Neutrinos in PPD@RAL

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Science and Technology Facilities Council

Neutrino Mixing: The PMNS Matrix

- Assume that neutrinos do have mass:
  - mass eigenstates ≠ weak interaction eigenstates
  - Analogue to CKM-Matrix in quark sector!

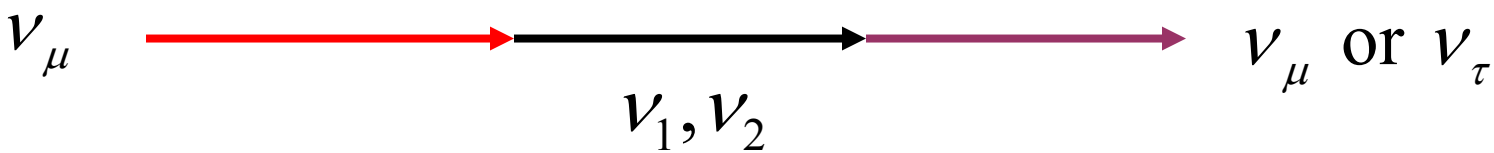
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

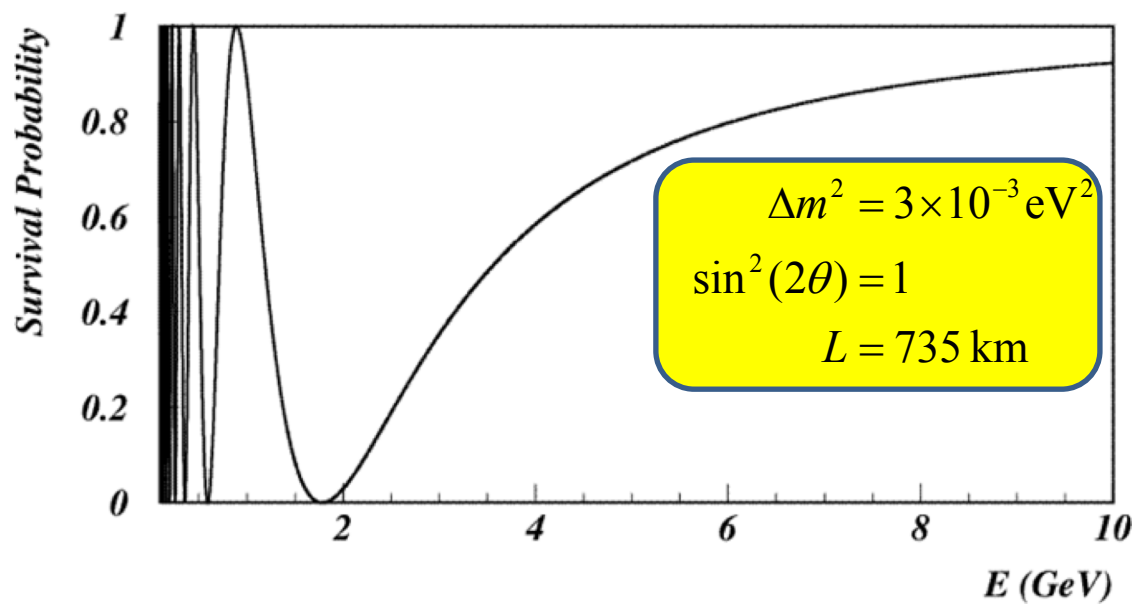
with $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$, θ_{ij} = mixing angle and Δm_{ij}^2 = mass^2 difference

Oscillations for Dummies



$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

- Measure prob.
  - Survival
  - Appearance
- Result
  - Mixing angle
  - Mass differences



