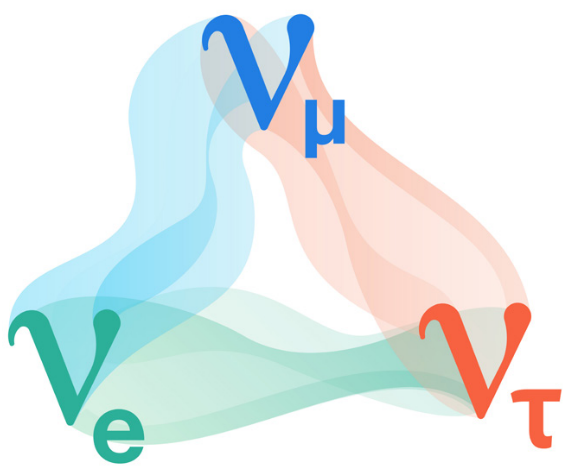
Neutrino Status circa 2018

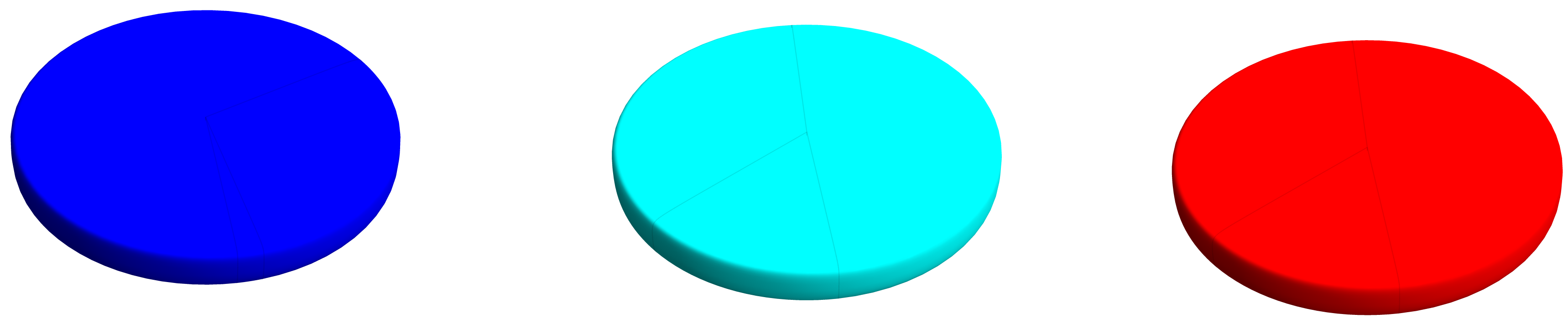
wrt

DUNE and the Fermilab Program

Flavor / Interactions States

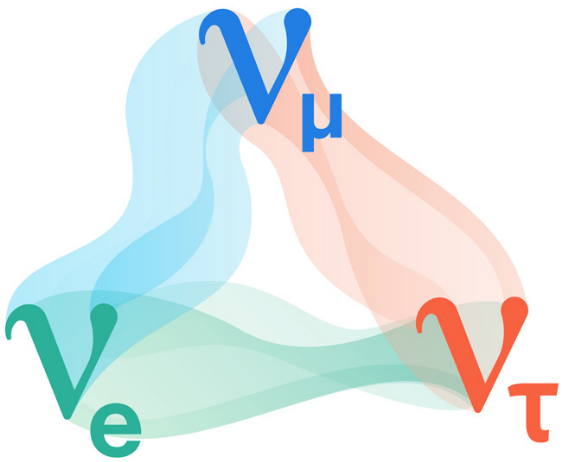


$W^+ \rightarrow e^+\nu_e$ $W^+ \rightarrow \mu^+\nu_\mu$ $W^+ \rightarrow \tau^+\nu_\tau$

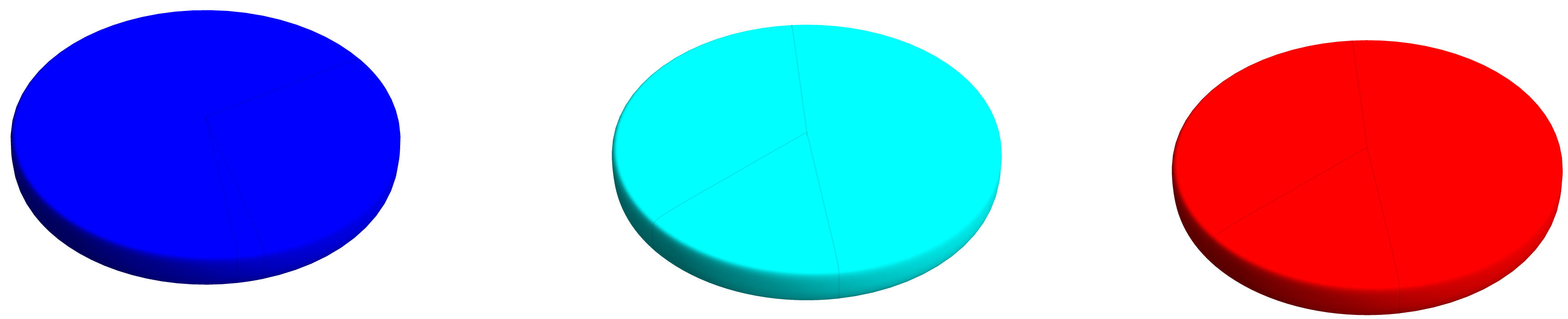


ν_e ν_μ ν_τ

Flavor / Interactions States

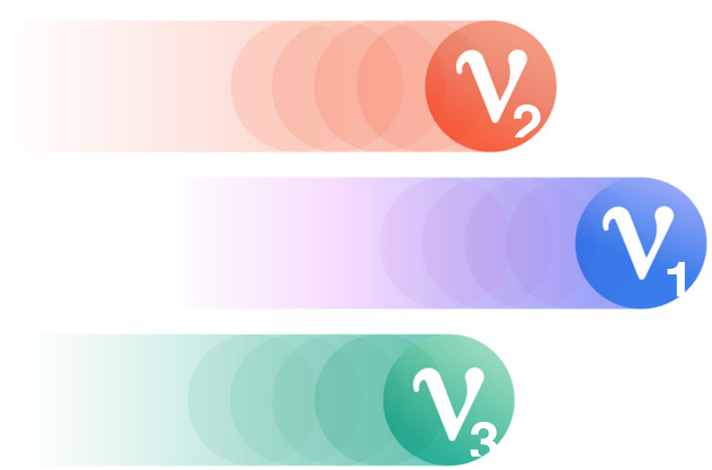


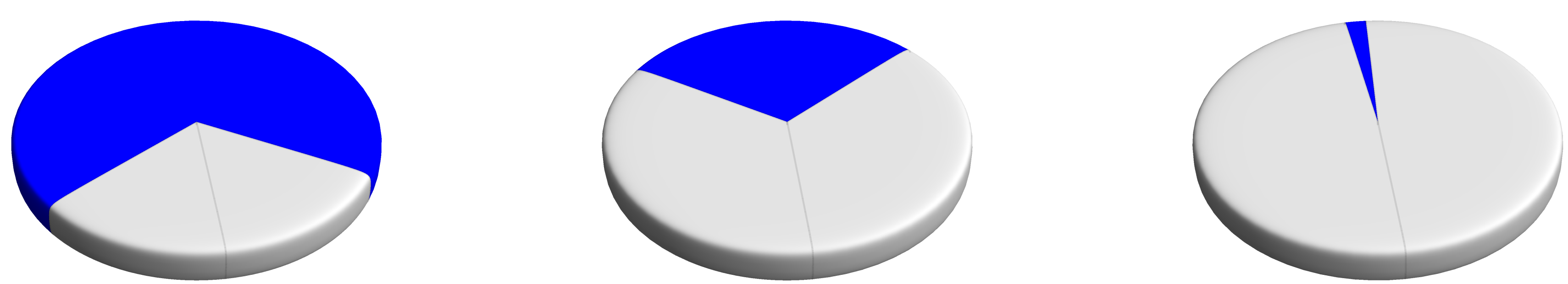
$W^+ \to e^+\nu_e$ $W^+ \to \mu^+\nu_\mu$ $W^+ \to \tau^+\nu_\tau$



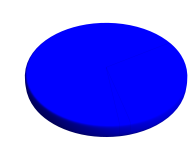
ν_e ν_μ ν_τ

Mass / Propagation States

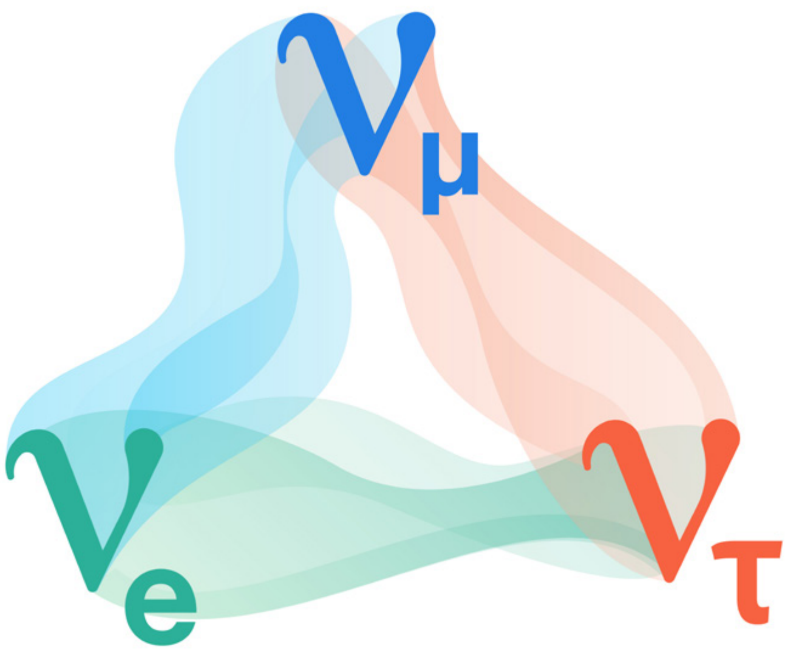




ν_1 ν_2 ν_3

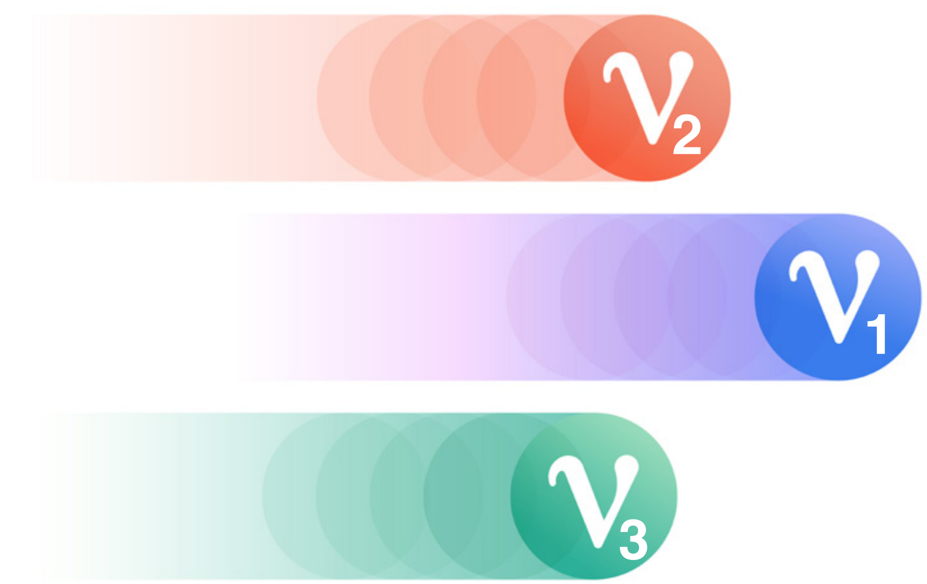
$\nu_e =$ 

Interactions

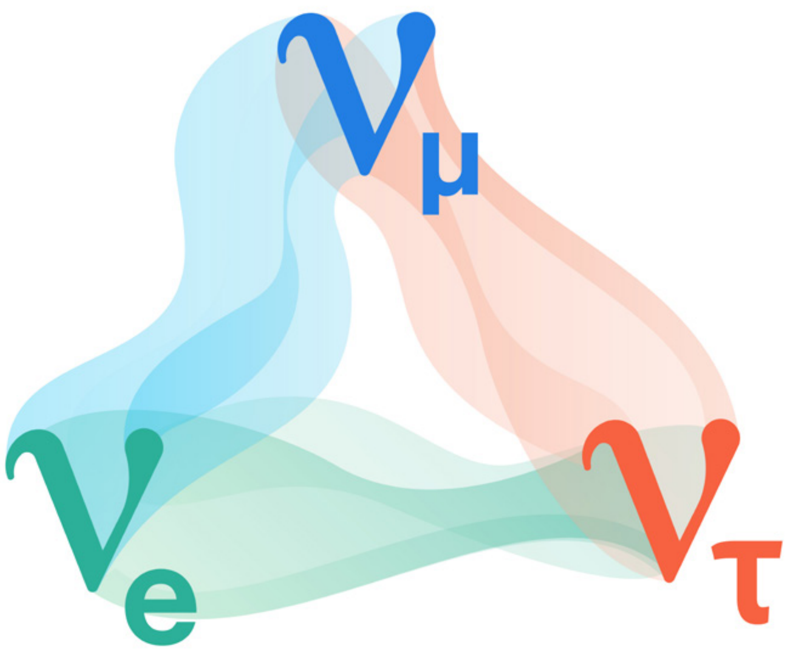


=U

Propagation



Interactions



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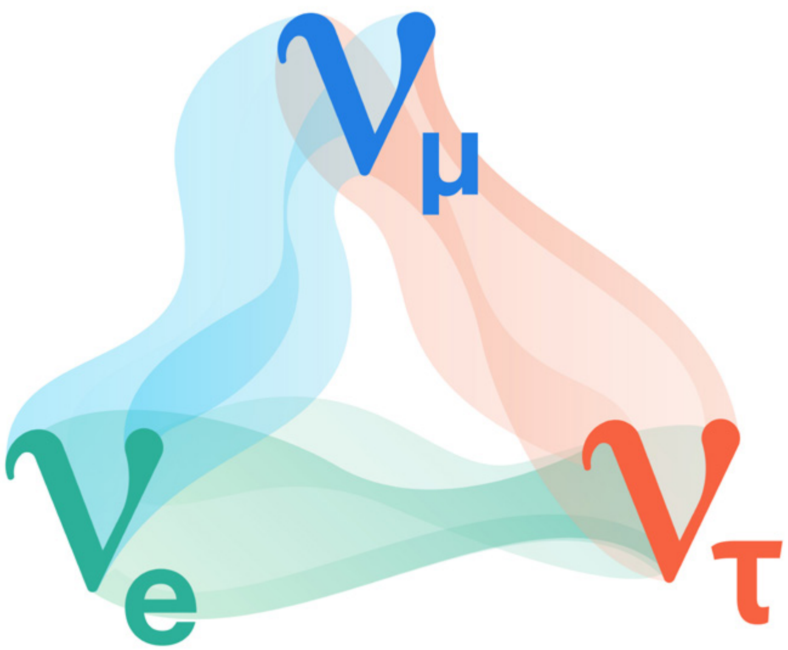
Propagation

ν_s ?

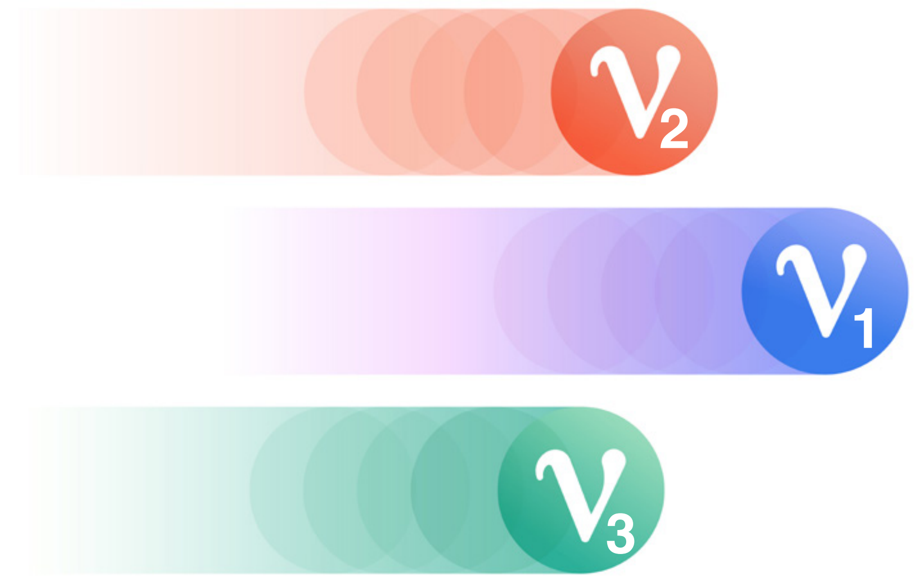
NSI ?

Interactions



=U

Propagation



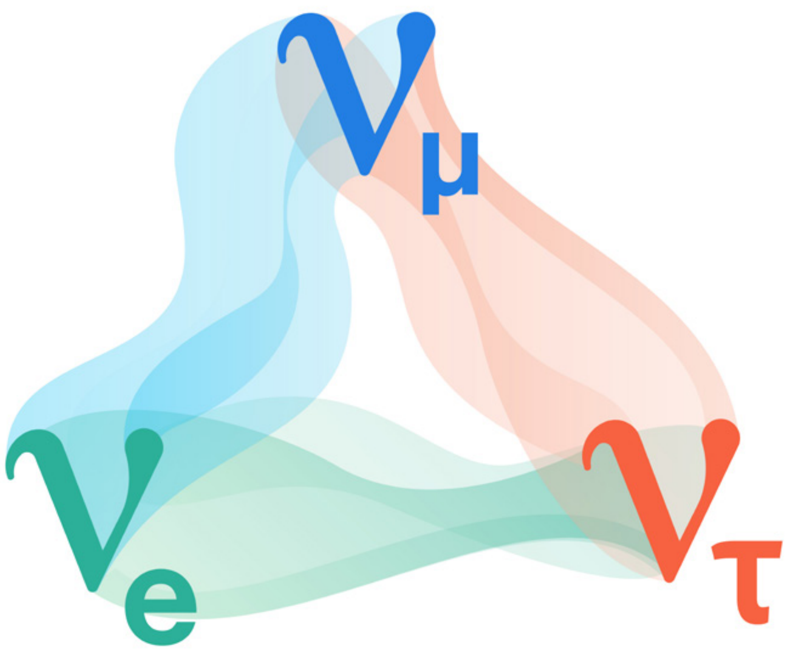
ν_s ?

CPV?

NSI ?

unitarity?

Interactions



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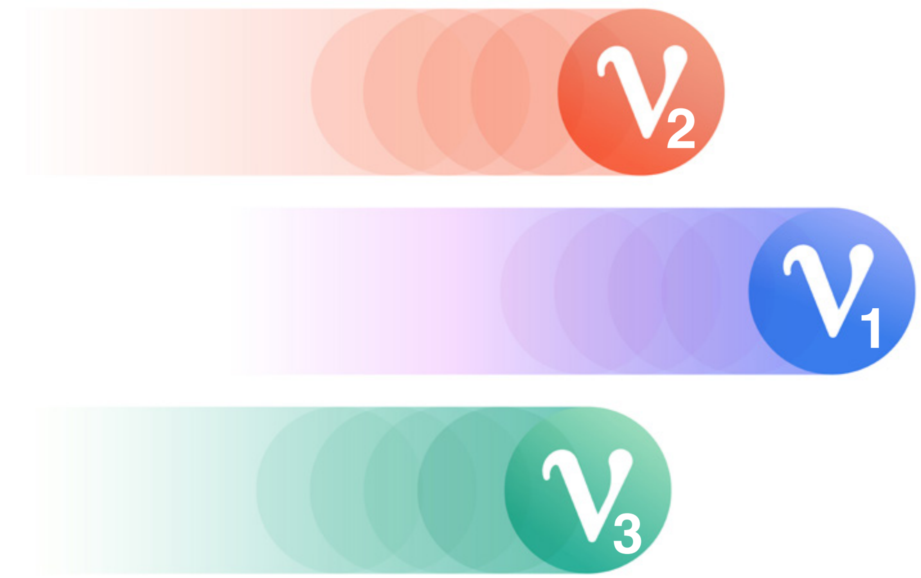
Propagation



ν_s ?

CPV?

masses ?

NSI ?

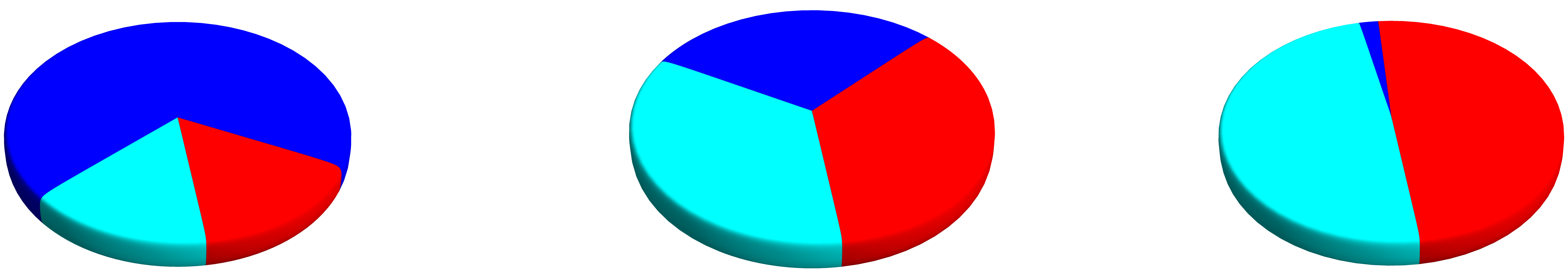
unitarity?

decays ?

Neutrino Mass EigenStates or Propagation States:

$$\text{Propagator } \nu_j \to \nu_k \;= \delta_{jk}\, e^{-i\left(\frac{m_j^2 L}{2E_\nu}\right)}$$

ν_1 most ν_e | ν_2 | ν_3 least ν_e



$\nu_e =$ (blue)

Solar Exp, SNO, SK,
KamiLAND
Daya Bay, RENO, …

$\nu_\mu =$ (cyan)

SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

$\nu_\tau =$ (red)

Unitarity
SK, Opera
ICECUBE

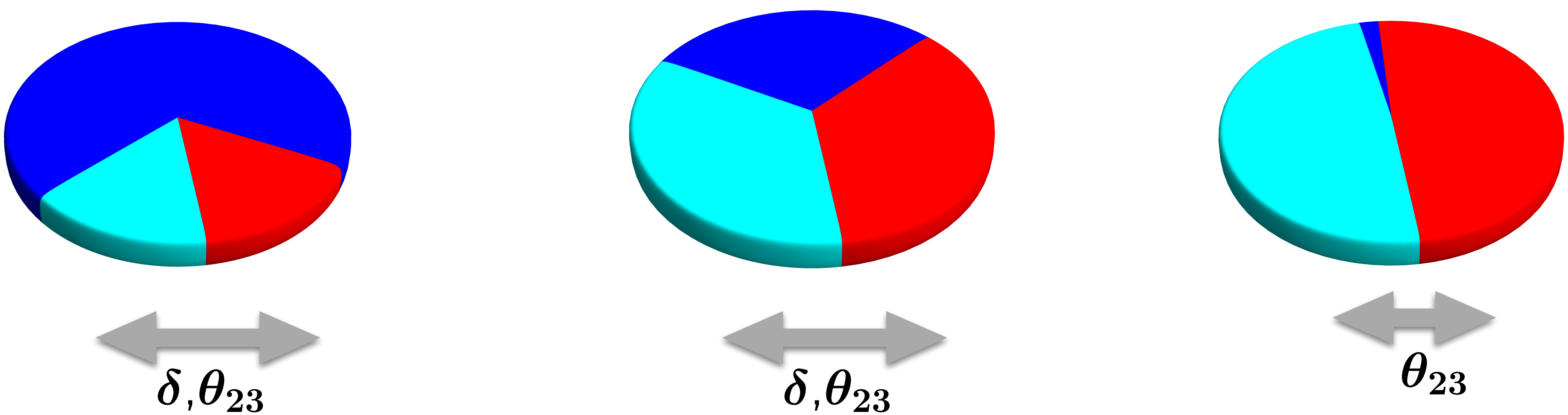
Neutrino Mass EigenStates or Propagation States:

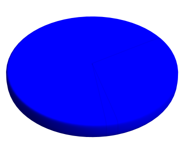
$$\text{Propagator } \nu_j \to \nu_k \;=\; \delta_{jk}\, e^{-i\left(\frac{m_j^2 L}{2E_\nu}\right)}$$

ν_1 most ν_e

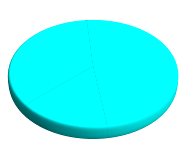
ν_2

ν_3 least ν_e

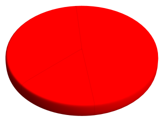


$\nu_e =$ 

Solar Exp, SNO, SK, KamiLAND
Daya Bay, RENO, …

$\nu_\mu =$ 

SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

$\nu_\tau =$ 

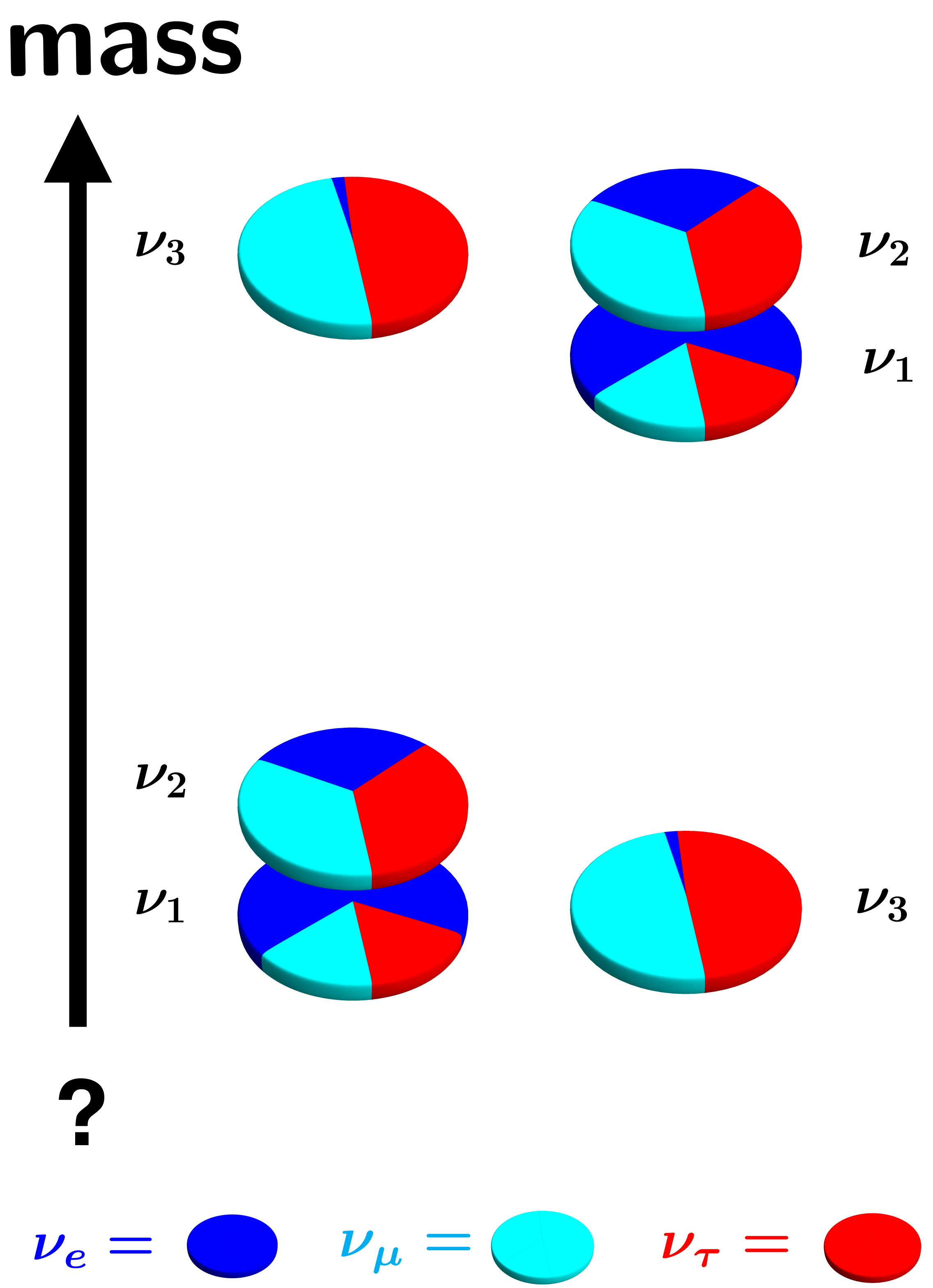
Unitarity
SK, Opera
ICECUBE

Within Three Neutrino Paradigm:

- Majorana or Dirac (2 or 4 states)
- Mass Ordering
- Dominant Flavor of ν_3
- CP violation parameter δ
- Mass of lightest ν_j

ν_3, ν_1/ν_2 Mass Ordering:

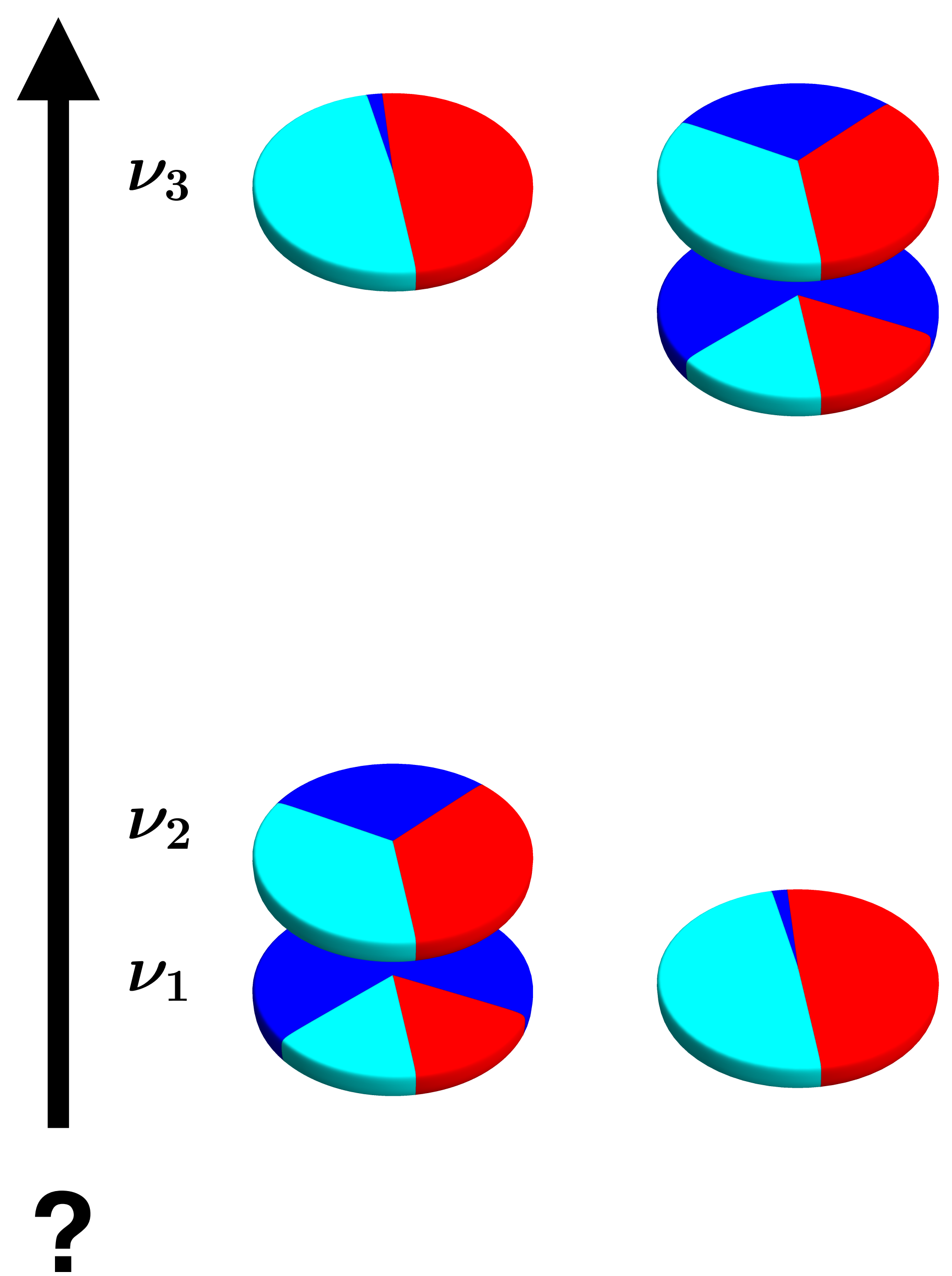
–atmospheric mass ordering

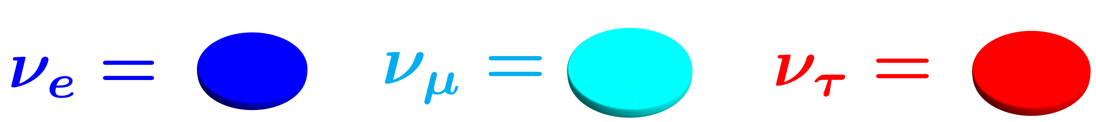


ν_3, ν_1/ν_2 Mass Ordering:

