$$P(\nu_e \rightarrow \nu_e) \approx 1 - \sin^2 2\theta_{13} \sin(\Delta m^2_{23} L/E)$$

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin(\Delta m^2_{23} L/E)$$

VO Max

$$\Delta m^2_{23} L/E = \pi/2$$

$P(\nu_e \rightarrow \nu_e) \approx 1 - \sin^2 2\theta_{13} \sin(\Delta m^2_{23} L/E)$

"Getting the most from future Long BaseLine neutrino experiments"

"General" Overview

Olga Mena (La Sapienza, INFN)

$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin(\Delta m^2_{23} L/E)$

VO Max

$\Delta m^2_{23} L/E = \pi/2$

STANDARD THREE NEUTRINO MIXING

$$|\nu_\alpha\rangle = U_{\alpha i}|\nu_i\rangle$$

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\nu_\mu \leftrightarrow \nu_\tau$

$\nu_\mu \leftrightarrow \nu_e$

$\nu_e \longrightarrow \nu_{\mu,\tau}$

$0\nu\beta\beta$

Atmospheric

L/E~500Km/GeV

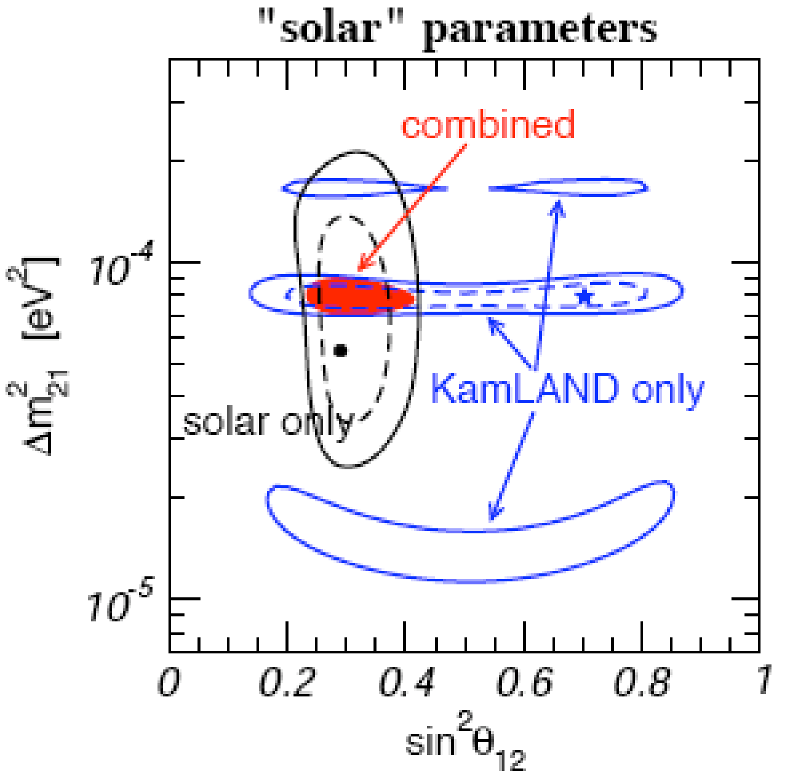
Solar

Majorana phases

STANDARD THREE NEUTRINO EVOLUTION

$$i\frac{d}{dx}\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \frac{1}{2E} U_{PMNS} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{12} & 0 \\ 0 & 0 & \Delta m^2_{13} \end{pmatrix} U^\dagger_{PMNS} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

(12) : SNO, KamLAND, SK

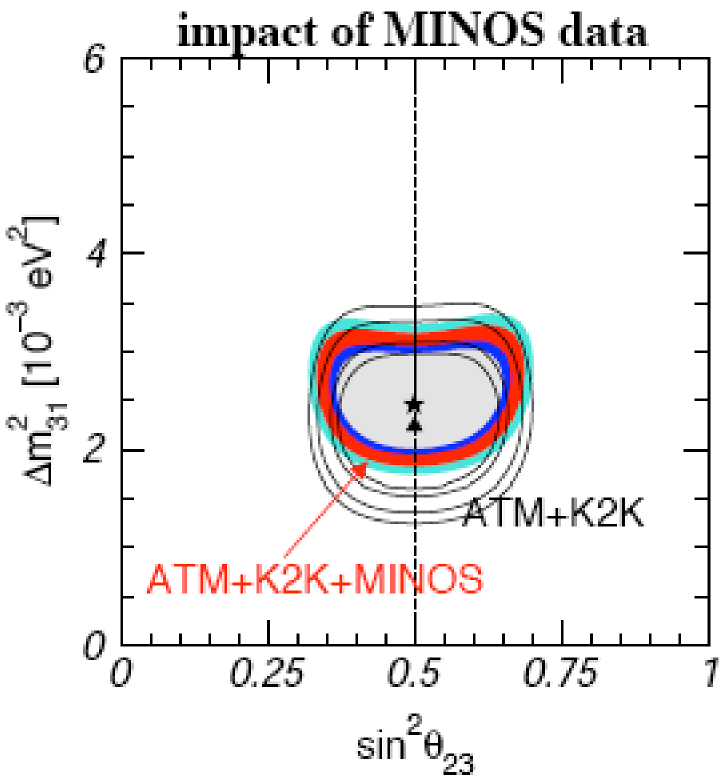


$$\Delta m^2_{12} = 7.3 - 8.5 \times 10^{-5} \ \ \mathbf{eV}^2$$

$$\sin^2\theta_{12} = 0.26 - 0.36$$

T. Schwetz
hep-ph/0606060
2σ ranges

(23) : SK, K2K, MINOS



$$|\Delta m^2_{23}| = 2.1 - 3.0 \times 10^{-3} \ \ \mathbf{eV}^2$$

$$\sin^2\theta_{23} = 0.38 - 0.64$$

Both poorly known!
Sign undetermined!

(13) : CHOOZ, SK, K2K, MINOS

$$\sin^2\theta_{13} \ < \ 0.03$$

$$0 < \delta < 2\pi$$

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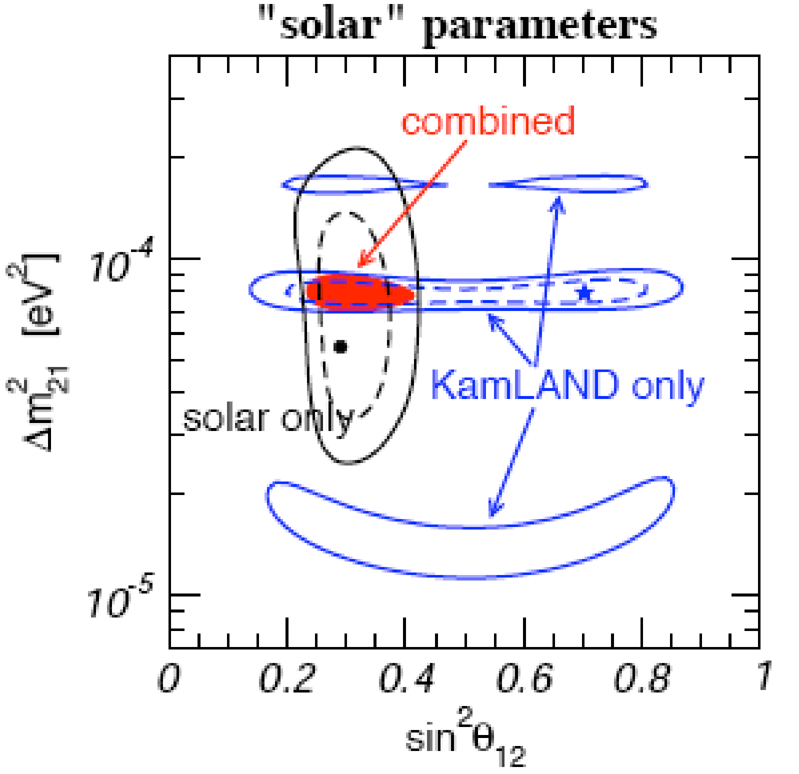

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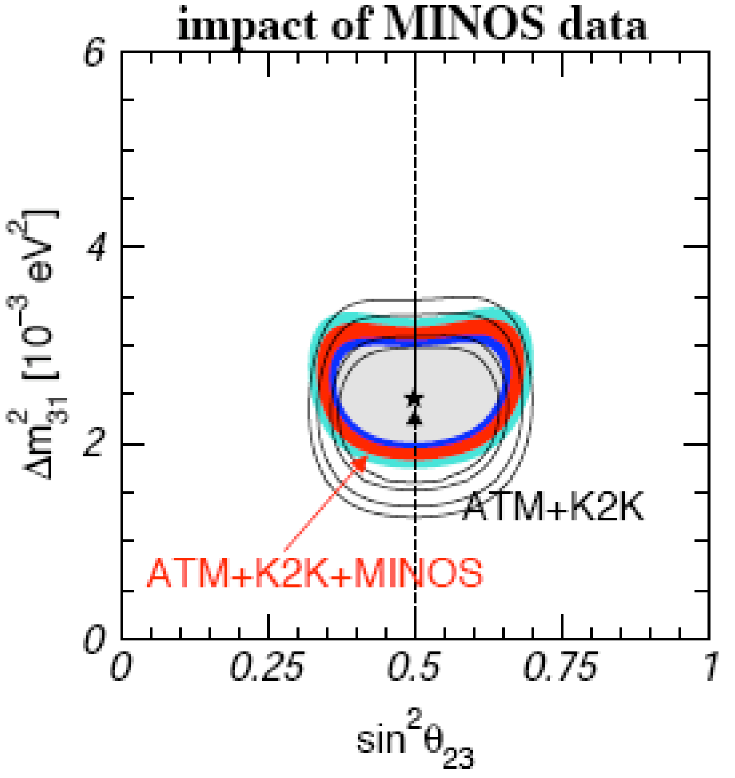

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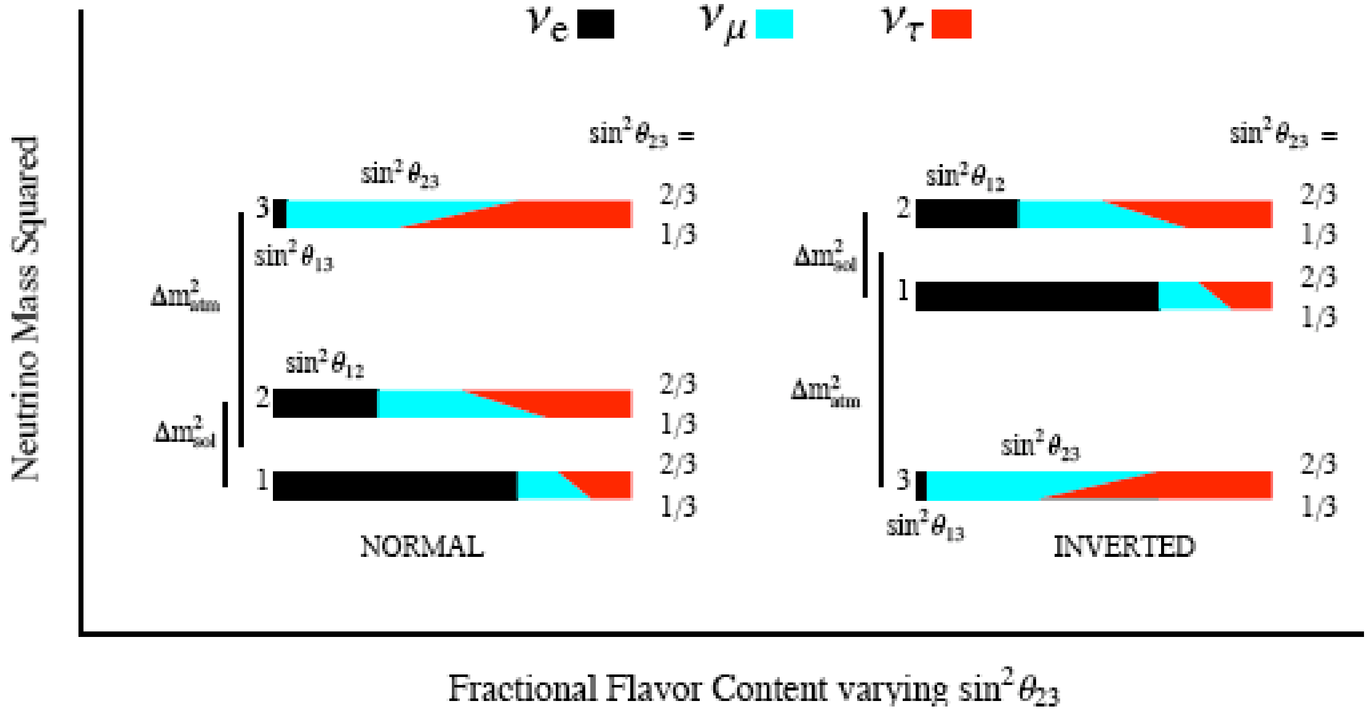

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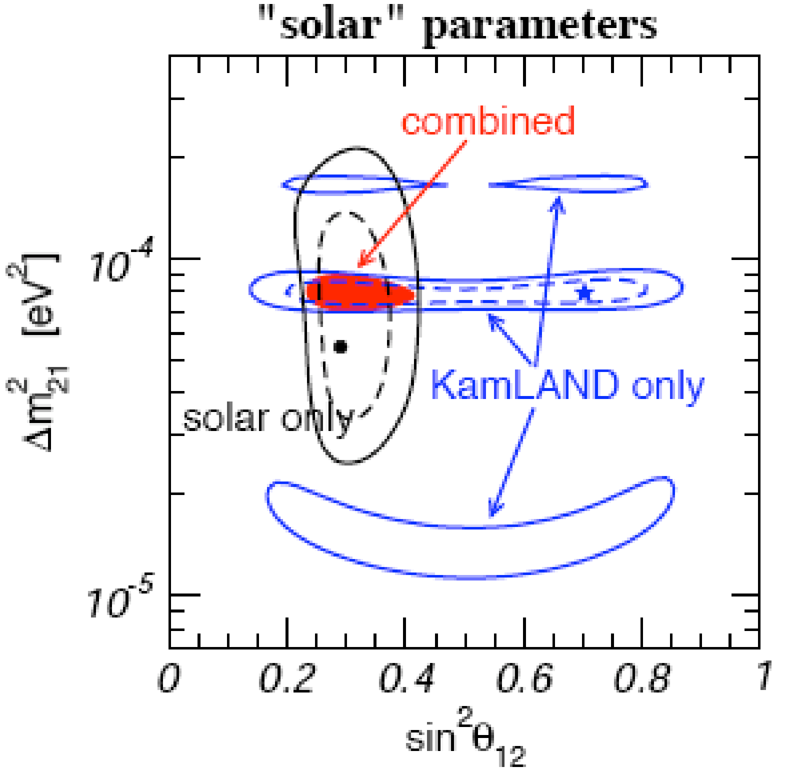

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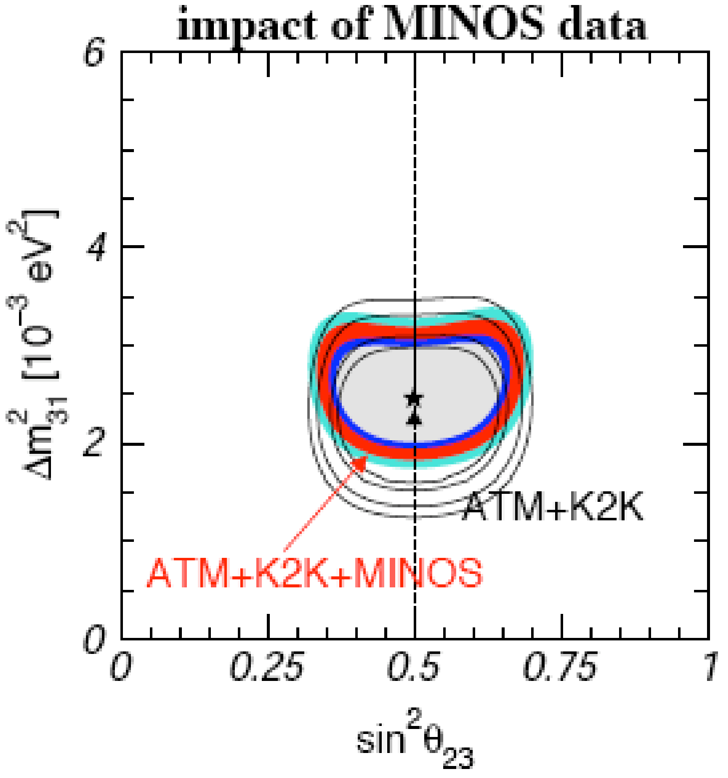

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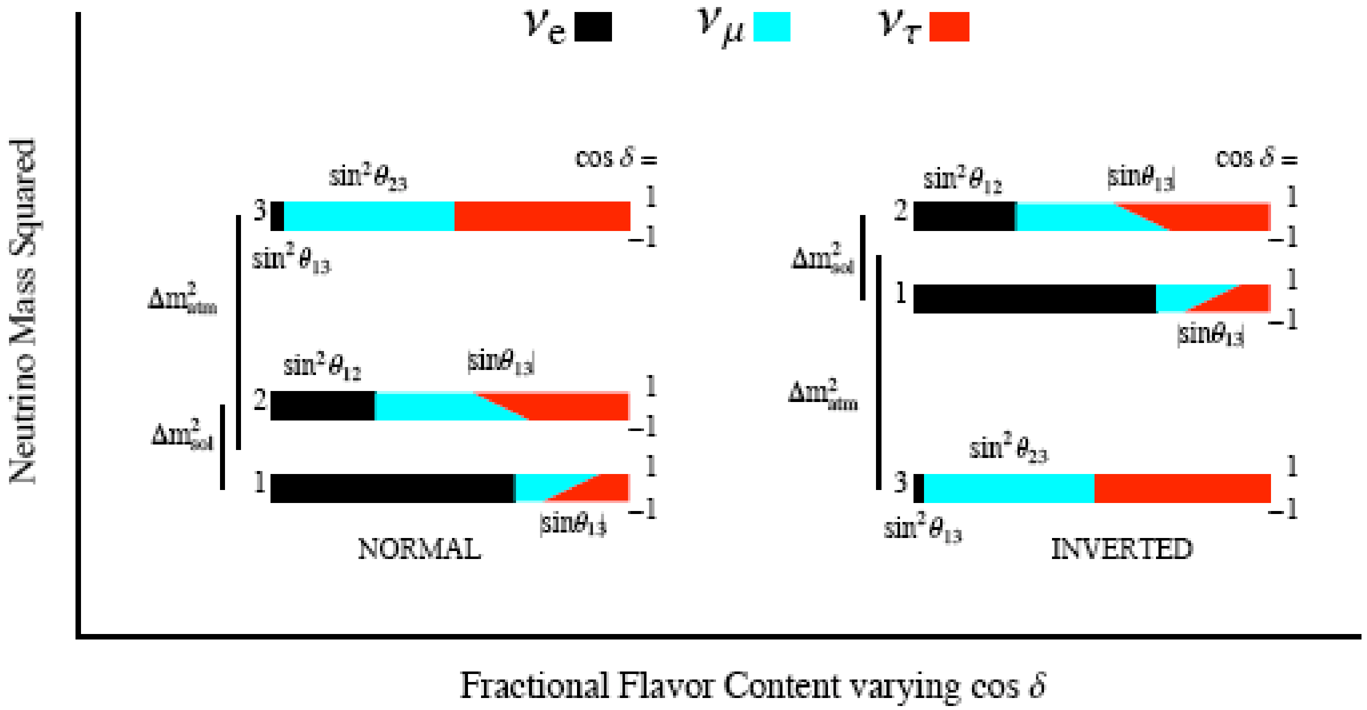

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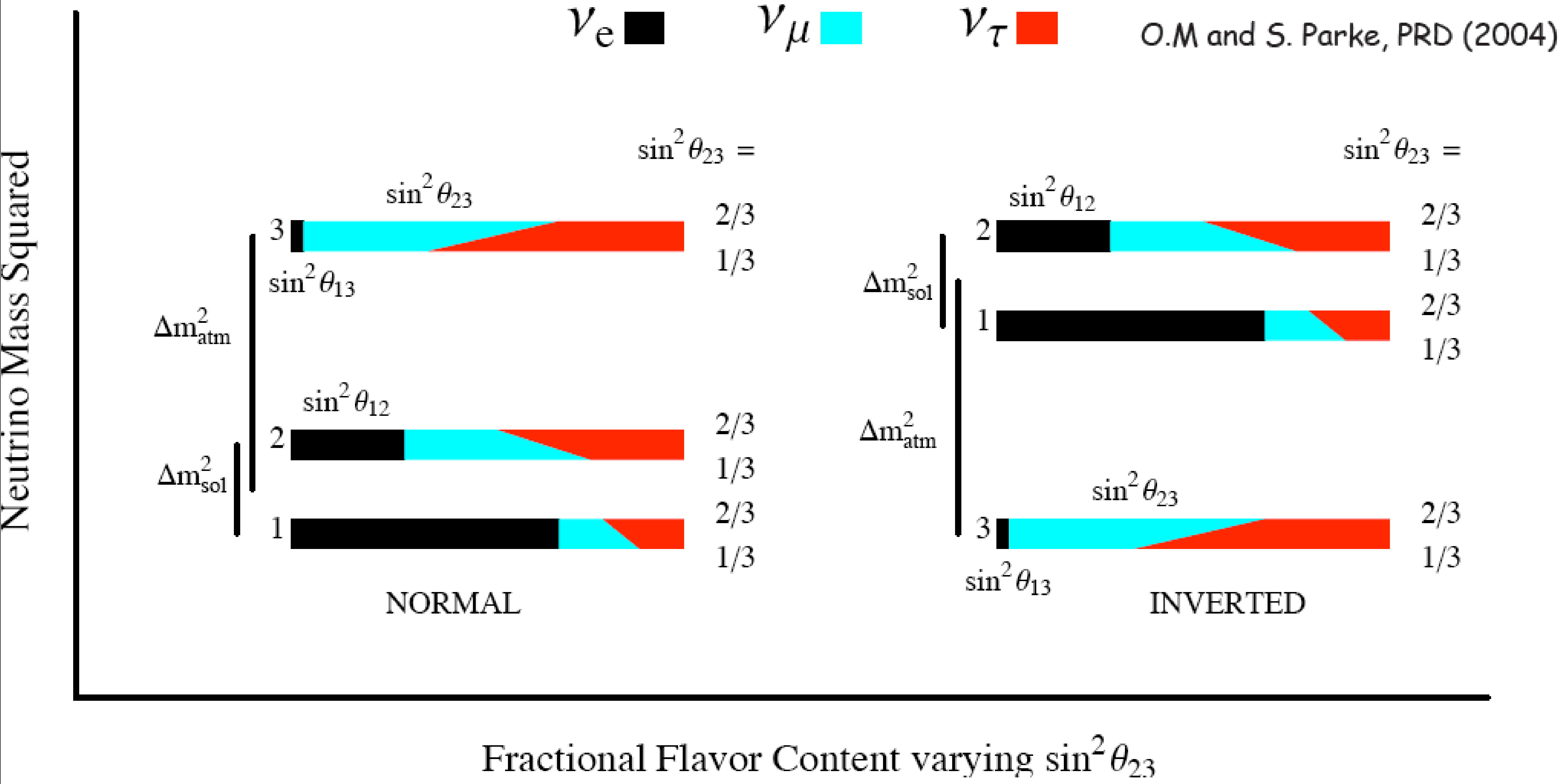

O.M and S. Parke, PRD (2004)

What is the probability of finding ν_e in ν_3 , $|U_{e3}|^2$?

What is the neutrino mass ordering ?

What is the value of the CP Violating Phase, δ ?

Is the atmospheric mixing angle θ_{23} maximal? Is it > or < $\frac{\pi}{4}$?

Sensitivity to KNOWNS at $\frac{E_\nu}{L} \sim |\Delta m^2_{23}|$

$$P^{\pm}_{\nu_\mu \nu_\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2 (\frac{\Delta m^2_{23}\, L}{4E}) + \mathcal{O}(\theta^2_{13} \sin^2 \left(\Delta m^2_{23}\, L/4E\right))$$

$$+ \quad \mathcal{O}(\cos\delta_{CP} \cdot \theta_{13} \cdot \Delta_{12} \cdot \sin(\Delta m^2_{23}\, L/4E)) + \mathcal{O}(\Delta^2_{12})$$

Variable Measured	LBL $\nu_\mu \to \nu_\mu$	LBL $\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$	Reactor $\bar{\nu}_e \to \bar{\nu}_e$	Comments
$\lvert\Delta m^2_{32}\rvert$	Y	n	n	magnitude but not sign
$\sin^2 2\theta_{23}$	Y	n	n	$\theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23}$ ambiguous

Atmospheric parameters errors (MINOS, T2K, NOvA)

$$\delta(\sin^2 2\theta_{23}) \approx 1\% - 3\% \quad \delta(\Delta m^2_{23}) \approx 5\% - 10\%$$

Atmospheric neutrino experiments -> Maltoni's talk!

But the sensitivity to MAXIMAL MIXING....

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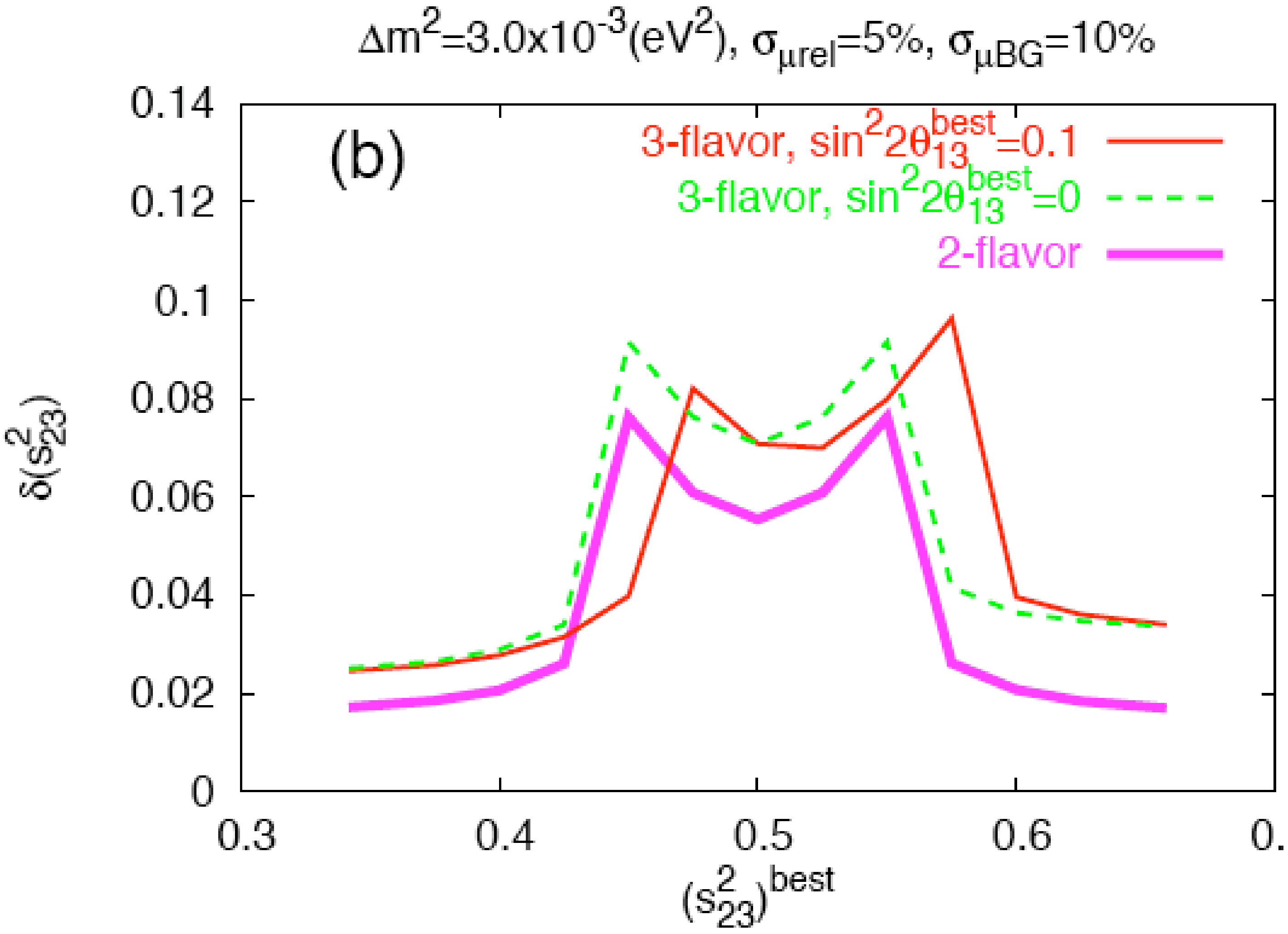
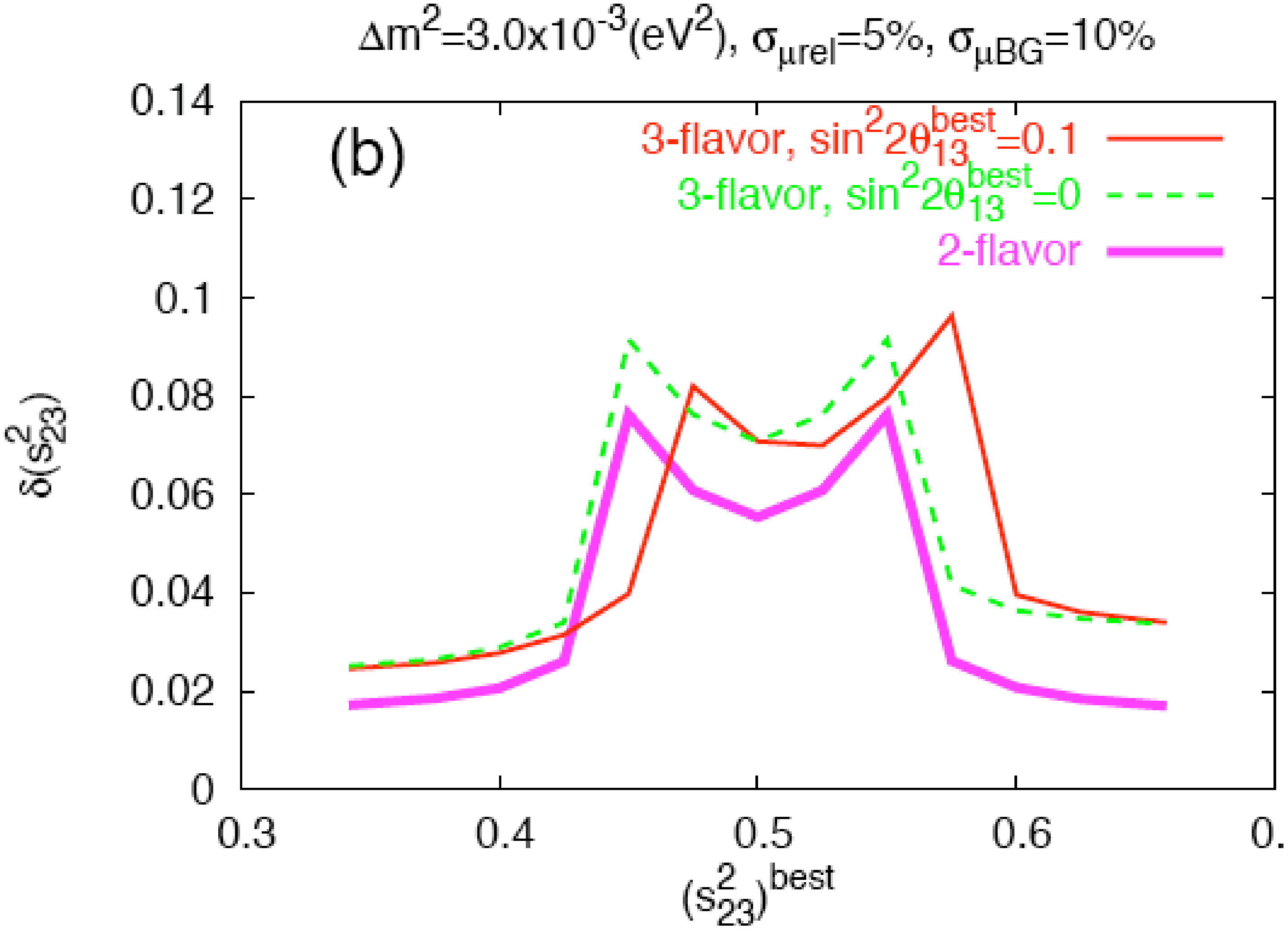


T2K phaseI@90%CL

H.Minakata, M.Sonoyama and H.Sugiyama, PRD70 (2004)

But the sensitivity to MAXIMAL MIXING....



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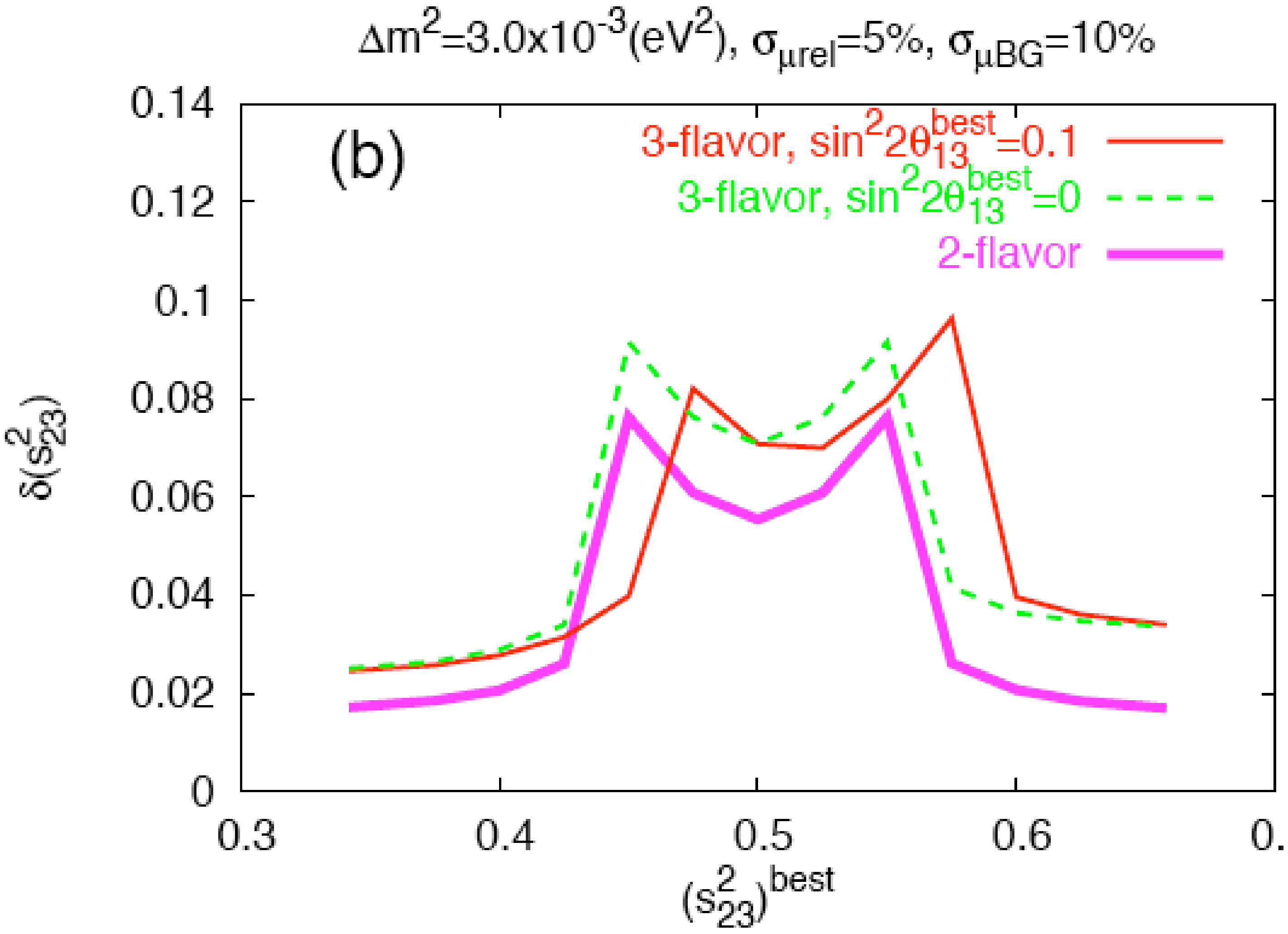

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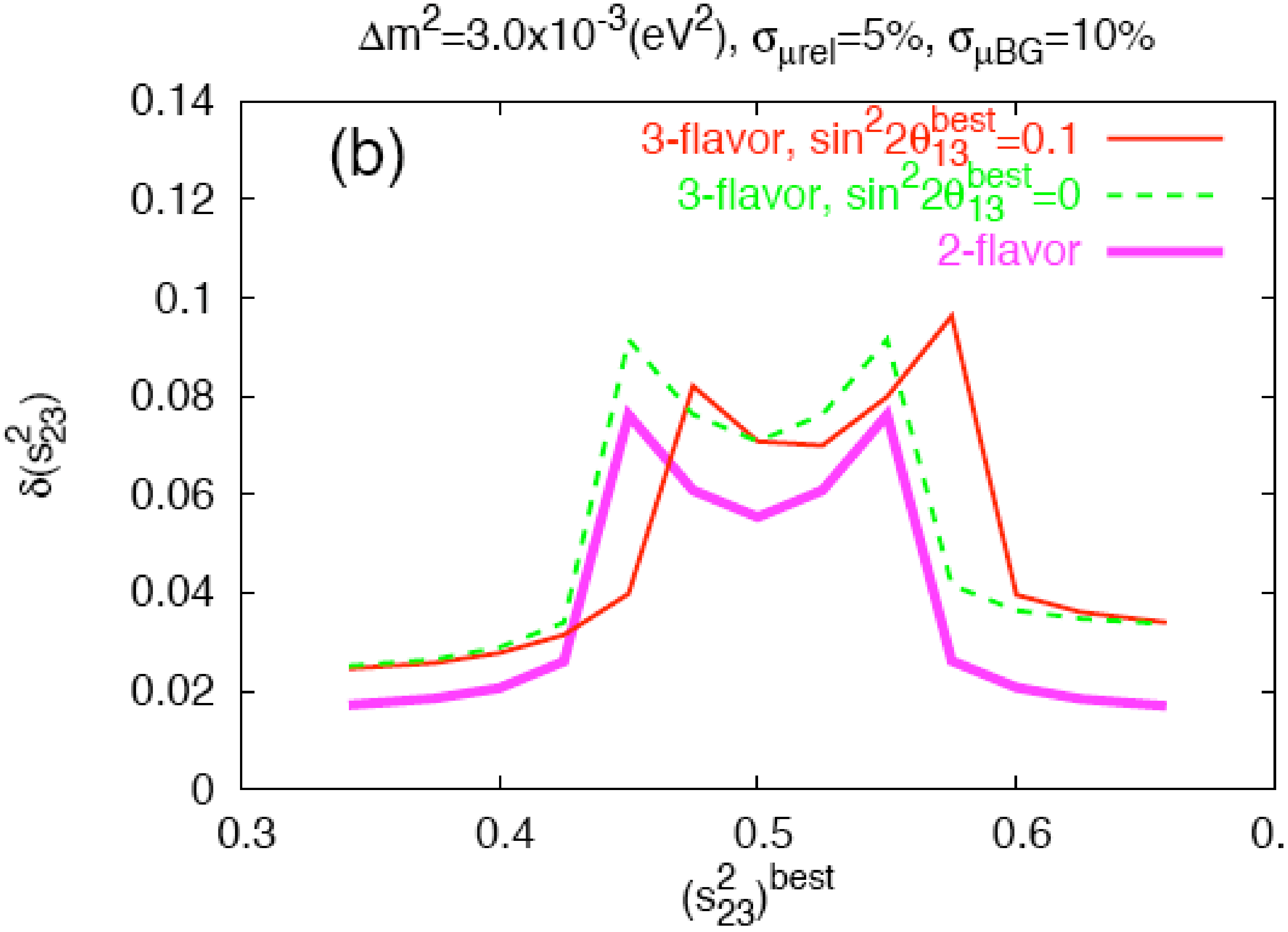

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The error remains 10%-20%, NOT MUCH BETTER than the actual error

$$\frac{\delta(\sin^2\theta_{23})}{\delta(\sin^2 2\theta_{23})} = \frac{1}{4cos2\theta_{23}}$$

Large around π/4!

Variable Measured	LBL $\nu_\mu \longrightarrow \nu_\mu$	LBL $\nu_\mu \longrightarrow \nu_e$ $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$	Reactor $\bar{\nu}_e \longrightarrow \bar{\nu}_e$	Comments
$\sin^2\theta_{13}$	n	n	Y	direct measurement
$\sin^2\theta_{23}\sin^2\theta_{13}$	n	Y	n	combination of θ_{23} and θ_{13}
sign(Δm^2_{32})	n	Y	n	via matter effects
$\cos\theta_{23}\sin\delta_{CP}$	n	Y	n	CP violation
$\cos\theta_{23}\cos\delta_{CP}$	n	?	n	extremely difficult

Long BaseLine neutrino experiments:

More suitable scenario to extract unknown parameters!

Subleading transitions $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$ at $\frac{E_\nu}{L} \sim |\Delta m^2_{23}|$

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In vacuum:

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In vacuum:

$$P_{\nu_\mu\nu_e(\bar{\nu}_\mu\bar{\nu}_e)} = s^2_{23} \, \sin^2 2\theta_{13} \, \sin^2 \frac{\Delta m^2_{13} L}{4E}$$

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Atmospheric

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Atmospheric

$$+c^2_{23} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L}{4E}$$

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$$+c^2_{23}\ \sin^2 2\theta_{12}\ \sin^2 \frac{\Delta m^2_{12} L}{4E}$$ **Solar**

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Atmospheric

$$+c^2_{23}\ \sin^2 2\theta_{12}\ \sin^2 \frac{\Delta m^2_{12} L}{4E}$$

Solar

$$+\tilde{J}\ \cos\left(\pm\delta - \frac{\Delta m^2_{13} L}{4E}\right) \frac{\Delta m^2_{12} L}{4E} \sin \frac{\Delta m^2_{13} L}{4E}$$

Long BaseLine neutrino experiments:

More suitable scenario to extract unknown parameters!

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$$+c^2_{23} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L}{4E}$$ **Solar**

$$+\tilde{J} \cos\left(\pm\delta - \frac{\Delta m^2_{13} L}{4E}\right) \frac{\Delta m^2_{12} L}{4E} \sin \frac{\Delta m^2_{13} L}{4E}$$ **Interference**

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$$+c^2_{23}\ \sin^2 2\theta_{12}\ \sin^2 \frac{\Delta m^2_{12} L}{4E}$$ **Solar**

$$+\tilde{J}\ \cos\left(\pm\delta - \frac{\Delta m^2_{13} L}{4E}\right) \frac{\Delta m^2_{12} L}{4E} \sin \frac{\Delta m^2_{13} L}{4E}$$ **Interference**

$$\tilde{J} \equiv \cos\theta_{13}\ \sin 2\theta_{13}\ \sin 2\theta_{23}\ \sin 2\theta_{12} \sim 2\sin\theta_{13}$$

Long BaseLine neutrino experiments:

More suitable scenario to extract unknown parameters!

Subleading transitions $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$ at $\frac{E_\nu}{L} \sim |\Delta m^2_{23}|$

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Subleading transitions $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$ at $\frac{E_\nu}{L} \sim |\Delta m^2_{23}|$

In matter:

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Subleading transitions $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$ at $\frac{E_\nu}{L} \sim |\Delta m^2_{23}|$

In matter:

$$\sin\Delta_{13} \quad \to \quad \frac{\Delta_{13}}{\Delta_{13} \mp aL} \; \sin(\Delta_{13} \mp aL)$$

$$\sin\Delta_{12} \quad \to \quad \frac{\Delta_{12}}{\Delta_{12} \mp aL} \; \sin(\Delta_{12} \mp aL)$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E} \qquad\qquad a = G_F n_e/\sqrt{2}$$

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In matter:

$$\sin \Delta_{13} \quad \rightarrow \quad \frac{\Delta_{13}}{\Delta_{13} \mp aL} \quad \sin(\Delta_{13} \mp aL)$$

$$\sin \Delta_{12} \quad \rightarrow \quad \frac{\Delta_{12}}{\Delta_{12} \mp aL} \quad \sin(\Delta_{12} \mp aL)$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E} \qquad\qquad a = G_F n_e/\sqrt{2}$$

If the hierarchy is NORMAL $\Delta_{13} > 0$ $P_{\nu_\mu \nu_e}$ enhancement

If the hierarchy is INVERTED $\Delta_{13} < 0$ $P_{\bar{\nu}_\mu \bar{\nu}_e}$ enhancement

Hierarchy extraction: matter effects!

“NEAR-TERM” OR “NEXT-TO NEAR TERM” LBL Neutrino Experiments: Super Beams

(more intense conventional neutrino beams)

POSSIBLE EXPERIMENTAL SETUPS?

Off Axis? (Counting experiments)

@First peak
@Second peak
@Same E/L

On-Axis (Wide band)? (Spectrum information)

@First peak
@Second peak
@Beyond

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NOvA++(?)

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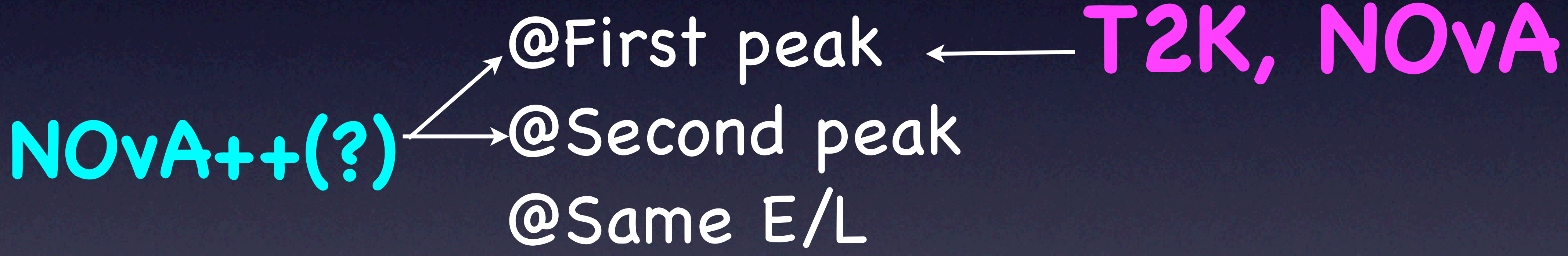

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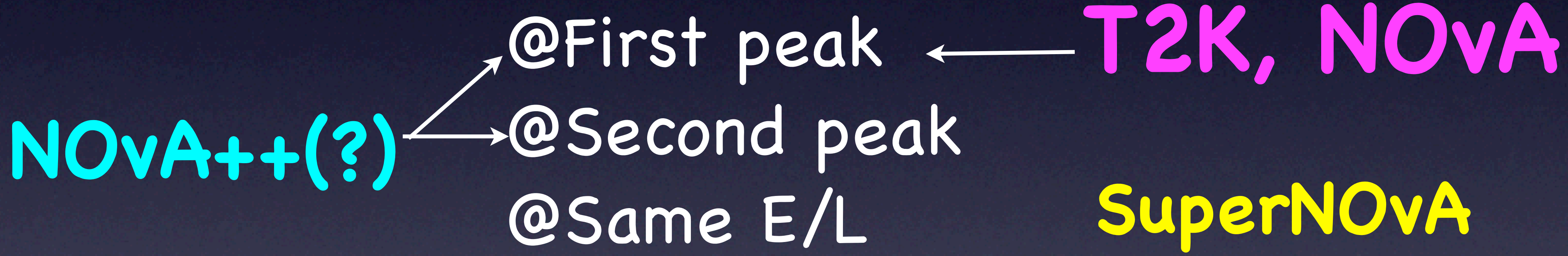

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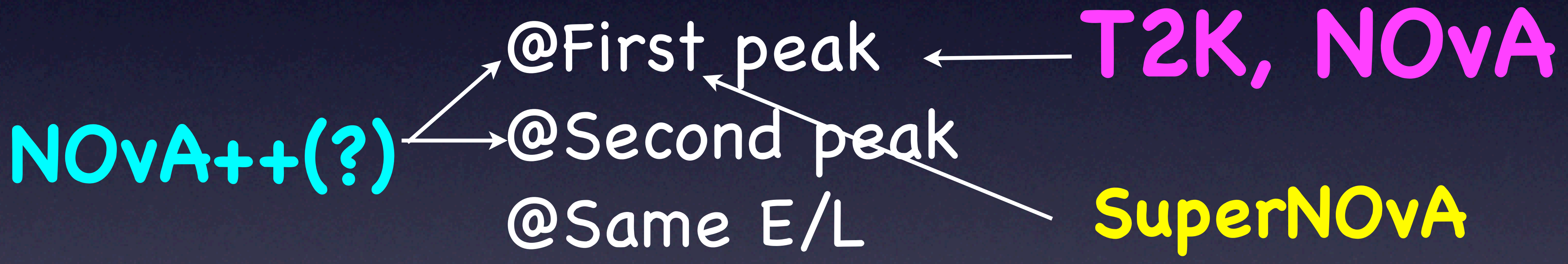

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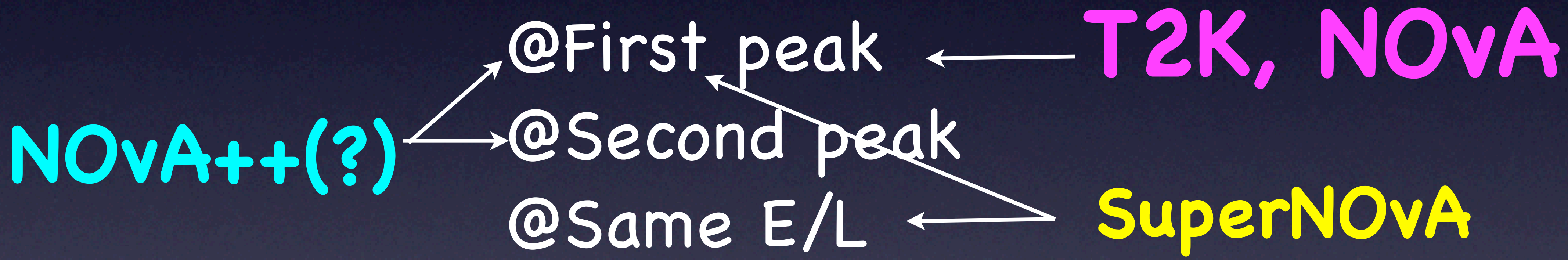

@First peak ← **T2K, NOvA**

NOvA++(?) → @First peak, @Second peak

@Second peak

@Same E/L ← **SuperNOvA** → @First peak

On-Axis (Wide band)? (Spectrum information)

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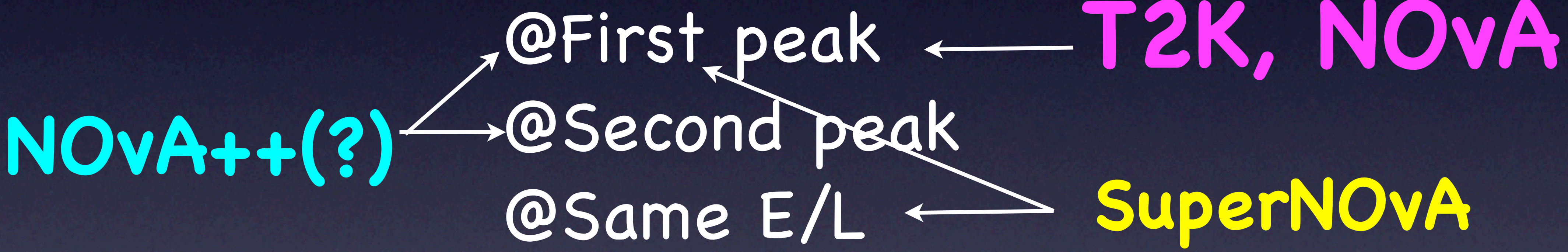

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NOvA++(?) → @First peak, @Second peak, @Same E/L

@Second peak

@Same E/L

SuperNOvA → @First peak, @Same E/L

On-Axis (Wide band)? (Spectrum information)

BNL

@First peak

@Second peak

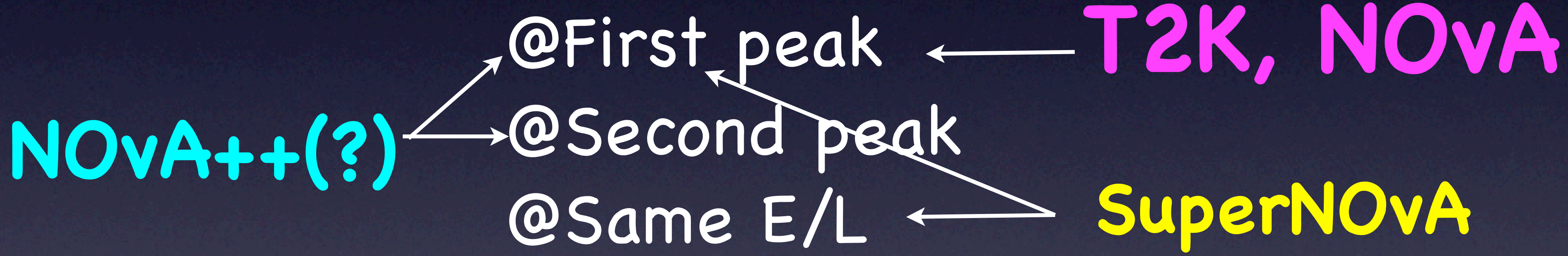
@Beyond

“NEAR-TERM” OR “NEXT-TO NEAR TERM” LBL Neutrino Experiments: Super Beams

(more intense conventional neutrino beams)

POSSIBLE EXPERIMENTAL SETUPS?

