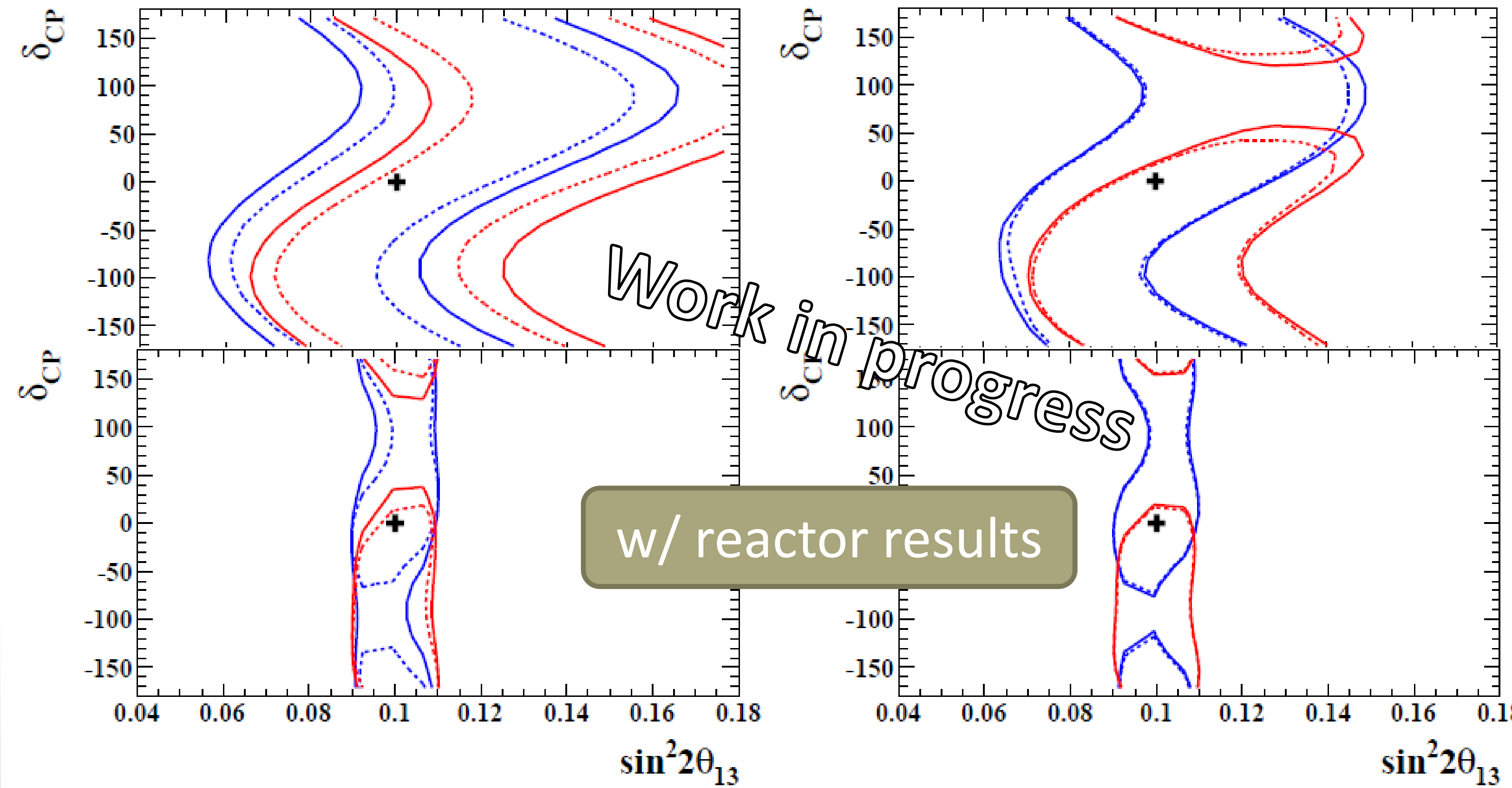
T2K full sensitivity
Expected 90% C.L. allowed region

δ_{CP}=0, $\sin^2 2\theta_{23}$=1.0
Normal Hierarchy

Allowed region assuming NH or IH
Solid : w/ current systematic error
Dashed : w/o systematic error