−atmospheric mass ordering

mass

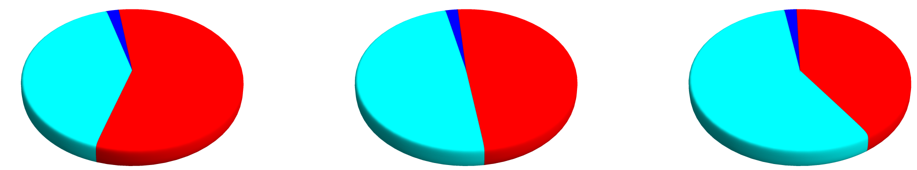




Octant of θ_{23}

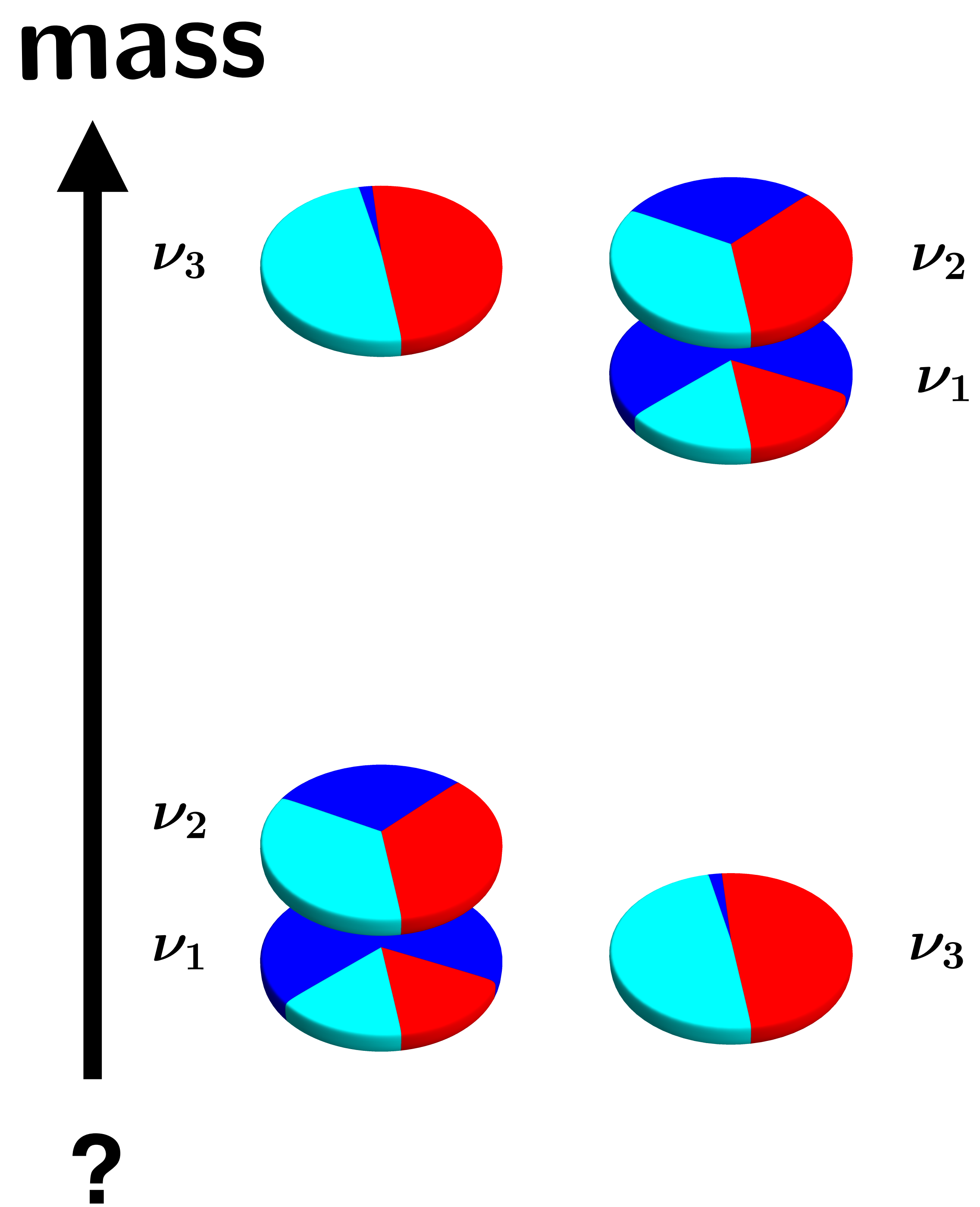
$\sin^2\theta_{23}$	0.40	0.50	0.60

ν_3



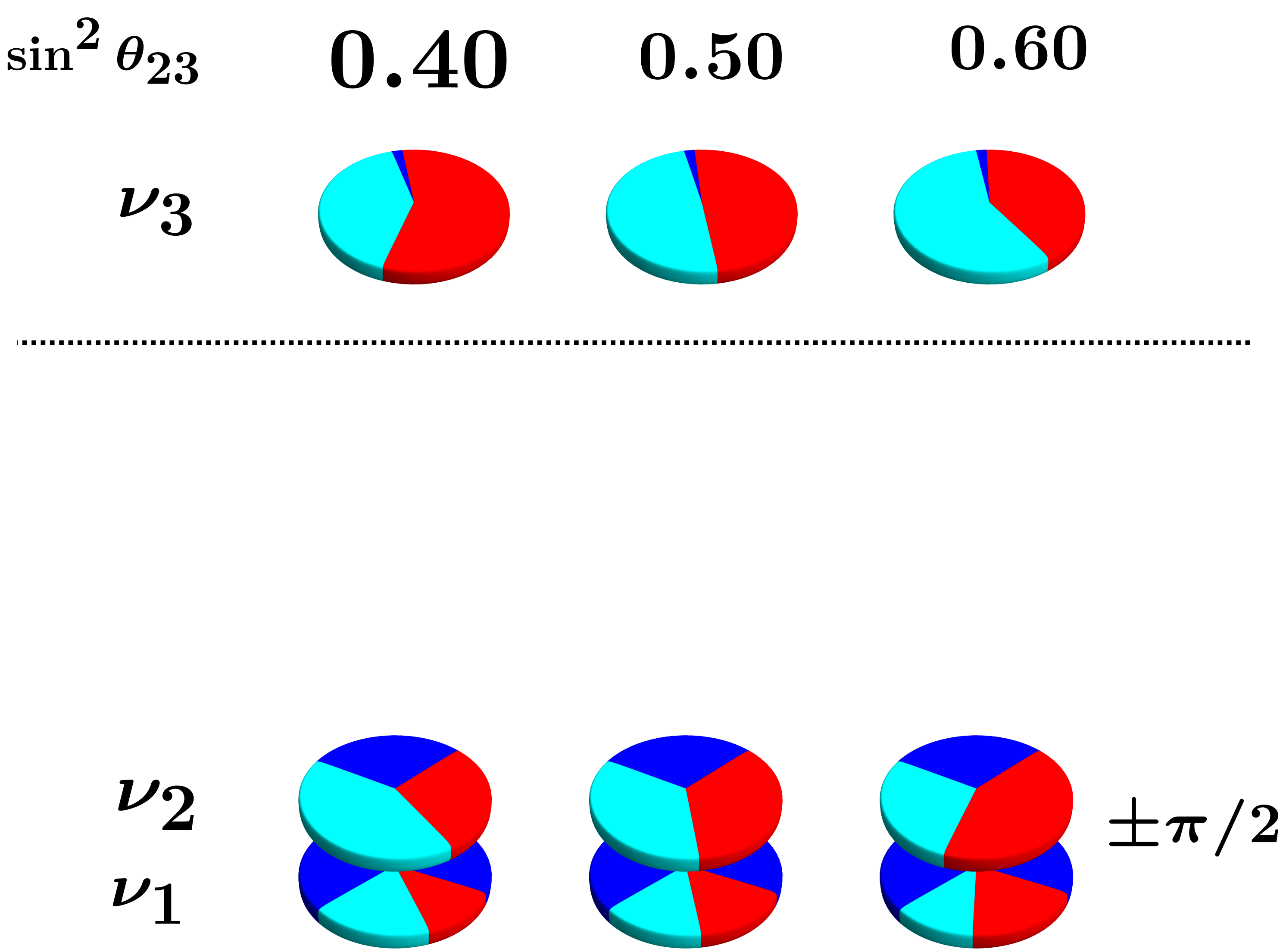
ν_3, ν_1/ν_2 Mass Ordering:

–atmospheric mass ordering



$\nu_e =$ $\nu_\mu =$ $\nu_\tau =$

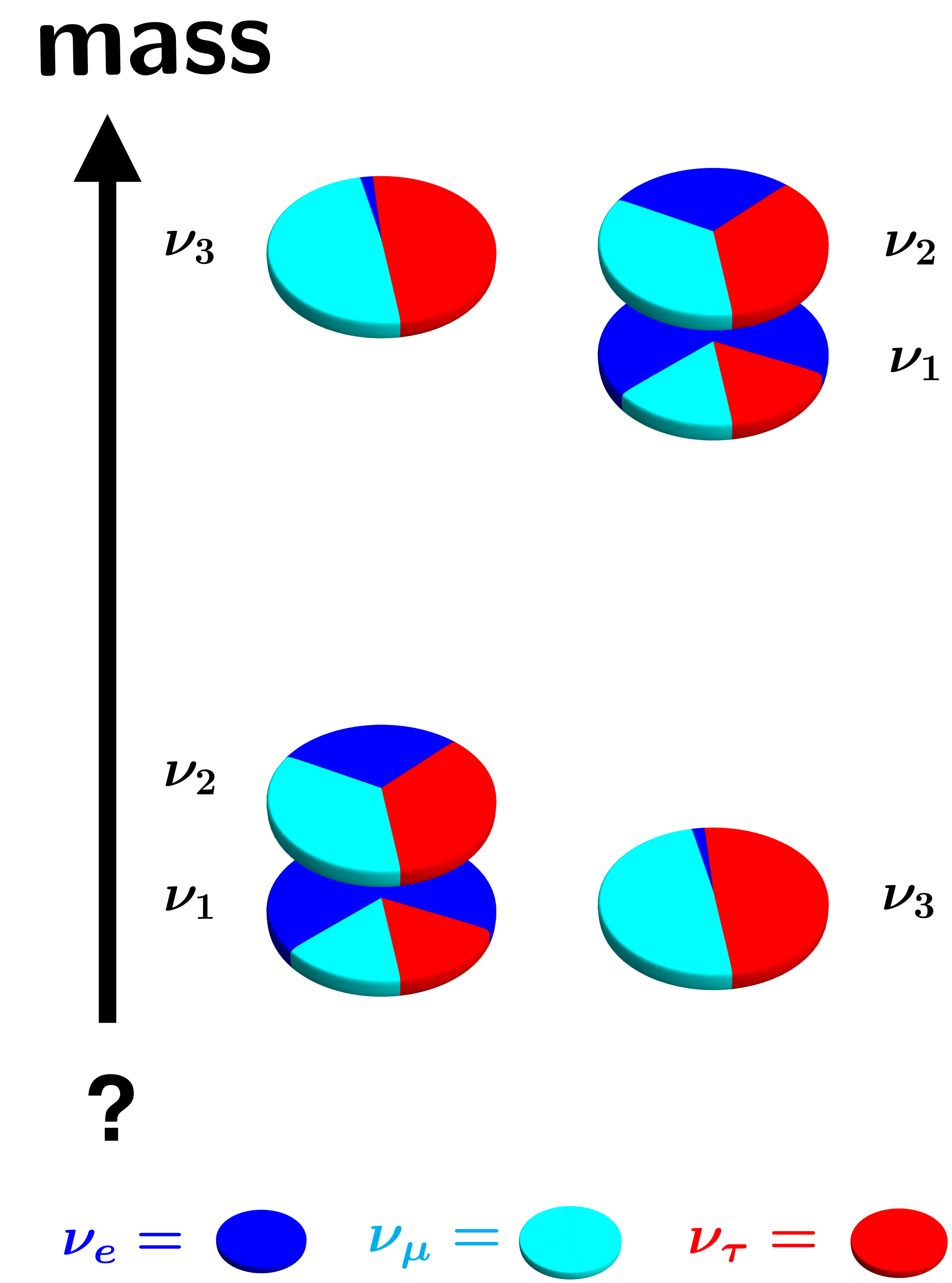
Octant of θ_{23}



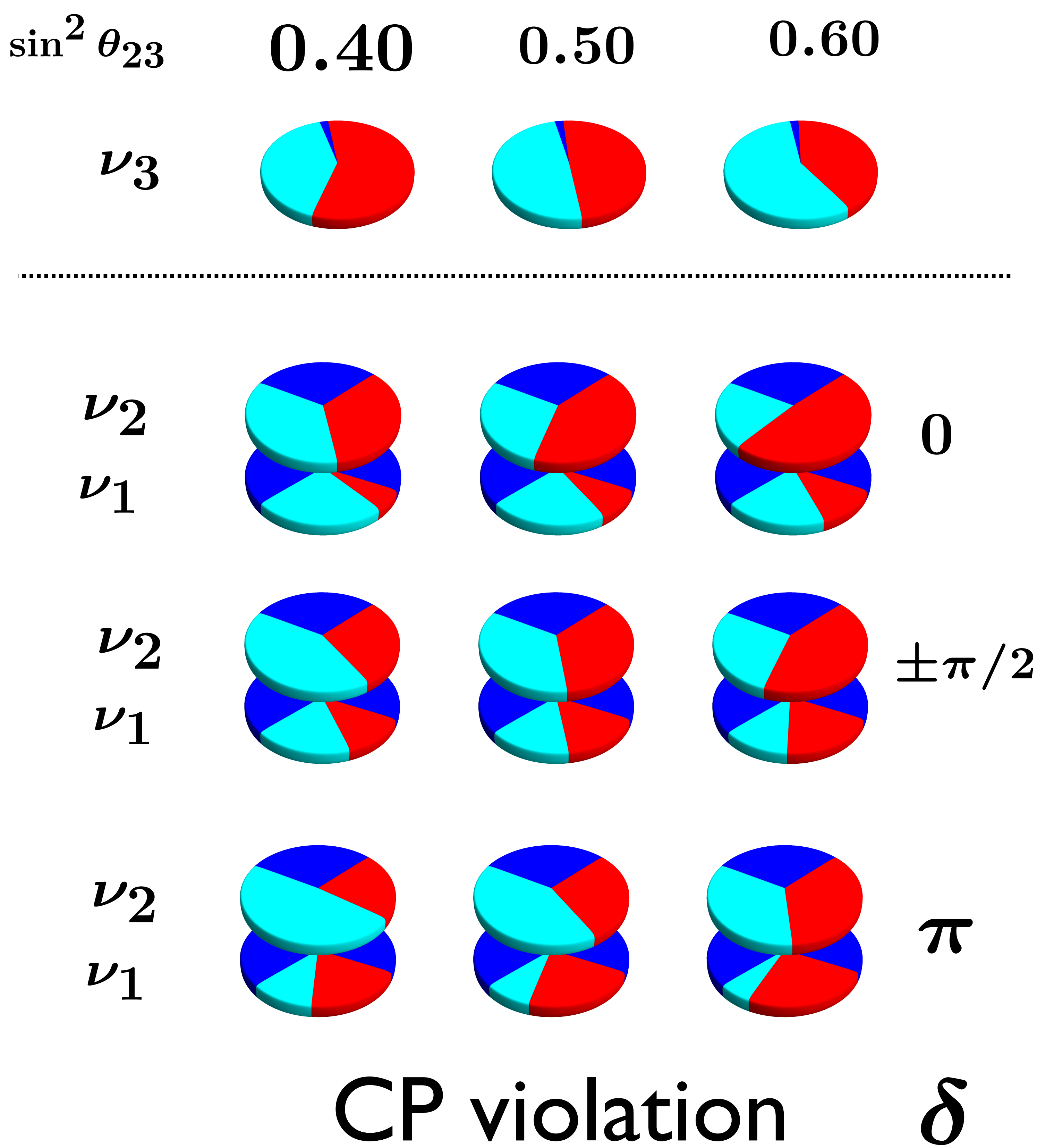
CP violation δ

ν_3, ν_1/ν_2 Mass Ordering:

–atmospheric mass ordering

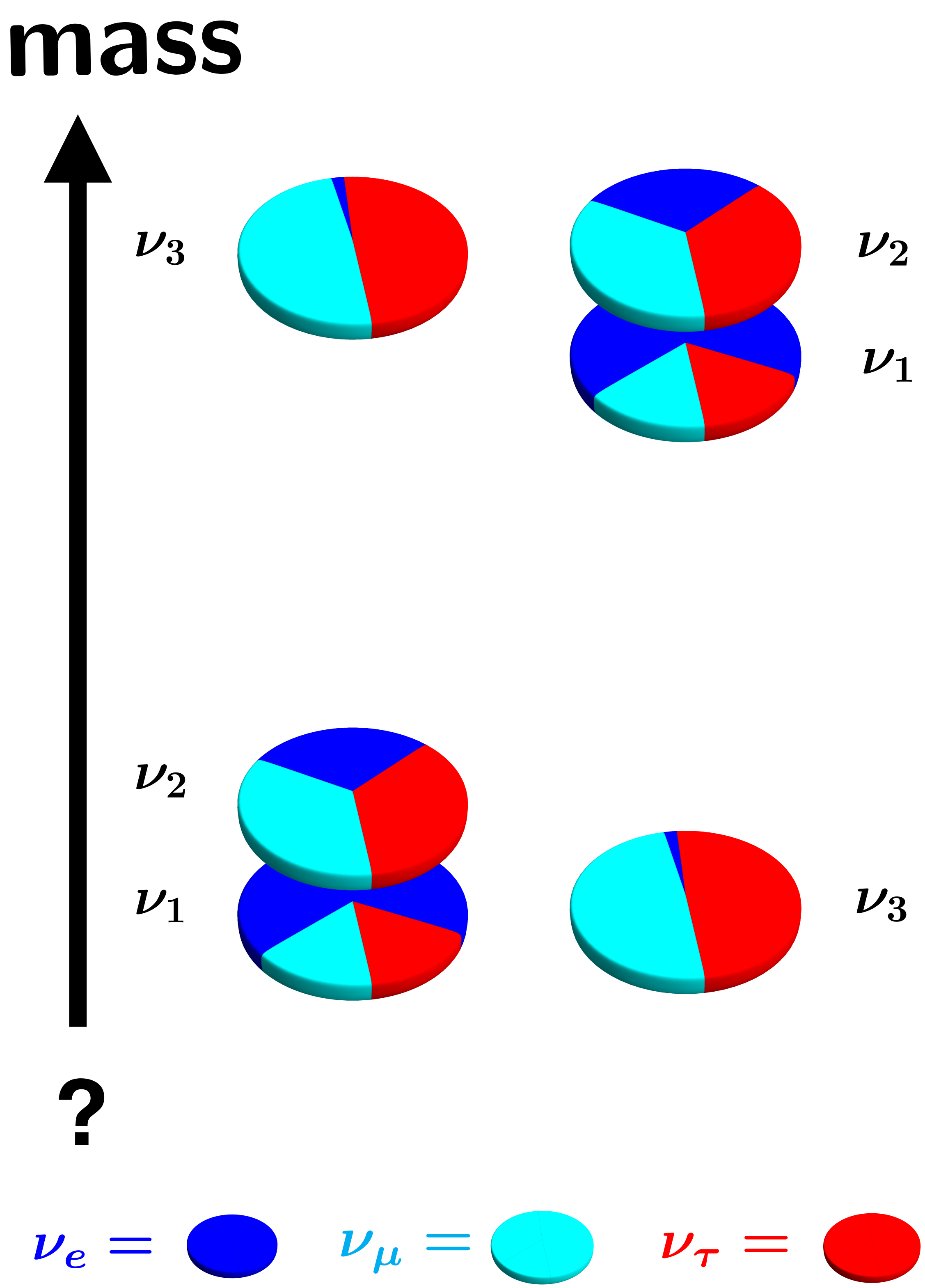


Octant of θ_{23}

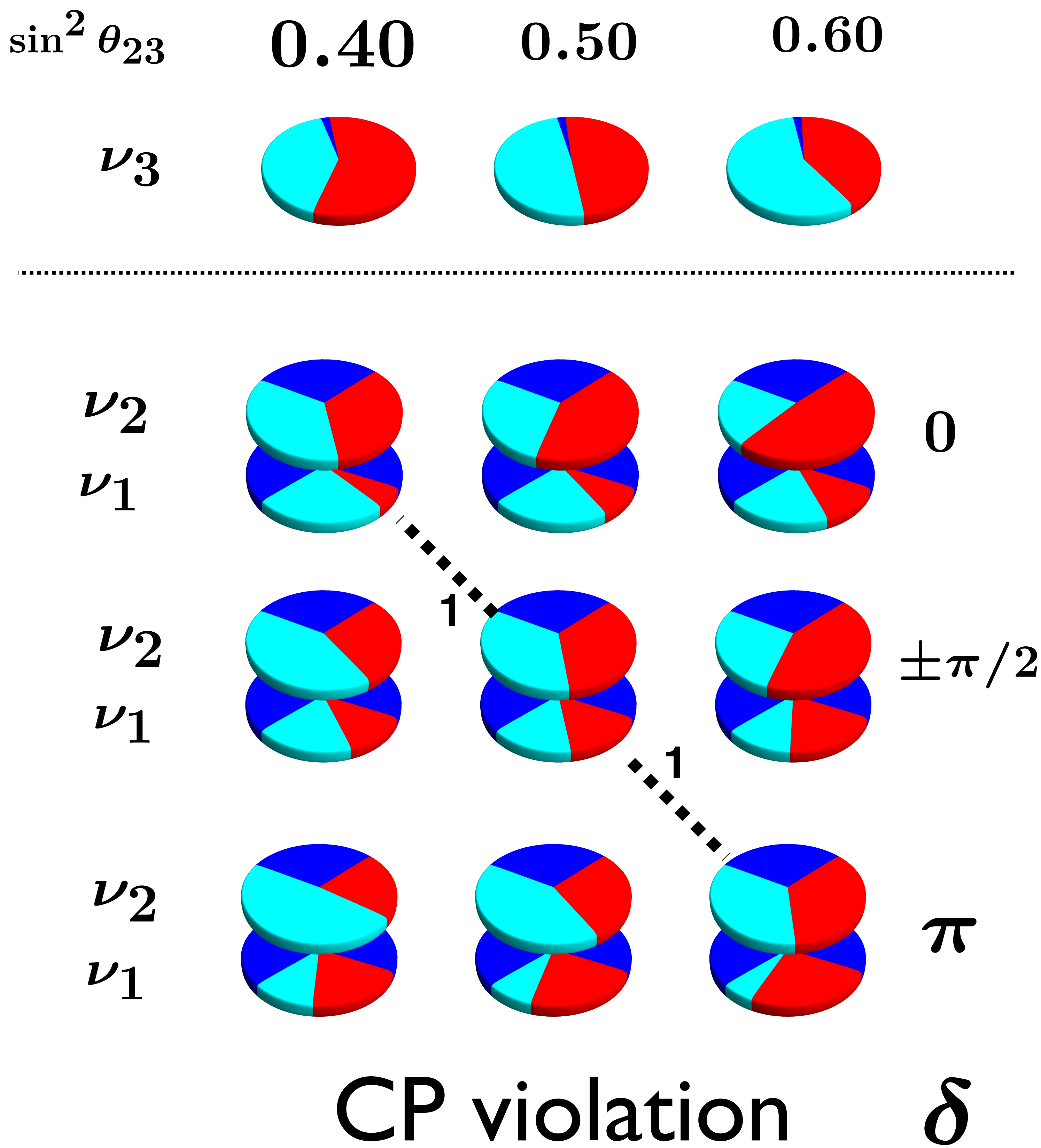


ν_3, ν_1/ν_2 Mass Ordering:

–atmospheric mass ordering

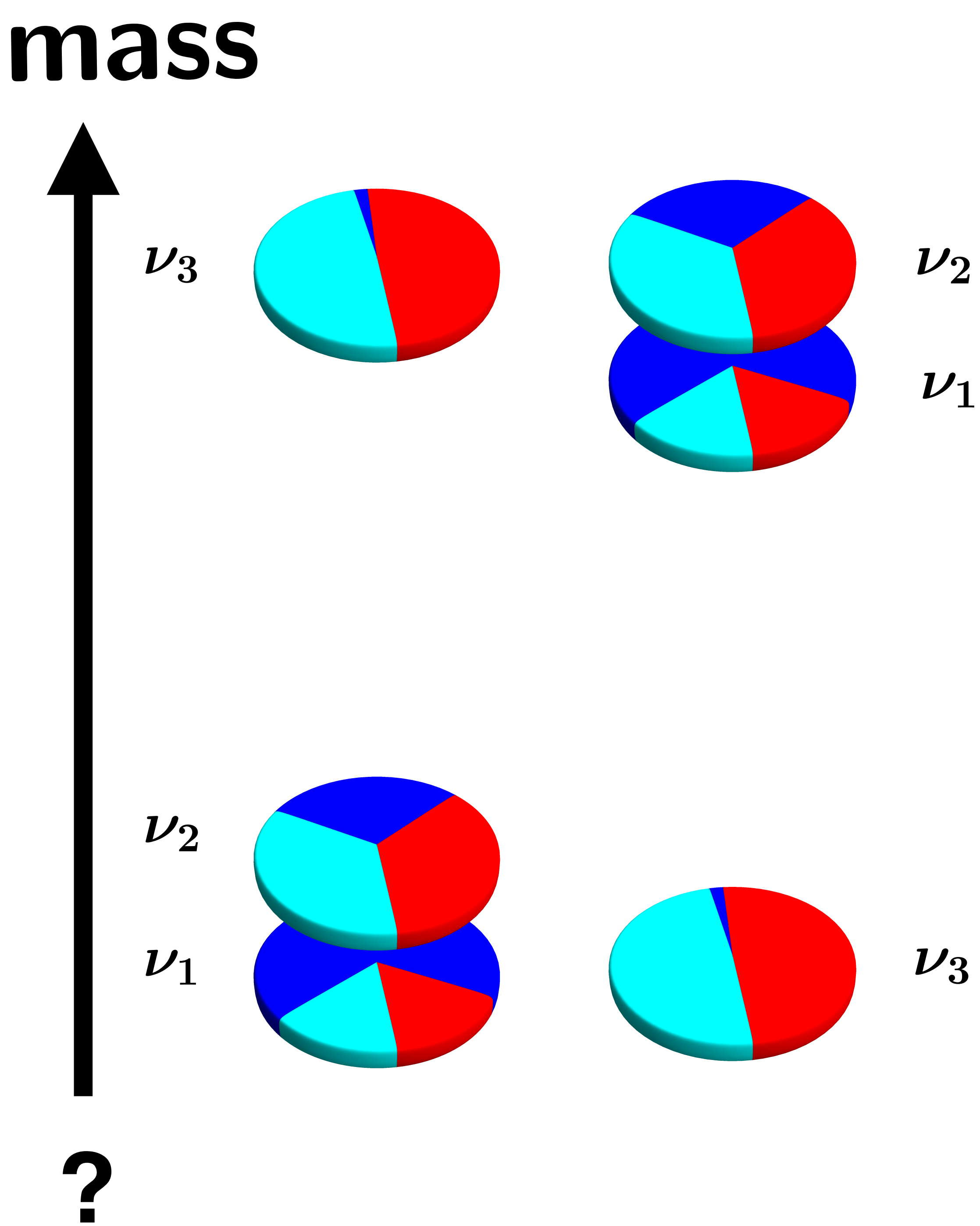


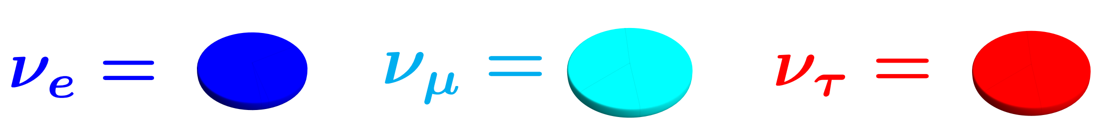
Octant of θ_{23}



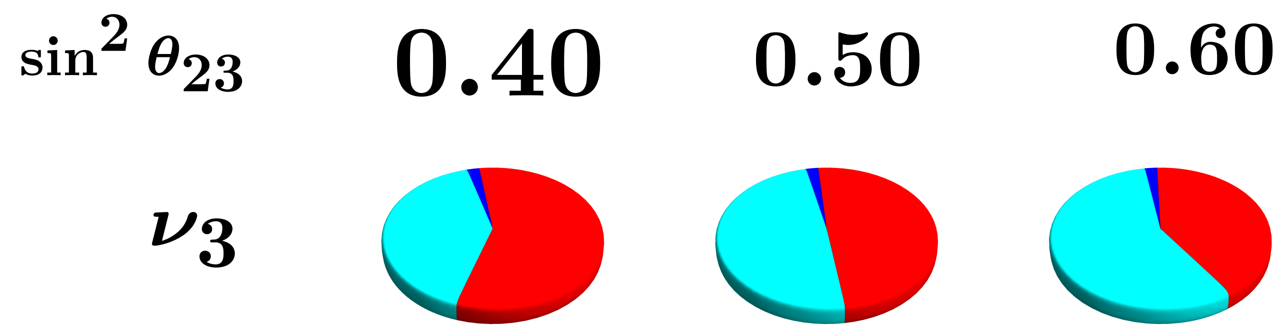
ν_3, ν_1/ν_2 Mass Ordering:

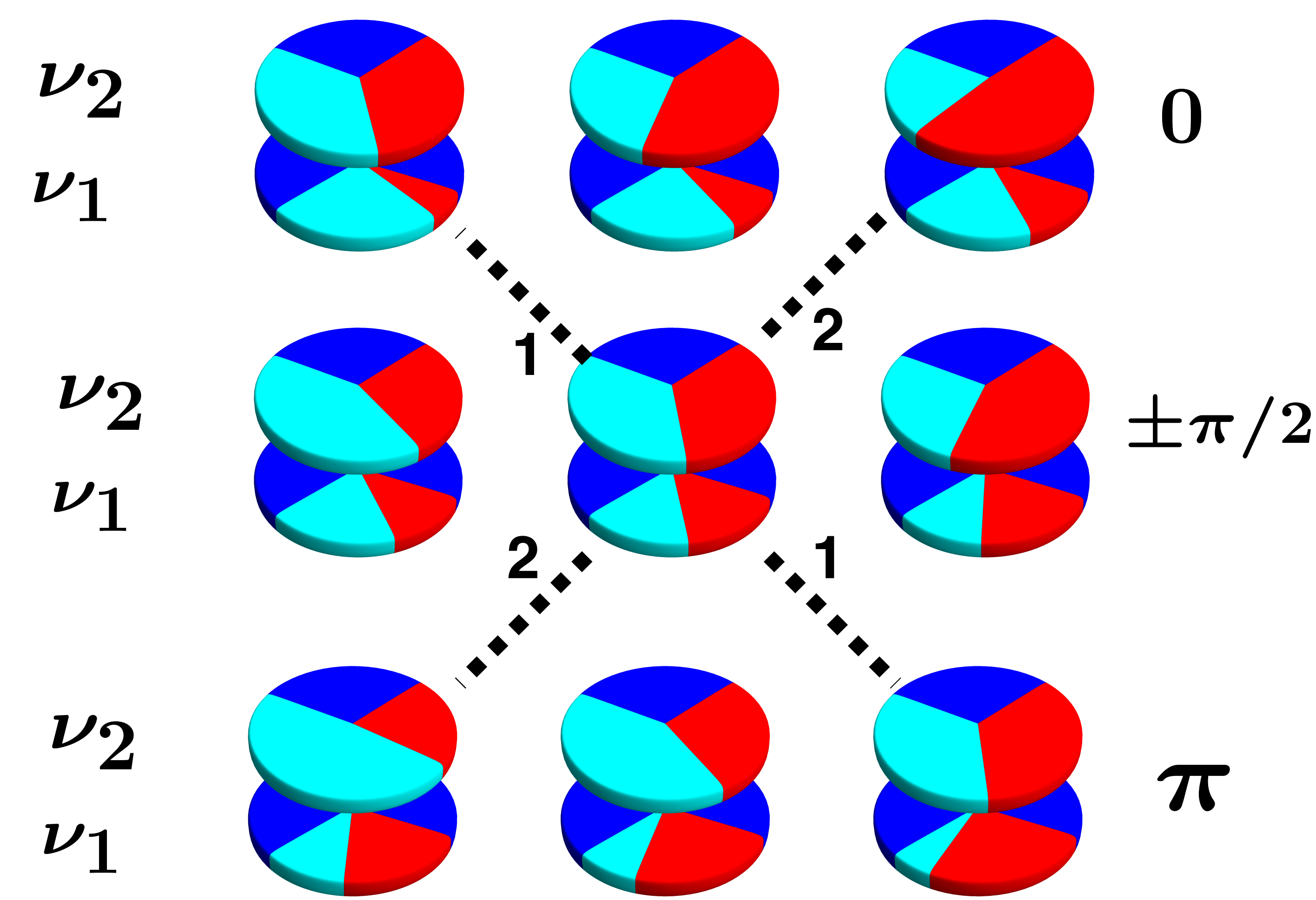
–atmospheric mass ordering





Octant of θ_{23}





CP violation δ

WHY?

