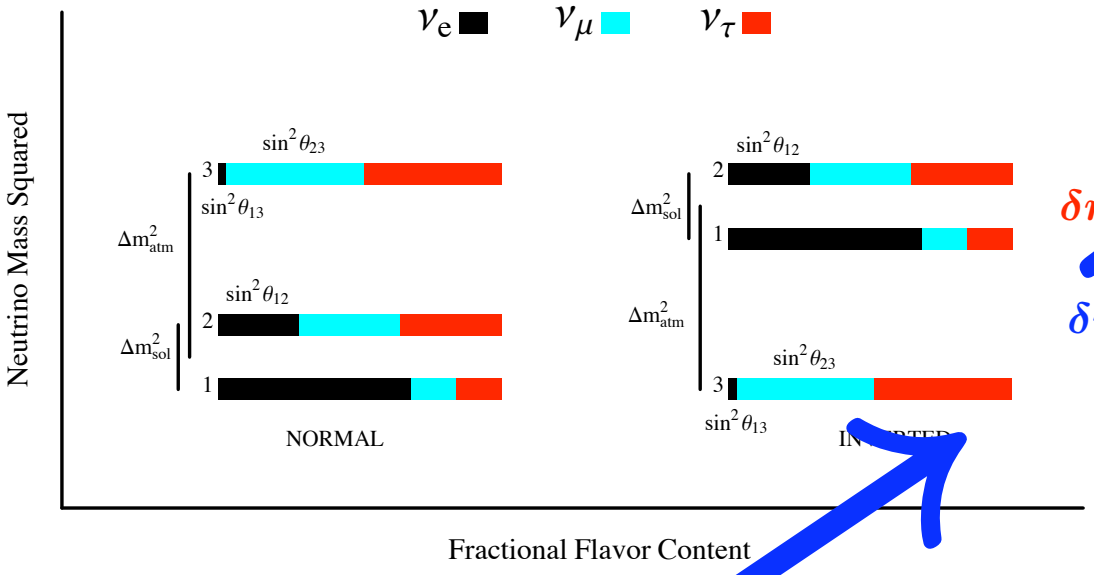
Workshop on Long Baseline Neutrino Experiments:

"Concluding Talk"

Stephen Parke
Fermilab
March 7, 2006



$\delta m^2_{sol} = .0 \pm 0.4 \times 10^{-5}\ eV^2$

$\delta m^2_{atm} \geq 30\ \delta m^2_{sol}$

- Approx. Fraction ν_e in ν_3: $\sim \sin^2\theta_{13}$
- Mass Hierarchy: sign δm^2_{31}
- CP Violation: $\sin\delta \neq 0$
- Is ν_τ or ν_μ the dominant component of ν_3? $(\sin^2 2\theta_{23} \neq 1)$ $\sin^2\theta_{23} > or < \frac{1}{2}$

In Vacuum:

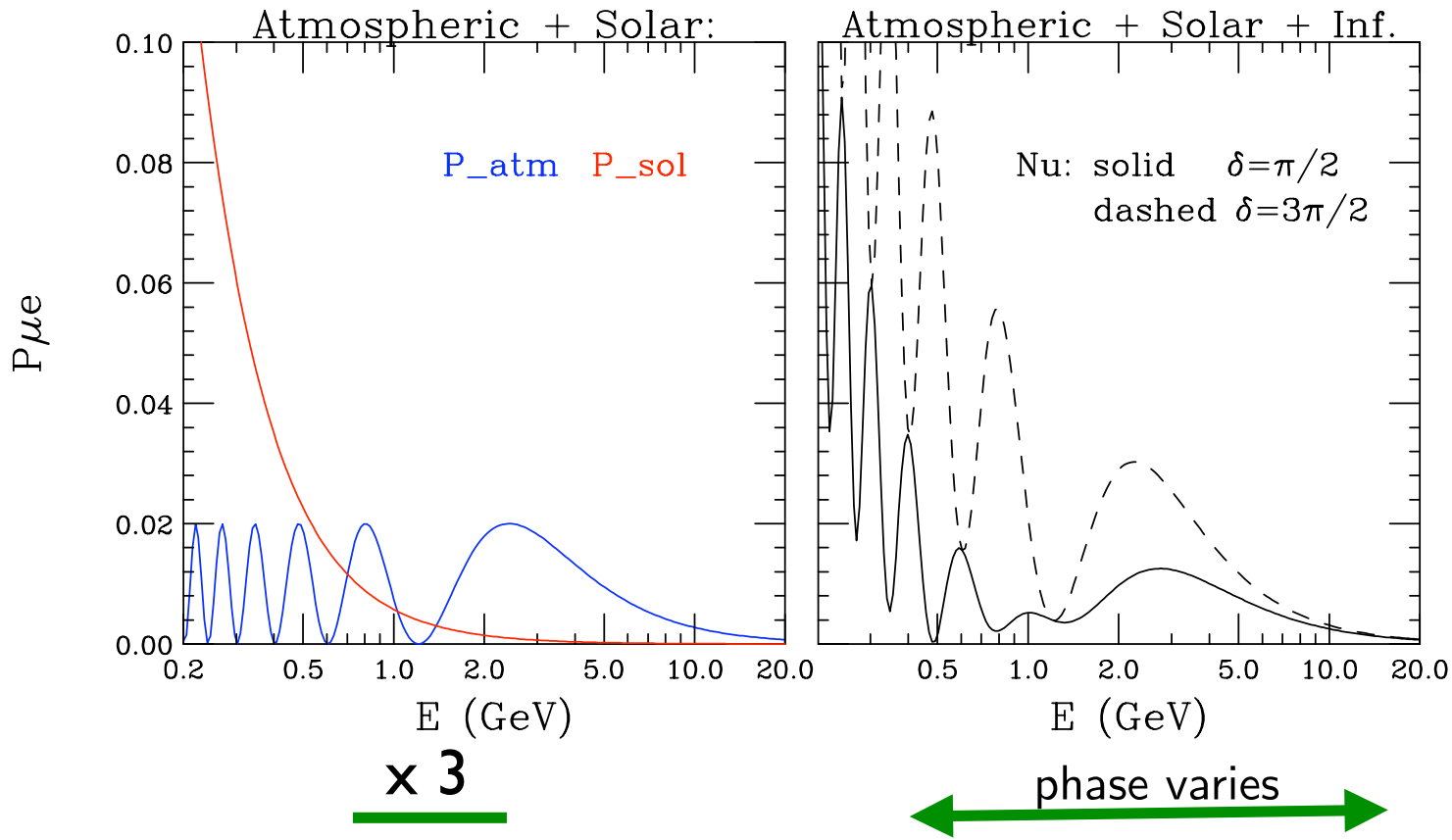
$$P(\nu_\mu \to \nu_e) \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2$$

