Neutrino Oscillations

The next 10 years
Personal View from Jenny Thomas world,
Planet UCL
Introduction

• **What are the burning questions?**
  
  – Amazingly, we know what they are and how to answer them (some this decade)!
    
    • $\theta_{23}$ octant: this is now the least well-known angle
      
      – MINOS+, NOVA, T2K, ICECUBE!
    
    • Mass Hierarchy: which mass eigenstate is smallest?
      
      – DBII+LBL, NOVA (40% chance), PINGU
    
    • CP violation: and the answer to everything
      
      – CHIPS+NOVA+T2K
    
    • **Number of sterile flavors**: and a whole new field
      
      – MINOS+, MICROBOONE
MINOS and T2K on $\theta_{13}$

- MINOS $10.71 \times 10^{20}$ p.o.t and $3.36 \times 10^{20}$ p.o.t of antineutrinos
- T2K now really using the power of the L/E choice
- MINOS used ND for background measurements
- Are T2K, MINOS and reactors only consistent with $\delta_{CP} = -\pi/2$?
- Now we know $\theta_{13}$, number of sigma away from 0 less interesting than error bars?
  - MINOS smaller for NH
  - T2K smaller for IH

Daya Bay: $\sin^2 2\theta_{13} = 0.089 \pm 0.010$ (stat) $\pm 0.005$ (syst)
Introduction

• This is the speaker’s (subjective) crystal ball about the next decade

• We will dash around the world looking at the experiments taking data
  – NOVA, MINOS+, DAYA BAY, ICECUBE, T2K(?), MicroBOONE
  – What could we learn without any new facilities?

• And at the ones who might take data
  – CHIPS 😊
  – DB-II (JUNO)
  – PINGU

• Where will we be this time, next decade?
  – I will be retired
  – But the measurements will go on...
WHAT'S HAPPENING AT FNAL?

World's premier neutrino oscillation laboratory
FNAL’s Neutrino facility

• FNAL is the premier neutrino oscillation laboratory in the world

• Experiments on NuMI beam
  – MINOS+ ($\theta_{23}$ octant, $\Delta m^2$, steriles)
  – NOνA (MH, $\theta_{23}$ octant, $\Delta m^2$)
  – CHIPS ($\delta_{CP}$)
  – Minerva (x-secs)

• Experiments on the Booster beam
  – MicroBOONE (BOOSTER-steriles)
  – LAr1?

• Plans for the NBT in neutrino physics with LBNE
FNAL’s NuMI beam

Total NuMI protons

Party like its 2009 (well 2008 really)
The New Goal Posts (post $\theta_{13}$)

$$\mathcal{P}(\nu_{\mu} \rightarrow \nu_{\mu}) = 1 - \sin^2(2\theta_{eff}) \sin^2 \left( \frac{\Delta m^2_{eff} L}{4E} \right) + \mathcal{O}(\theta_{13}^3)$$

$$\sin^2(\theta_{eff}) = |U_{\mu 3}|^2 = \sin^2 \theta_{23} \cos^2 \theta_{13} \quad (\sin^2 2\theta_{eff} \approx \sin^2 2\theta_{23} : \theta_{13} \approx 0)$$

\[
\begin{align*}
\Delta m^2_{ee} &\approx 0.7\Delta m^2_{31} + 0.3\Delta m^2_{32} \\
\Delta m^2_{\mu\mu} &\approx 0.3\Delta m^2_{31} + 0.7\Delta m^2_{32} + CP
\end{align*}
\]

- Disappearance has $\theta_{13}$ info embedded in it:
  - 2 flavor analysis is not good enough for large $\theta_{13}$
- 3 flavor fits done to MINOS disappearance data and atmospheric data (has mass hierarchy information)
- Then COMBINED with MINOS $\nu_e$ appearance data
- T2K are planning this result also, may be by NEUTRINO 2014
MINOS Alone

- Solar mixing parameters fixed
- $\theta_{13}$ fit as nuisance parameter, constrained by reactor results
- $\delta_{\text{CP}}, \theta_{23}, \Delta m^2$ unconstrained
- major systematic uncertainties included as nuisance parameters
• Preliminary results should be available by NEUTRINO 2014
• Full reach by end 2016 or 2017, depending on beam performance
Look at T2K and Super-K

LETS HEAD TO JAPAN
• Unlikely to see more precision from T2K (at least soon)
  – 2014 anti-neutrino “pilot” run for 1 month
  – Total POT to be 7.8e21 by 2021
  – T2K cannot tell us their plans presently for running schedule or desires
The land o’ lakes