Running fraction

ν mode:anti-ν mode = 100%:0% | 66%:33%



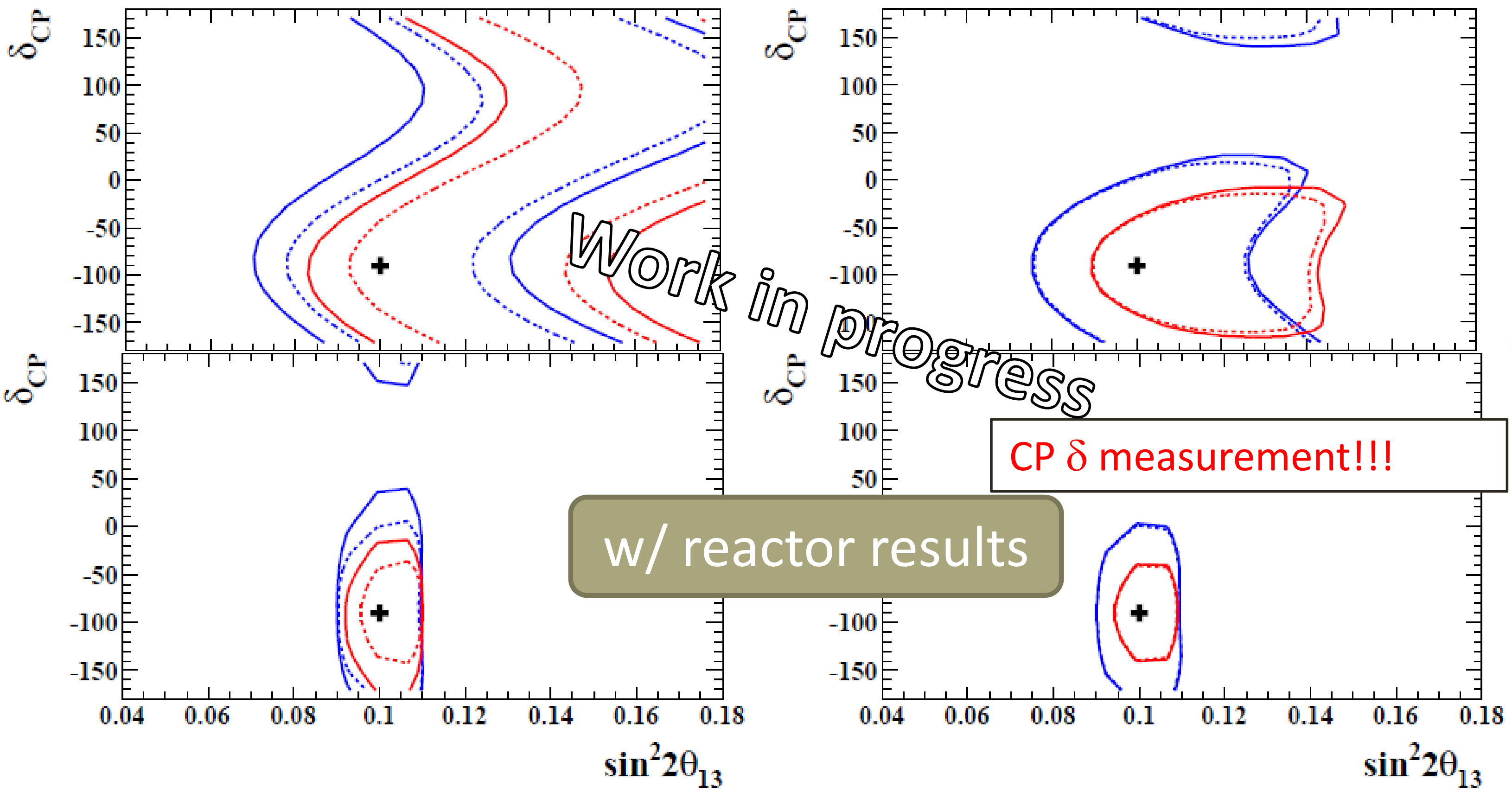
T2K full sensitivity
Expected 90% C.L. allowed region

δ_{CP}=-90, $\sin^2 2\theta_{23}$=1.0
Normal Hierarchy

Allowed region assuming NH or IH
Solid : w/ current systematic error
Dashed : w/o systematic error

Running fraction

ν mode:anti-ν mode = 100%:0% 66%:33%



T2K full sensitivity

Expected 90% C.L. allowed region.

