Neutrino Oscillations: Present and Future

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Pheno 2014
U. of Pittsburgh
May 7, 2014
Grand Physics Goals and Questions with Neutrino Studies

- Experimental input to the understanding of the matter-antimatter asymmetry in the universe
  - Leptogenesis (a new paradigm?)
  - Measurement of CPV ($\delta_{CP}$) in the lepton sector
  - Clearer theoretical connection between low E CPV to high E CPV critical
    - There are some papers on this but we need more

- Understanding of the neutrino mass and its impact on the evolution of the universe
  - Measurement of the absolute neutrino mass
  - Cosmological constraints
  - Is non-zero neutrino mass an evidence for Grand Unification?
  - Seesaw mechanism?
    - Proton decay searches
Grand Physics Goals and Questions with Neutrino Studies

- Detection and study of astrophysical neutrinos
  - Identifying point sources of astrophysical neutrinos
    - Study of ultra high energy acceleration mechanism
  - Detection of neutrinos from core-collapse supernovae
    - Galactic supernova → detailed study of supernova mechanism
  - Detection of diffuse/relic supernova neutrinos
  - Neutrino astronomy

- Determining Dirac or Majorana nature of neutrino
  - Neutrino-less double beta decay experiments

- Exploration of new physics
  - Precision measurements of all neutrino oscillation parameters
    - Test of PMNS framework
  - Search for sterile neutrinos
Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Lepton Mixing Matrix (a la CKM matrix)

If $\nu$ is majorana particle, 2 more extra (Majorana) phases

$\# \text{ of extra phases} = N - 1 \quad (w/ \ N = 3)$
3-flavor Neutrino Oscillations
(in Vacuum)

In general,

\[ P_{\alpha \rightarrow \beta} = \delta_{\alpha \beta} - 4 \sum_{i>j} \Re (U_{\alpha i}^* U_{\beta i} U_{\beta j} U_{\alpha j}^*) \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4 E} \right) + 2 \sum_{i>j} \Im (U_{\alpha i}^* U_{\beta i} U_{\beta j} U_{\alpha j}^*) \sin \left( \frac{\Delta m_{ij}^2 L}{2 E} \right) \]

For three generation, \( \nu_e \) appearance (accelerator experiments)

\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{32}^2 L}{4 E} + \text{subleading terms} \]

Full appearance probability includes term that goes as \( \sin(\delta) \):

CPV term \( \propto \pm \sin \theta_{12} \sin \theta_{13} \sin \theta_{23} \sin \delta \)

Sign flip for neutrino vs. antineutrino

Need non-zero value for all three mixing angles including \( \theta_{13} \)

For anti-\( \nu_e \) disappearance (reactor experiments)

\[ P(\nu_e \rightarrow \nu_e) = 1 - 4C_{13}^2 S_{13}^2 \cdot \left( C_{12}^2 \sin^2 \Delta_{13} + S_{12}^2 \sin^2 \Delta_{23} \right) + 4S_{12}^2 C_{12}^2 C_{13}^4 \sin^2 \Delta_{12} \]

No CPV-\( \delta \) dependence, Pure \( \theta_{13} \) measurement

Sensitivity to \( \theta_{23} \) octant

Sensitivity to CPV-\( \delta \)

Complementary
Remarkable progress!
All mixing angles are now known
- $\theta_{12} = 33.9^\circ \pm 1.0^\circ$
- $\theta_{13} = 8.7^\circ \pm 0.4^\circ$
- $\theta_{23} = 45^\circ \pm 6^\circ$ (90% C.L.)
  → largest uncertainty
All three angles are non-zero and relatively large
→ allows exploration of CPV in the lepton sector

$P(\nu_\mu \rightarrow \nu_e) \propto$ leading term + ...
+ term($\sin \theta_{12} \sin \theta_{23} \sin \theta_{13} \sin \delta_{CP}$)

Why is nature so kind to us?

Critical for the $\nu$-less double-$\beta$ decay searches that would determine the Majorana-nature of $\nu$
Note that the measurements by the accelerator experiments (T2K and MINOS) which assumes $\delta_{CP} = 0$ and $\theta_{23} = 45^\circ$ should not be directly compared to the measurements by the reactor experiments.
In collider physics, theory has led experiment for the past decades, on the contrary in neutrino physics, experiment has led theory, especially in recent decades.