The Who-is-Who

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

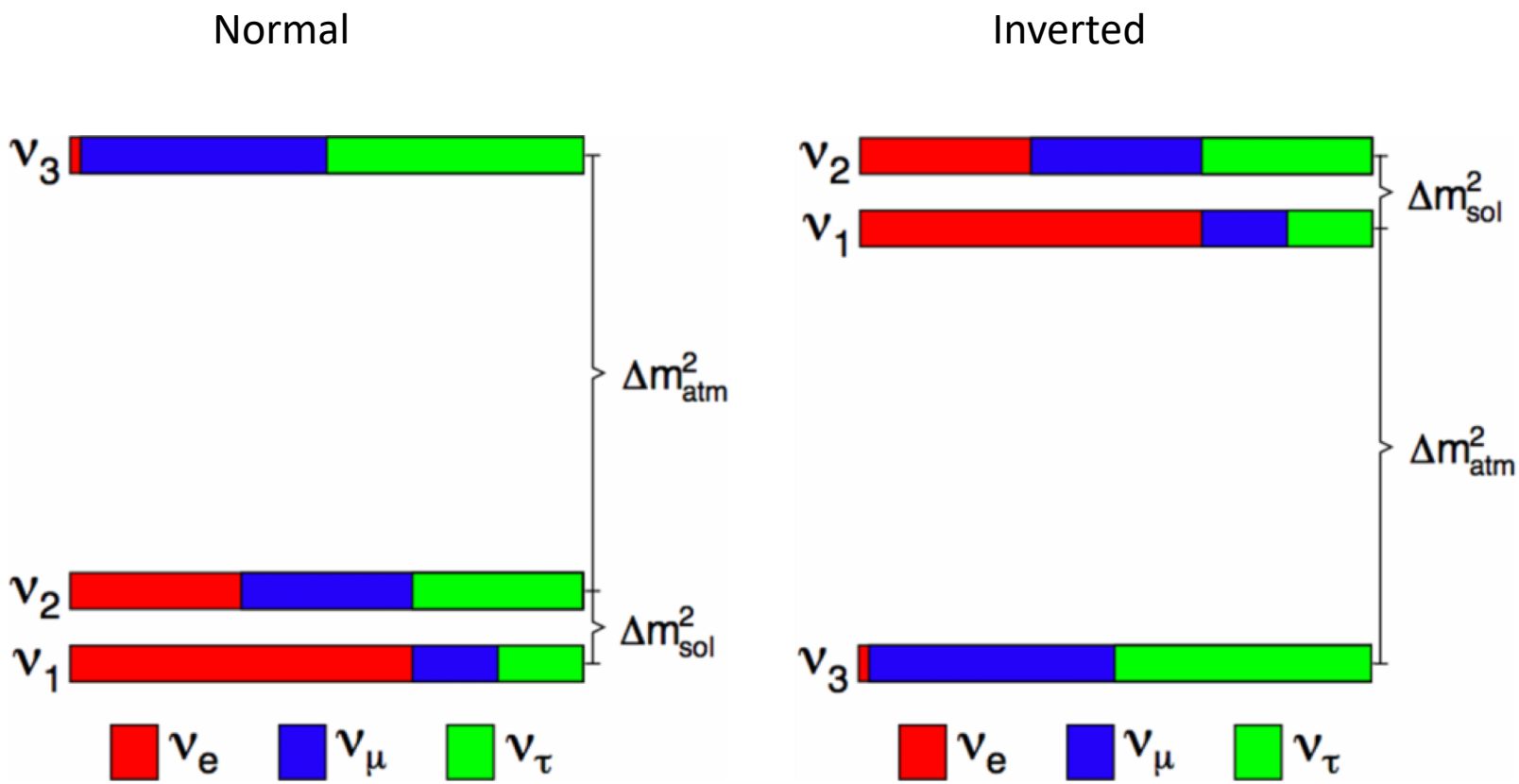
ν_μ disappearance

Solar neutrino oscillation

ν_e appearance in ν_μ beam
Or
reactor neutrino experiments

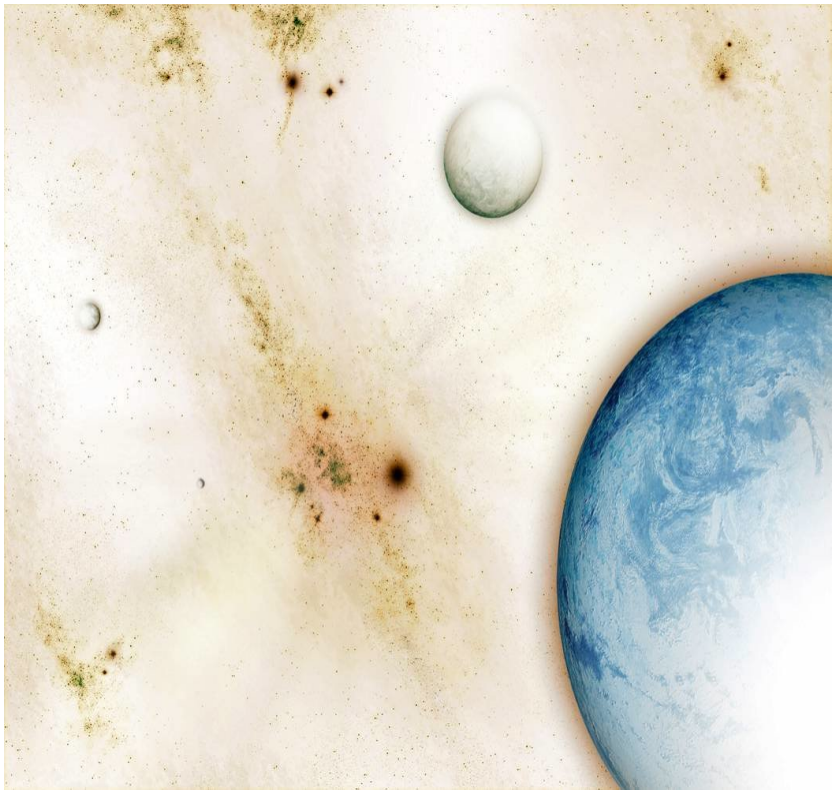
ν–less double beta decay

Mass Ordering (Hierarchy)