Off Axis? (Counting experiments)



T2K, NOvA

NOvA++(?)

@First peak

@Second peak

@Same E/L

SuperNOvA

On-Axis (Wide band)? (Spectrum information)

BNL

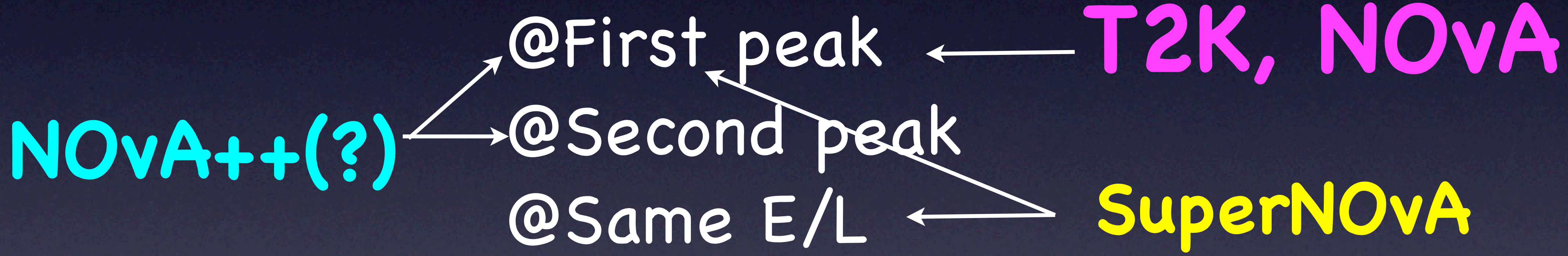
- @First peak
- @Second peak
- @Beyond

“NEAR-TERM“ OR “NEXT-TO NEAR TERM“
LBL Neutrino Experiments: Super Beams

(more intense conventional neutrino beams)

POSSIBLE EXPERIMENTAL SETUPS?

Off Axis? (Counting experiments)



On-Axis (Wide band)? (Spectrum information)

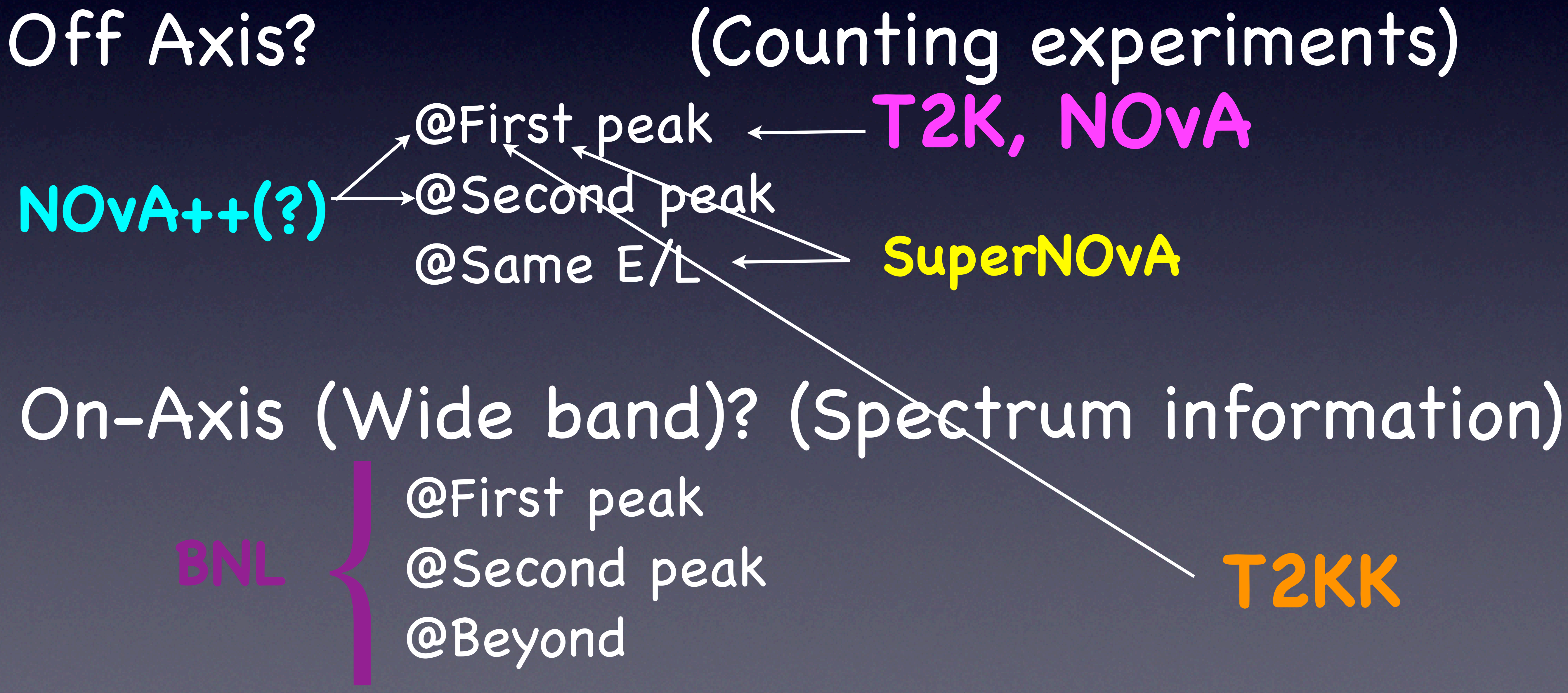
BNL
- @First peak
- @Second peak
- @Beyond

T2KK

“NEAR-TERM” OR “NEXT-TO NEAR TERM” LBL Neutrino Experiments: Super Beams

(more intense conventional neutrino beams)

POSSIBLE EXPERIMENTAL SETUPS?



Off Axis? (Counting experiments)

@First peak

@Second peak

@Same E/L

T2K, NOvA

NOvA++(?)

SuperNOvA

On-Axis (Wide band)? (Spectrum information)

BNL

@First peak

@Second peak

@Beyond

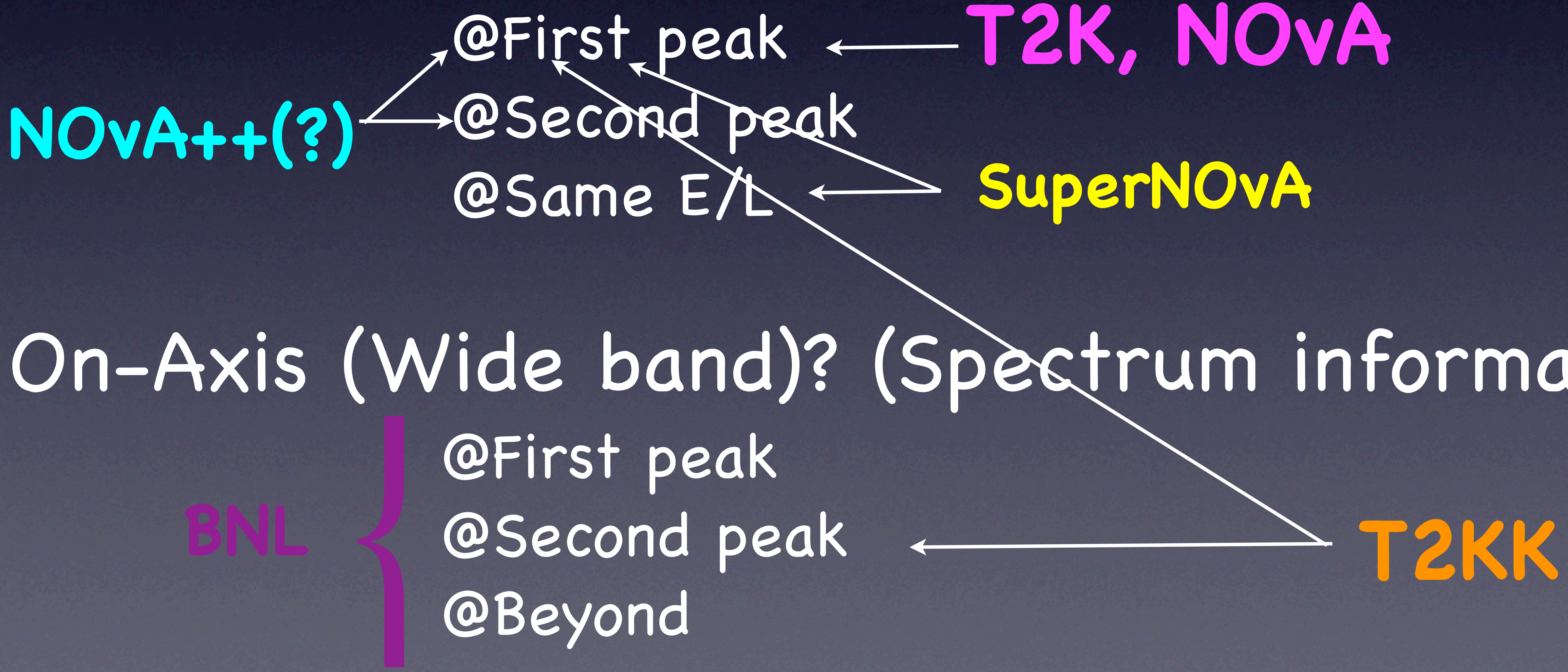
T2KK

“NEAR-TERM“ OR “NEXT-TO NEAR TERM“ LBL Neutrino Experiments: Super Beams

(more intense conventional neutrino beams)

POSSIBLE EXPERIMENTAL SETUPS?

Off Axis? (Counting experiments)



@First peak

@Second peak

@Same E/L

T2K, NOvA

NOvA++(?)

SuperNOvA

On-Axis (Wide band)? (Spectrum information)

BNL

@First peak

@Second peak

@Beyond

T2KK

"NEAR-TERM" OR "NEXT-TO NEAR TERM"
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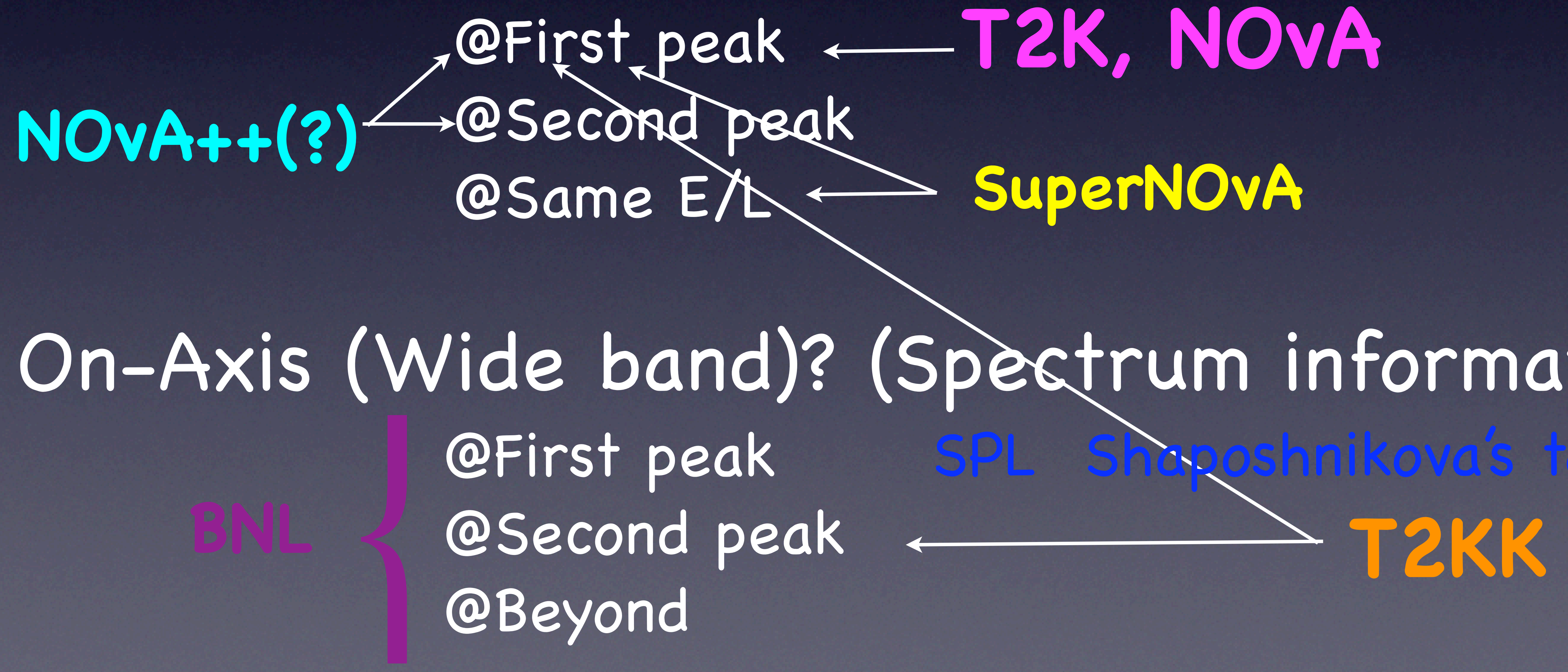
(more intense conventional neutrino beams)

POSSIBLE EXPERIMENTAL SETUPS?

Off Axis? (Counting experiments)



@First peak

@Second peak

@Same E/L

NOvA++(?)

T2K, NOvA

SuperNOvA

On-Axis (Wide band)? (Spectrum information)

BNL

@First peak

@Second peak

@Beyond

SPL Shaposhnikova's talk

T2KK

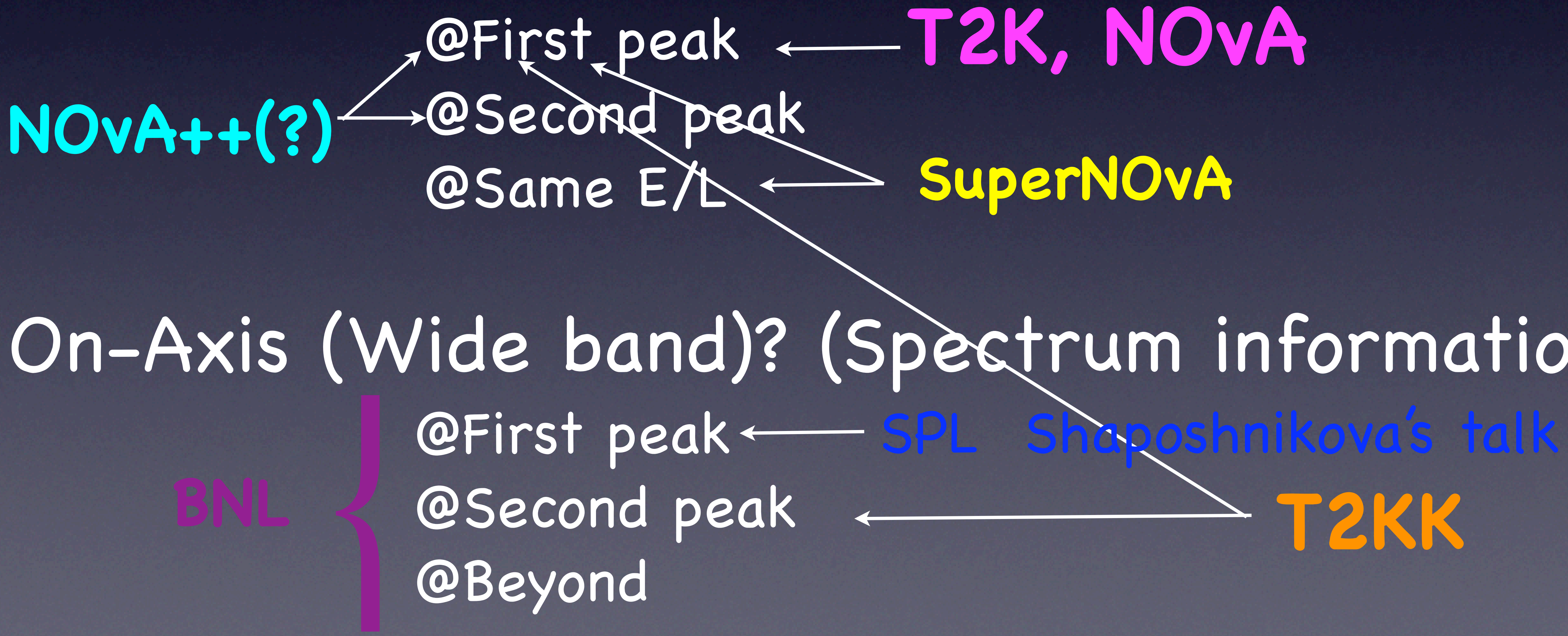
“NEAR-TERM” OR “NEXT-TO NEAR TERM”

LBL Neutrino Experiments: Super Beams

(more intense conventional neutrino beams)

POSSIBLE EXPERIMENTAL SETUPS?

Off Axis? (Counting experiments)



NOvA++(?)

@First peak ← T2K, NOvA

@Second peak

@Same E/L ← SuperNOvA

On-Axis (Wide band)? (Spectrum information)

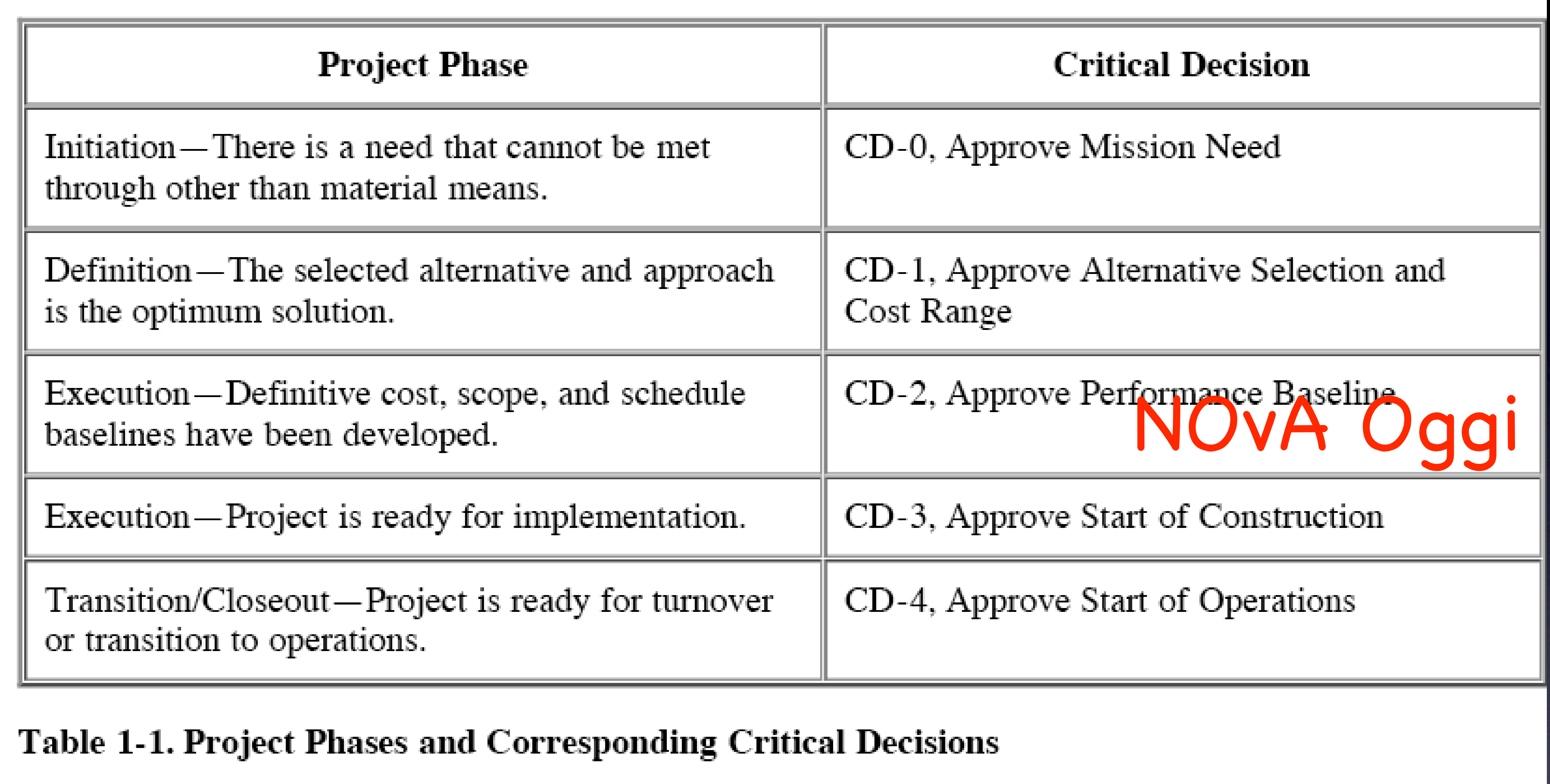
BNL

@First peak ← SPL Shaposhnikova’s talk

@Second peak ← T2KK

@Beyond

How NEAR is "NEAR"?



Project Phase	Critical Decision
Initiation—There is a need that cannot be met through other than material means.	CD-0, Approve Mission Need
Definition—The selected alternative and approach is the optimum solution.	CD-1, Approve Alternative Selection and Cost Range
Execution—Definitive cost, scope, and schedule baselines have been developed.	CD-2, Approve Performance Baseline
Execution—Project is ready for implementation.	CD-3, Approve Start of Construction
Transition/Closeout—Project is ready for turnover or transition to operations.	CD-4, Approve Start of Operations

Table 1-1. Project Phases and Corresponding Critical Decisions

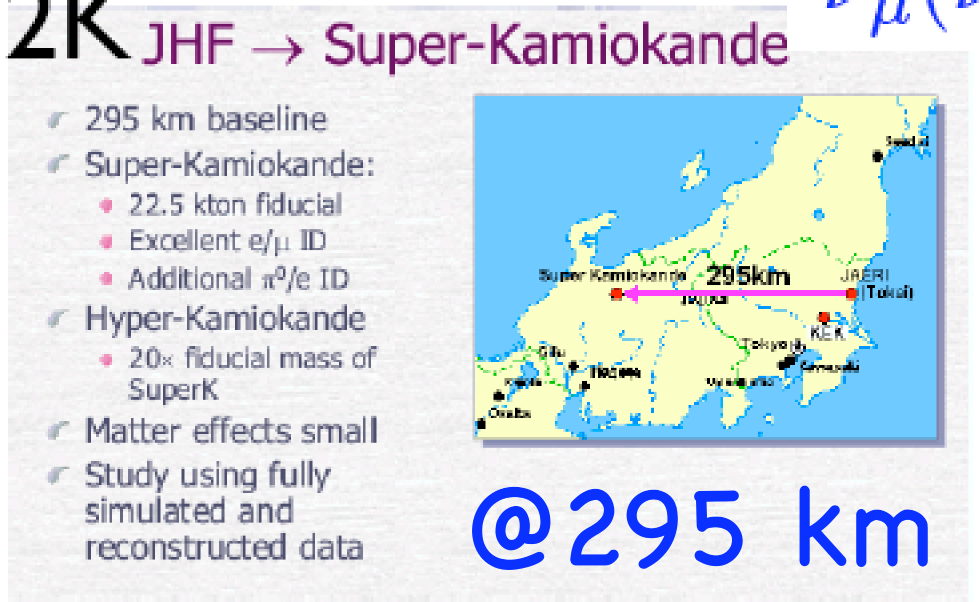
NOvA Oggi

Schedule

- Apr 2006: CD-1 review. Unanimous recommendation to approve CD-1.
- Oct 2006: CD-2 review.
- Jan 2007: CD-3a
- Oct 2007: CD-3b, begin Far Detector enclosure
- Oct 2008: First module factory ready
- Jun 2009: Occupancy of the FD enclosure
- Nov 2010: 5 kT completed, start taking data
- Nov 2011: Far Detector completed

T2K

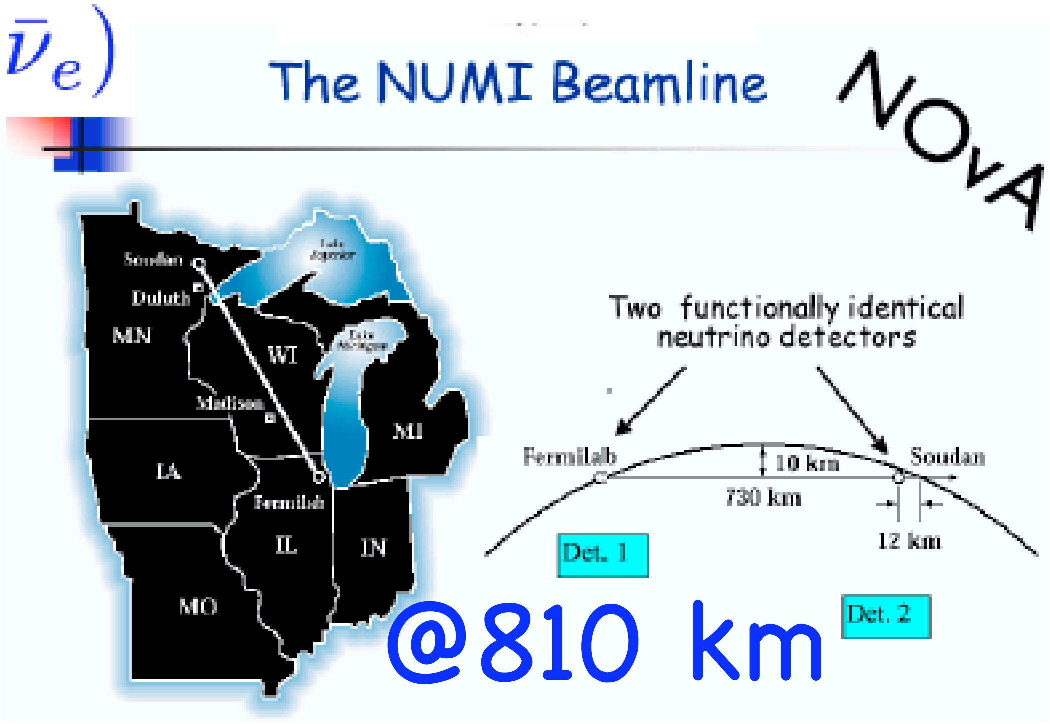
$$\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)$$



JHF → Super-Kamiokande

- 295 km baseline
- Super-Kamiokande:
  - 22.5 kton fiducial
  - Excellent e/μ ID
  - Additional π^0/e ID
- Hyper-Kamiokande
  - 20× fiducial mass of SuperK
- Matter effects small
- Study using fully simulated and reconstructed data

@295 km



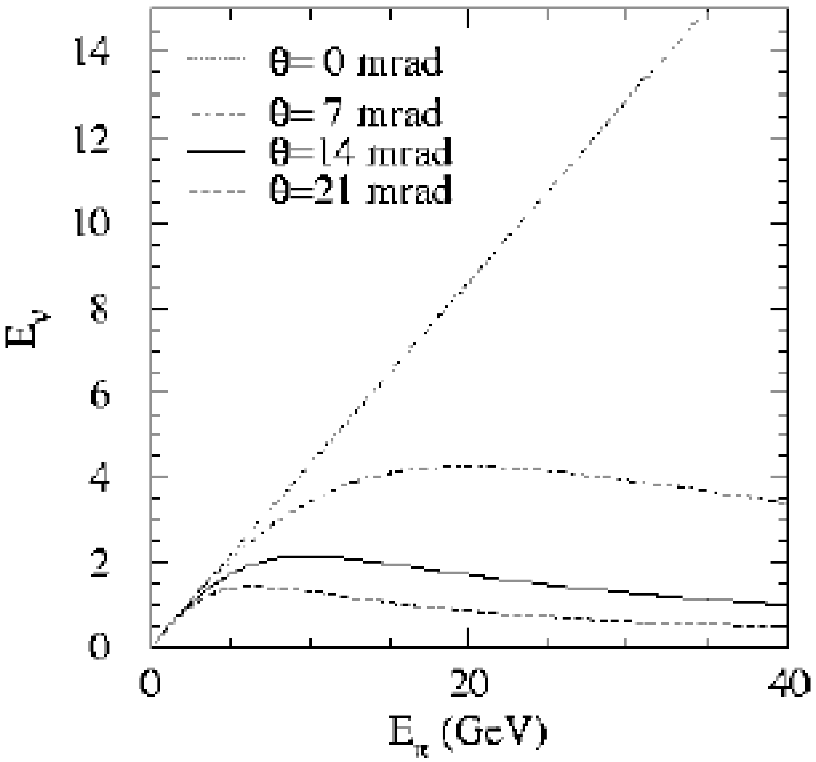
@810 km

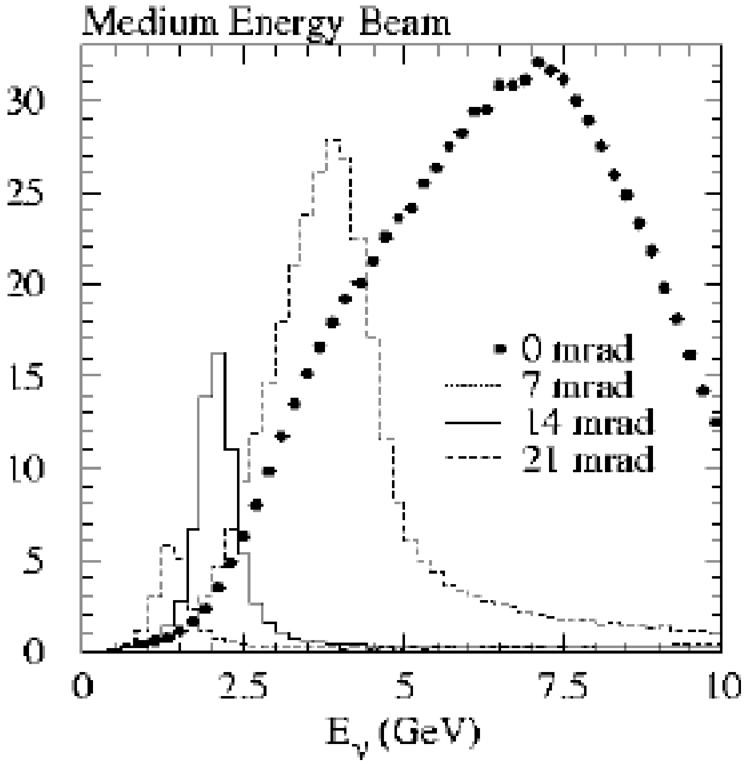
By using a conventional, albeit more intense, neutrino beam:

$$\pi^+ \longrightarrow \mu^+\nu_\mu \qquad < 1\% \nu_e$$

In an Off-Axis detector location

$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$





Medium Energy Beam

Why off-axis?

Simple tuning of BEAM ENERGY

Narrow beam: concentrates the events @ OM (counting exp)

“Lower” electron neutrino intrinsic background

No high energy tail: High energy neutrinos produce NC events, kinematical suppression of NC background

Why NOT off-axis?

Narrow beam: concentrates the events @ OM (counting exp)

Absolute numbers are crucial: HIGH STATISTICS

ONLY TWO MEASUREMENTS:
NUMBER OF NEUTRINO AND ANTINEUTRINO EVENTS.

VIRTUALLY **IMPOSSIBLE** TO RESOLVE THE DEGENERACIES

The attack of the clones!

Why NOT off-axis adding a 2nd detector?

Where?

A) AROUND SECOND PEAK, @ DIFFERENT L/E?

CP Violating and matter effects are very different

NOvA++ 25 kton, L= 810 km @ 12 km off axis (E = 2 GeV

Second @735 km @ 30 km off-axis (E = 0.64 GeV)

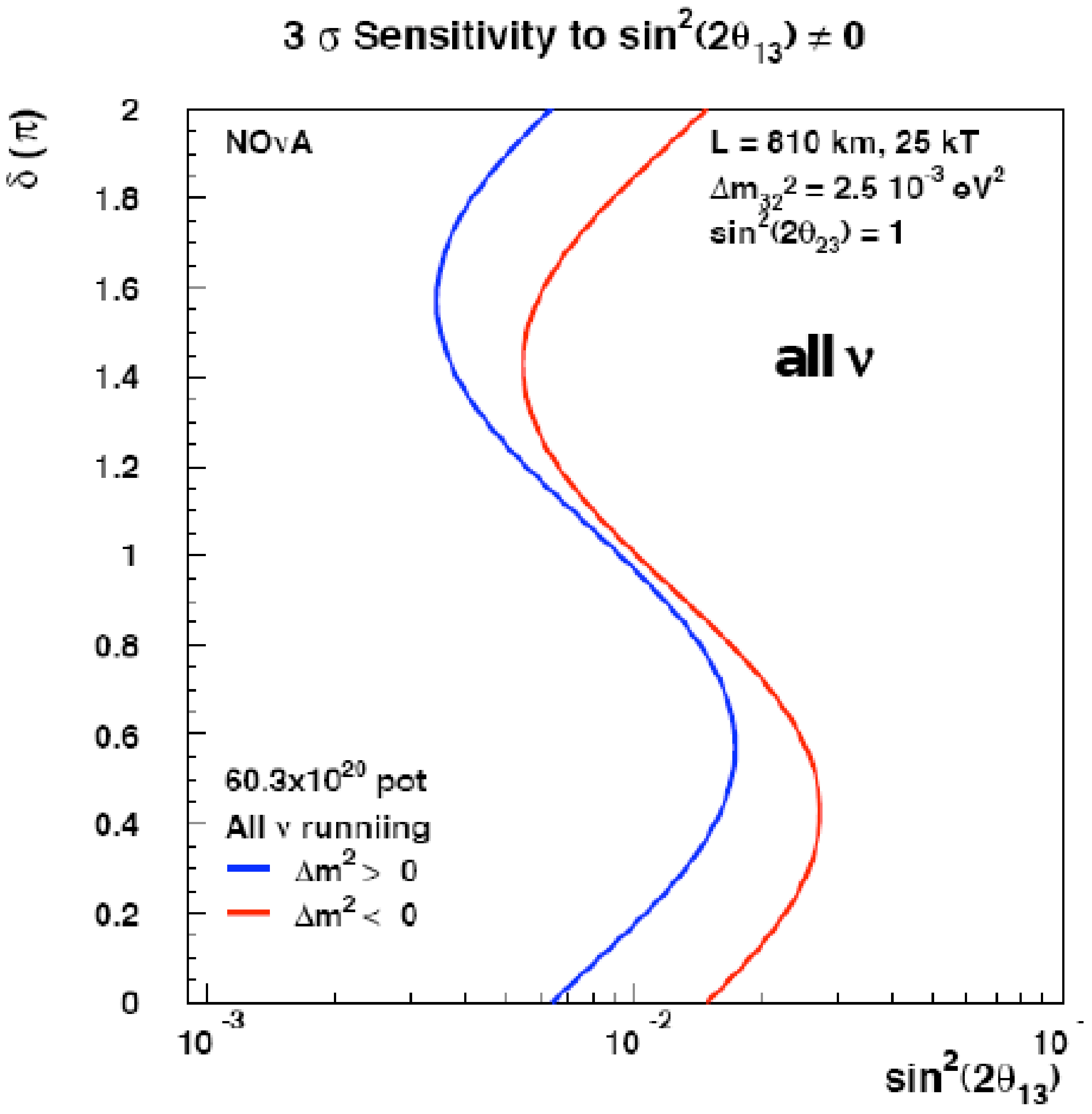
CP Violating effects are larger by 3 and matter effects are smaller by a factor of 3.

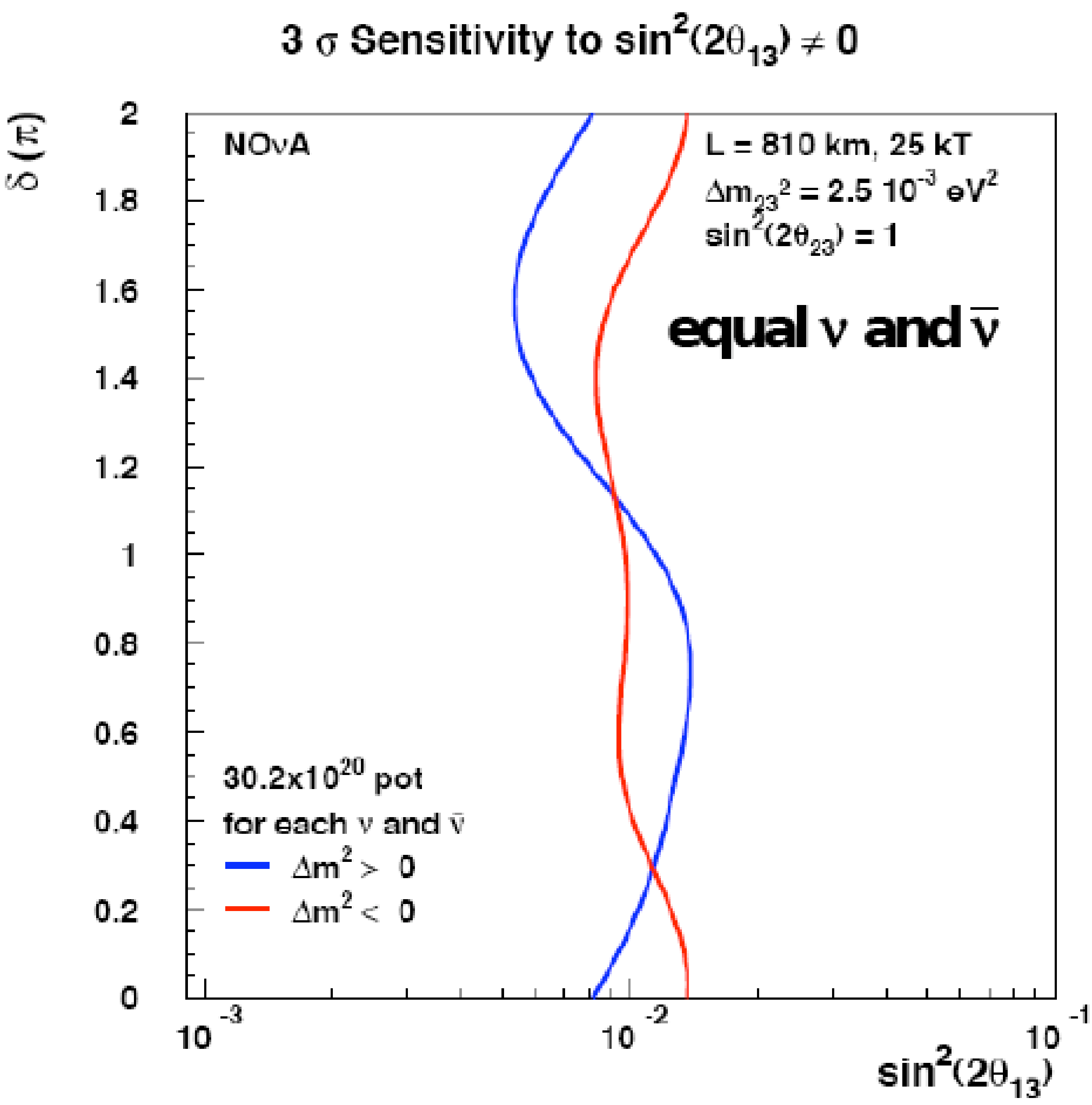
1/3x $$s^2_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right)$$

$$\tilde{B}_\mp \equiv |A \mp \Delta_{13}|$$

3x $$\tilde{J}\,\frac{\Delta_{12}}{A}\,\frac{\Delta_{13}}{\tilde{B}_\mp}\,\sin\left(\frac{AL}{2}\right)\sin\left(\frac{\tilde{B}_\mp L}{2}\right)\cos\left(\pm\delta - \frac{\Delta_{13}L}{2}\right)$$

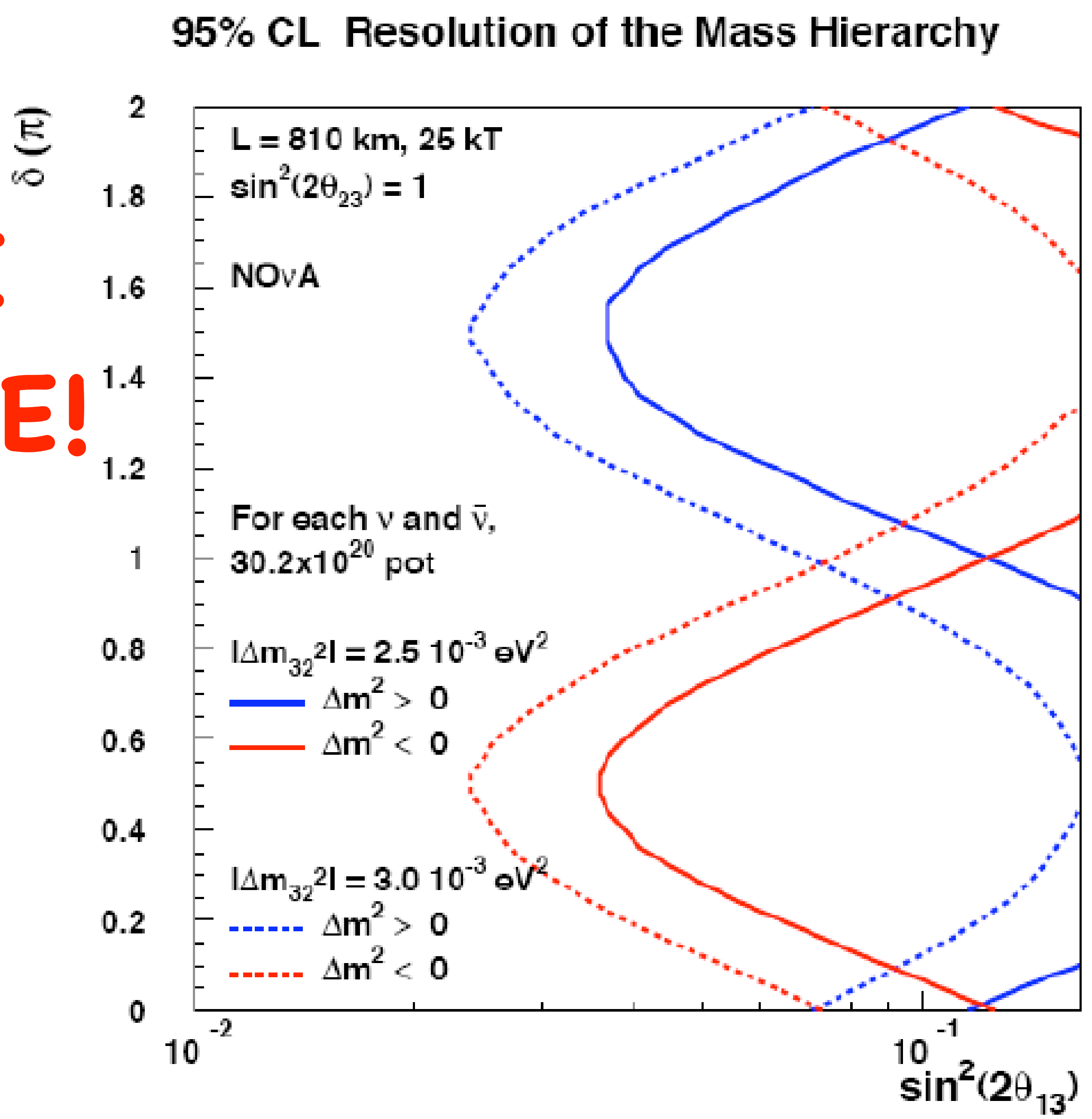
3 σ Sensitivity to $\theta_{13} \neq 0$





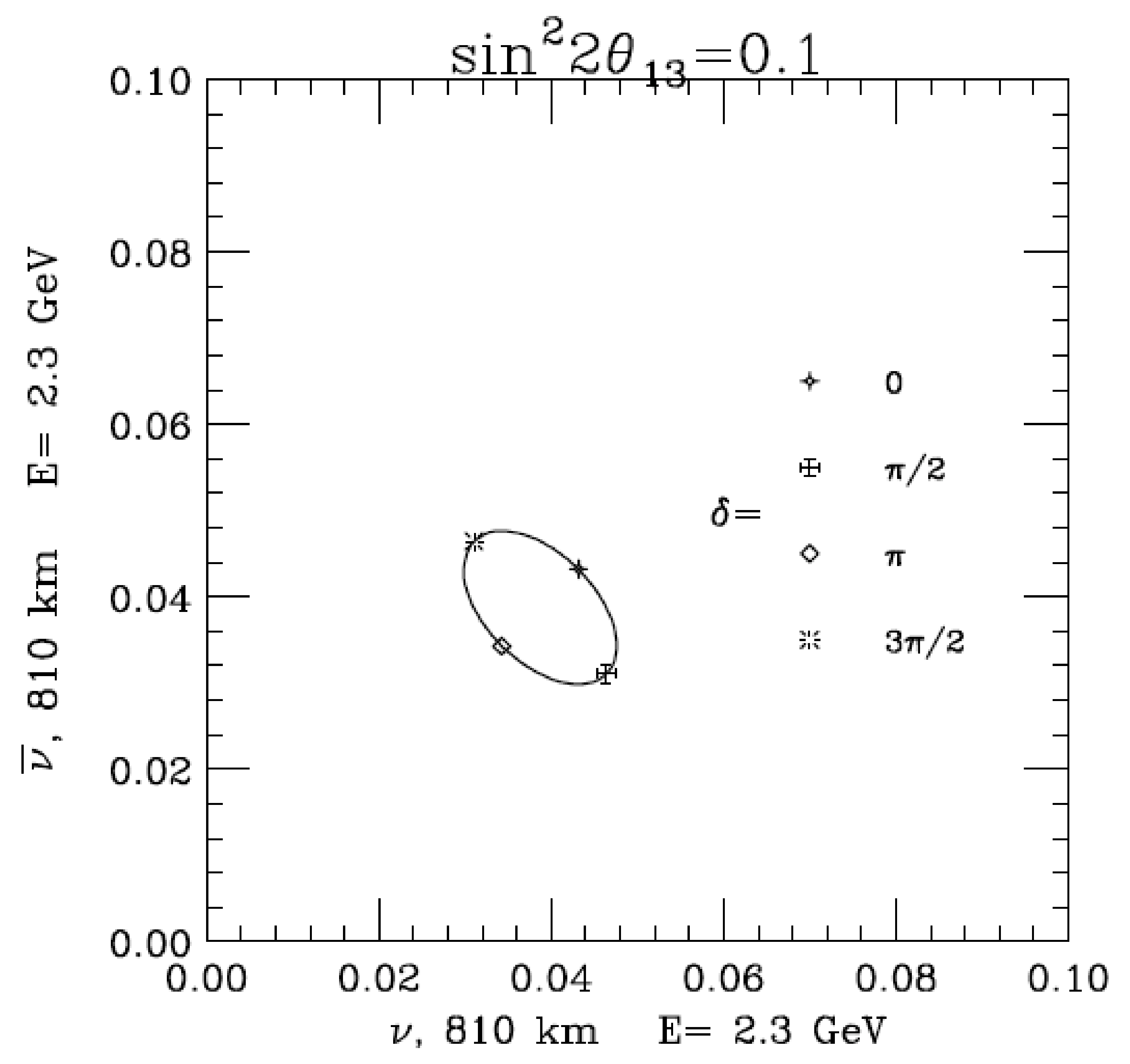
95% CL Resolution of the Mass Ordering

HUGE DEPENDENCE ON CP-PHASE!