(ckj’s personal opinion)
Why are the mixing matrices for the lepton sector and quark sector so much different?

\[
U_{CKM} \approx \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}
\]
\[\delta = 60^\circ\]

\[
U_{PMNS} \approx \begin{pmatrix} 0.8 & 0.55 & 0.15 \\ -0.4 & 0.6 & 0.7 \\ 0.4 & -0.6 & 0.7 \end{pmatrix}
\]
\[\delta = ?\]
Are neutrino masses suppressed by new physics at very high energy?

\[ m(\nu_i) = \frac{m^2_{D_i}}{M} \]

Present lab limits:
- \(~2\text{ eV}\)
- \(~0.6\text{ eV}\)
- \(~0.05\text{ eV}\)
- \(~2\text{ eV}\)
- \(~10^5\)
- \(~10^7\)

Seesaw in SO(10)

C.K. Jung

Pheno 2014 Pittsburgh, May 2014

Chang Kee Jung

Stony Brook University
Probing the earliest time and the highest energies
Remaining Unknown Neutrino Properties

- $\theta_{23} > 45^\circ$, $= 45^\circ$ (maximal) or $< 45^\circ$
  - maximal mixing may indicate a profound hidden symmetry
- $\delta_{CP}$ ($\neq 0$, i.e. CPV?)
- Mass ordering (NH or IH?)
- Absolute $m_\nu$
- Dirac/Majorana
- Any sterile $\nu$
2013 Breakthroughs in Neutrino Physics

- 2013 - another great year in neutrino physics – a year of 28

T2K: Observation of $\nu_e$ appearance from a $\nu_\mu$ beam!
Opens the door to study CPV in neutrinos!

7.3\sigma level of significance

ICECUBE: Evidence for extraterrestrial neutrinos!
Opens the door for neutrino astronomy!

4\sigma level of significance
Hunt for the Unknowns

Is $\theta_{23} = 45^\circ$, $< 45^\circ$, or $> 45^\circ$?

Running Exps: SuperK, T2K, NOvA, MINOS/MINOS+

Approved Exps: LBNE, INO

Proposed Exps: HyperK

(When comparing sensitivities of experiments attention should be paid to the different stages of the experiments being compared.)
Full 3-flavor $\nu_\mu$ Disappearance Probability (in Vacuum)

- For a precision measurement, the next-to-leading term must be included in the fit due to the non-zero and relatively large $\theta_{13}$

\[ P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - (c_{13}^4 \sin^2 2\theta_{23} + s_{23}^2 \sin^2 2\theta_{13}) \sin^2 \frac{\Delta m^2_{31} L}{4E} \]

- The next-to-leading term contains $\sin^2 \theta_{23}$ while the leading term contains $\sin^2 2\theta_{23}$
  - Natural to fit $\sin^2 \theta_{23}$ not $\sin^2 2\theta_{23}$
- Oscillation maximum occurs at $\theta_{23} \sim 45.7^\circ \neq 45^\circ$ maximal mixing

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Results from SuperK and MINOS

MINOS $\nu_\mu$ disappearance + $\nu_e$ appearance
10.71 x $10^{20}$ POT $\nu_\mu$-dominated beam
3.36 x $10^{20}$ POT $\nu_\mu$-enhanced beam
37.88 kt-yr atmospheric neutrinos

MINOS

Normal hierarchy

Inverted hierarchy

MINOS

Global minimum

SuperK

IH

Local minimum

NH

Local minimum

$\Delta m^2_{32} \left(10^{-3} \text{eV}^2\right)$

$\sin^2 \theta_{23} \sim 0.4$

$\sin^2 \theta_{23} \sim 0.6$
Stable operation at ~220 kW achieved at the end of Run 4
- World record proton per pulse (> 1.2 x 10^{14}) extracted for a synchrotron

Total POT delivered: 6.72 (6.63 for physics run) x 10^{20} POT
→ ~ 8.6% of the total approved POT (7.8 x 10^{21})
- Data analyzed: 6.57 x 10^{20} POT (collected at SuperK by May 2013)
T2K New Results on $\nu_\mu$ Disappearance

Almost complete disappearance of $\nu_\mu$ → 120 events observed

Data
Best fit
No oscillation

no oscillation hypothesis

Events/0.10 GeV
Reconstructed $\nu$ Energy (GeV)
T2K New Results on $\nu_\mu$ Disappearance

Maximum dip:
location $\rightarrow \Delta m_{32}^2$
size $\rightarrow \sin^2 2\theta_{23}$
\( \nu_\mu \) Disappearance Confidence Regions (New T2K Results)