$$\sqrt{P_{atm}} = \sin\theta_{23}\ \sin 2\theta_{13} \sin\Delta_{31}$$

$$\sqrt{P_{sol}} = \cos\theta_{23}\ \sin 2\theta_{12} \sin\Delta_{21}$$

$$\Delta = \frac{|\delta m^2|L}{4\hbar cE} = 1.27\frac{|\delta m^2|L}{4E}$$

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$



In Matter:

$$P(\nu_\mu \to \nu_e) \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2$$

$$\sqrt{P_{atm}} = \sin\theta_{23}\ \sin 2\theta_{13}\ \frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\ \Delta_{31}$$

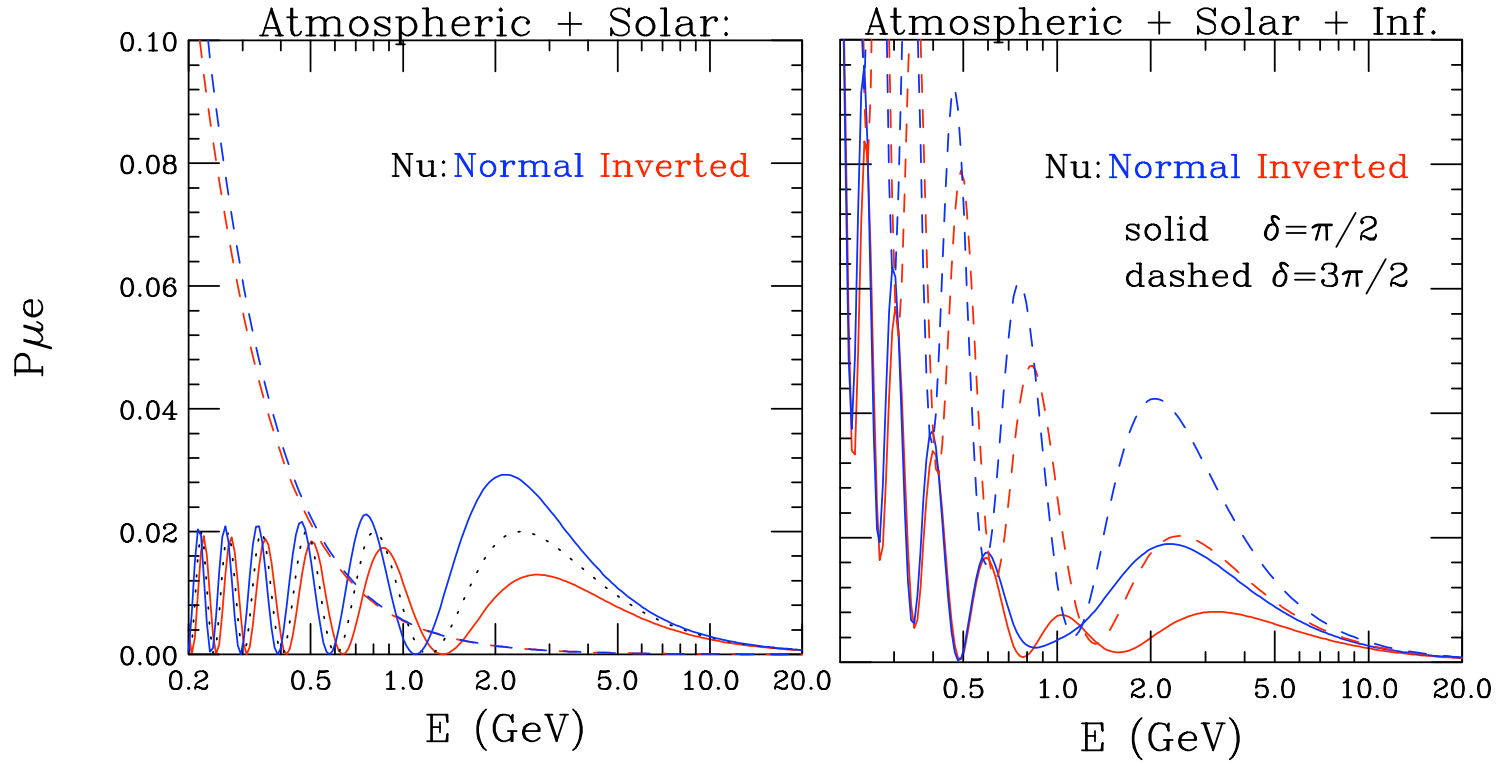
in vac: $\sin\Delta_{31}$

$$\sqrt{P_{sol}} = \cos\theta_{23}\ \sin 2\theta_{12}\ \frac{\sin(aL)}{(aL)}\ \Delta_{21}$$

in vac: $\sin\Delta_{21}$

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$

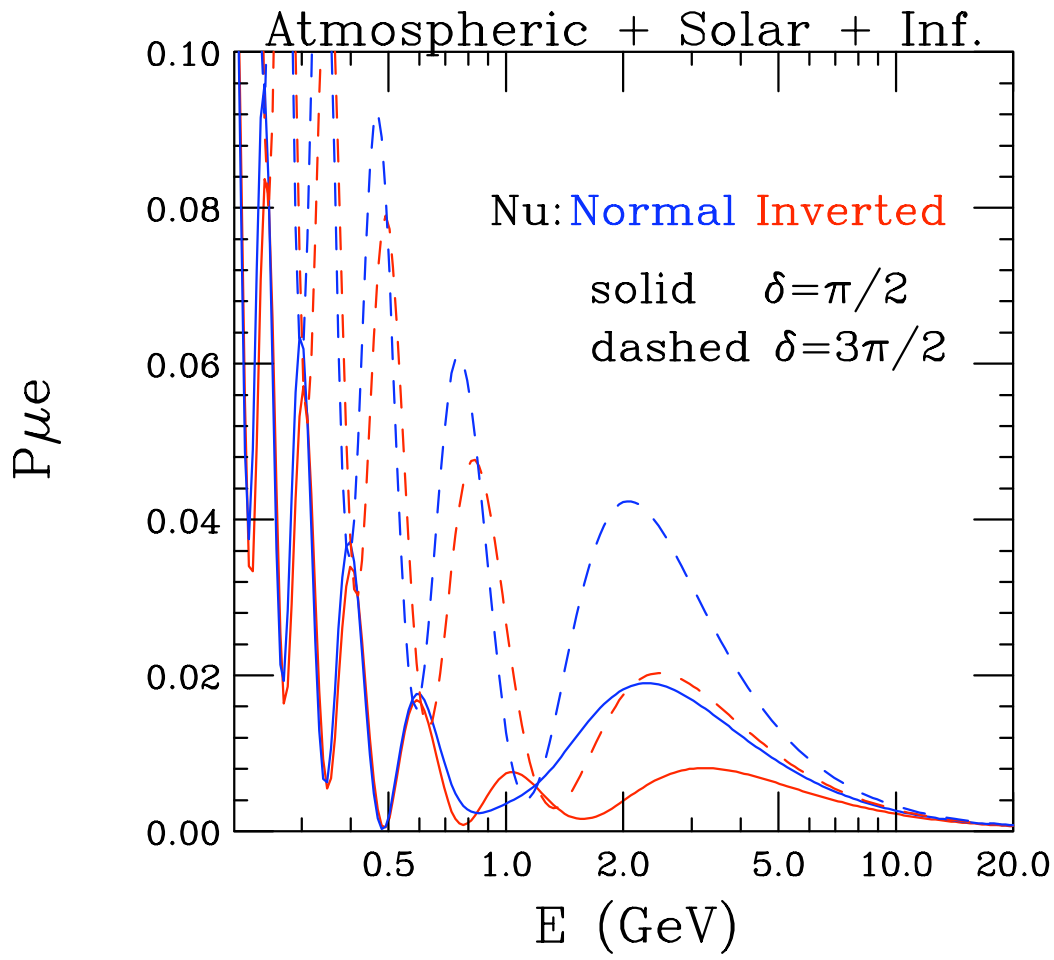
$$\pm = sign(\delta m^2_{31}), \quad a = G_F N_e/\sqrt{2} \approx (4000\ km)^{-1}$$