θ_{23} octant degeneracy, $\sin^2\theta_{23}$=0.39 case

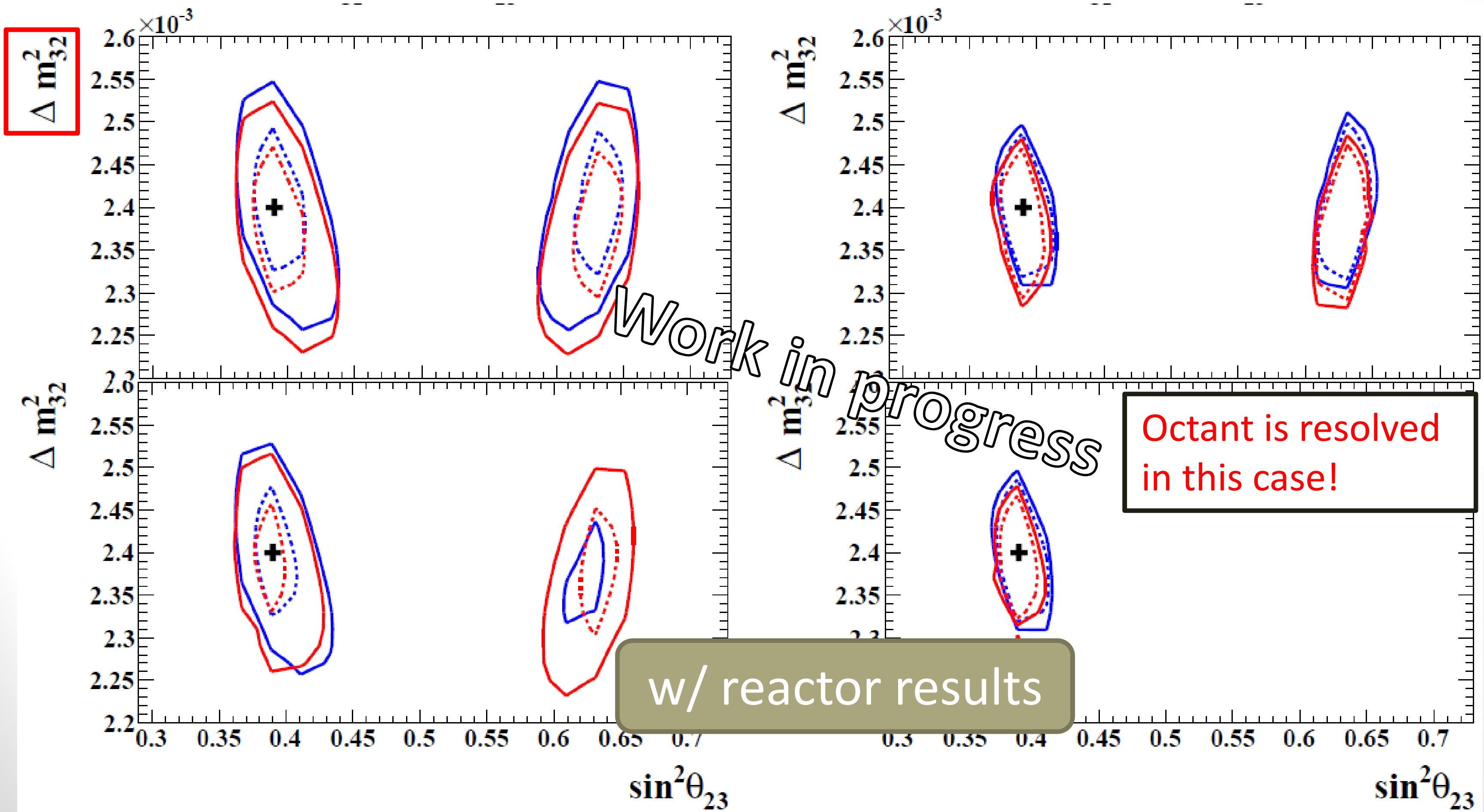
Allowed region assuming NH or IH
Solid : w/ current systematic error
Dashed : w/o systematic error

Running fraction

True δ=0

* 0.39 corresponds to current 90% limit.

