### Long Baseline Neutrino Physics

#### Asher Kaboth PPAP Community Meeting 26 July 2016





Science & Technology Facilities Council Rutherford Appleton Laboratory

#### Outline

- Overview
- Current Experiments
  - T2K
  - NoVA
  - MINOS+
- Future (non-HK, non-DUNE) Experiments
  - T2K-II
  - CHIPS
  - PINGU
- Summary & Prospects

#### Neutrino Mixing

Neutrinos have two sets of eigenstates: mass (propagation) and flavor (detection)



$$\begin{pmatrix} \mathbf{v}_{e} \\ \mathbf{v}_{\mu} \\ \mathbf{v}_{\tau} \end{pmatrix} = \begin{pmatrix} \mathbf{U}_{e1} & \mathbf{U}_{e2} & \mathbf{U}_{e3} \\ \mathbf{U}_{\mu 1} & \mathbf{U}_{\mu 2} & \mathbf{U}_{\mu 3} \\ \mathbf{U}_{\tau 1} & \mathbf{U}_{\tau 2} & \mathbf{U}_{\tau 3} \end{pmatrix} \begin{pmatrix} \mathbf{v}_{1} \\ \mathbf{v}_{2} \\ \mathbf{v}_{3} \end{pmatrix}$$

$$\int \sqrt{\frac{1}{6}} \sqrt{\frac{1}{3}} \sqrt{\frac{1}{2}} \sqrt{\frac{2}{3}}$$

PMNS mixing matrix tells us how mass and flavor eigenstates are related



#### Neutrino Oscillation



4

#### Known

- Three mixing angles:  $\theta_{13}$ ,  $\theta_{12}$ ,  $\theta_{23}$
- Two mass splittings:  $\Delta m_{21}$  and  $|\Delta m_{32}|$

- The value of  $\delta_{CP}$
- Mass ordering
- Is  $\theta_{23}$  maximal
- More than three?
- Absolute mass
- Nature of mass: Majorana or Dirac?

 $c_{ij} = \cos \theta_{ij}$   $s_{ij} = \sin \theta_{ij}$ 



#### T2K UK Leadership

- International Co-Spokesperson: M. Wascko
- Operations: DAQ, ECal, electronics, Run Coordination, Calibration
- Oscillation Physics: 2 analyses and the ND280 analysis for OA are UK-led
- ND280 Physics: cross sections,  $\pi^0$ ,  $v_e$ , exotics, ND280 leadership

The UK is leading all aspects of T2K Second largest member of T2K, after Japan

#### T2K in Summer 2015 First Antineutrino Analyses



#### T2K in Summer 2016

- Added  $3 \times 10^{20} \overline{v}$  POT for a total of 7.4x10<sup>20</sup> and beam power exceeded 400 kW
- Joint v-v analysis, including water target data at the ND
- $v + \overline{v}$  gives powerful insight into  $\delta_{CP}$  constraints

	Obs	δ <sub>CP</sub> =-π/2	δ <sub>CP</sub> =0	δ <sub>CP</sub> =+π/2	δ <sub>CP</sub> =π
Ve	32	27.0	22.7	18.5	22.7
Ve	4	6.0	6.9	7.7	6.8
sin <sup>2</sup> θ <sub>23</sub> =0.528, NH					



#### T2K in Summer 2016



	sin <sup>2</sup> θ <sub>23</sub> ≤0.5	sin <sup>2</sup> 0 <sub>23</sub> >0.5	Total
NH	0.218	0.529	0.747
IH	0.072	0.181	0.253
Total	0.290	0.71	1.0

- T2K+reactor combination prefers  $\delta_{CP}=-\pi/2$
- Excludes no CP-violation at the 90% level
- Prefers NH around 3:1

#### Non-Oscillation Physics

- Based on UK Theses:
  - Single π Cross Section on Water
  - <u>Coherent π production on Carbon</u>
  - Or <u>Charge Current Oπ on Carbon</u>
     On Carbon
     On
     On
- Other Cross Section

- Novel kinematic variables
- Π
- Short baseline steriles
- 13 posters by UK students and postdocs about T2K at <u>Neutrino2016</u> (hosted in London by Imperial!)