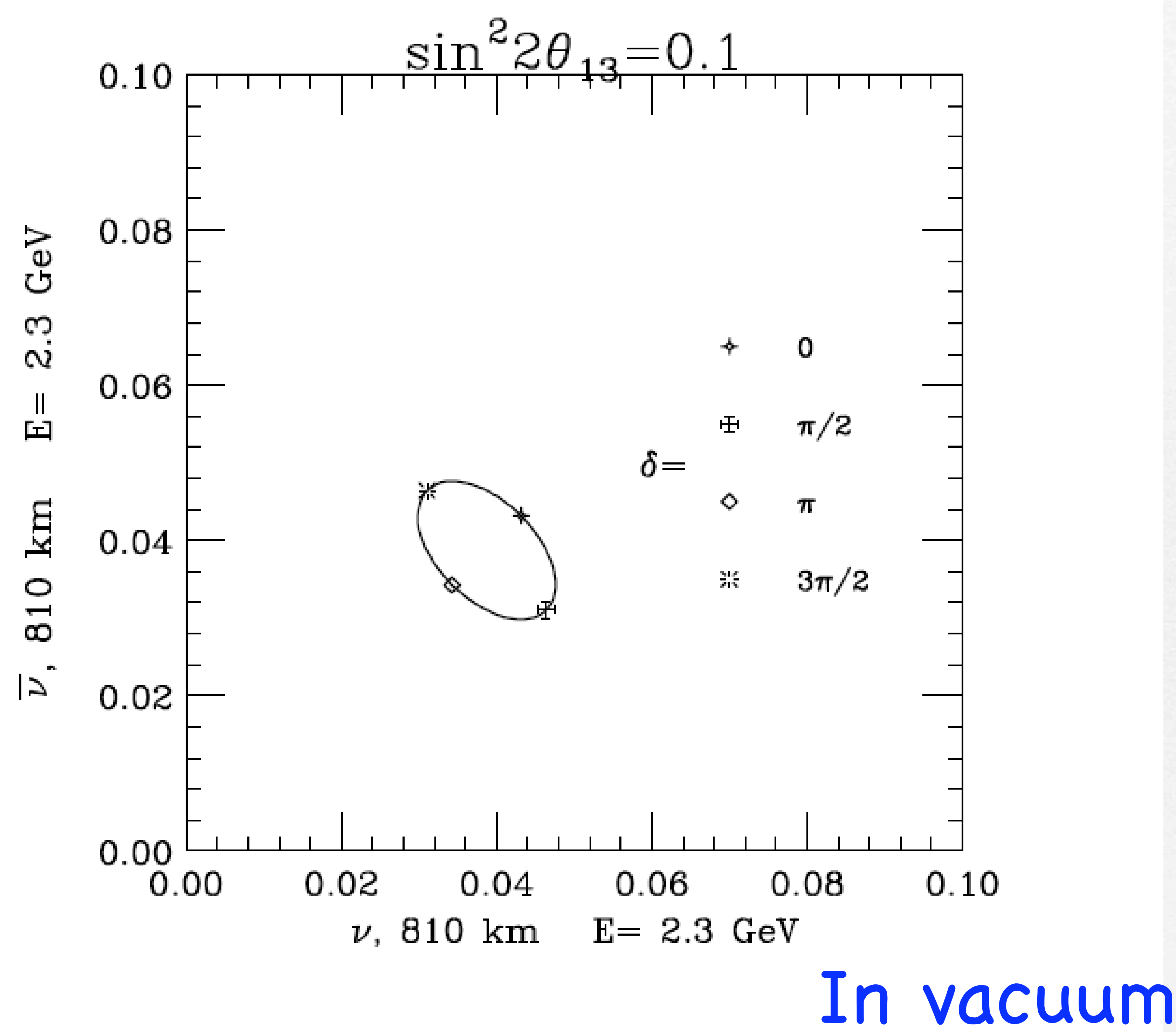


95% CL Resolution of the Mass Hierarchy

Neutrino - Antineutrino

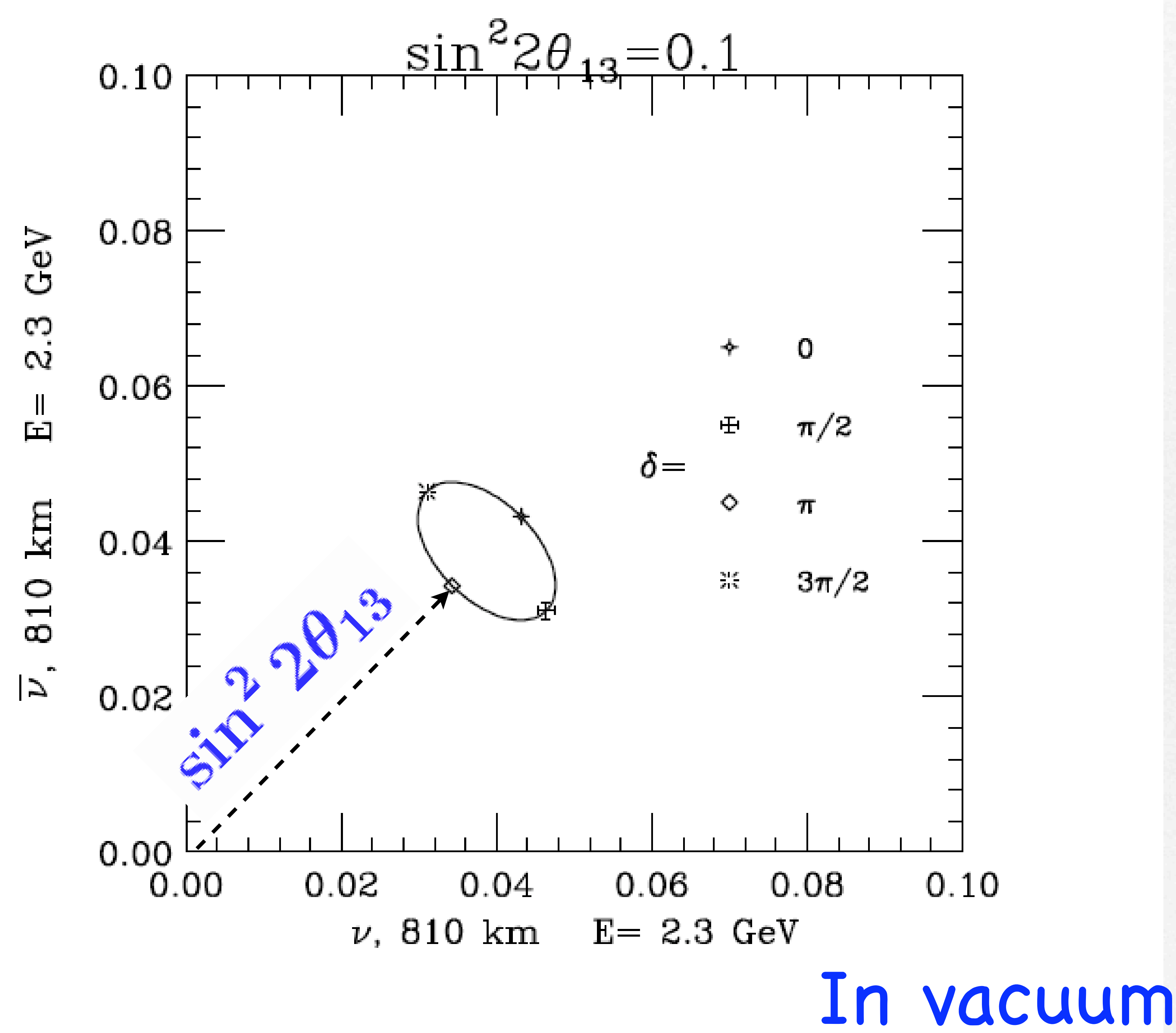


Neutrino - Antineutrino



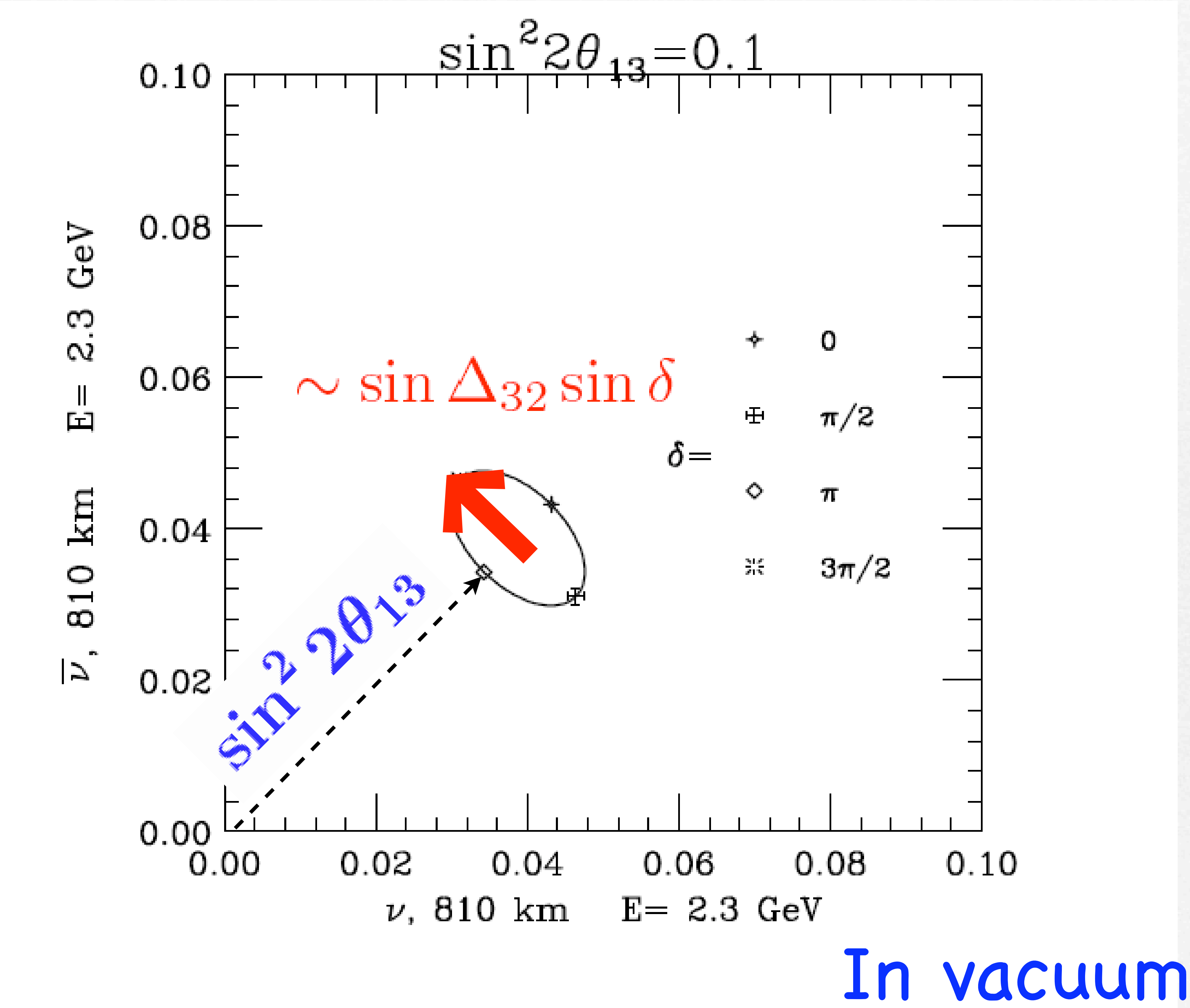
In vacuum@810 km

Neutrino - Antineutrino



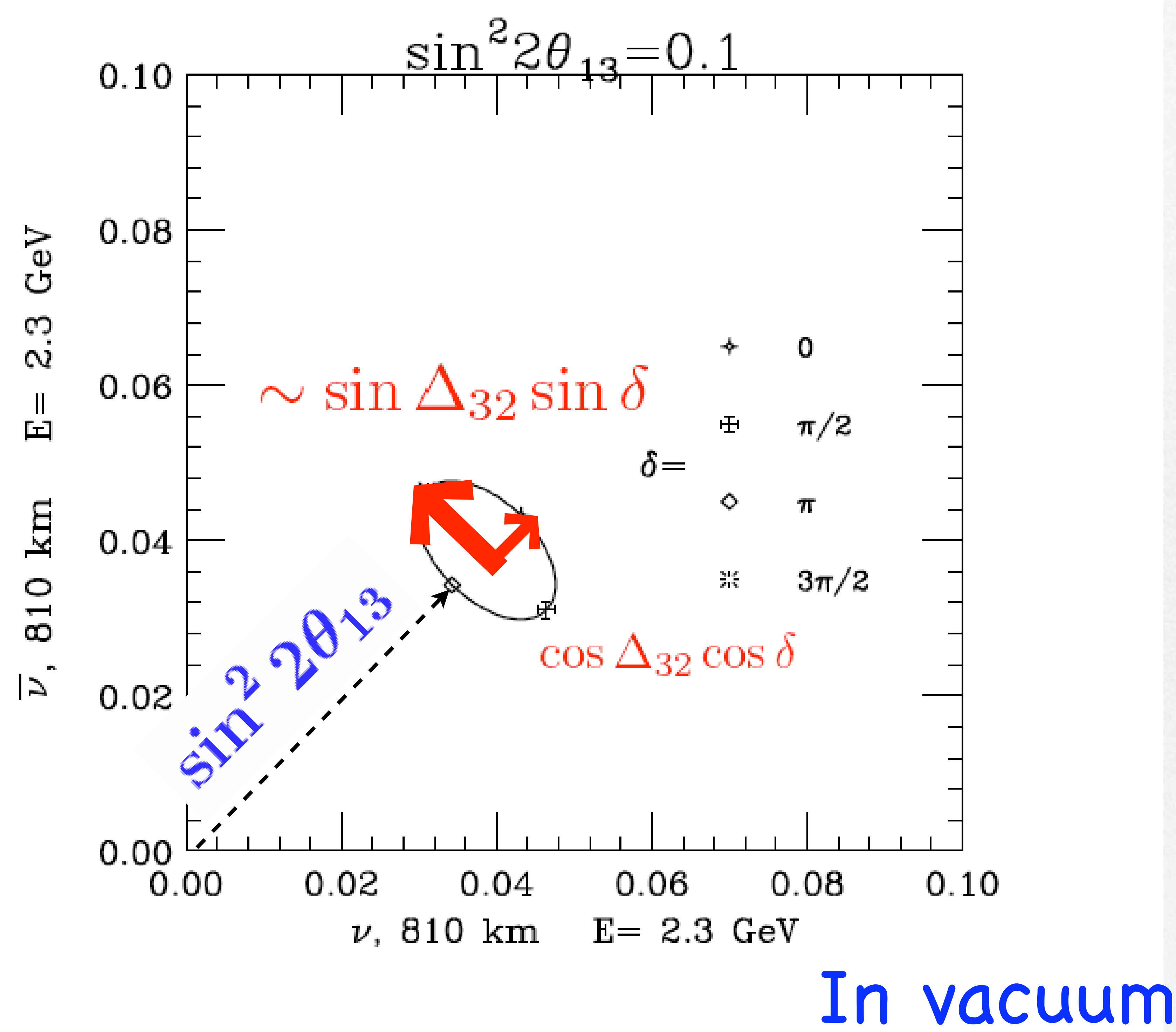
In vacuum@810 km

Neutrino - Antineutrino



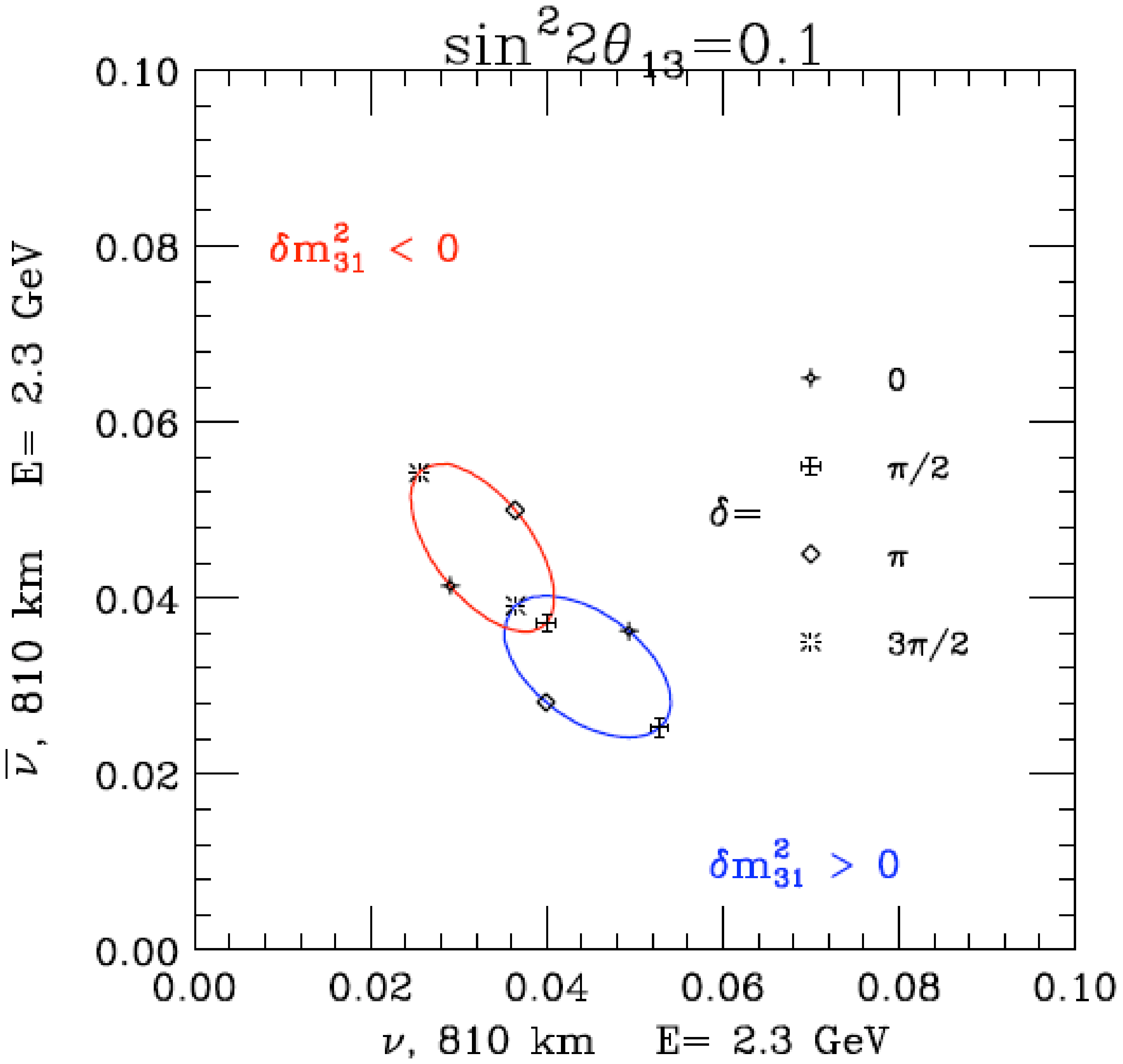
In vacuum@810 km

Neutrino - Antineutrino



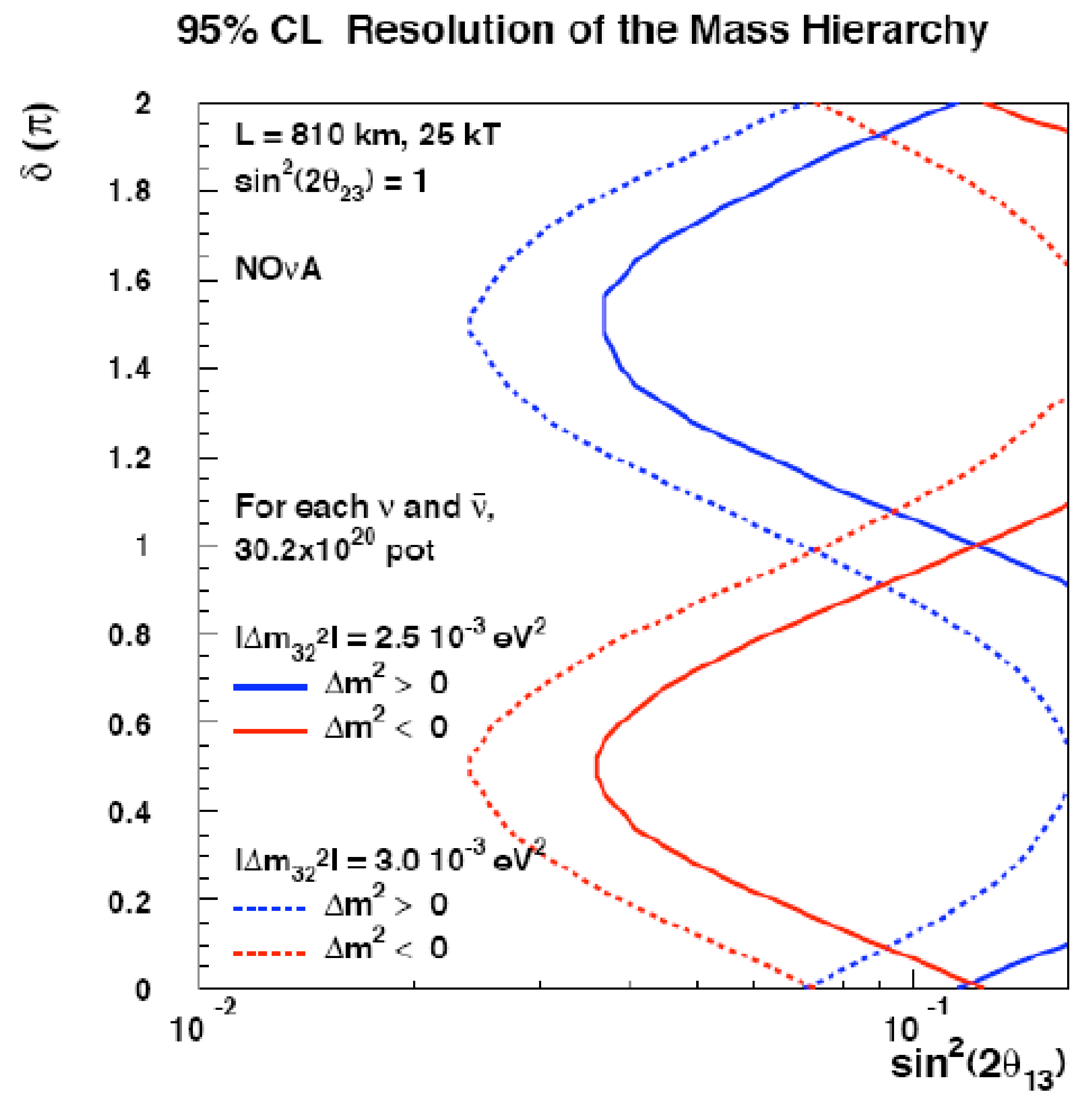
In vacuum@810 km

Neutrino - Antineutrino

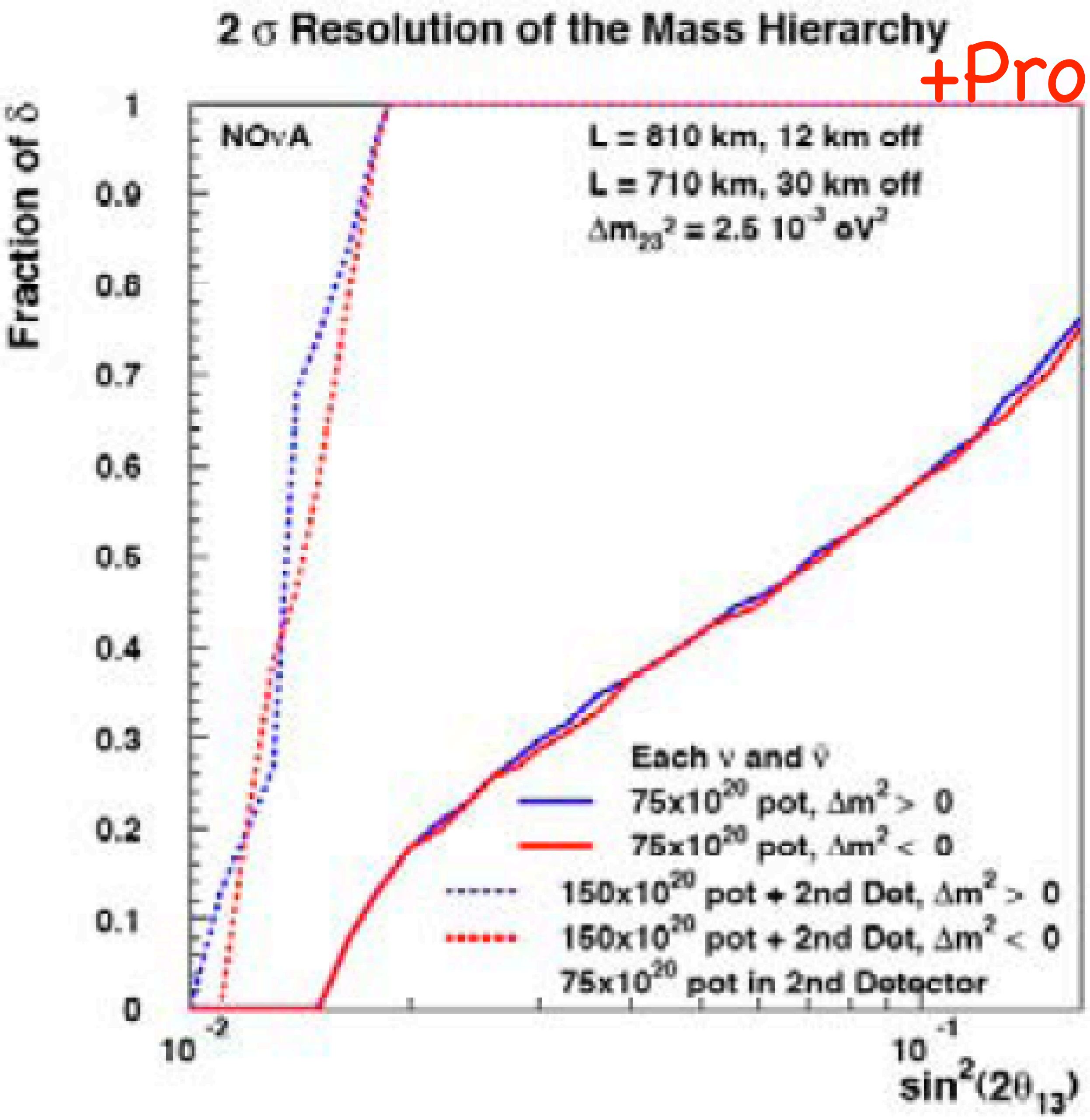


In matter! @810 km

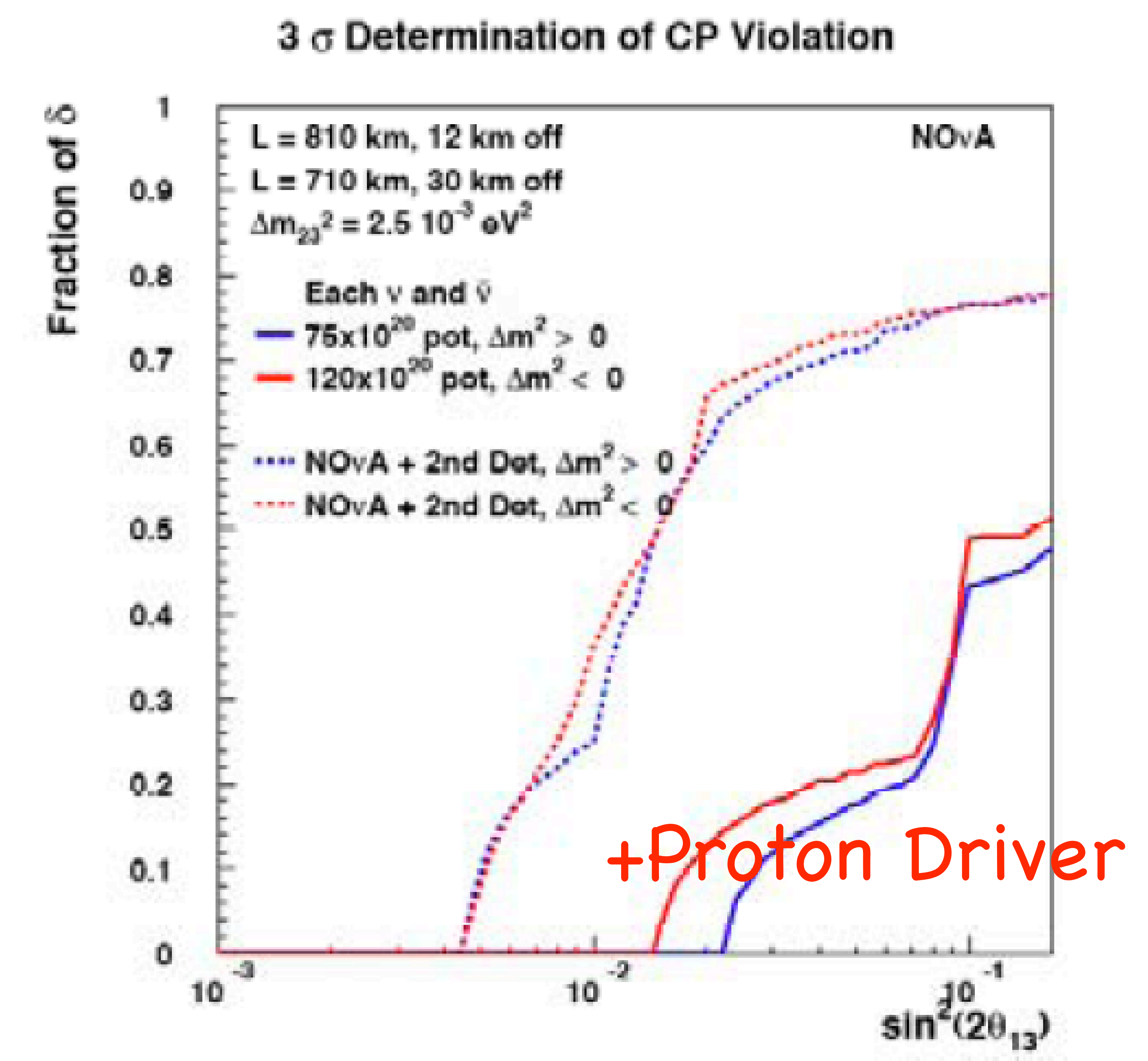
95% CL Resolution of the Mass Ordering



95% CL Resolution of the Mass Ordering



+Proton Driver



+Proton Driver

Why NOT off-axis adding a 2nd detector?

Where?

A) AROUND SECOND PEAK, @ DIFFERENT L/E?

CP Violating and matter effects are very different

T2KK 4 MW

270 kton,L= 295 km, 2.5 deg off axis (E=0.65GeV)

270 kton,L= 1050 km, 2.5 deg off axis (E=0.65 GeV)

CP Violating effects are larger by a factor of 3

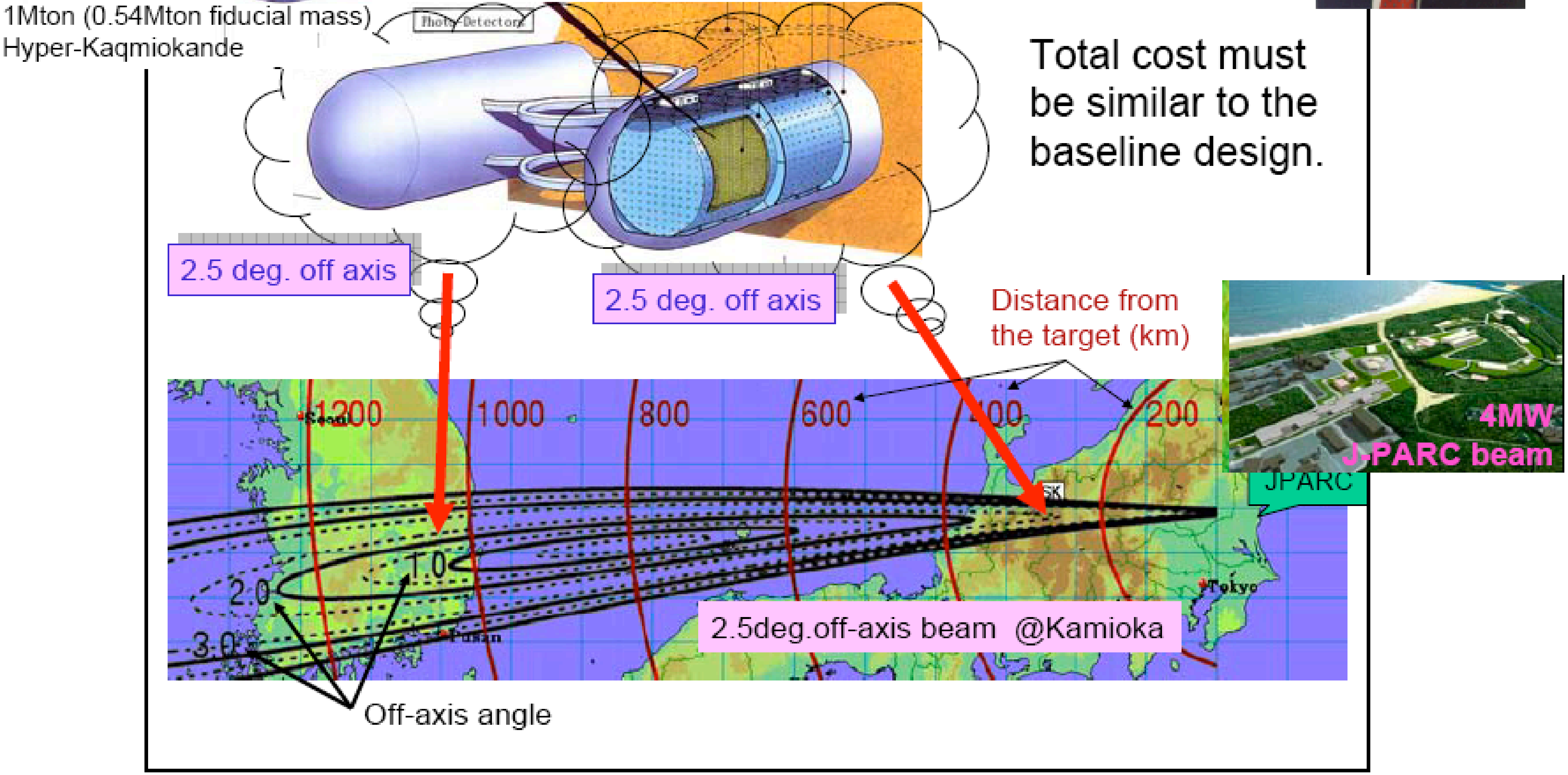
while matter effects remain the same.

However, by making use of the energy information at the second peak, they can resolve the hierarchy and the intrinsic degeneracy.

5 energy bins for appearance, 20 for disappearance

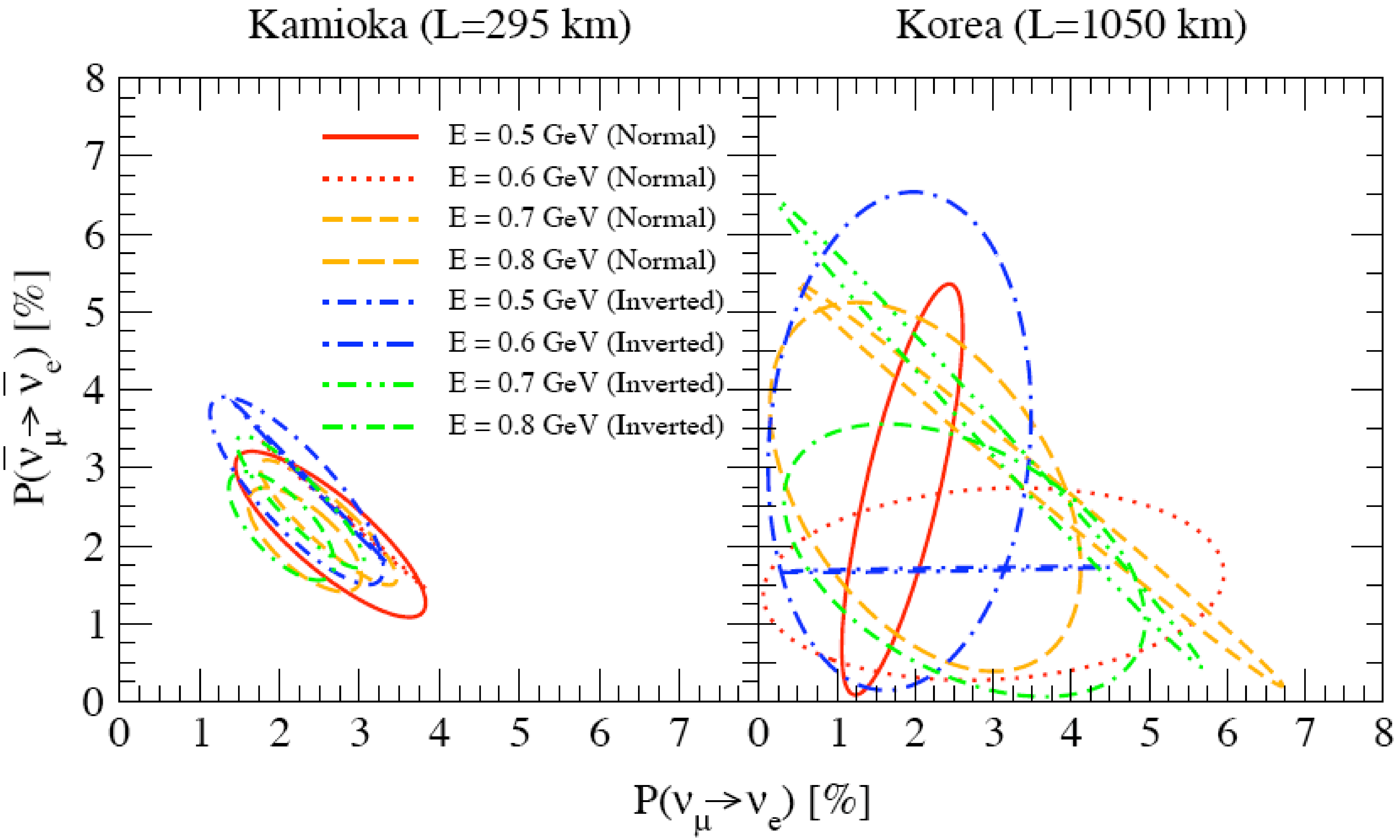
Off Axis:

Some recent progress: detector in Korea



Total cost must be similar to the baseline design.

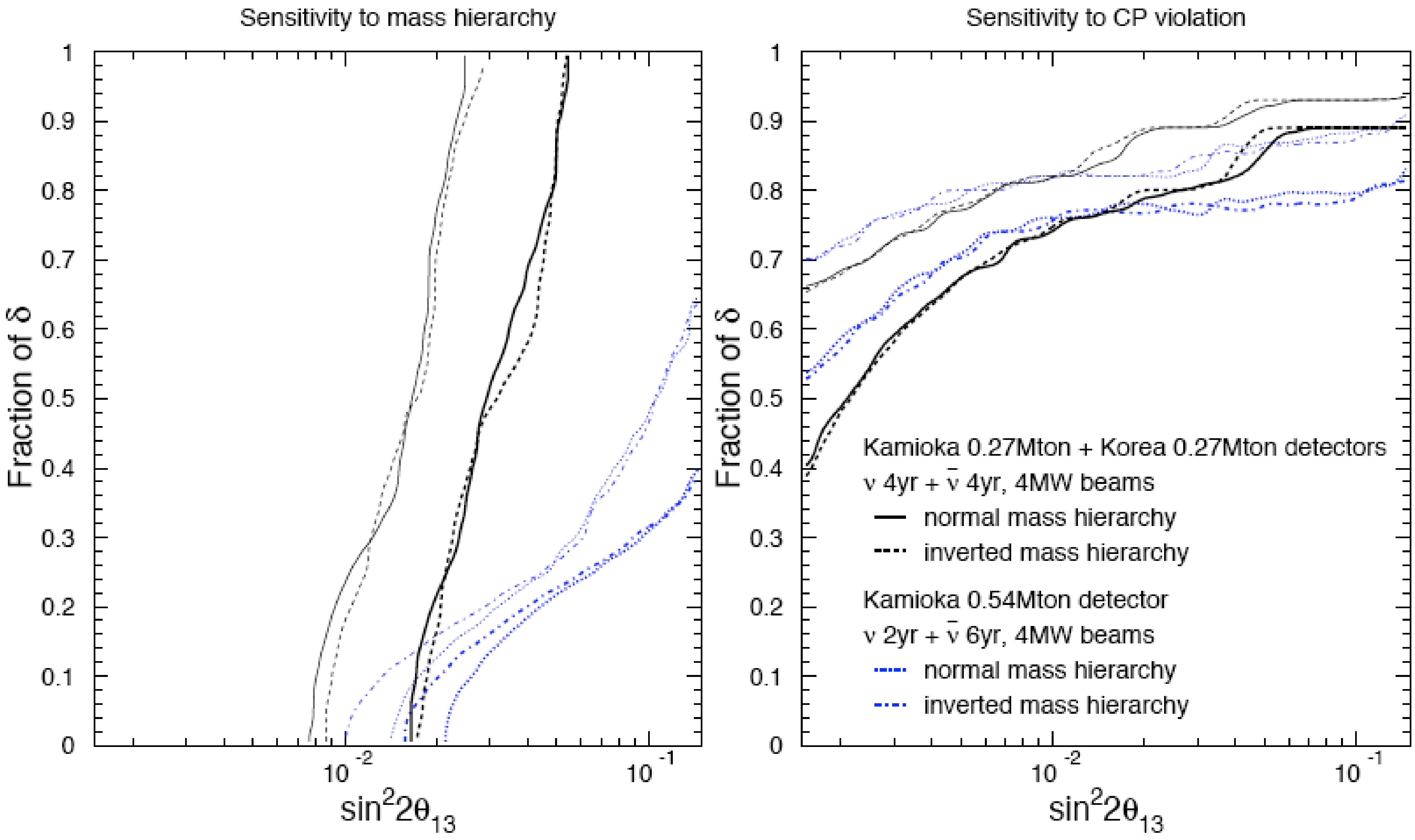
One of the authors (TK) thanks Edward Witten for the encouragement of exploring the possibility discussed in this paper. This work was supported in part by the Grant-in-Aid



M. Ishitsuka, T. Kajita, H. Minakata and H. Nunokawa, PRD'05

``Resolving neutrino mass hierarchy and CP degeneracy by two identical detectors with different baselines,"

4 MW 270 kton + 270 kton, 4 years neutrino and 4 years antineutrino



$$|\chi^2_{min}(\text{wrong hierarchy}) - \chi^2_{min}(\text{true hierarchy})| > 4$$

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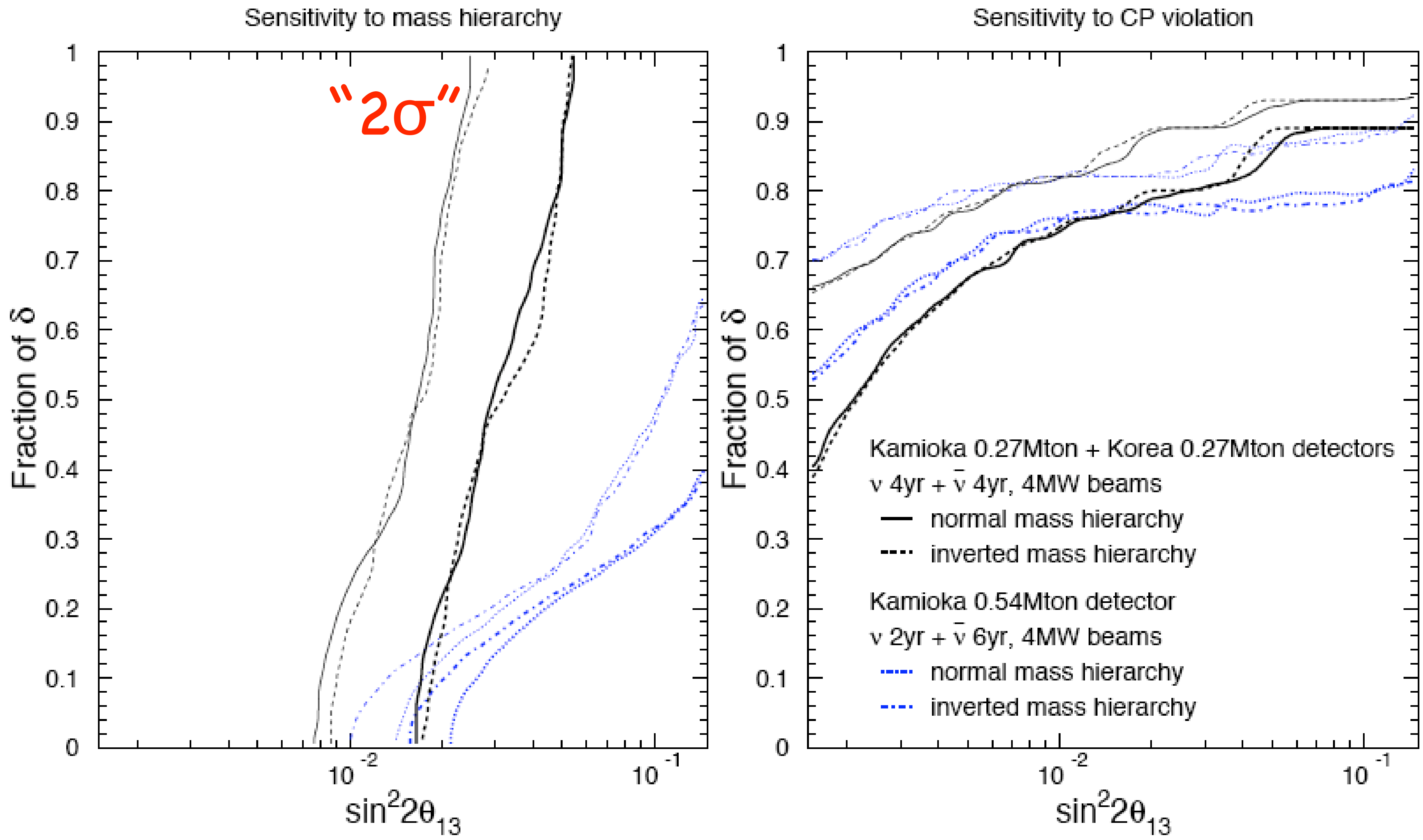

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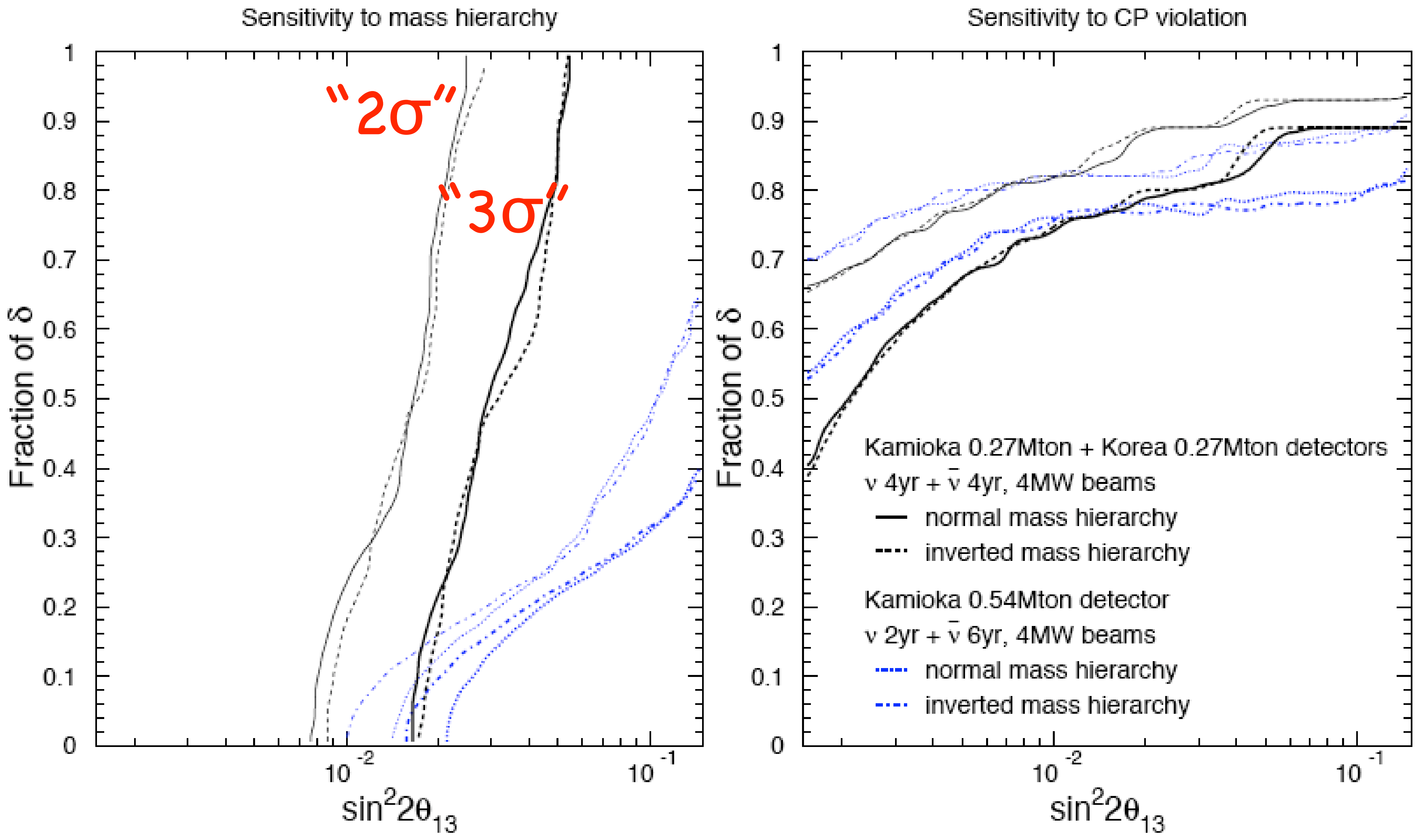

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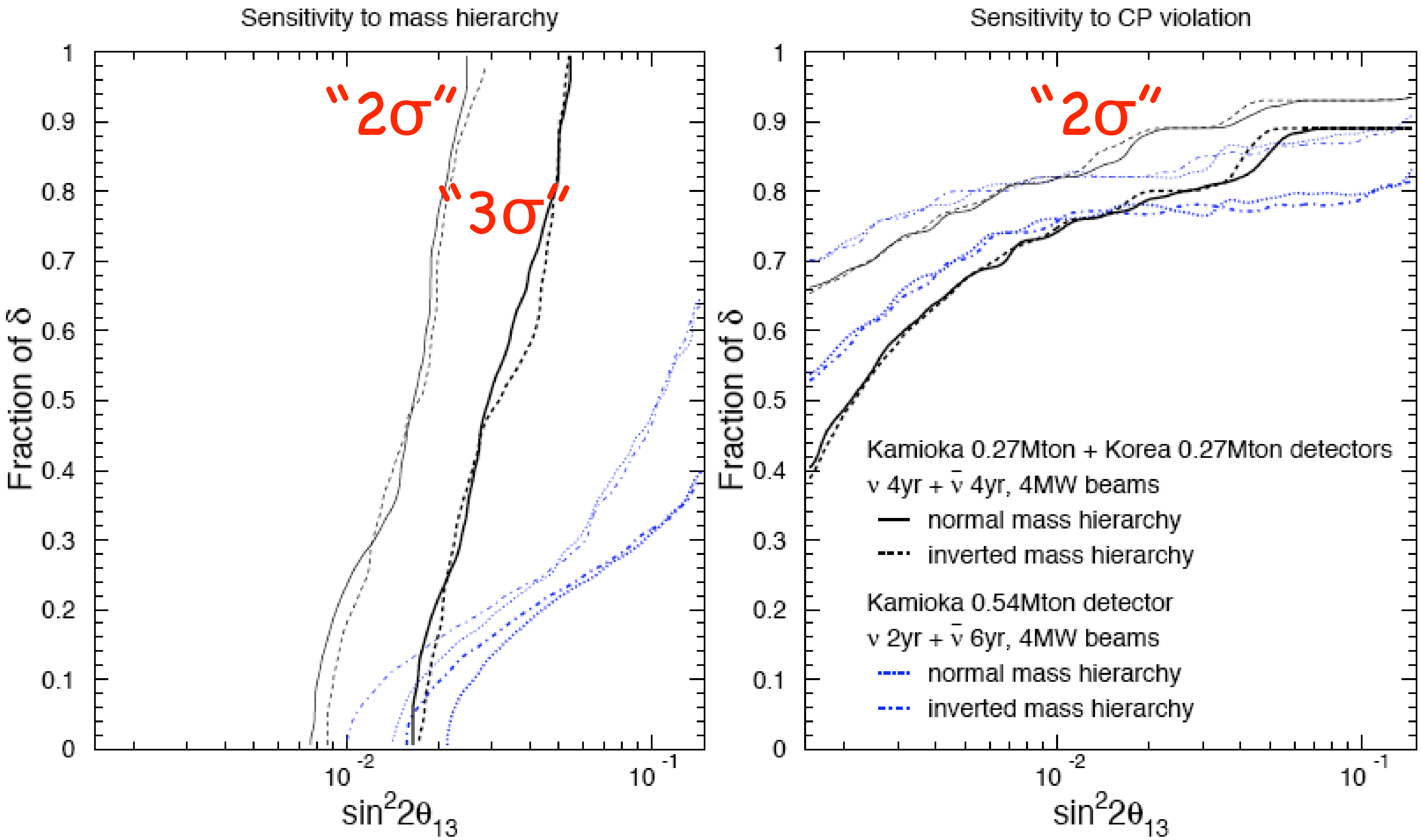

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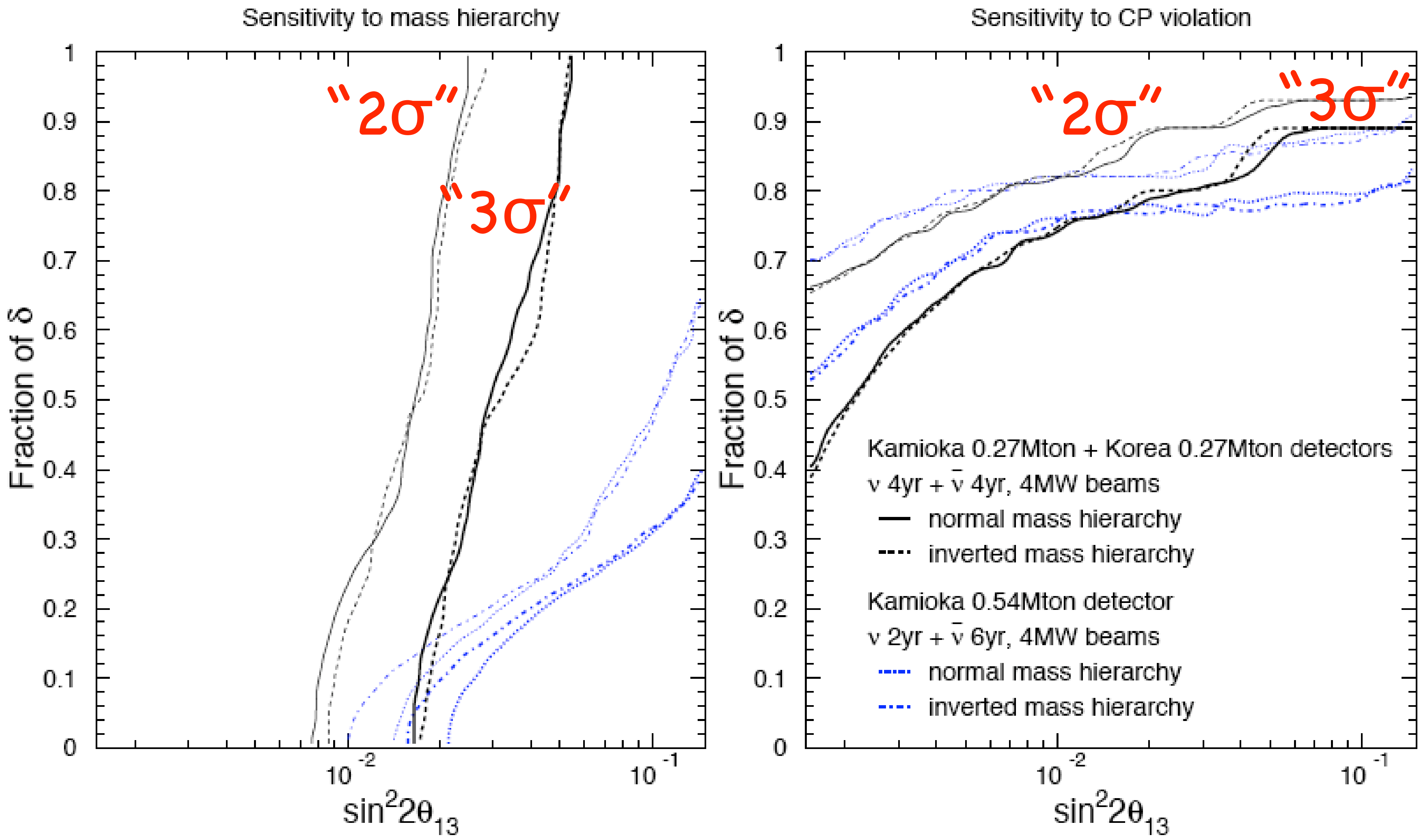