BACK TO FNAL : MINNESOTA TOO!
The NOvA Far Detector
NOvA on $\Delta m^2$

- Nova should get 2-3% finally on $\Delta m^2$: energy scale systematic limited
• Back of the envelope
• Combination of NOVA and MINOS+ will give this level of accuracy by 2016 (2\(\sigma\))
  • MINOS 12e20 NOVA 9e20
• Maybe 1-2% (1\(\sigma\)) by MINOS+ turn off
MEANWHILE, AT THE SOUTH POLE.
Ice Cube on $\theta_{23}$

- Another player has joined the $\theta_{23}$ game
- Marvellous confirmation of oscillations at completely different neutrino energy and baseline
- Personally very excited about the result ($\theta_{23} \neq 45^\circ$?)
Where the buffalos roam

BACK TO FERMILAB....
NOVA on Mass Hierarchy

NOvA hierarchy resolution, 3+3 yr

$\sin^2 2\theta_{13} = 0.095$, $\sin^2 2\theta_{23} = 1.00$

$\Delta m^2 < 0$

$\Delta m^2 > 0$
NOVA on Mass Hierarchy

NOvA hierarchy resolution, 3+3 yr

\[
\sin^2 2\theta_{13} = 0.095, \quad \sin^2 2\theta_{23} = 1.00
\]

+ T2K at \(5.5 \times 10^{21}\) POT

Significance of hierarchy resolution \((\sigma)\)

- \(\Delta m^2 < 0\)
- \(\Delta m^2 > 0\)

\[\delta / \pi\]
WHAT WILL HAPPEN IN CHINA?

Mountains shield detectors from cosmic ray backgrounds

Daya Bay NPP 2.9GW x 2

Ling Ao II NPP 2.9GW x 2

Ling Ao NPP 2.9GW x 2

Reactor experimental plans
Final precision, \( \sim 0.003 \), is still dominated by statistics (3%).

Major systematics: relative efficiencies.
Daya Bay: Projected Precision of $|\Delta m_{ee}^2|$ 

$$\sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E} \right) = \cos^2 \theta_{12} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) + \sin^2 \theta_{12} \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right)$$

- Final precision of $\sim 0.075 \times 10^{-3}$ eV$^2$ (3%) is limited by statistics (in 2017)
- Major systematics: Relative energy response, relative efficiencies, and background
- Precision of $|\Delta m_{ee}^2|$ is comparable to results obtained with $\nu_\mu$
Next Experiment: JUNO

<table>
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<tr>
<th>Site</th>
<th>Daya Bay</th>
<th>Huizhou</th>
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<th>Taishan</th>
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<td>Under construction</td>
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</table>

Overburden ~ 700 m

Current Status & Brief Schedule

- Project approved by CAS for R&D and design
- Geological survey completed
  - Granite rock, tem. ~ 31 °C, little water
- Engineering design underway
- Detector design and R&D underway
- International Collaboration: China, Czech, France, Germany, Italy, Russia, US, ...

Schedule:

Civil preparation: 2013-2014
Civil construction: 2014-2017
Detector R&D: 2013-2016
Detector component production: 2016-2017
PMT production: 2016-2019
Detector assembly & installation: 2018-2019
Filling & data taking: 2020
4-6 years to Mass Hierarchy result
Physics Reach by 2024-6

For 6 years, mass hierarchy can be determined at 4σ level, if Δm²_µµ can be determined at 1% level!
Actually to Middle-of-Nowhere, Minnesota

BACK TO FNAL....
δ_{CP} : CHIPS concept

- Look for a deep water mass in Minnesota intersected by the NuMI beam
- Deploy from floating platform: pit water acts as mechanical support
- Replace nets with roofing liner and will with cleaned water
- Deployment Idea developed by Madison/PSL groups for LBNE
- Approved by FNAL PAC for 1st year of R&D
CHIPS@NuMI

- CHIPS can make very big inroads into $\delta_{CP}$
- Racing against the ticking NuMI / LBNE changeover clock
Getting started fast

- Starting small can yield important results if we are fast

![Graph showing CP resolution over years from NOνA start](chart.png)

- Slow but continuous detector growth ($3-10M/yr$)
- Real costs fully understood using stepwise approach: avoid huge contingencies
- 100kt end result gives impressive gain over NOVA alone