Precision Neutrino Measurements:

WHY?

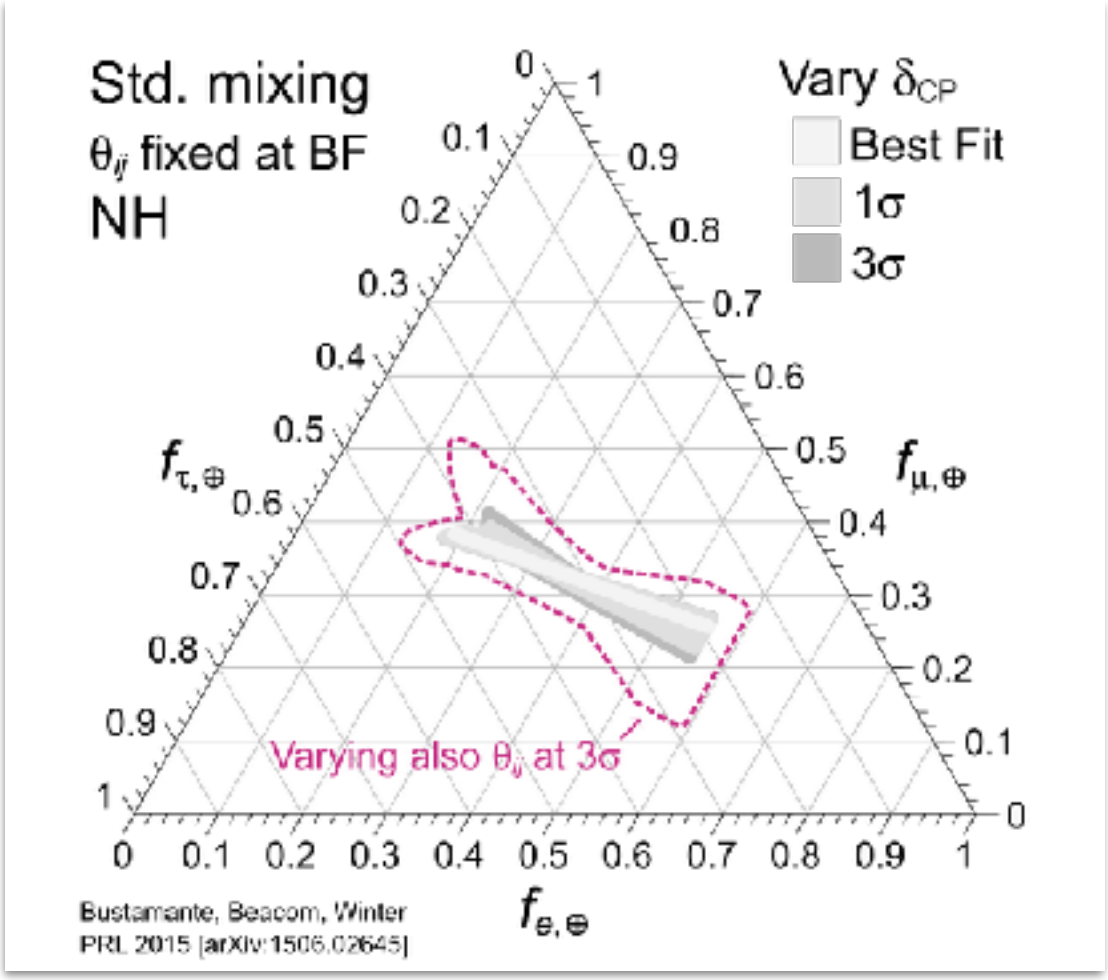
Precision Neutrino Measurements:

To discover neutrino BSM,
one needs precision predictions for nuSM

Determine flavor fractions of neutrino mass states

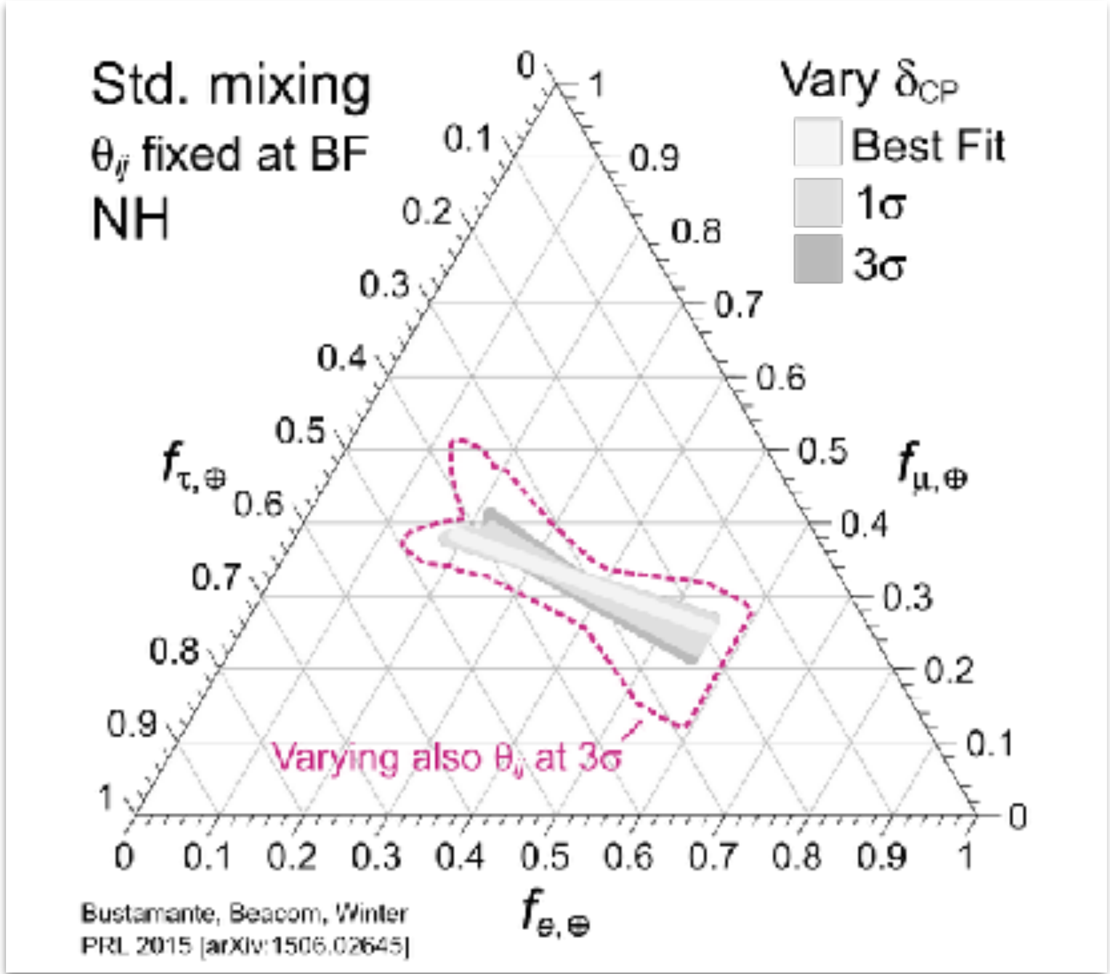
Determine flavor fractions of neutrino mass states

Precision Predictions for flavor ratios at ICECUBE.



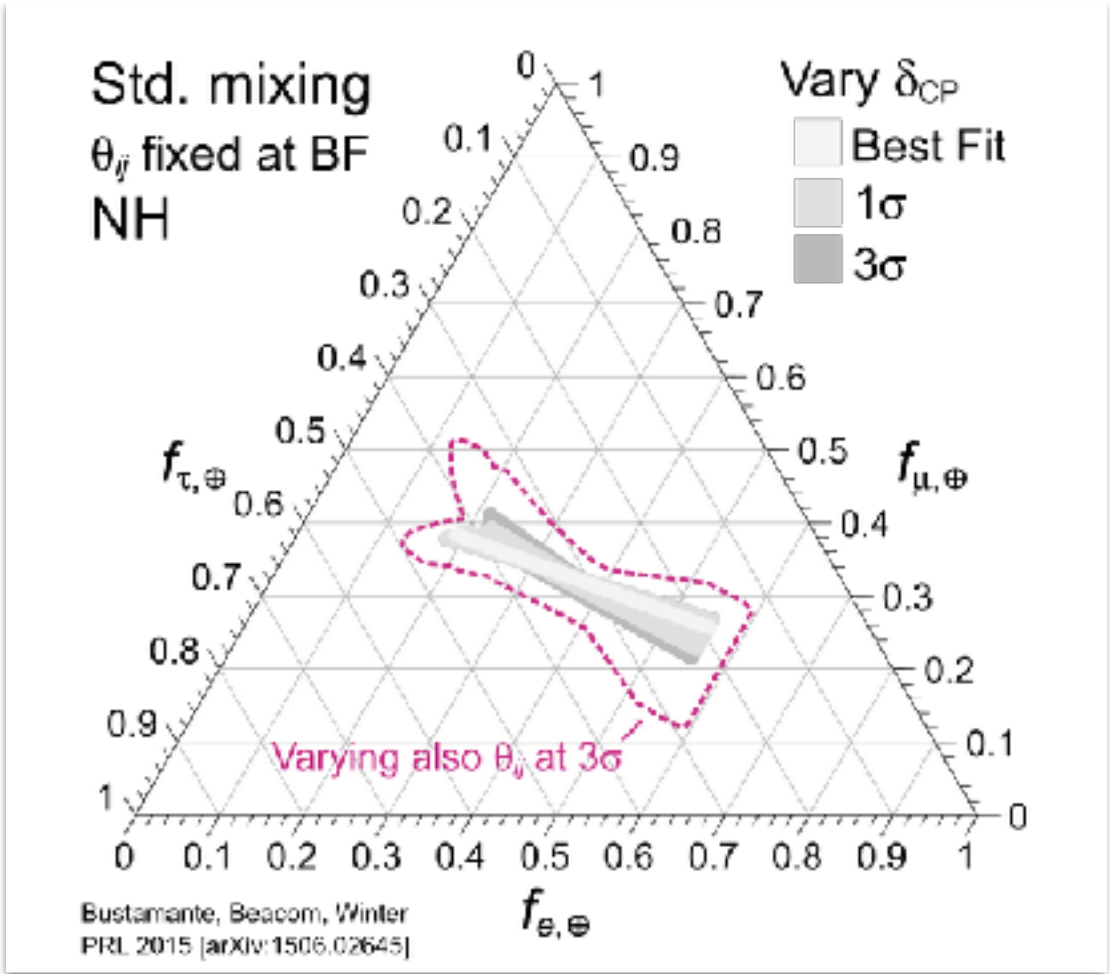
Determine flavor fractions of neutrino mass states

Precision Predictions for flavor ratios at ICECUBE.

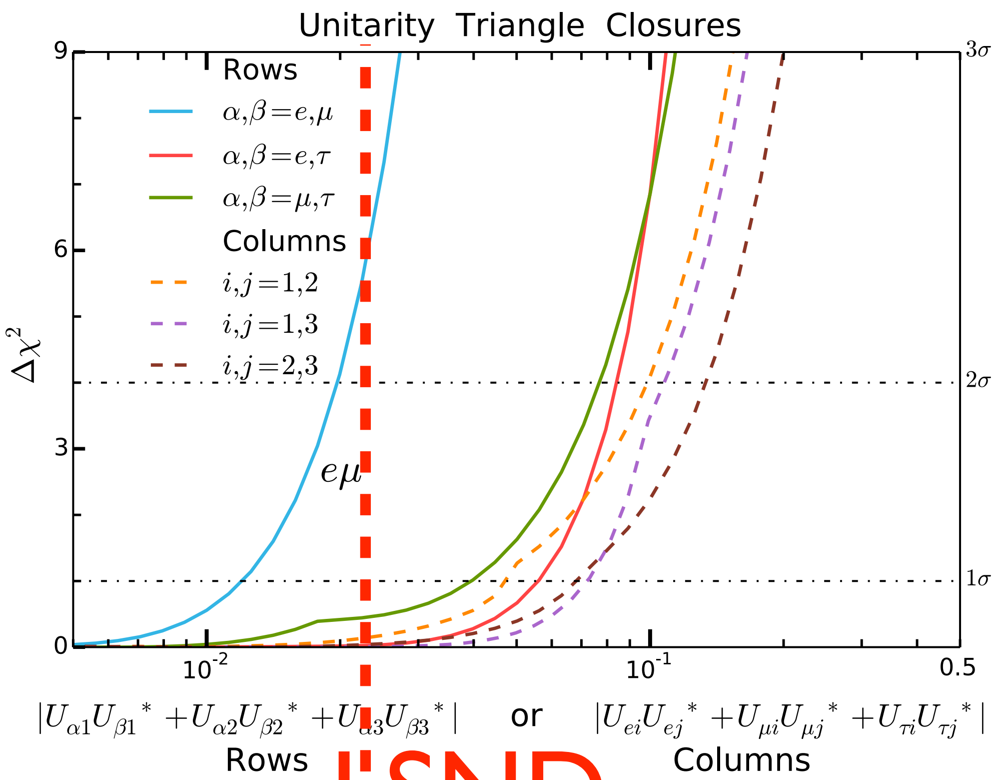


Stress Test
Neutrino paradigm
search for new physics

Determine flavor fractions of neutrino mass states



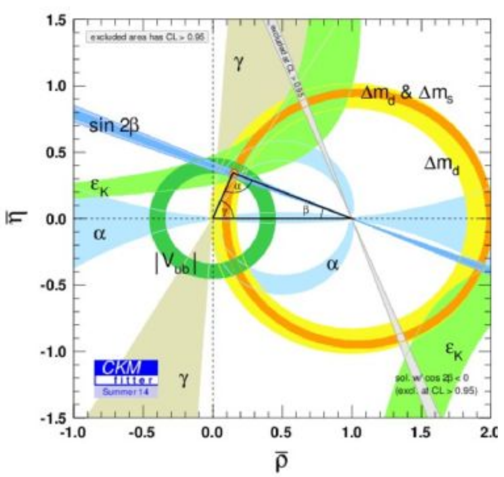
Precision Predictions for flavor ratios at ICECUBE.



LSND

M. Ross-Lonergan + SP
arXiv:1508.05095

Quarks:

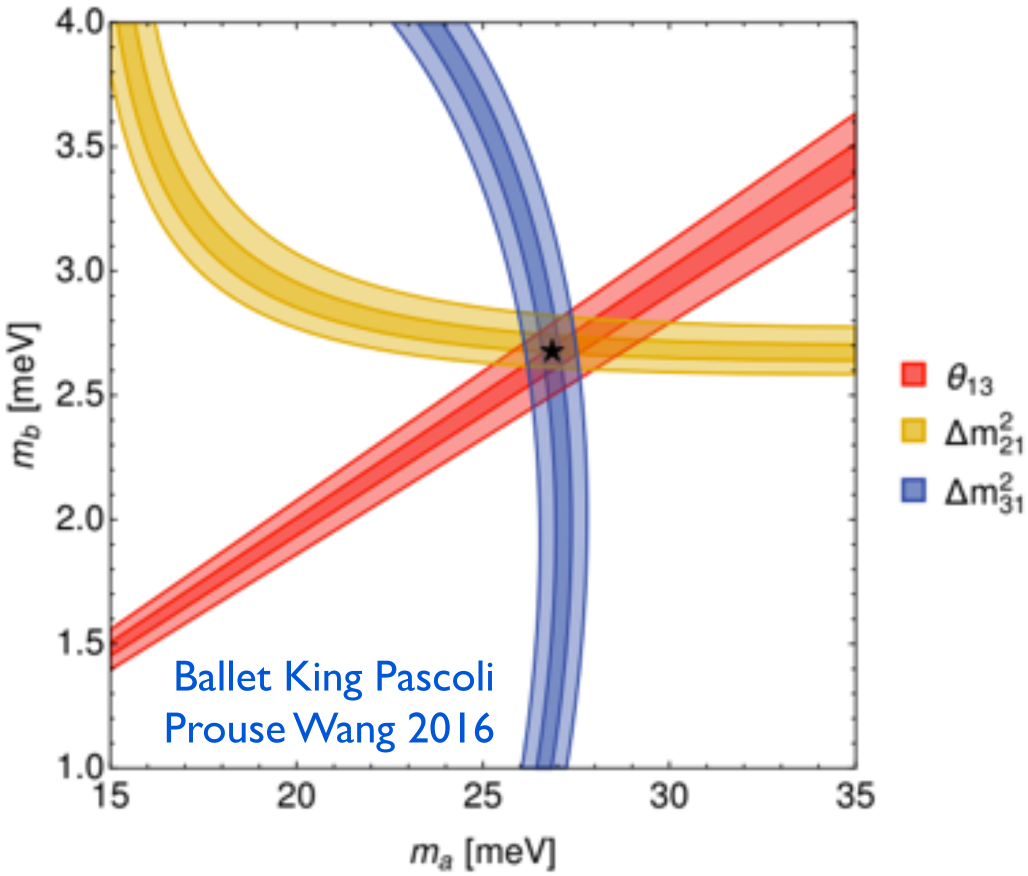


$A\lambda^3$

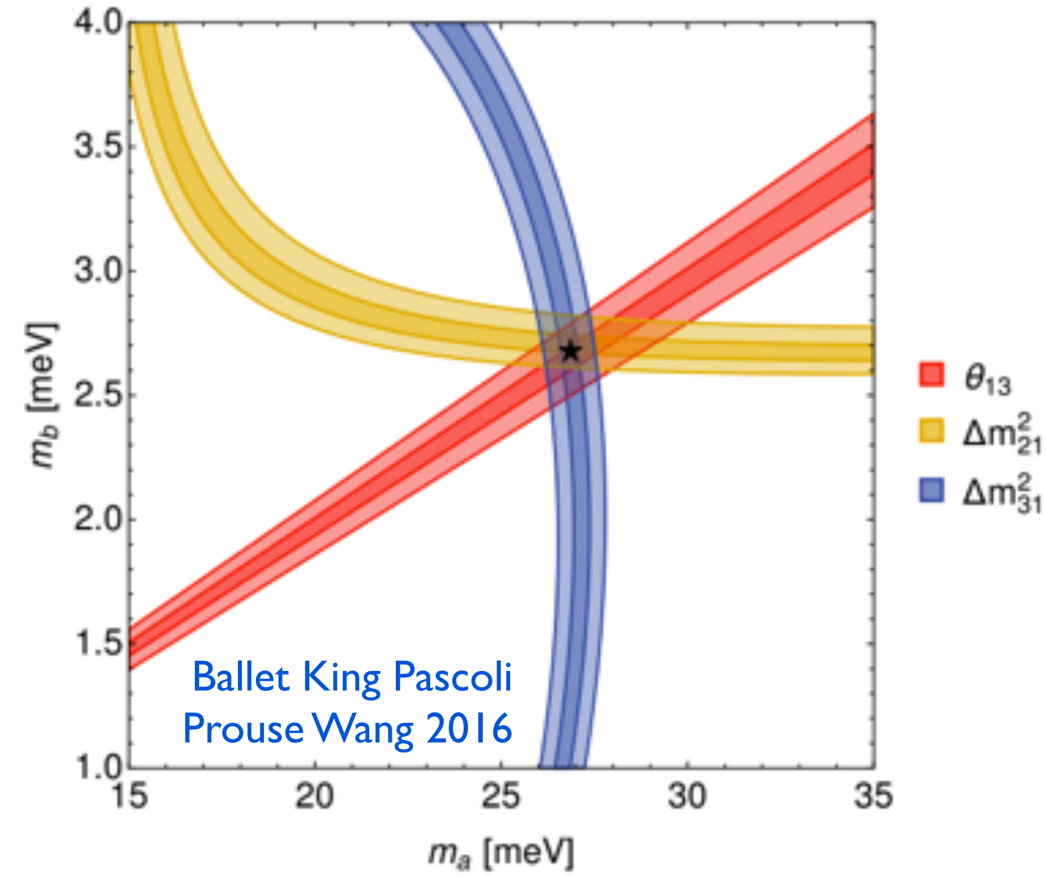
Stress Test Neutrino paradigm search for new physics

Connection to Leptogenesis Understanding Universe

Connection to
Leptogenesis
Understanding Universe

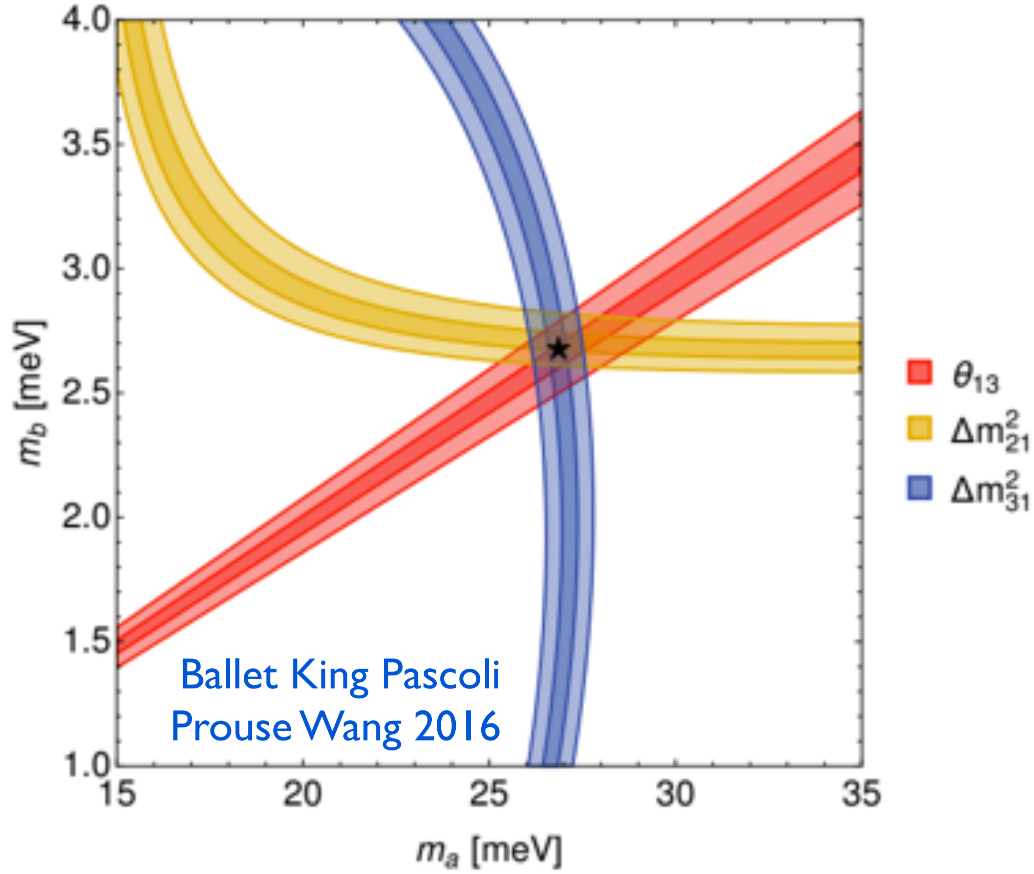


Connection to Leptogenesis Understanding Universe

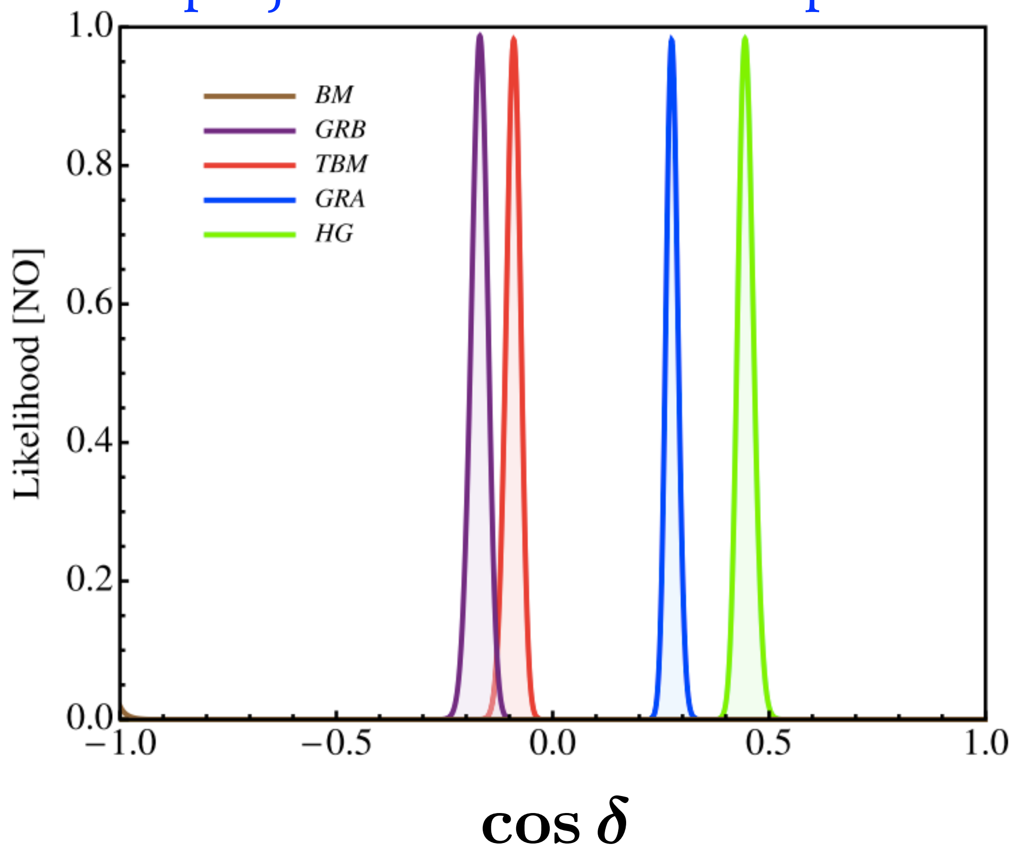


Test Theoretical Neutrino Models

Connection to Leptogenesis Understanding Universe



Predictions of flavor symmetry forms with projected measurement precision



Test Theoretical Neutrino Models

- Atmospheric Neutrinos (SK)
- LBL Disappearance (T2K & NOvA)
- LBL Appearance (T2K & NOvA)
- Sterile Neutrinos (MiniBooNE & 3+1 models)

Atmospheric Neutrino Results from Super-Kamiokande

Yoshinari Hayato (Kamioka, ICRR)
for the Super-Kamiokande collaboration

Neutrino oscillation studies using atmospheric ν

High statistics atmospheric neutrino data

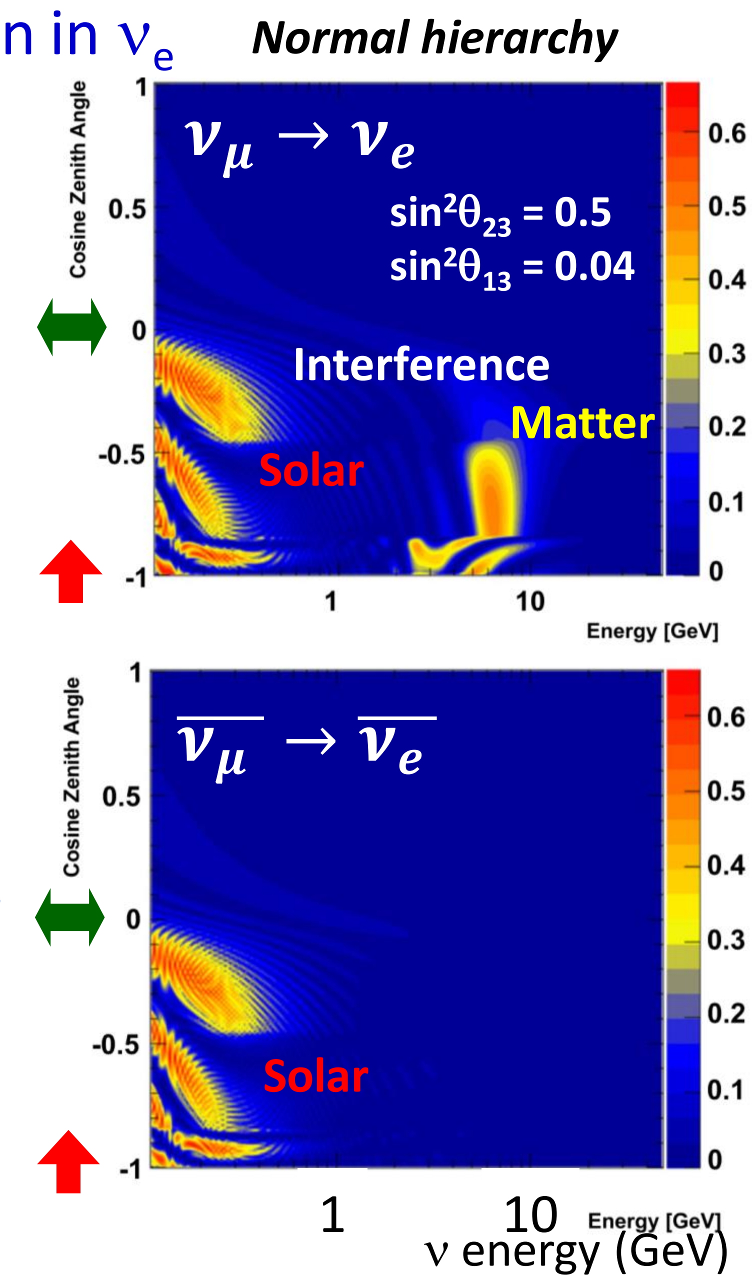
~ Possibility in observing small distortion in ν_e

Difference in # of electron events:

$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) + \Delta_2(\Delta m_{12}^2) + \Delta_3(\theta_{13}, \Delta m_{12}^2, \delta)$$

- $\Delta_1(\theta_{13})$ ← Matter effect
- $\Delta_2(\Delta m_{12}^2)$ ← Solar term
- $\Delta_3(\theta_{13}, \Delta m_{12}^2, \delta)$ ← Interference

- Matter effect ~ from mass hierarchy
  Possible enhancement in several GeV passed through the earth core
  One of the flavors (ν_e or $\overline{\nu_e}$) shows this enhancement.
- Solar term ~ from θ_{23} octant degeneracy
  Possible ν_e enhancement in sub-GeV
- Interference
  CP phase could be studied.