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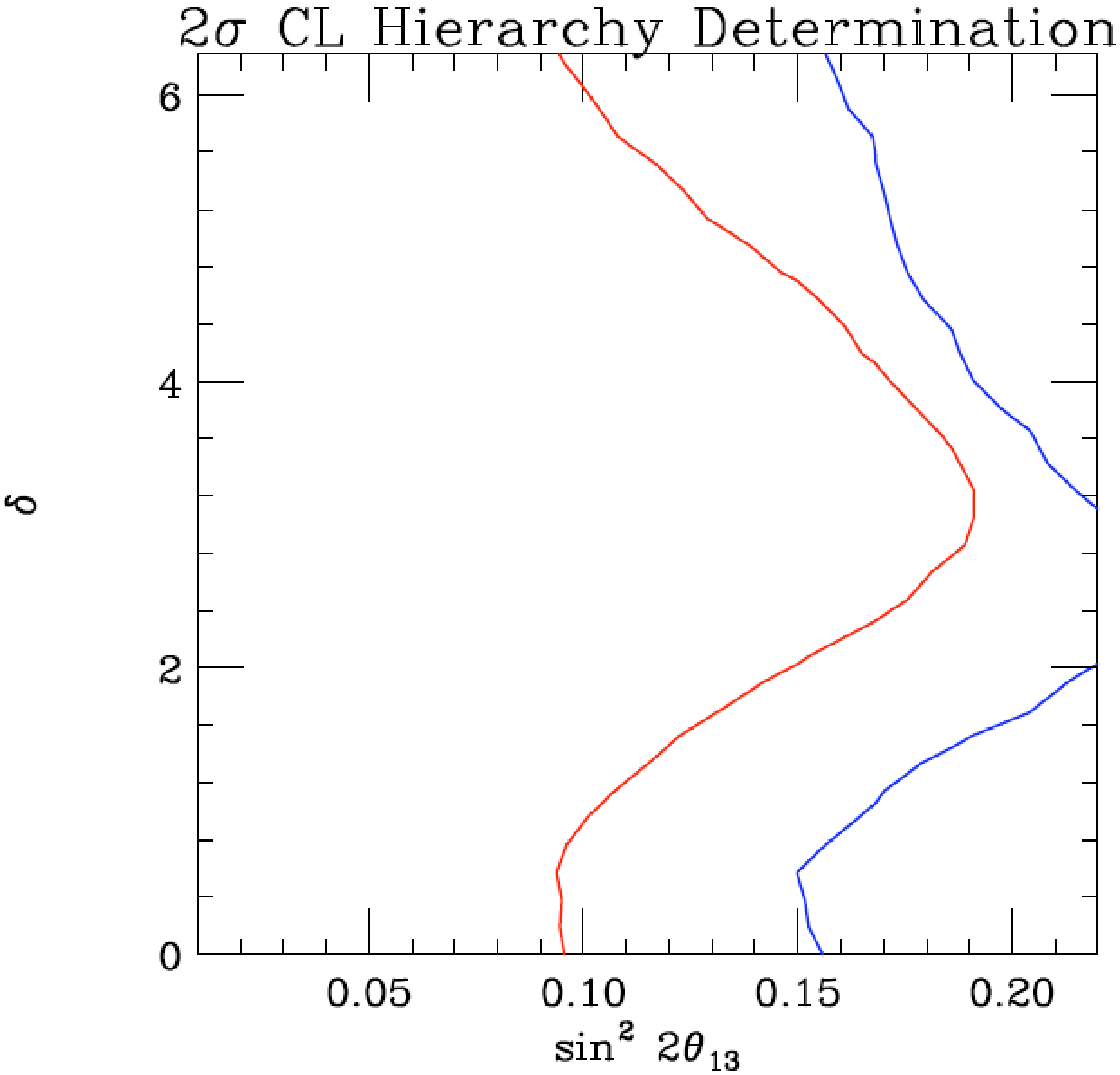
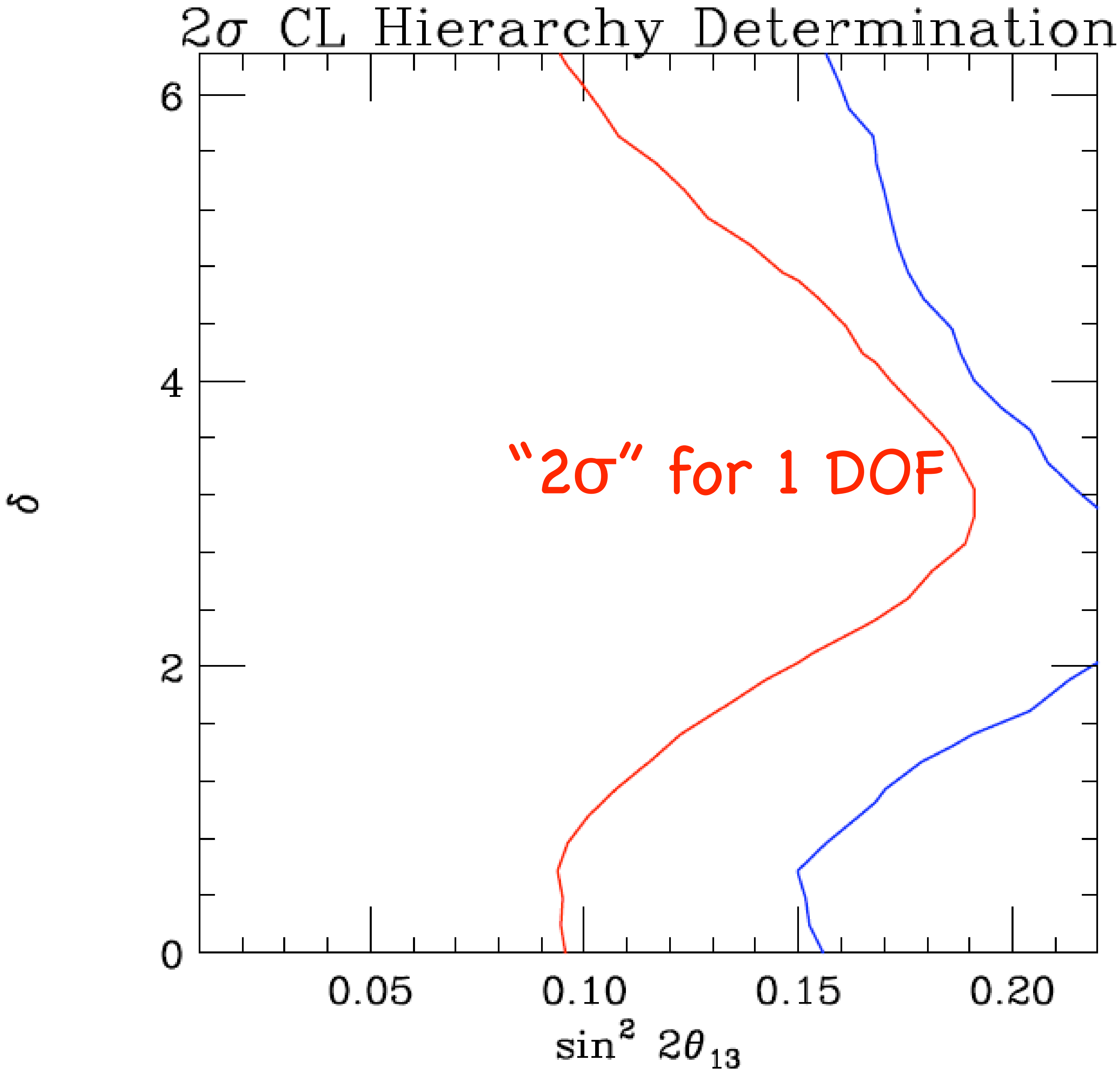
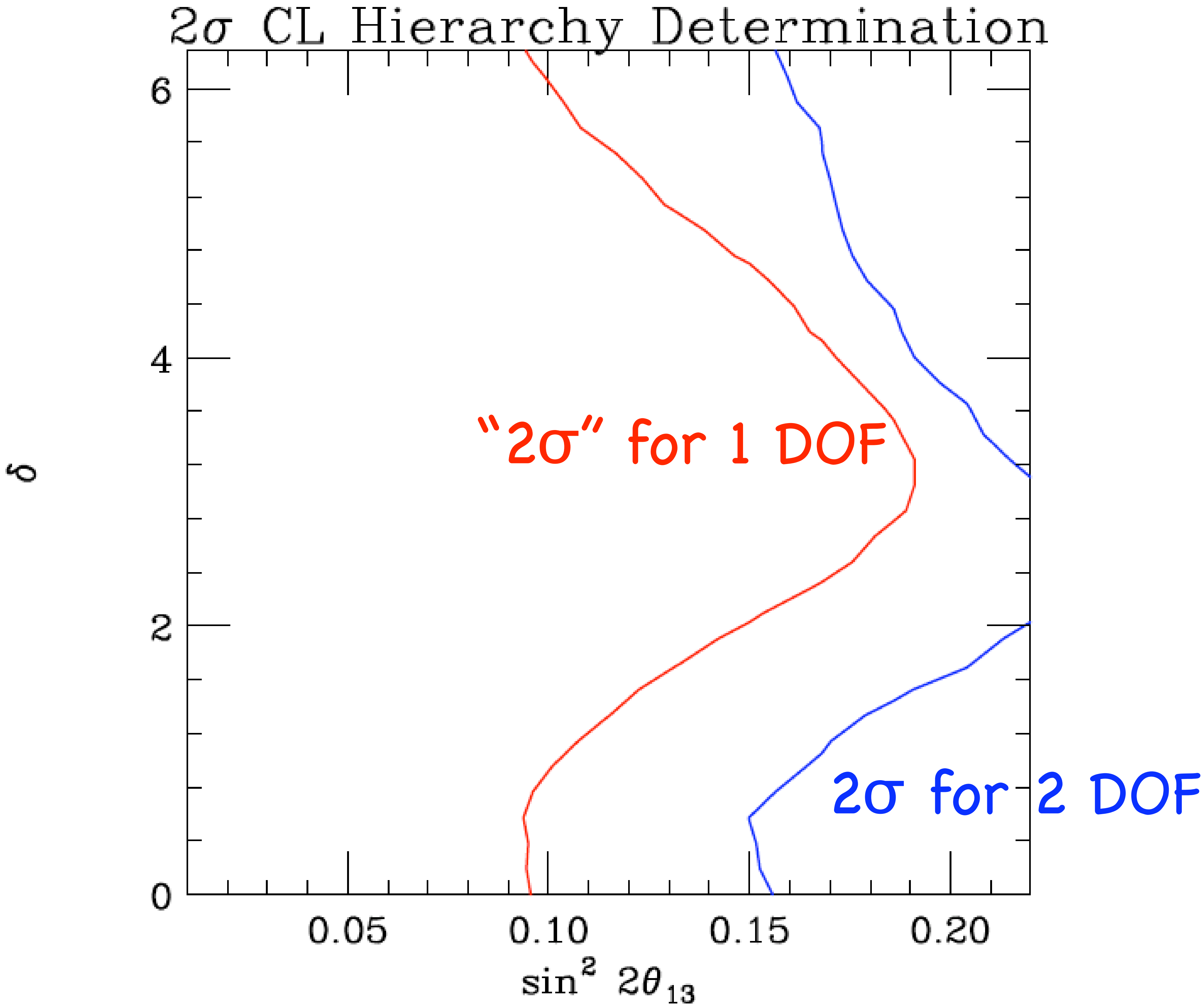


2σ CL Hierarchy Determination


2σ CL Hierarchy Determination
6
4
2
0
δ
0.05
0.10
0.15
0.20
$\sin^2 2\theta_{13}$

“2σ” for 1 DOF

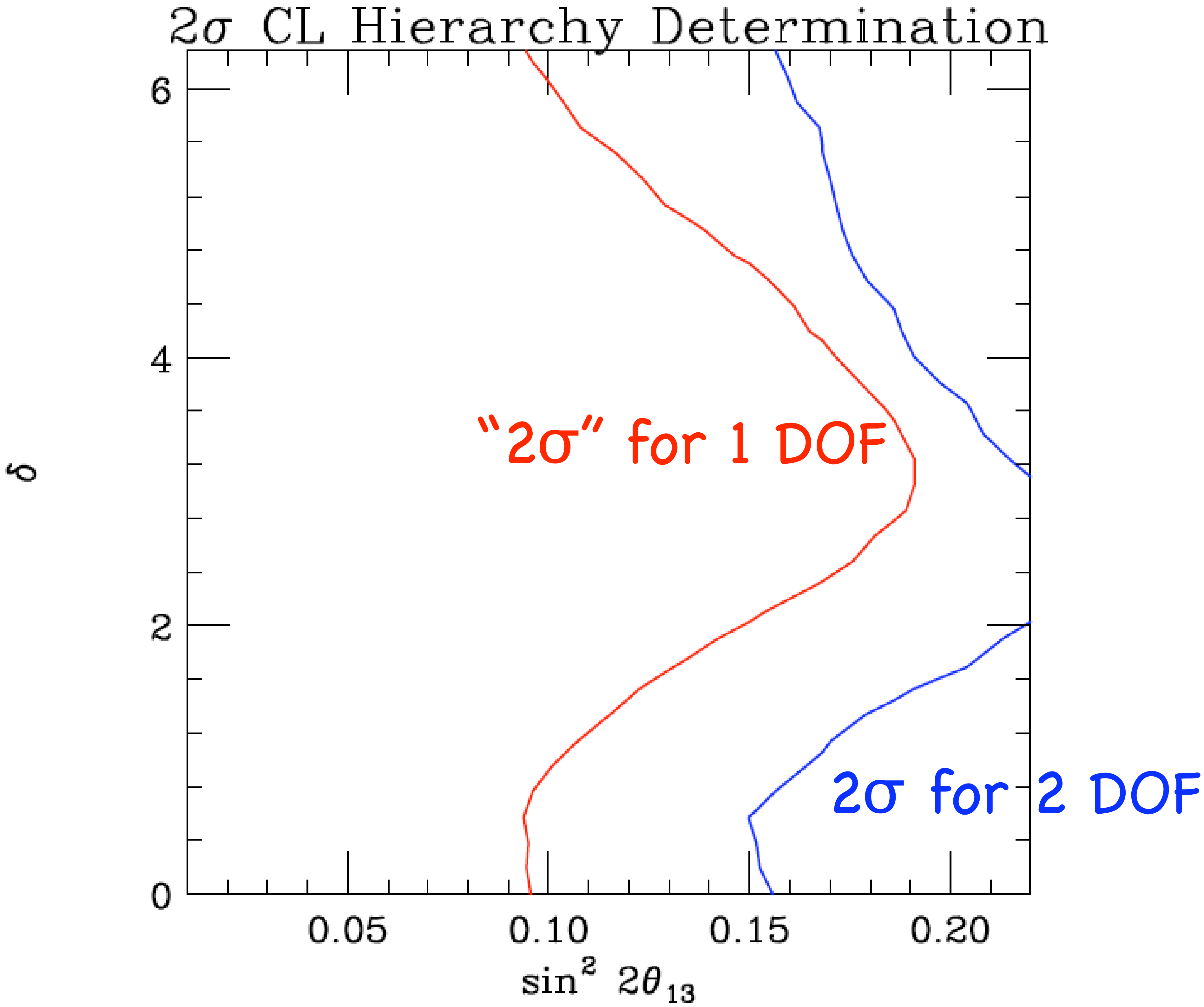


“2σ” for 1 DOF

2σ for 2 DOF

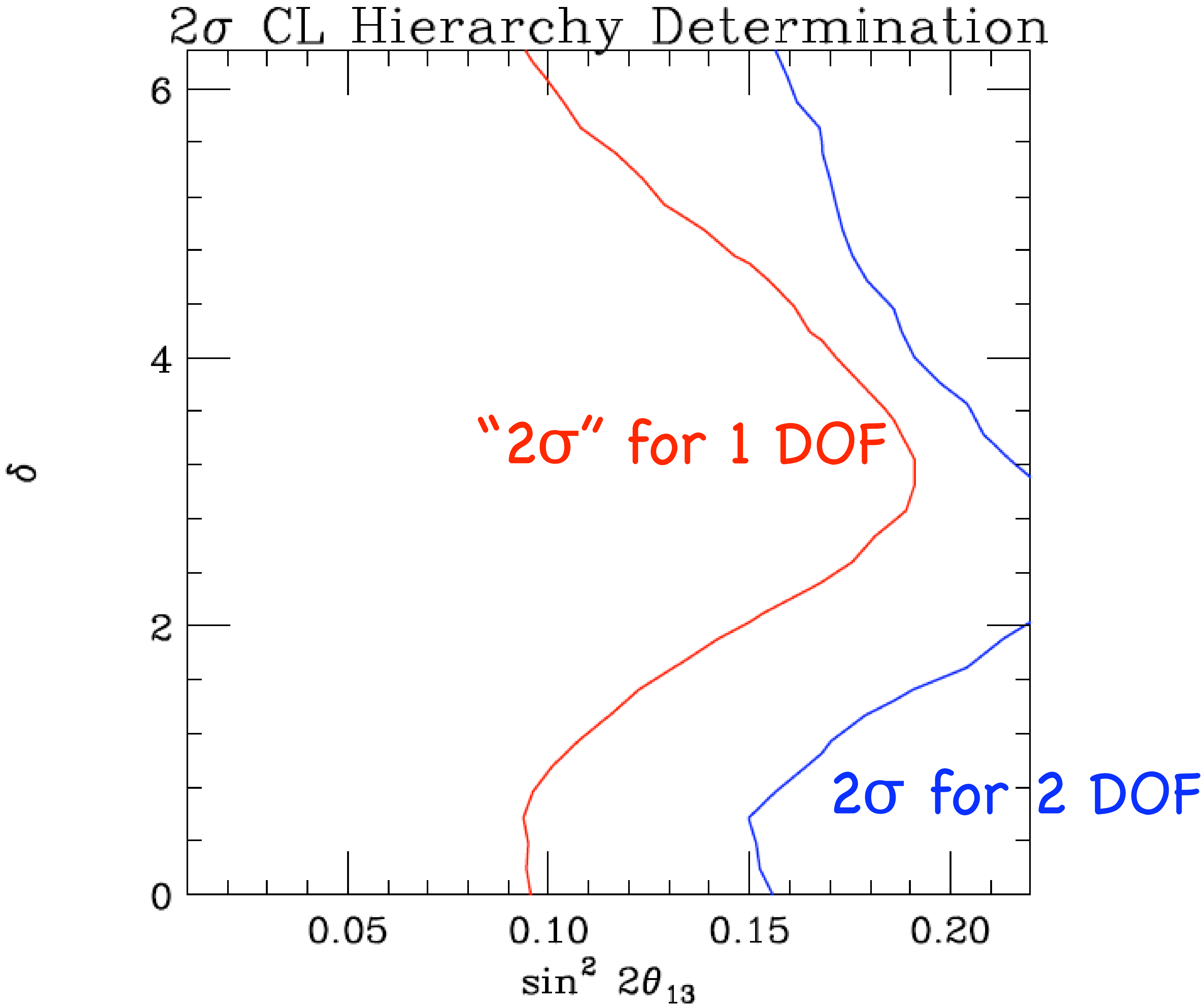
2σ (95.45%) CL for 1 DOF IS LESS THAN 85% CL FOR 2 DOF

By running a Monte Carlo technique for each parameter space point, generating 10 random experiments, one can see that the results do NOT FOLLOW the 1 DOF ASSUMED STATISTICS

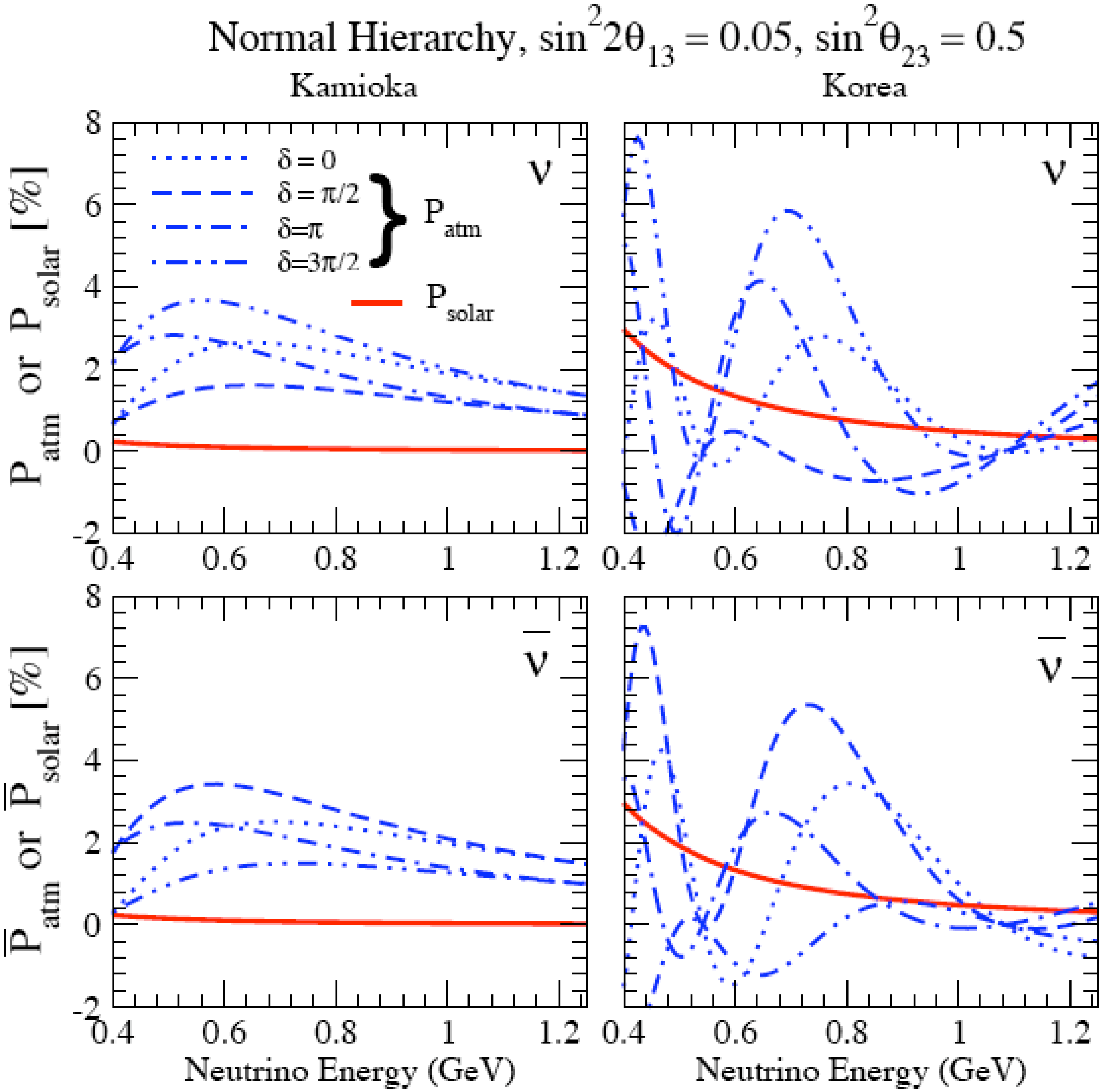

2σ CL Hierarchy Determination

2σ (95.45%) CL for 1 DOF IS LESS THAN 85% CL FOR 2 DOF

By running a Monte Carlo technique for each parameter space point, generating 10^6 random experiments, one can see that the results do NOT FOLLOW the 1 DOF ASSUMED STATISTICS



By making use of the **solar term** and its different relative size and oscillation patterns for Kamioka and Korea baselines (due, obviously to the longer Korea baseline):

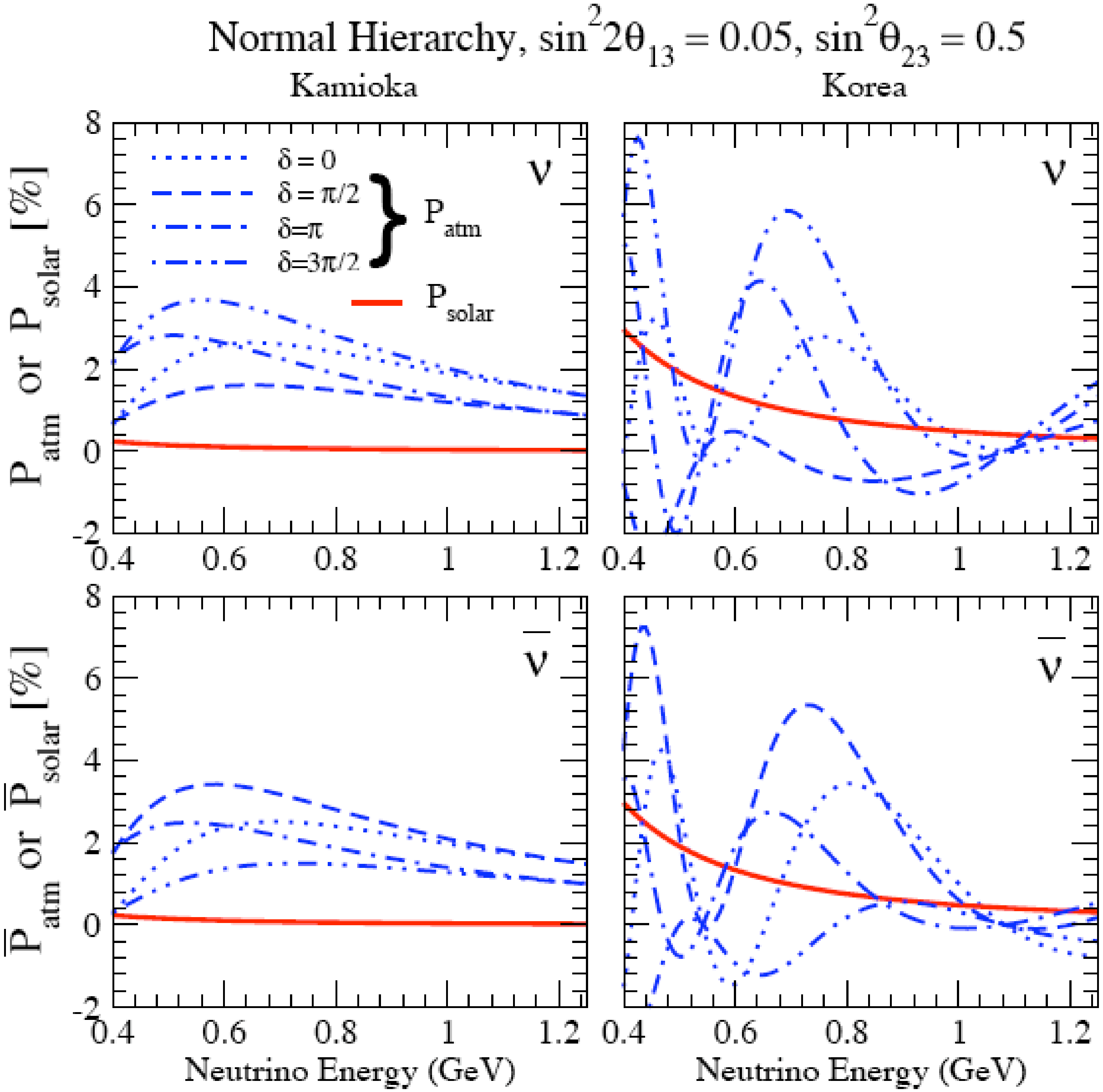


T. Kajita, H. Minakata, S. Nakayama and H. Nunokawa, hep-ph/0609286

``Resolving Eight-Fold neutrino parameter degeneracy by two identical detectors with different baselines,"

By making use of the **solar term** and its different relative size and oscillation patterns for Kamioka and Korea baselines (due, obviously to the longer Korea baseline):

$$+c_{23}^2 \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{12}^2 L}{4E}$$



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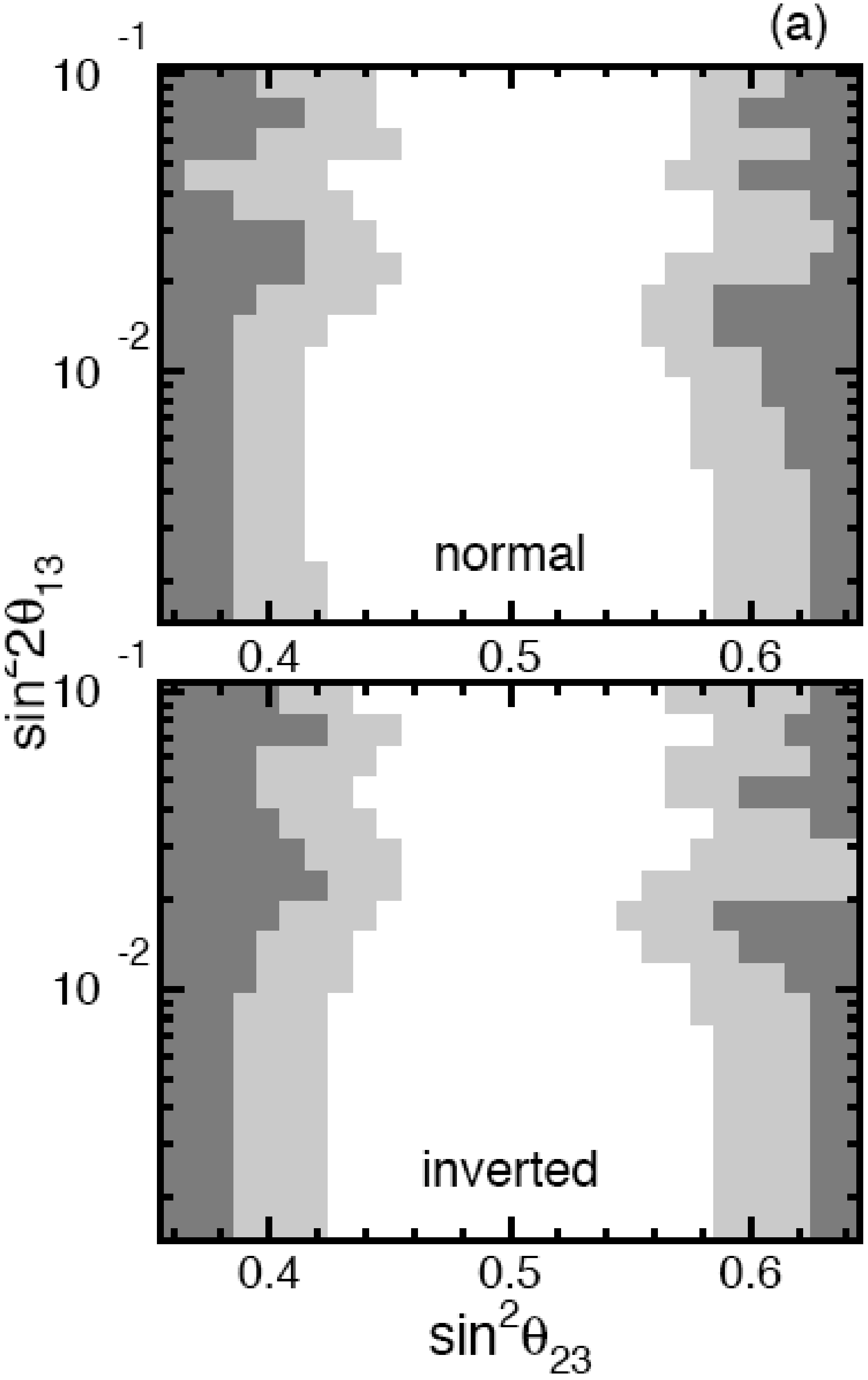
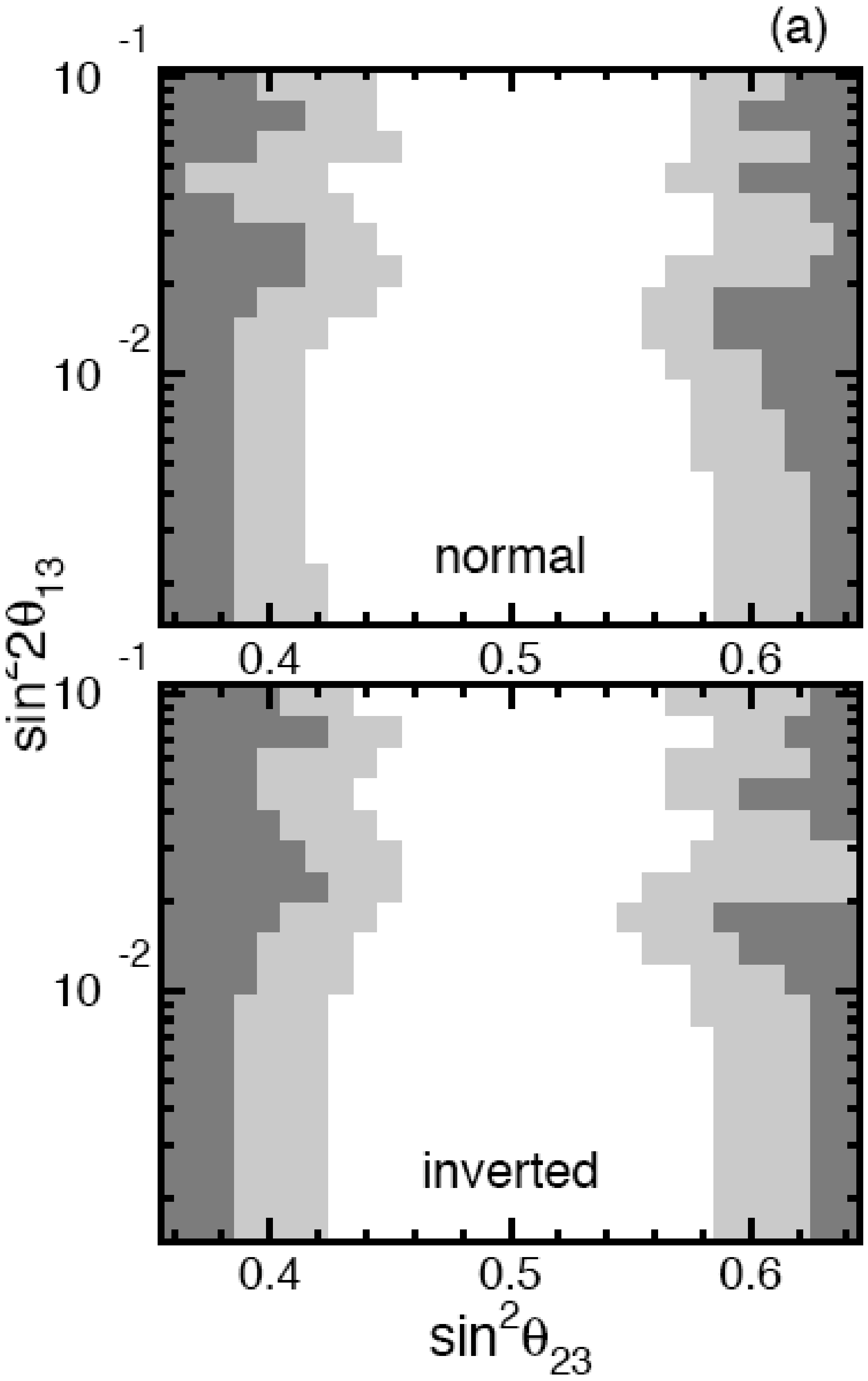


T. Kajita, H. Minakata, S. Nakayama and H. Nunokawa, hep-ph/0609286

``Resolving Eight-Fold neutrino parameter degeneracy by two identical detectors with different baselines,"

By making use of the **solar term** and its different relative size and oscillation patterns for Kamioka and Korea baselines:

“2σ, 3σ”
for the resolution
of the
octant degeneracy



T. Kajita, H. Minakata, S. Nakayama and H. Nunokawa, hep-ph/0609286

``Resolving Eight-Fold neutrino parameter degeneracy by two identical detectors with different baselines,''

Why NOT off-axis adding a detector?

Where?

A) AROUND SECOND PEAK, @ DIFFERENT L/E?

CP Violating and matter effects are very different

B) AT THE SAME E/L, @ DIFFERENT L?

Matter effects are very different

Needs only neutrino running

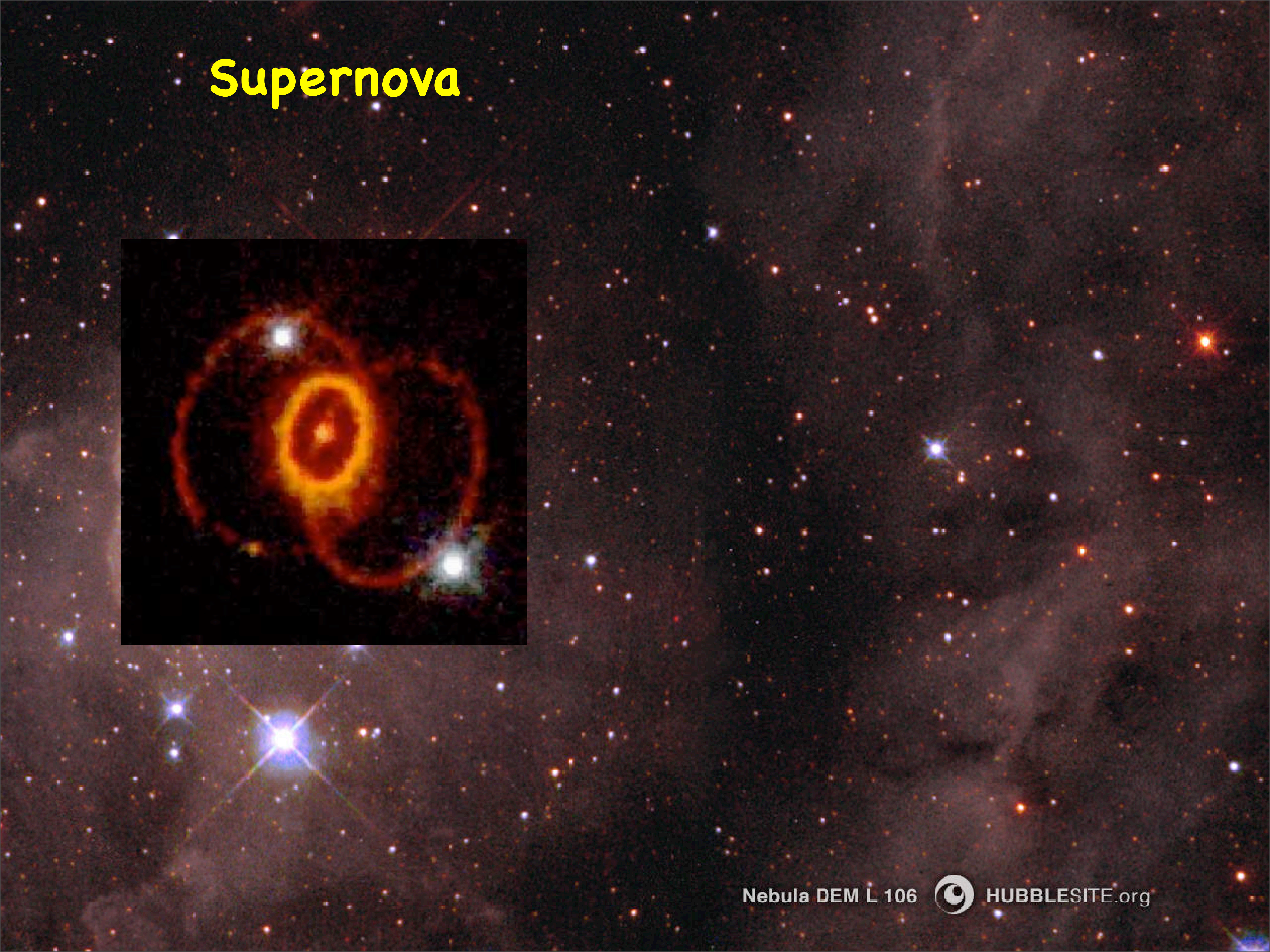
Only valid (although optimal, degeneracy free!) for the hierarchy extraction (though!)

SuperNOvA

Nebula DEM L 106

HUBBLESITE.org

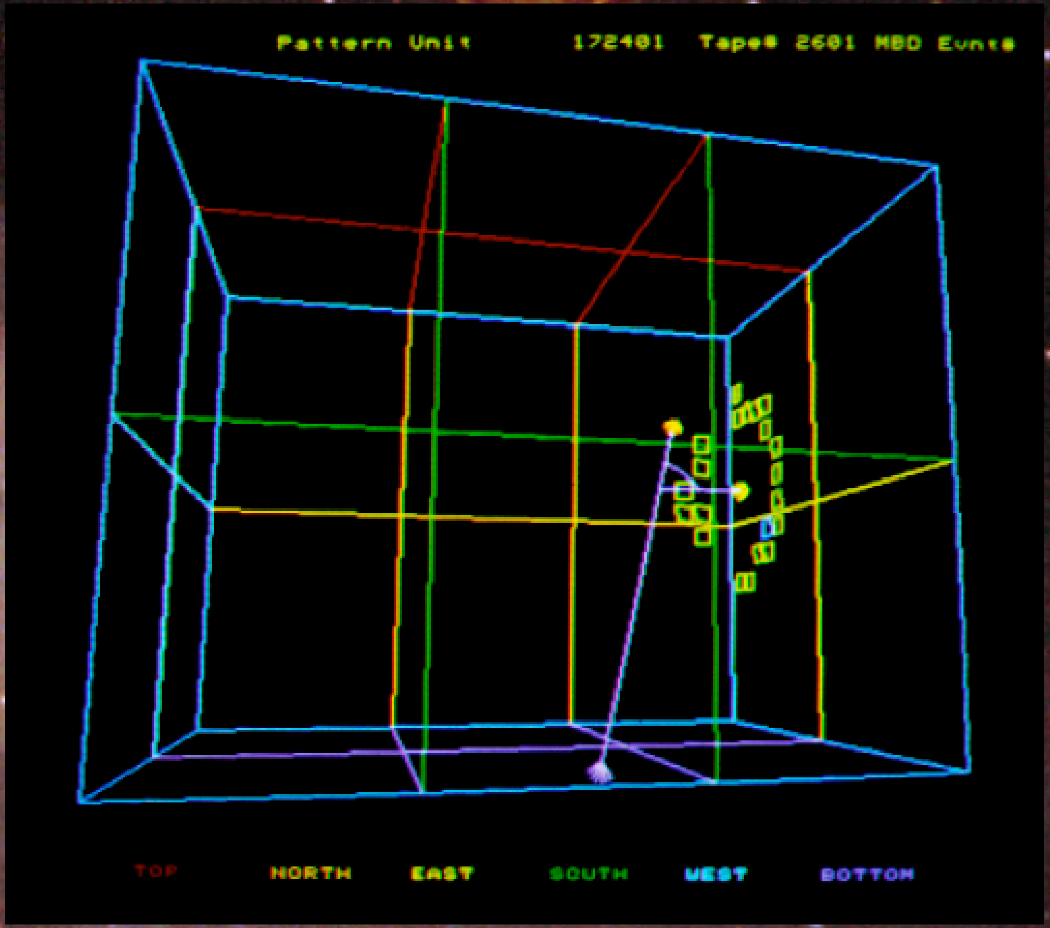
Supernova



Nebula DEM L 106 HUBBLESITE.org

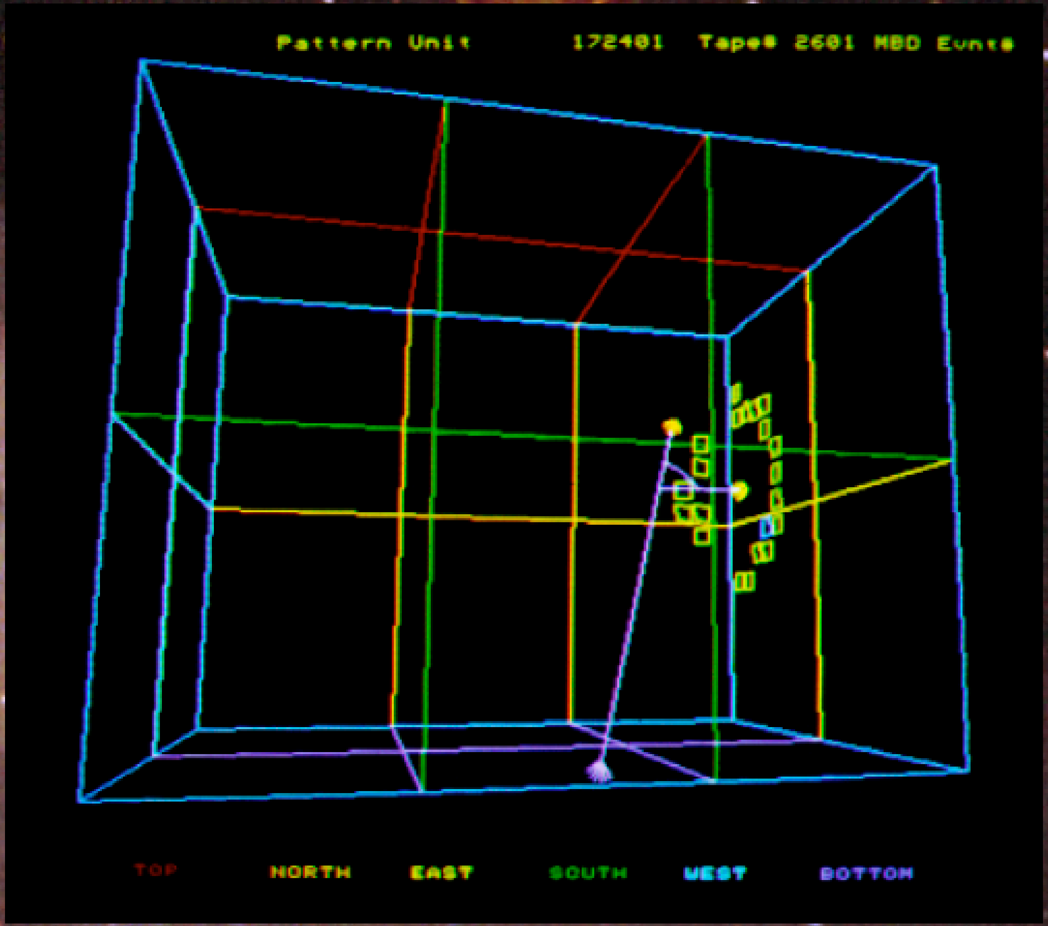
Supernova

neutrino event@IMB



Nebula DEM L 106 HUBBLESITE.org

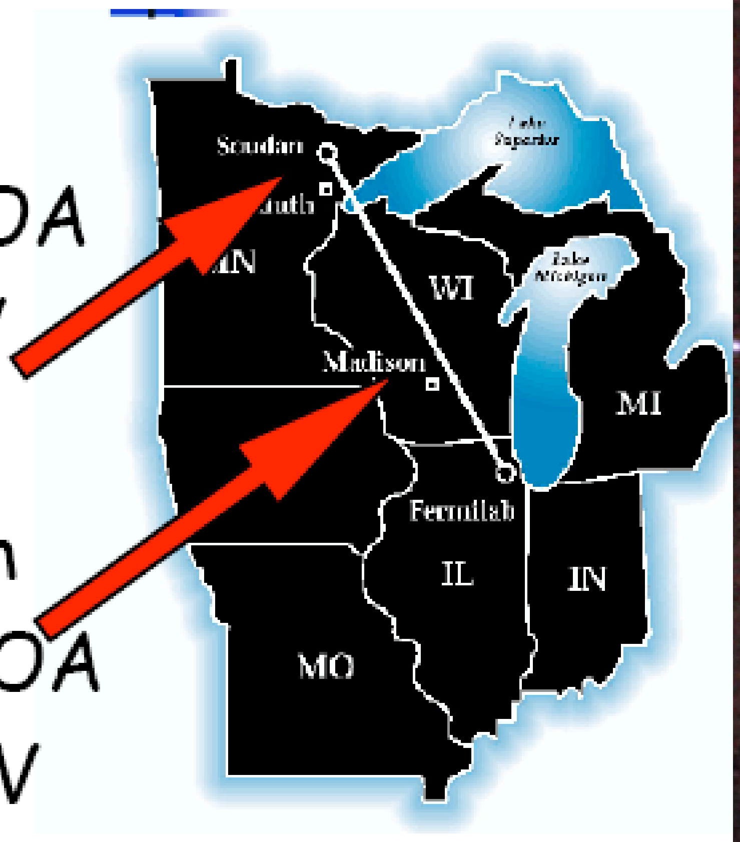
Supernova neutrino event@IMB



SuperNOvA

``A long-baseline neutrino experiment with two off-axis detectors,''

O.M, S.Palomares-Ruiz and S.Pascoli, PRD (2005).