- Starting at all (!) can allow external money to be applied for
CHIPS

• PMTs are the major cost driver
  – Pushing on PMT technology as well as increasing competition will be a plank of the CHIPS philosophy

• In contact with KM3Net collaboration
  – Electronics developed already for a 31x3” PMT DOM
  – This may actually be better for us than large tubes
  – Have received pieces from NIKEF at UT to benchmark

New Photodetector Technologies

Examples of two promising new large-area photosensors in development are:

Hybrid Photo-Detector: ~600 to 2200 psec timing resolution depending on HPD size
Large Area Pico-Second Photodetector: ~100 psec timing + ~1cm spatial res
Look at T2K and Super-K

BACK TO JAPAN
Figure 26: The expected $\Delta \chi^2$ for $\sin \delta_{CP} = 0$ plotted as a function of POT. Plots assume true $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = +90^\circ$, inverted MH, and various true values of $\sin^2 \theta_{23}$. The solid curves include statistical errors only, while the dash-dotted (dashed) curves assume the 2012 systematic errors (the projected systematic errors). Note that the sensitivity heavily depends on the assumed conditions, and that the conditions applied for these figures ($\delta_{CP} = +90^\circ$, inverted MH) correspond to the case where the sensitivity for $\sin \delta_{CP} \neq 0$ is maximal.
What next?

BACK TO THE SOUTH POLE!!
PINGU

- PINGU goal is to start data taking in 2021
- Evidence of Mass Hierarchy in both cascade AND muon events

- Big techno-synergy with CHIPS
- PMTs, readout
- Complementary experiment
What about the sterile search

BACK HOME AGAIN TO FNAL
A Staged Multi-LAr TPC
Short-Baseline Neutrino Program

Phase 0: MicroBooNE
86 t active volume TPC
L = 470 m
start in 2014

Phase 1: LAr1-ND
82 t active volume TPC
L = 100 m
2017-2018

Phase 2: LAr1-FD
1000 t active volume TPC
L = 700 m
2020+
MicroBOONE

• MicroBooNE is a very small detector (70t)
• It will not have much reach in the sterile limit
• But it will tell us whether the MiniBoone excess is photons or electrons!
• Will we stop looking if they are photons??

THE SEARCH FOR STERILES

1x10^{20} POT

e-like: 2.2\sigma
\gamma-like: 1.6\sigma

3x10^{20} POT

e-like: 3.8\sigma
\gamma-like: 2.8\sigma

6.6x10^{20} POT

e-like: 5.7\sigma
\gamma-like: 4.2\sigma
$\nu_\mu \rightarrow \nu_e$ Appearance

6.6x10^{20} POT exposure for MicroBooNE alone, assuming 20% systematic uncertainties on $\nu_e$ background prediction

+ND

Same MicroBooNE exposure + 2.2x10^{20} POT exposure for LAr1-ND to constrain background prediction

---

Graphs showing the $\Delta m^2 - \sin^2 2\theta$ dependence for MicroBooNE (470m) and LAr1-ND (100m). The graphs compare data from LSND and Global fits, with 90% and 99% CL regions and best fit points indicated.
MicroBOONE(6.6e20)+LAr1-ND(2.2e20)

Same MicroBooNE exposure + 2.2x10^{20} POT exposure for LAr1-ND to constrain background prediction

ESTIMATE ONLY

MINOS

MINOS 90% CL
MINOS + Bugey 90% CL
MEANWHILE....IN THE ARLINGTON HILTON
Reasonable Synopsis

Several current or planned experiments will have sensitivity to the neutrino mass hierarchy in the next 10-15 years.

- LBNE/NOvA: $\delta_{CP}$
- JUNO: $\sigma_{E} (3.0-3.5\%)$
- PINGU/INO: $\theta_{23} (38.7º–51.3º, 40º–50º)$

Other projections presented here assume worst-case parameters (1st octant).

PINGU timeline based on aggressive but feasible schedule; LBNE from LBNE-doc-8087-v10, all others from Blennow. 

Reasonable Synopsis
Summary

- Probably by the end of the coming decade we will know the mass hierarchy
  - It is not yet a slam dunk
  - PINGU will have the best reach if it can get started soon
  - Daya Bay II could be lucky, they have surprised us before
    - Two approaches, belts and braces, but no cigar

- We will know $\theta_{23}$ to few % (NOVA)
- We will know $\theta_{13}$ to 3% (still stats limited)
- We will know $\Delta m^2_{12}$ to 0.6% (DBII)
- We will know $\Delta m^2_{13}$ to 0.6% (DBII)
- We will know $\Delta m^2_{32}$ to 1-2% (NOVA+MINOS+)
  - The combined data will be hinting about MH ...