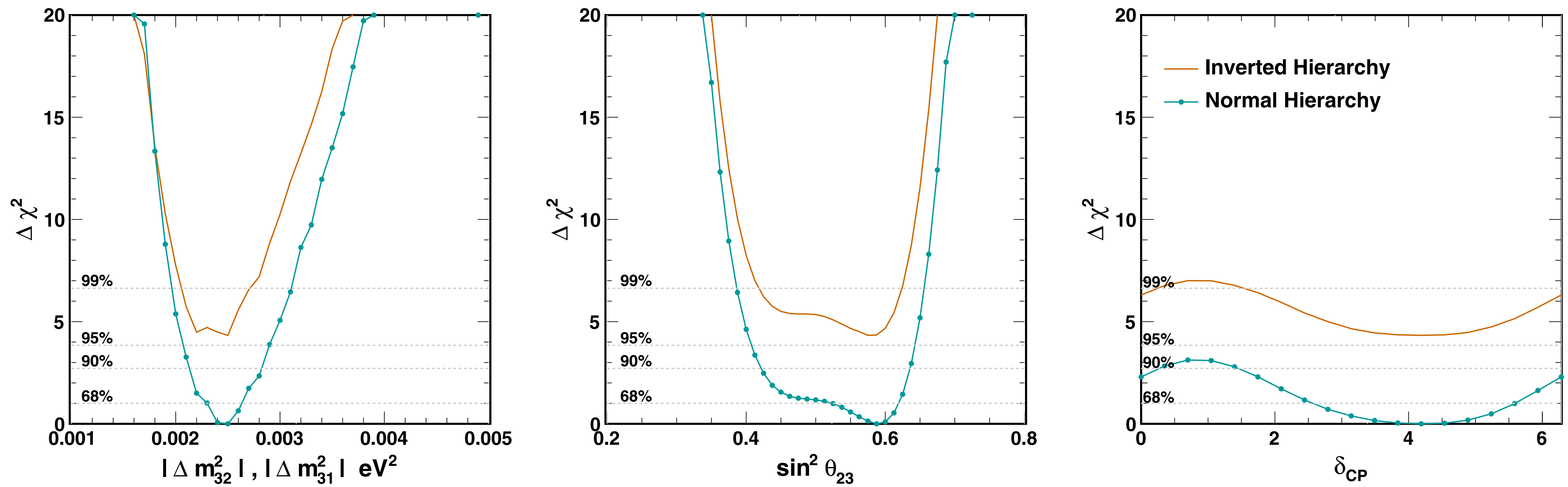
Determination of ν oscillation parameters

SK-I to SK-IV, 5326 days (2519 days from SK-IV), 328 kt·yr

input

$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\mathrm{ev}^2,$$
$$\sin^2\theta_{12} = 0.304 \pm 0.014,$$
$$\sin^2\theta_{13} = 0.0219 \pm 0.012$$

ATMOSPHERIC NEUTRINO OSCILLATION ANALYSIS … PHYS. REV. D **97,** 072001 (2018)



$$|\Delta m^2_{32}| = 2.50^{+0.13}_{-0.20} \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.588 \pm^{0.031}_{0.064}$$

$$(\chi^2_{NH,min} - \chi^2_{IH,min} = -4.34)$$

LBL

$\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$

What can we learn from $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$?

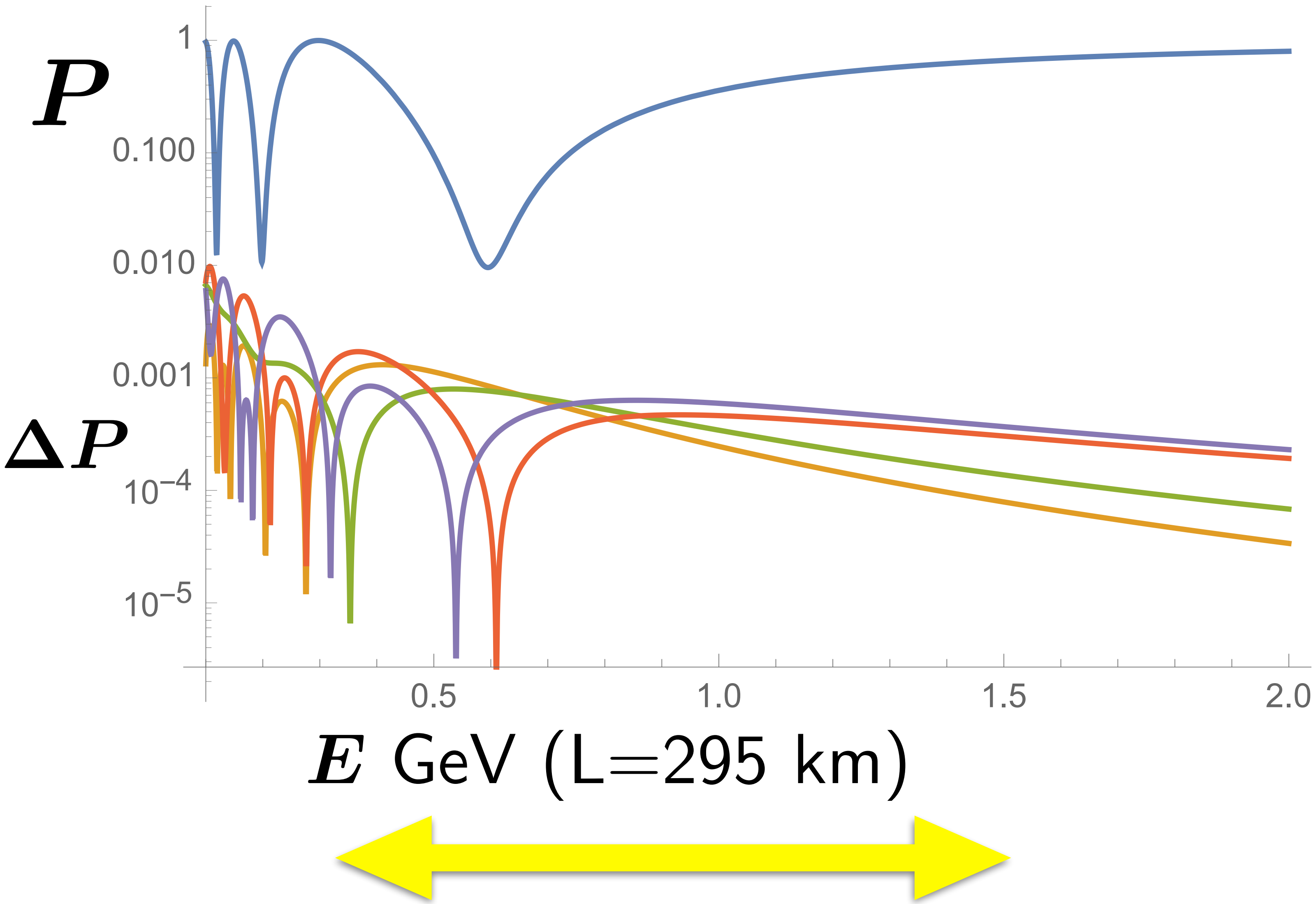
- first approx: measure only $4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)$ and $\Delta m^2_{\mu\mu}$
  - Need $\sin^2\theta_{13}$ to extract $\sin^2\theta_{23}$
  - $\sin^2\theta_{12}$, Δm^2_{21}, mass ordering $(\cos\delta)$ to extract Δm^2_{32}

What can we learn from $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$?

- first approx: measure only $4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)$ and $\Delta m^2_{\mu\mu}$
  - Need $\sin^2\theta_{13}$ to extract $\sin^2\theta_{23}$
  - $\sin^2\theta_{12}$, Δm^2_{21}, mass ordering $(\cos\delta)$ to extract Δm^2_{32}

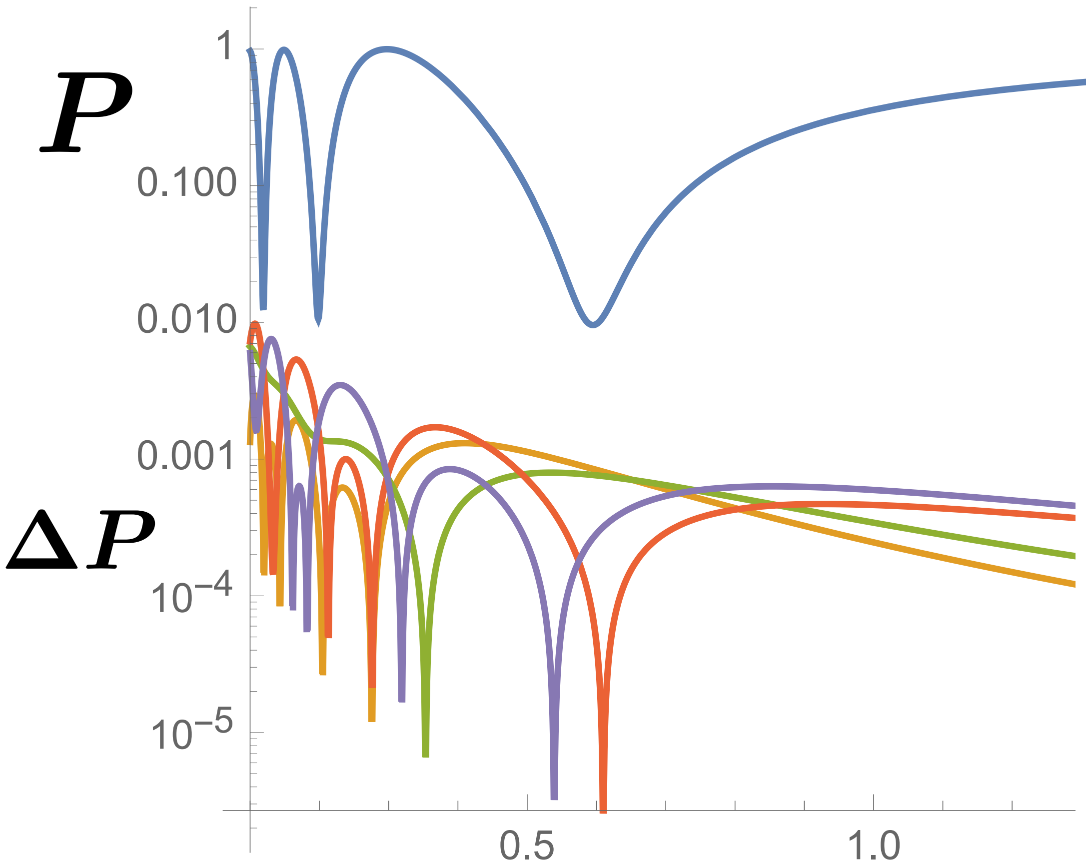
- Approx Symmetries:
  - $|U_{\mu 3}|^2 \Leftrightarrow 1-|U_{\mu 3}|^2$ equiv. $\sin^2\theta_{23} \Leftrightarrow 1/\cos^2\theta_{13} - \sin^2\theta_{23}$
  - $\nu \Leftrightarrow \bar{\nu}$; insensitive to matter effects
  - Normal Ordering $\Leftrightarrow$ Inverted Ordering
  - insensitive to $\cos\delta$

$P(\nu_\mu \to \nu_\mu)$, $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$

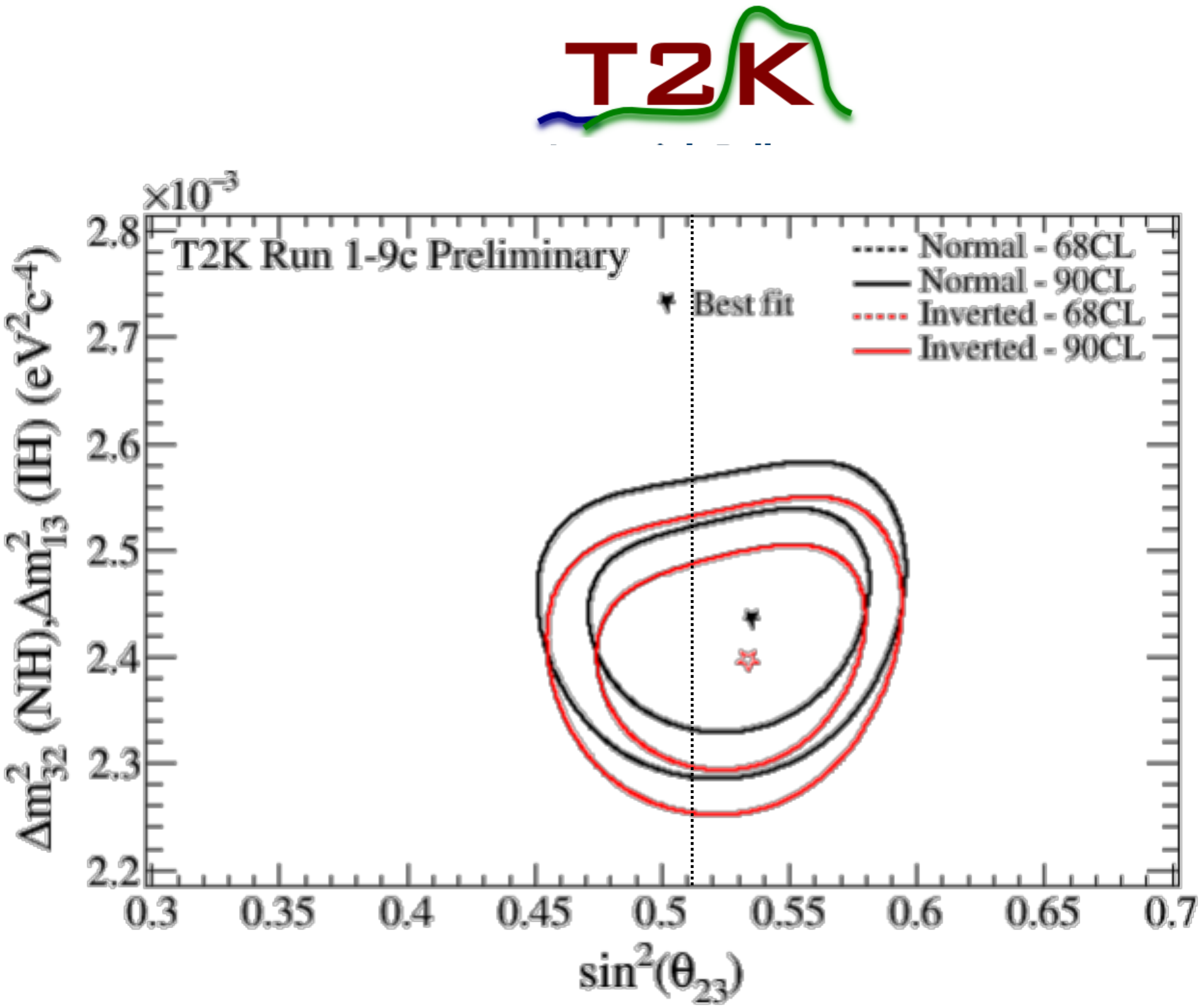


$|U_{\mu 3}|^2 =$ 0.45 and 0.55 then $4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2) = 0.99$

$P(\nu_\mu \to \nu_\mu)$, $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$

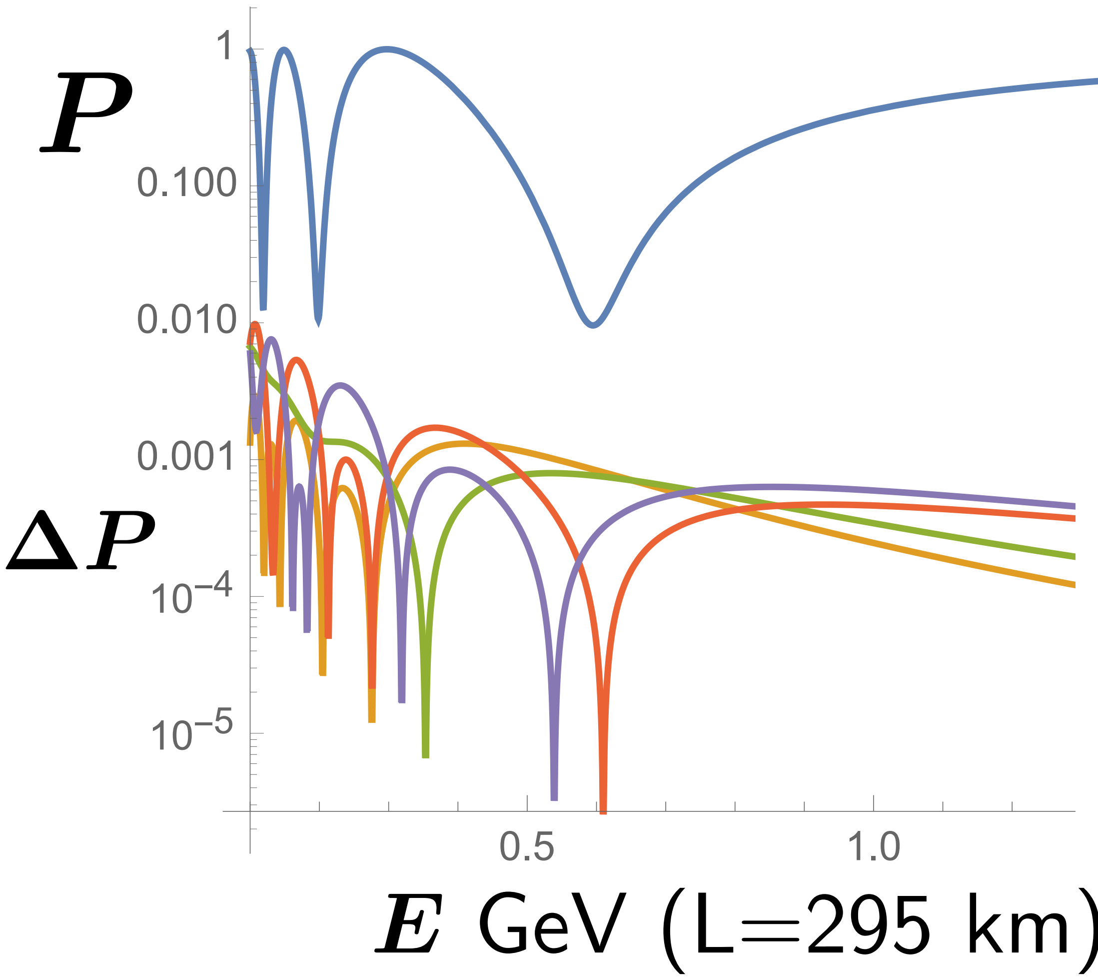


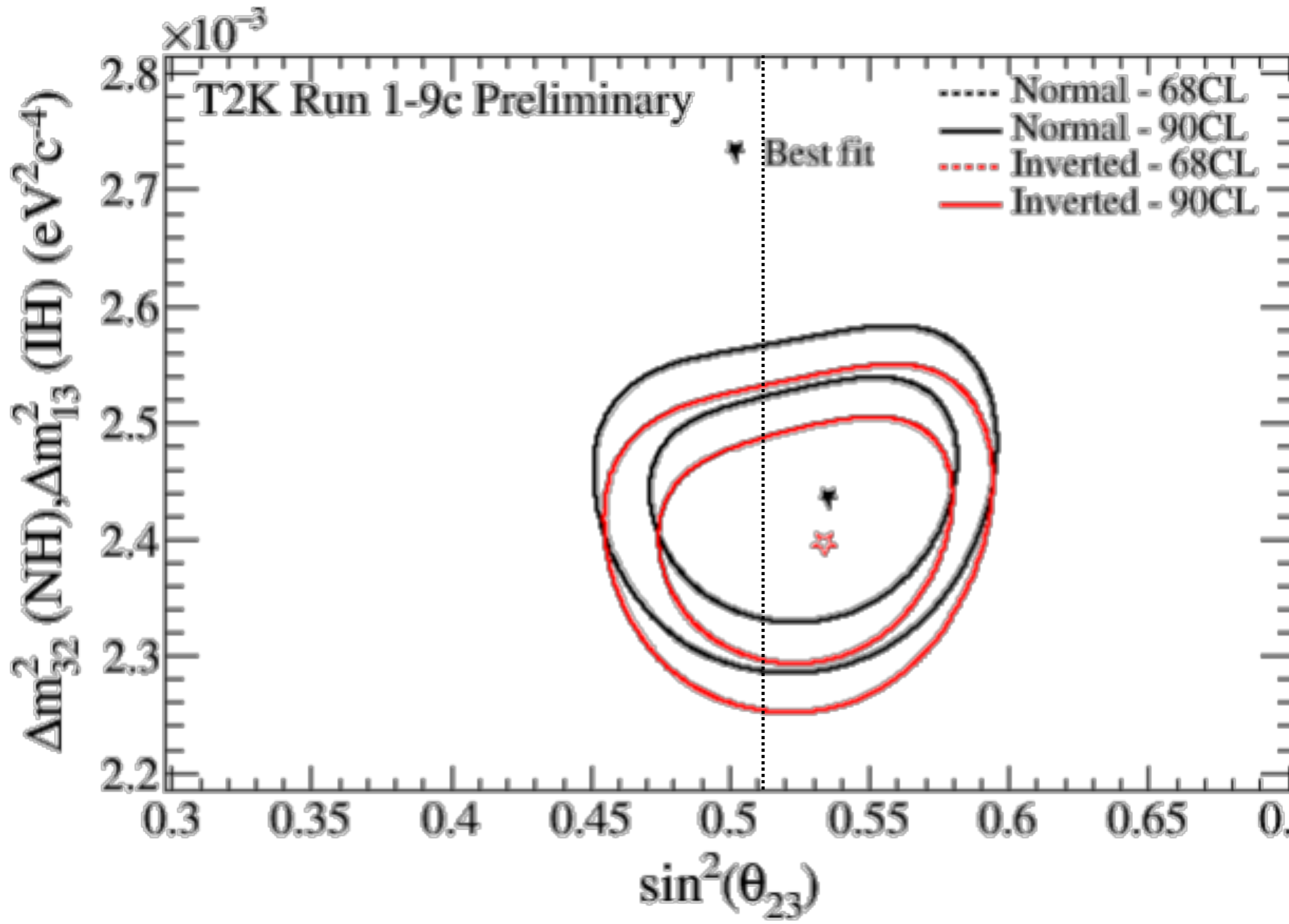
E GeV (L=295 km)



$|U_{\mu 3}|^2 = 0.45$ and 0.55

$$P(\nu_\mu \to \nu_\mu),\ P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$$

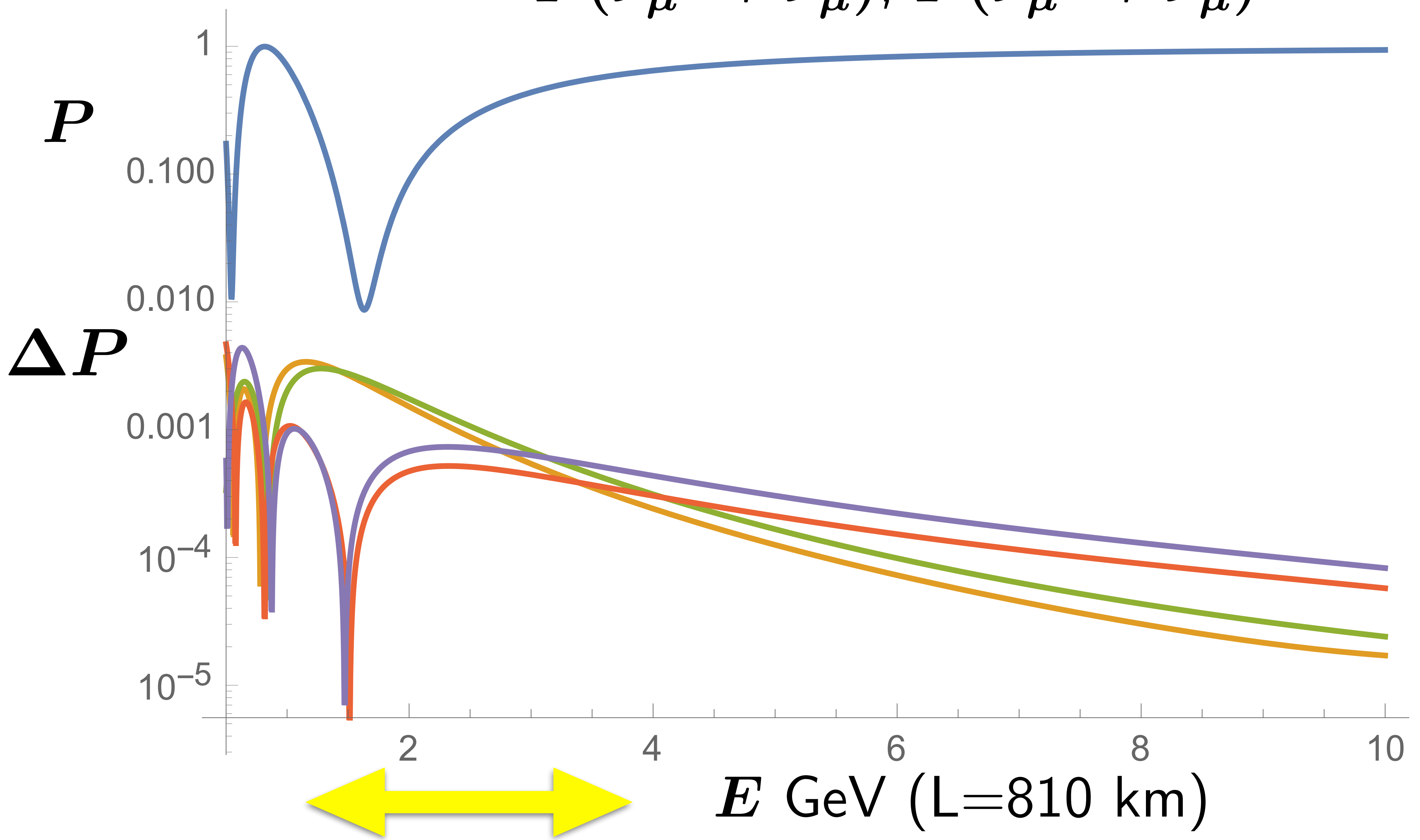




$|U_{\mu 3}|^2 = 0.45$ and 0.55

- Small preference for *Upper octant* from disappearance alone

$P(\nu_\mu \to \nu_\mu)$, $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$



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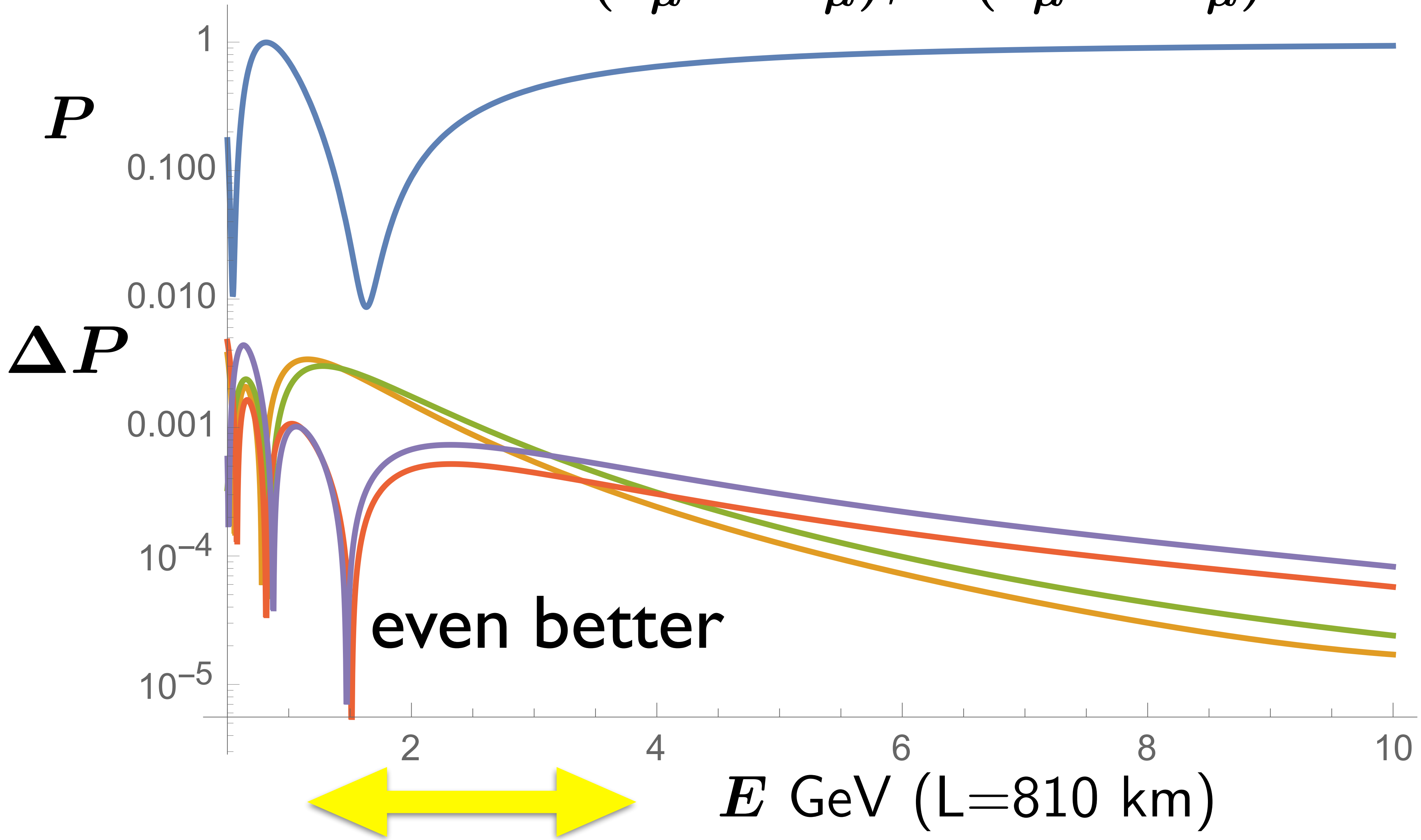


$$P(\nu_\mu \to \nu_\mu),\ P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$$