Matter-Antimatter Asymmetry

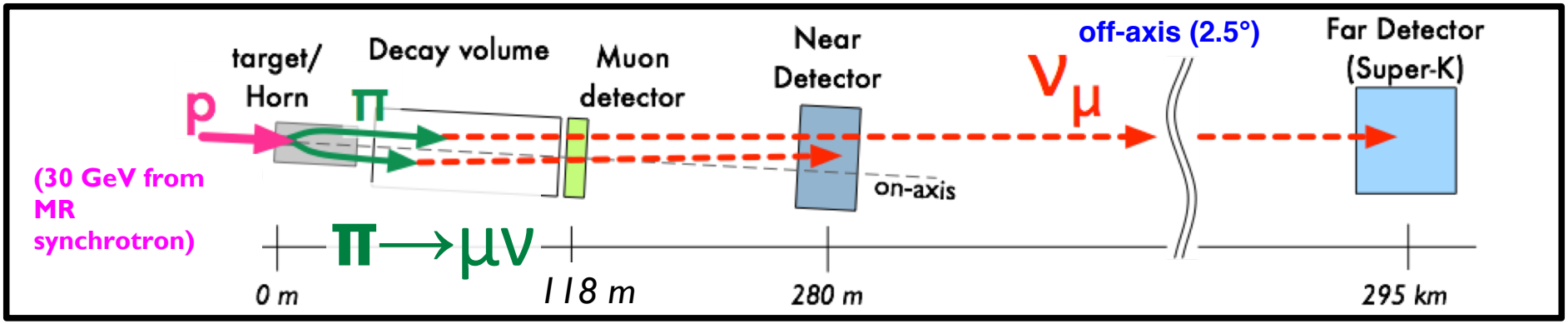
$\neq$

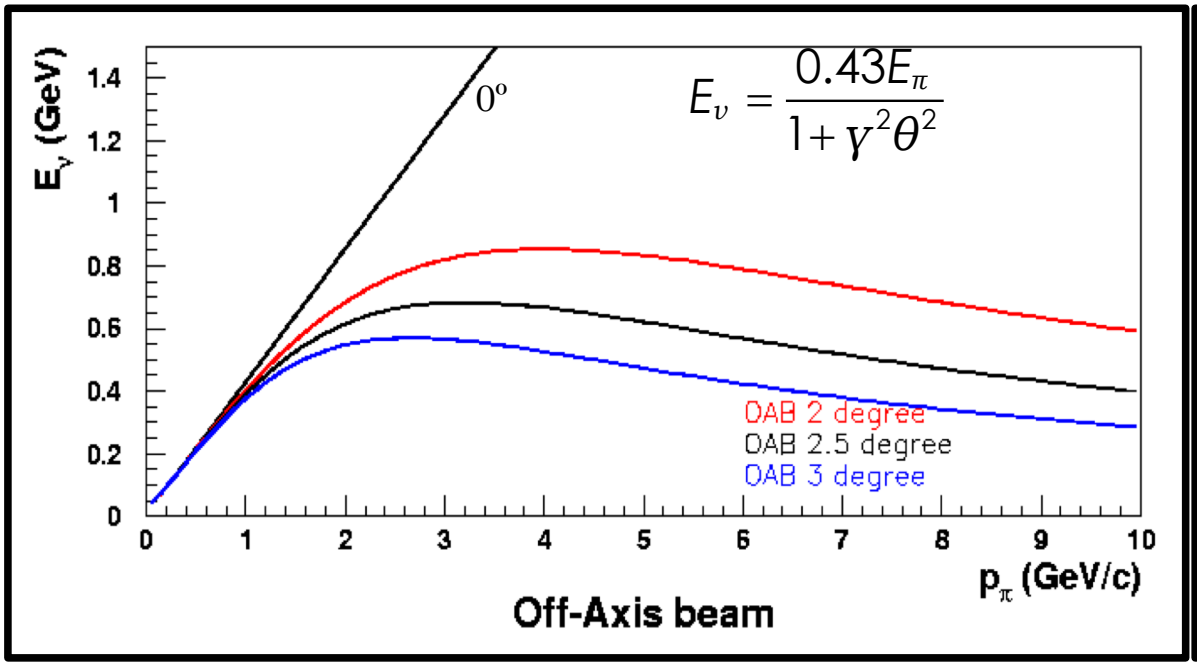


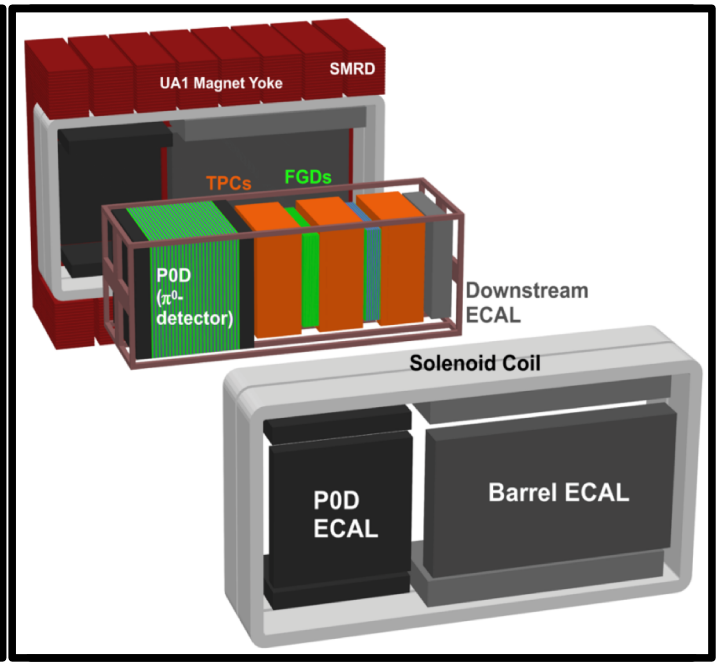
The T2K Experiment

- Neutrino Beam from J-PARC
  - Beam power 50 – 515 kW
- Far Detector
  - SuperKamiokande
  - 40 kton water Cherenkov

