UNIVERSITY OF LIVERPOOL

Science & Technology Facilities Council
Particle Physics Department

Neutrino activities and studentship

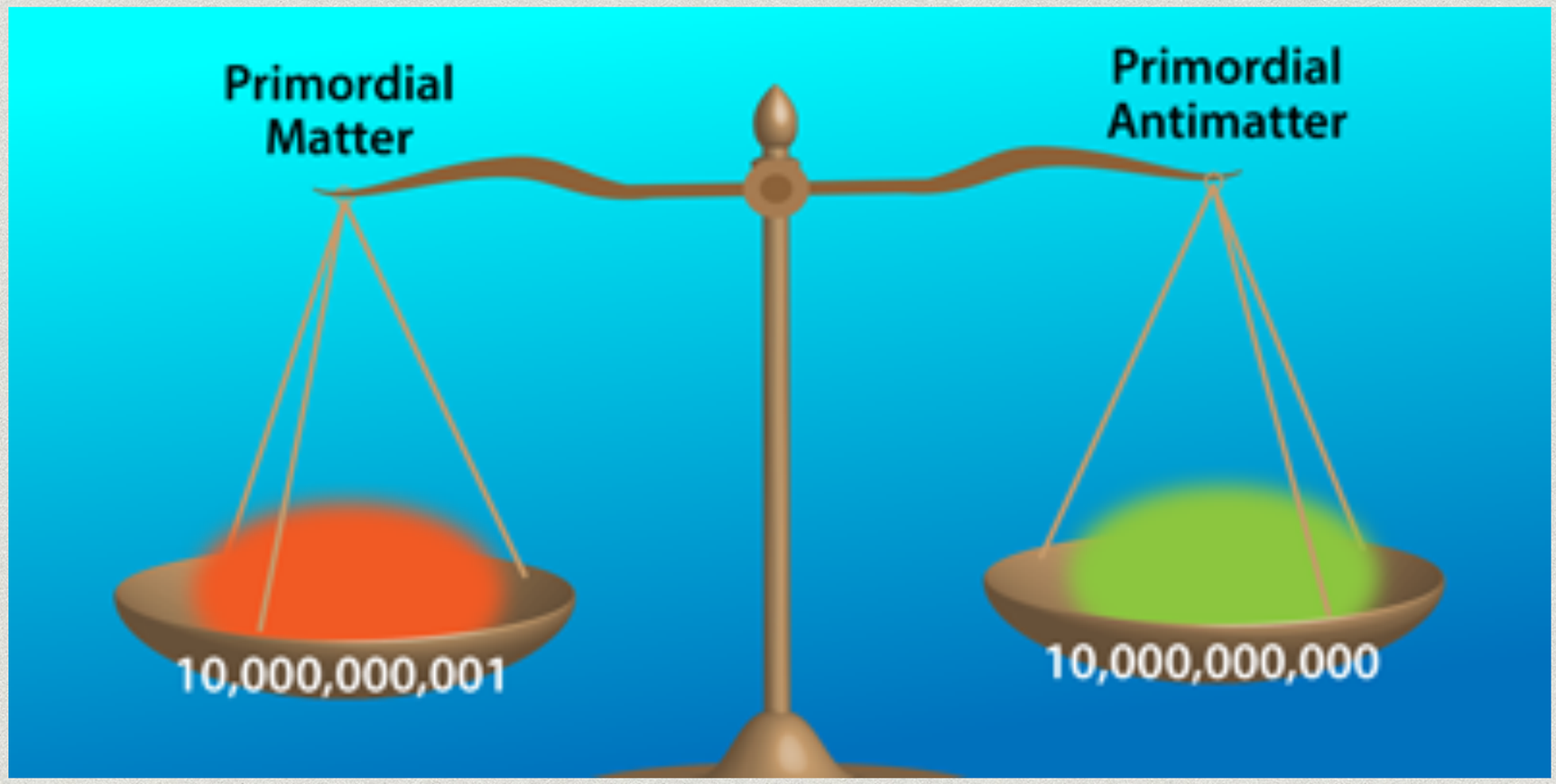
RAL/PPD PhD Open Day 2019

Professor **Costas Andreopoulos**

constantinos.andreopoulos@cern.ch

Motivation - Baryon Asymmetry of the Universe (BAU)

Everything (we see) in the Universe today, is the result of a **1 part in O(10^{10})** difference between the primordial matter and antimatter!



What caused it? This is one of the biggest mysteries in modern science!

$$\eta = \frac{N_B - N_{\bar{B}}}{N_\gamma} = 6 \times 10^{-10} \frac{excess\ baryons}{photon}$$ [*WMAP*]

Charge-Parity Invariance Violation

The necessary conditions for BAU were described A. Sakharov in 1967.