$|U_{\mu 3}|^2 =$ 0.45 and 0.55 then $4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2) = 0.99$

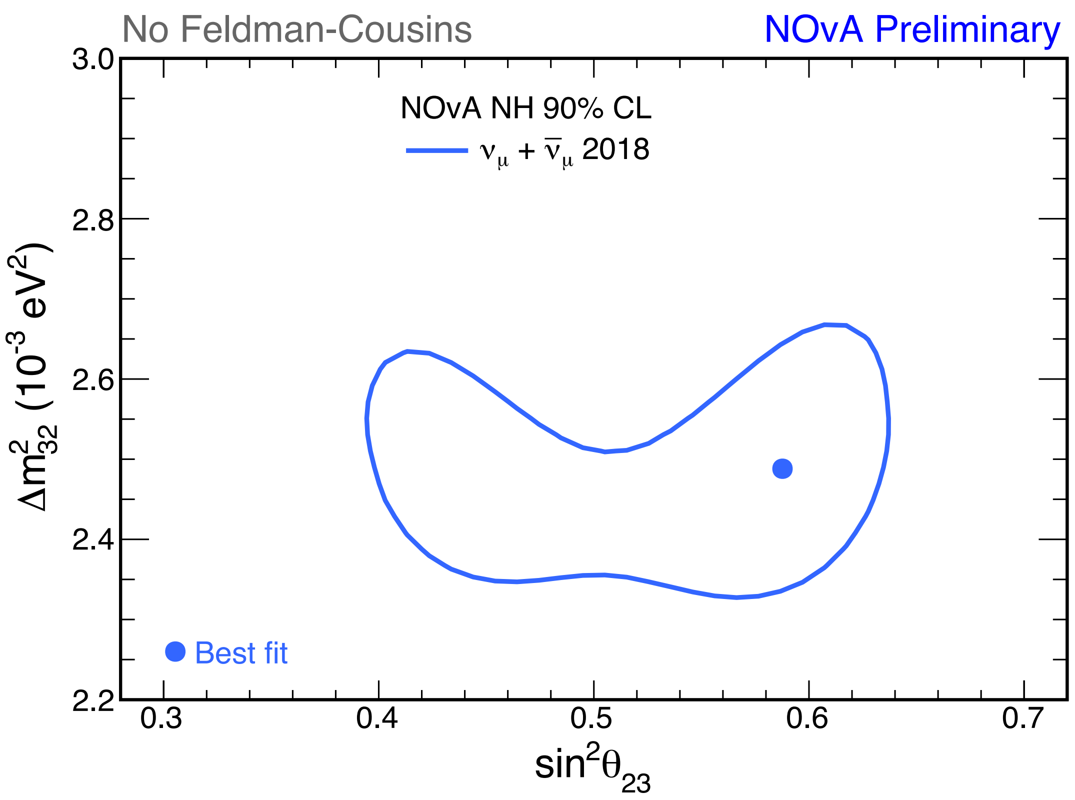
- Even better Symmetry:

  Upper Octant/Normal Order "degenerate" Lower Octant/Inverted Order for ν and $\bar{\nu}$ plus vice versa

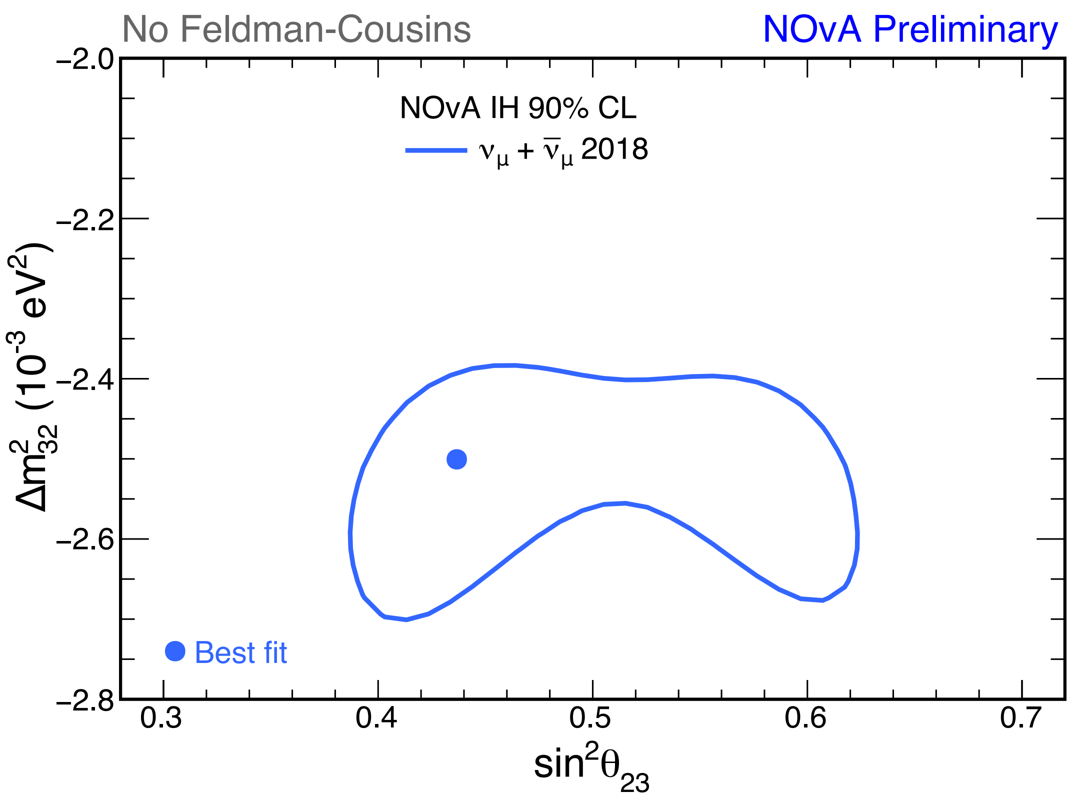
NOvA:

$$P(\nu_\mu \to \nu_\mu),\ P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$$

NO



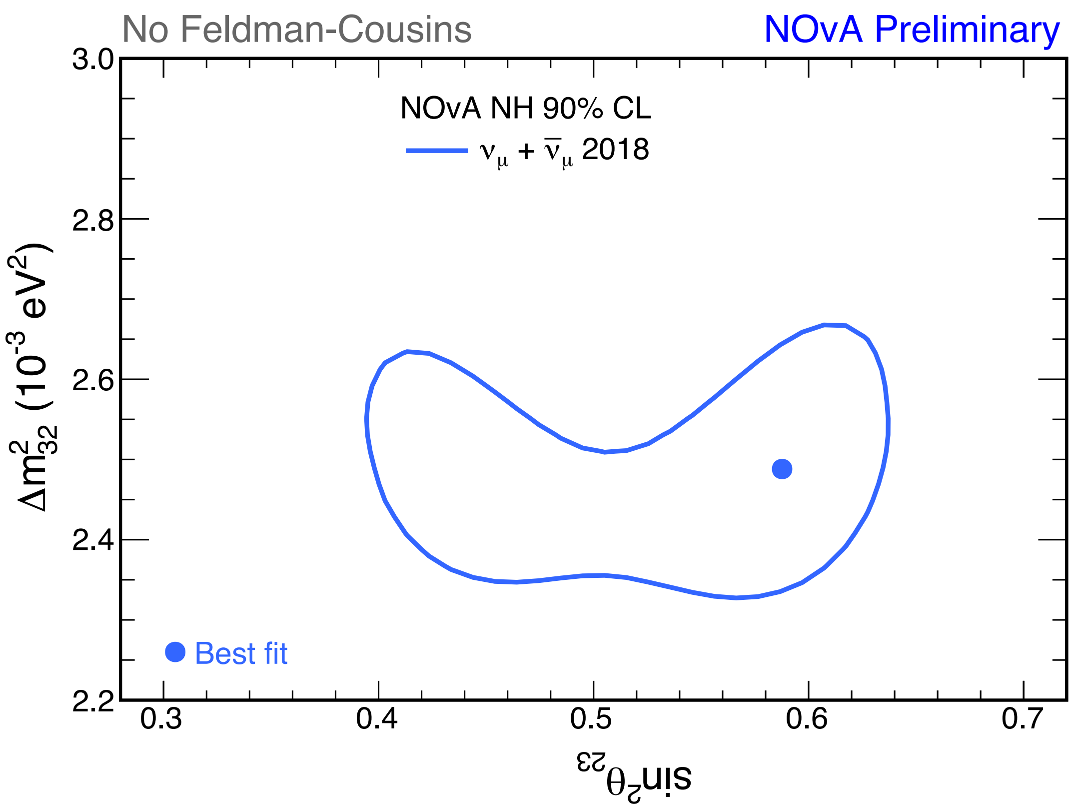
IO



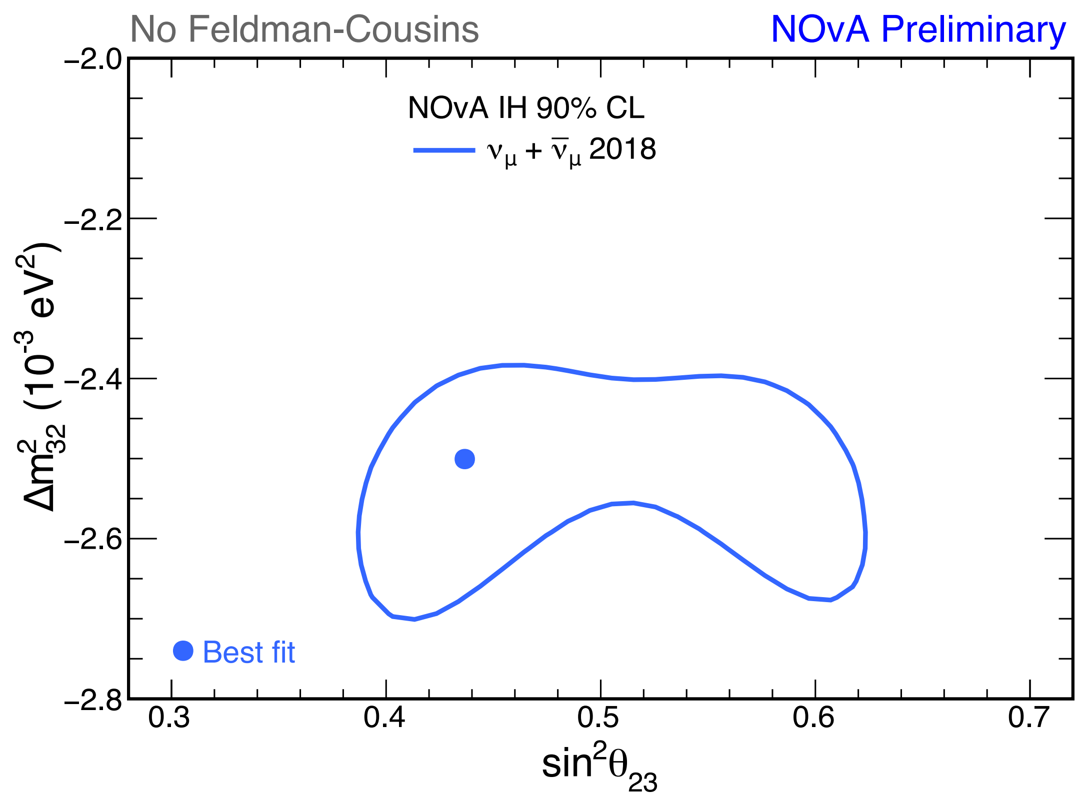
NOvA:

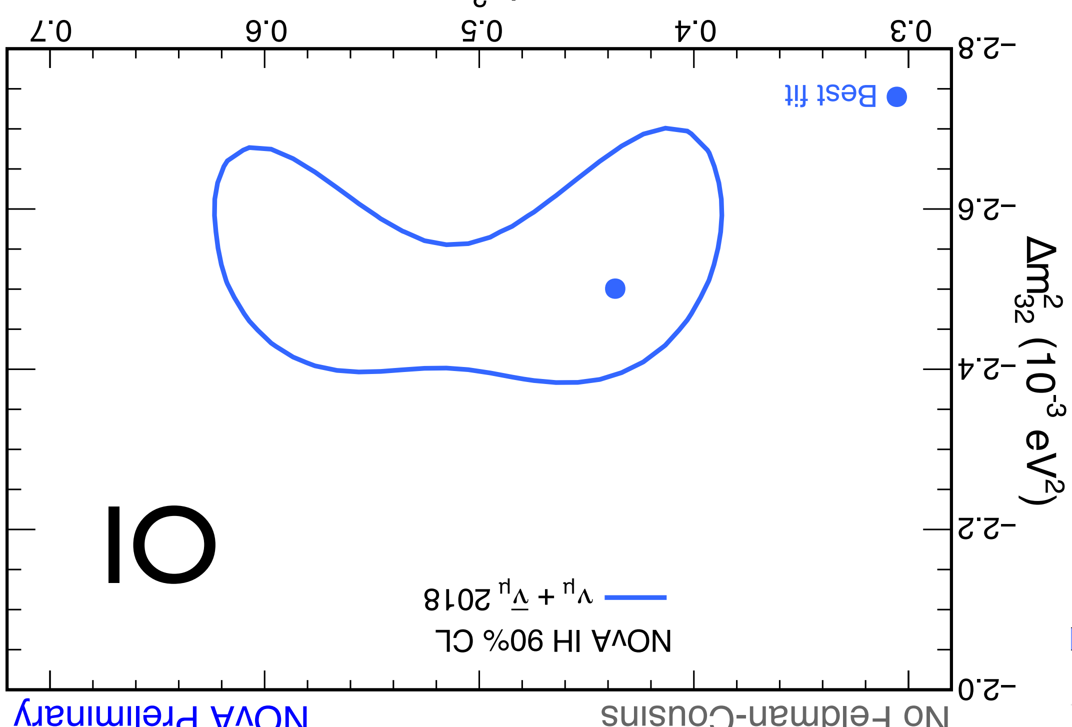
$$P(\nu_\mu \rightarrow \nu_\mu),\ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$$

NO



IO





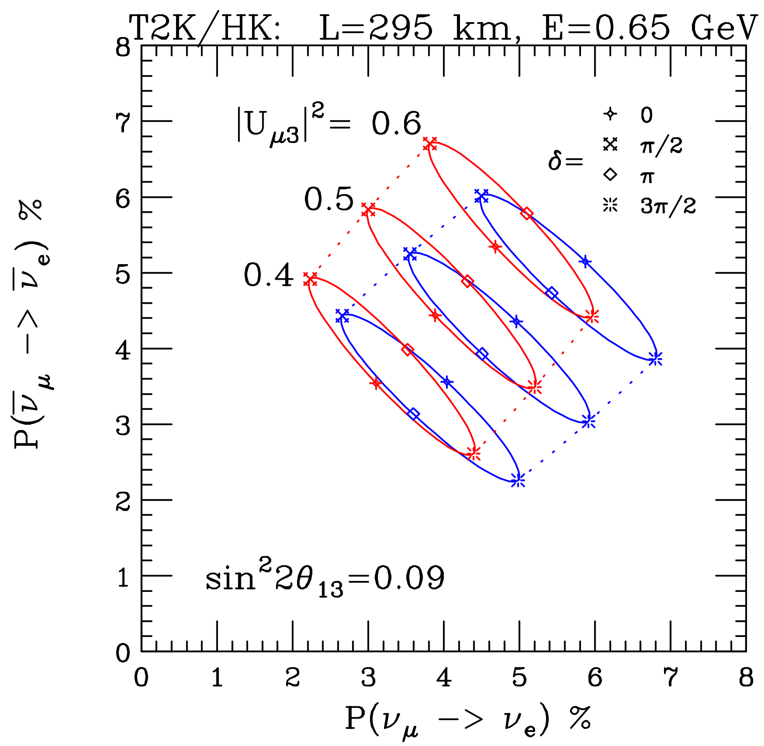
double flip

LBL

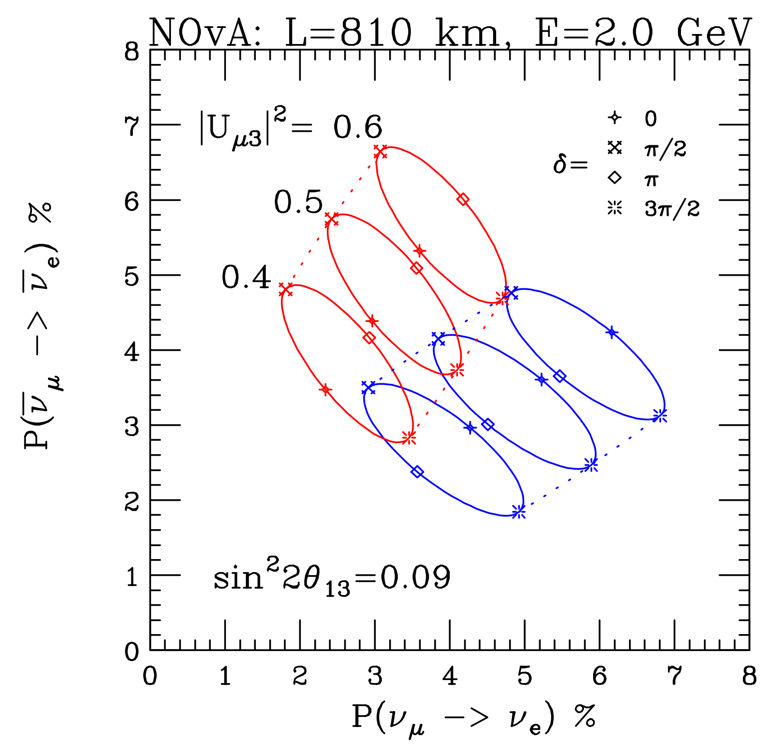
$\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