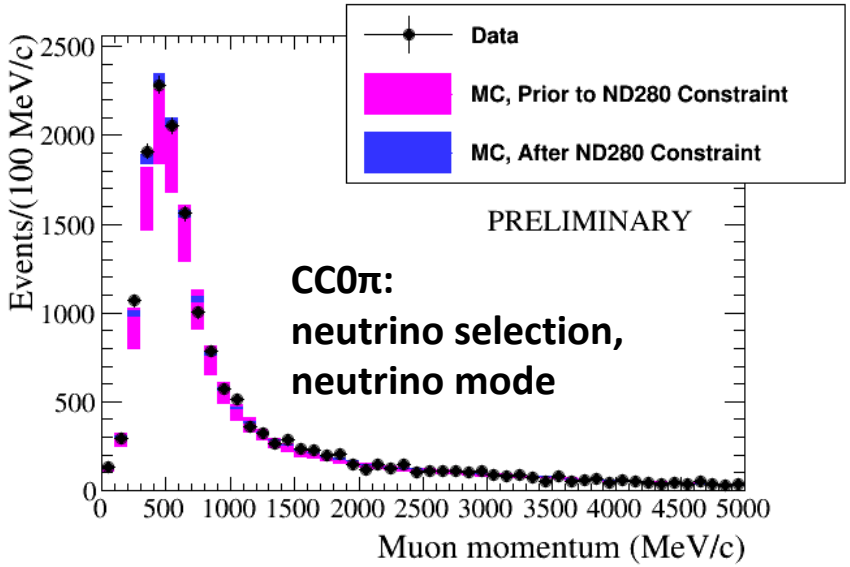
Producing Neutrinos





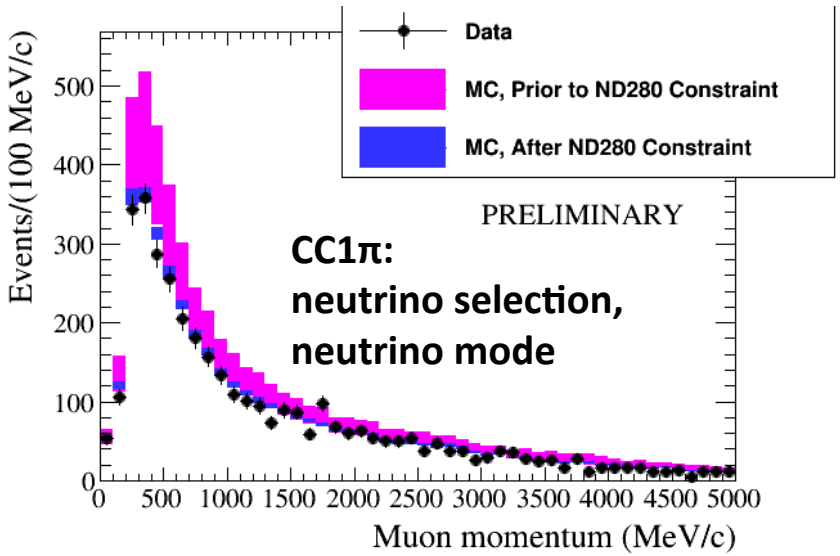


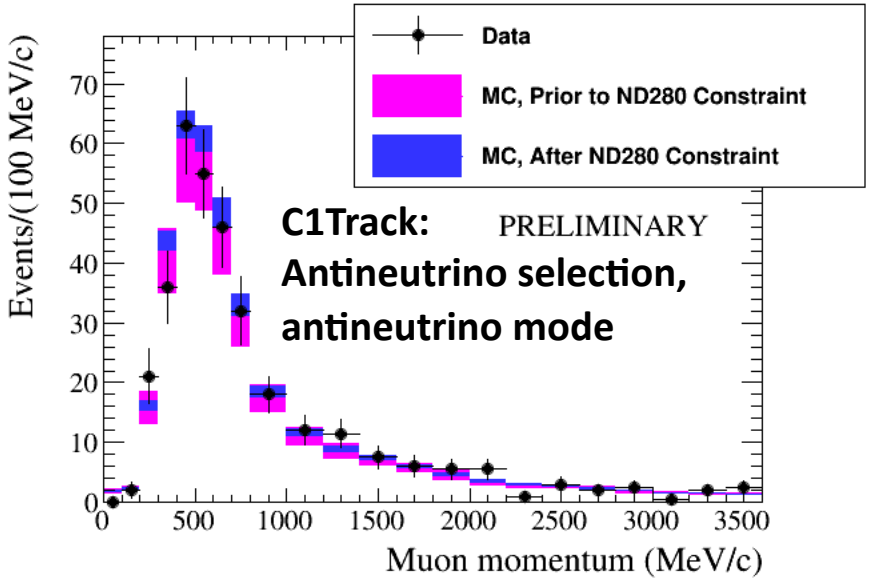
ND Measurements are Essential



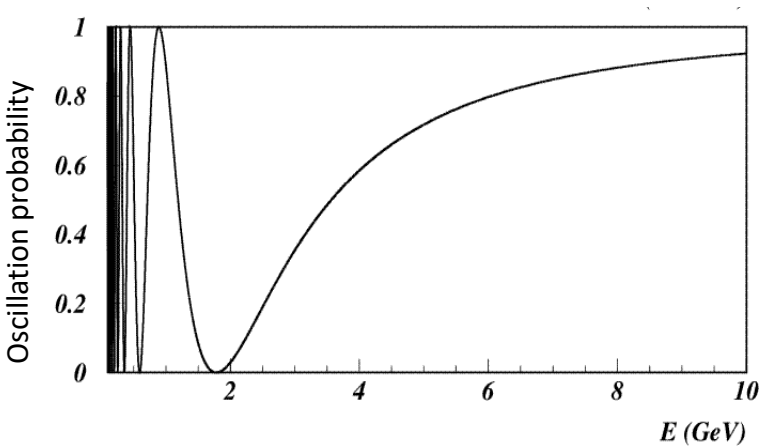
Far detector expectations tuned with fit to ND samples

- (Anti-)Neutrino fluxes highly correlated between ND and FD
- Cross sections highly correlated
- Significant reduction to overall uncertainties