<sup>•</sup> V<sub>e</sub>

#### SK in the UK

- Sheffield, QMUL, Liverpool, Imperial, and Oxford are now officially members of SK
- Responsibilities:
  - Calibration
  - Gd in water
     cherenkov detectors
  - Analysis



### Looking Forward

- T2K has now taken ~18% of expected POT, and will add another 10% in the next 12 months
- T2K will begin autumn running in v mode to maximize statistics
- Expect a lot of physics very quickly!

#### The NoVA Experiment

University of Sussex



Strong involvement in  $v_{\mu} \rightarrow v_{\mu}$  analysis





#### NoVA Results 2016

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## Looking Forward

- NoVA still has data in the can from 2016
- Expect to double dataset in the next year
- Begin antineutrino running in Spring 2017

#### MINOS+

Manchester, Cambridge, UCL, Oxford, Sussex, Lancaster

- New results on PMNS disappearance
- New results on steriles, exotics, and non-standard interactions
- Last data taken at the end June MAN
- Many leadership roles: cospokesperson, MANCHESTER The University of Manchester Iysis coordinator, steriles





#### Global Combinations

- T2K, NoVA, and SK data is generally in agreement about δ<sub>CP</sub>
- Combinations are pointing towards stronger evidence
- Doesn't have full systematic correlation, but experiments are at the beginning of that process



#### **T2K-II**

- There is ~5 years between the nominal end of T2K and the start of HK
- Continuing to run the beam can triple the POT to ~20x10<sup>20</sup> in the intervening time
- J-PARC PAC hearing proposal this week
- All UK institutions on T2K have expressed interest in extending work on T2K to T2K-II



# $\Lambda \sim^2$ to exclude sing

#### **T2K-II**

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- Sensitivity also enhanced by improvements in data selections and systematic uncertainties
- Robust set of proposals for near detector upgrades to follow
- Potential for >3σ observation of CP-violation by 2026

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Protons-on-Target (x10<sup>21</sup>)

T2K-II

w/ eff. stat. improvements (no sys. errors

15

w/ eff. stat. & sys. improvement

**T2K** 

- True sin<sup>2</sup>θ<sub>23</sub>=0.43

- True  $\sin^2\theta_{22}=0.50$ 

- True  $\sin^2\theta_{23}$ =0.60

 $\Delta~\chi^2$  to exclude sin $_{\rm CP}$ =0

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3σ C.I



Protons-on-Target (x10<sup>21</sup>)

#### PINGU

- Low energy extension of IceCube
  - Determination of the neutrino mass ordering
  - Test of PMNS matrix unitary via ∨⊤ appearance
  - Best sensitivity for spin-dep. interactions of low mass DM
- New baseline PINGU geometry: 40 strings with 96 pDOM each→26 strings with 192 pDOM each
- This change does not lose NMO sensitivity, but it brings significant cost savings via:
  - only two deployment seasons
  - fewer holes to drill



This reduces total cost to \$47M, and enables PINGU to fit in the NSF "midscale" program – proposal is being prepared.

Updated LoI will be released soon





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#### CHIPS CHIPS (U) ADDIE (U)

- Use 3" PMTs in natural water as an off-axis detector to measure the second oscillation max
- 50 ton prototype tested in 2015
- Attenuation length of water measured with recirculation
- Major simulation progress: studying PMT coverage—may only need 6%
- Design of 1.5 kton
   "slice"underway









## PhyStat-v

- A UK-led initiative to bring the PhyStat workshop series to neutrino physics
- First meeting in Kashiwa this year was a resounding success: 90 participants and high praise from attendees
- Second meeting at FNAL in September
- Timely discussions for the exciting physics arriving from neutrinos
- Workshops will continue!



### Summary

- The past year has been extremely exciting in LBL neutrino physics
  - ${\scriptstyle \odot}$  Stronger hints in  $\delta_{CP}$
  - Tighter constraints in  $\theta_{23}$  and  $\Delta m_{32}^{2}$
  - New cross section and exotics measurements
  - Many more results from <u>Neutrino2016</u>
- The UK holds strong leadership in ongoing experiments and drives these analyses
- There is still much to do, and near-term future experiments have great potential