$\bar{\nu}$

$a \to -a$ and $\delta \to -\delta$

$$P(\bar{\nu}, \delta m^2_{31}, \delta) = P(\nu, -\delta m^2_{31}, \delta + \pi)$$



Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$

dashes $\Leftrightarrow$ *solid* and *solid* $\Leftrightarrow$ *dashes*

Experimental Setups:

Off Axis

- Counting Exp: $(\nu, \bar{\nu})$

  Off Axis (narrow band)

  - near 1st Peak
  - near 2nd Peak

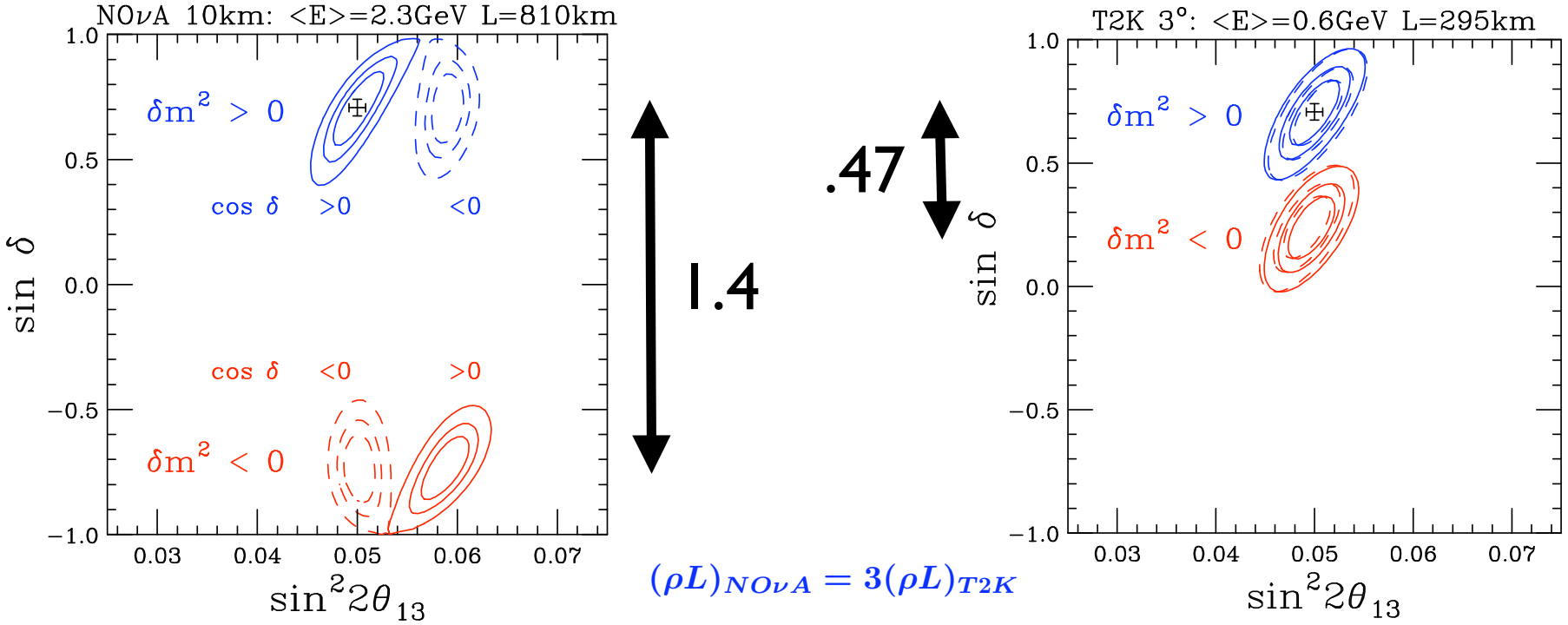
T2K, NOvA



- Spectrum Measurements: $(\nu, \bar{\nu})$

  On (wide band) or Off Axis (narrow band)

  - around 1st Peak
  - around 2nd Peak
  - beyond



$$(\rho L)_{NO\nu A} = 3(\rho L)_{T2K}$$

$$\langle \sin\delta \rangle_+ - \langle \sin\delta \rangle_- \approx 1.4\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

$$\langle \sin\delta \rangle_+ - \langle \sin\delta \rangle_- \approx 0.47\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

$$\left|\langle \sin\delta \rangle^{T2K}_{fake} - \langle \sin\delta \rangle^{NO\nu A}_{fake}\right| \approx 0.93\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

Experimental Setups:

- Counting Exp: $(\nu, \bar{\nu})$

  Off Axis (narrow band)

  - near 1st Peak
  - near 2nd Peak

- Spectrum Measurements: $(\nu, \bar{\nu})$

  On (wide band) or Off Axis (narrow band)

On Axis

BNL

  - around 1st Peak
  - around 2nd Peak
  - beyond

Why Broadband Beam?

observe multiple nodes extraction of oscillating signal from background.