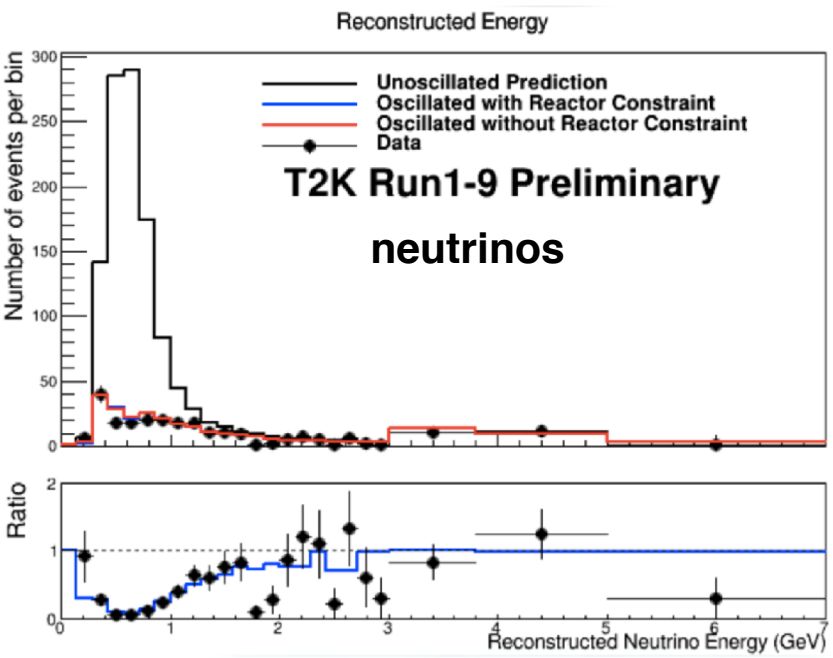


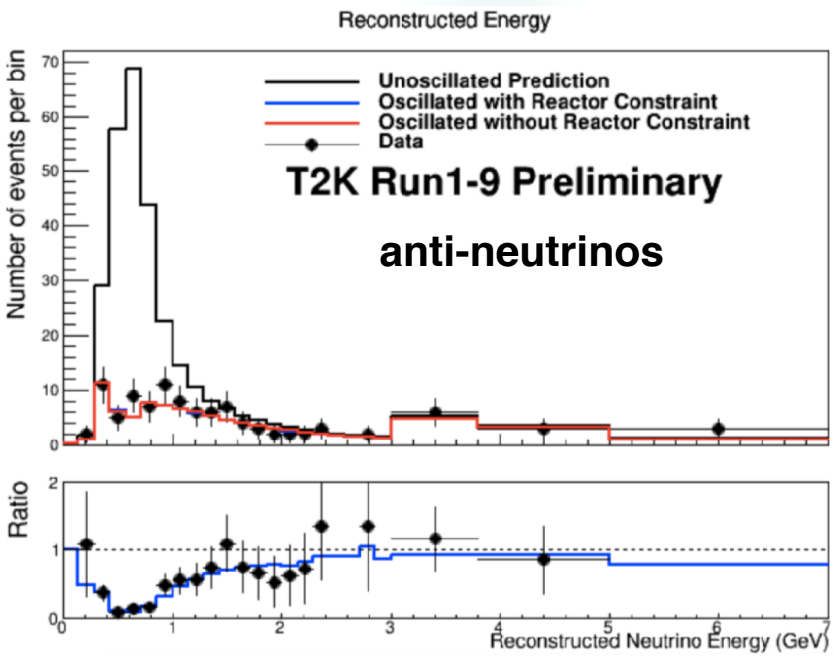


Muon Neutrino Disappearance



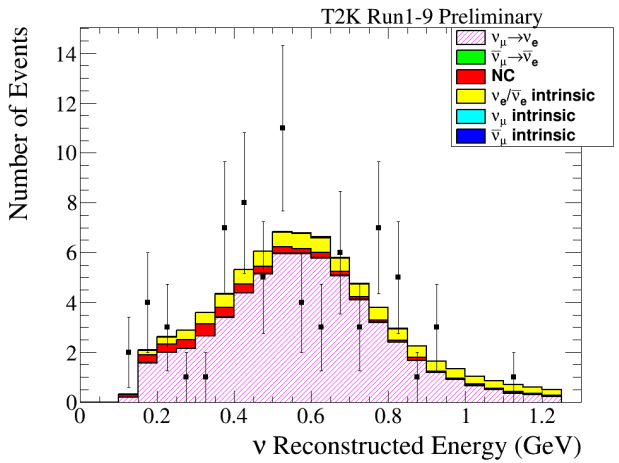
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L}{E_\nu}\right)$$