ν mode:anti-ν mode = 100%:0%   66%:33%



Comparison/Combination w/NOvA

- Baseline length 810 km (c.f. T2K 295km)
- Detector Mass 15kT
- 3.6×10^{21} POT in 6 years.
- (Start in May 2013 w/ partial detector)
- No systematic error for comparison/combination
- GLoBES (General Long Baseline Experiment Simulator) is used
  - Use the flux and cross sections in GLoBES (Mostly consistent w/ numbers in NOvA TDR)

	# signal events	# bkg events
ν mode	60.4	10.2
anti-ν mode	25.9	11.1

c.f. T2K (ν:anti-ν=50%:50% case)
ν mode 106 signal events, 39 bkg. events
anti-ν mode 24 signal events, 22 bkg events (5.6 from $\nu_\mu \to \nu_e$)

POT dependence

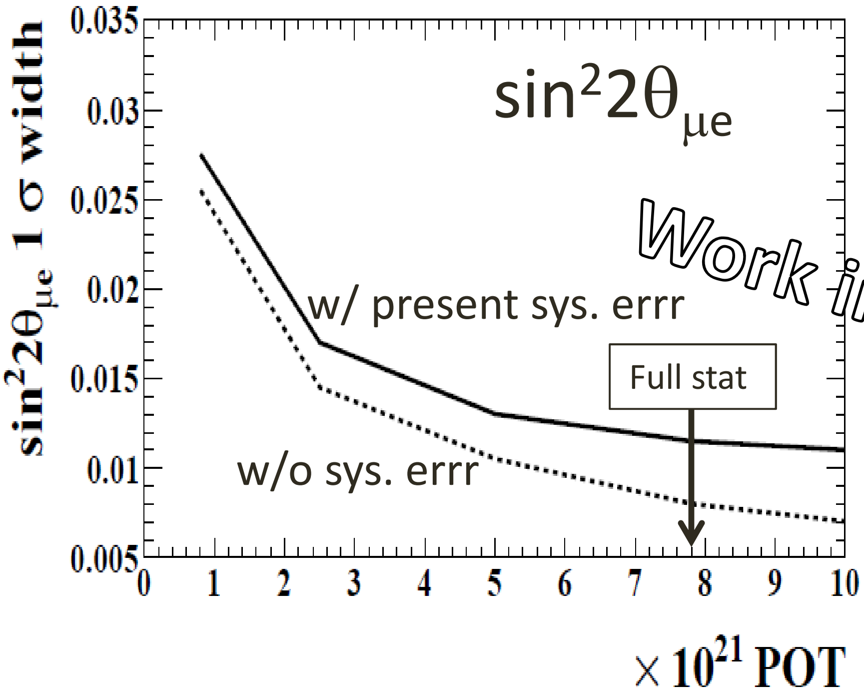
Precision(1σ)

ν mode: anti-ν mode=100%:0%

Black:δ=0deg
Red:δ=90deg
Dashed : w/o sys. Error
Solid : w/ current sys.error
MH is fixed to NH(true)

Precision on $P(\nu_\mu \rightarrow \nu_e)$

Effective 2 flavor mixing angle for $P(\nu_\mu \rightarrow \nu_e)$ (obtained by fixing other oscillation parameters than θ_{13})



Work in progress

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

Due to the uncertainty of δ, θ_{23} and Δm^2_{32}, precision is worse than $\sin^2 2\theta_{\mu e}$

Summary (1 page before last slide)

- ν_e appearance
  - Next update in Summer. (~5σ significance w/ 8x10^20 POT)
- ν_μ disappearance
  - (almost) starting to break the world records
- Systematic errors
  - Still << statistical
  - Much room for reduction -- T2K will keep sys. errors smaller than stat. errors
    - Flux : more NA61 data
    - ND280 : new category of samples.
    - ν interaction : understanding of nuclear models.
    - SK : detection efficiency error, more pi0 rejection by new fitter
- Future sensitivity
  - Possibility of first measurement of CP δ
  - T2K has sensitivities for non-maximal θ_{23} and octant, CP violation.
  - The sensitivities would be increased w/ NOvA , SK and reactor experiments.
  - ν-mode:anti-ν-mode running time will be optimized.
- Other physics analyses
  - Cross section measurements, νTOF, Sterile neutrino and so on.