Charge-**P**arity Invariance **V**iolation (CPV) is one of the necessary conditions

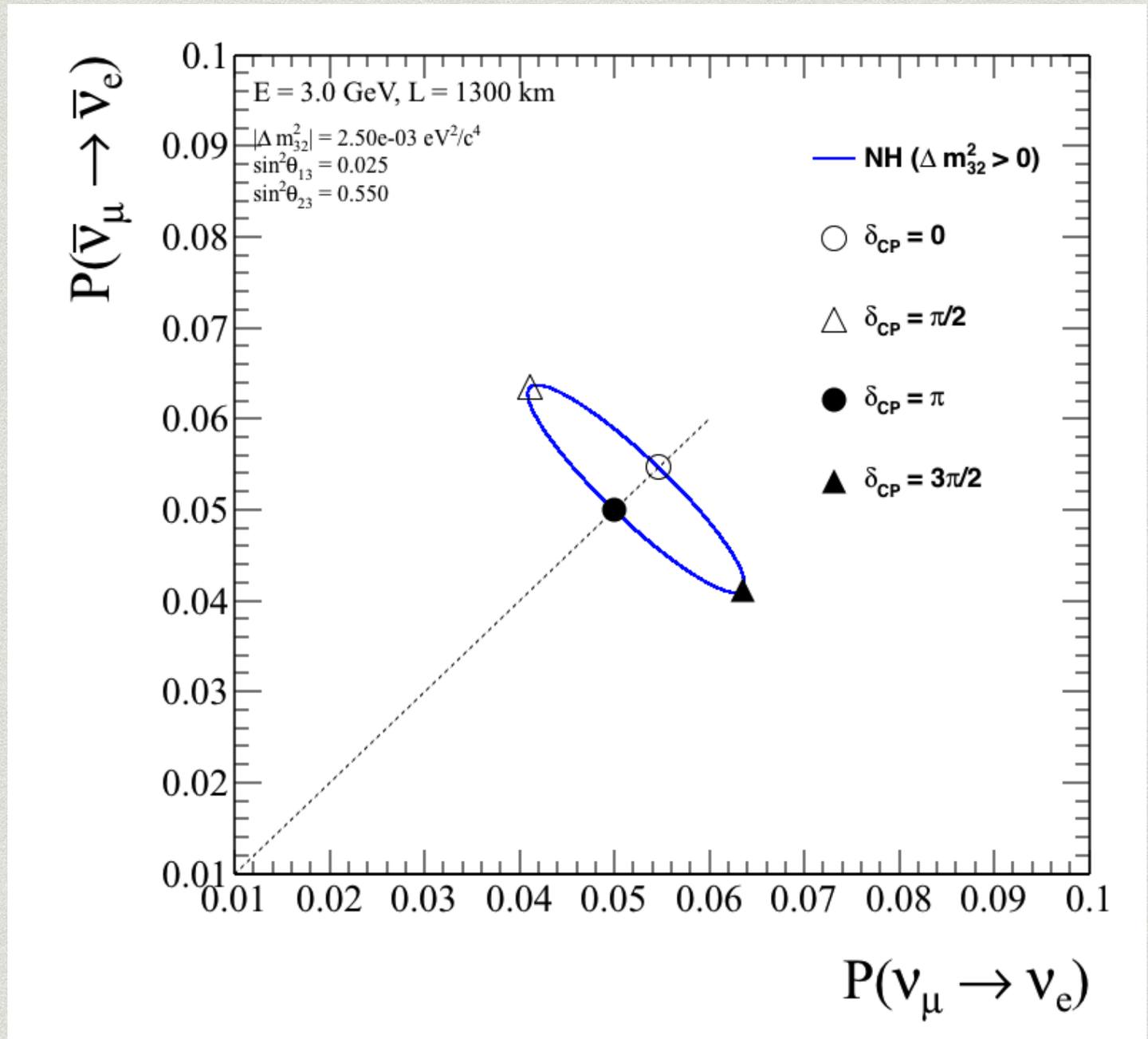
Sources of CPV in the Standard Model (SM):

- **QCD vacuum**
  - No CPV! A mystery on its own right!
  - Axions?

- **Quark mixing**
  - CPV seen in the decays of K and B mesons
  - Can not explain the size of the baryon asymmetry

- **Neutrino mixing**
  - Within the standard 3-flavour model, neutrino CPV is driven by δ_{CP}

Measuring δ_{CP}



Through a comparison of **electron neutrino** and **electron antineutrino** **appearance** probabilities.