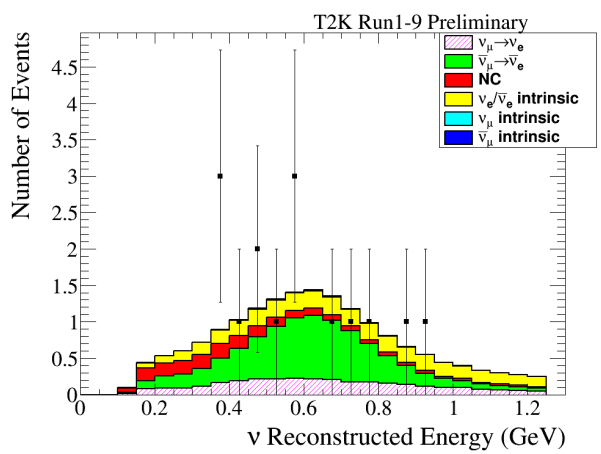


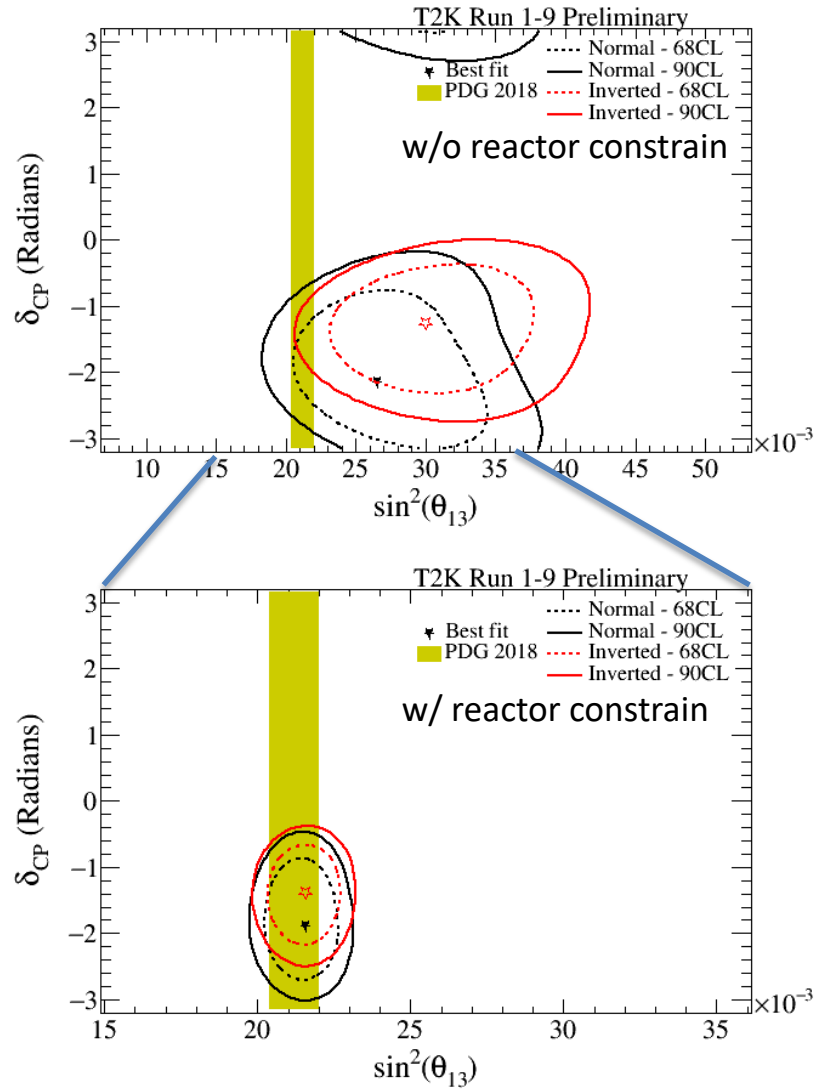


Electron Neutrino Appearance

- Electron (anti-)neutrinos tell us about CP violation





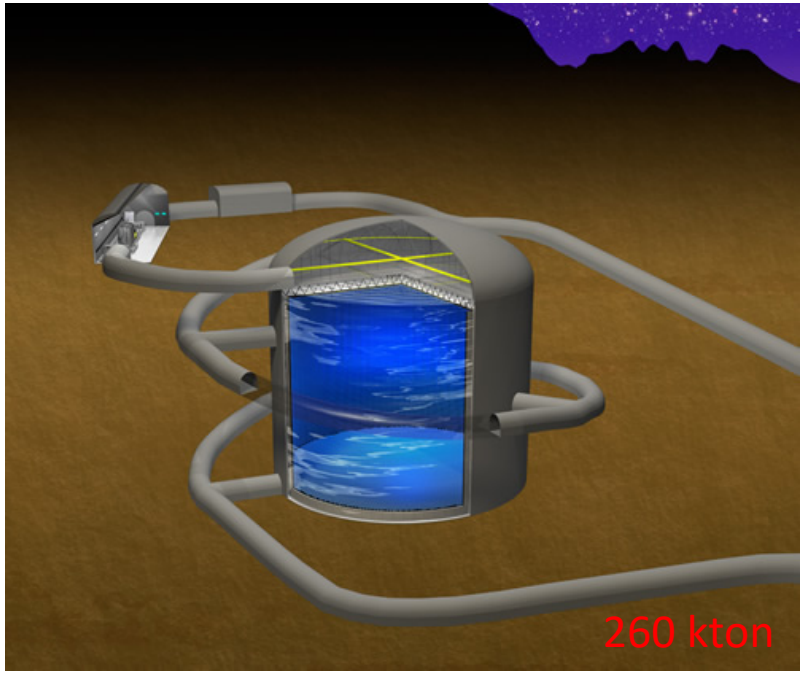


T2K Thesis

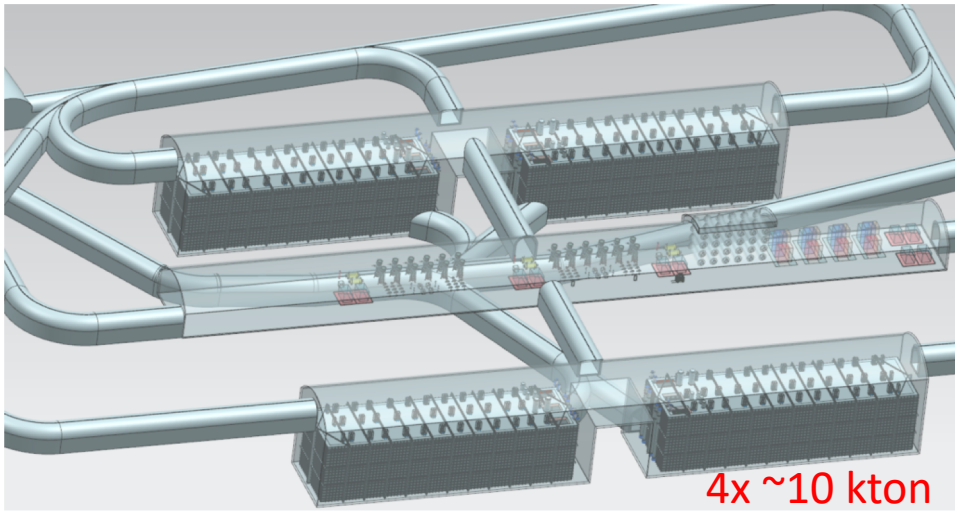
- Supervisors
  - Helen O'Keeffe, University of Lancaster
  - Federico Nova, PPD
  - Alfons Weber, University of Oxford & PPD
- Thesis
  - Many options
    - Measuring CP-violation with T2K
    - Use ND constrains to reduce systematic uncertainties
    - Measure neutrino cross sections
    - Opportunity to prepare for T2K-II/HyperK
    - All interlinked
  - DAQ/electronics expert
  - Detector calibrations to improve detector performance

The Future

HyperK



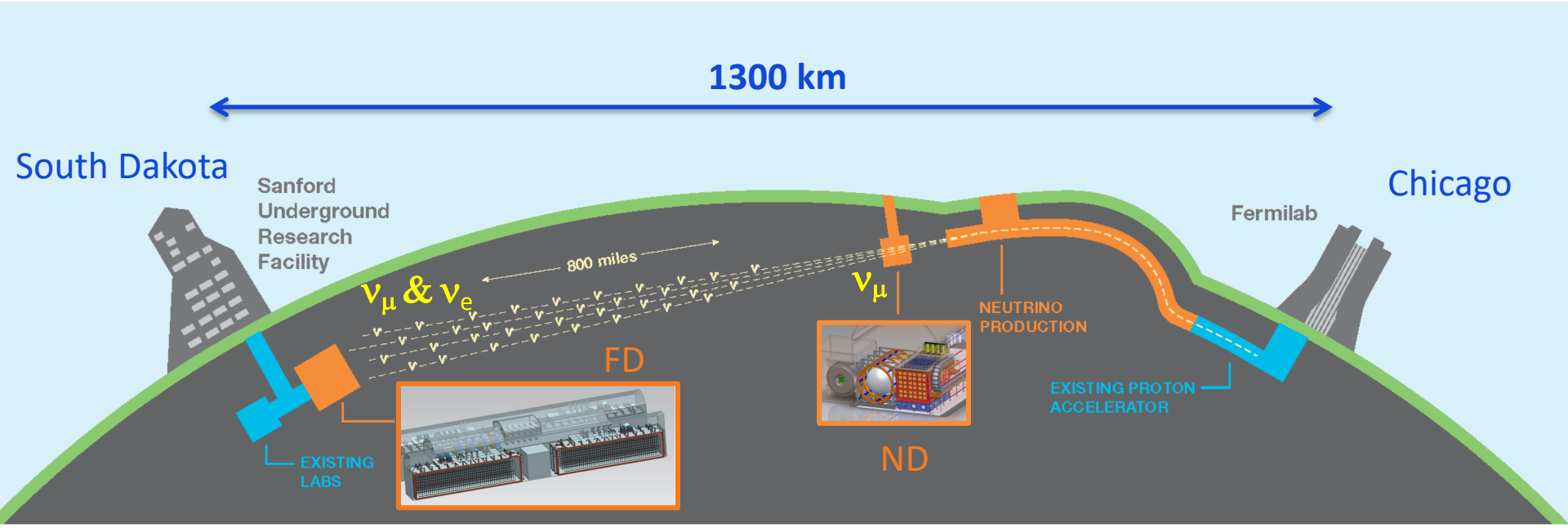
DUNE



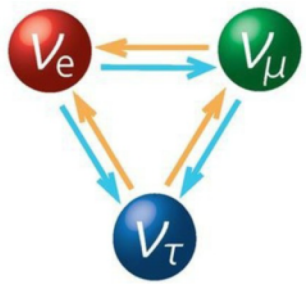
- Bigger Detectors
- Mega-Watt Beams

DUNE

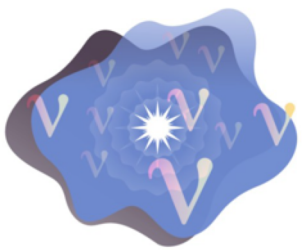
- LBNF/DUNE will consist of
  - An intense 1.2 MW upgradeable ν-beam fired from Fermilab
  - A massive 68 kt (40kt instrumented) deep underground LAr detector in South Dakota and a large Near Detector at Fermilab
  - A large international collaboration