T2K and SuperK: Separate C.L. for NH & IH
MINOS: C.L. from the global minimum

T2K Run 1-4 Best Fit Point (NH):
\[ \Delta m^2_{32} = 2.51 \pm 0.1 \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 \theta_{23} = 0.514^{+0.055}_{-0.056} \]

- The best fit is consistent with the maximal mixing but not exactly at the maximal mixing
- T2K now has the smallest error on \( \theta_{23} \), (~3°)

Note: osc. Max for \( \sin^2 2\theta_{13} = 0.098: \)
\[ \sin^2 \theta_{23} = 0.513 \text{ (or } \theta_{23} = 45.74^\circ) \]

Distinguishing the maximal mixing from the oscillation maximum requires measurements w/ a ~2% precision
\( \Rightarrow \) Very difficult
Effects of Multi-Nucleon Processes

Estimated bias in the observed oscillation parameters <1%

T2K

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Hunt for the Unknowns

Measurement of $\delta_{CP}$

T2K, NOvA

LBNE

HyperK
First step to measure $\delta_{\text{CP}}$

**T2K $\nu_e$ Appearance Analysis**

T2K: Marginalized over $\Delta m^2_{32}$, sin$^2 \theta_{23}$ and sin$^2 2 \theta_{13}$

Best fit values of $\delta_{\text{CP}}$: $-1.65$ (NH), $-1.57$ (IH)

(Note the physical boundaries at ±$\pi$/2)

90% C.L. excluded regions using Feldman-Cousins method:

$$\Delta \chi^2 = \chi^2_{\text{true}} - \chi^2_{\text{min}}$$

(global minimum)

$$\Delta \chi^2 < \Delta \chi^2_{\text{crit}}$$

NH: $0.19 \pi < \delta_{\text{CP}} < 0.80 \pi$,
IH: $-\pi < \delta_{\text{CP}} < -0.97 \pi$ and $-0.04 \pi < \delta_{\text{CP}} < \pi$
Impact of Reactor Measurement of $\theta_{13}$ on $\delta_{CP}$ and Comparison with MINOS

T2K: Marginalized over $\Delta m^2_{32}$, $\sin^2 2\theta_{23}$ and $\sin^2 2\theta_{13}$

Note the x-axis scales are different and the y-axis scales are adjusted to be same
What does this mean?

- We have a long way to go
- However, it is an intriguing and encouraging result stemming from the strong tension between the T2K and the reactor $\sin^2 2\theta_{13}$ measurements
- Assuming this trend holds in the long run, it is an excellent news for the current and future accelerator-based neutrino oscillation experiments
  - T2K, NOvA, LBNE and Hyper-Kamiokande
- Need continued precision measurements of $\theta_{13}$ by the reactor experiments

Daya Bay projected error on $\sin^2 2\theta_{13}$
$\Rightarrow$ $\sim 0.003$ (4%) ultimately
Comments on T2K $\sin^2 \theta_{23}$ and $\delta_{\text{CP}}$ Best Fit Values

- Both T2K $\sin^2 \theta_{23}$ and $\delta_{\text{CP}}$ best fit values are at the physical boundaries
  - $\sin^2 \theta_{23} : 0.514^{+0.055}_{-0.056}$
    - More $\nu_\mu$ disappearance than maximally predicted
  - $\delta_{\text{CP}} : -\pi/2$
    - More $\nu_e$ appearance than maximally allowed
- Possibilities
  - Simple coincidental statistical fluctuations
  - Something new?
  - Systematic (correlated) effects
    $\rightarrow$ Joint $\nu_\mu$ and $\nu_e$ Analysis
T2K Joint $\nu_\mu$ and $\nu_e$ Analysis

- Likelihood ratio fit to both candidate event samples
- Full representation of correlations among oscillation parameters: $\theta_{13}$, $\theta_{23}$, $\Delta m^2_{32}$ and $\delta_{CP}$
- Constraint on $\theta_{13}$ from reactor measurements
  \[ \sin^2 2\theta_{13} = 0.095 \pm 0.010 \text{ (PDG2013)} \]
  $\rightarrow$ No qualitative difference compared to $\nu_e$ fit

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<th>90% CL Inclusion</th>
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<tbody>
<tr>
<td>NH</td>
<td>$\delta_{CP} \in [-1.18, 0.15]\pi$</td>
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<tr>
<td>IH</td>
<td>$\delta_{CP} \in [-0.91, -0.08]\pi$</td>
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T2K Joint $\nu_\mu$ and $\nu_e$ Bayesian Analysis