810km
@ 10 km OA
2.3 GeV

200km
@ 8 km OA
0.7 GeV

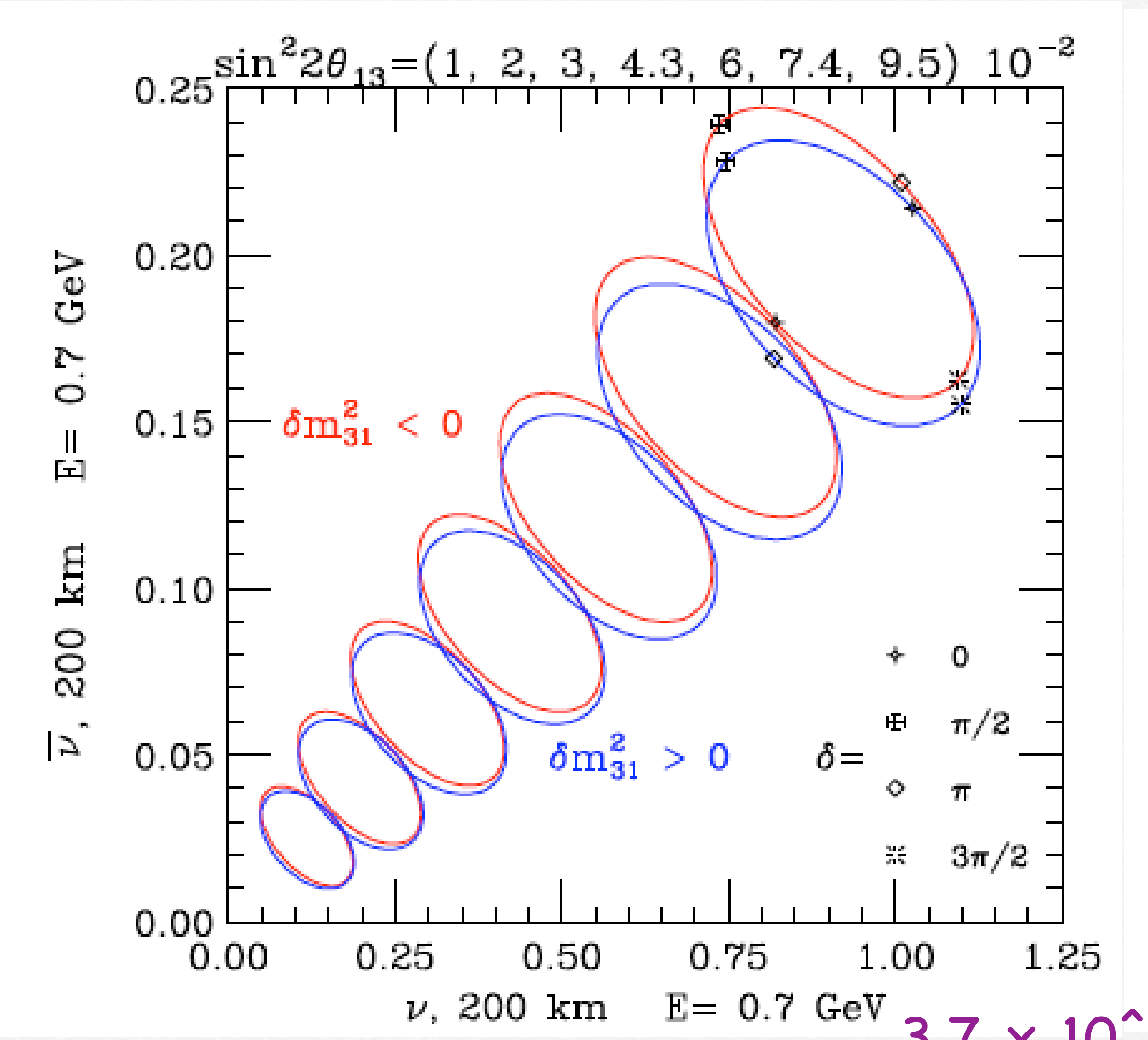
same E/L

H. Minakata, H. Nunokawa and S. Parke, PRD (2003).

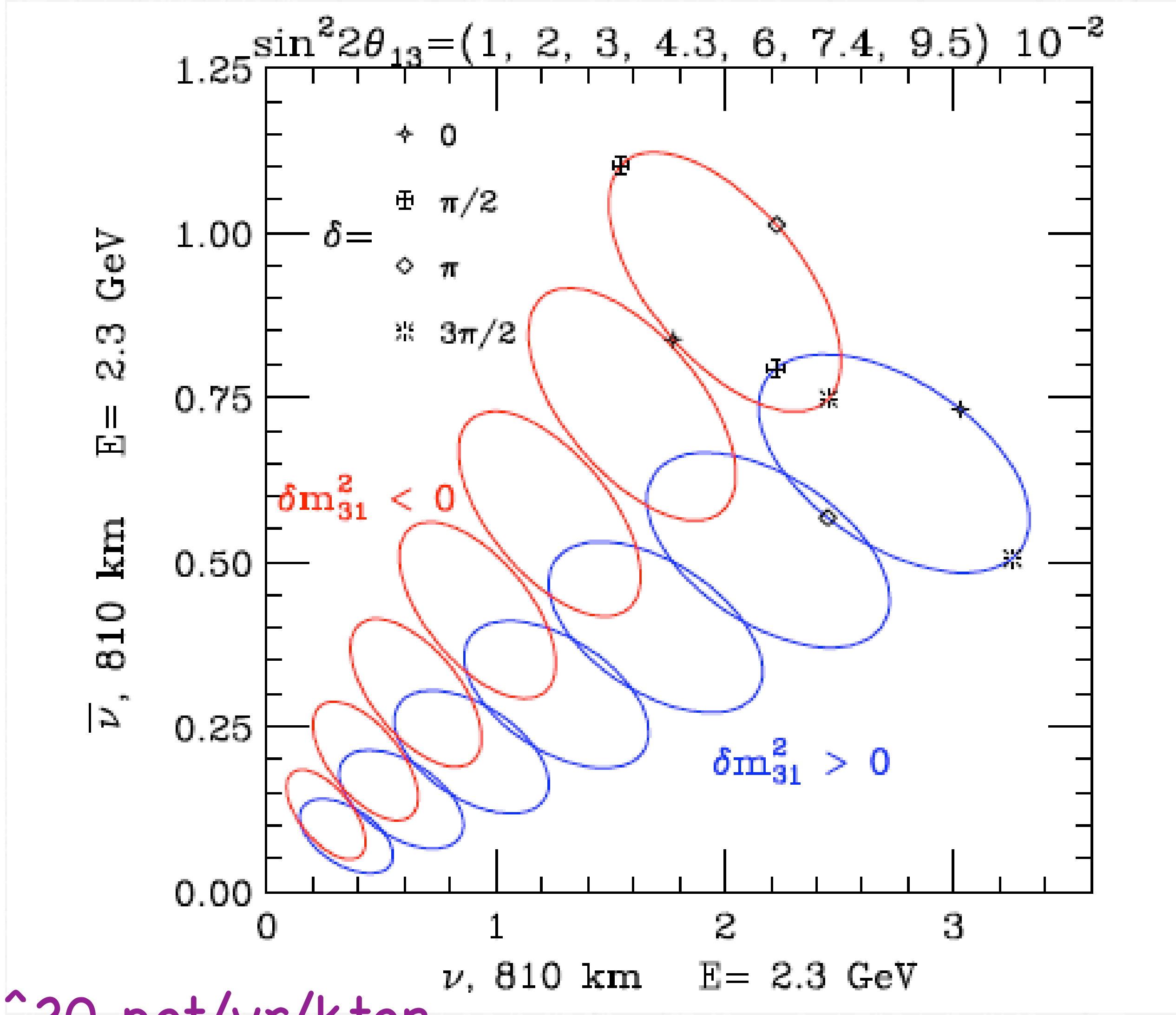
Nebula DEM L 106 HUBBLESITE.org

Neutrino - Antineutrino

NEAR@200 km

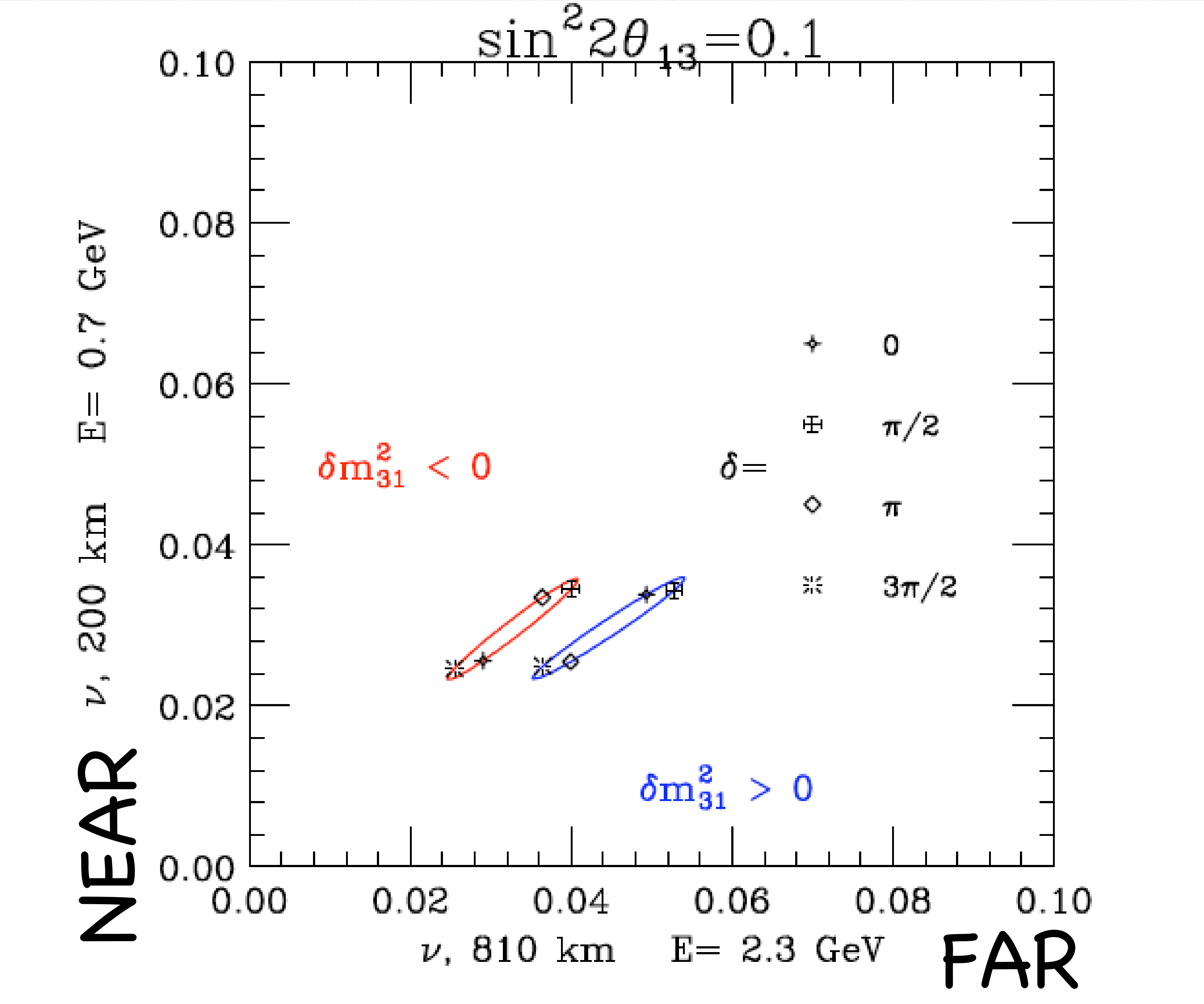


FAR@810 km



3.7 x 10^20 pot/yr/kton

Neutrino - Neutrino



α=slope

Neutrino - Neutrino

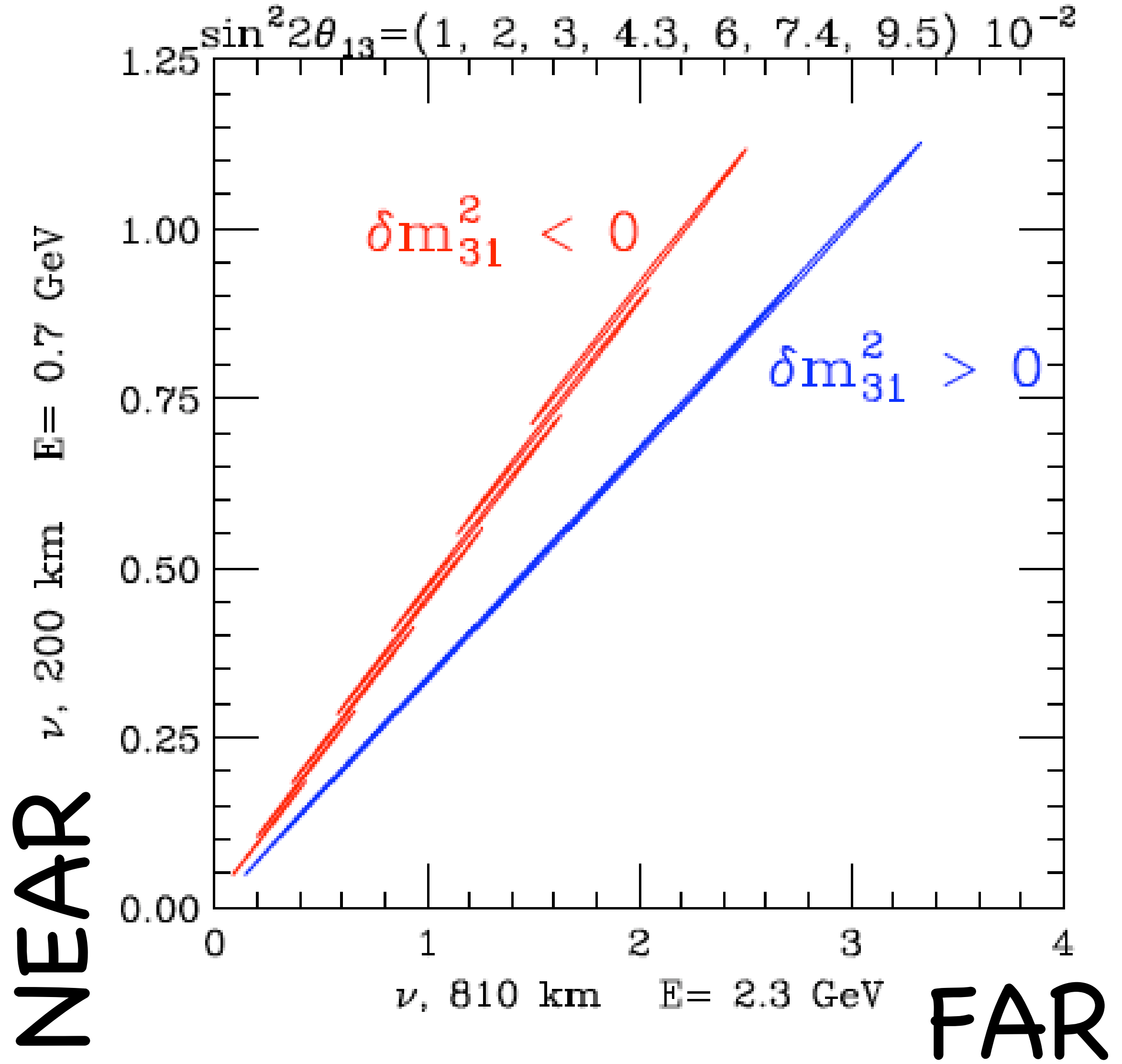
H. Minakata, H. Nunokawa and S. Parke, PRD (2003).

$$\frac{\alpha_+}{\alpha_-} \simeq 1 + 2\,(a_{\rm N} L_{\rm N} - a_{\rm F} L_{\rm F})\left(\frac{1}{\Delta_{13}} - \frac{1}{\tan(\Delta_{13})}\right)$$

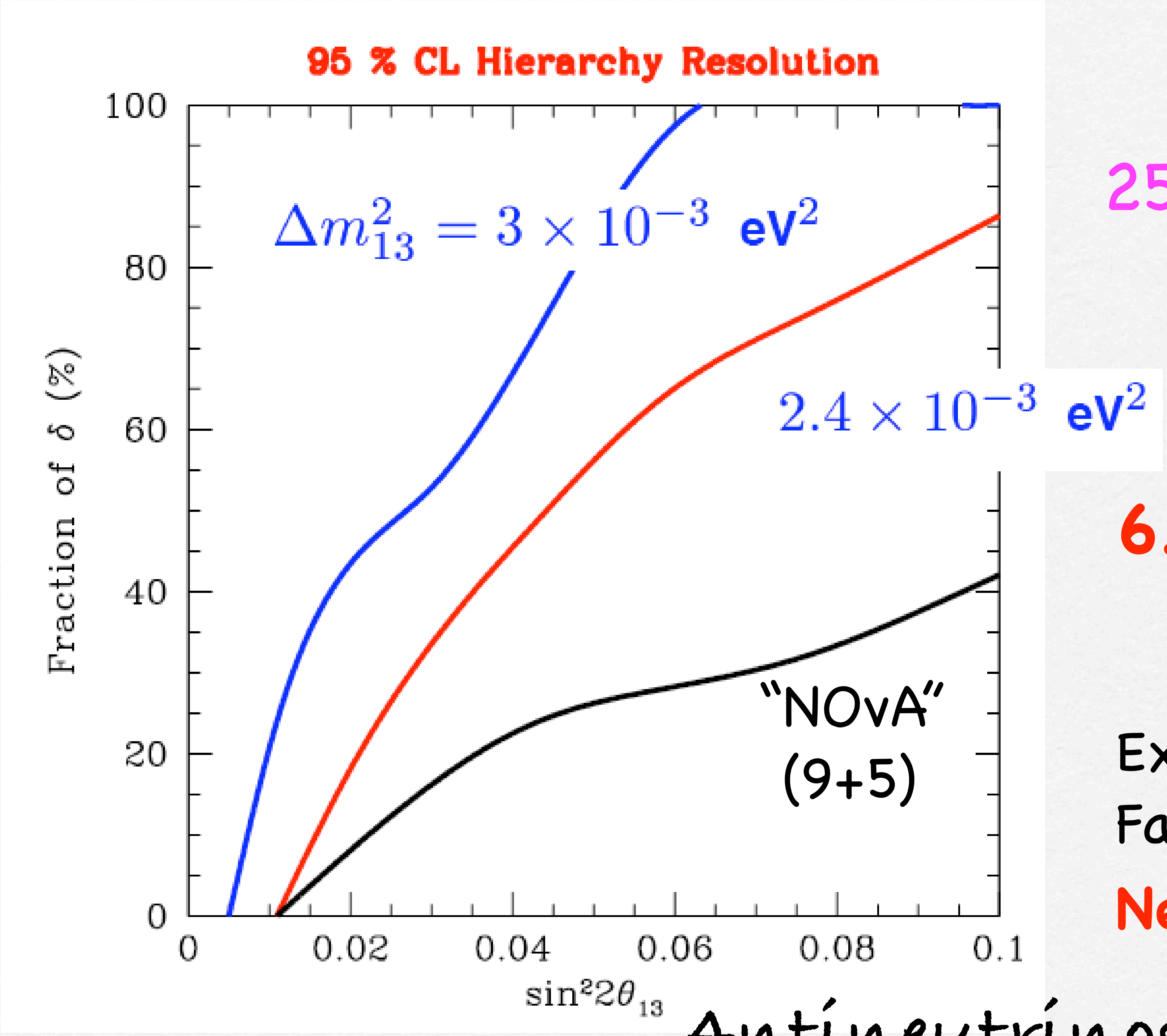
It is important that the matter effects are significantly different for both locations.

Ellipses flattens as the E/L's become identical.

Even if the ratio of the slopes is large, the WIDTH is crucial, the ellipses might overlap:
Keeping E/L constant
KEY to resolve the hierarchy



O.M, S. Palomares-Ruiz and S. Pascoli,
"Determining the neutrino mass hierarchy and CP violation in NOvA with a second off-axis detector", PRD (2006)



NOvA +
25 kton near (200 km)
Water Cherenkov
70% effs

6.5 e20 pot/yr

Exposure (yrs)
Far: 3 nu + 3 nubar
Near + Far: 6 nu+ 2 nubar

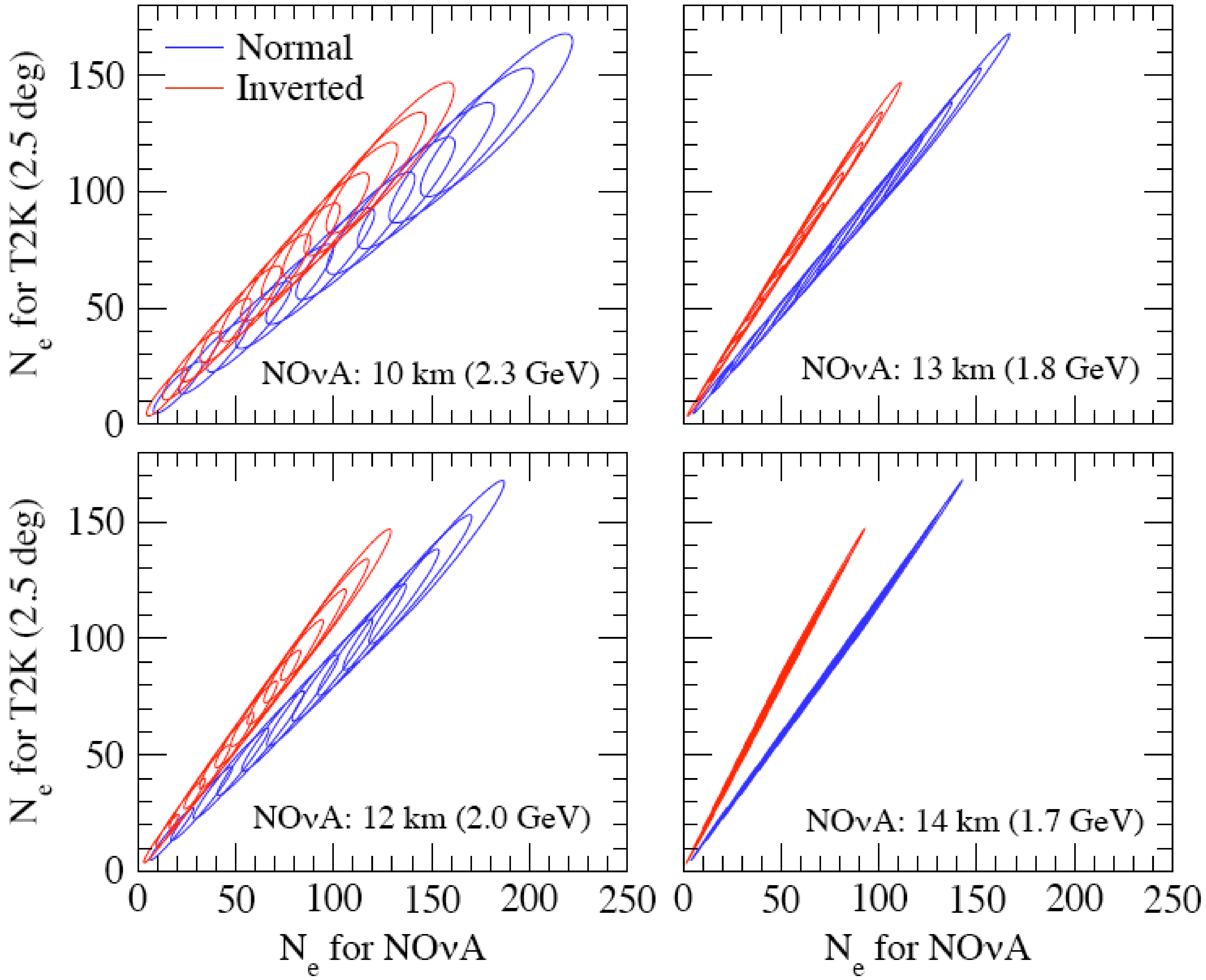
Antineutrinos = irrelevant!


止まれ


ARRÊT


STOP

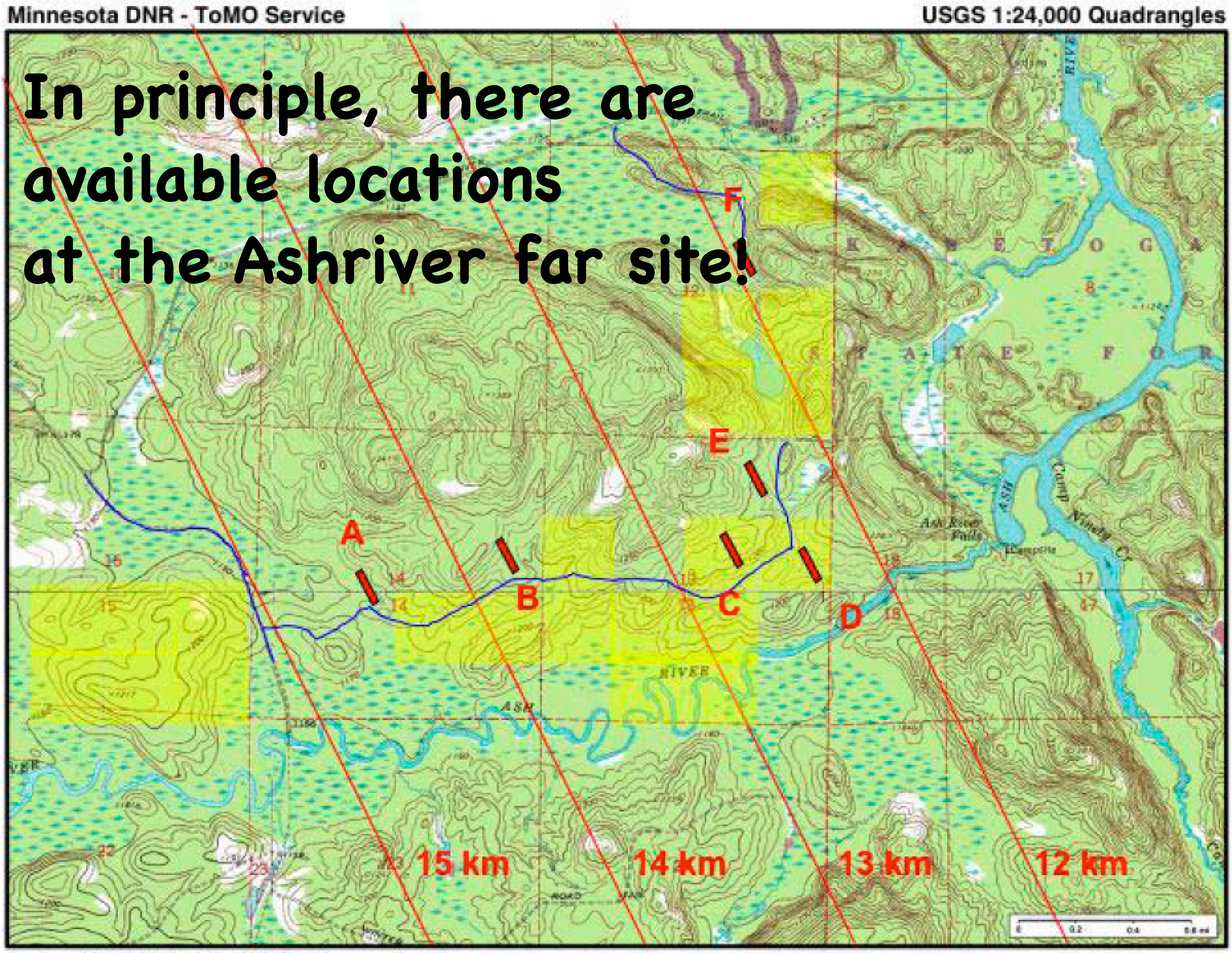
What about combining T2K and NOvA?



NOνA and T2K: The race for the neutrino mass hierarchy

Olga Mena[1], Hiroshi Nunokawa[2] and Stephen Parke[1] hep-ph/0609011

In principle, there are available locations at the Ashriver far site!



What does PHASE I mean?

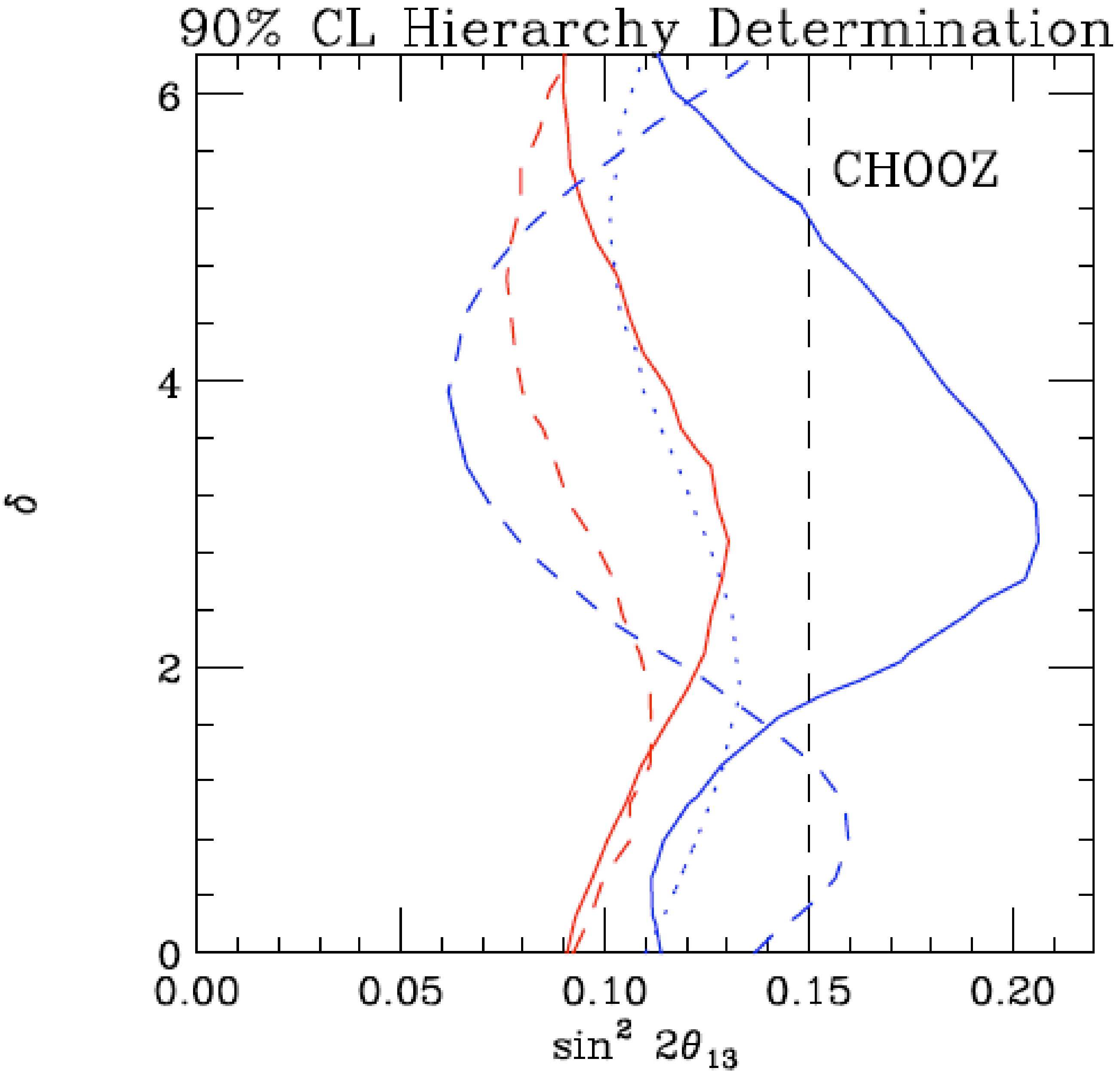
NOvA 30 kton detector 24% eff
0.66 MW 6.5 10^20 POT/yr
5 years of neutrino running

T2K 22.5 kton detector 70% eff
0.75 MW 10^21 POT/yr
5 years of neutrino running

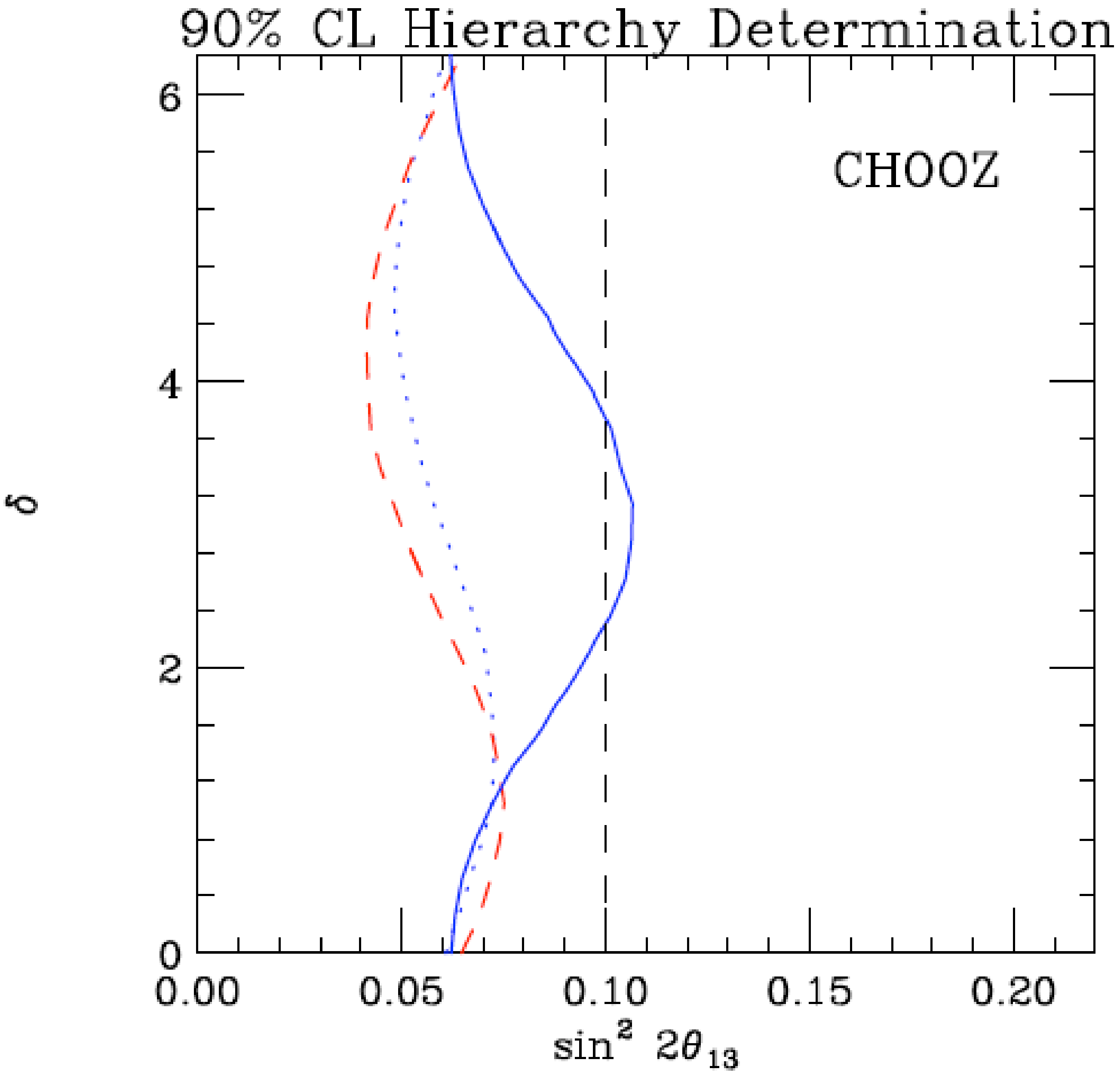
Both experiments have been considered as counting experiments: No binning!

PHASE I (ONLY NEUTRINOS!)

Nature's choice: positive hierarchy



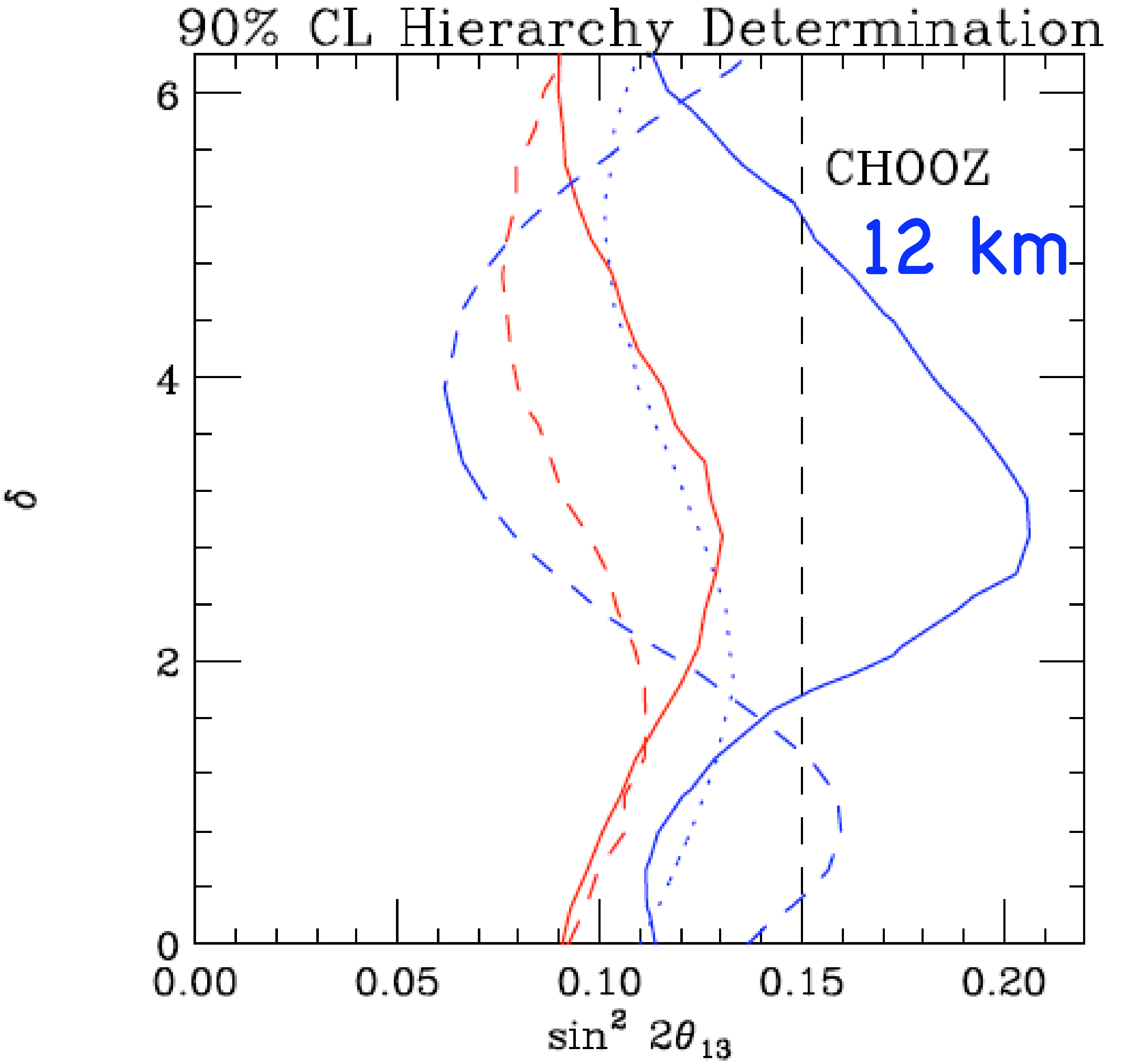
$$\Delta m^2_{13} = 2.4 \times 10^{-3} \text{ eV}^2$$



$$\Delta m^2_{13} = 3 \times 10^{-3} \text{ eV}^2$$

PHASE I (ONLY NEUTRINOS!)

Nature's choice: positive hierarchy



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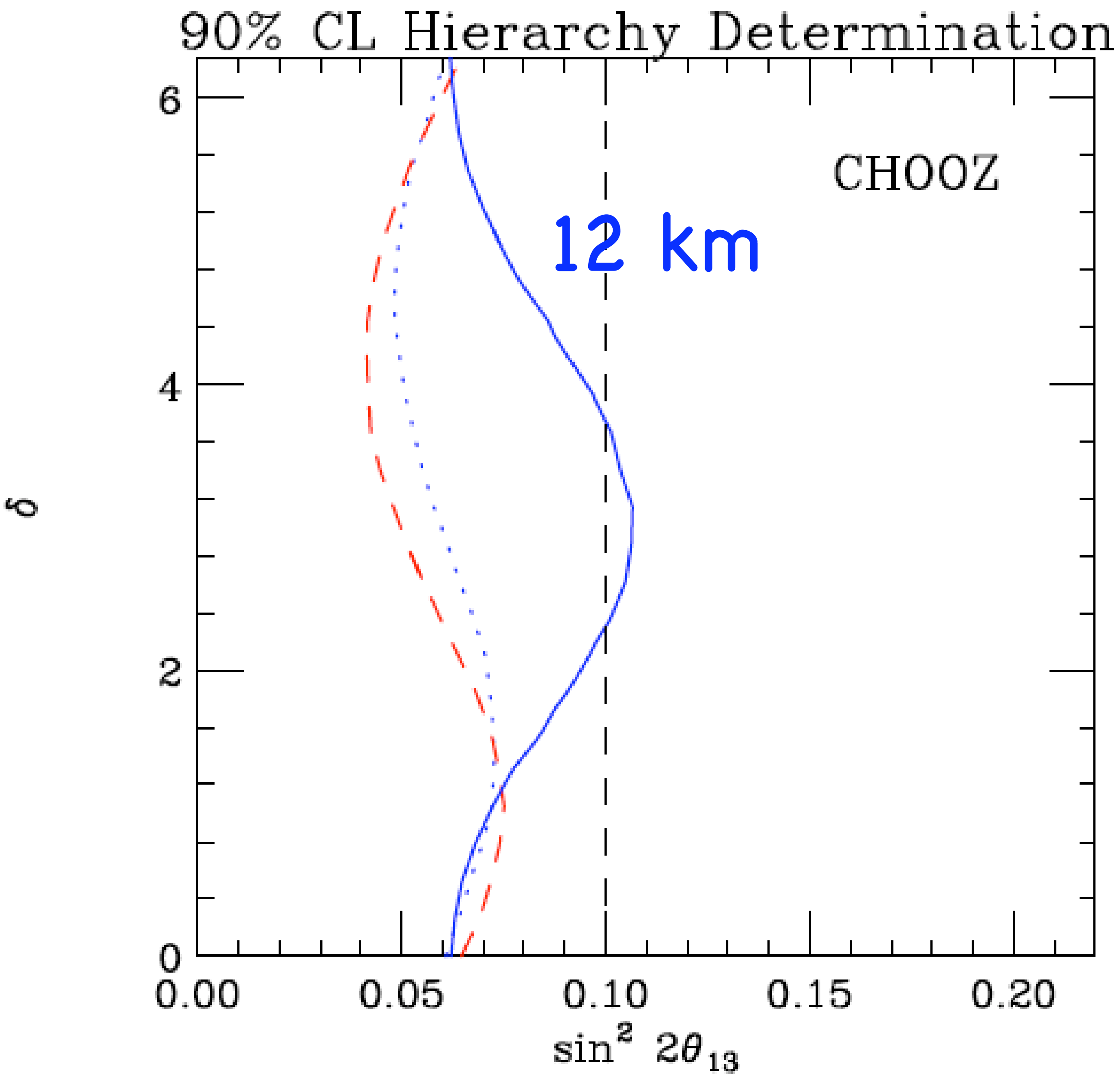

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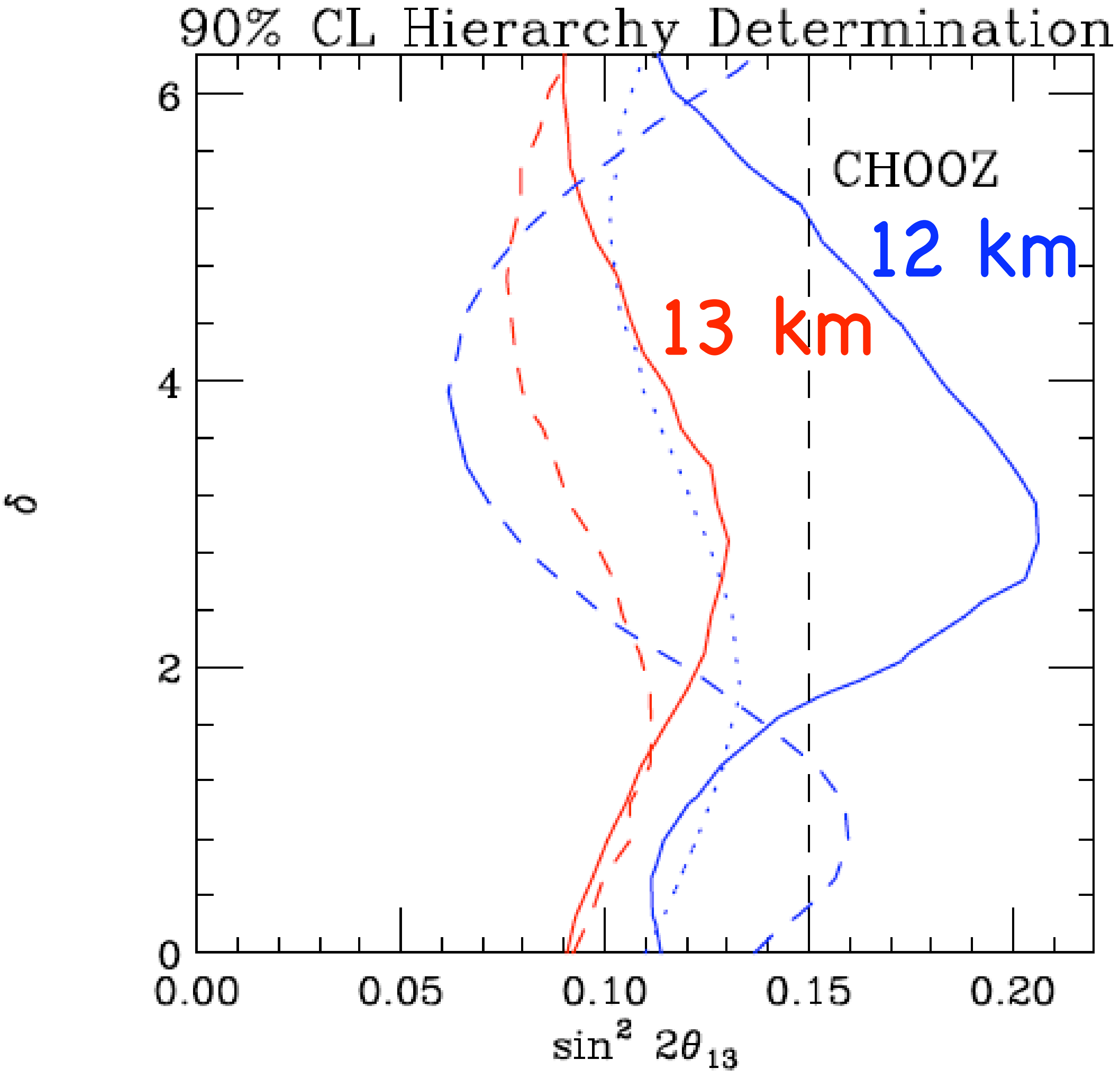

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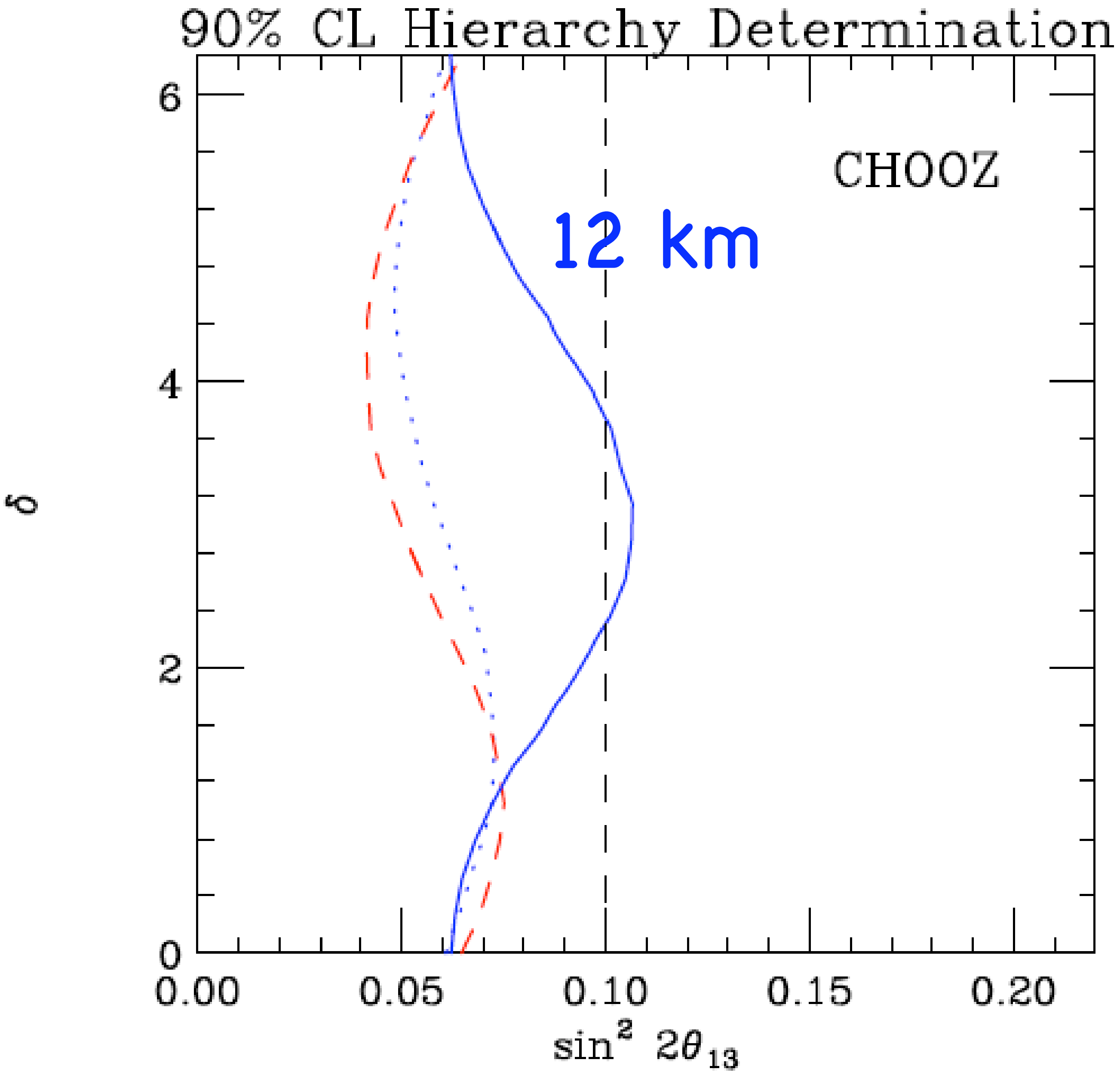

$$\Delta m^2_{13} = 3 \times 10^{-3}\ \text{eV}^2$$

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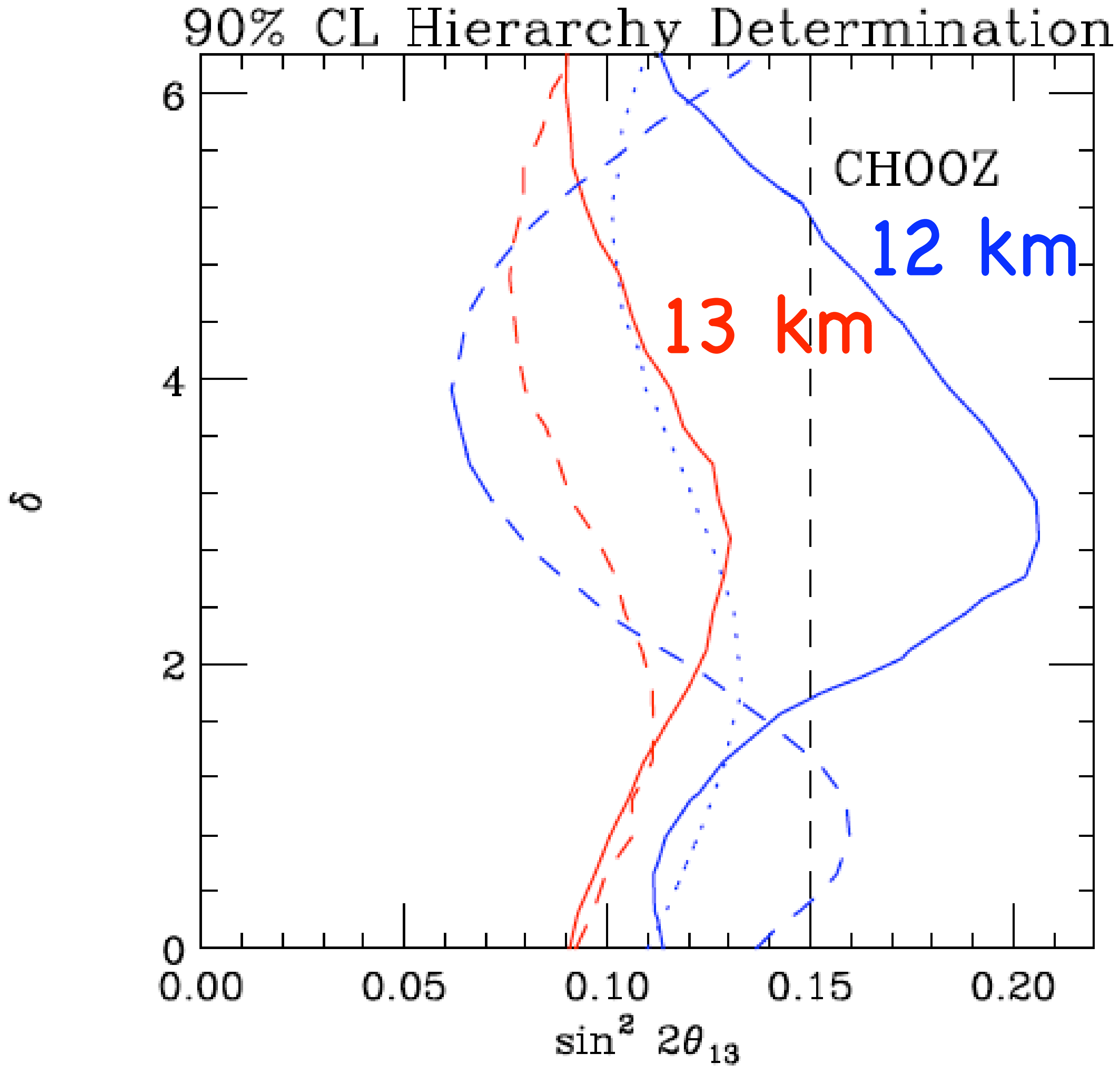

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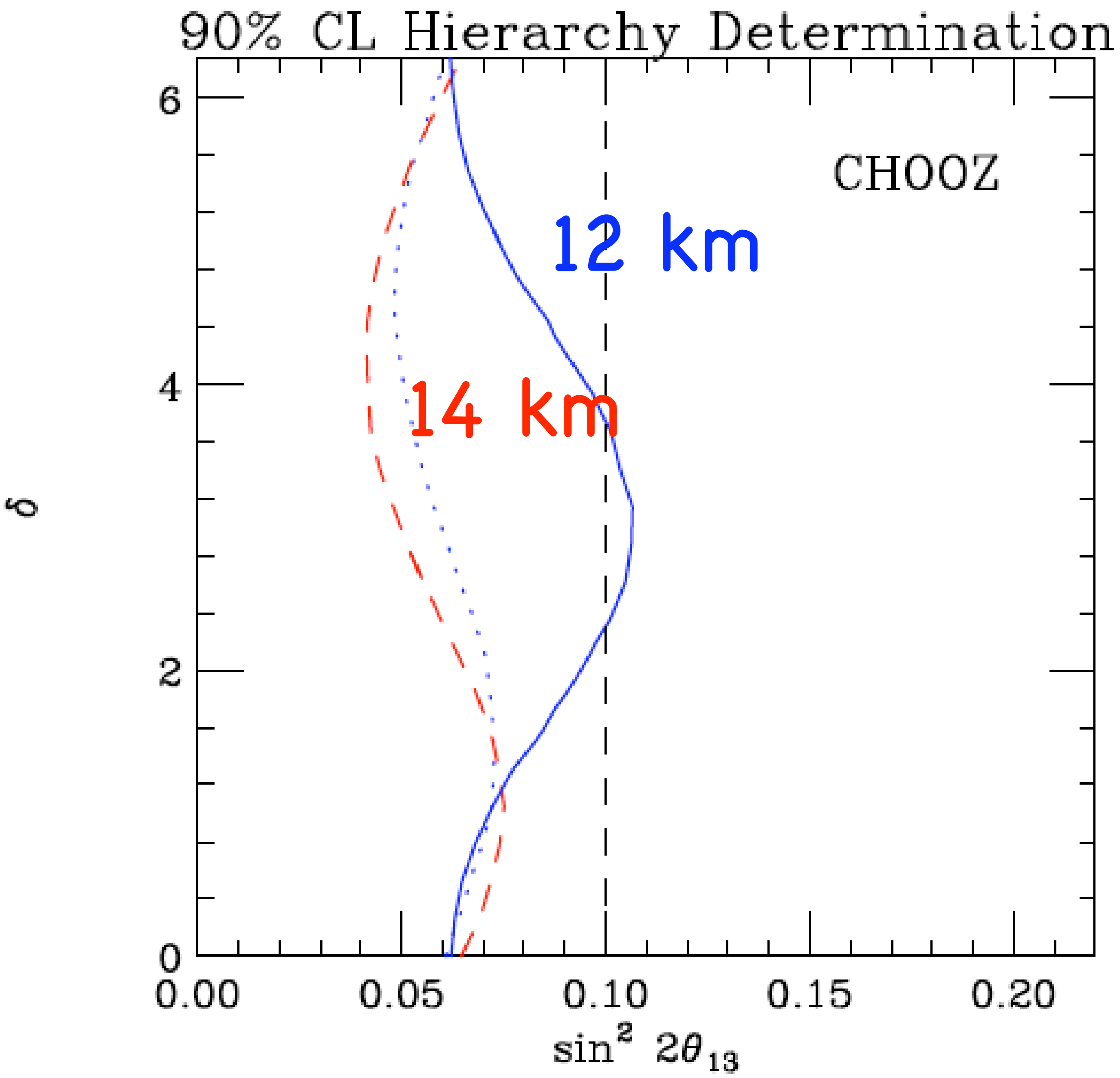