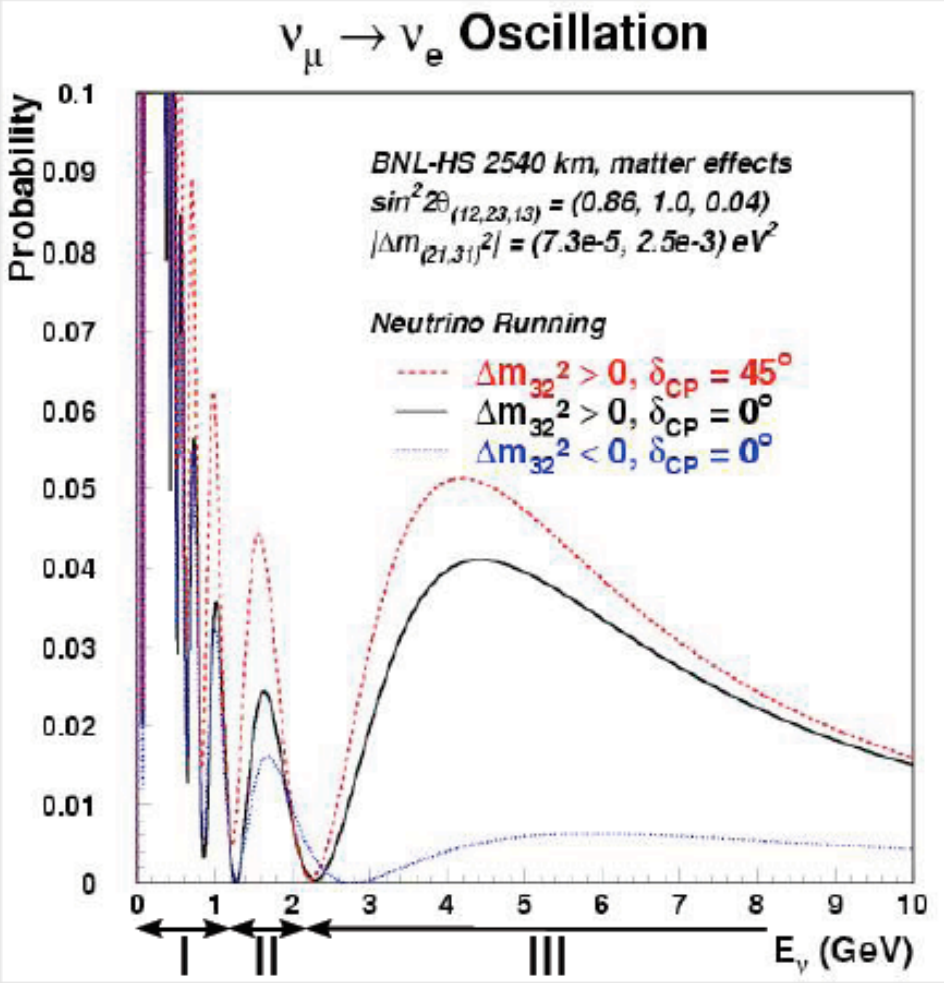
larger energies

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	++	+	+



Experimental Setups:

- Counting Exp: $(\nu, \bar{\nu})$

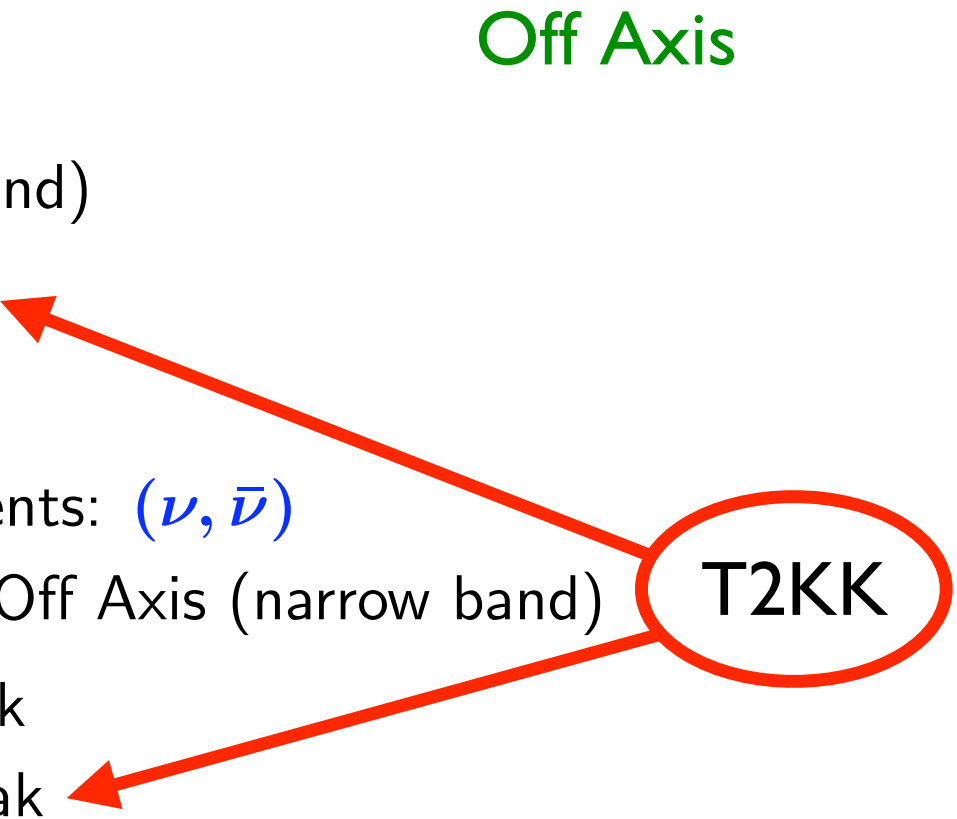
  Off Axis (narrow band)

  - near 1st Peak
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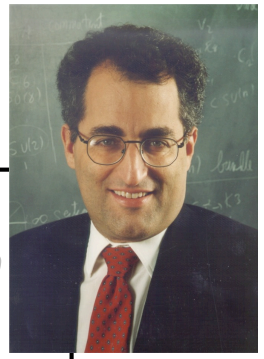
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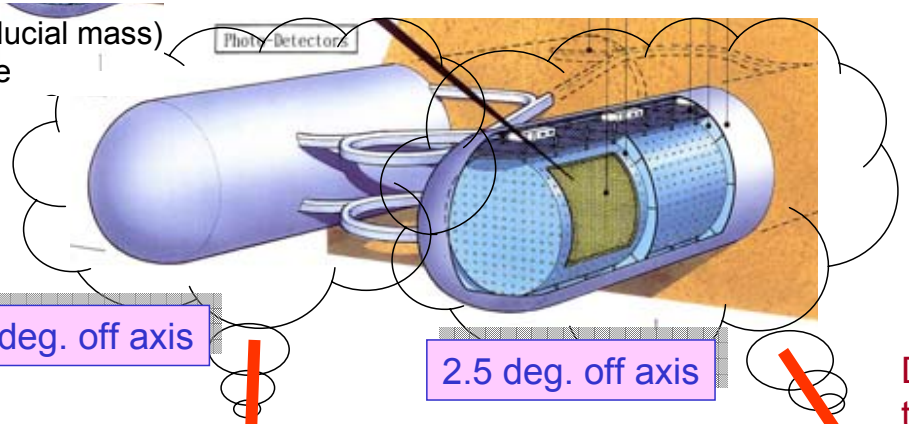


Off Axis:



Some recent progress: detector in Korea

1Mton (0.54Mton fiducial mass)
Hyper-Kaqmiokande



Total cost must be similar to the baseline design.

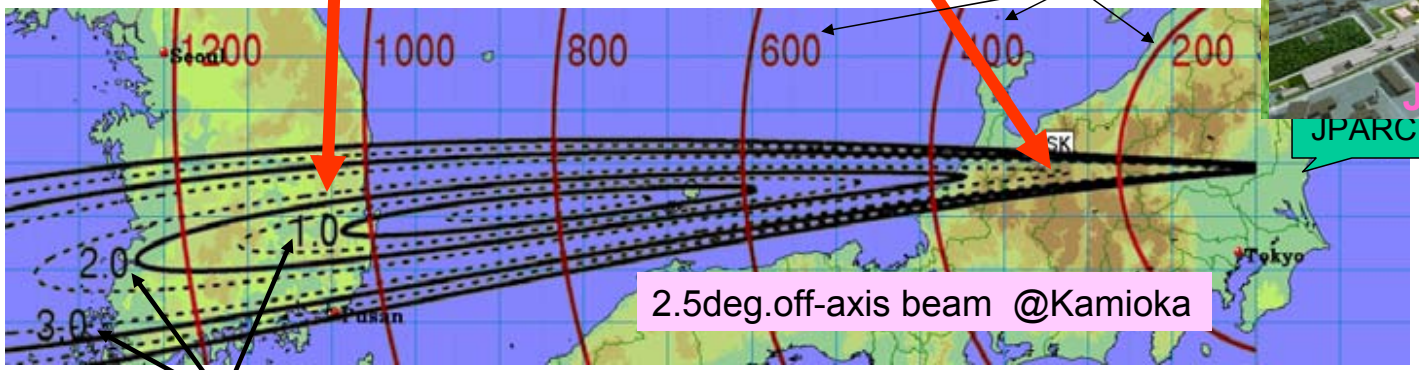
2.5 deg. off axis

2.5 deg. off axis

Distance from the target (km)