- We should have strong limits on steriles
- But what of life after retirement?.....................
Going forward, the remaining question is:
What is $\delta_{CP}$??
Do we already know it? (T2K, MINOS and Reactors)
Without CHIPS, it could take another 20 years to find out!

The further future

THE NEXT DECADE STARTS AT FNAL!
Plausible Schedule for International LBNE

Question 1: “a brief summary of … a notional timeline…”

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LBNE

• Much longer baseline to measure mass hierarchy
• On-axis Liquid Argon detector (35kt)
• Planned to be operating in 2026
• CHIPS could also provide the complementary off-axis detector
  – After all, we already paid for all those phototubes....

There is (at least) one (40m depth) reservoir in the beam line @ 20mr (Pactola Reservoir, SD)
CHIPS@LBNE (20mr off axis)

- 2\textsuperscript{nd} oscillation maximum located around 0.8 GeV
- Large quasi-elastic x-section
- Suitable for water Cerenkov detector
  - High efficiency for QE events
- 2\textsuperscript{nd} oscillation maximum is a necessary upgrade/augmentation path for LBNE
• This is the region of $\delta_{CP}$ which we will cover with 10kt LBNE after 10 years (green shaded region)
• Obviously, with 35kt it is better
NO CHIPS + 35kt LAr

- IF LBNE is 35kt LAr detector
  - Better at small $\delta_{\text{CP}}$
  - Worse at large $\delta_{\text{CP}}$
CHIPS@NuMI

- CHIPS can make very big inroads into $\delta_{cp}$
- LBNE could build SUBSTANTIALLY on CHIPS@NuMI and together with CHIPS@LBNE
- 10kt LAr+100kt CHIPS now on the same page as the NF!
• CHIPS can make very big inroads into $\delta_{cp}$
• LBNE could build SUBSTANTIALY on CHIPS@NuMI and together with CHIPS@LBNE
• 10kt LAr+100kt CHIPS now on the same page as the NF!
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• 10kt LAr+100kt CHIPS now on the same page as the NF!

Pilar Coloma, NuFACT 2012
Hyper-K plans: my guess is that data taking does not start until 2024.
### Notional Timeline

#### Construction start

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
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<td>-4</td>
<td>J-PARCv w/ 220kW</td>
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<td>7</td>
<td>Water filling</td>
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<td>8</td>
<td>T2K accumulates approved POT (7.8x10^{21})</td>
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<tr>
<td>9</td>
<td>Operation</td>
</tr>
</tbody>
</table>

#### Assuming construction budget being approved from JPY2016

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**(Optimistic) Timeline for anticipated results**

- **2022**: \( \sim 2\sigma \) CPV indication \( \sin \delta = 1 \) by T2K+reactors (also in Nova)
- **2023**: Start Hyper-K data taking
- **2026**: Discovery of leptonic CPV w/ >5\( \sigma \) (MH at the same time or earlier)
- **2028**: Discovery of proton decays
- **20XX**: Always ready for Supernova neutrino burst
## Cost Estimate

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<th>Total</th>
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<tbody>
<tr>
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<tr>
<td>Near Detector</td>
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*The cost of rock disposal and water purification system to be added in the future

- Contribution from each country is under discussion in the Hyper-K WG
- Proportional sharing in an international project is ideal.
- The target for international contribution is 30% to 50% of the cost.
The last word

FNAL ONE LAST TIME
CHIPS@NuMI + CHIPS@LBNE+10kt LAr

- CHIPS can make very big inroads into $\delta_{cp}$
- LBNE could build SUBSTANTIALLY on CHIPS@NuMI and together with CHIPS@LBNE
- 10kt LAr+100kt CHIPS now on the same page as the NF!

Pilar Coloma, NuFACT 2012
CHIPS@NuMI + CHIPS@LBNE + 35kt LAr

- CHIPS can make very big inroads into $\delta_{\text{CP}}$
  - FNAL can be in every way as good as HK on $\delta_{\text{CP}}$

- LBNE could build SUBSTANTIALLY on CHIPS@NuMI and together with CHIPS@LBNE

- 35kt LAr+100kt CHIPS now on the same page as the NF!

- What if it were 200kt...or 500kt

Pilar Coloma, NuFACT 2012
Thank you for listening

BACK TO EARTH. DINNER.