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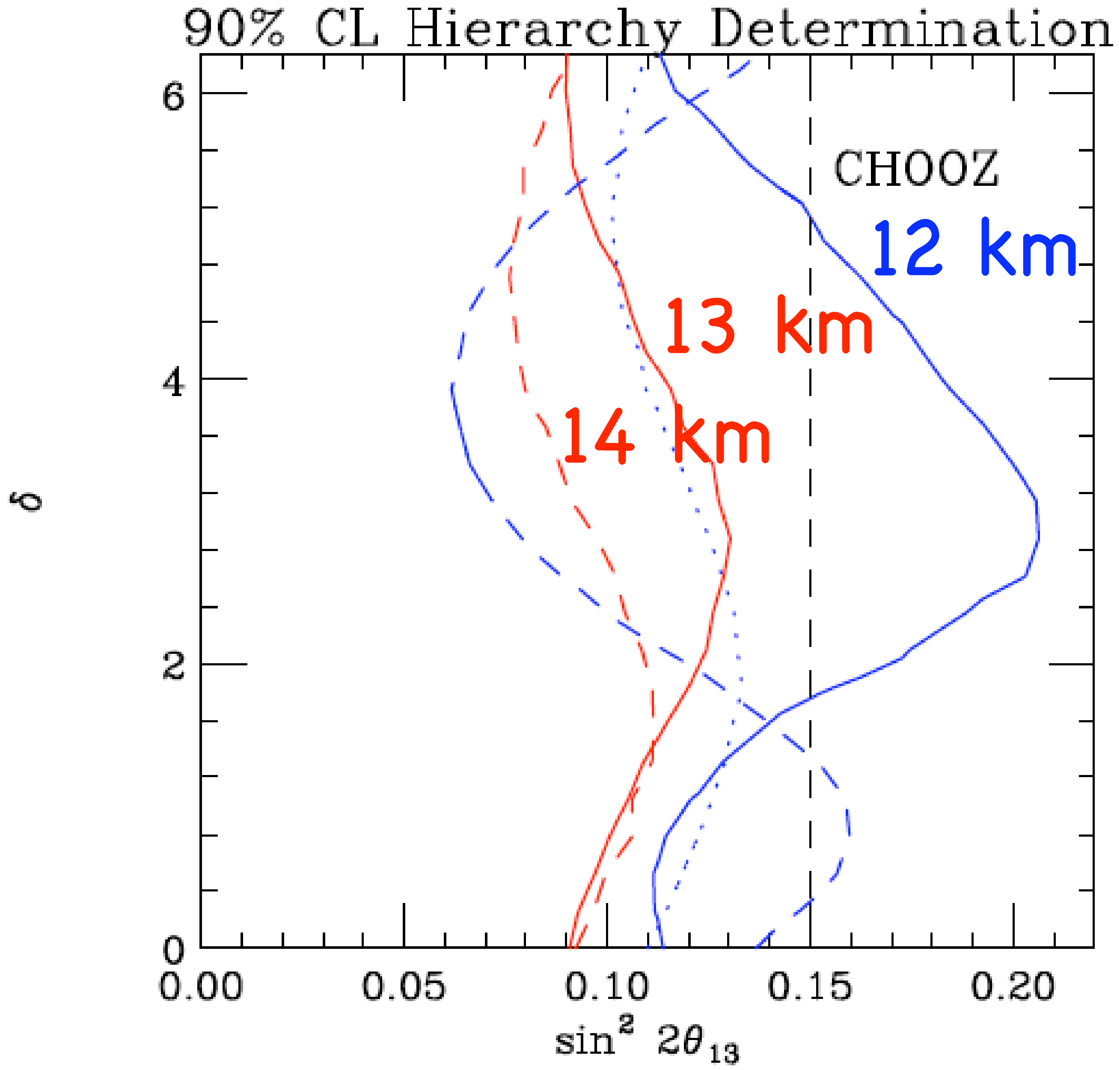
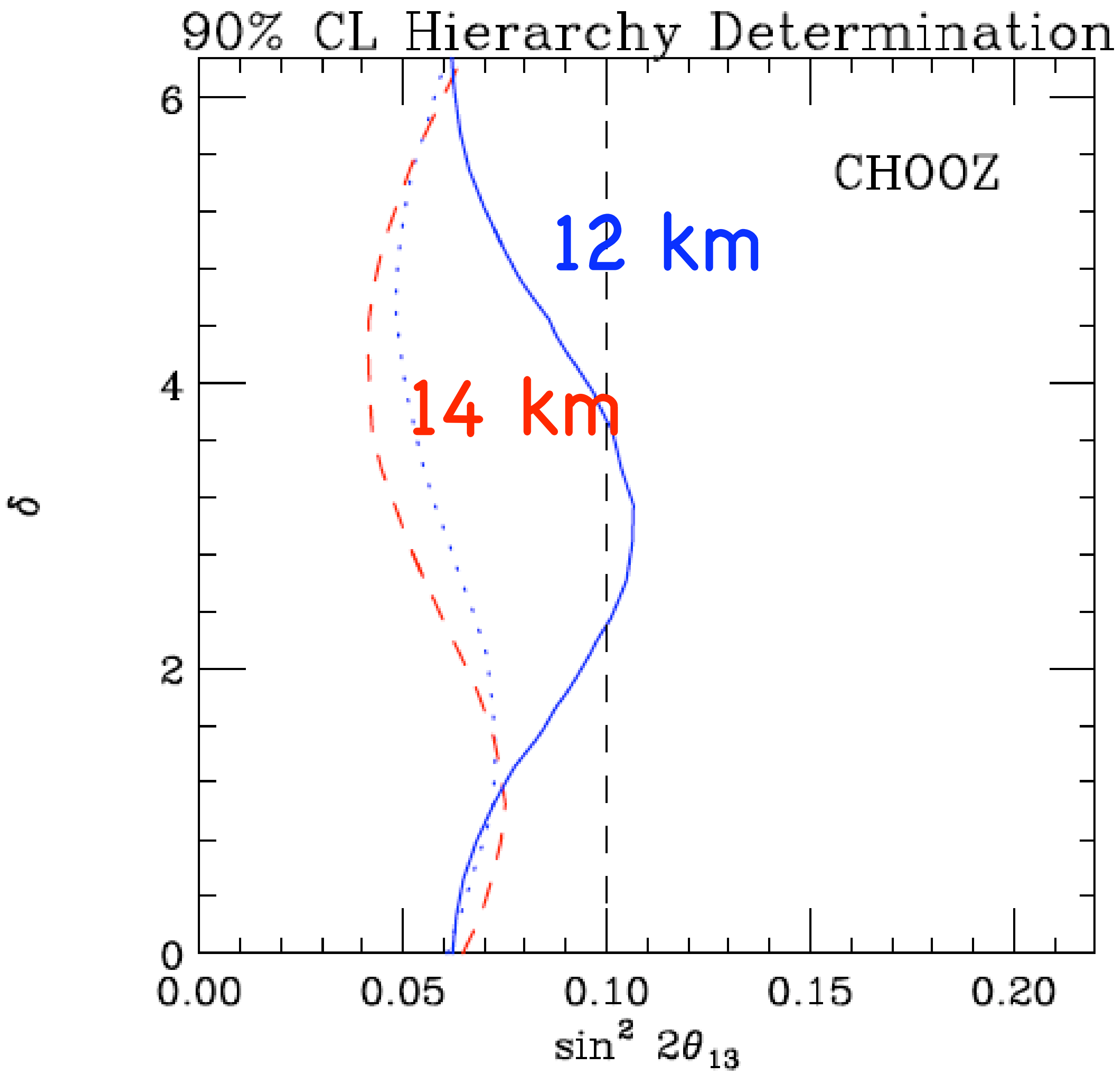
Nature's choice: positive hierarchy



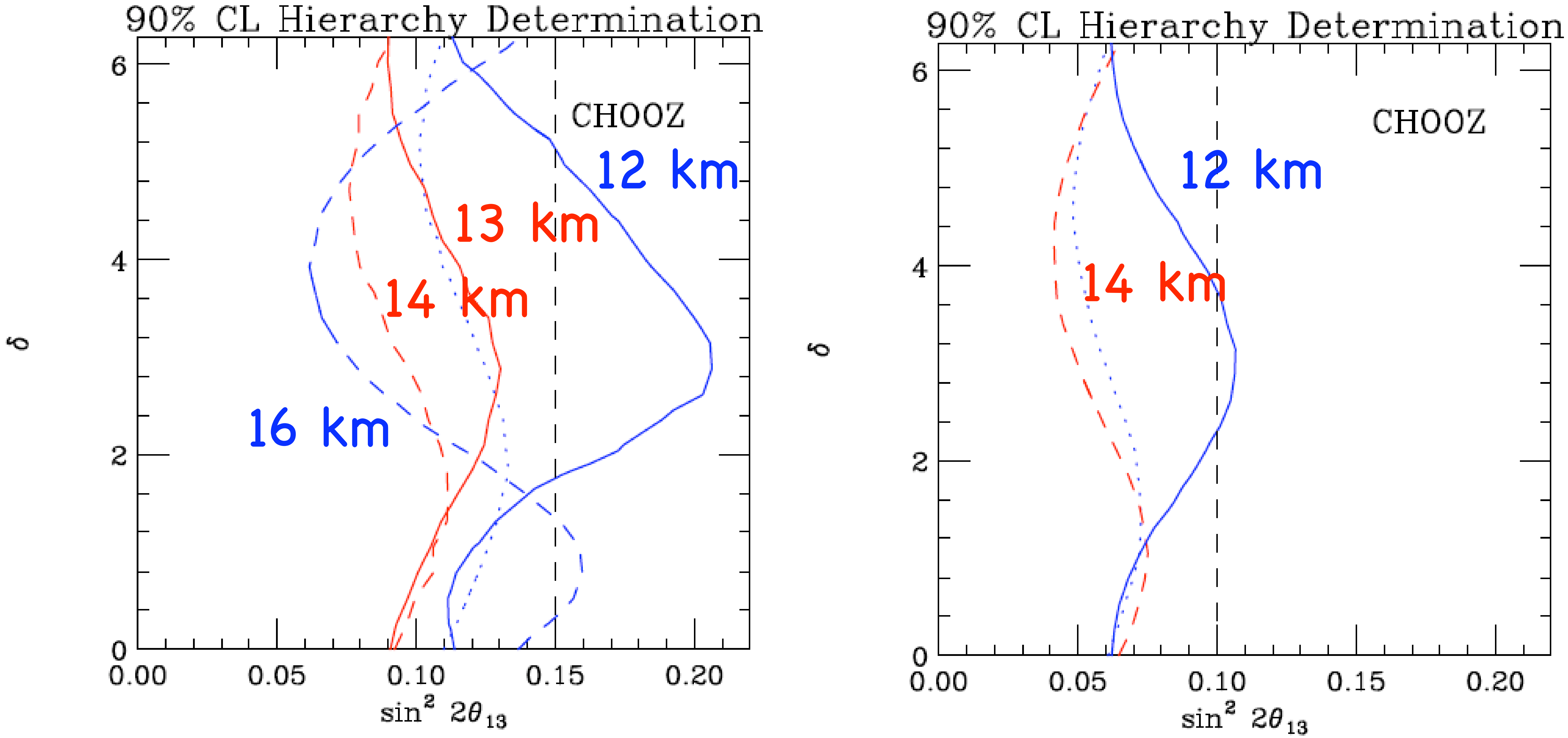
$$\Delta m^2_{13} = 2.4 \times 10^{-3}\ \text{eV}^2$$



$$\Delta m^2_{13} = 3 \times 10^{-3}\ \text{eV}^2$$

PHASE I (ONLY NEUTRINOS!)

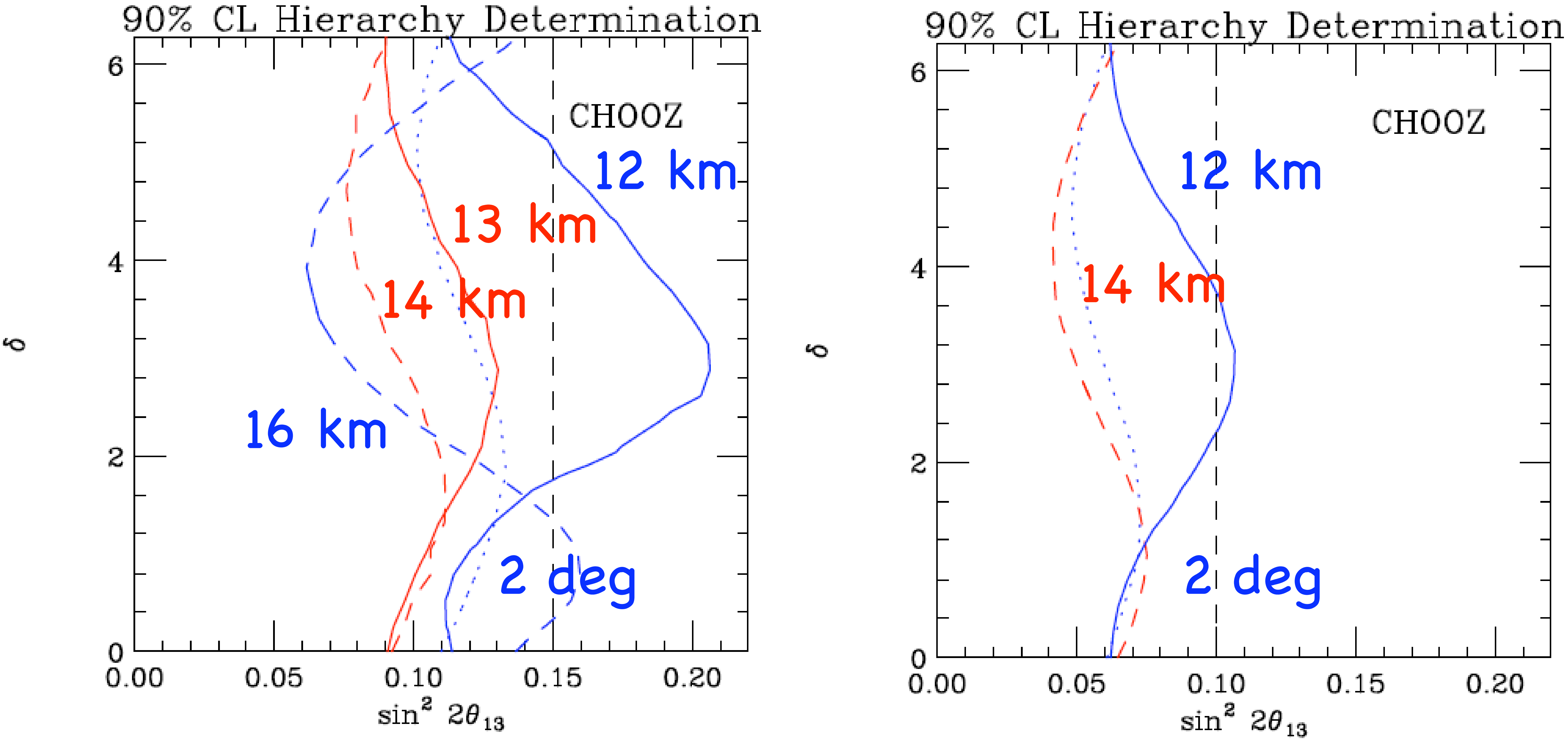
Nature's choice: positive hierarchy



$\Delta m^2_{13} = 2.4 \times 10^{-3}$ eV^2 $\Delta m^2_{13} = 3 \times 10^{-3}$ eV^2

PHASE I (ONLY NEUTRINOS!)

Nature's choice: positive hierarchy

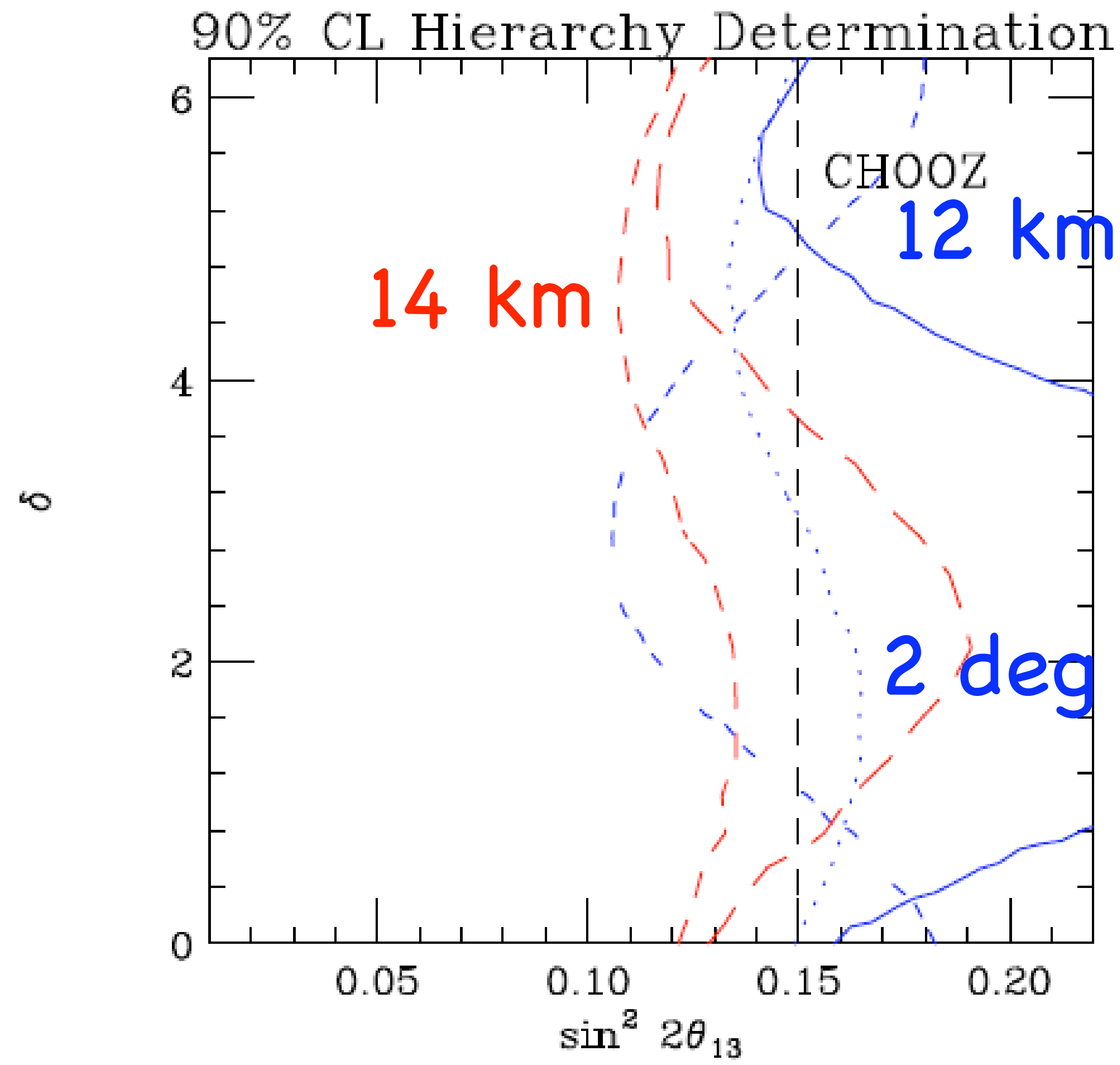


$\Delta m^2_{13} = 2.4 \times 10^{-3}$ eV^2

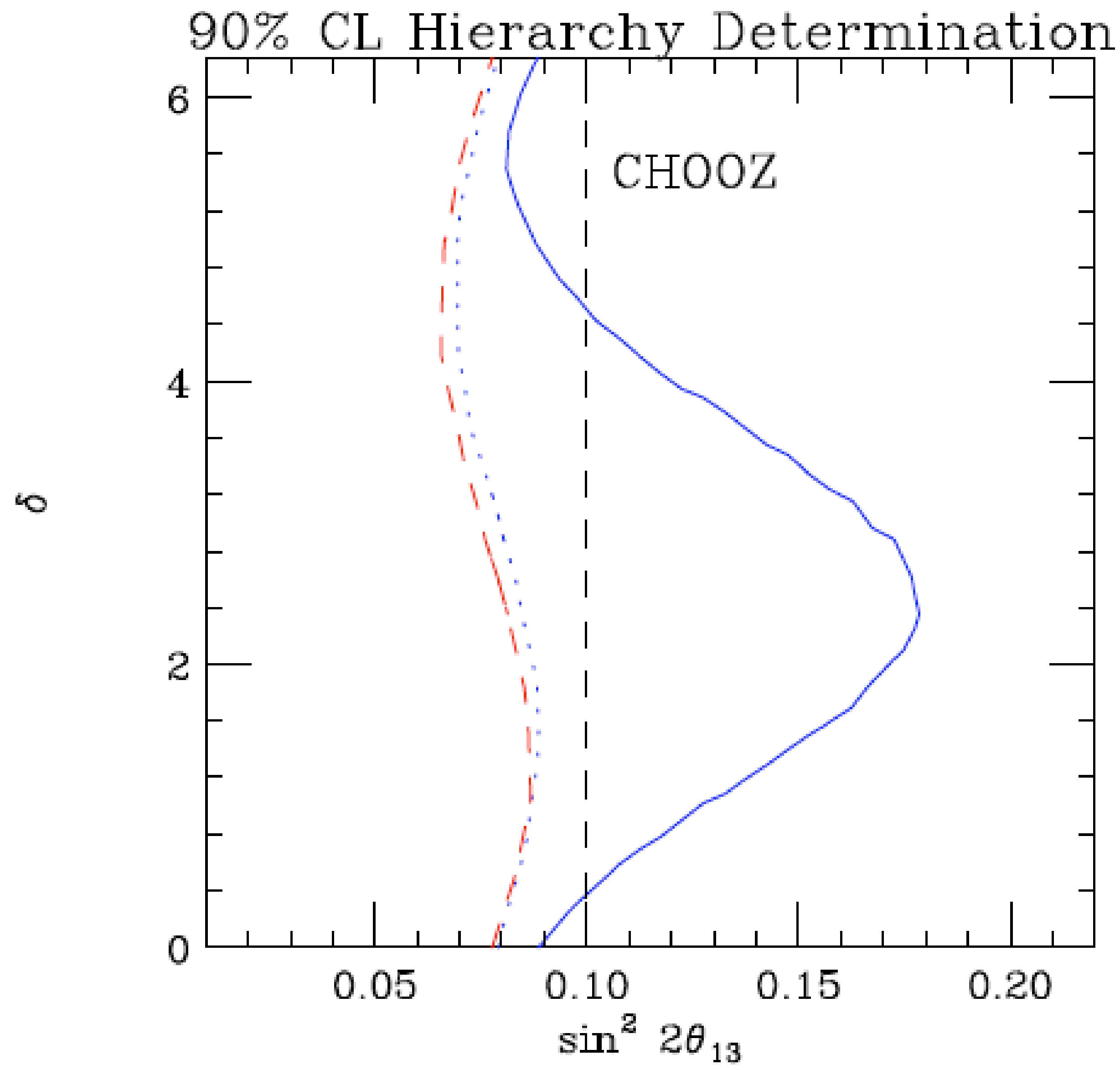
$\Delta m^2_{13} = 3 \times 10^{-3}$ eV^2

PHASE I (ONLY NEUTRINOS!)

Nature's choice: negative hierarchy



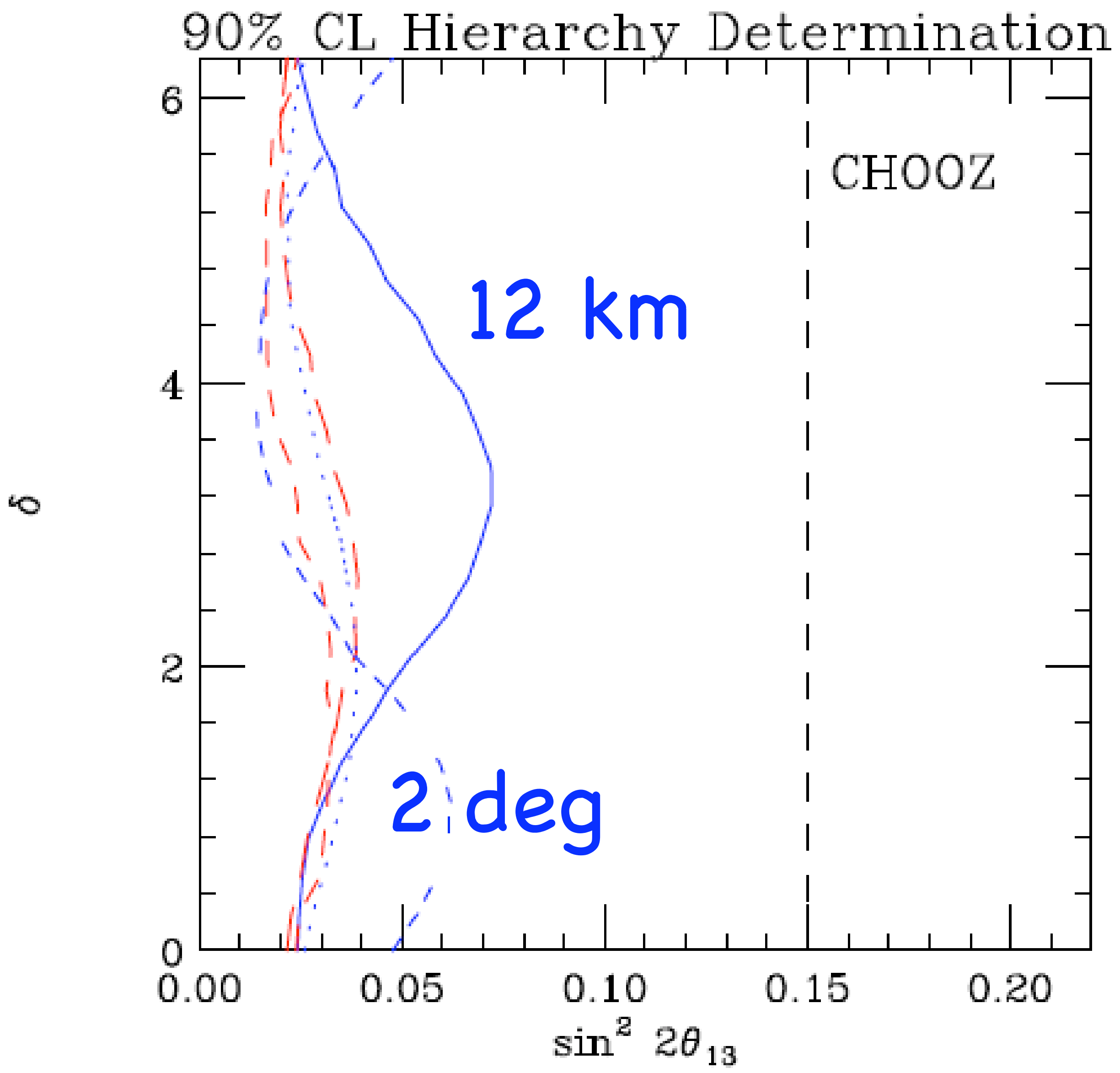
$$\Delta m^2_{13} = 2.4 \times 10^{-3} \text{ eV}^2$$



$$\Delta m^2_{13} = 3 \times 10^{-3} \text{ eV}^2$$

PHASE "II" (I x 5), ONLY NEUTRINOS

Nature's choice: positive hierarchy



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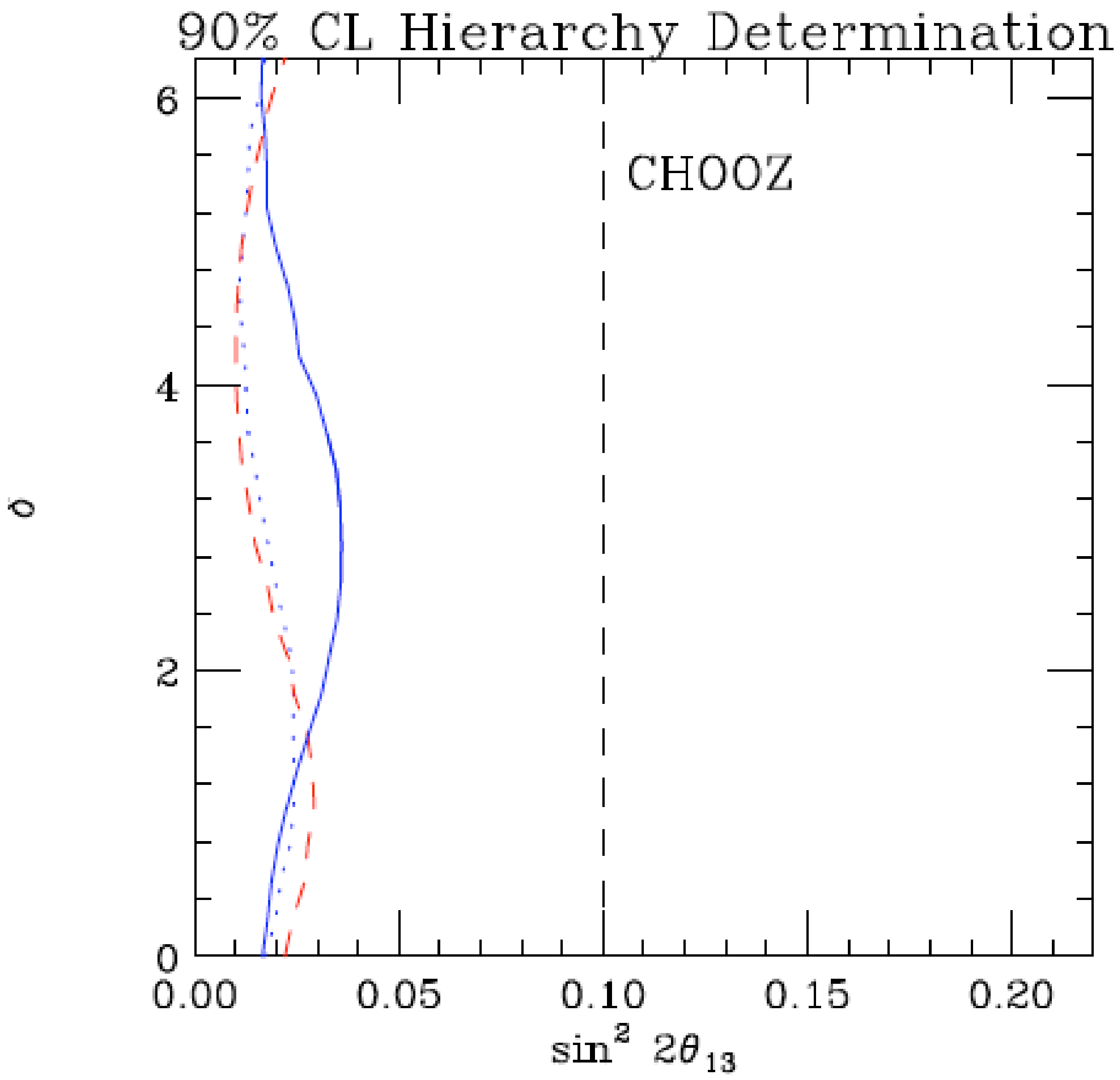

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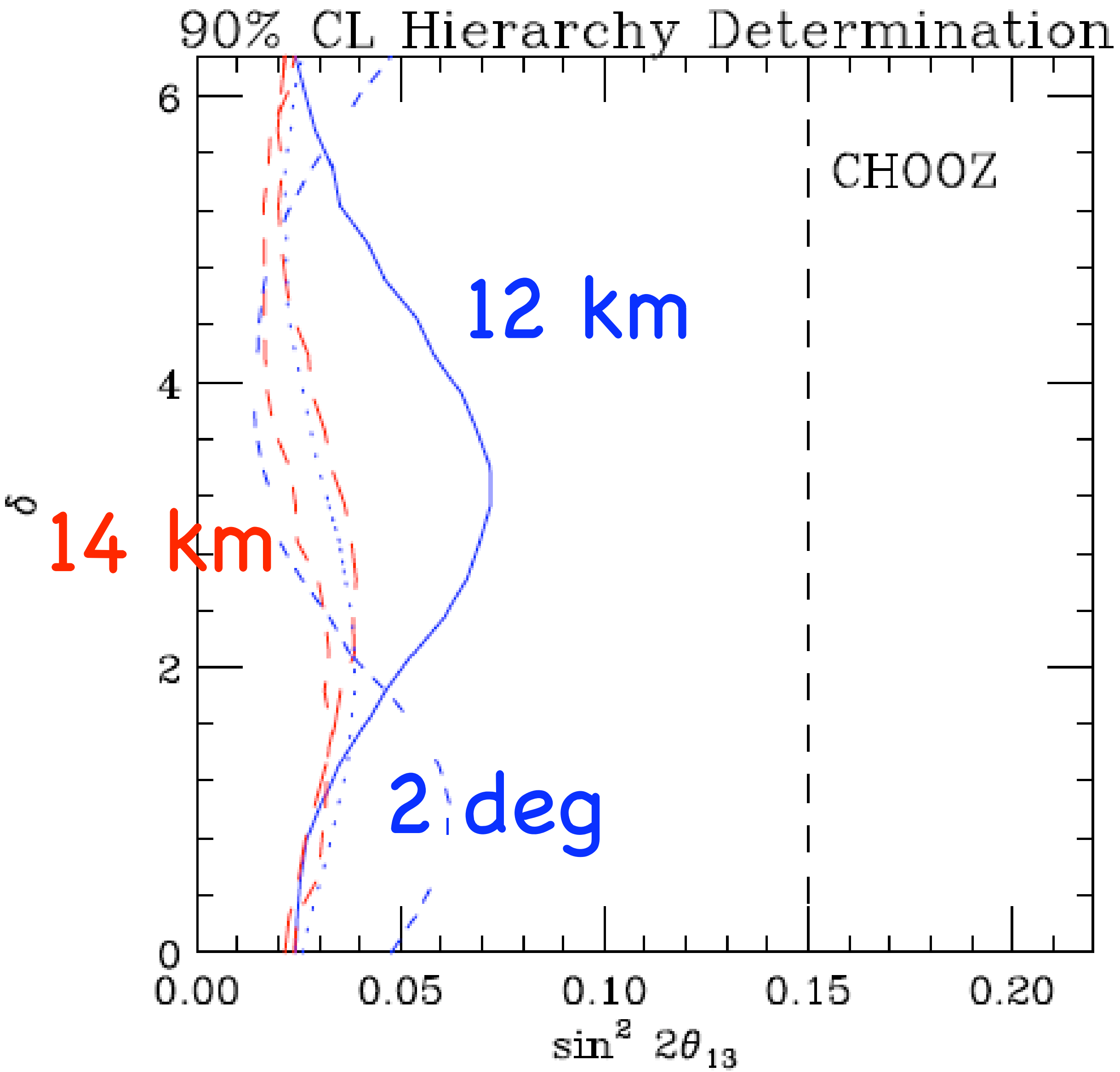
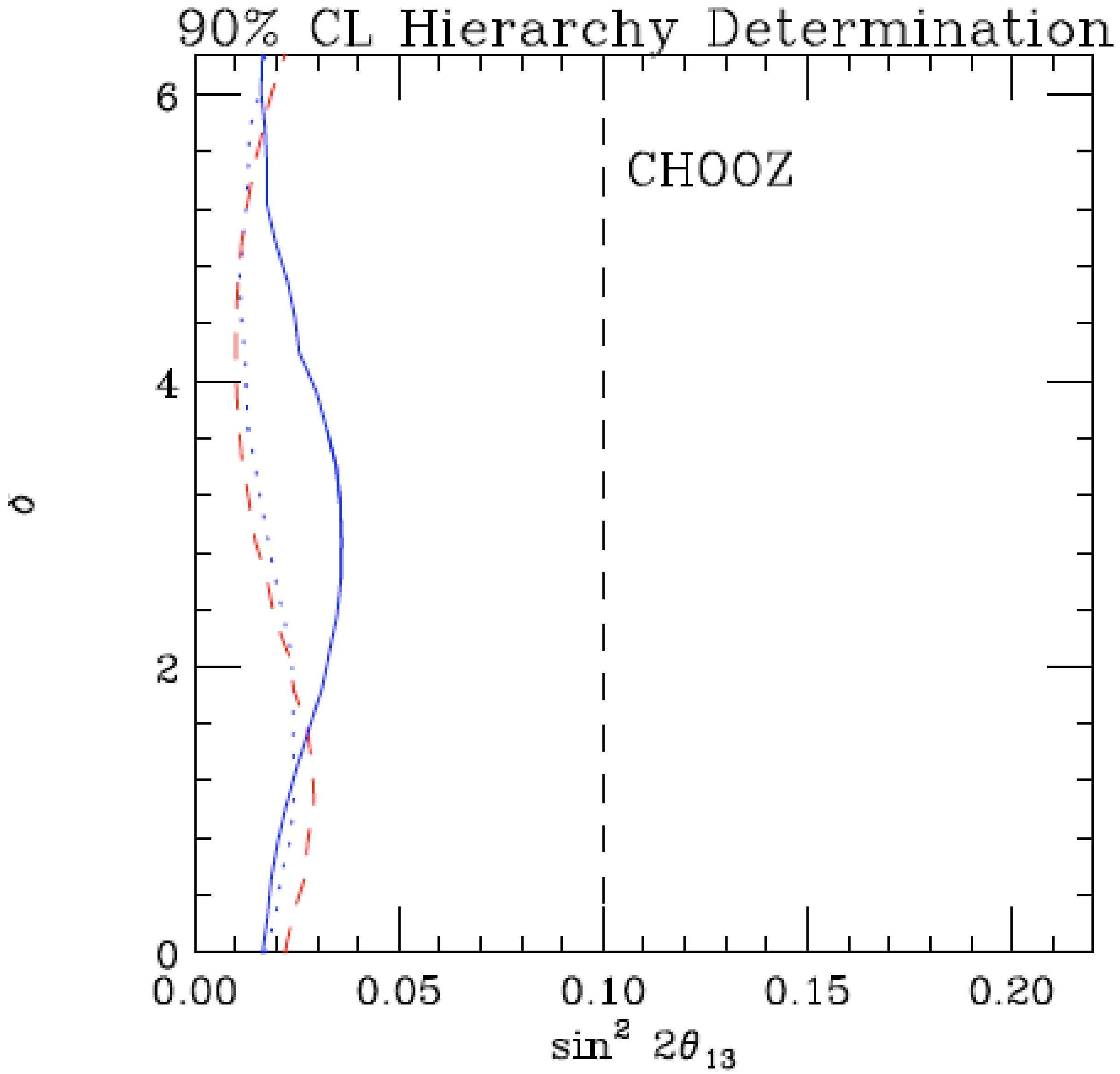
PHASE “II” (I x 5), ONLY NEUTRINOS

Nature’s choice: positive hierarchy



$\Delta m^2_{13} = 2.4 \times 10^{-3}$ eV^2

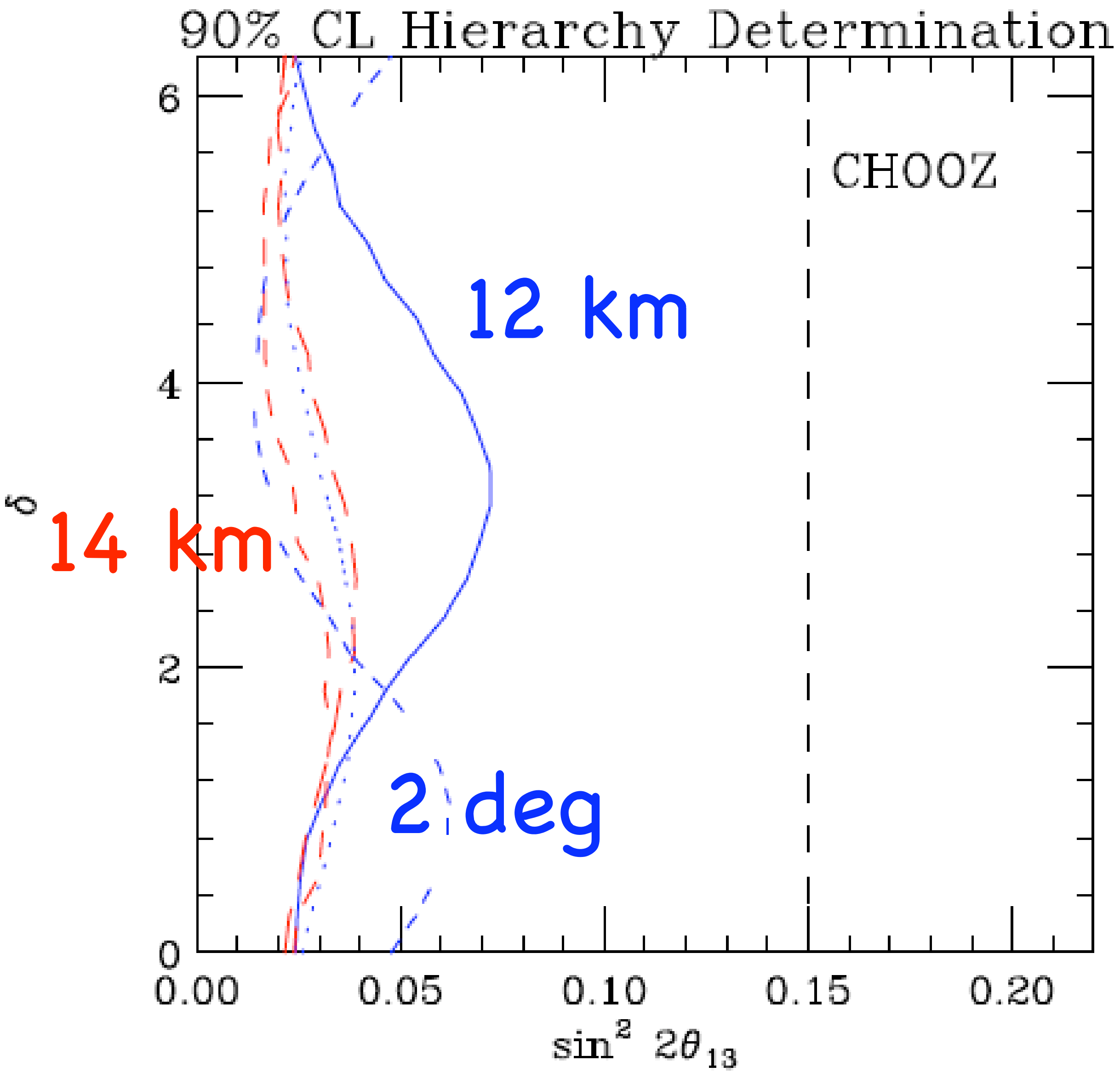


$\Delta m^2_{13} = 3 \times 10^{-3}$ eV^2

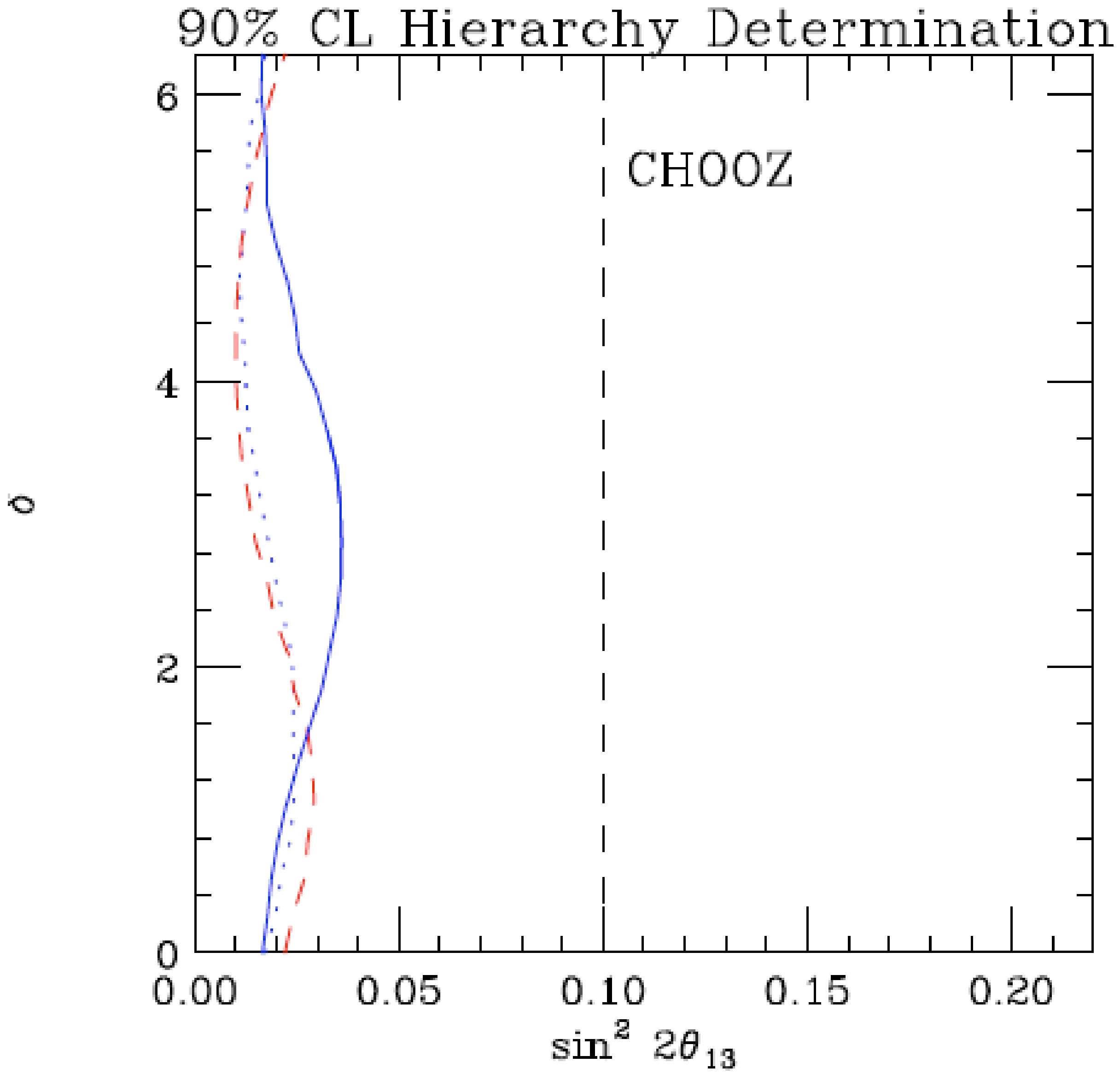
PHASE “II” (I x 5), ONLY NEUTRINOS

Nature’s choice: positive hierarchy

NOvA and T2K, or T2K and NOvA
could provide the ideal scenario for precision lepton flavor physics, due to the different matter effects in the two experiments: It is CRUCIAL to optimize the detector(s) location(s)



$$\Delta m^2_{13} = 2.4 \times 10^{-3}\ \text{eV}^2$$



$$\Delta m^2_{13} = 3 \times 10^{-3}\ \text{eV}^2$$

Why on-axis, i.e wide band beam?

Higher energy implies longer baselines, larger matter effects

(BNL-> Homestake (2540 km), Diwan et al, PRD'03).

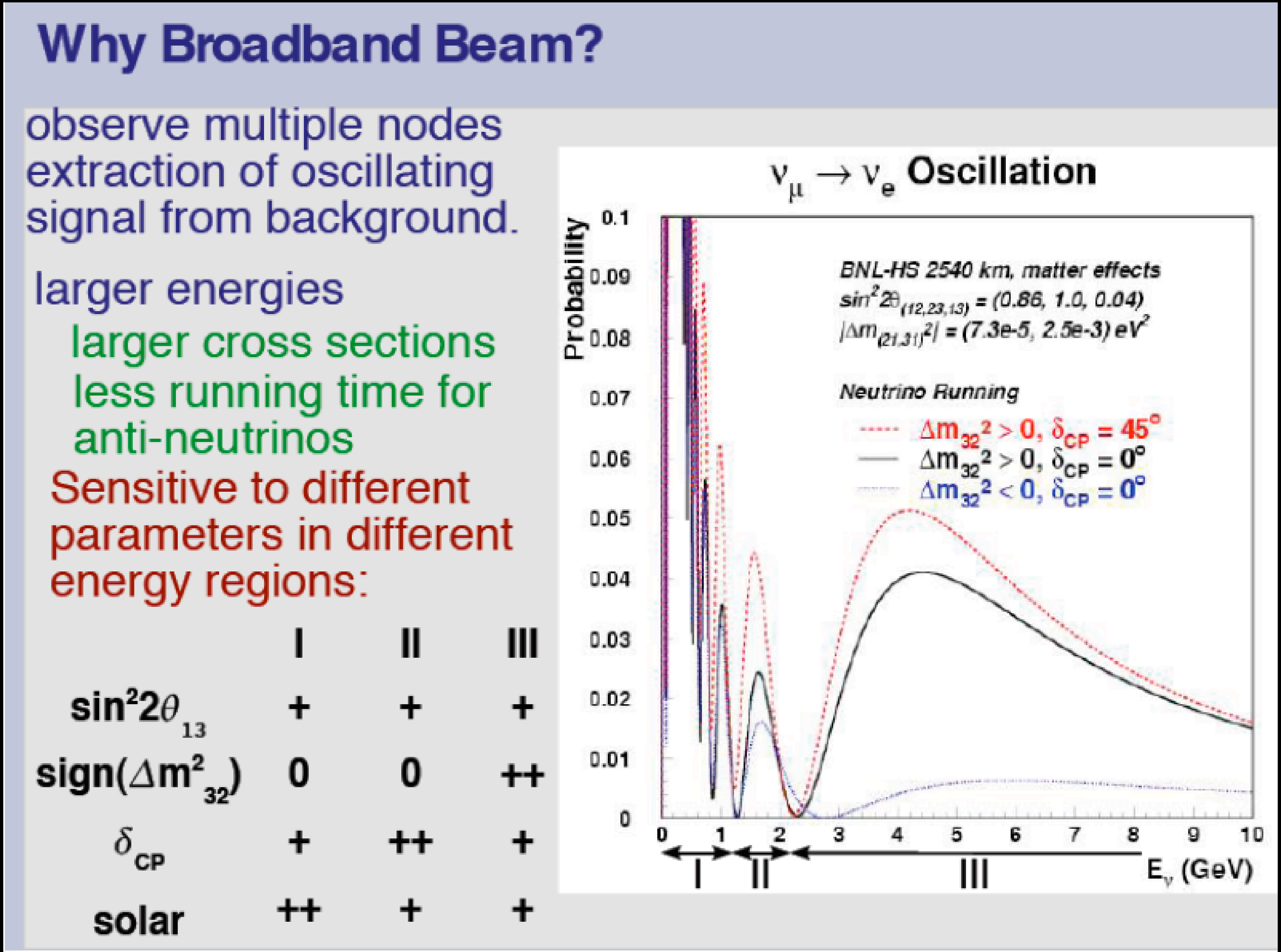
(FNAL-Homestake (1280 km), FNAL-> Henderson (1480 km)?

Higher on-axis flux

Broad spectrum: many different E/L 's simultaneously

Energy information, not only rely on systematics

Diwan et al, PRD'03



Why Broadband Beam?

observe multiple nodes extraction of oscillating signal from background.

larger energies

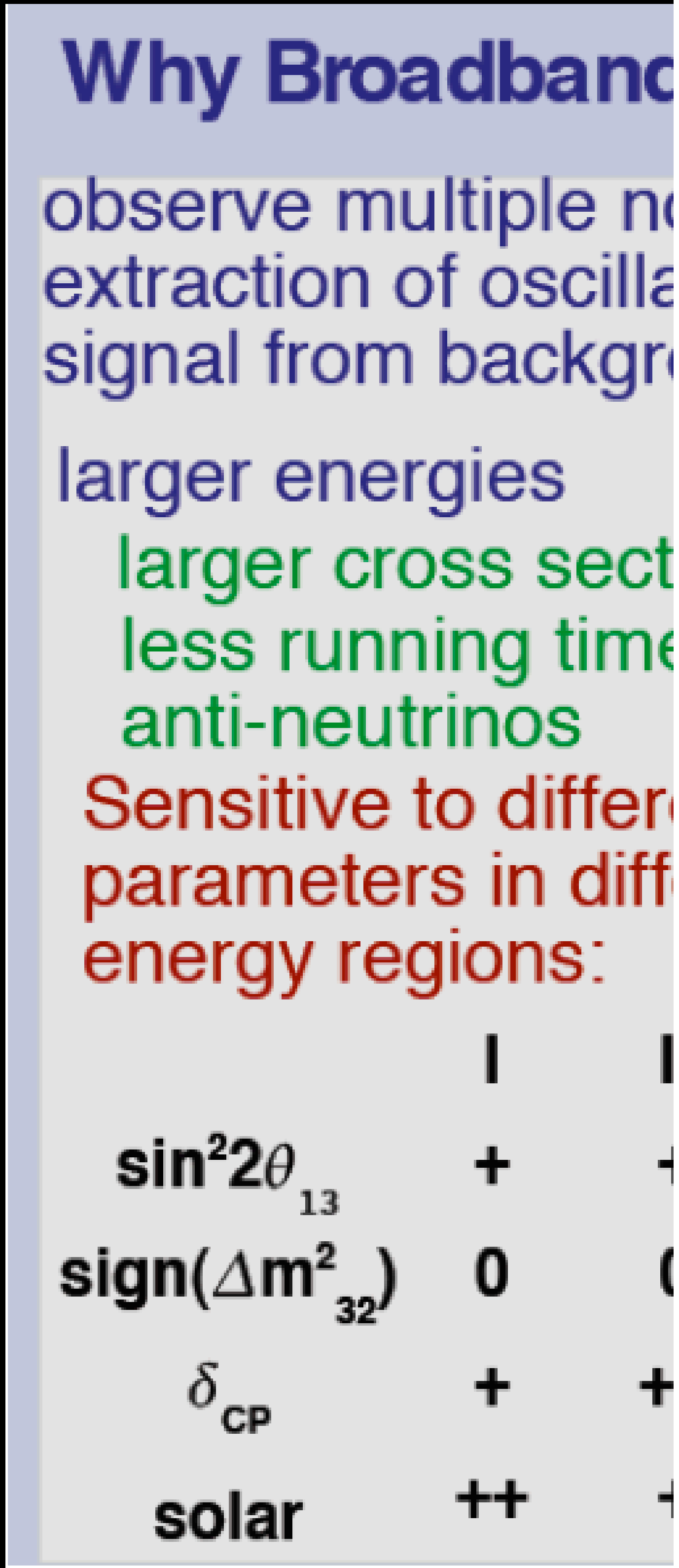
- larger cross sections
- less running time for anti-neutrinos

Sensitive to different parameters in different energy regions:

	I	II	III
$\sin^2 2\theta_{13}$	+	+	+
$\text{sign}(\Delta m^2_{32})$	0	0	++
δ_{CP}	+	++	+
solar	++	+	+

$\nu_\mu \rightarrow \nu_e$ Oscillation

Diwan et al, PRD'03



Why Broadbanc

observe multiple n
extraction of oscilla
signal from backgr

larger energies
- larger cross sect
- less running time
- anti-neutrinos

Sensitive to differ
parameters in diff
energy regions:

	I	I
$\sin^2 2\theta_{13}$	+	+
$\mathrm{sign}(\Delta m^2_{32})$	0	0
δ_{CP}	+	+
solar	++	+

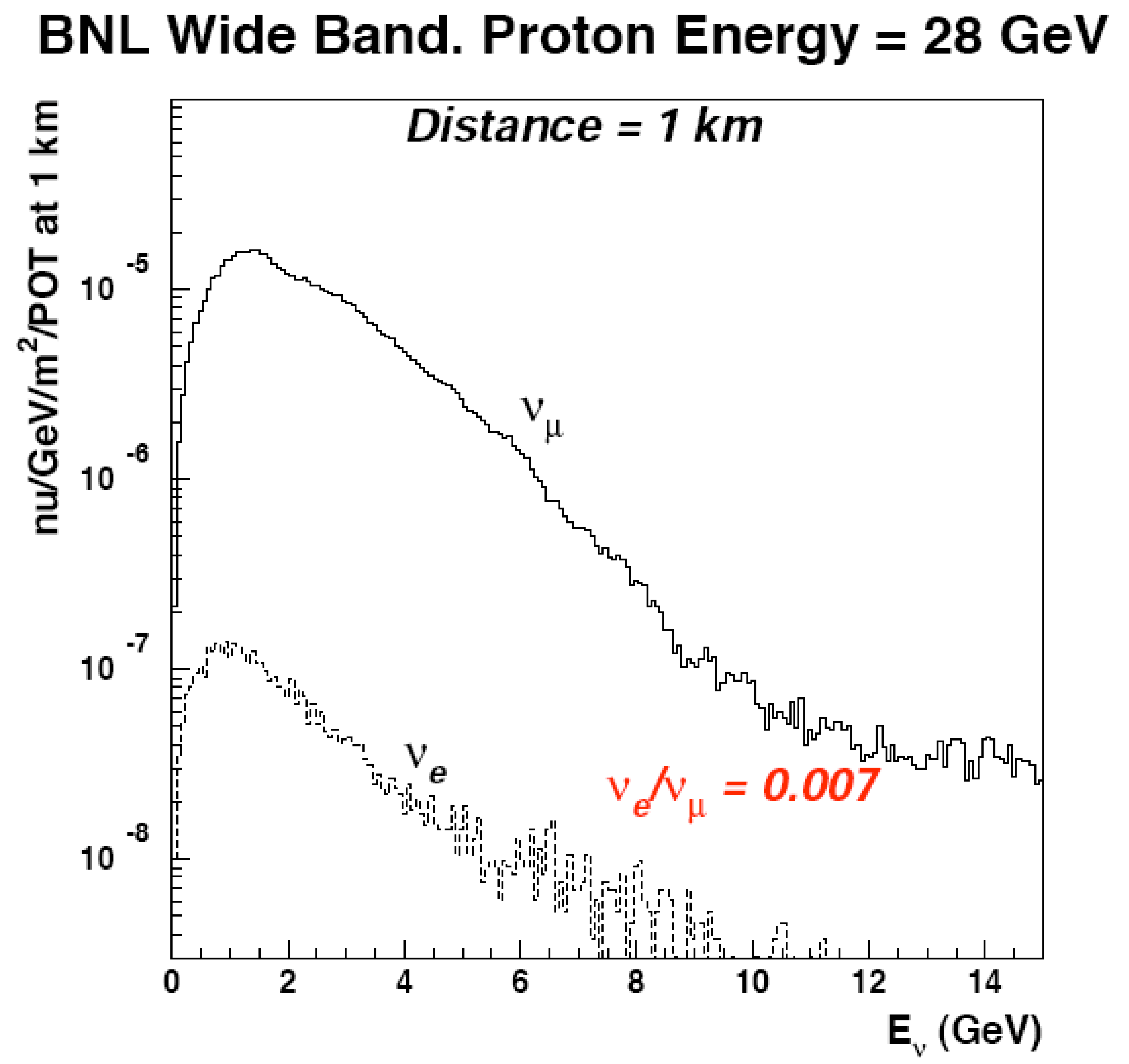


Figure 1: BNL wide band spectrum with the new graphite target and horn design. This spectrum is at 0 degrees with respect to the proton beam on target and the normalization is at 1 km from the target.