Correlations btw $\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$

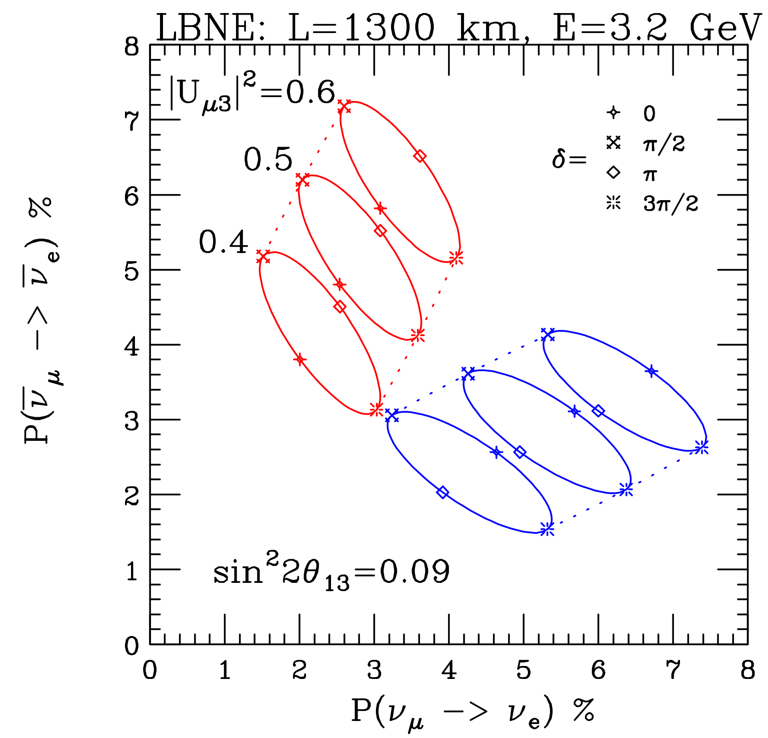
T2K/HK



NOvA



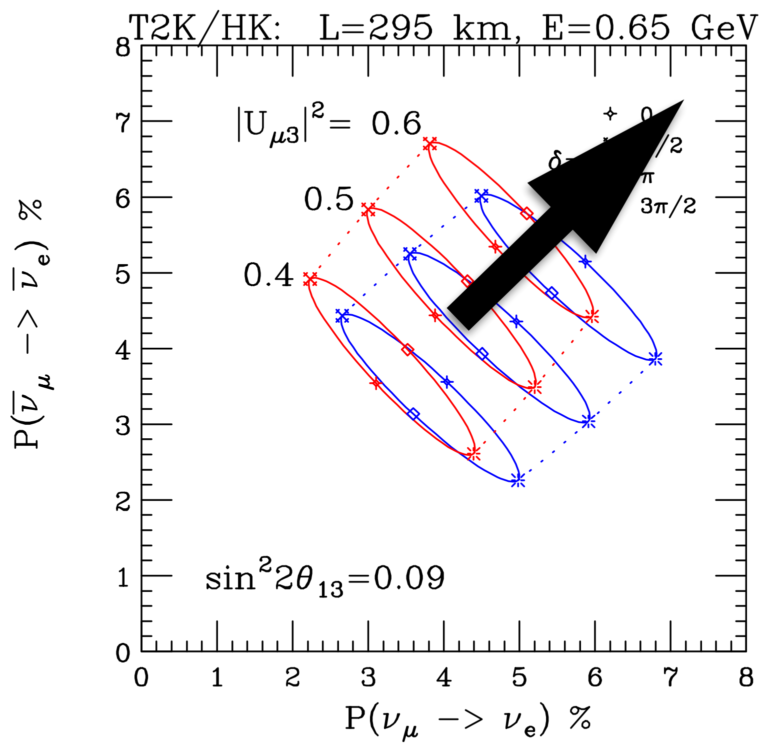
DUNE Same L/E as NOνA



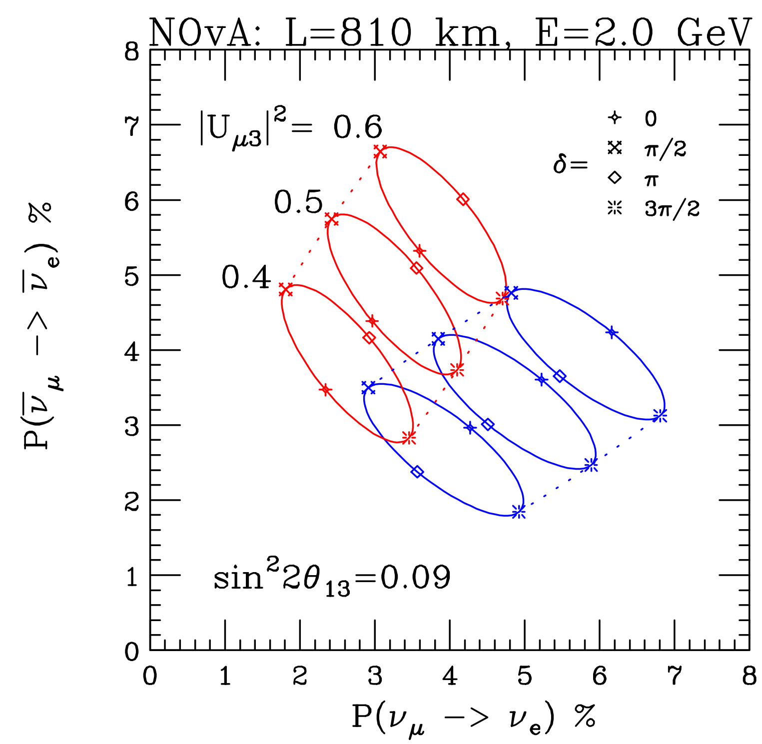
arXiv:hep-ph/020417

Correlations btw $\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$

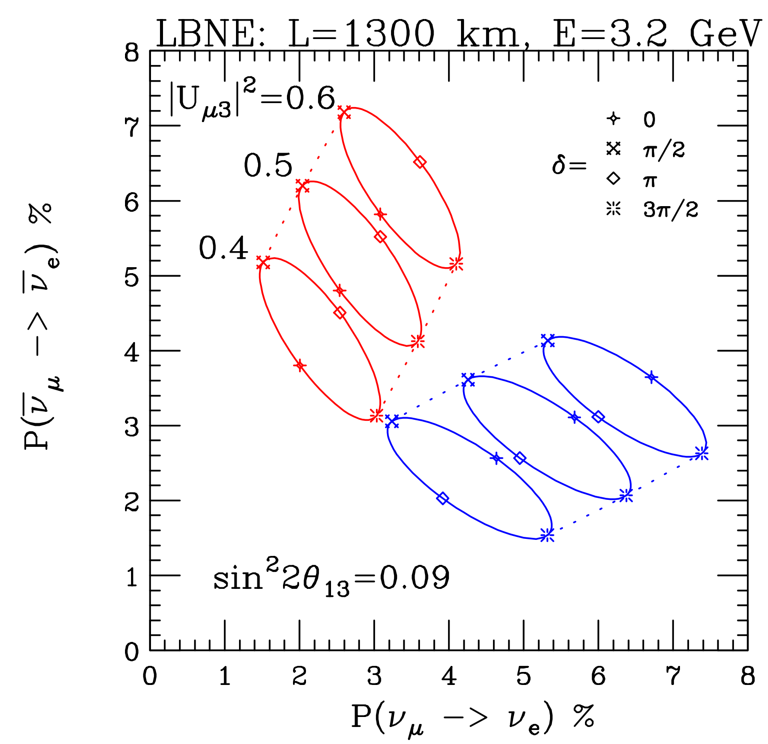
T2K/HK



NOvA



DUNE Same L/E as NOνA

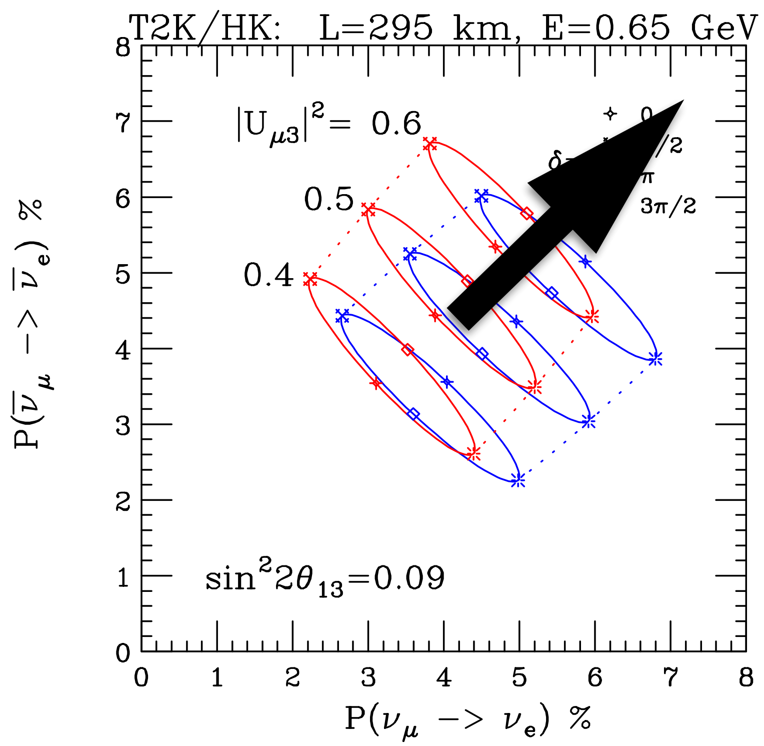


$\sin^2\theta_{23}$

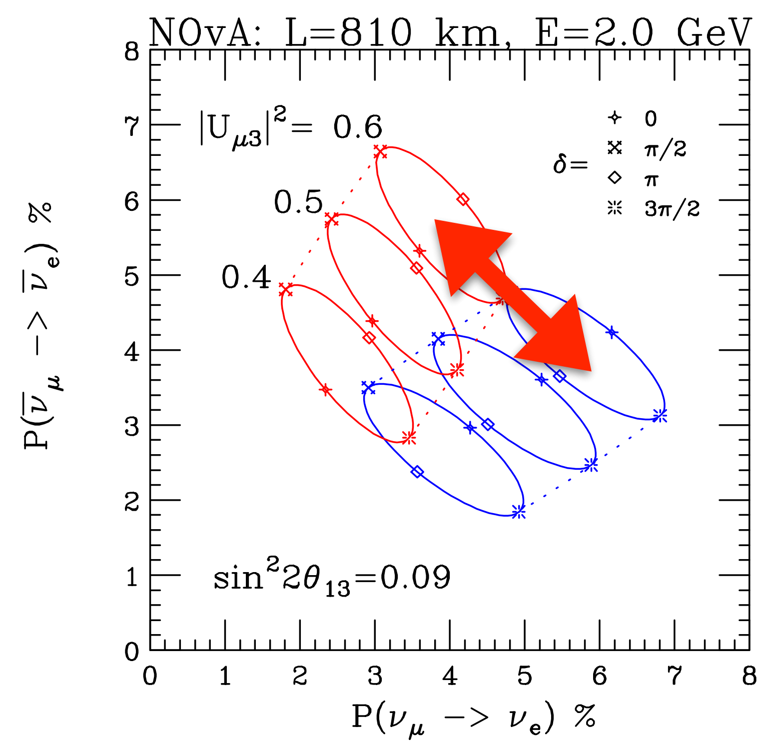
arXiv:hep-ph/020417

Correlations btw $\nu_\mu \to \nu_e \quad \bar{\nu}_\mu \to \bar{\nu}_e$

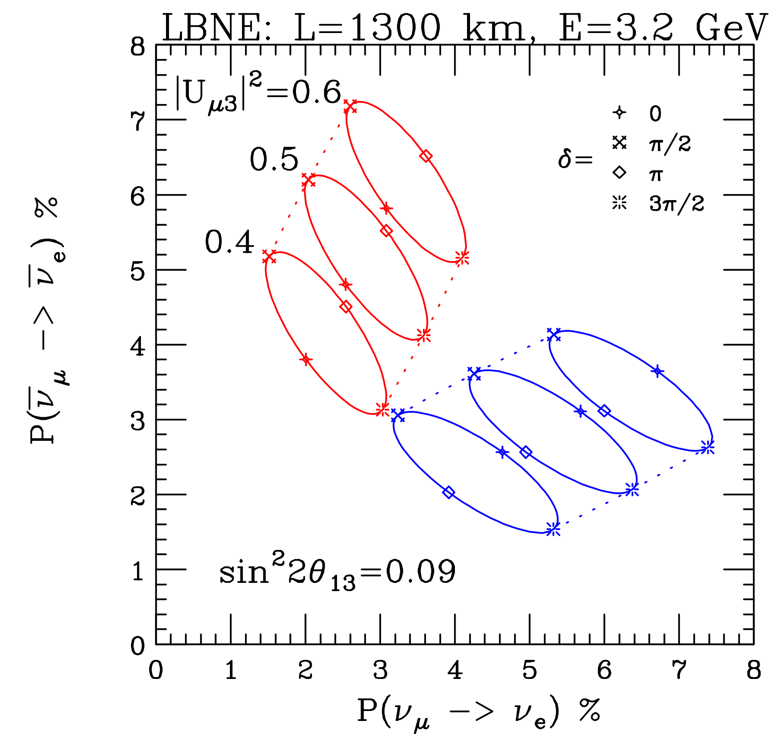
T2K/HK

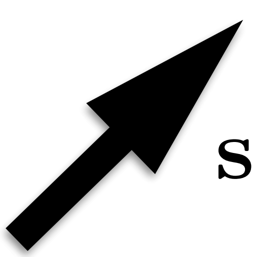


NOvA

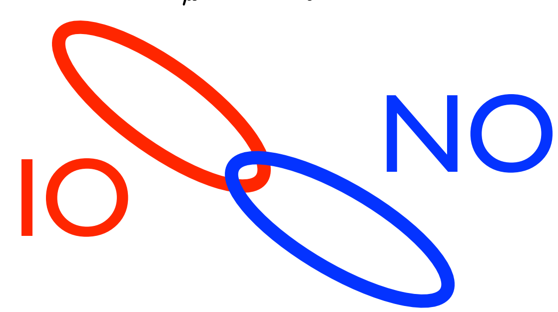


DUNE Same L/E as NOνA





$\sin^2\theta_{23}$

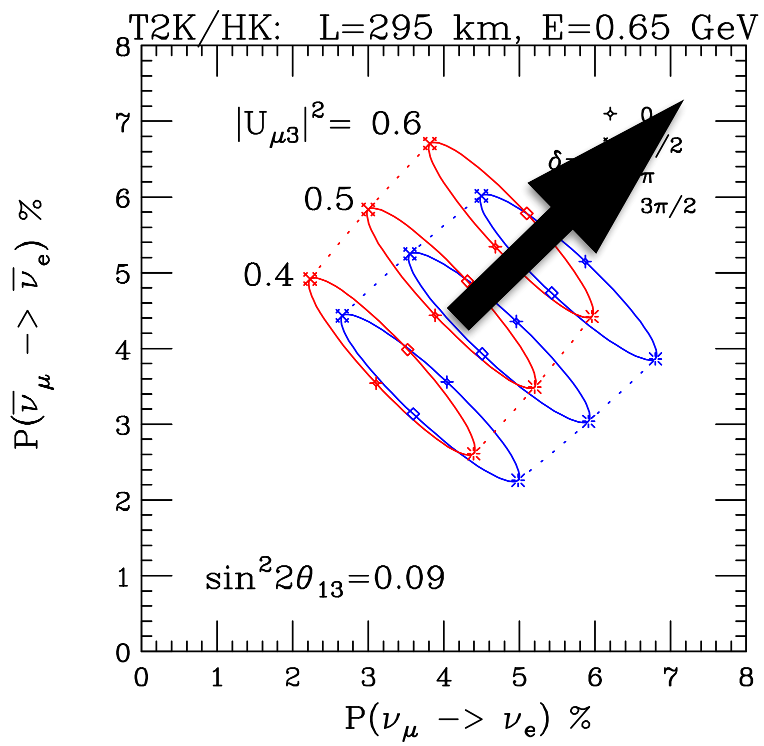


$\propto \rho L \ \sin^2\theta_{23}$

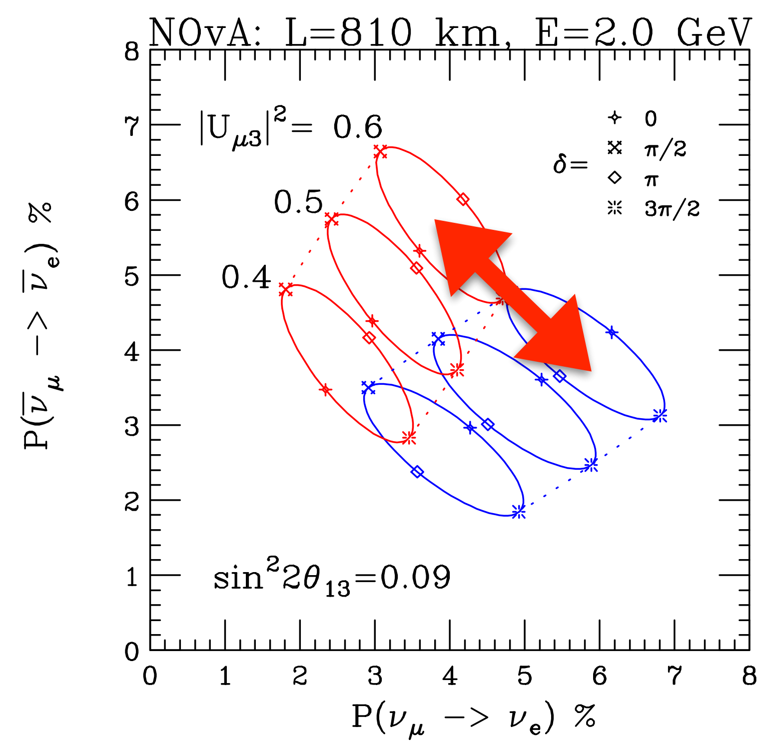
arXiv:hep-ph/020417

Correlations btw $\nu_\mu \to \nu_e \quad \bar{\nu}_\mu \to \bar{\nu}_e$

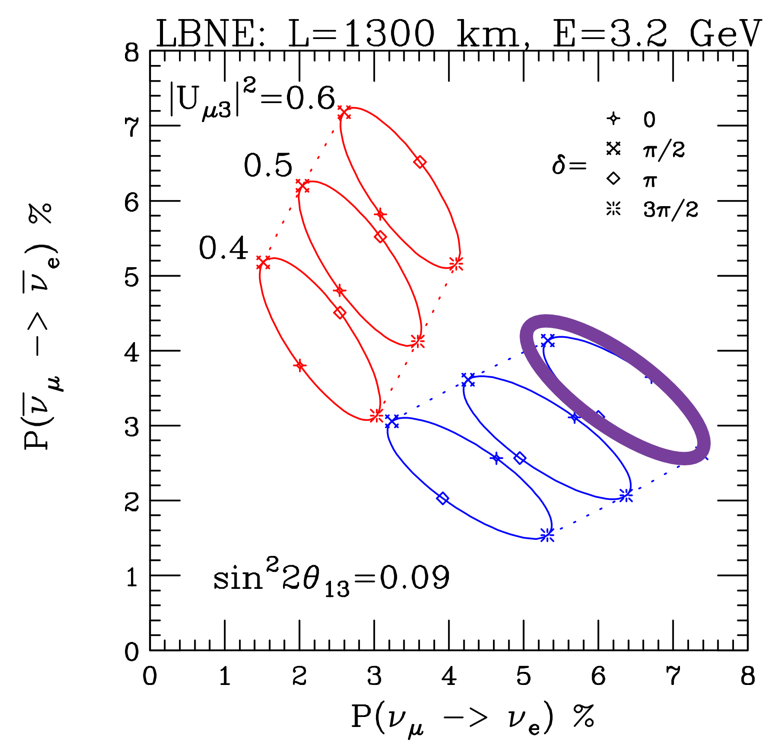
T2K/HK

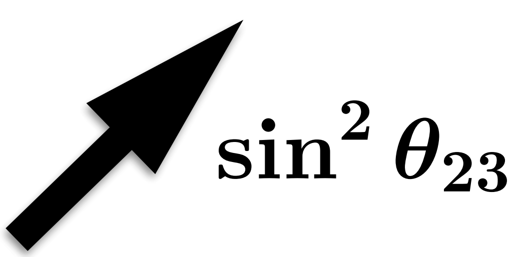


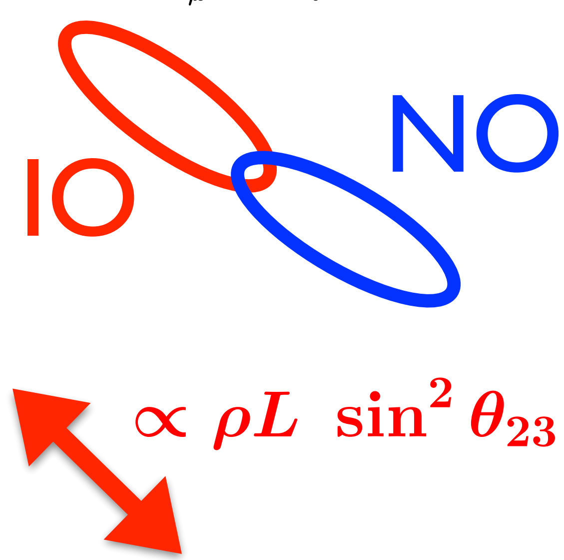
NOvA

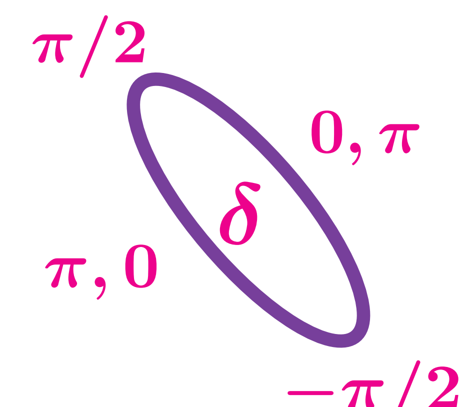


DUNE Same L/E as NOνA



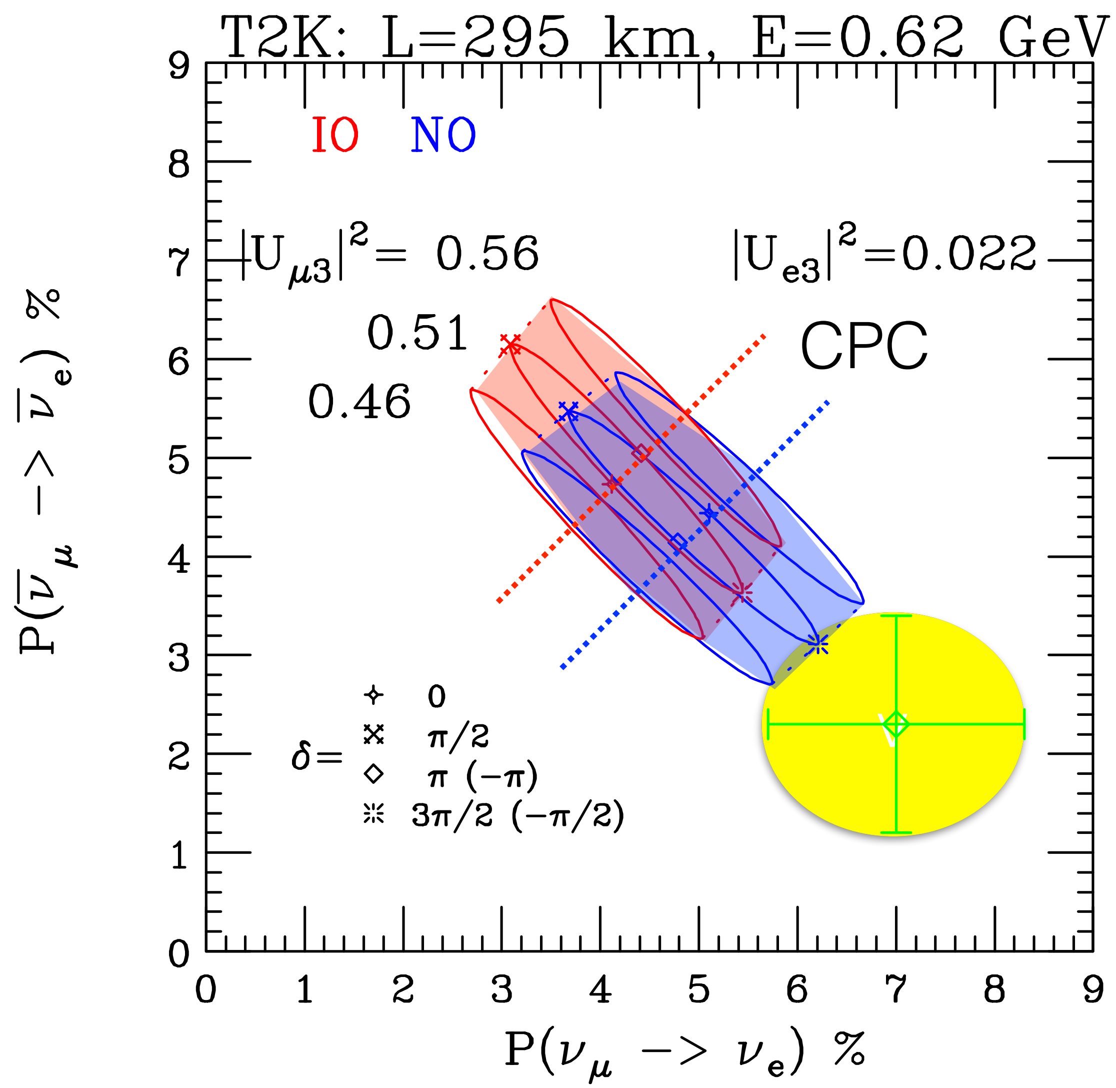


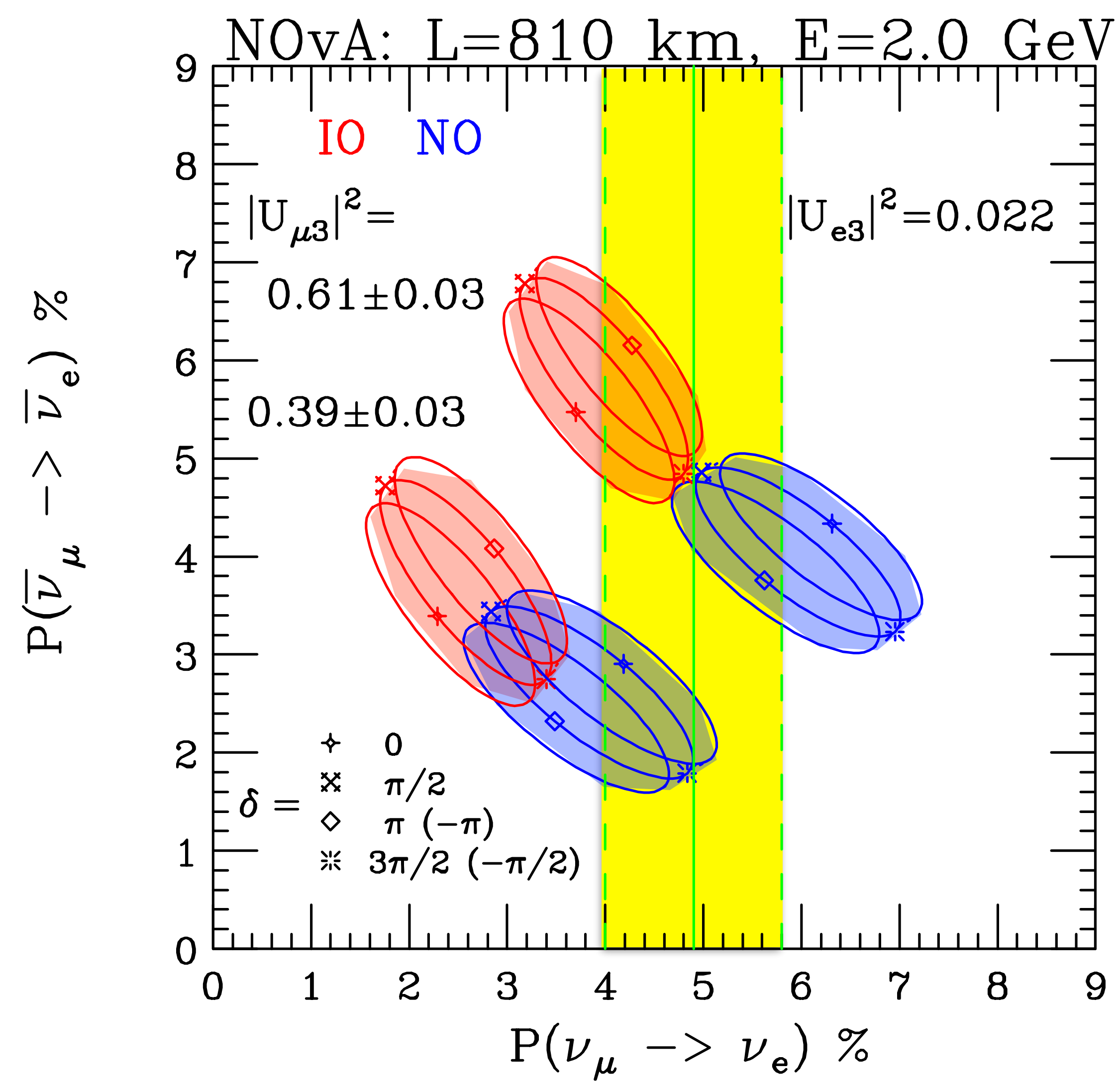




arXiv:hep-ph/020417

T2K & NOvA: circa 2016





1 sigma: NO IO Appearance data

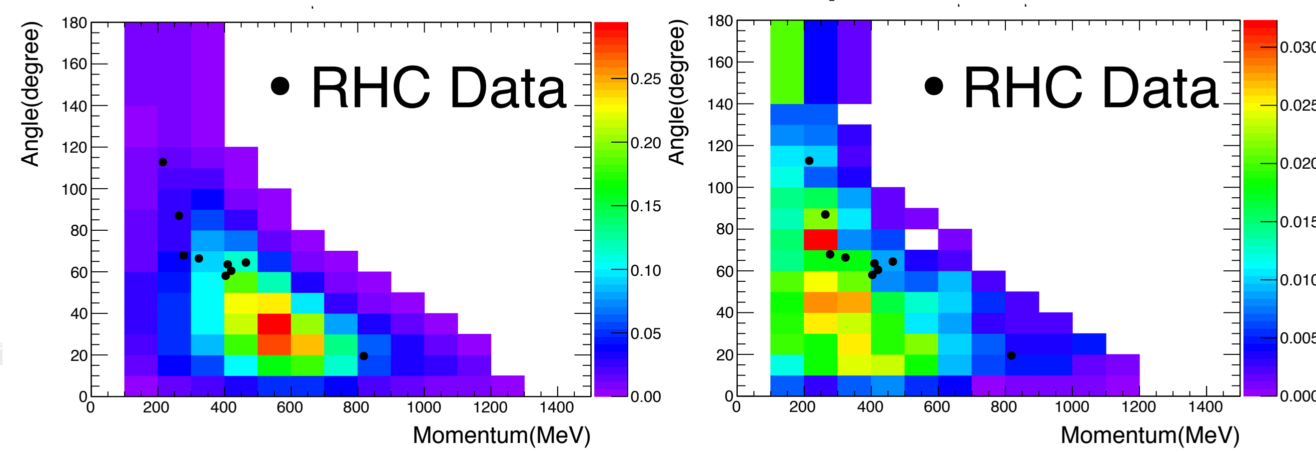
$\bar{\nu}_e$ appearance

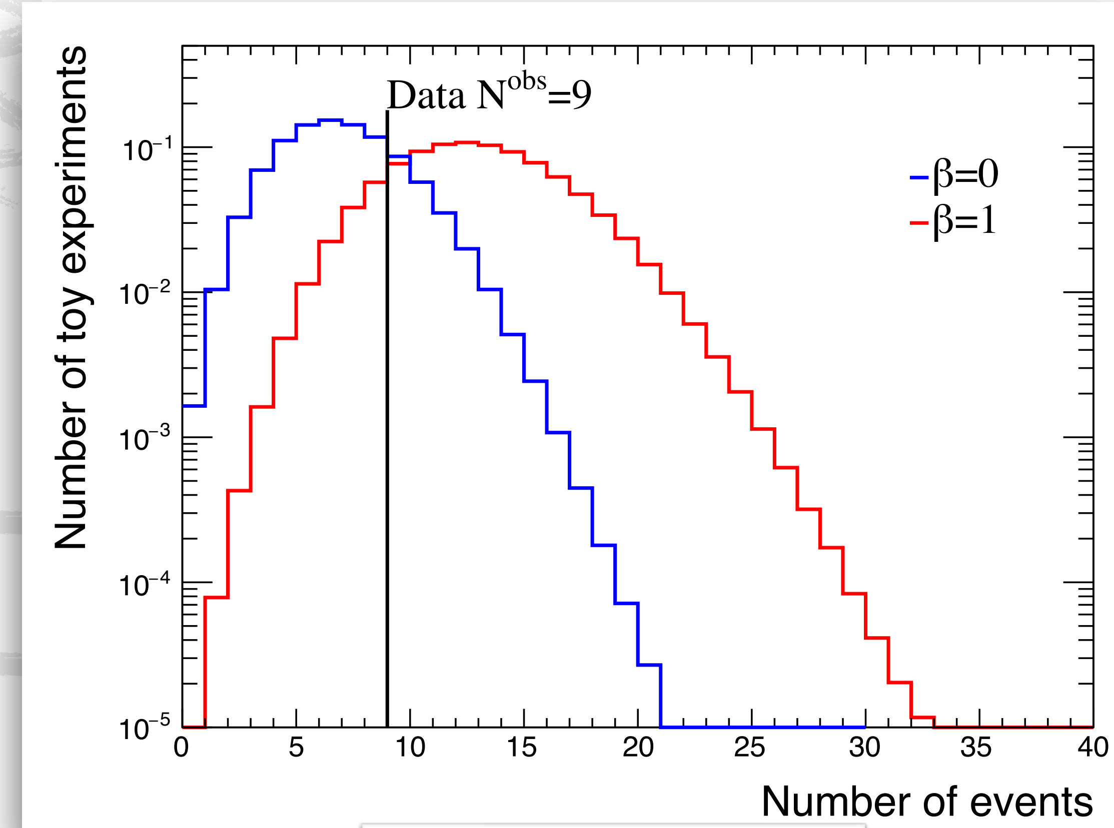
- Compare consistency with PMNS $\bar{\nu}_e$ appearance ($\beta = 1$) and no $\bar{\nu}_e$ appearance ($\beta = 0$)
  - if $\beta = 0$ expect 6.5 events
  - if $\beta = 1$ expect 11.8 events
- The data shapes look more consistent with background spectra than $\bar{\nu}_e$ signal spectrum
- Use rate+shape analyses:

β	HYPOTHESIS	P-VALUE
β=0	NO appearance	p=0.233
β=1	PMNS appearance	p=0.0867

- **No strong statistical conclusion yet**

Shape of $\bar{\nu}_e$ signal *Shape of mis-ID BGs*





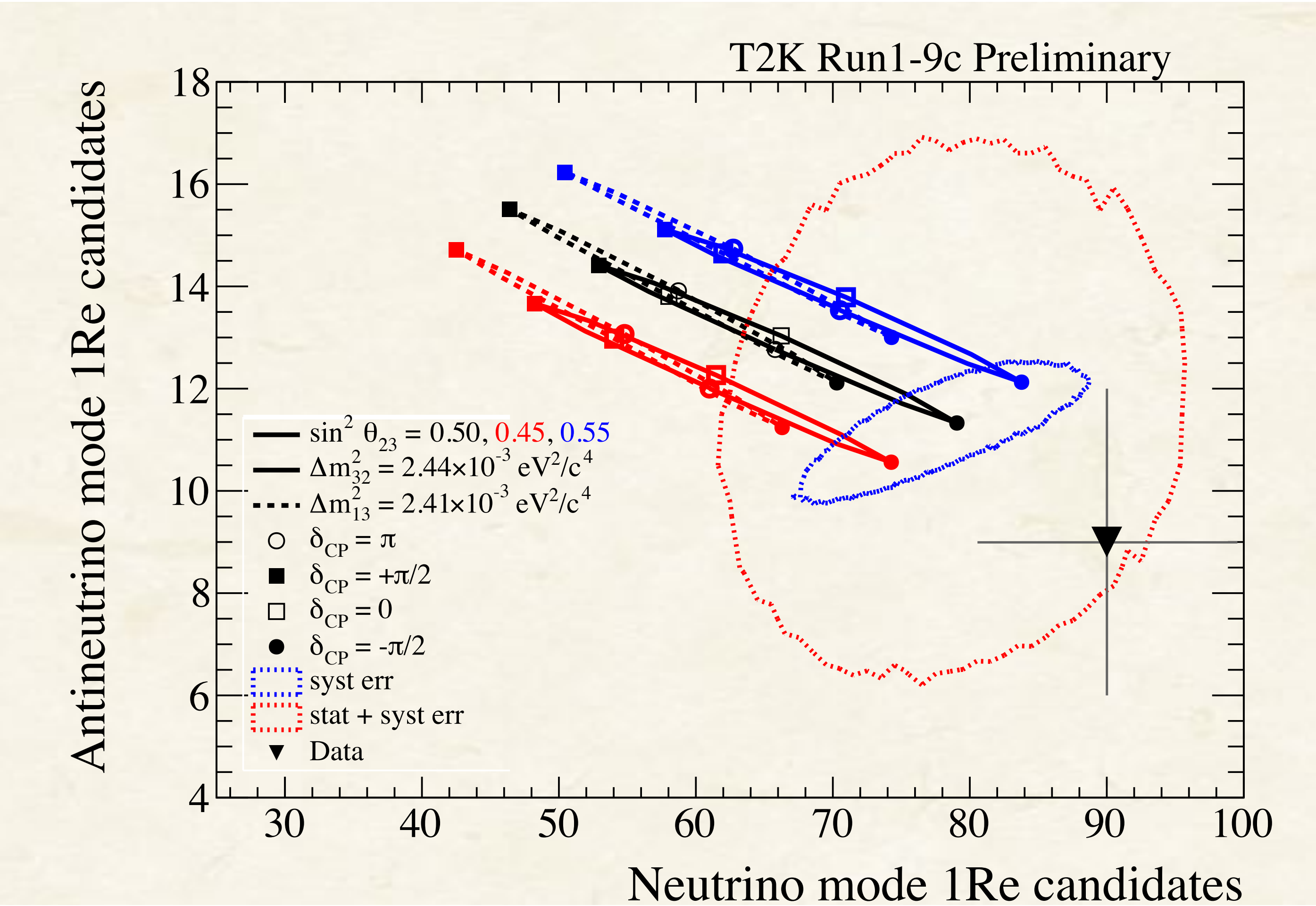
see posters by:
F. Bench, #277, Wed

Imperial College London 2018 / 06 / 04

Neutrino 2018

Morgan O. Wascko 20

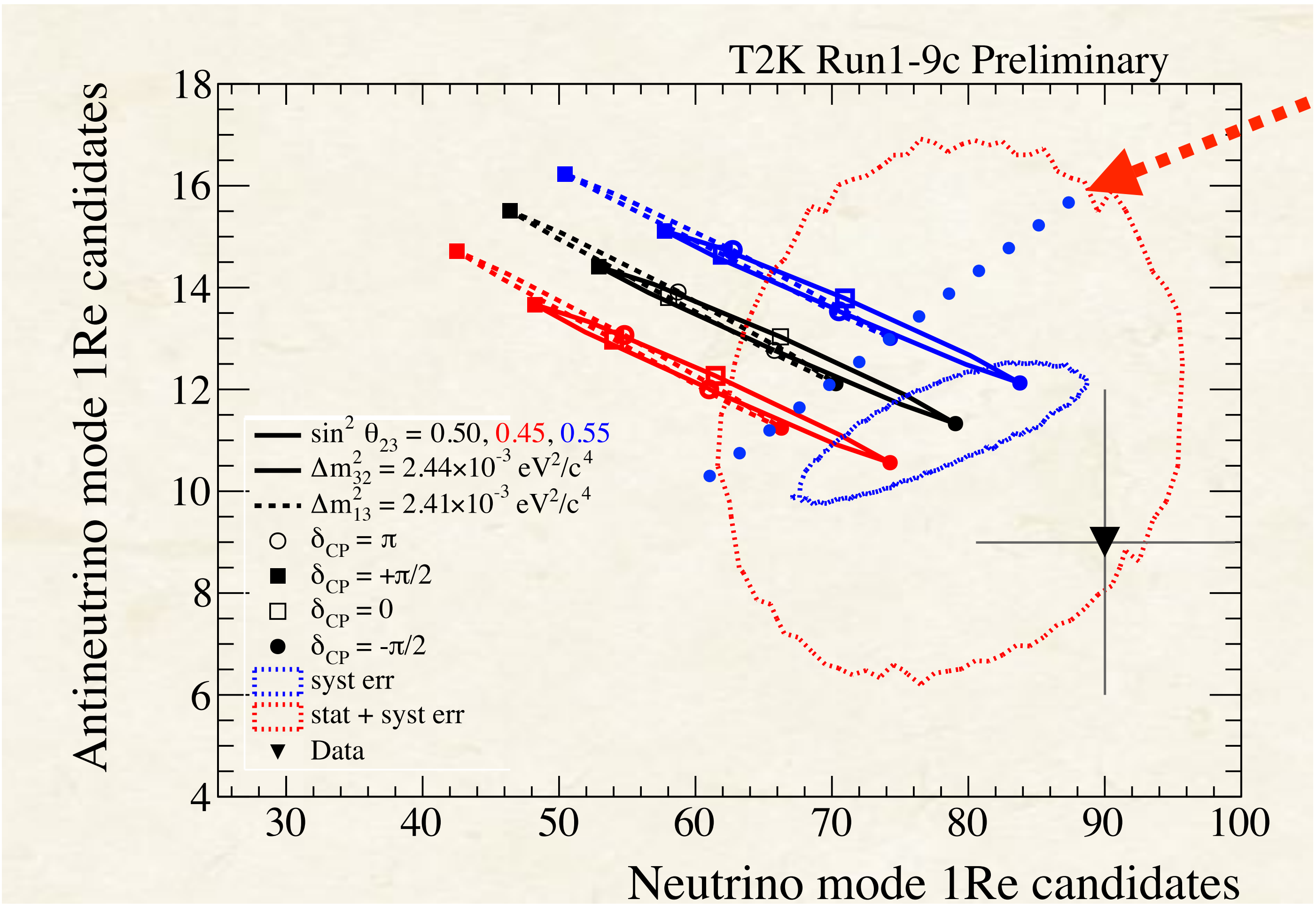
Neutrino 2018



	$\sin^2\theta_{23}\leq 0.5$	$\sin^2\theta_{23}>0.5$	SUM
NH ($\Delta m^2_{32}>0$)	0.204	0.684	0.888
IH ($\Delta m^2_{31}<0$)	0.023	0.089	0.112
SUM	0.227	0.773	1