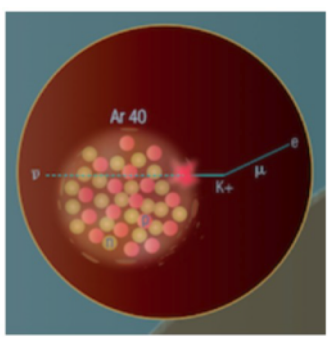
Physics Program



- Neutrino Oscillations
  - Search for leptonic CP violation
  - Determine neutrino mass ordering
  - Precision PMNS measurements



- Supernova Physics
  - Observation of time and flavour profile provides insight into collapse and evolution of supernova
  - Unique sensitivity to electron neutrinos

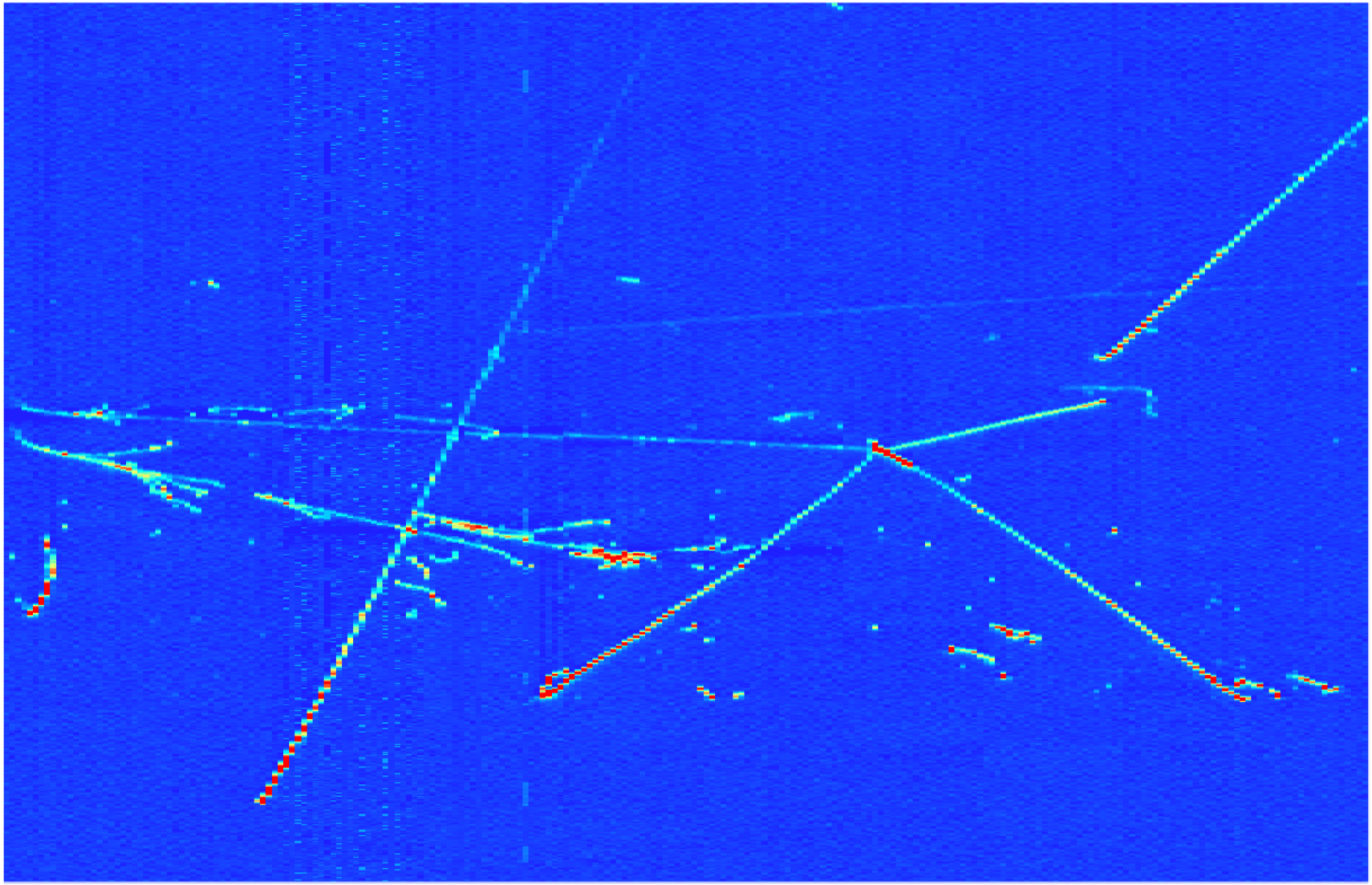


- Baryon number violation
  - Predicted by many BSM theories
  - LAr TPC technology well-suited to certain proton decay channels (*e.g.*, $p \rightarrow K^+ + \bar{\nu}$)
  - $\Delta(B\text{-}L) \neq 0$ channels accessible (*e.g.*, $n \rightarrow \bar{n}$)