If CP is violated

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

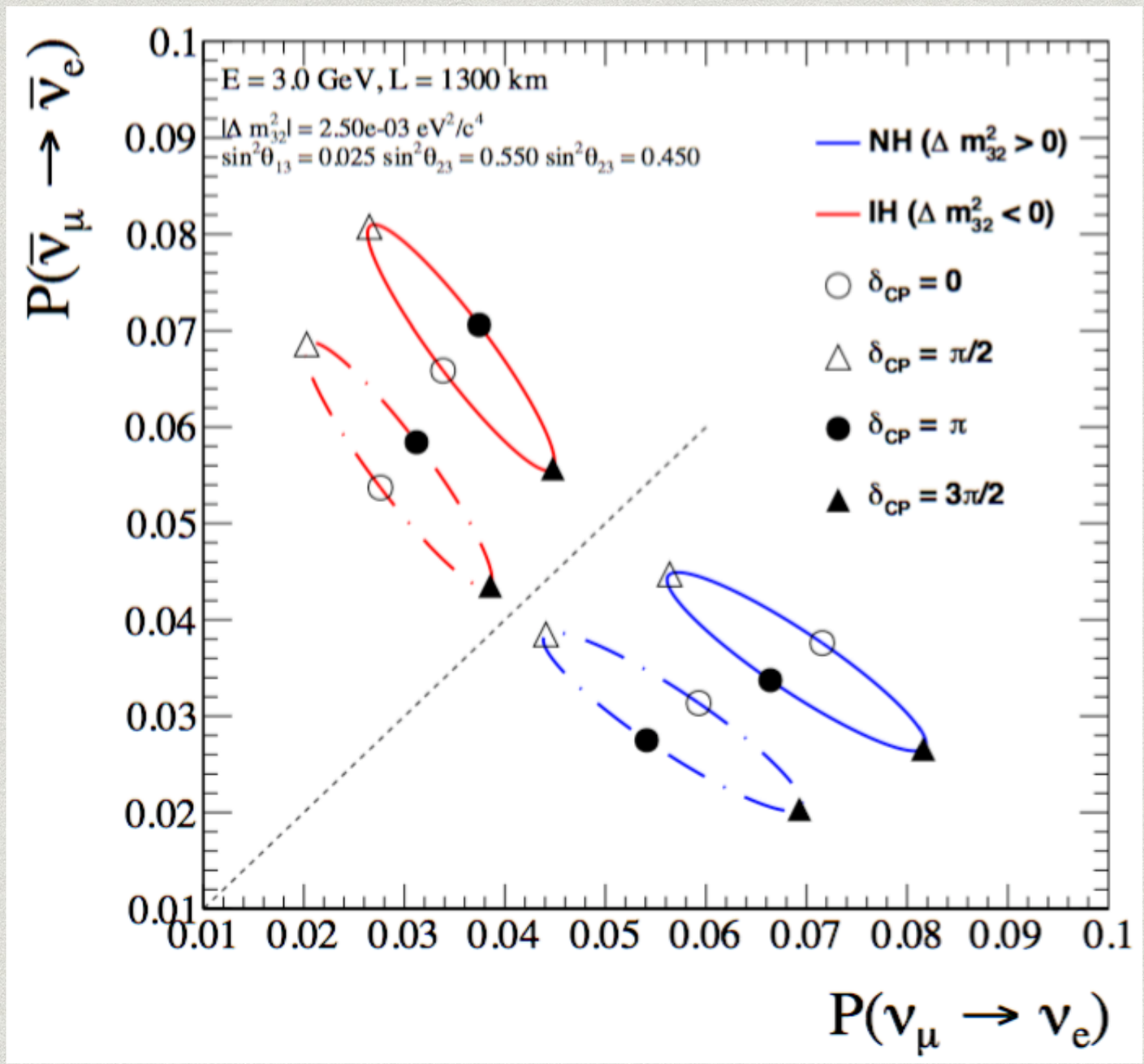
δ_{CP} appears in a $e^{\pm i\delta_{CP}}$ term so it has a **cyclical effect.**

A measurement in the $\left(P(\nu_\mu \rightarrow \nu_e), P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)\right)$ plane yields δ_{CP}.

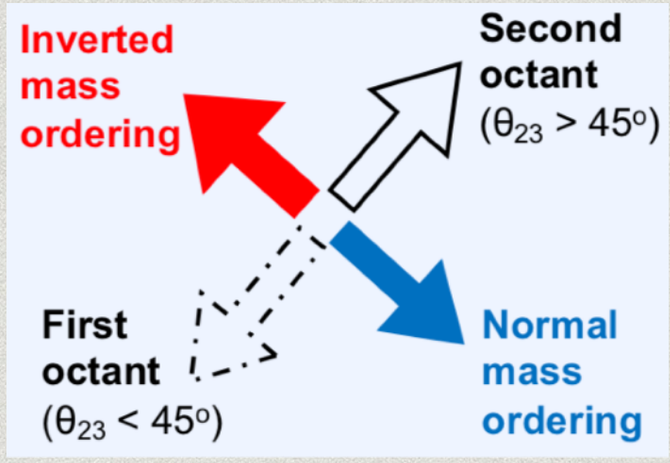
Simple, no?

Measuring δ_{CP}

Actually, it is darn difficult!



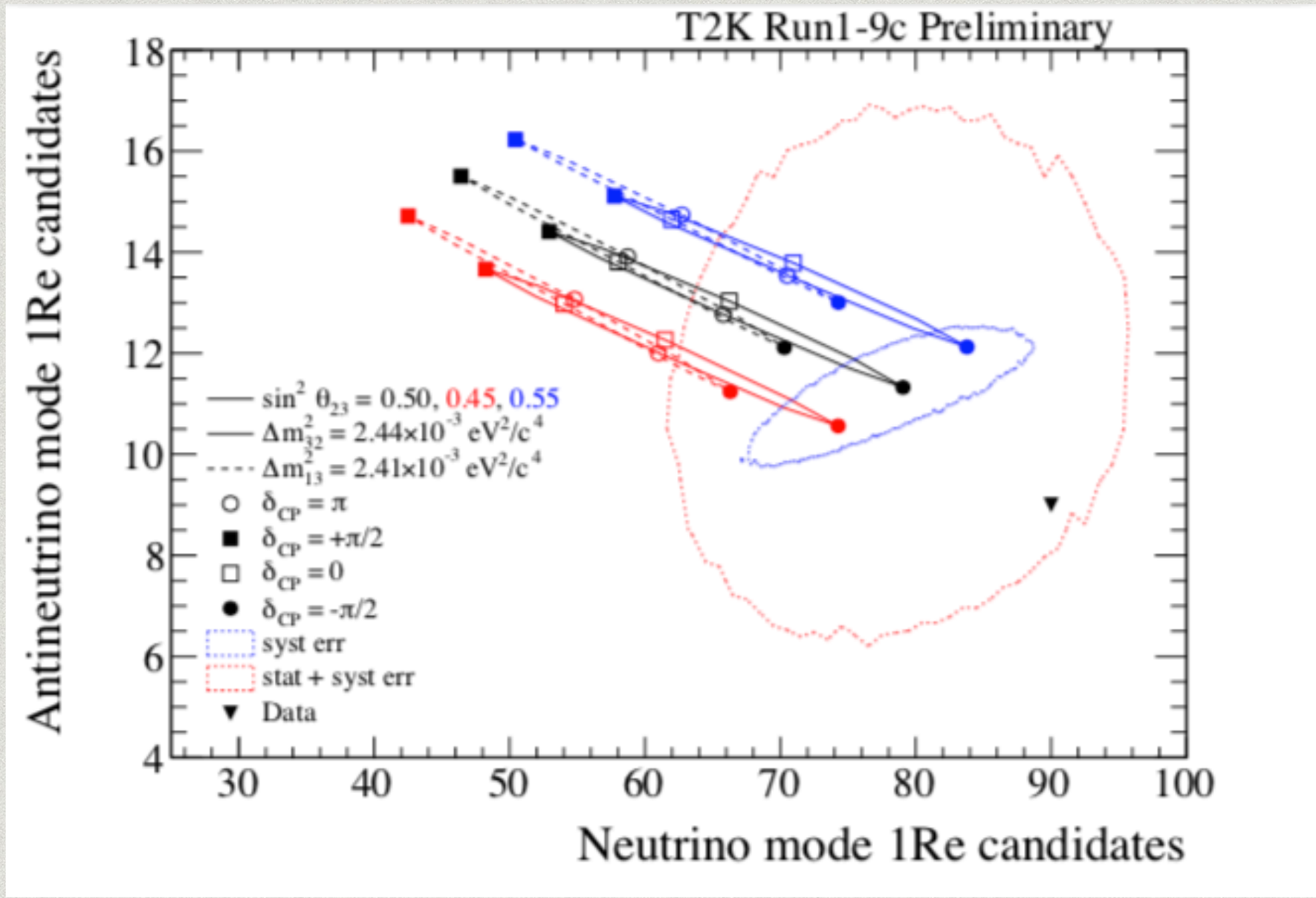
- **Degeneracies** and **CPV-like asymmetry induced by matter effects** (Earth is not CP symmetric!)