Neutrino 2018

IO/NO boundary

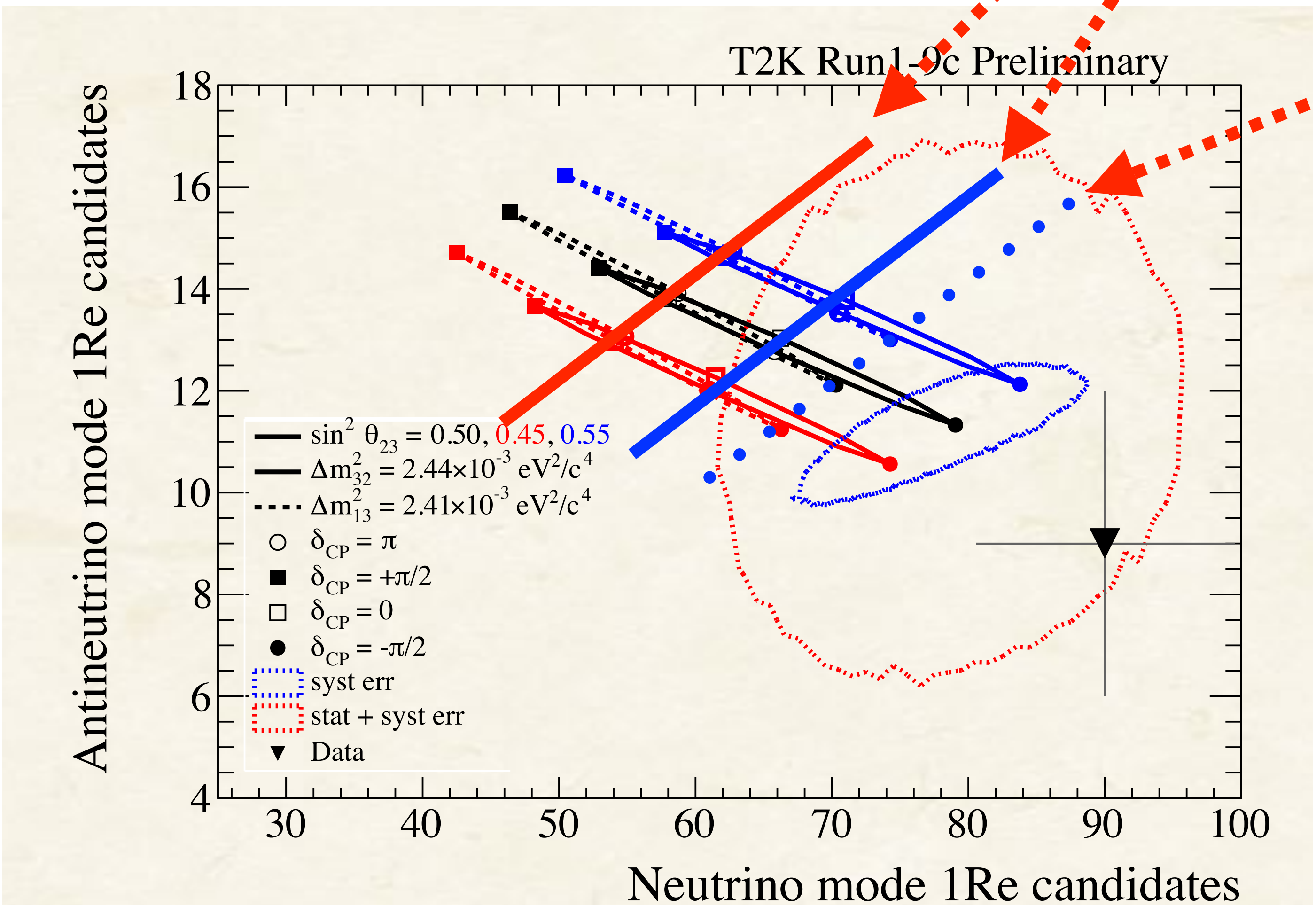


	$\sin^2\theta_{23} \leq 0.5$	$\sin^2\theta_{23} > 0.5$	SUM
NH ($\Delta m^2_{32}>0$)	0.204	0.684	0.888
IH ($\Delta m^2_{31}<0$)	0.023	0.089	0.112
SUM	0.227	0.773	1

Neutrino 2018

CPC
IO, NO

IO/NO boundary



	$\sin^2\theta_{23}\leq 0.5$	$\sin^2\theta_{23}>0.5$	SUM
NH ($\Delta m^2_{32}>0$)	0.204	0.684	0.888
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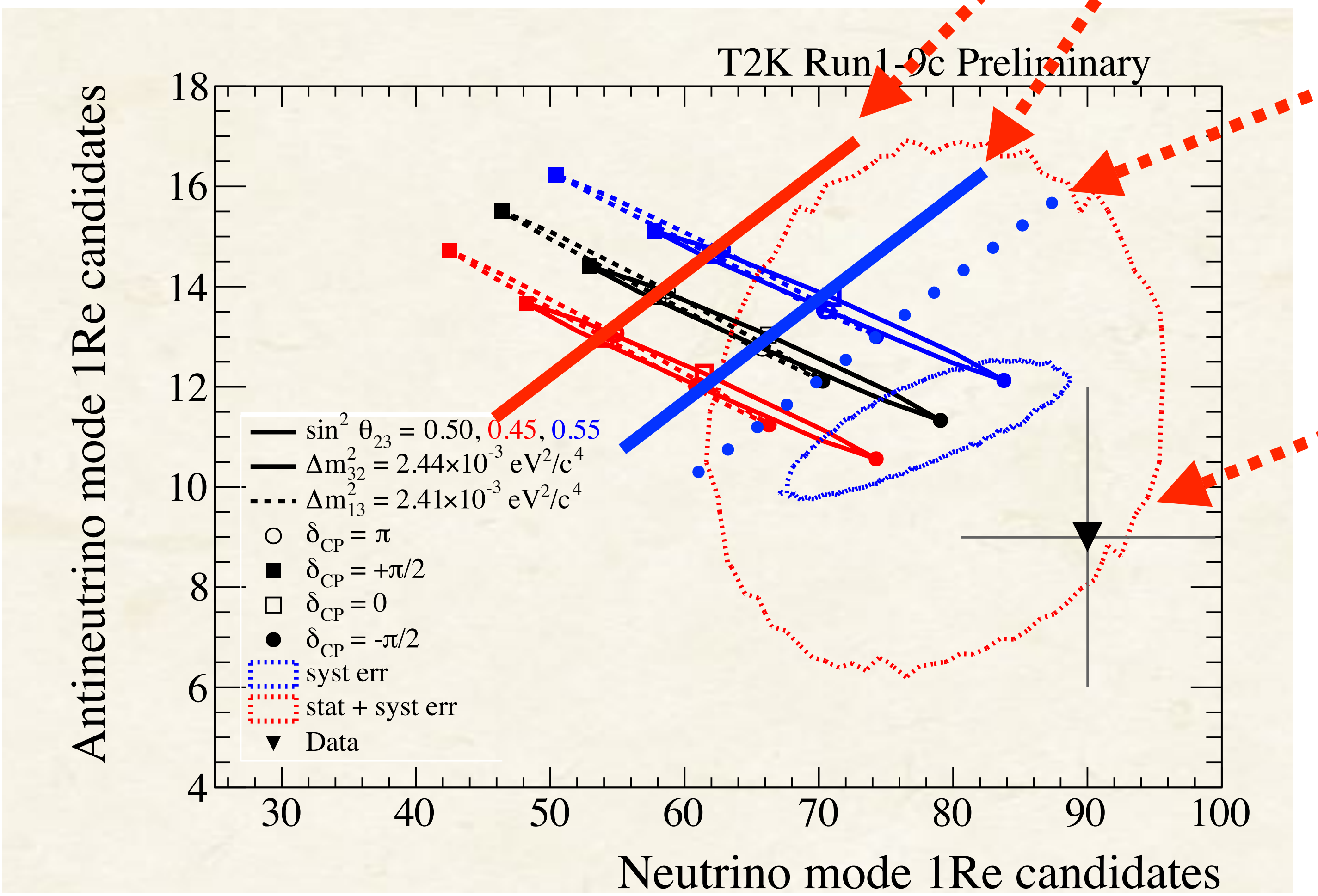
Neutrino 2018



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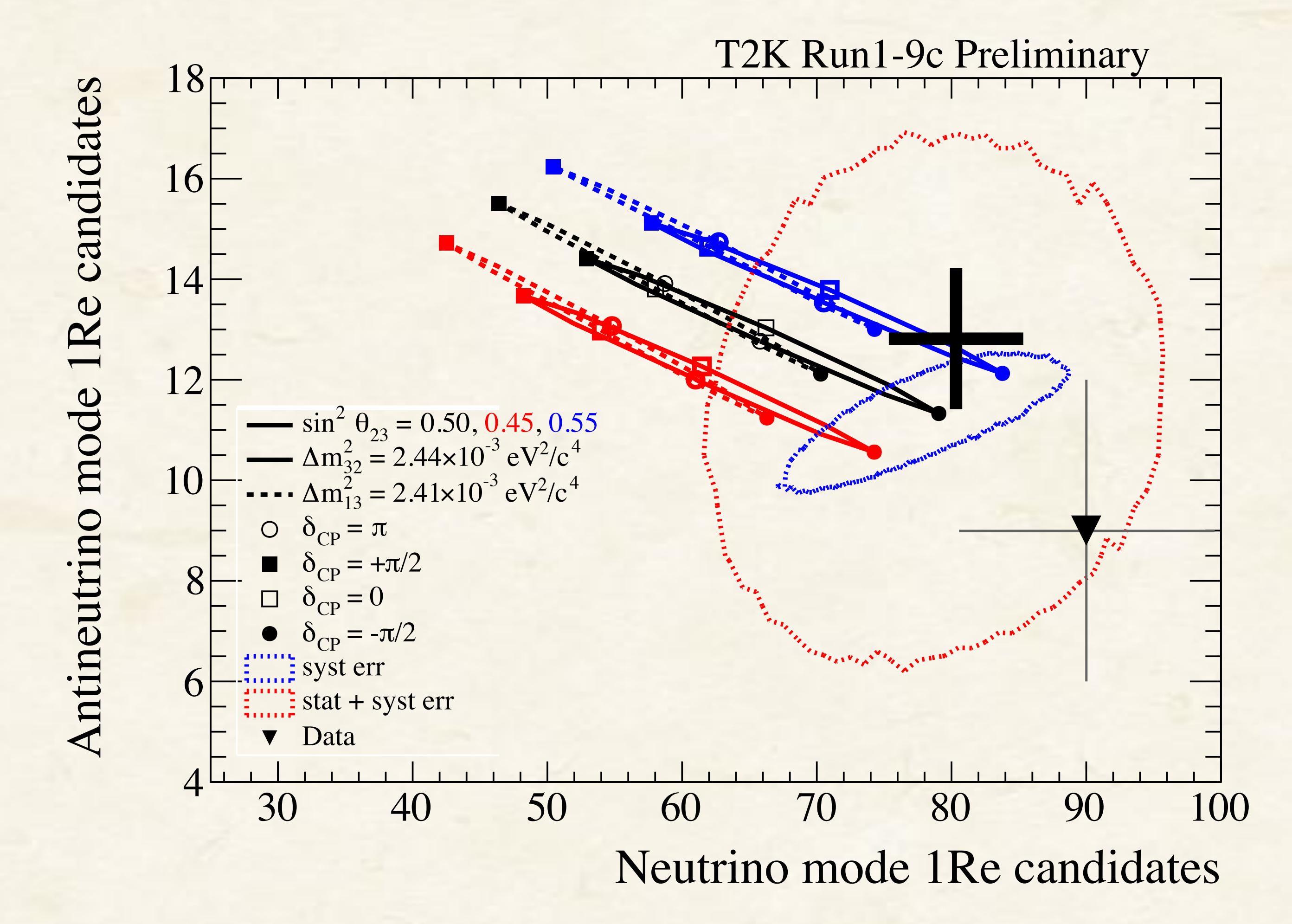
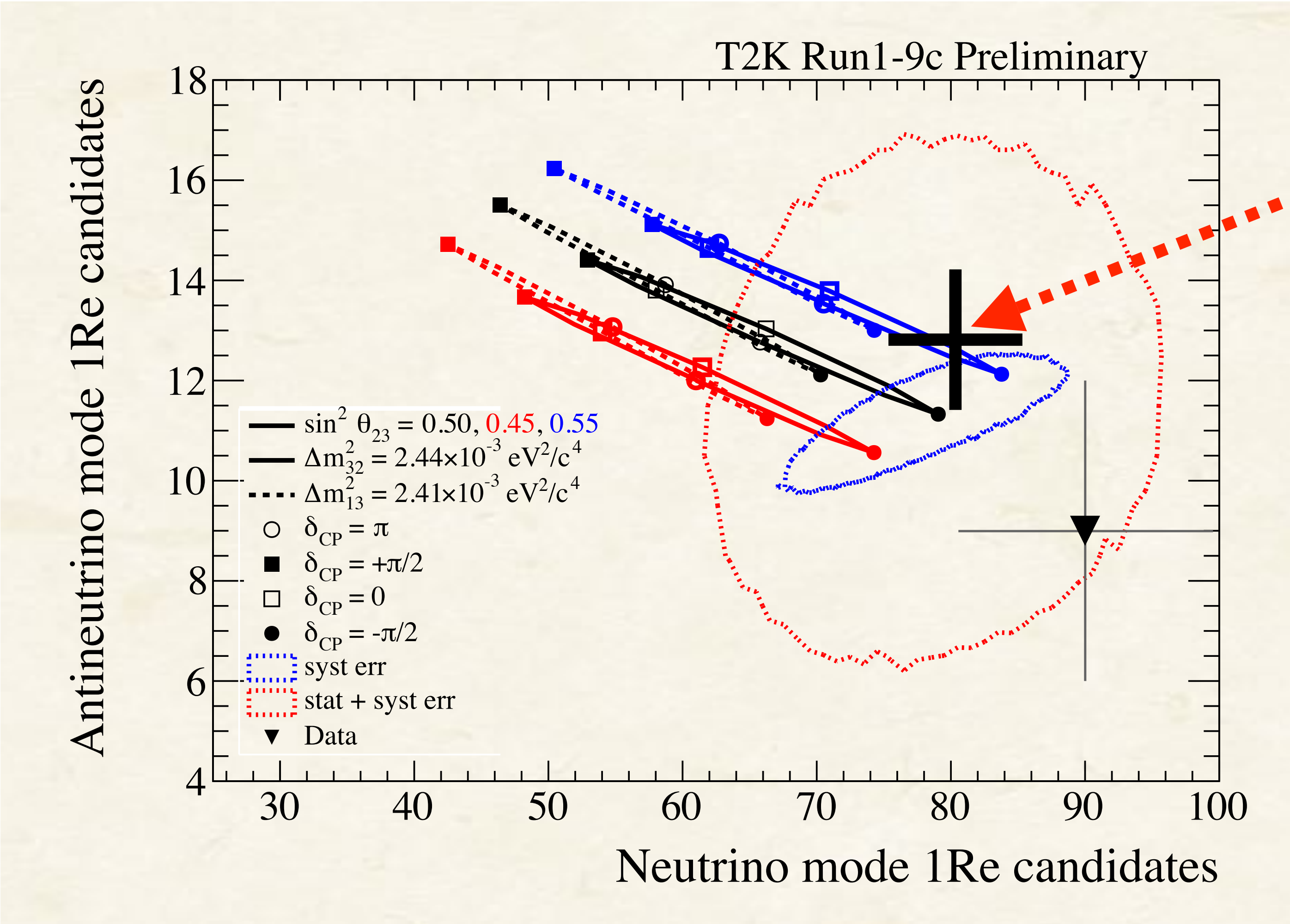
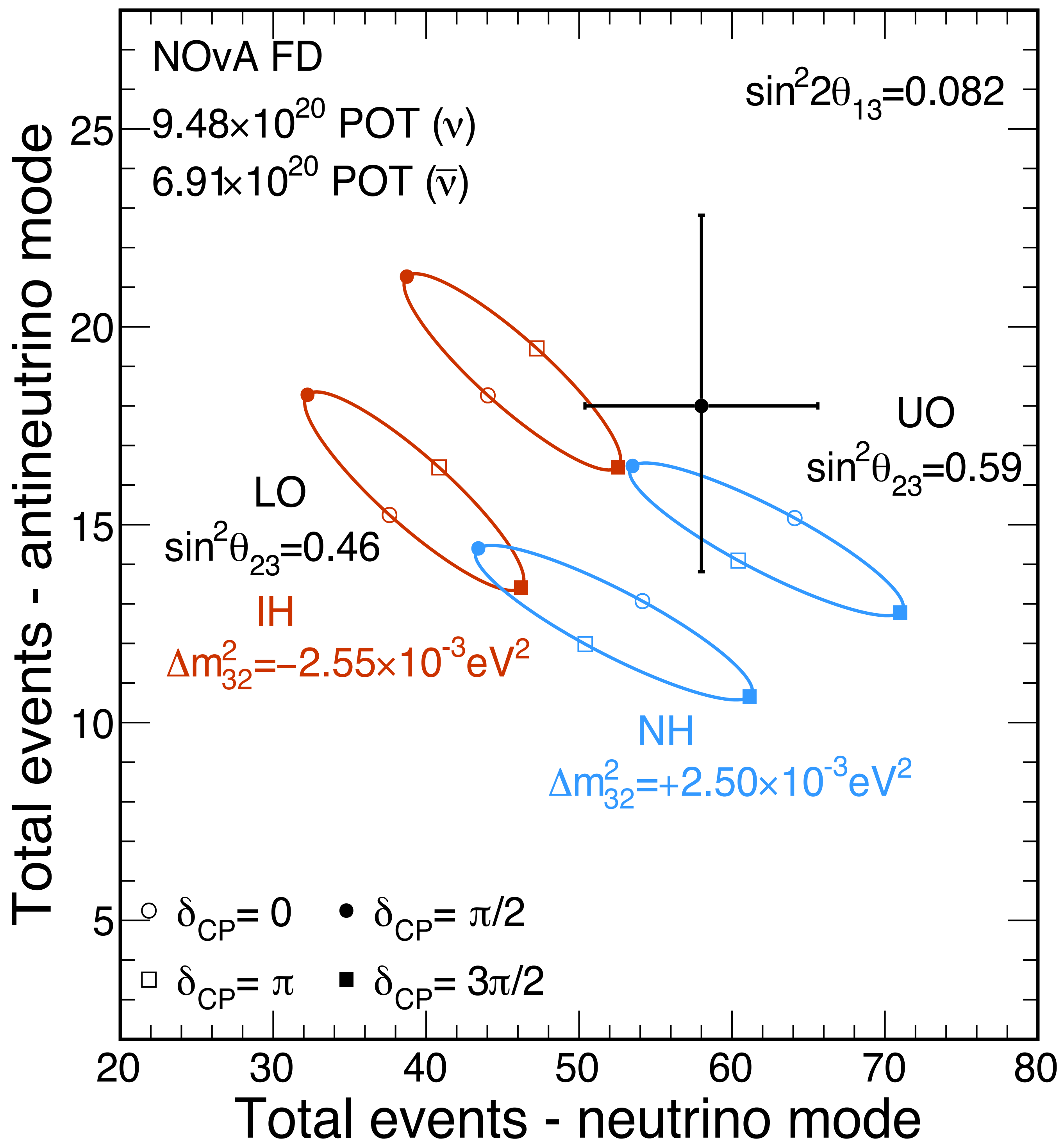


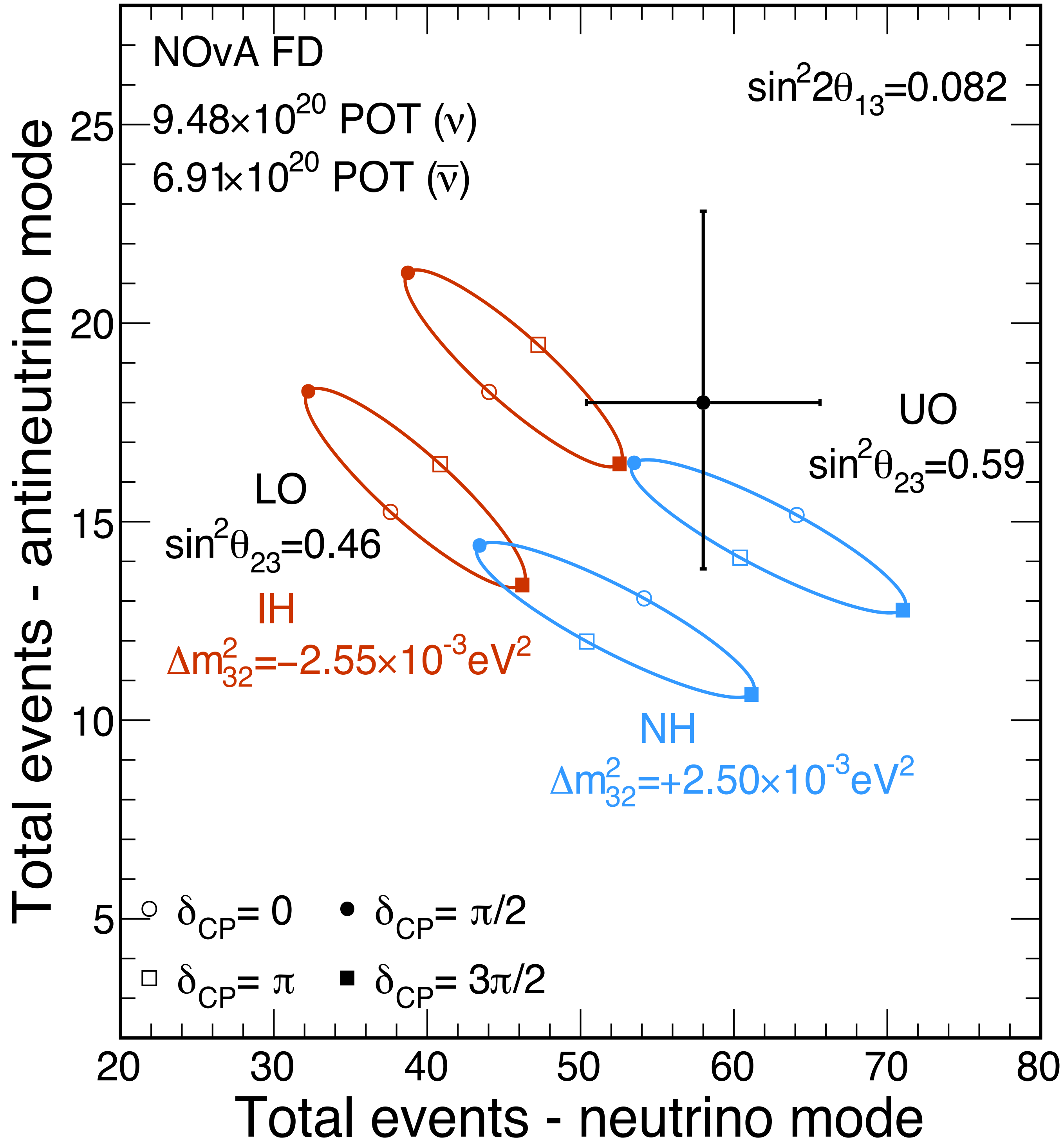
Neutrino 2018



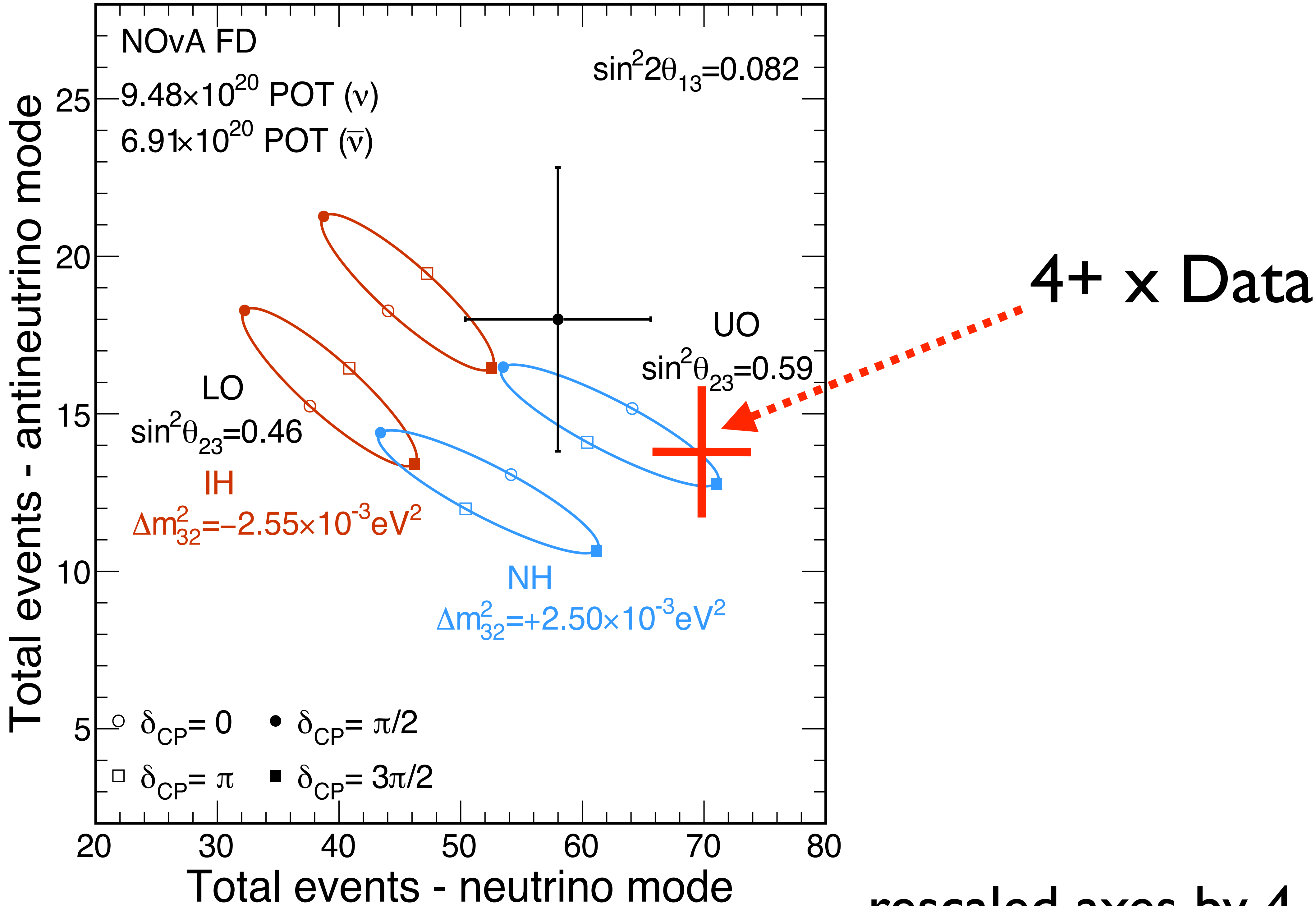
4+ x Data

rescaled axes by 4


NOvA FD
9.48×10^20 POT (ν)
6.91×10^20 POT (ν̄)
sin²2θ13=0.082
UO
sin²θ23=0.59
LO
sin²θ23=0.46
IH
Δm²32=−2.55×10⁻³eV²
NH
Δm²32=+2.50×10⁻³eV²
δCP= 0
δCP= π/2
δCP= π
δCP= 3π/2
Total events - antineutrino mode
Total events - neutrino mode
5
10
15
20
25
20
30
40
50
60
70
80

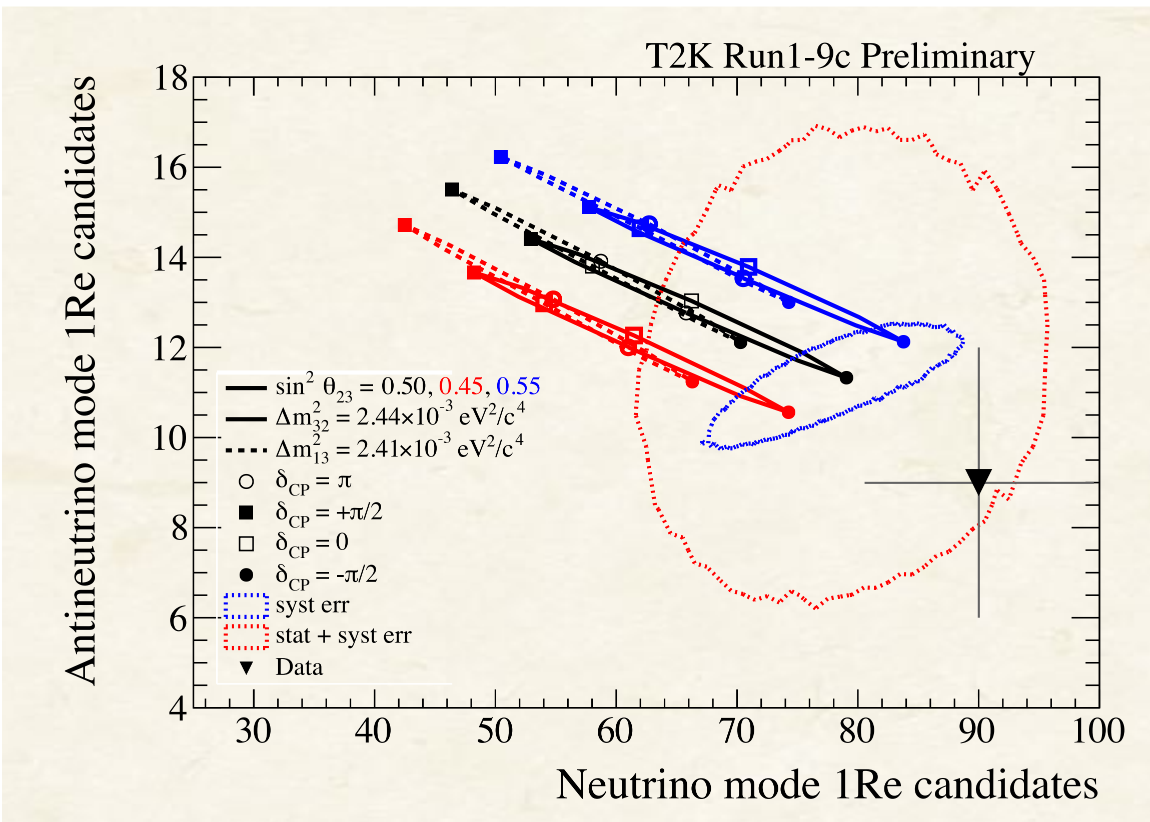


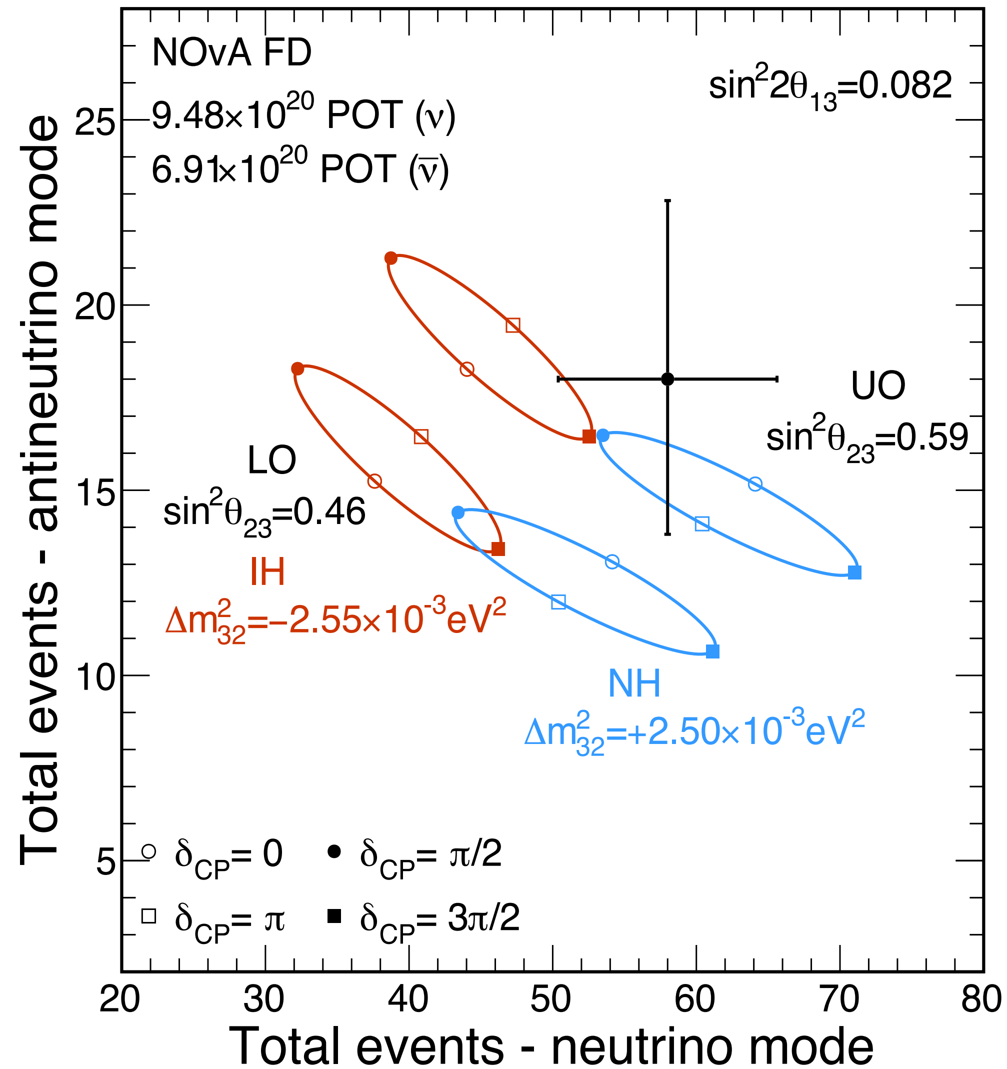
- We observe >4 σ evidence of electron antineutrino appearance.



rescaled axes by 4

- We observe >4 σ evidence of electron antineutrino appearance.