Why NOT on-axis?

Higher energy implies longer baselines, lower fluxes

High energy tail: NC backgrounds

Broad spectrum: Only useful if good energy resolution

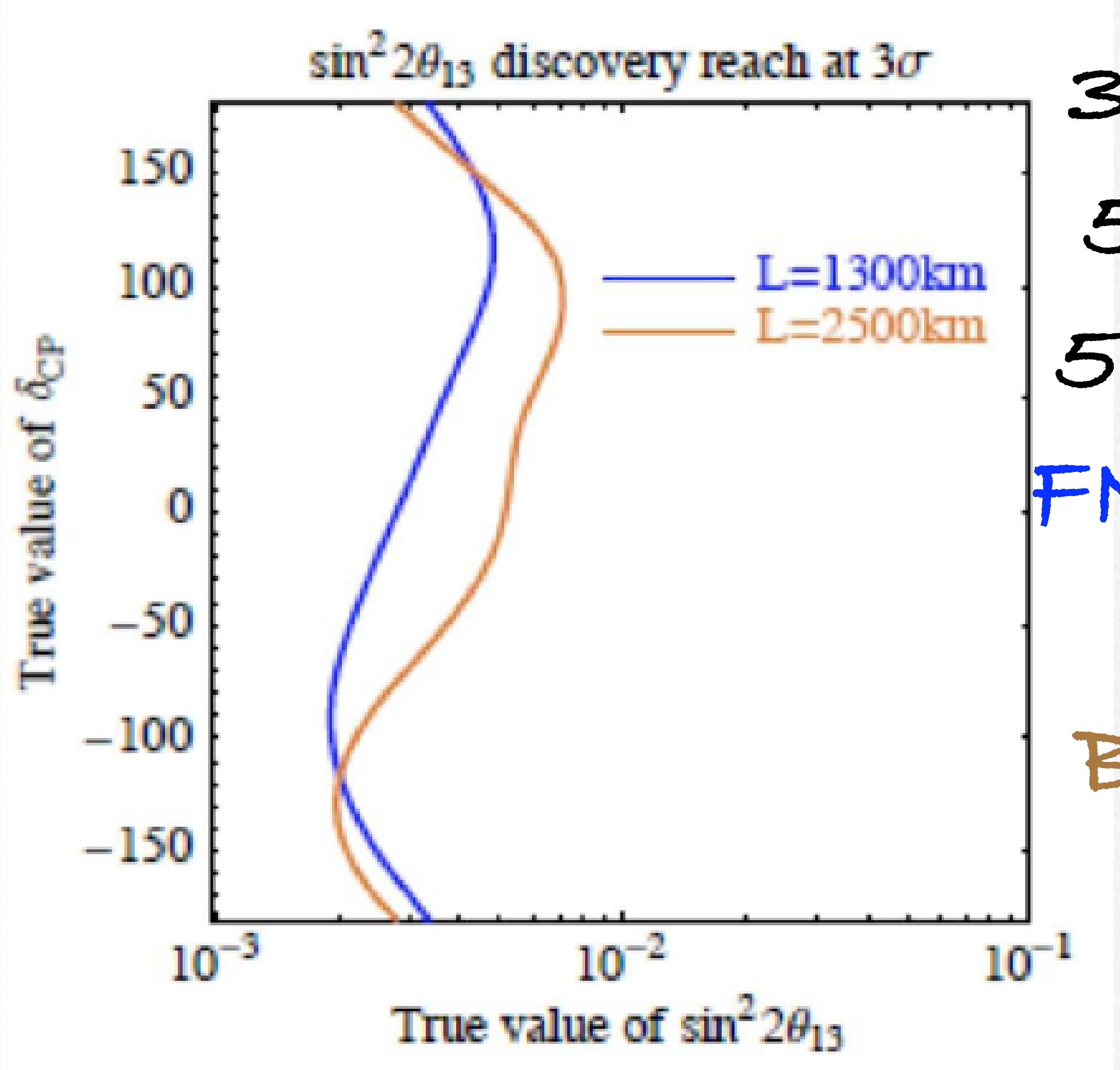
An excellent detection technique is needed:

Large mass to compensate larger baselines

GOOD ENERGY RESOLUTION AND NC REJECTION

arXiv:hep-ex/0608023 v1 8 Aug 2006

PROPOSAL FOR AN EXPERIMENTAL PROGRAM IN NEUTRINO PHYSICS AND PROTON DECAY IN THE HOMESTAKE LABORATORY



300 kton x 1MW

5 yr neutrino +

5 yr antineutrino

FNAL-Homestake:

1300 km

BNL-Homestake

2500 km

arXiv:hep-ex/0608023 v1 8 Aug 2006

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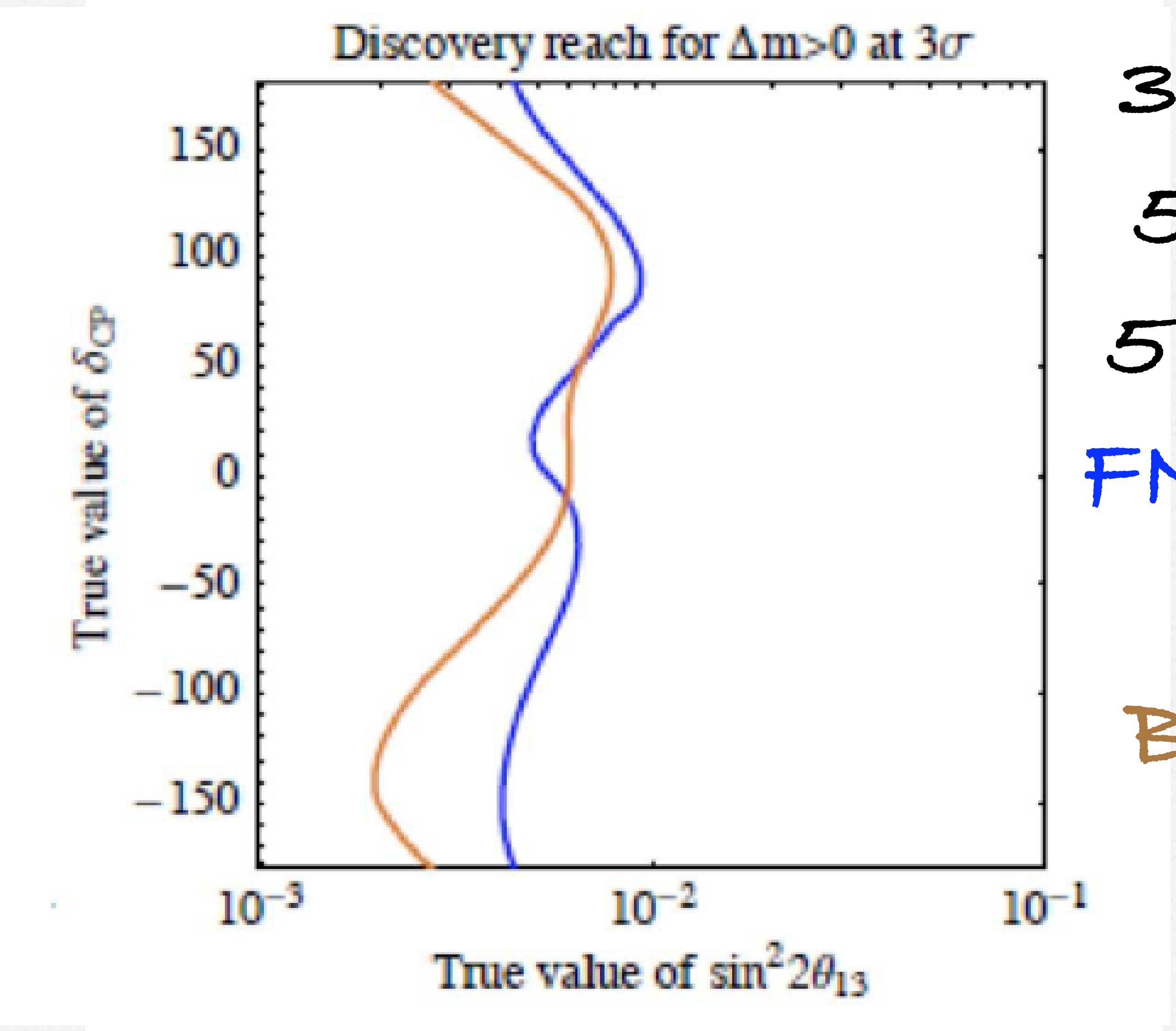

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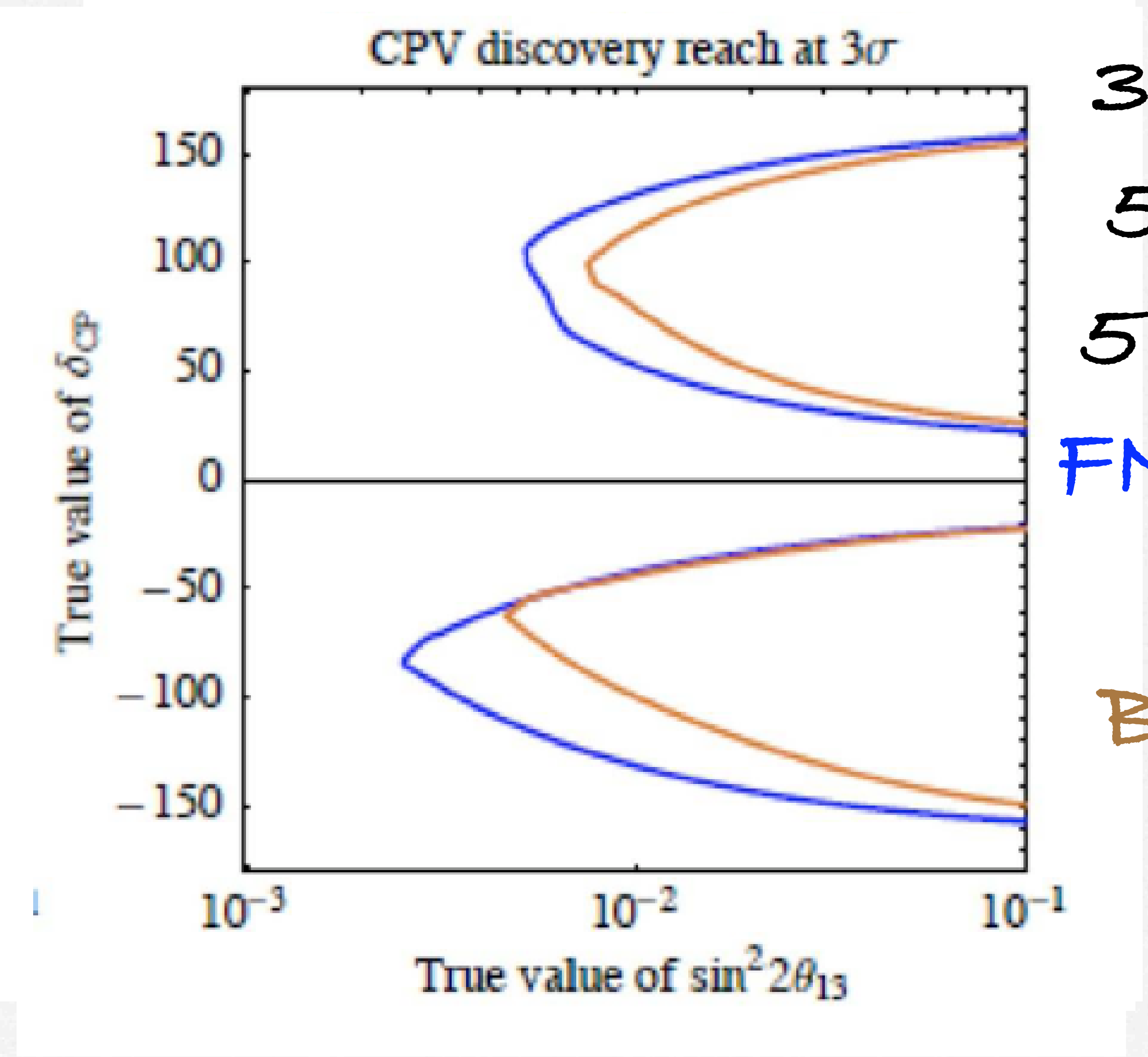


300 kton x 1MW

5 yr neutrino +

5 yr antineutrino

FNAL-Homestake:

1300 km

BNL-Homestake

2500 km

US Long Baseline Neutrino experiment FNAL/BNL joint study: report will appear soon!

Broad band vs off-axis beam, detection techniques, proton plan...large underground detector presumably located at the:

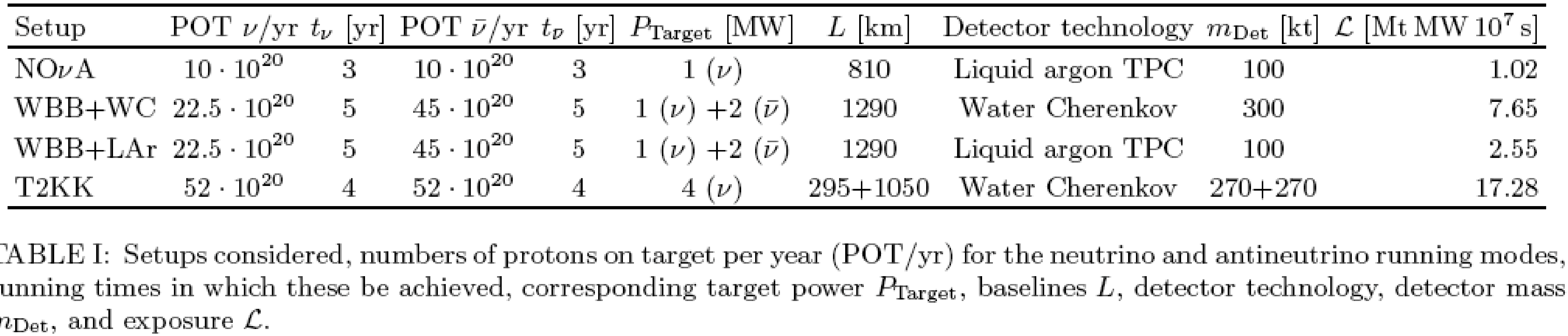
NSF's planned DUSEL facility

(Deep Underground Science and Engineering Laboratory)

Soudan mine (MN), Henderson mine (CO), Homestake mine (SD) and others are being considered as possible sites.

Dark matter, Neutrinoless double beta decay, Solar neutrinos, Geoneutrinos, Proton decay, LBL neutrinos, Nuclear Astrophysics...

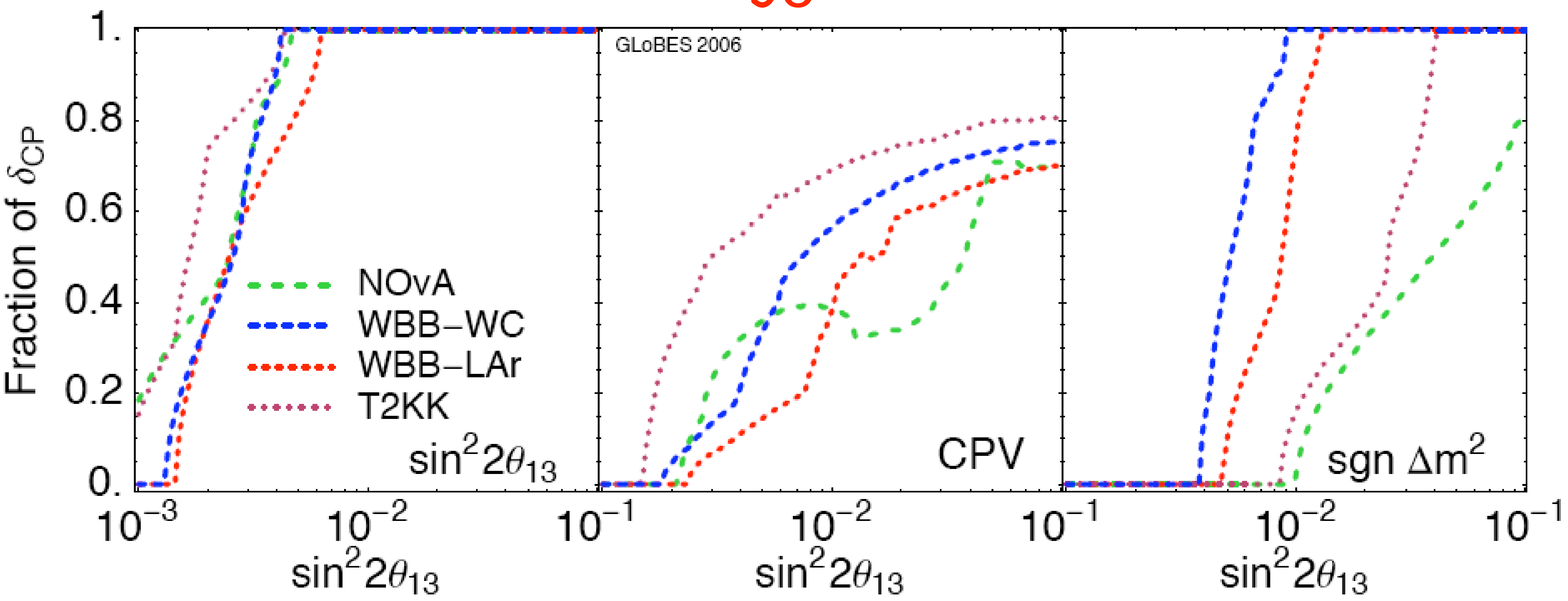
Barger et al. hep-ph/0610301



Setup	POT ν/yr	t_ν [yr]	POT $\bar{\nu}$/yr	$t_{\bar{\nu}}$ [yr]	P_{Target} [MW]	L [km]	Detector technology	m_{Det} [kt]	$\mathcal{L}$ [Mt MW 10^7 s]
NOνA	$10 \cdot 10^{20}$	3	$10 \cdot 10^{20}$	3	1 (ν)	810	Liquid argon TPC	100	1.02
WBB+WC	$22.5 \cdot 10^{20}$	5	$45 \cdot 10^{20}$	5	1 (ν) +2 ($\bar{\nu}$)	1290	Water Cherenkov	300	7.65
WBB+LAr	$22.5 \cdot 10^{20}$	5	$45 \cdot 10^{20}$	5	1 (ν) +2 ($\bar{\nu}$)	1290	Liquid argon TPC	100	2.55
T2KK	$52 \cdot 10^{20}$	4	$52 \cdot 10^{20}$	4	4 (ν)	295+1050	Water Cherenkov	270+270	17.28

TABLE I: Setups considered, numbers of protons on target per year (POT/yr) for the neutrino and antineutrino running modes, running times in which these be achieved, corresponding target power P_{Target}, baselines L, detector technology, detector mass m_{Det}, and exposure $\mathcal{L}$.

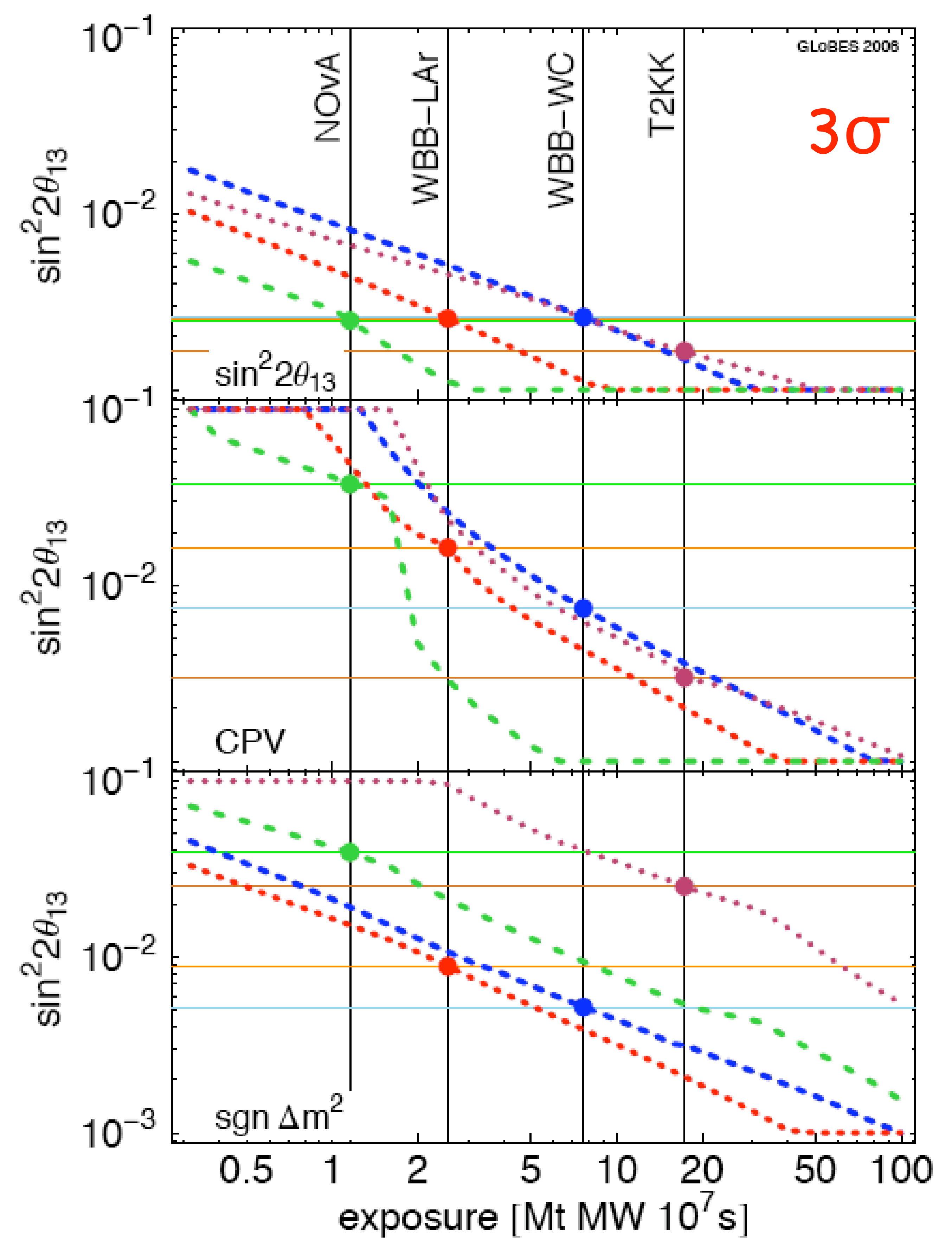
3σ



Barger et al. hep-ph/0610301

NOvA CP performance is really good

For the sign extraction, better WBB option



Fraction of delta =0.5

"The" Thing Everybody can Agree on:

- Physics of $\nu_\mu \to \nu_e$ together with $\nu_\mu \to \nu_\mu$

  is a Fantastic Laboratory for Lepton Flavor Physics!!!

  - Fraction ν_e in ν_3
  - ν Mass Hierarchy
  - Leptonic CP Violation
  - Is ν_τ or ν_μ the dominant component of ν_3?

Other Things Everybody can Agree on:

- Power of Neutrino Beam:
  at least a 1 Mega-Watt proton source
- Size of Neutrino Detector:
  fraction of Mega-Ton detector
- π^0 rejection:
  EXCELLENT
- Physics Reach:
  Be Capable of detetmining
  $\sin^2 2\theta_{13}, \quad sign(\delta m^2_{31}), \quad \sin\delta$
  pushing to $\sin^2 2\theta_{13} \Rightarrow 0.002$
  ($P_{atm} = P_{sol}$ @ 1st pk)
- Other Physics:
  Proton Decay, Supernova, . . .

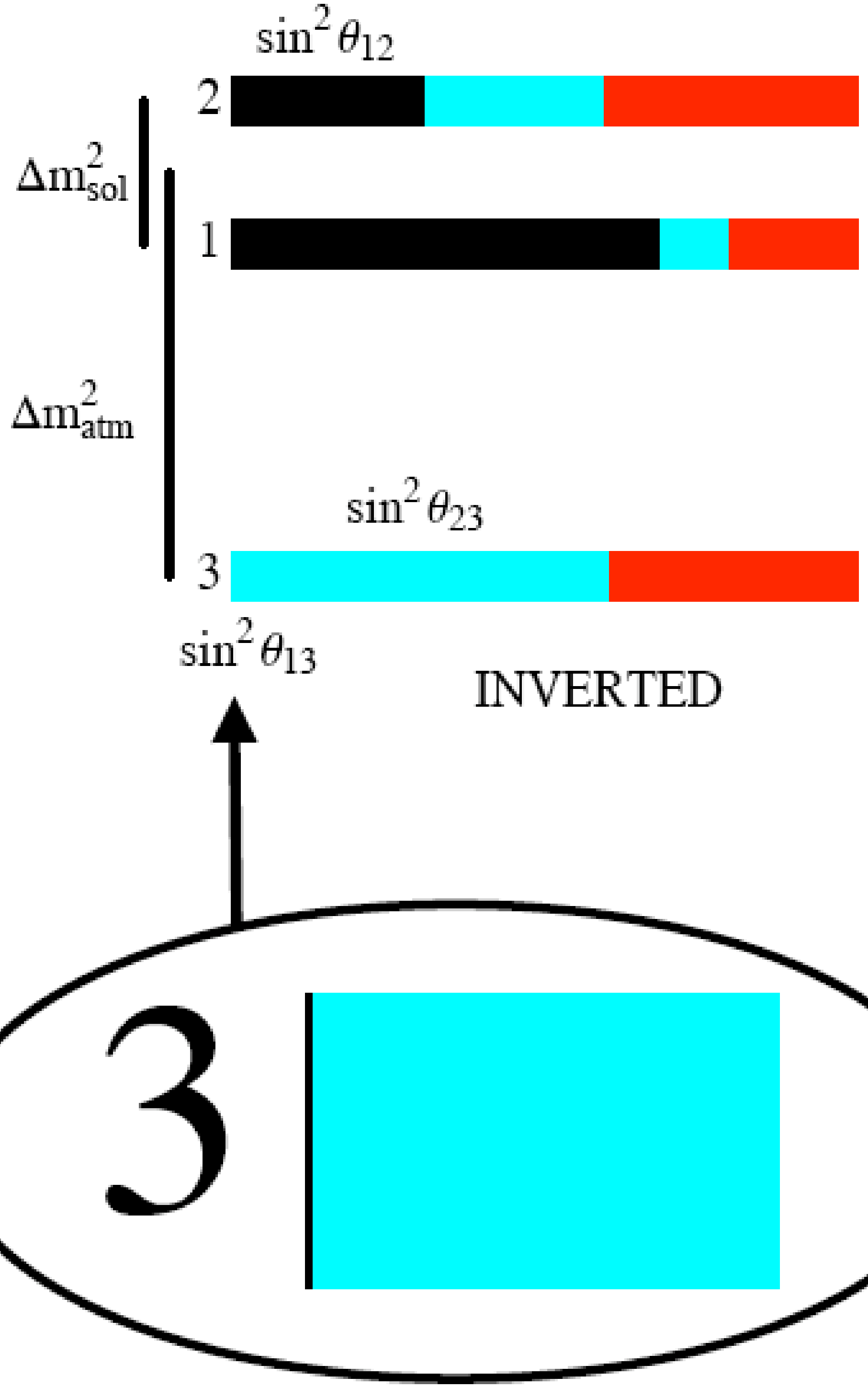
Less Agreement:

- Counting v Spectrum
- On Axis v Off Axis
- Location of Detector
- Detector Technology
- etc

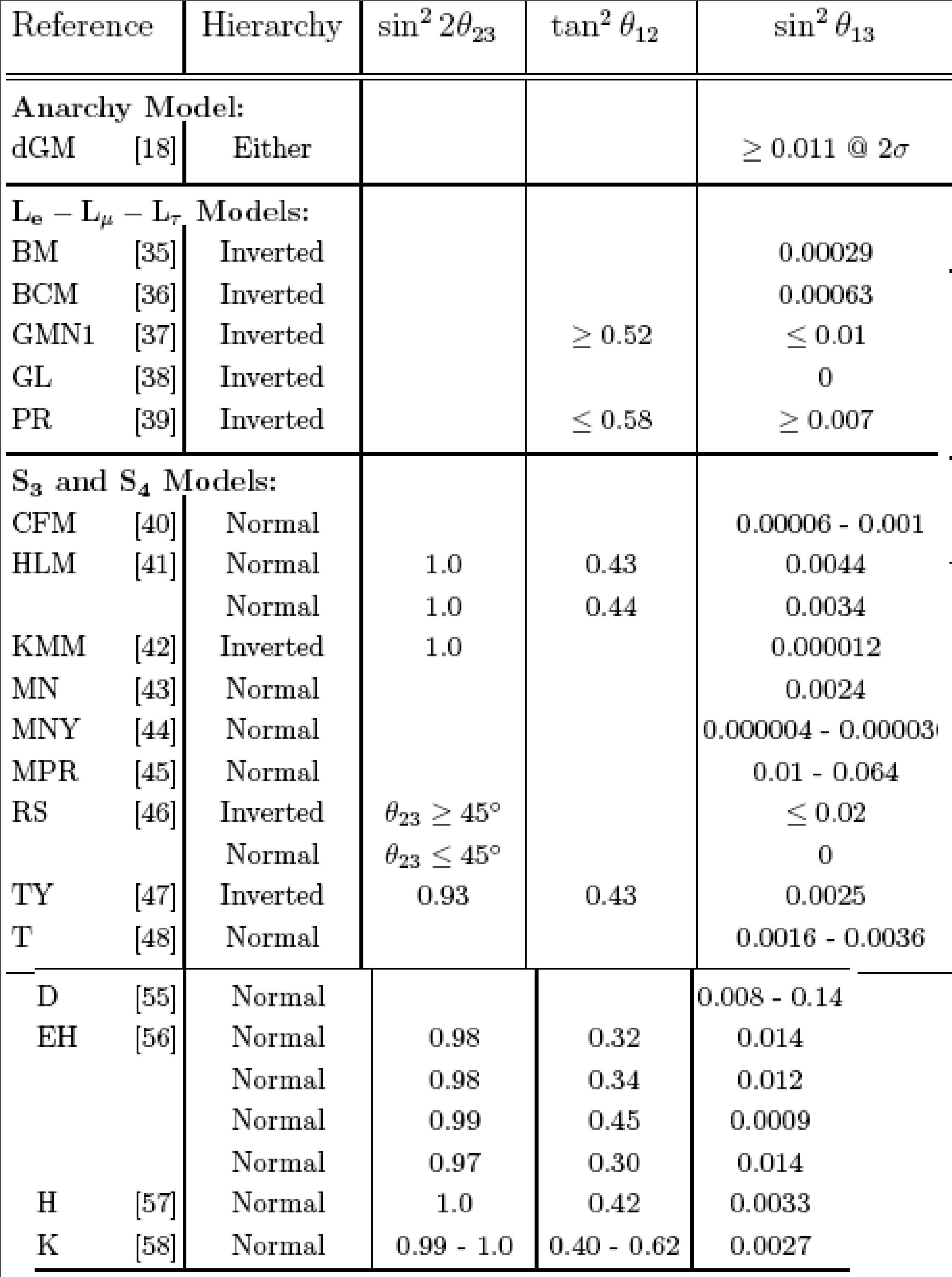
DIVIDED,

we will be CONQUERED !!!

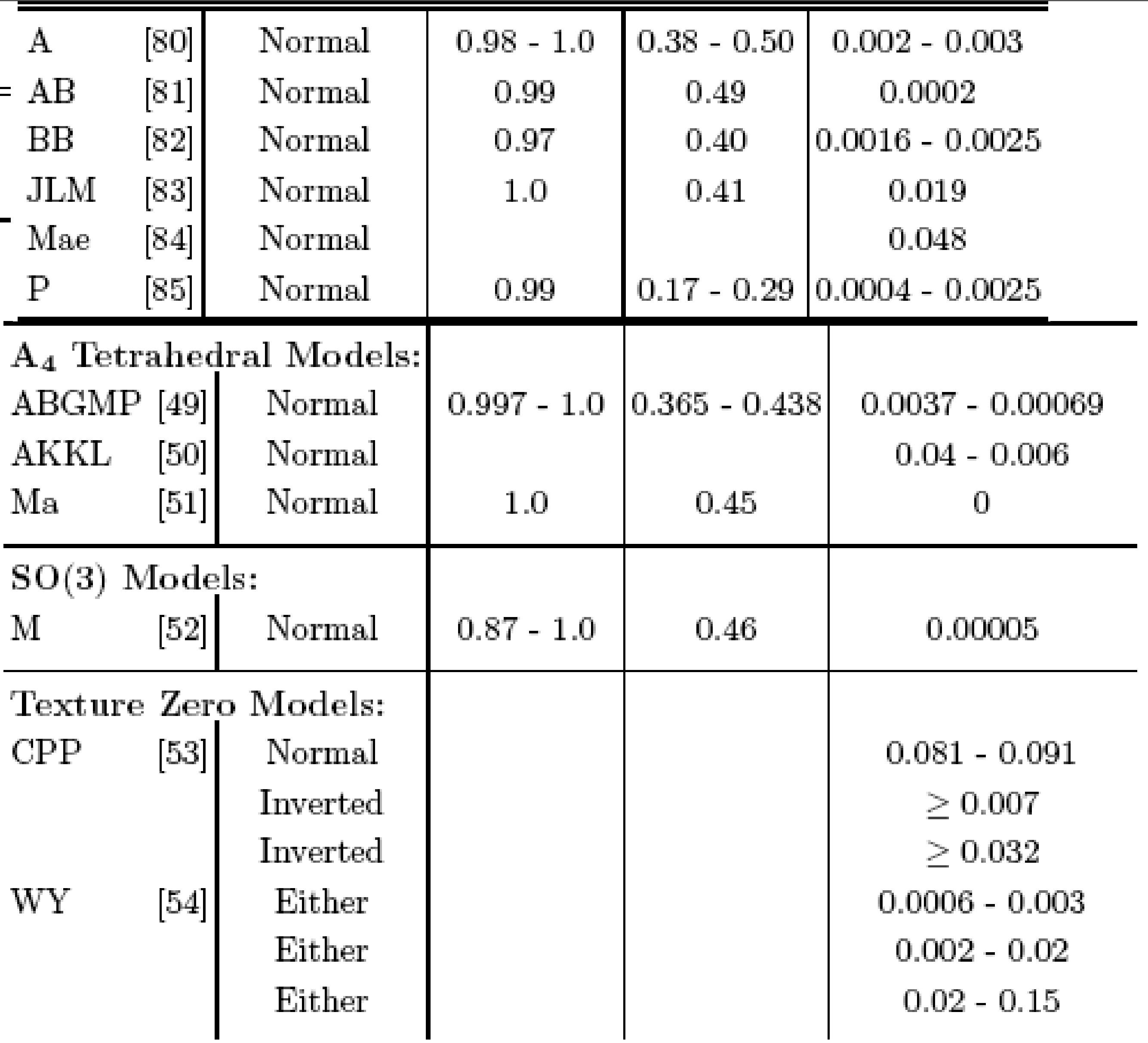
pdg 2026:



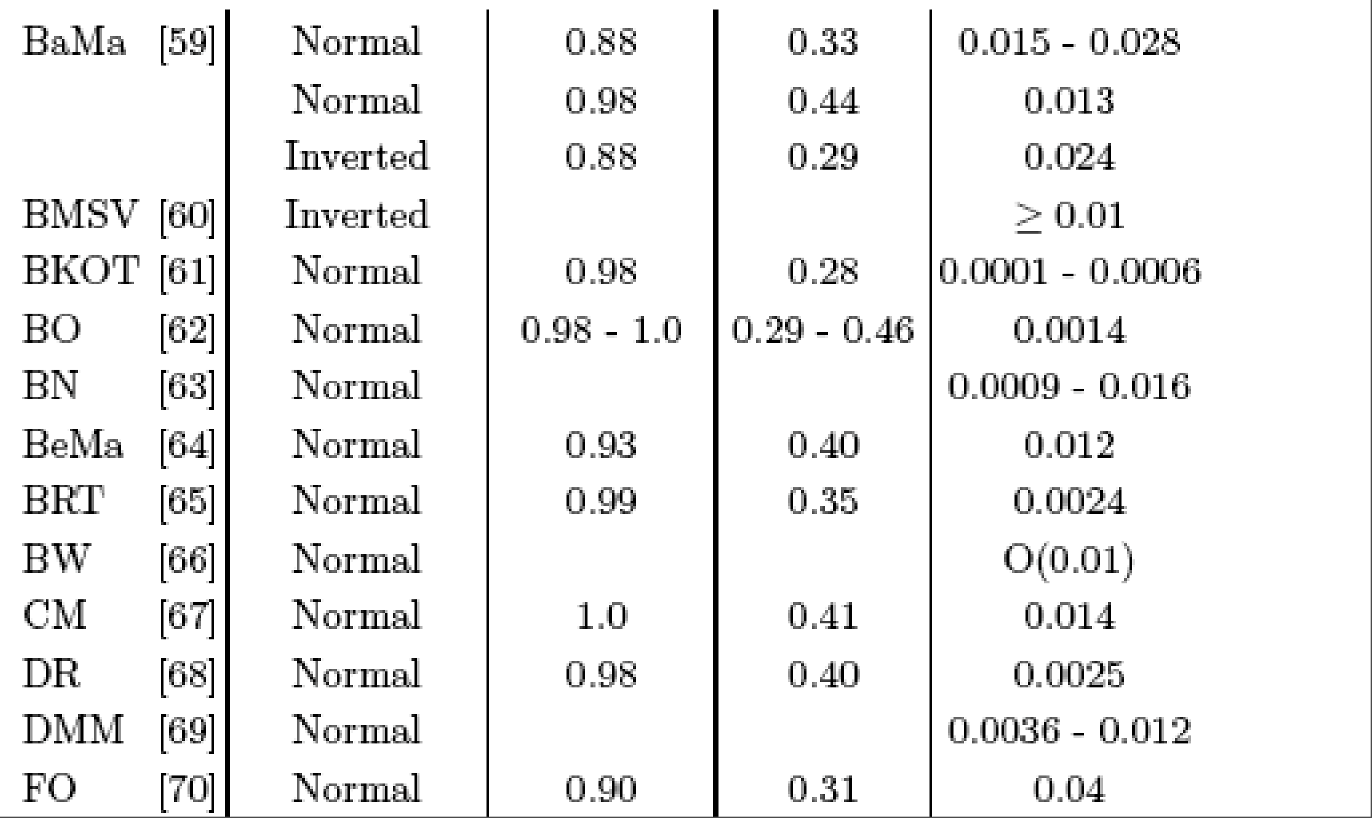
$$\begin{aligned} \sin^2\theta_{12} &\approx 0.31 \\ \sin^2\theta_{13} &\approx 0.007 \\ \sin^2\theta_{23} &\approx 0.60 \\ \delta &\approx 3\pi/4 \end{aligned}$$



Reference	Hierarchy	$\sin^2 2\theta_{23}$	$\tan^2 \theta_{12}$	$\sin^2 \theta_{13}$
Anarchy Model:				
dGM [18]	Either			≥ 0.011 @ 2σ
$L_e - L_\mu - L_\tau$ Models:				
BM [35]	Inverted			0.00029
BCM [36]	Inverted			0.00063
GMN1 [37]	Inverted		≥ 0.52	≤ 0.01
GL [38]	Inverted			0
PR [39]	Inverted		≤ 0.58	≥ 0.007
S_3 and S_4 Models:				
CFM [40]	Normal			0.00006 - 0.001
HLM [41]	Normal	1.0	0.43	0.0044
	Normal	1.0	0.44	0.0034
KMM [42]	Inverted	1.0		0.000012
MN [43]	Normal			0.0024
MNY [44]	Normal			0.000004 - 0.00003
MPR [45]	Normal			0.01 - 0.064
RS [46]	Inverted	$\theta_{23} \geq 45°$		≤ 0.02
	Normal	$\theta_{23} \leq 45°$		0
TY [47]	Inverted	0.93	0.43	0.0025
T [48]	Normal			0.0016 - 0.0036
D [55]	Normal			0.008 - 0.14
EH [56]	Normal	0.98	0.32	0.014
	Normal	0.98	0.34	0.012
	Normal	0.99	0.45	0.0009
	Normal	0.97	0.30	0.014
H [57]	Normal	1.0	0.42	0.0033
K [58]	Normal	0.99 - 1.0	0.40 - 0.62	0.0027

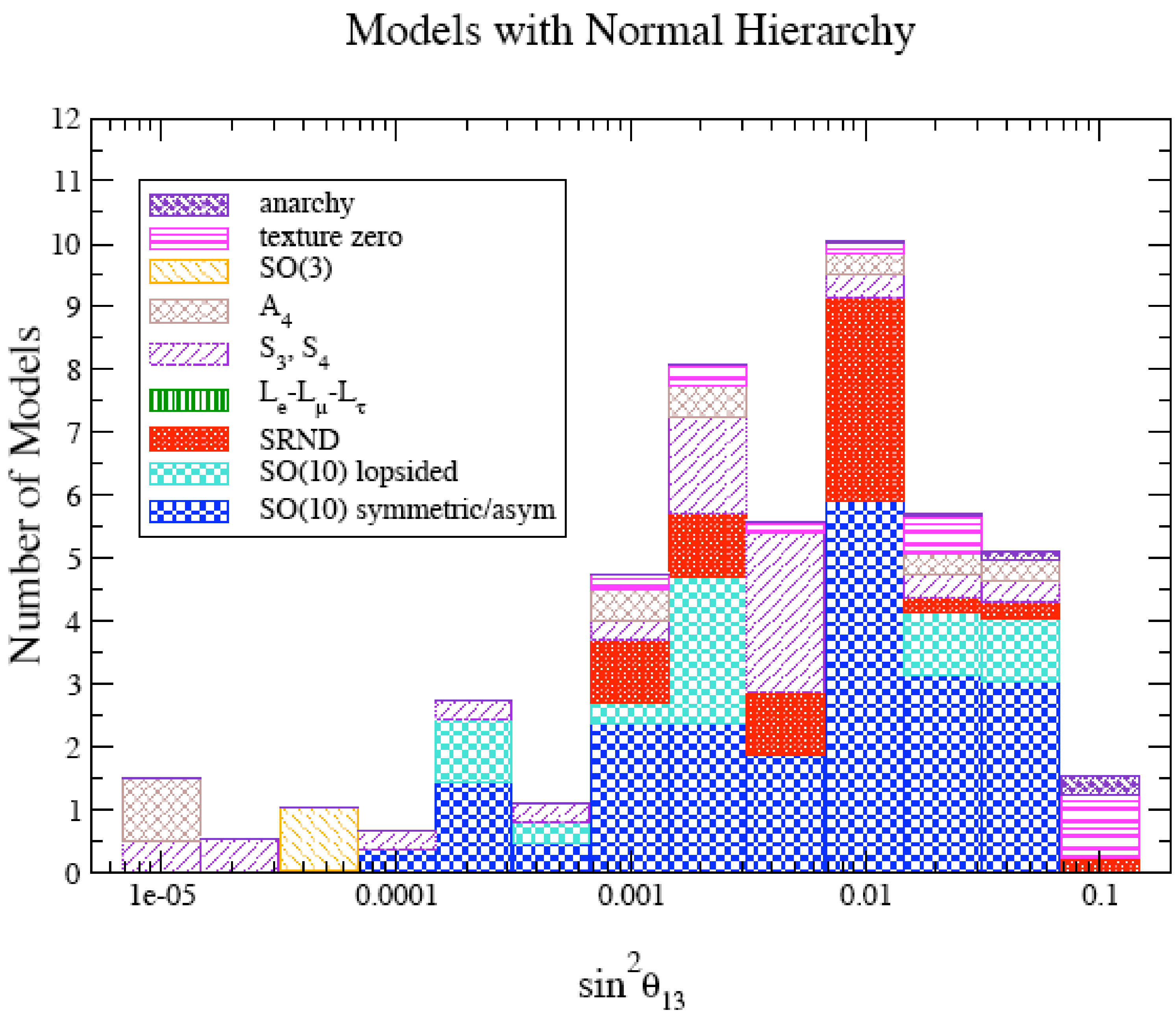


A [80]	Normal	0.98 - 1.0	0.38 - 0.50	0.002 - 0.003
AB [81]	Normal	0.99	0.49	0.0002
BB [82]	Normal	0.97	0.40	0.0016 - 0.0025
JLM [83]	Normal	1.0	0.41	0.019
Mae [84]	Normal			0.048
P [85]	Normal	0.99	0.17 - 0.29	0.0004 - 0.0025
A_4 Tetrahedral Models:				
ABGMP [49]	Normal	0.997 - 1.0	0.365 - 0.438	0.0037 - 0.00069
AKKL [50]	Normal			0.04 - 0.006
Ma [51]	Normal	1.0	0.45	0
SO(3) Models:				
M [52]	Normal	0.87 - 1.0	0.46	0.00005
Texture Zero Models:				
CPP [53]	Normal			0.081 - 0.091
	Inverted			≥ 0.007
	Inverted			≥ 0.032
WY [54]	Either			0.0006 - 0.003
	Either			0.002 - 0.02
	Either			0.02 - 0.15



BaMa [59]	Normal	0.88	0.33	0.015 - 0.028
	Normal	0.98	0.44	0.013
	Inverted	0.88	0.29	0.024
BMSV [60]	Inverted			≥ 0.01
BKOT [61]	Normal	0.98	0.28	0.0001 - 0.0006
BO [62]	Normal	0.98 - 1.0	0.29 - 0.46	0.0014
BN [63]	Normal			0.0009 - 0.016
BeMa [64]	Normal	0.93	0.40	0.012
BRT [65]	Normal	0.99	0.35	0.0024
BW [66]	Normal			O(0.01)
CM [67]	Normal	1.0	0.41	0.014
DR [68]	Normal	0.98	0.40	0.0025
DMM [69]	Normal			0.0036 - 0.012
FO [70]	Normal	0.90	0.31	0.04

Albright and Chen, hep-ph/0608137



Albright and Chen,
hep-ph/0608137

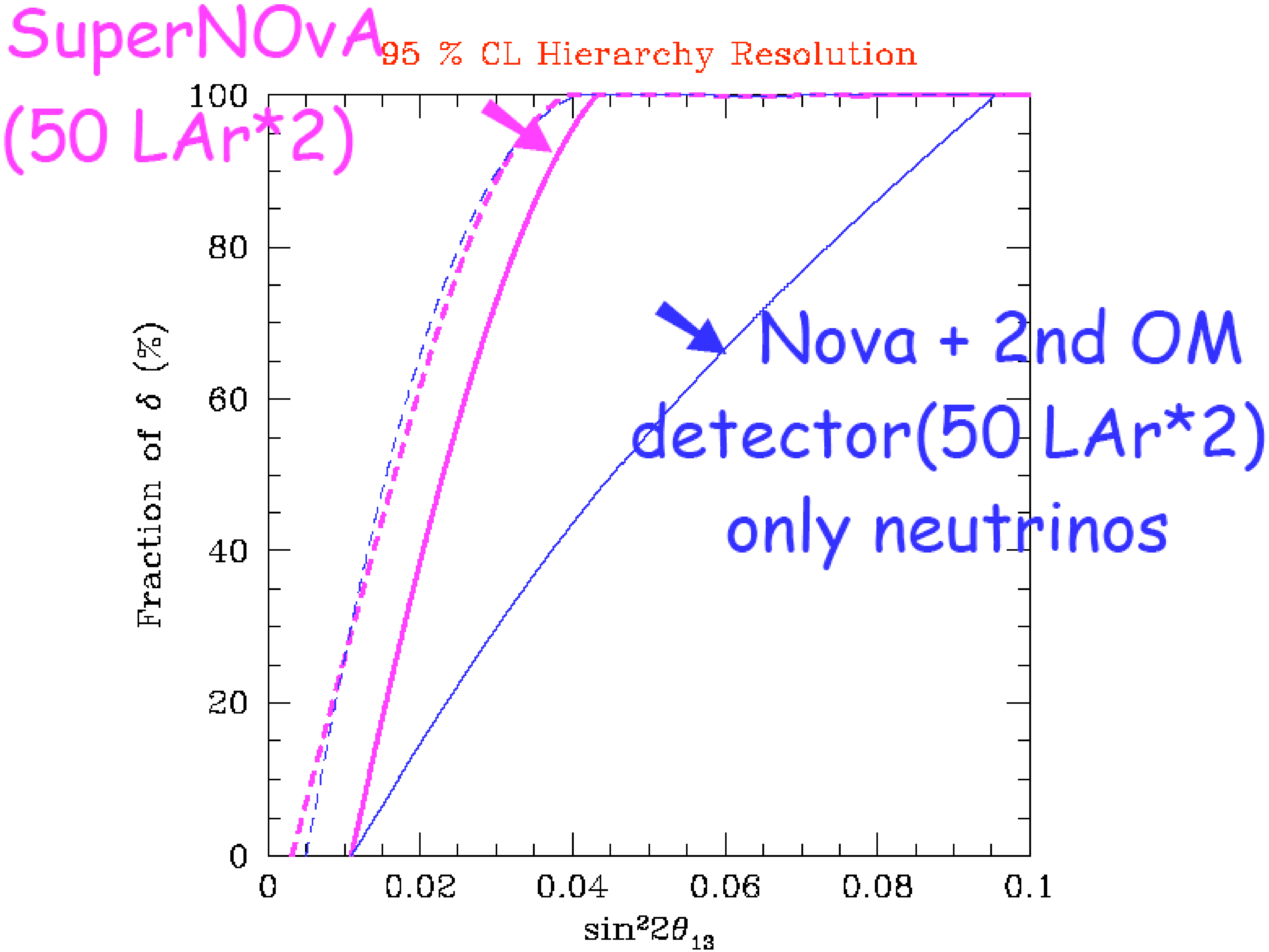
Thank you very much!