- **Systematic uncertainties**
  - Need ~1%, but can not make any prediction to better than 30-40% !!
  - Huge auxiliary programme to mitigate effect of uncertainties

CPV hints from T2K

Hints at ~2σ level for CPV, exceeds sensitivity! Preference for δ_{CP} around -π/2.



Weak tension with predictions of 3-flavour model

Towards establishing neutrino CPV

Two highly-complementary efforts in US and in Japan

DUNE

A WBB over a very long baseline (1,300 km) coupled with a high-granularity LArTPC detector.

HyperK

A low-energy NBB over a somewhat shorter baseline (300 km) coupled with a Water Cherenkov detector.

UK, and RAL in particular, has very strong involvement on both DUNE and HyperK

building up from leading contributions in the past and current generation of LBL experiments

Should I get into this field?

- This entire field seems mainly geared up towards measuring a single number ($\boldsymbol{\delta_{CP}}$)
- Already, there is evidence at ~2σ level that $\sin(\delta_{CP}) \neq 0$
- I do not see the novelty, excitement, and where is the “new physics”

Should I get into this field?

Heck yeah!!

CPV in quarks was discovered in **1964** and we are **still studying it** today!

We have not even established neutrino CPV yet! We are in it for the long haul!

If you start your career now, **neutrino physics should be your option #1!**

(unless you are satisfied working on novel ways of not finding new physics)

It is not "just about δ_{CP}"

Even if we discover CPV, what is its origin?

- If you assume the standard 3 flavour paradigm, then there is only δ_{CP}
- But this is an assumption which could well prove to be wrong!

What about sterile neutrinos?

- The **existence of such gauge neutrino singlets is well motivated** and is a natural consequence of a non-zero neutrino mass.
- If you have mixture between active and sterile neutrinos, then there are **additional CP phases and all bets are off**! The picture can become extremely complicated!

We found neutrino oscillations in an experiment studying proton decay!

- The opposite is a distinct possibility!

CPT violation? NSI? Dark matter? Neutrino decay? [many possibilities]

Genuine excitement and hope that neutrinos offer a window to new physics

The teams

Science & Technology Facilities Council
Rutherford Appleton Laboratory

UNIVERSITY OF LIVERPOOL

Neutrinos @ RAL / PPD

Dave Wark, FRS
Professor
(with Uni of Oxford)

- T2K-UK PI
- Former intl' T2K cospokes

Alfons Weber
Professor
(with Uni of Oxford)

- DUNE-UK PI
- DUNE ND Design leader

Costas Andreopoulos
Professor
(with Uni of Liverpool)

- SBND Physics coord.
- SBN Oscillations coord.
- DUNE-UK Physics coord.
- GENIE cospokes

Asher Kaboth
Lecturer
(with Royal Holloway)

- T2K Oscillations coord,
- DUNE GArTPC ND coord.

Federico Nova
Post-Doc

Lukas Koch
Post-Doc

Leading current generation of neutrino LBL experiments [T2K]

- Led 2 of the 3 established T2K oscillation analyses and produced all published results!
- Provided the T2K Off-Axis Near Detector electronics and DAQ system.
- Held several leadership/management positions on T2K.
- RAL (TD) provided the T2K neutrino target system.