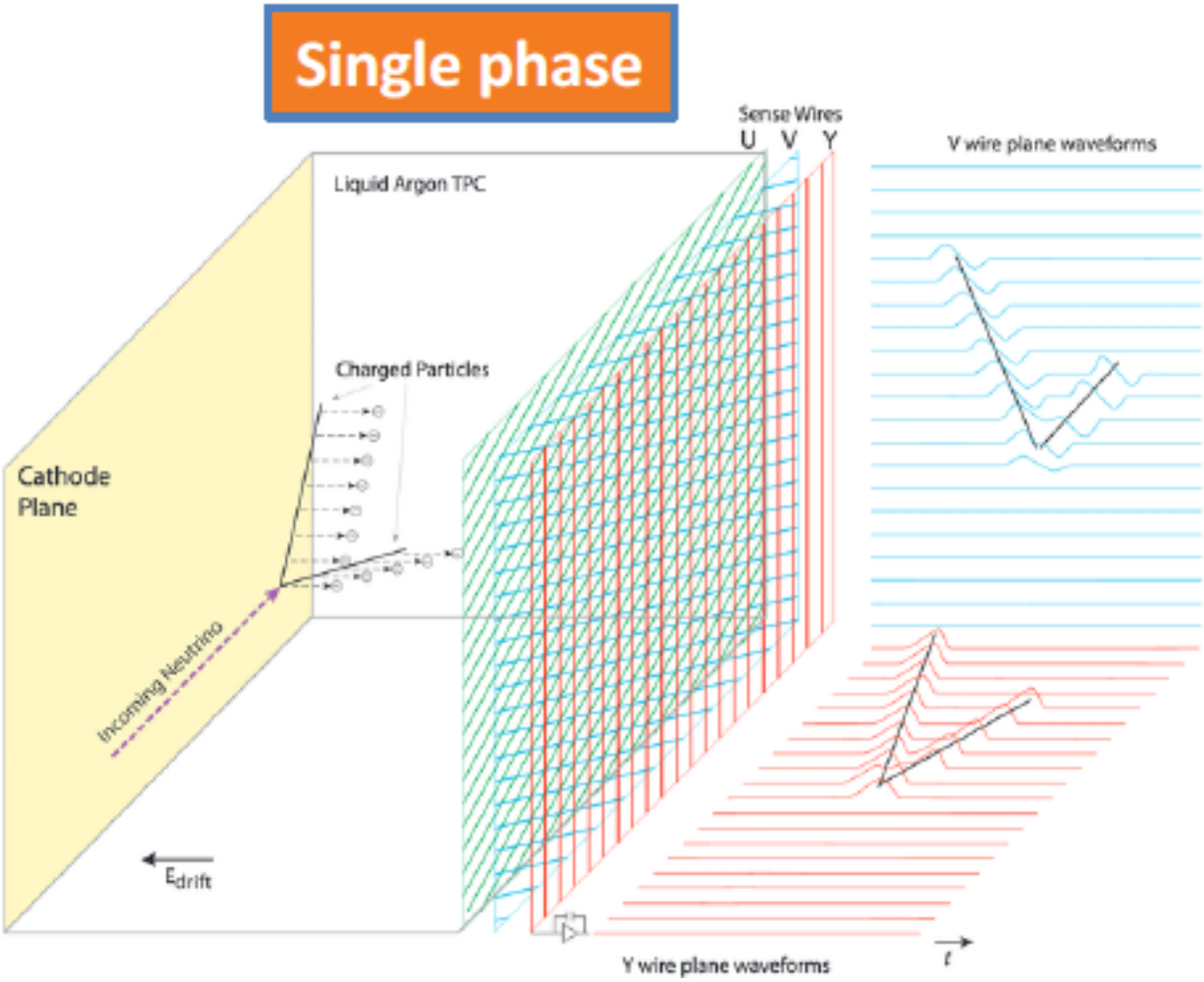
Liquid Argon Detectors (TPC)

- **Dense**:
  40% denser than water
- **Cheap**:
  abundant (1% of atmos.)
- **Ionizes easily**:
  55,000 electrons/cm
- **Excellent scintillation**:
  20,000 photons/MeV
  (@ 500 V/cm)

Unmatched Imaging Details

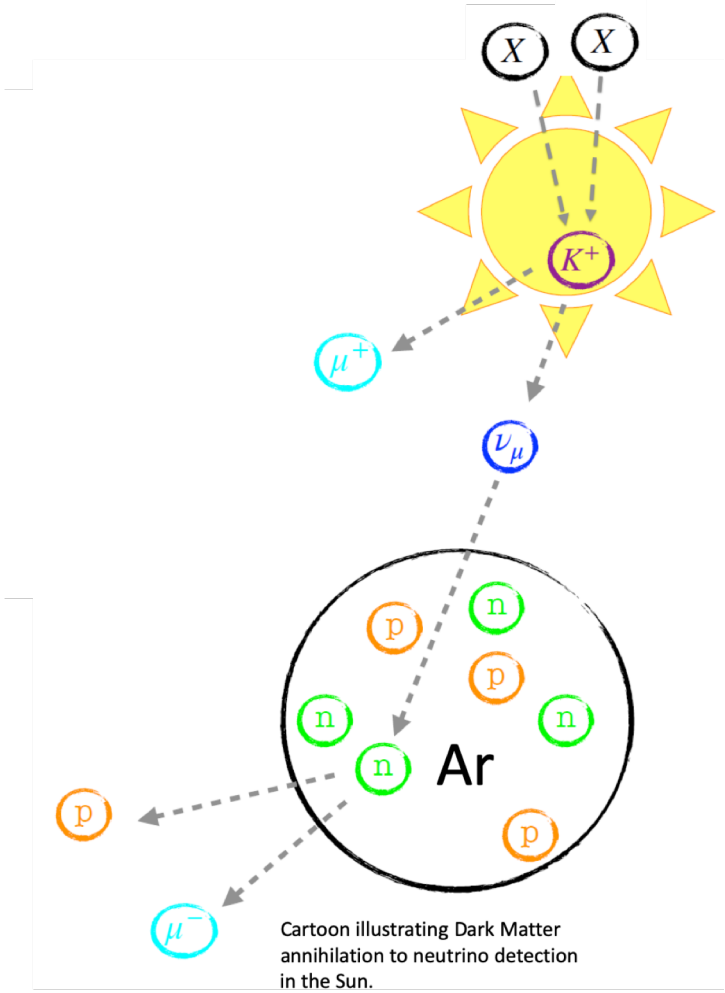


Single Phase Technology



Dark Matter in DUNE

- Neutrino Detector is not Dark Matter Detector
- But
  - DM can be captured in sun
  - Can interact and/or annihilate
  - Produce neutrinos
  - DUNE is neutrino detector



Cartoon illustrating Dark Matter annihilation to neutrino detection in the Sun.

DUNE Thesis

- Supervisors
  - Simon Peeters, University of Sussex
  - Antonis Papanestis, PPD
  - Claire Shepherd-Themistocleous, PPD
- Thesis
  - Can we find Dark Matter (DM) in DUNE?
    - Model building (DM in the sun)
    - Can we trigger on DM neutrinos
    - Develop DM-neutrino triggering for DUNE
    - Help develop DAQ
  - Interface between theory and hardware
  - Algorithms can be tested at ProtoDUNE @CERN

Summary

- Neutrino Oscillation
  - Only indication of physics beyond the Standard Model
- Particle Physics Department
  - at the heart of neutrino physics in the UK
- Our activities
  - Detector development incl. DAQ
  - Neutrino generators & Cross section measurements
  - Data analysis & oscillation fitting
- Unique opportunity for students to join the team