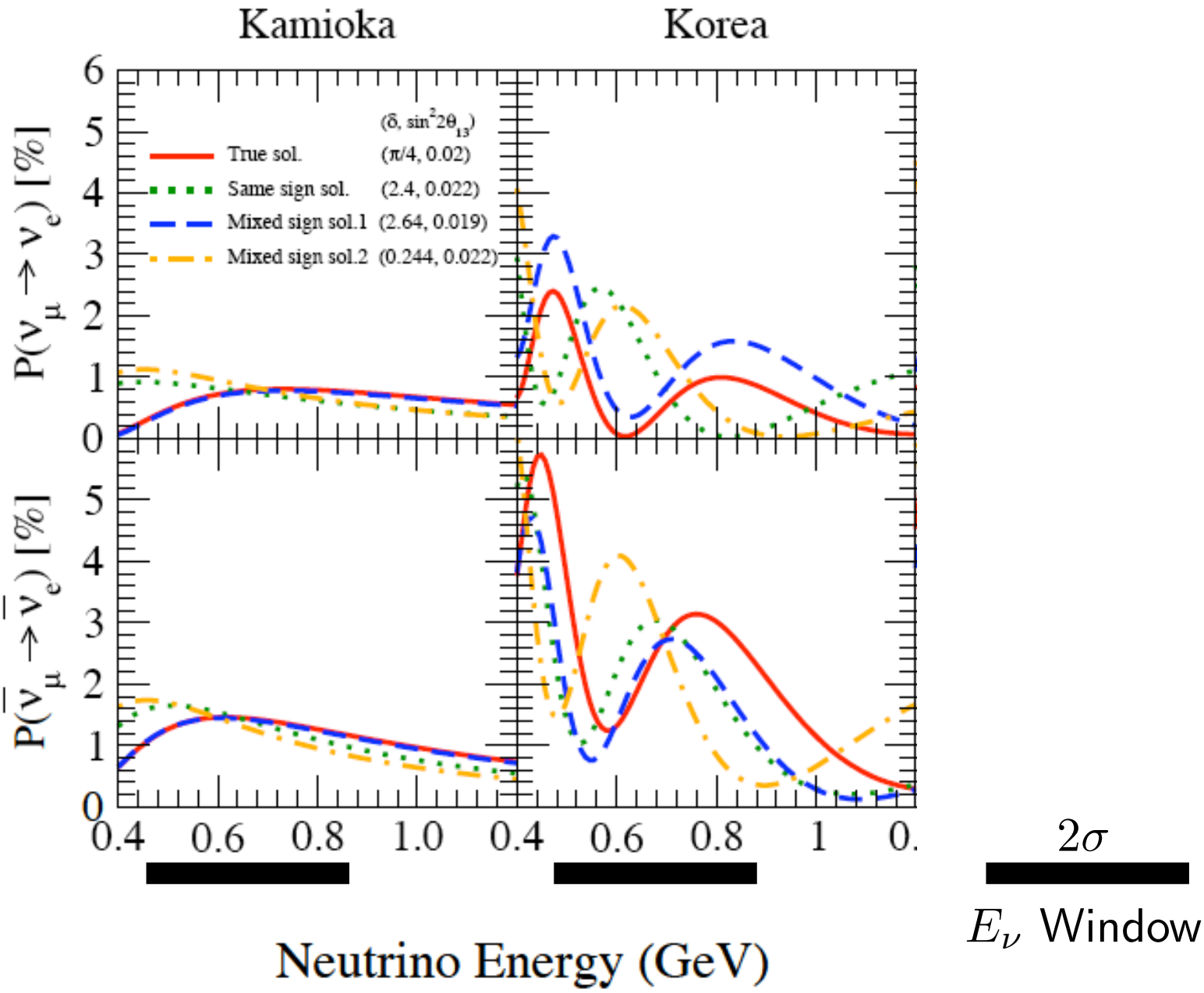


JPARC



2.5deg.off-axis beam @Kamioka

Off-axis angle



Ishitsuka, Kajita, Minakata and Nunokawa hep-ph/0504026

Experimental Setups:

Off Axis

- Counting Exp: $(\nu, \bar{\nu})$

  Off Axis (narrow band)

  - near 1st Peak
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T2K, NOvA

- Spectrum Measurements: $(\nu, \bar{\nu})$

  On (wide band) or Off Axis (narrow band)

On Axis

BNL

- around 1st Peak
- around 2nd Peak
- beyond

T2KK

Other Possibilities???

- New Neutrino Beams
  - β Beams
  - Neutrino Factory (muon decay)

"The" Thing Everybody can Agree on:

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

  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 !!!