Now, taking a **leading role in the design of the next generation of LBL experiments**

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Post-Doc

Lukas Koch
Post-Doc

Recent expansion to support DUNE

Dave Newbold
Professor
(with Uni of Bristol)

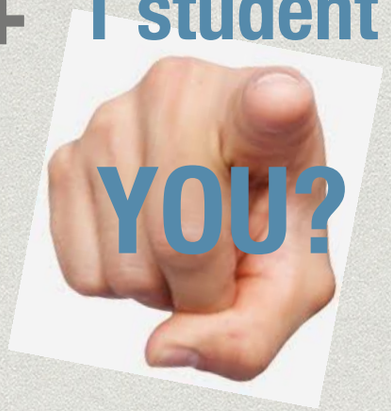
- DUNE DAQ Consortium leader

Antonis Papanestis
Staff Scientist

- DUNE-UK Project Manager

+ several other RAL staff scientists

+ 1 student



If you had any doubt you are joining an **elite research organisation,** look at the calibre and leadership of RAL staff.

The neutrino studentship is joint with the **Uni of Liverpool**

The studentship will be incorporated in **LIV.DAT**

Liverpool Big Data Science Centre for Doctoral Training

A hub for training students in managing, analysing and interpreting large, complex datasets and high rates of data flow.

For more information, see **https://www.liverpool.ac.uk/livdat/**

The University of Liverpool

- Founded in **1881**
- Member of the **Russell Group** of UK research intensive Universities
- Campuses at: Liverpool - London -Suzhou, *China* - Singapore
- 22,000 students in campus
  - 8,000 of which are international
- Offers ~400 courses.
- £600 million investment in teaching, research and facilities

Liverpool Physics Dept.

- **4 research clusters:** Particle Physics, Nuclear Physics, Accelerator Science, Condensed Matter
- Consists of ~ 50 academics, ~ 70 postdocs & fellows, ~20 technical staff and ~70 PhD students

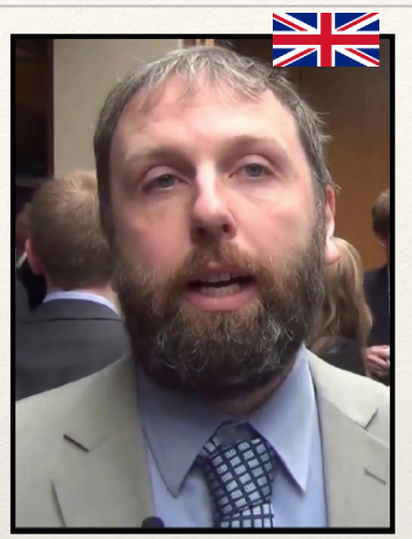
Neutrinos @ Liverpool

Christos Touramanis
Professor
T2K, SBND, (Proto-)DUNE, APA consortium

Costas Andreopoulos
Professor
T2K, SBND, DUNE, VALOR, GENIE

Neil Mc Cauley
Professor
T2K, SK, HK, SNO+

Joachim Rose
Reader
SNO+



Jon Coleman
Reader /
Royal Society Fellow
T2K, Reactor Neutrino Monitoring (VIDARR), Atom interferometry / MAGIS

Kostas Mavrokoridis
Senior Lecturer
T2K, SBND, DUNE, LArTPC R&D (ARIADNE)

- The Liverpool neutrino group has **6 academics**
- Supported by:
  - **6 postdocs**
  - **15 PhD students**

My group at Liverpool

Liverpool HEP group

Liverpool Neutrino group

Very talented group of students and post-docs!

Strong **support structure** within the group!

PI

Post-Docs

Marco Roda

SBN/SBND, **DUNE**, GENIE, POSITRINO

Steve Dennis

SBN/SBND, **DUNE**, T2K GENIE

Chris Barry

POSITRINO, GENIE

PhD students

You?

SBN/SBND, DUNE, ML

?