- **Markov Chain Monte Carlo (MCMC) method fitting**
  - simultaneous both T2K near and far detector ($\nu_\mu$ and $\nu_e$) data
  - can easily marginalize over other oscillation parameters including MH and compare the probabilities for each MH and octant combination

- **The 90% Credible Interval (CI) inclusion range:**
  $[-1.13, 0.14]\pi$ is similar to the F.C. 90% CL inclusion range: $[-1.18, 0.15]\pi$ obtained from a joint fit for NH
T2K and NOvA Sensitivity to Resolve $\delta_{CP} \neq 0$

- The combined fit improves the sensitivity significantly
- The combined sensitivity to CPV could reach up to 2~3 $\sigma$ for some values of $\delta_{CP}$

Stat Only
With Syst.

Syst. assuming 5% (10%) normalization uncertainty on signal (background)
NOvA Status

- The last block (28) installed on Feb. 25, 2014
- All 28 blocks are filled with liquid scintillator and 21 blocks are instrumented with electronics (as of May 5, 2014)
- Expected to complete the installation and commissioning in 2014
NOvA started taking data…

1st Neutrino Event in the NOvA Far Detector
(Fermilab Press Release, Feb. 11, 2014)

- On average, $\sim 10^{18}$ POT/day of data is being recorded
- A total of $3.24 \times 10^{20}$ POT is projected to be delivered in FY14
- A detailed status update at the Neutrino 2014 conference in Boston is eagerly anticipated …
Do we need next generation experiments such as LBNE and HyperK to measure $\delta_{CP}$?

Yes, absolutely.

The combined sensitivity of T2K and NOvA is not sufficient for an unequivocal discovery of CPV.
LBNE Sensitivities and HyperK Resolution on $\delta_{CP}$

LBNE 35 kt

HyperK Resolution on $\delta_{CP}$

Overall good sensitivities and resolution
Determining the Mass Ordering: NH or IH?

NOvA, SuperK, (T2K)
JUNO, INO, LBNE
HyperK, PINGU, ORCA (?)
- T2K alone has almost no sensitivity
- The combined fit improves the sensitivity substantially
  - Adding SuperK to the fit should further enhance the sensitivity
- The combined sensitivity to CPV could reach up to $\sim 3\sigma$ for some values of $\delta_{\text{CP}}$
JUNO: a New Kid in Town
(expected data taking operation start time: 2020)

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<th>Daya Bay</th>
<th>Huizhou</th>
<th>Lufeng</th>
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For 6 years, mass hierarchy can be determined at 4$\sigma$ level, if $\Delta m^2_{\text{\tiny atm}}$ can be determined at 1% level.

Detector size: 20kt
Energy resolution: 3$/%$/E
Thermal power: 36 GW

Some concerns about the control of energy scale non-linearity, etc.
\rightarrow Certainly a technically challenging experiment, but better to have money and work on challenging issues than having no money at all!!!

Congratulation to JUNO for obtaining a (provisional) project approval in such a short time! (envied by others, especially from U.S.)

Best Wishes!
Adding PINGU in the Mix

Suddenly a fierce race! At least on paper…
Conclusions

- “Observation of $\nu_e$ appearance from a $\nu_\mu$ beam” has now been made
  - This opens the door to study CPV in neutrinos

- Physics goals for the post non-zero $\theta_{13}/\nu_e$ appearance era are now clearly defined for the world neutrino oscillation community
  - Determination of $\delta_{CP}$, mass hierarchy and $\theta_{23}$ ($=45^\circ$, $<45^\circ$, $>45^\circ$?)
    - We may have an initial hint that $\delta_{CP} = -\pi/2$
  - T2K along with NOvA will lead the world in determining these parameters at least for the next decade
  - Next generation experiments should follow in order to ensure the discoveries

- Neutrino oscillation (i.e. the existence of massive neutrino states) is the only phenomena beyond the Standard Model observed in laboratory venue today

- Measurement of CPV will provide critical experimental input to our understanding of the matter–antimatter asymmetry in the universe

- Nature kindly gave us the non-zero neutrino mixing angles and $\nu_e$ appearance in order for us to be able to probe CP violation
“Full Steam Ahead!”

Happy State of Neutrino

Olimpia Zagnoli

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The End