T2K Run1-9c Preliminary
Antineutrino mode 1Re candidates
Neutrino mode 1Re candidates
sin² θ23 = 0.50, 0.45, 0.55
Δm²32 = 2.44×10⁻³ eV²/c⁴
Δm²13 = 2.41×10⁻³ eV²/c⁴
δCP = π
δCP = +π/2
δCP = 0
δCP = -π/2
syst err
stat + syst err
Data


NOvA FD
9.48×10²⁰ POT (ν)
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sin²2θ13=0.082
UO
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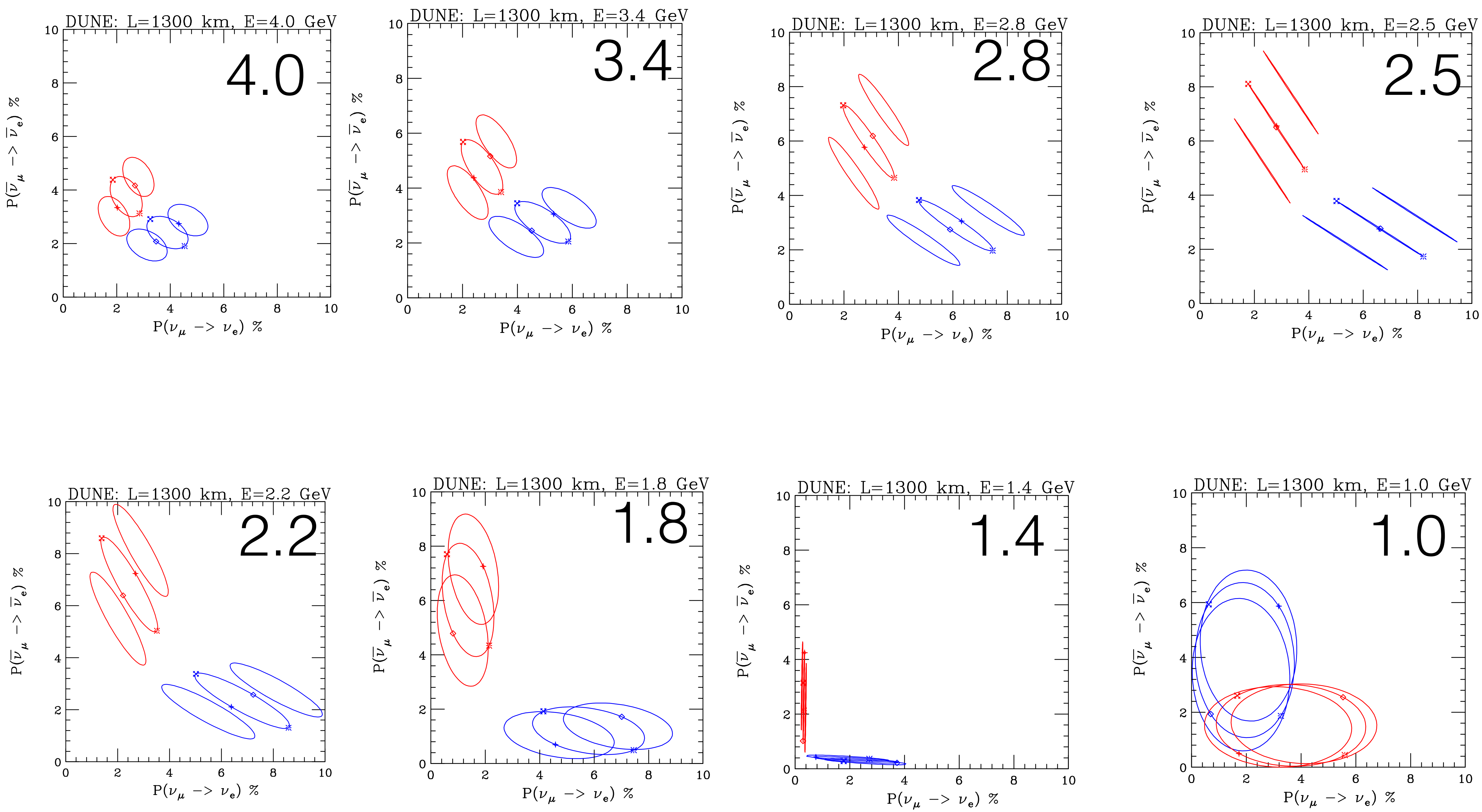
LO
sin²θ23=0.46
IH
Δm²32=−2.55×10⁻³eV²
NH
Δm²32=+2.50×10⁻³eV²
δCP= 0
δCP= π/2
δCP= π
δCP= 3π/2
Total events - antineutrino mode
Total events - neutrino mode

DUNE bi-Probability Diagrams:

Normal Ordering — Inverted Ordering

VOM

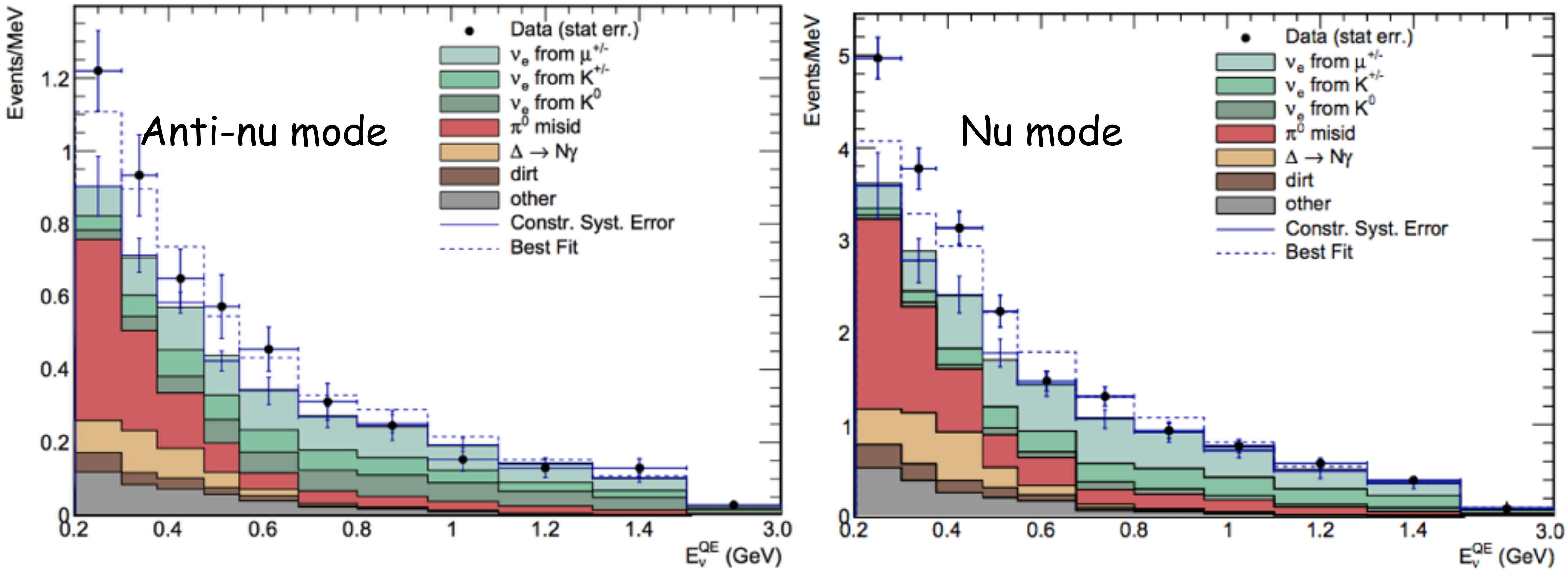


near Osc Min

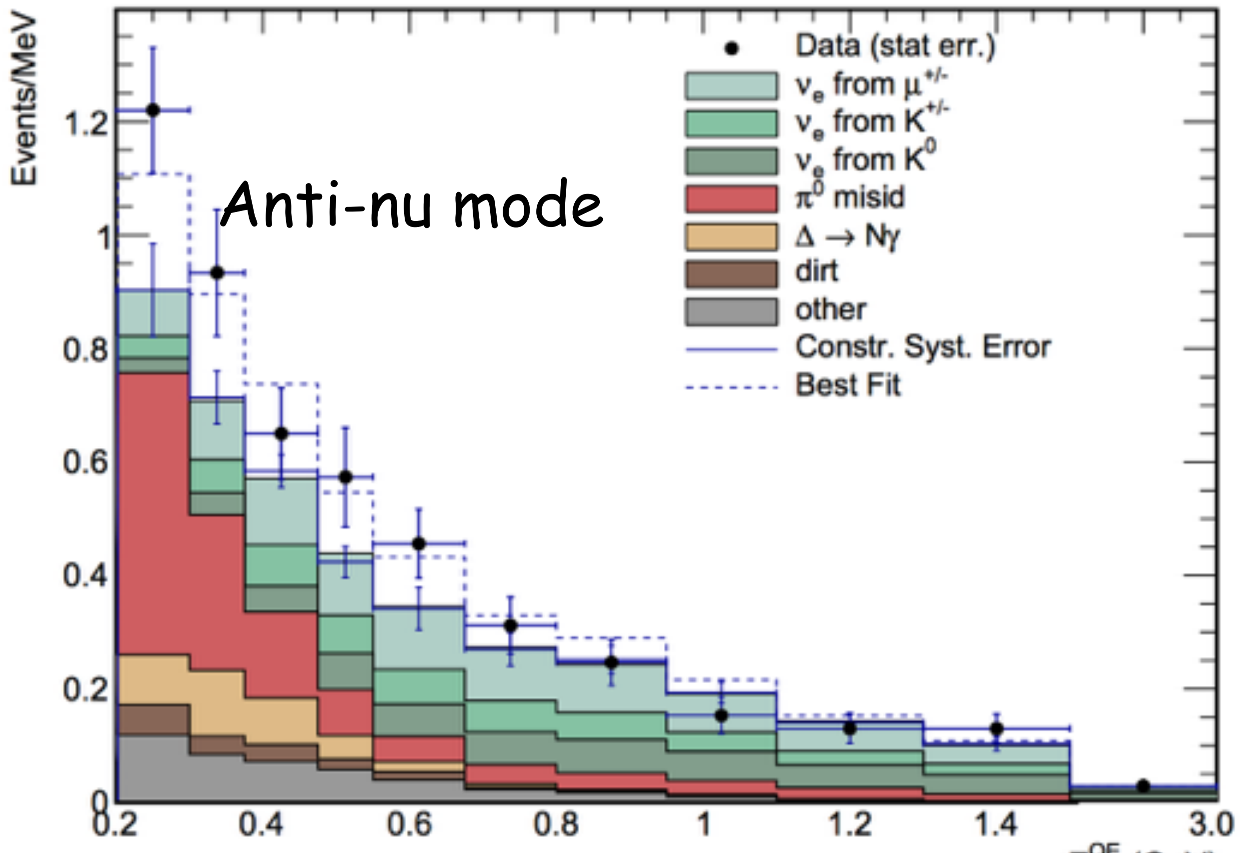
Beyond 3 neutrino Paradigm:

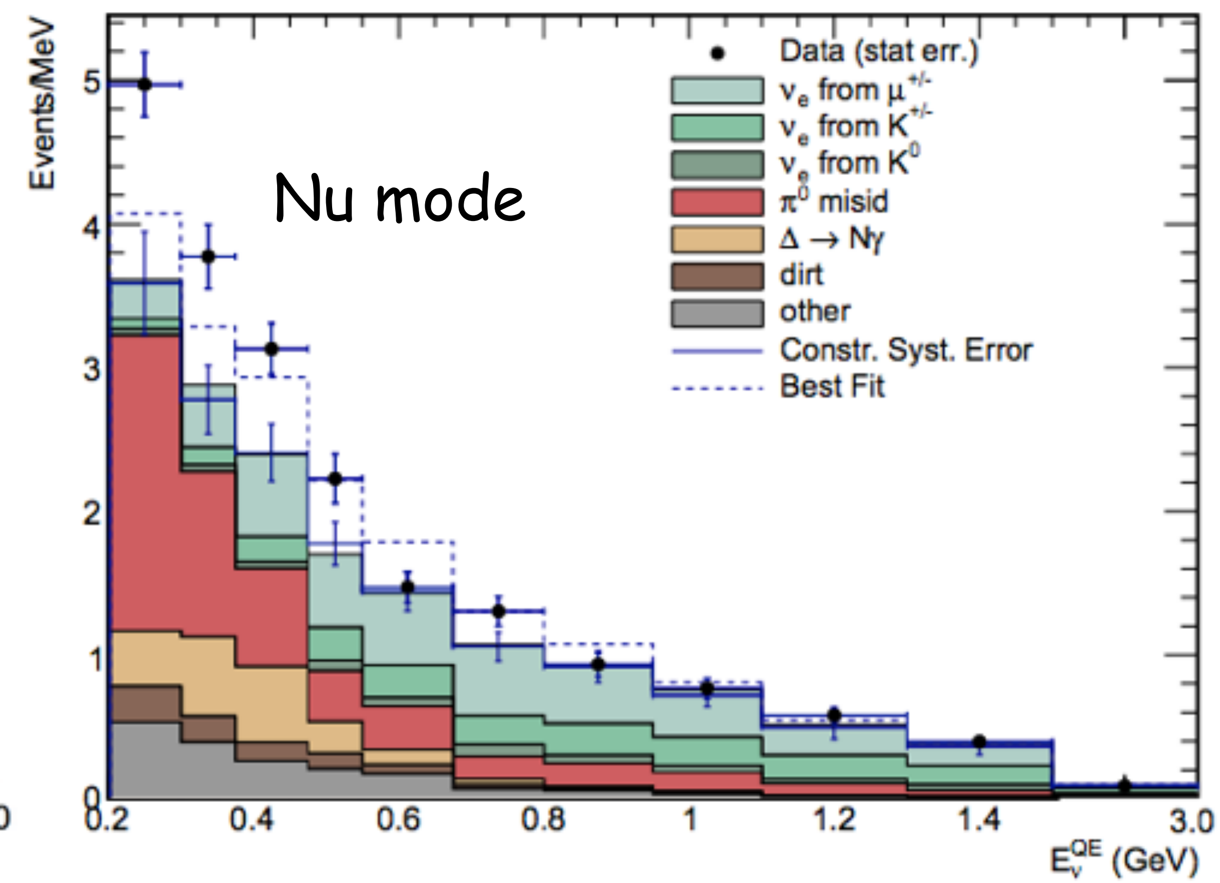
- Sterile Neutrinos (MiniBooNE & 3+1 models)

MicroBooNE:


Anti-nu mode
Nu mode
Data (stat err.)
ν_e from $\mu^{+/-}$
ν_e from $K^{+/-}$
ν_e from K^0
π^0 misid
$\Delta \rightarrow N\gamma$
dirt
other
Constr. Syst. Error
Best Fit
Events/MeV
E_ν^{QE} (GeV)

MicroBooNE:





	ν mode 12.84×10^{20} POT	$\bar{\nu}$ mode 11.27×10^{20} POT	Combined
Data	1959	478	2437
Unconstrained Background	1590.5	398.2	1988.7
Constrained Background	1577.8	398.7	1976.5
Excess	381.2 ± 85.2 4.5σ	79.3 ± 28.6 2.8σ	460.5 ± 95.8 4.8σ
0.26% (LSND) $\nu_\mu \to \nu_e$	463.1	100.0	563.1

- Total excess for neutrino + antineutrino:

$$460.5 \pm 95.8(4.8\sigma)$$

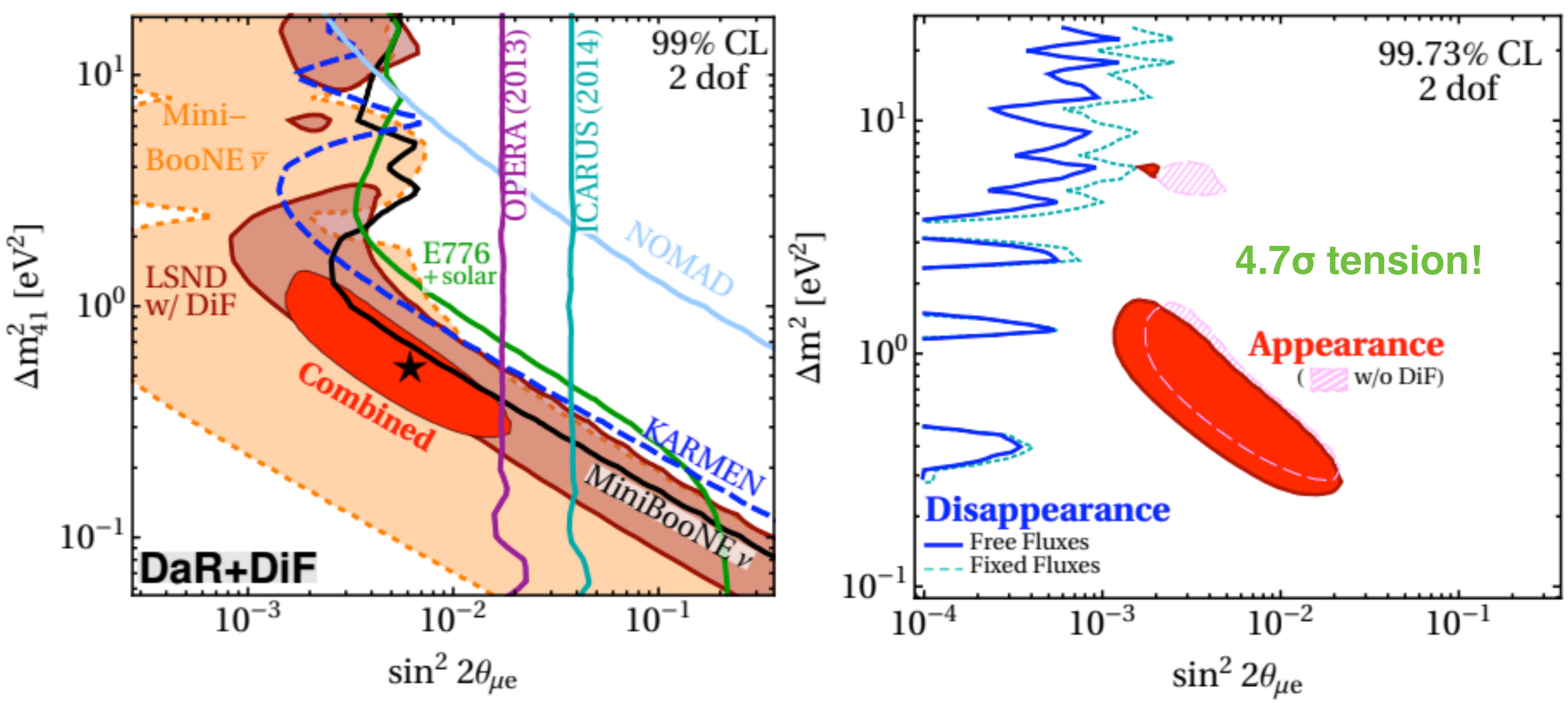
Are there light sterile neutrinos?

arXiv:1803.10661 — To be updated soon!
Accepted for publication by JHEP

Updated global analysis of neutrino oscillations in the presence of eV-scale sterile neutrinos

Dentler, Hernandez-Cabezudo, Kopp, **Machado**, Maltoni, Martinez-Soler, Schwetz

Invisibles visitor — Invisibles visitor — Former RA — future FNAL RA



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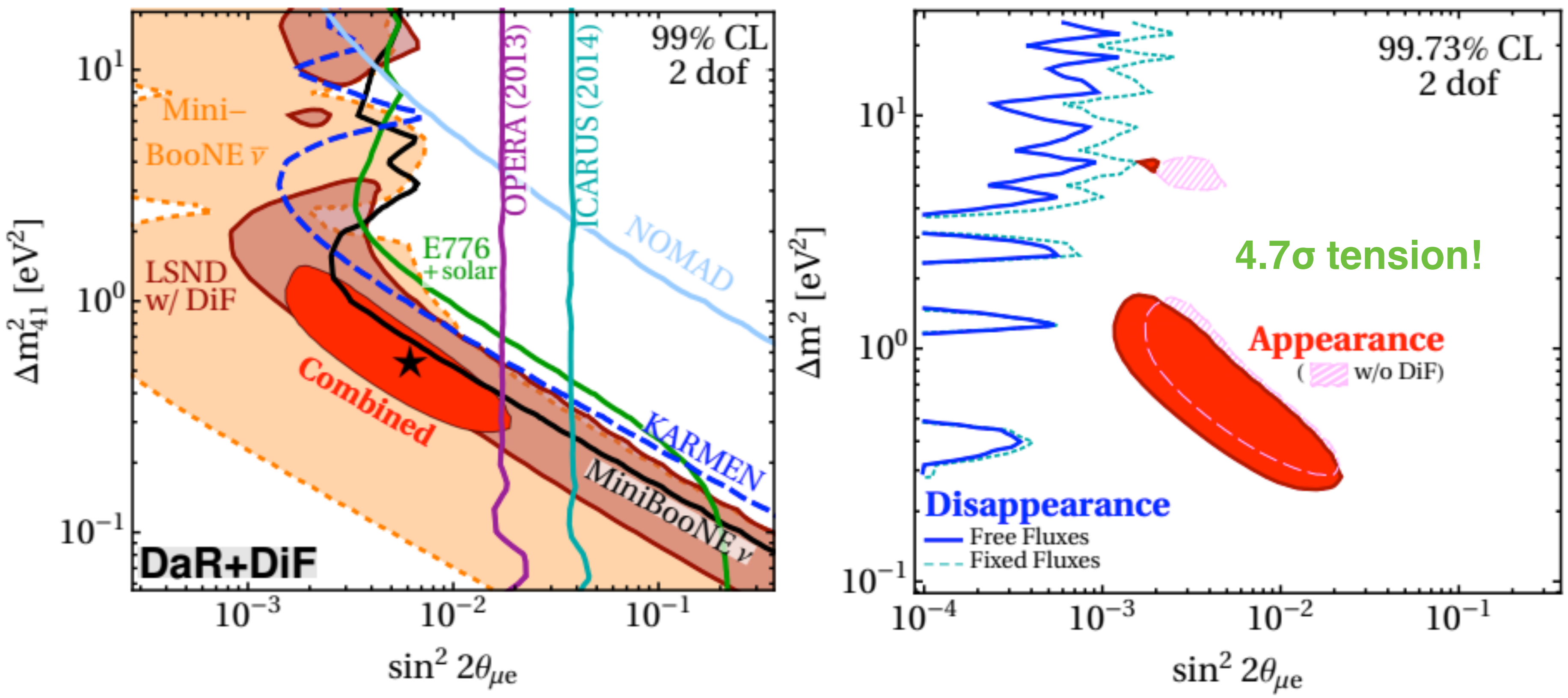

What is the Nature of The Excess ???

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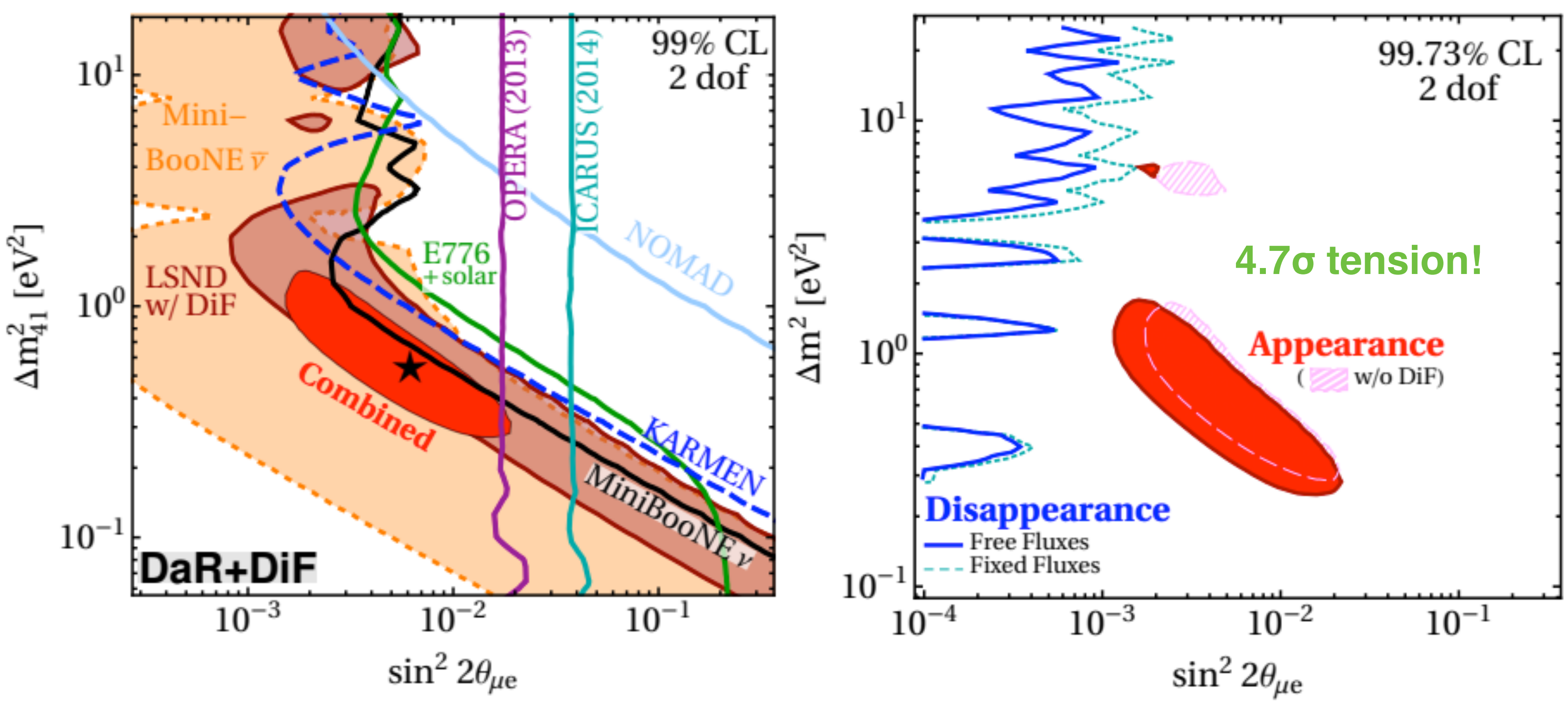

What is the Nature of The Excess ???

Spotlighted MicroBooNE, ICARUS & SBND

Nu 2020 ChicagoLand

Summary / Score Card:

Summary / Score Card:

- **Mass Ordering:**

  SK ($\sim 2^{+}\sigma$) and T2K ($\sim 2^{-}\sigma$) preference for Norm. Ord.
  NOvA ($\sim 2^{-}\sigma$) preference for Norm. Ord.

Summary / Score Card:

- **Mass Ordering:** — **Norm. Ord.** $\sim 3\ \sigma$

  SK ($\sim 2^+\sigma$) and T2K ($\sim 2^-\sigma$) preference for Norm. Ord.
  NOvA ($\sim 2^-\sigma$) preference for Norm. Ord.

Summary / Score Card:

- **Mass Ordering:** **— Norm. Ord. $\sim 3\ \sigma$**

  SK ($\sim 2^{+}\sigma$) and T2K ($\sim 2^{-}\sigma$) preference for Norm. Ord.
  NOvA ($\sim 2^{-}\sigma$) preference for Norm. Ord.

- **Dominant Flavor of ν_3:**

  SK ($\sim 1^{+}\sigma$) preference for Up. Oct. (ν_μ dominates)
  T2K ($\sim 1^{+}\sigma$) preference for Up. Oct.
  NOvA ($\sim 1^{+}\sigma$) preference for Up. Oct.

Summary / Score Card:

- **Mass Ordering:** — **Norm. Ord.** $\sim 3\ \sigma$

  SK ($\sim 2^+\sigma$) and T2K ($\sim 2^-\sigma$) preference for Norm. Ord.
  NOvA ($\sim 2^-\sigma$) preference for Norm. Ord.

- **Dominant Flavor of** ν_3**:** — **Upper Octant** $\sim 2\ \sigma$

  SK ($\sim 1^+\sigma$) preference for Up. Oct. (ν_μ dominates)
  T2K ($\sim 1^+\sigma$) preference for Up. Oct.
  NOvA ($\sim 1^+\sigma$) preference for Up. Oct.

Summary / Score Card:

- **Mass Ordering: — Norm. Ord. $\sim 3\ \sigma$**

  SK ($\sim 2^{+}\sigma$) and T2K ($\sim 2^{-}\sigma$) preference for Norm. Ord.
  NOvA ($\sim 2^{-}\sigma$) preference for Norm. Ord.

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  SK ($\sim 1^{+}\sigma$) preference for Up. Oct. (ν_μ dominates)
  T2K ($\sim 1^{+}\sigma$) preference for Up. Oct.
  NOvA ($\sim 1^{+}\sigma$) preference for Up. Oct.

- **CP violation parameter δ:**

  SK and T2K best fit close to $\delta \approx -\pi/2$
  NOvA best fit:
  $\delta \approx \pi/5$ for NormOrd and $\delta \approx -\pi/2$ for Inv. Ord.

Summary / Score Card:

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Summary / Score Card:

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  SK ($\sim 2^{+}\sigma$) and T2K ($\sim 2^{-}\sigma$) preference for Norm. Ord.
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  NOvA ($\sim 1^{+}\sigma$) preference for Up. Oct.

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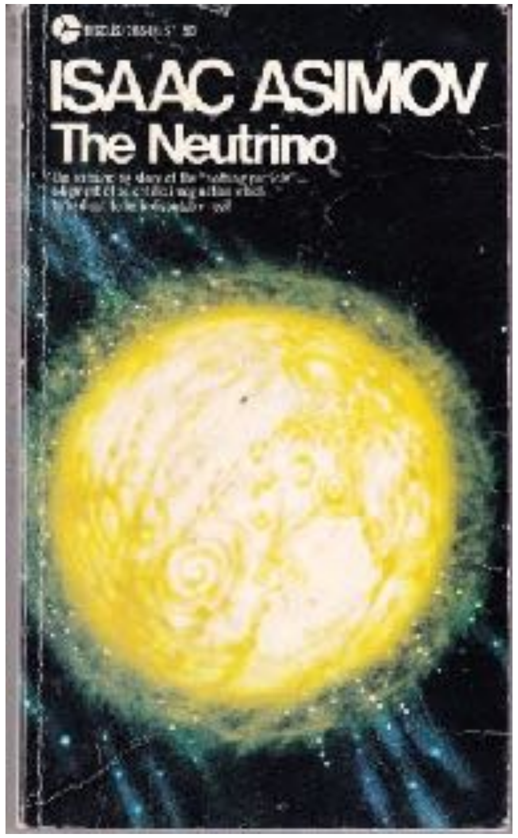
  SK and T2K best fit close to $\delta \approx -\pi/2$
  NOvA best fit:
  $\delta \approx \pi/5$ for NormOrd and $\delta \approx -\pi/2$ for Inv. Ord.

- **Steriles:**

  MiniBooNE excess (4.8σ)
  "Spotlights" the current and future Fermilab SBN
  (MicroBooNE, ICARUS, SBN)



"And yet the nothing-particle is not a nothing at all."

– Isaac Asimov 1966