T2K

Tom Ham

SBN/SBND, **DUNE**

Júlia Tena Vidal

SBND, **DUNE**, GENIE, POSITRINO

Jaggar Henzerling

SBN/SBND

Francis Bench

T2K

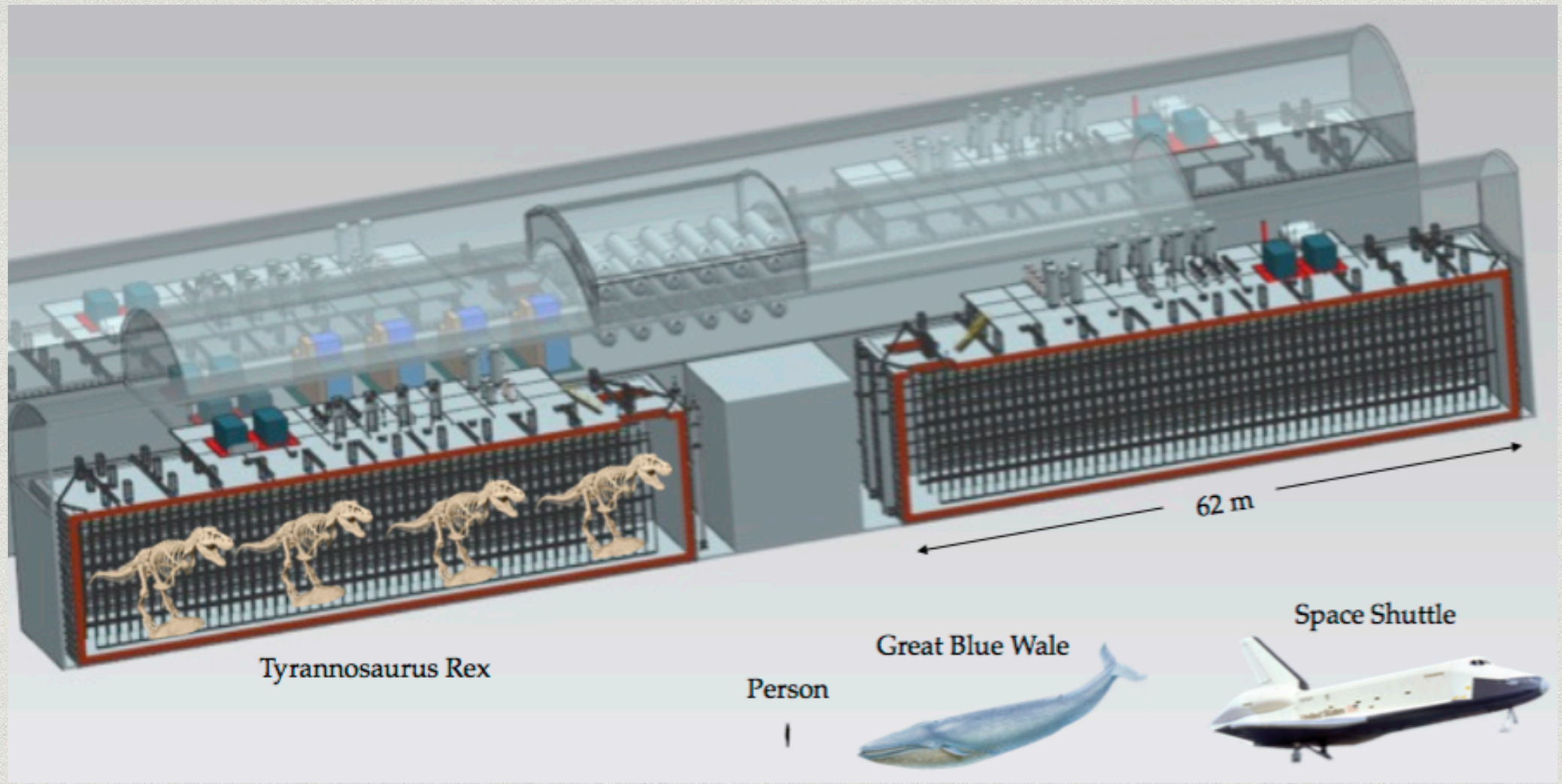
Rhiannon Jones

SBN/SBND, **DUNE**

The research project

Towards multi-ktonne scale LArTPC detectors

LArTPC detectors allow us to **instrument very large volumes** with **mm-scale resolution**!



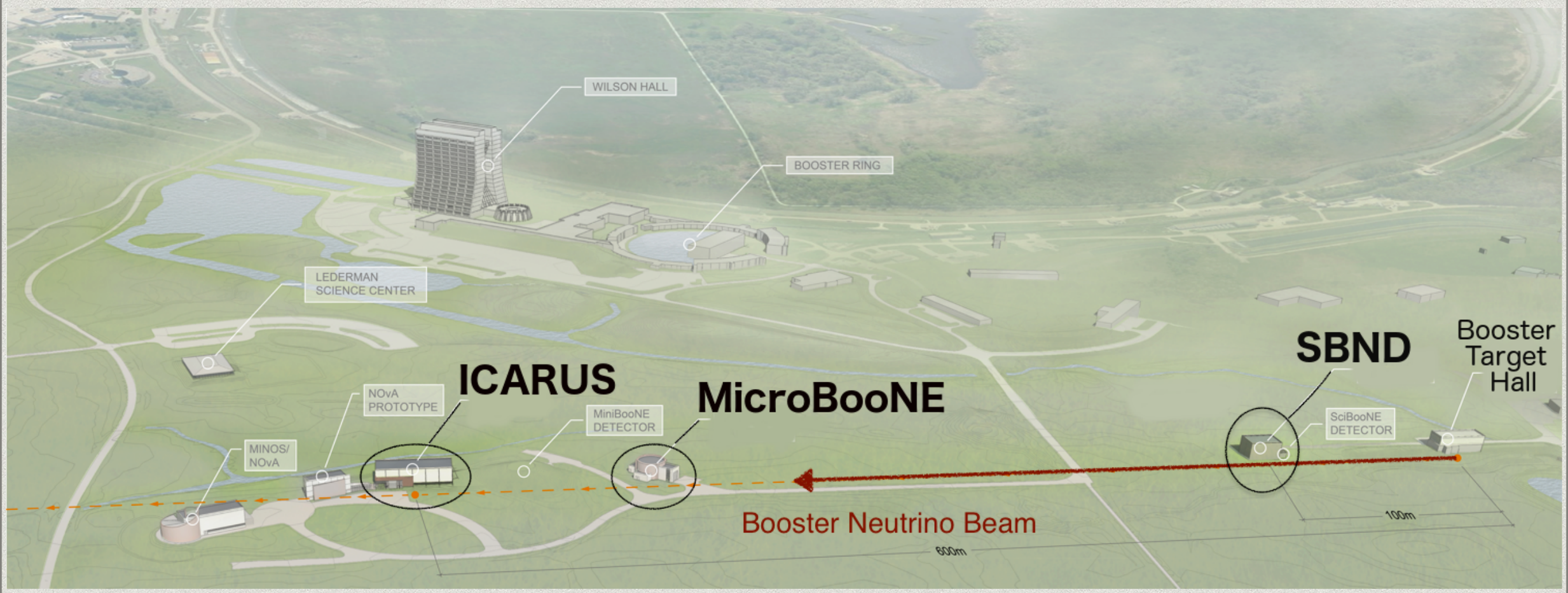
There is very little experience with LArTPCs!

An **extensive prototyping programme is required** to scale the technology to O(10 ktonnes)

Where best to put your prototype detector than in a neutrino beam?