Neutrino Patterns:

- How is $\sin^2\theta_{13}$ related $\frac{\delta m^2_{sol}}{\delta m^2_{atm}}$???

  $\frac{\delta m^2_{sol}}{\delta m^2_{atm}} = 0.03$, $\left(\frac{\delta m^2_{sol}}{\delta m^2_{atm}}\right)^2 = 0.001$, etc

- Is θ_{23} maximal ???

  $\sin^2 2\theta_{23} > 0.91 \quad \Rightarrow 0.35 < \sin^2\theta_{23} < 0.65$ 90% CL

  $\sin^2 2\theta_{23} > 0.99 \quad \Rightarrow 0.45 < \sin^2\theta_{23} < 0.55$

- Is there a (broken maybe) permutation symmetry, $\nu_\mu \Leftrightarrow \nu_\tau$???

  Then $\sin^2\theta_{13} \approx 0$ and $\sin^2\theta_{23} \approx \frac{1}{2}$

- Quark-Lepton Complimentarity:

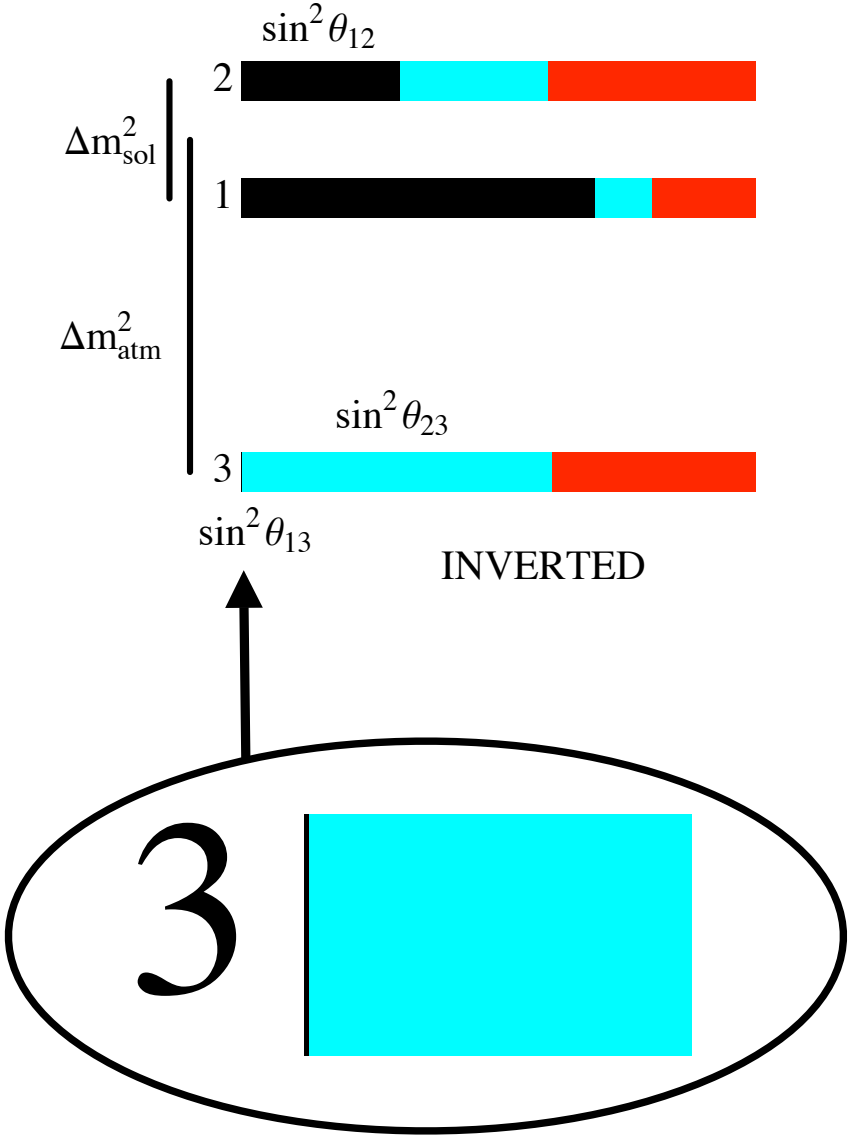
  Lepton Mixing = Bi-maximal Mixing - Quark Mixing

  $\theta_{12} + \theta_{us} \approx \pi/4$???

  $\theta_{23} + \theta_{cb} \approx \pi/4$???

- Mass Hierarchy: Quark Like or Inverted (Quasi-degenerate)

pdg 2026:



$$\sin^2\theta_{12} \approx 0.31$$

$$\sin^2\theta_{13} \approx 0.007$$

$$\sin^2\theta_{23} \approx 0.60$$

$$\delta \approx 3\pi/4$$

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

The Physics is Compelling

SURPRISES!!!