J. Burguet-Castell, A. Cervera, J. Cooper, A. Donini,
G. Feldman, B. Gavela, JJ. Gomez, P. Hernandez, H.Nunokawa,
S. Palomares, A. Para, S. Parke, S. Pascoli, S.Rigolin

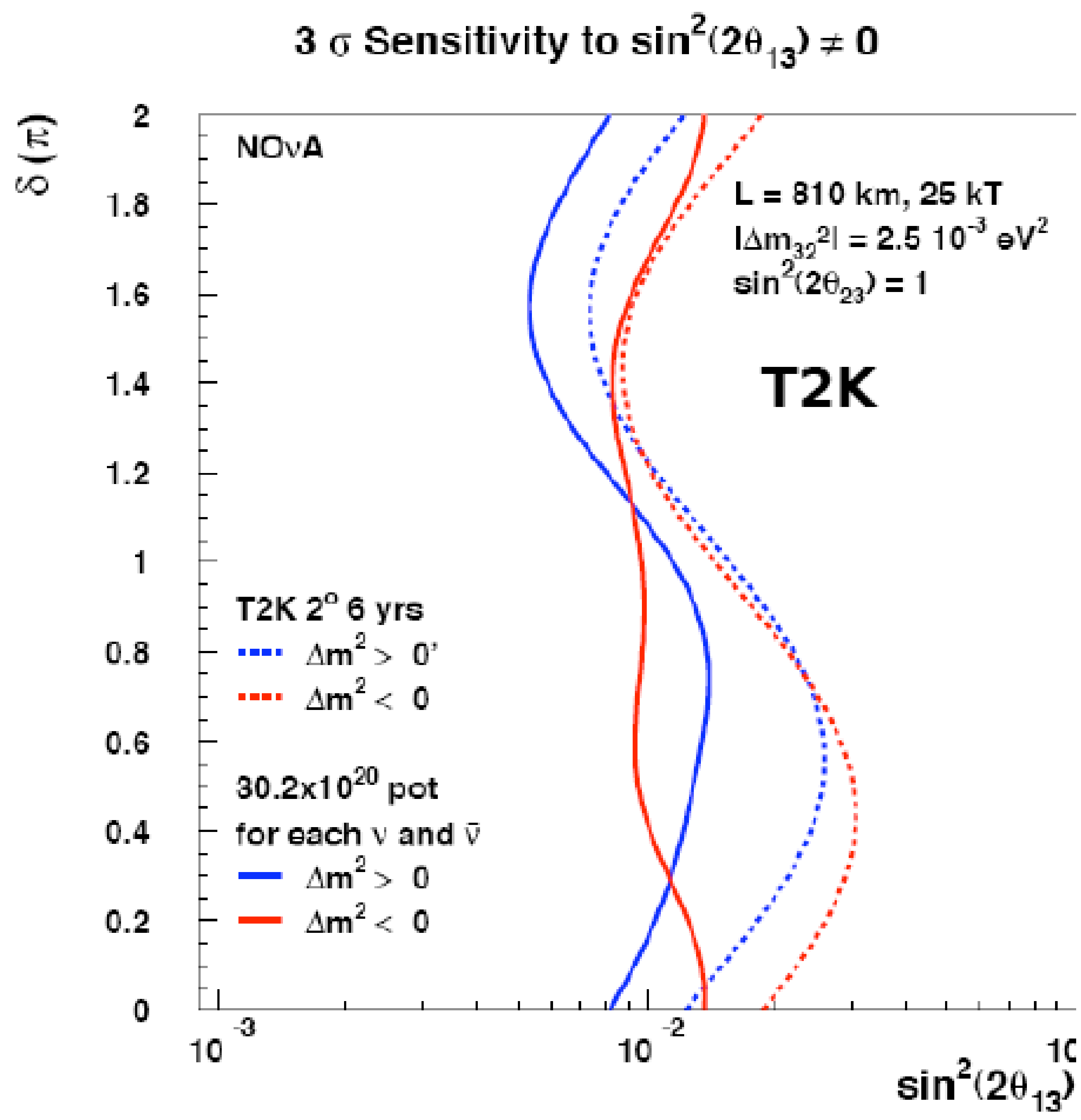
Why a near detector is better than @ second peak?

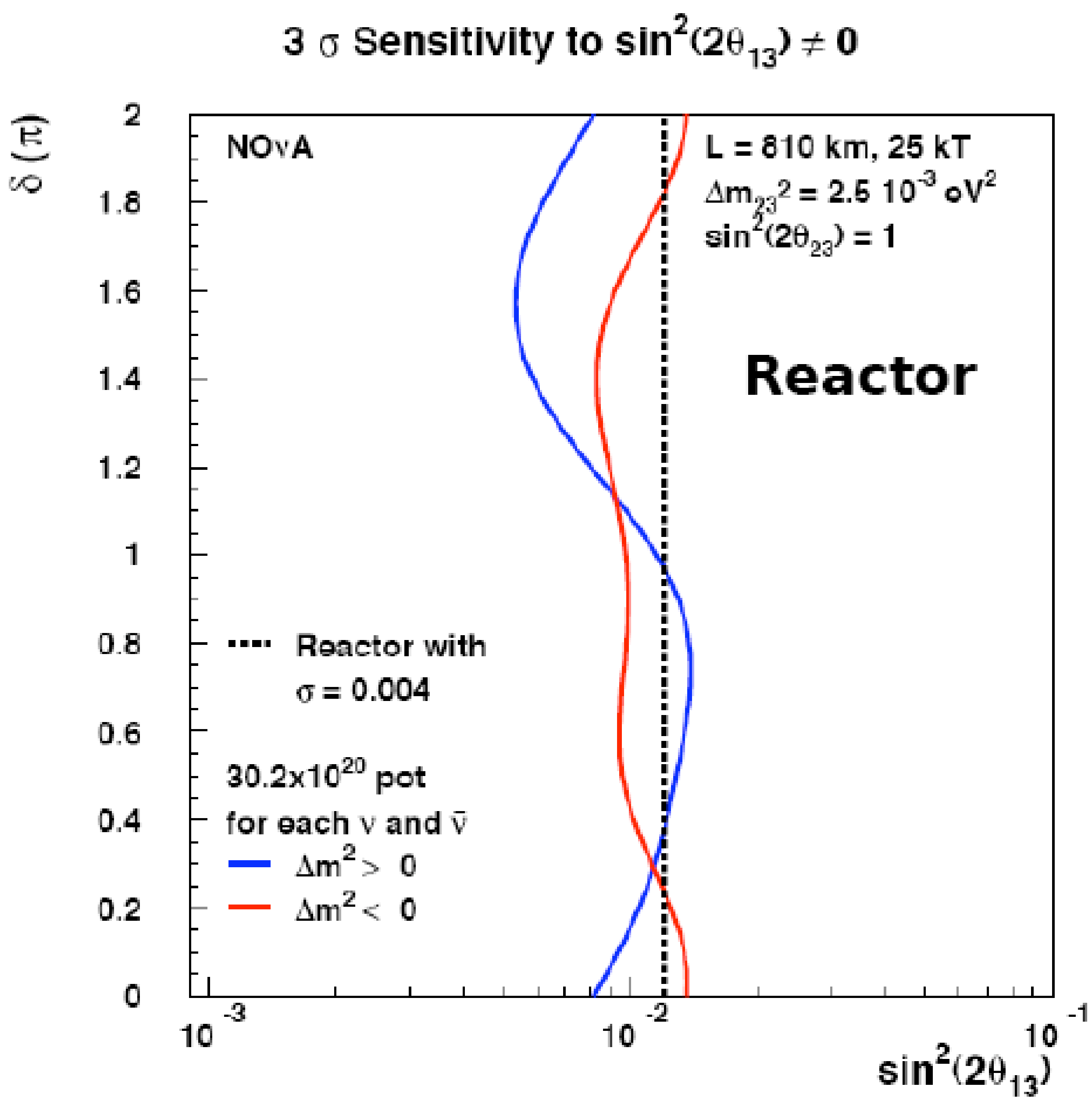
Because it needs just half exposure

(only for Hierarchy, though!)



Comparison to T2K and a Reactor Experiment



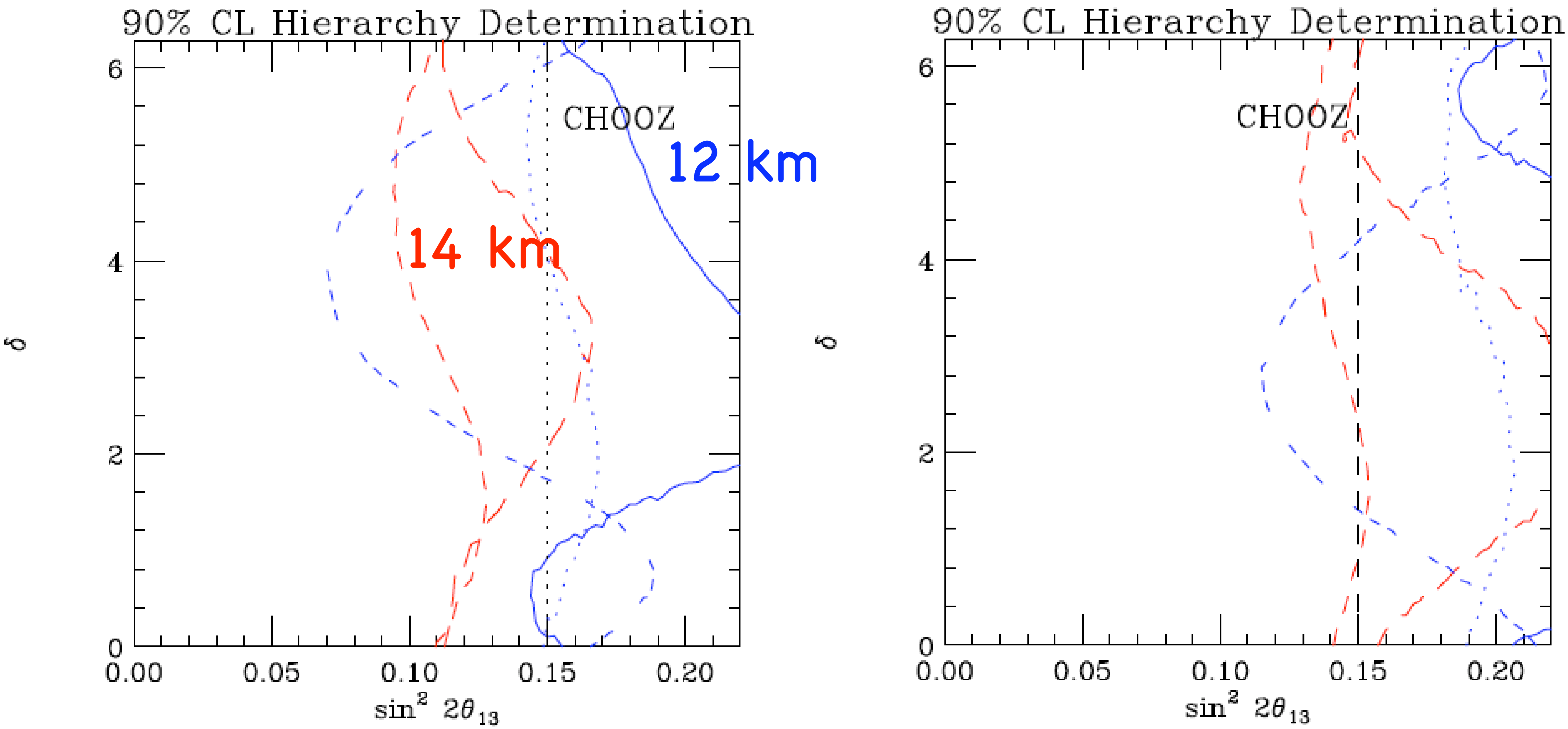


PHASE I (ONLY NEUTRINOS!)

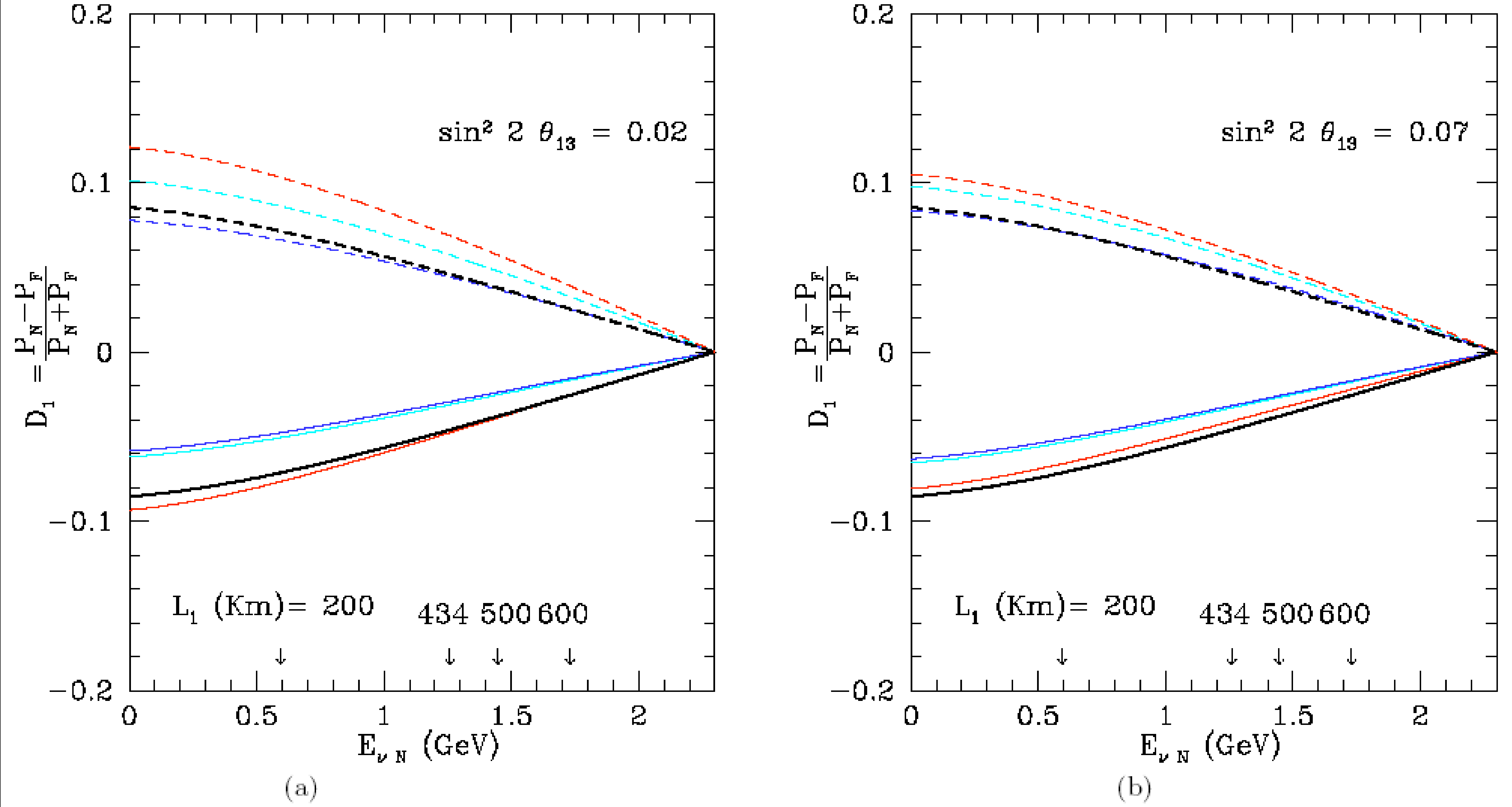
+ 4% Systematic Error

Normal hierarchy

Inverted hierarchy



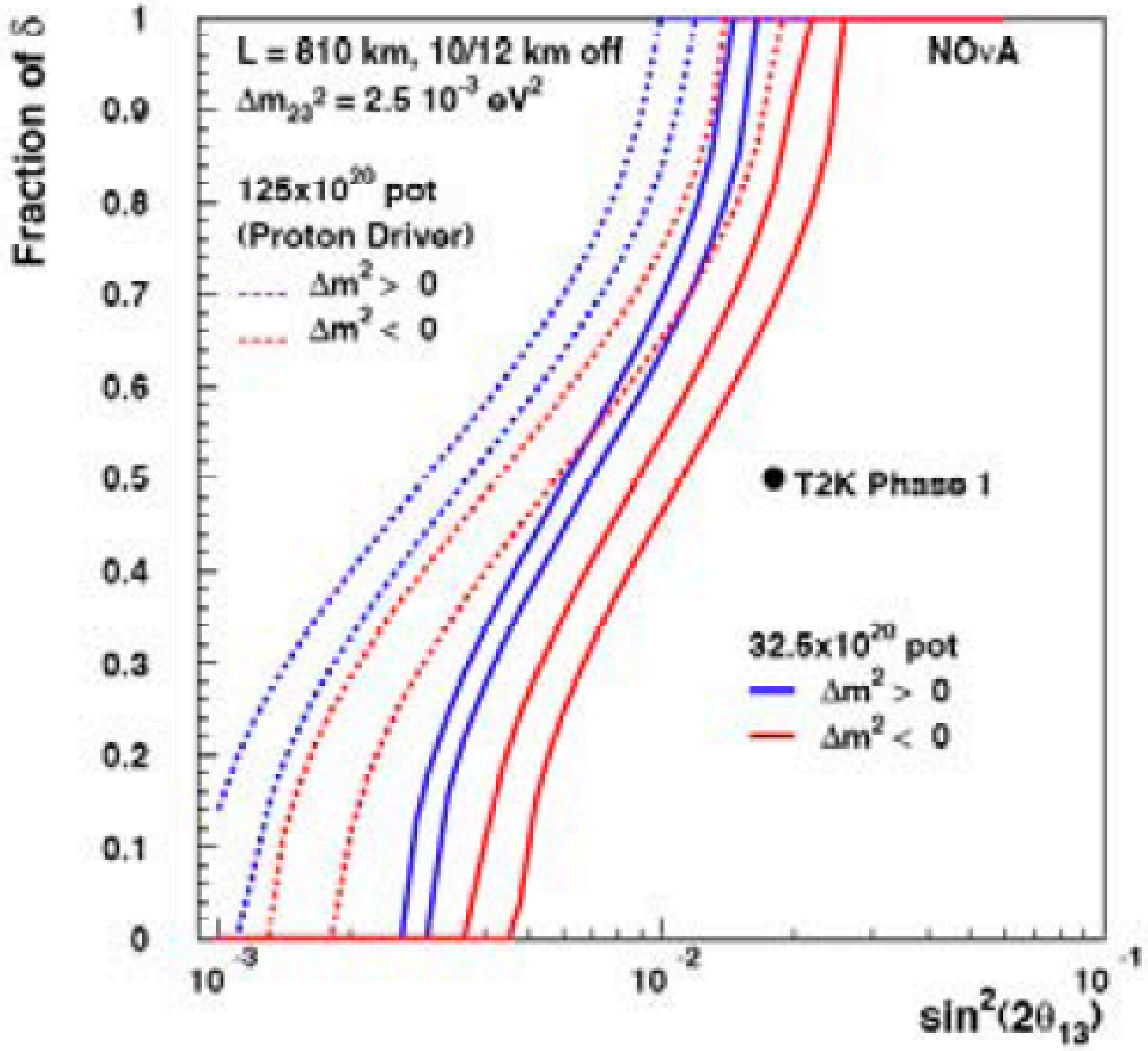
$$\Delta m^2_{13} = 2.4 \times 10^{-3}\ \mathbf{eV}^2$$



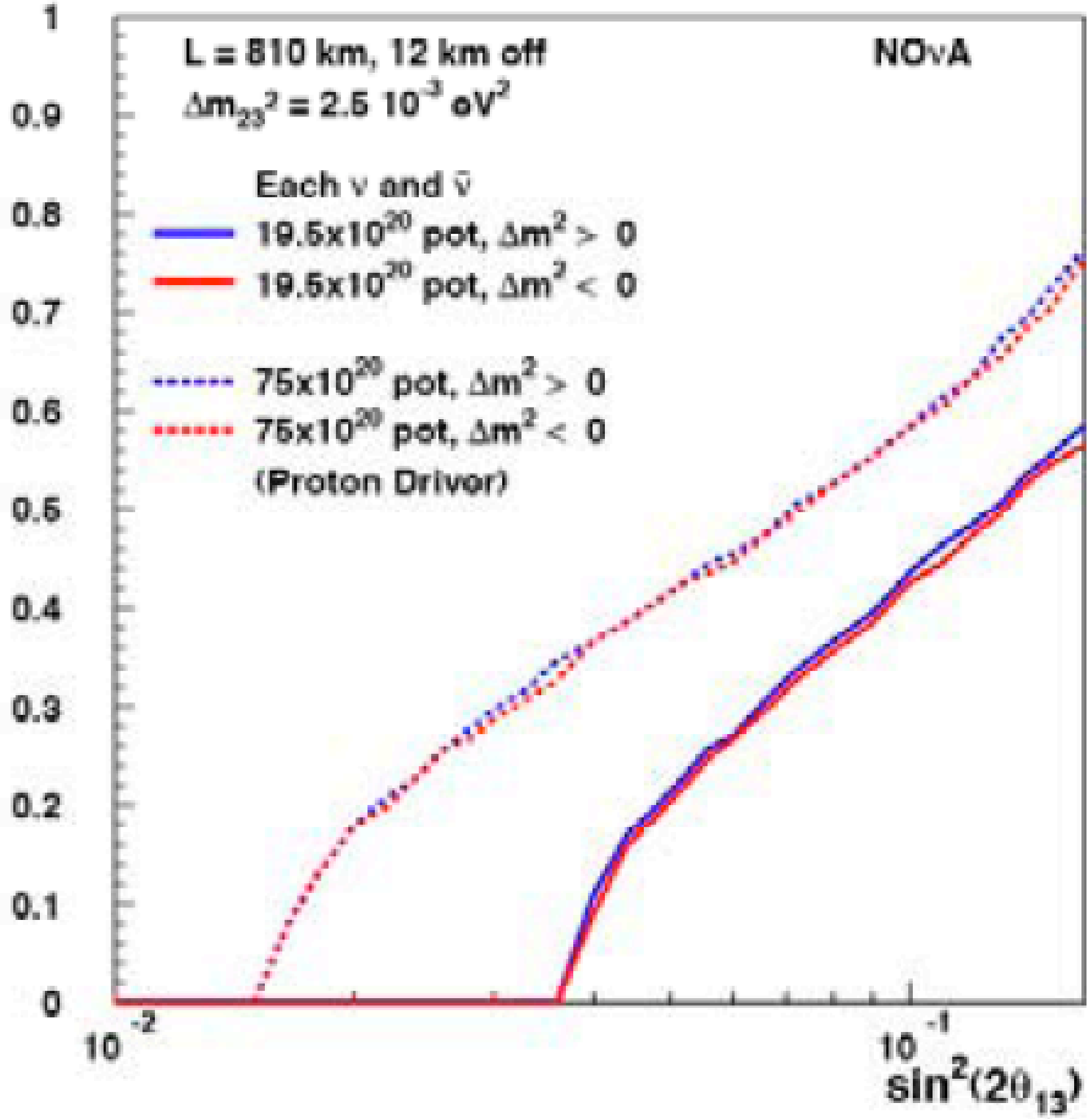
$$\mathcal{D}_1 \simeq \frac{A_N L_N - A_F L_F}{2} \left(\frac{1}{(\Delta_{13} L/2)} - \frac{1}{\tan(\Delta_{13} L/2)} \right)$$

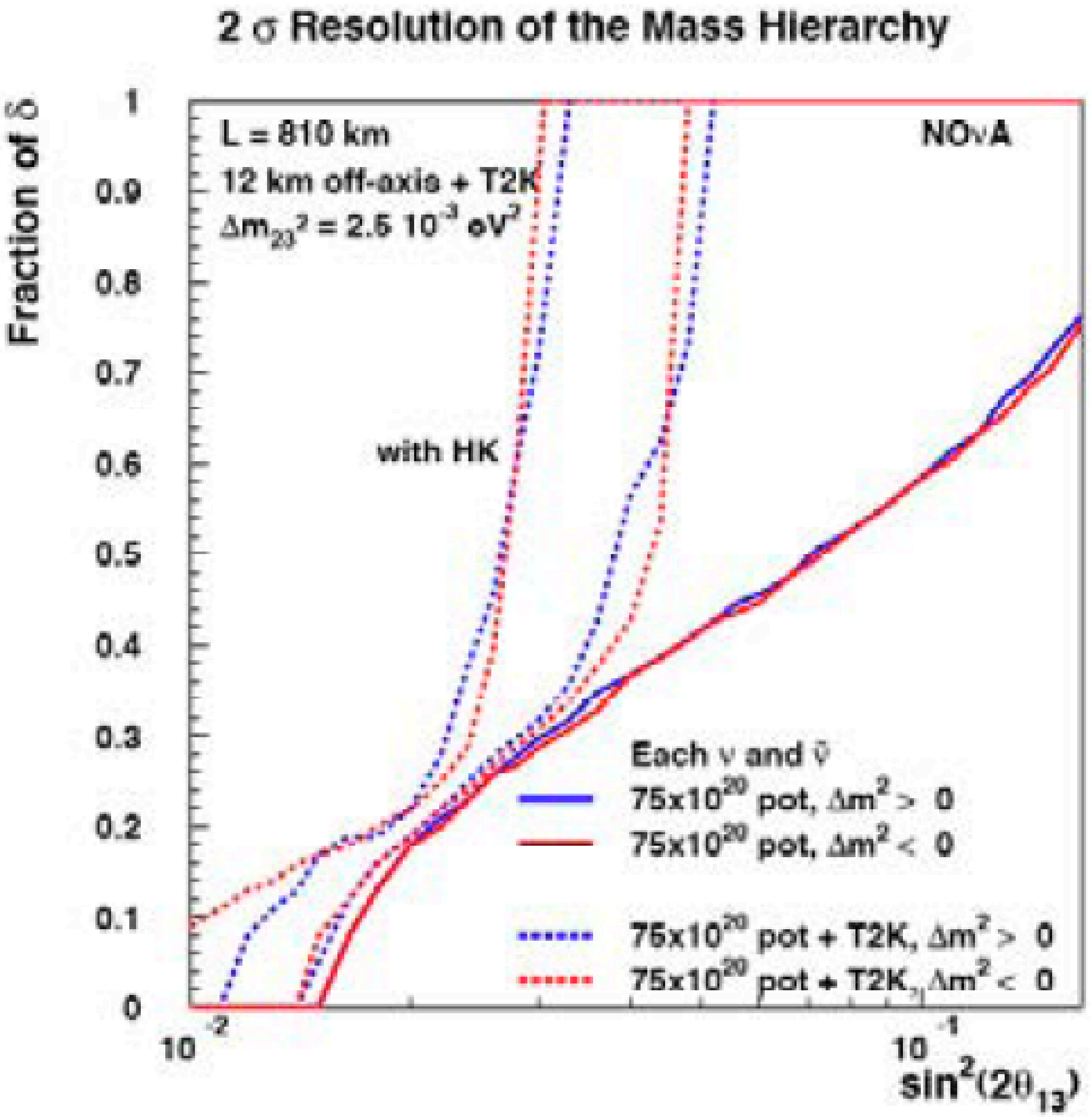
If the systematic errors are ~ 5% the sensitivity is ~0.02

3 σ Sensitivity to $\sin^2(2\theta_{13})$

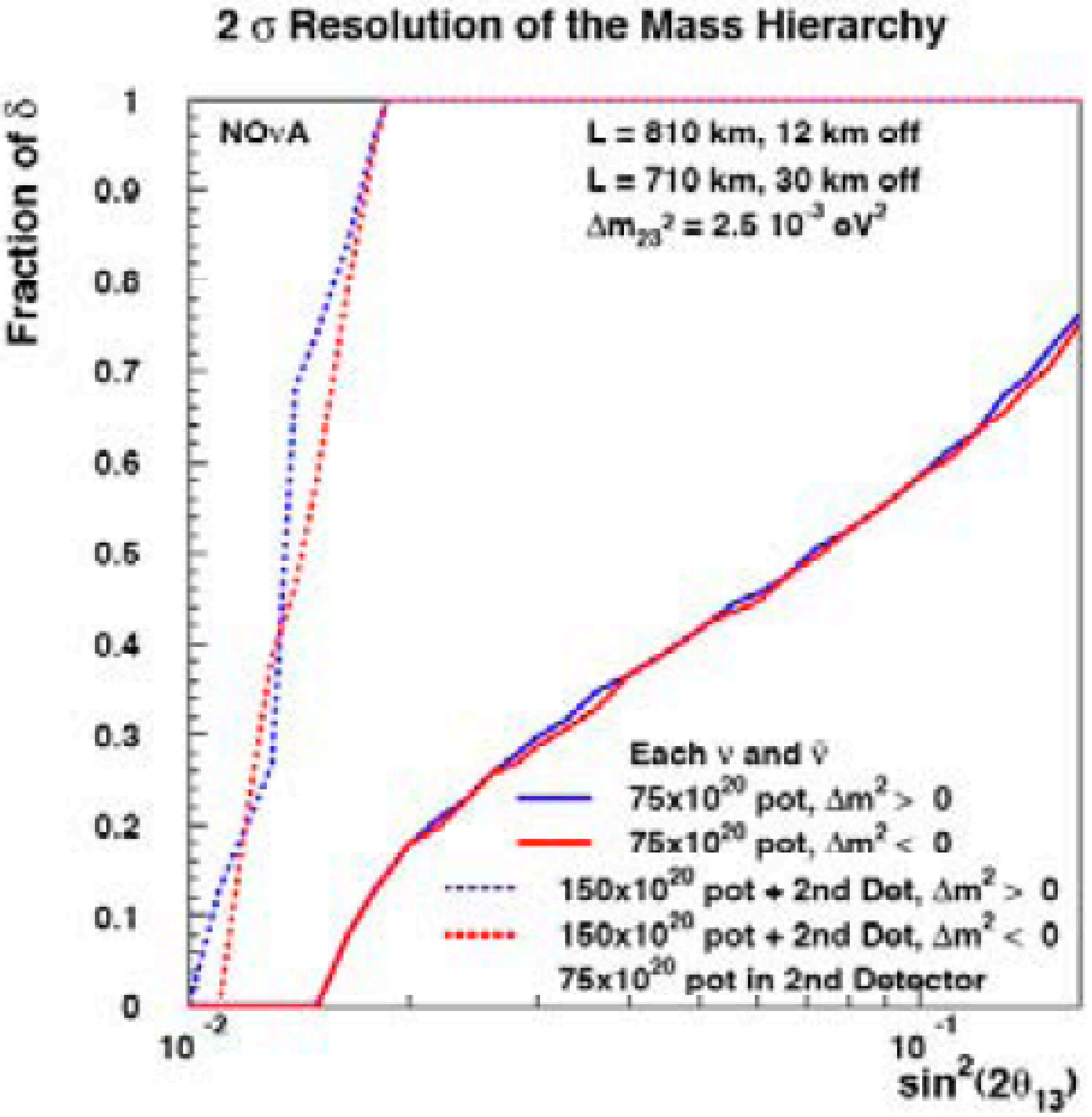


2 σ Resolution of the Mass Hierarchy

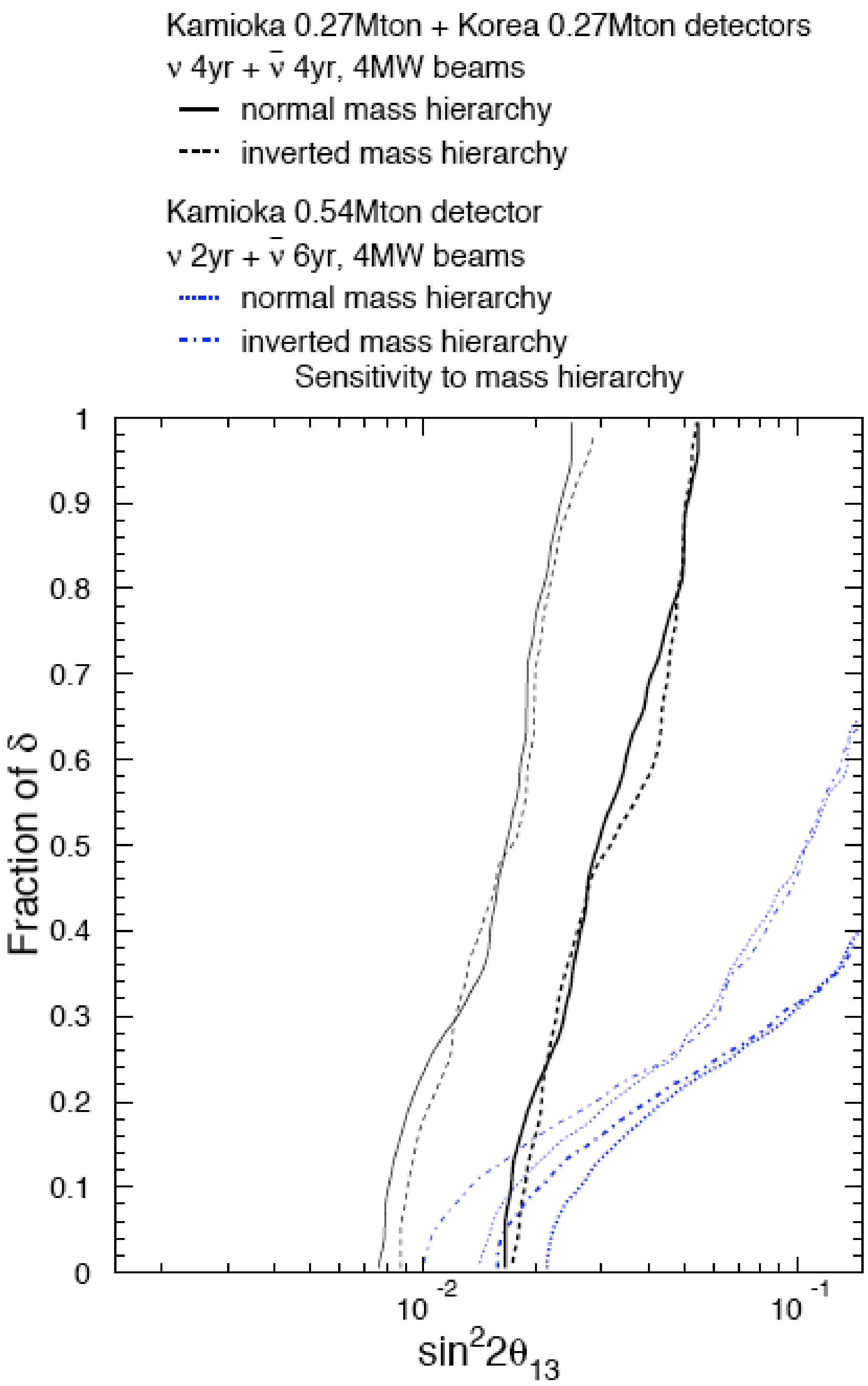




2 σ Resolution of the Mass Hierarchy

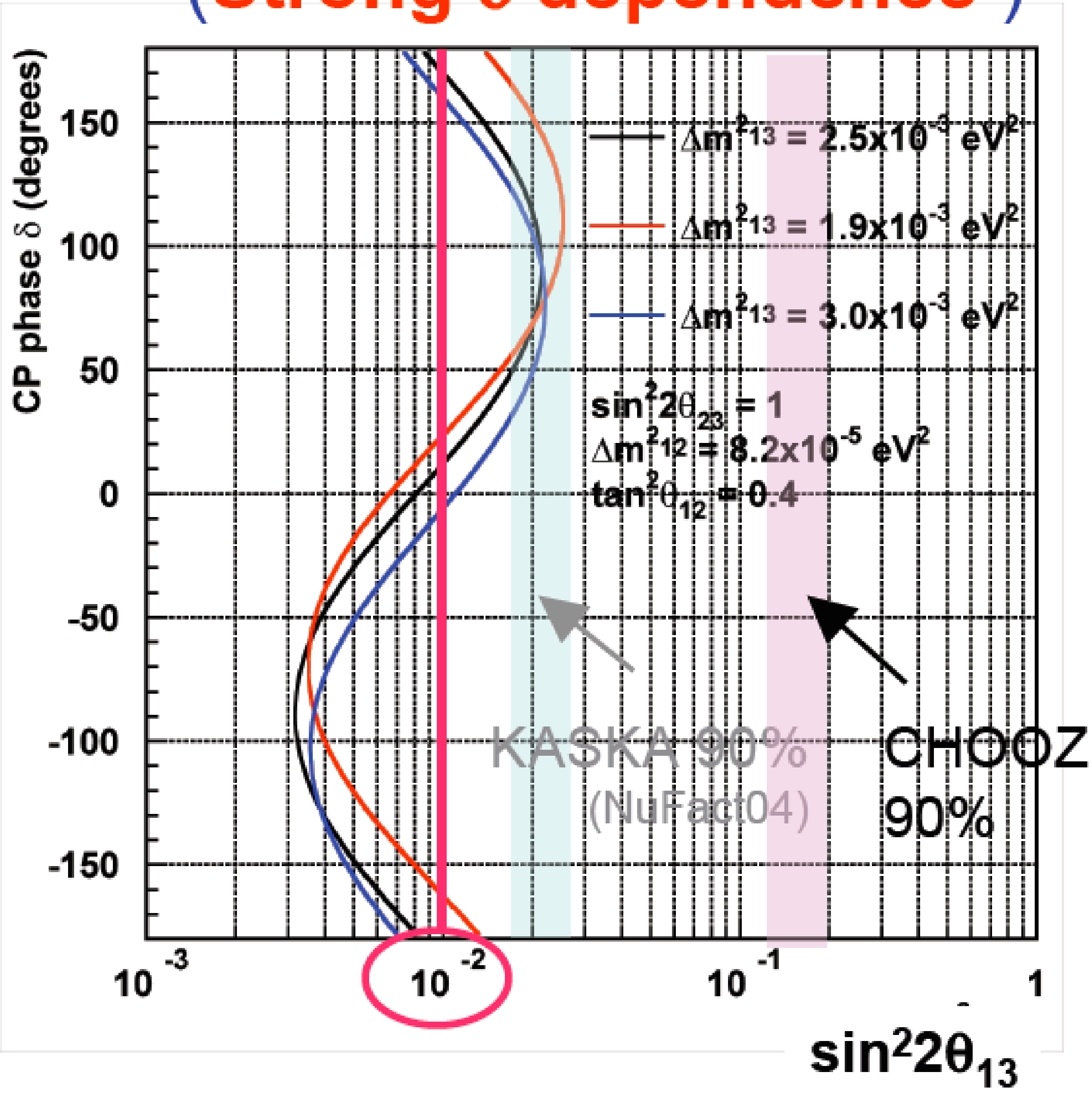


2 σ Resolution of the Mass Hierarchy



ν_e appearance

(Strong δ dependence)



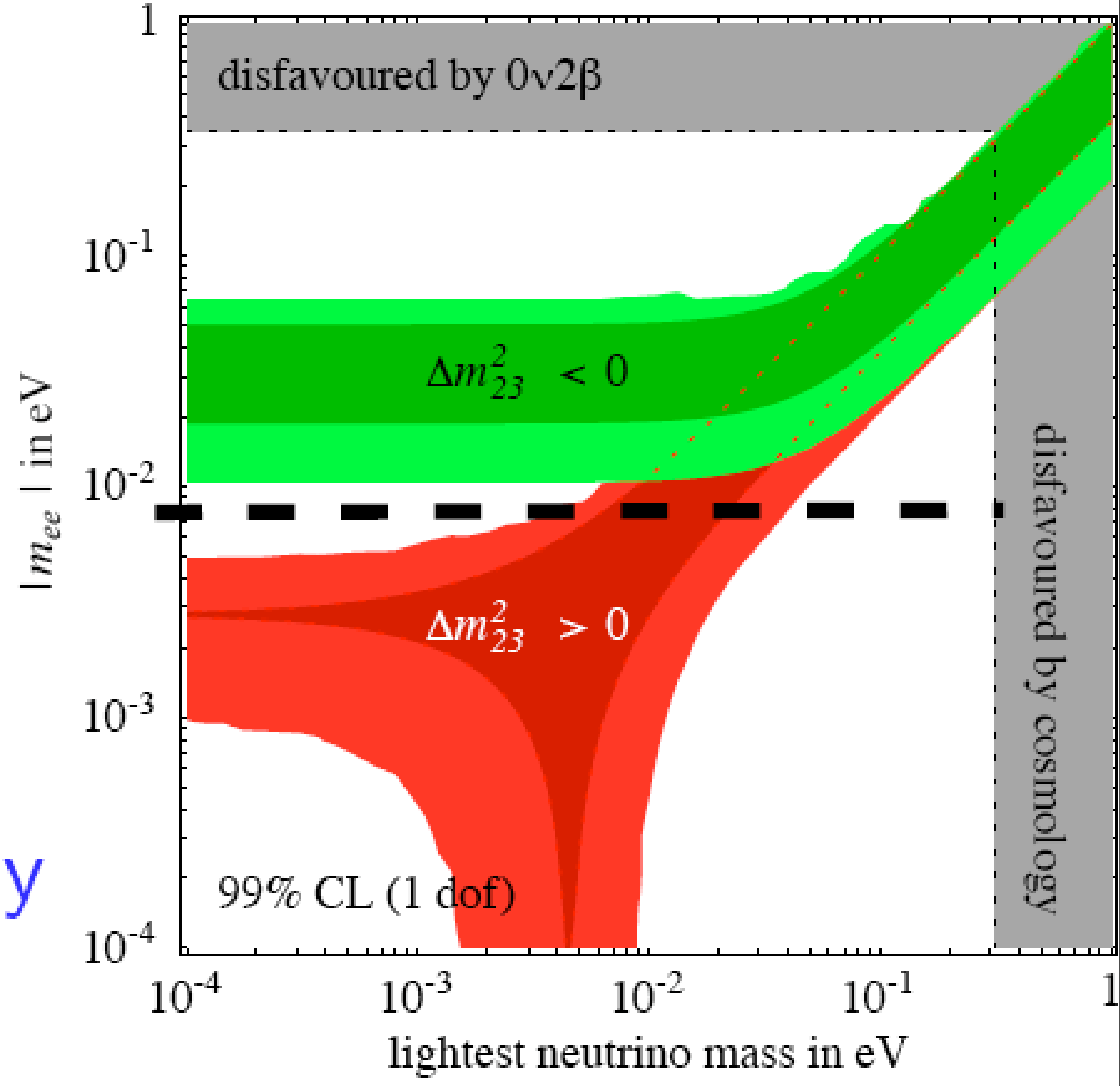
Ishitsuka, Kajita, Minakata and Nunokawa, PRD(2005)

Aihara

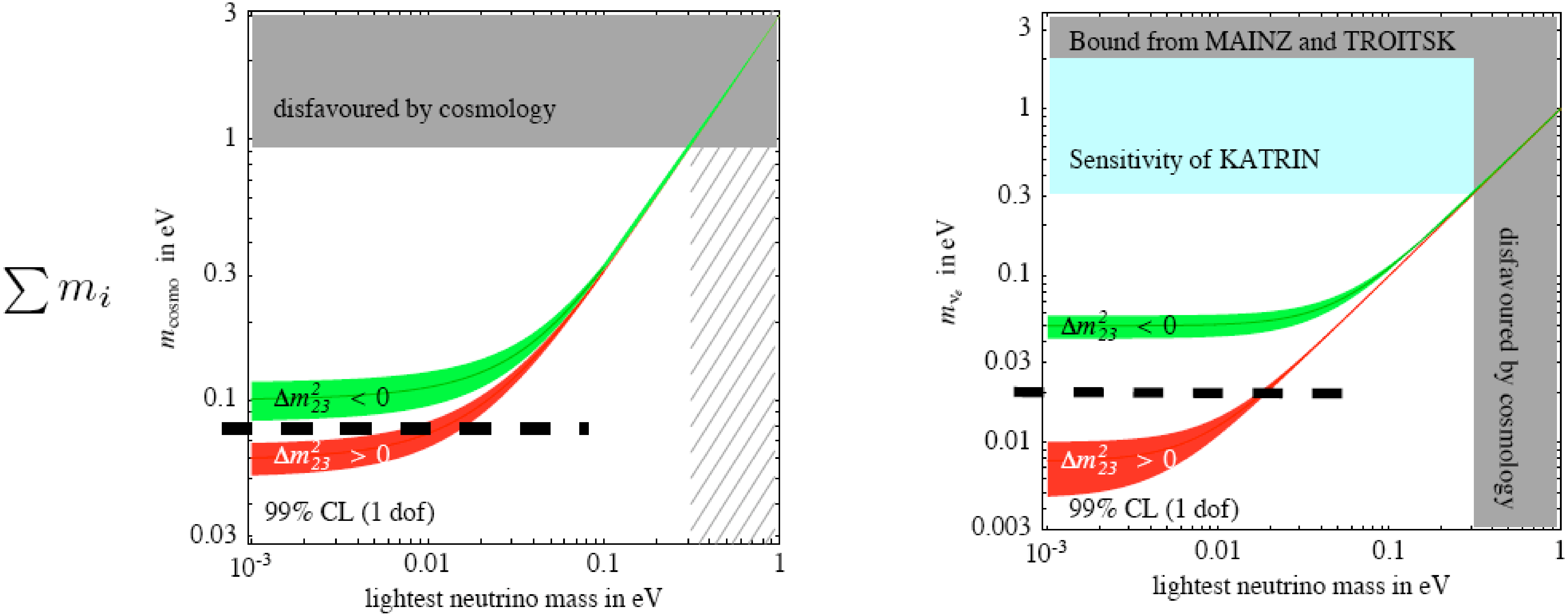
$$< m >_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$

$$= \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\beta} + m_3 s_{13}^2 e^{2i(\gamma-\delta)} \right|$$

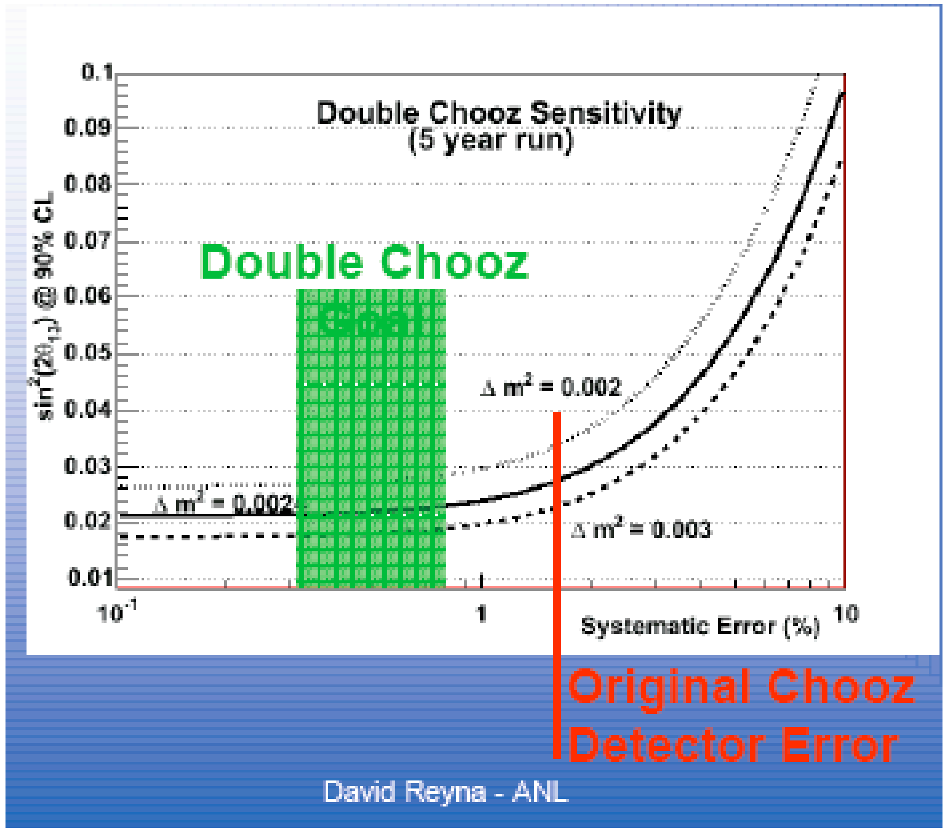
dividing point $m_{\beta\beta} \approx 10meV$ ⇒⇒

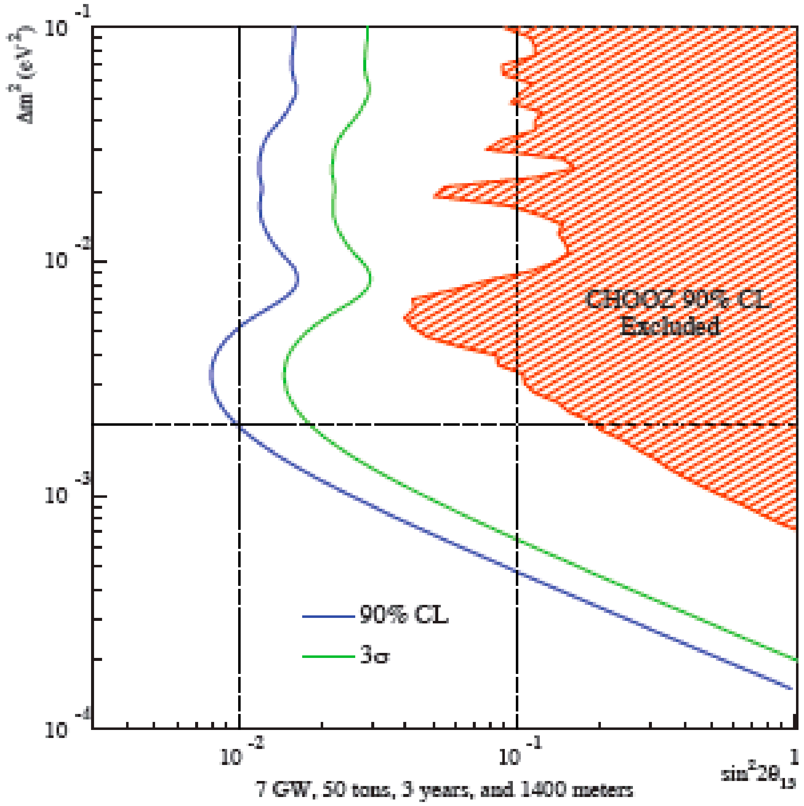


Signal below ∼ 10 meV would imply Majorana and Normal Hierarchy!



Similarly, if Tritium decay exp. (Hyper-Katrin) could exclude $m_{\nu_e} > \frac{1}{30}\ eV$, then Normal Hierarchy.





J. Link, Columbia

- Pure measurement of $\sin^2\theta_{13}$ — no contamination from $\theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23}$ degeneracy.

With Off-axis measurements of $\nu_\mu \to \nu_e$:

- of $\sin^2\theta_{23}\sin^2\theta_{13}$ can help resolve $\theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23}$ degeneracy for $\sin^2 2\theta_{23} \neq 1$.
- Help resolve hierarchy and $\sin\delta \neq 0$, maybe.

CONVERSION TABLE (A la spanish, CHULETA)

θ_{13} (*A la european*)	$\sin^2 2\theta_{13}$ (*A la american*)	**Experiment**
9^o	0.1	CHOOZ (present bound)
6^o	0.04	MINOS
3^o	0.01	Future reactors.
$3^o - 1^o$	0.01-0.001	JPARC, NuMI OffAxis.
$< 1^o$	0.001	Neutrino factory.

1 MASS GAP DOMINANCE:Δm^2_{13}

$$P_{\nu_e\nu_e(\bar{\nu}_e\bar{\nu}_e)} = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{13}\, L}{2}\right) \;,$$

$$\mathsf{P}_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = \sin^2 2\theta_{13}\; \sin^2\theta_{23}\; \sin^2\left(\frac{\Delta_{13}\, L}{2}\right) \;,$$

$$\mathsf{P}_{\nu_e\nu_\tau(\bar{\nu}_e\bar{\nu}_\tau)} = \sin^2 2\theta_{13}\; \cos^2\theta_{23}\; \sin^2\left(\frac{\Delta_{13}\, L}{2}\right) \;,$$

$$\mathsf{P}_{\nu_\mu\nu_\mu(\bar{\nu}_\mu\bar{\nu}_\mu)} =$$

$$1 - \cos^4\theta_{13}\sin^2\theta_{23}(1 - \cos^2\theta_{13}\sin^2\theta_{23})\; \sin^2\left(\frac{\Delta_{13}\, L}{2}\right) \;,$$

$$\mathsf{P}_{\nu_\mu\nu_\tau(\bar{\nu}_\mu\bar{\nu}_\tau)} = \cos^4\theta_{13}\; \sin^2 2\theta_{23}\; \sin^2\left(\frac{\Delta_{13}\, L}{2}\right) \;.$$

1 MASS GAP DOMINANCE:Δm^2_{12}

$$P_{\nu_e \nu_e (\bar{\nu}_e \bar{\nu}_e)} \simeq 1 - \sin^2 2\theta_{12} \, \sin^2 \left(\frac{\Delta_{12} \, L}{2} \right) \, ,$$

$$\mathsf{P}_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} \simeq \cos^2 \theta_{23} \, \sin^2 2\theta_{12} \, \sin^2 \left(\tfrac{\Delta_{12} \, L}{2} \right) \, ,$$
$$\mathsf{P}_{\nu_e \nu_\tau (\bar{\nu}_e \bar{\nu}_\tau)} \simeq \sin^2 \theta_{23} \, \sin^2 2\theta_{12} \, \sin^2 \left(\tfrac{\Delta_{12} \, L}{2} \right) \, .$$

REACTORS

$$P_{\nu_e \nu_e (\bar{\nu}_e \bar{\nu}_e)} = 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta_{13} \, L}{2} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \, \sin^2 \left(\frac{\Delta_{12} \, L}{2} \right)$$