Fermilab SBN programme

- A prototyping programme for DUNE, but also
- A **world-class physics experiment** of its own right!



Detector	**Baseline** (m)	**Active LAr mass** (tonnes)
SBND	110	112
ICARUS	600	476

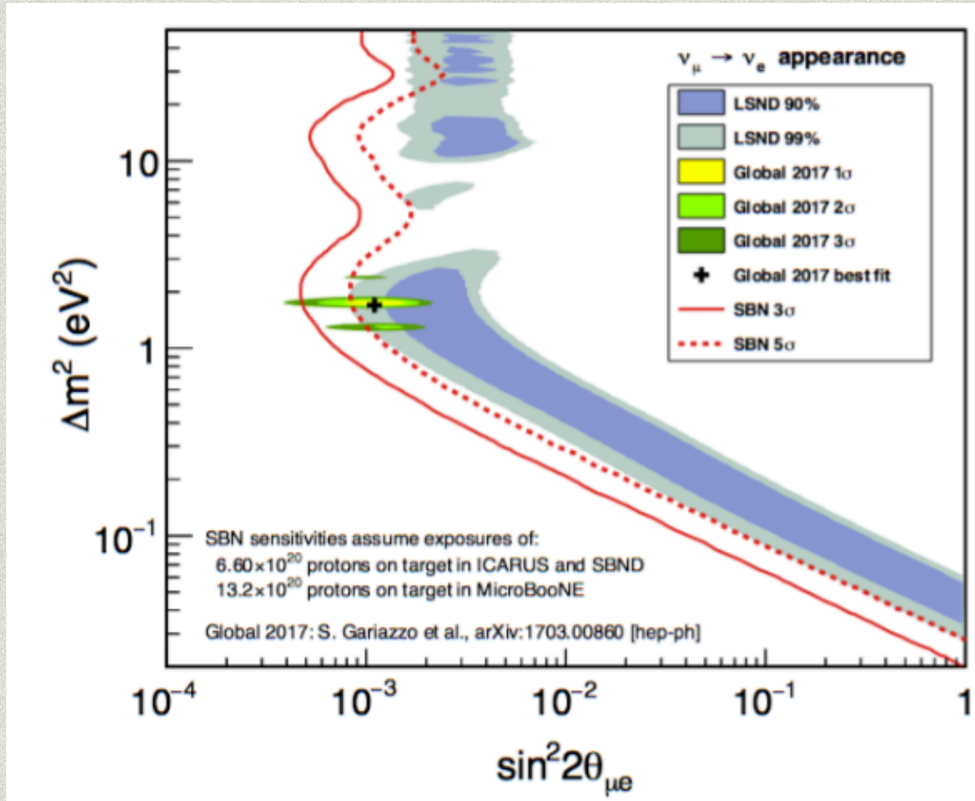
Unique sensitivity is enabled by the use of **multiple LArTPC detectors** at **different baselines**!

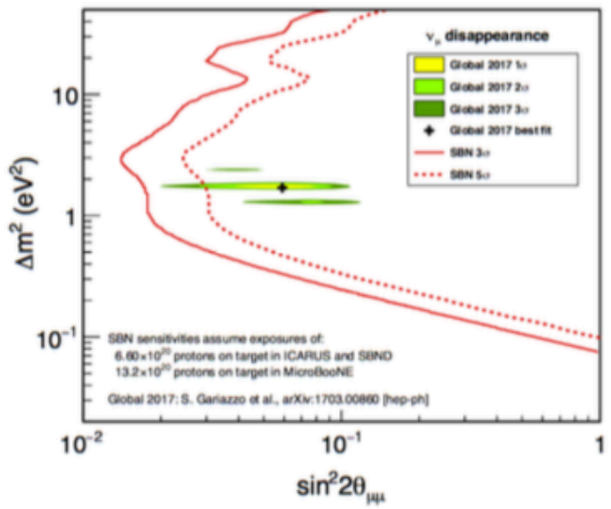
Fermilab SBN physics programme

A definitive (5σ) test of the light sterile neutrino hypothesis

Tensions in the 3-flavour paradigm

- LSND anomaly (~3.8σ)
- MiniBooNE anomaly (~4.7σ)
- Gallium anomaly (~2.7σ)
- Reactor anomaly (~3.0σ)





Complementarity between app. and disapp. (in a simple 3+1 scheme):

$sin^2 2\theta_{\mu e} = 4\ |U_{\mu 4}|^2 |U_{e4}|^2$

$sin^2 2\theta_{\mu\mu} = 4\ |U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2)$

A crucial neutrino-Argon cross-section measurement programme

New physics searches (boosted dark matter etc)

Fermilab SBN: ICARUS

ICARUS assembly well under way!

Part of Liverpool group on top of ICARUS

Data-taking starts this year!

Fermilab SBN: SBND

Still only a building, but

- All funding for completion secured
- Most detector components already at FNAL for assembly

Key Milestones (Directors Review)

S1	TPC ready to move	30-Aug-2019
S2	Ready to fill	15-Jul-2020
S3	Detector filled	28-Feb-2021
S4a	Ready for physics data	31-Mar-2021
S4b	Shielding in place	30-Apr-2021

Physics data in 2 yrs!

Towards fully automated reconstruction

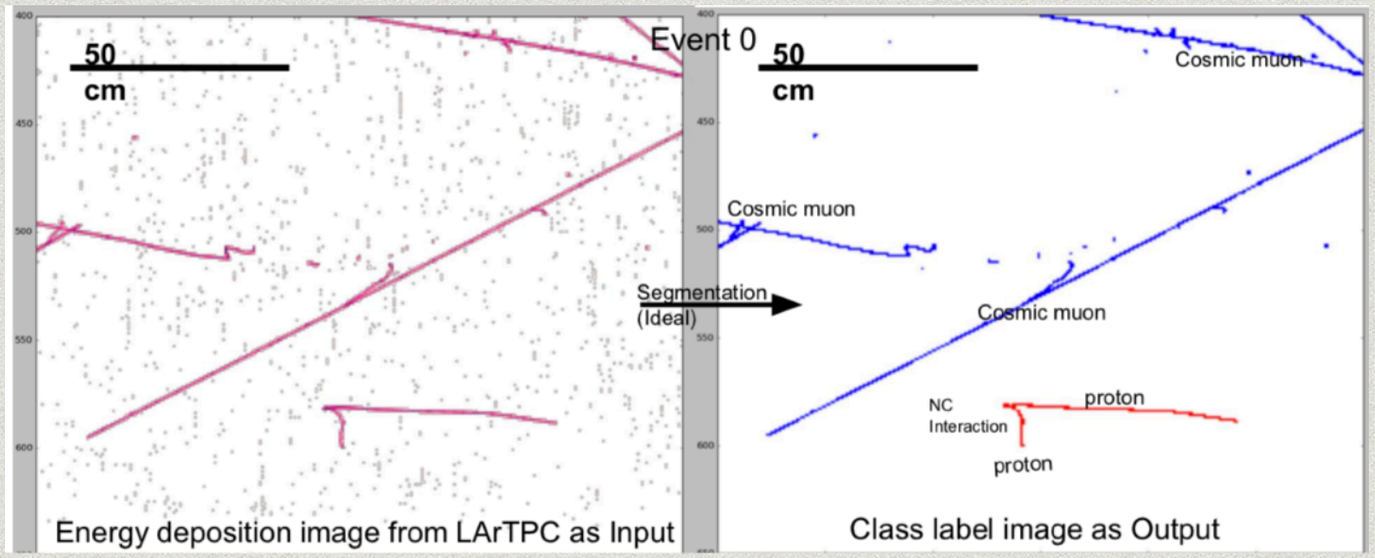
We will be flooded with data, the moment we switch SBND on!

O(100,000) neutrino interactions per month!!

Active work to ensure **analysis readiness / timely exploitation.**

Fully automated reconstruction a challenge

Deep Learning approaches are well suited for LArTPC event reconstruction and identification and will form an important part of the project.



Using semantic segmentation for classification at the level of individual hits (J.Henzerling, Liverpool)

SBN analysis experience with **real neutrino data** will be **instrumental** for DUNE

Integrated SBN/SBND exploitation plan

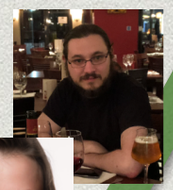
Measurement of characteristics of exclusive final states in SBND

The group is centrally involved in the overall SBN physics effort

CA is

- SBND Physics, and
- Overal SBN Oscillations

co-coordinator



Systematics constraints to enable SBN oscillation sensitivity

Development of Neutrino+Argon MC tunes for DUNE exploitation

VALOR/SBN sterile analysis

led by RAL/Liverpool

(**https://valor.pp.rl.ac.uk**)

GENIE neutrino interaction simulation

led by RAL/Liverpool

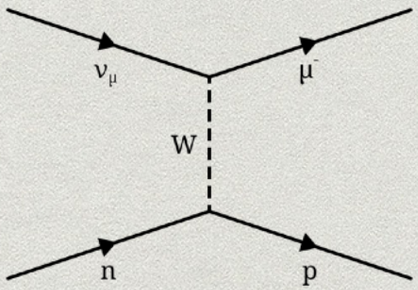
(**http://www.genie-mc.org**)

Potential physics measurement for this studentship

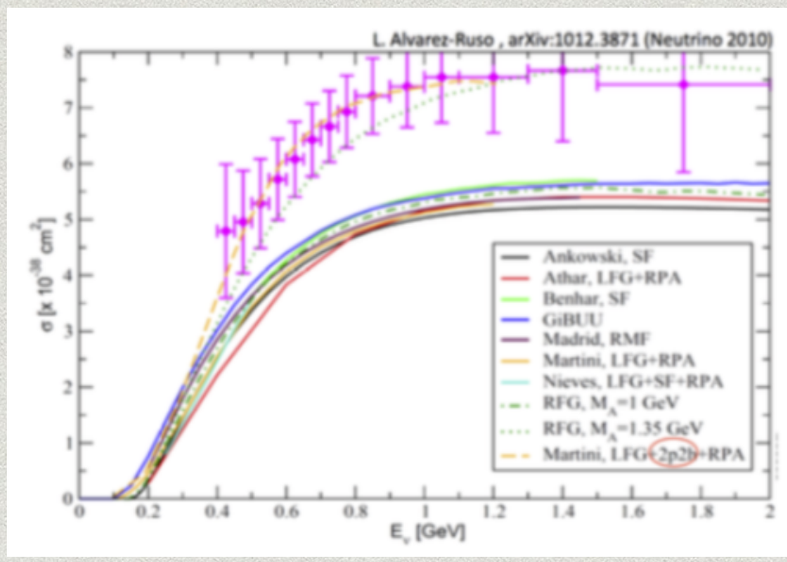
Student will focus on Deep Learning (DL), but we are physicists - not computer scientists.

Performing a physics measurement (using DL) will be the **central** part of your work.

A possible topic



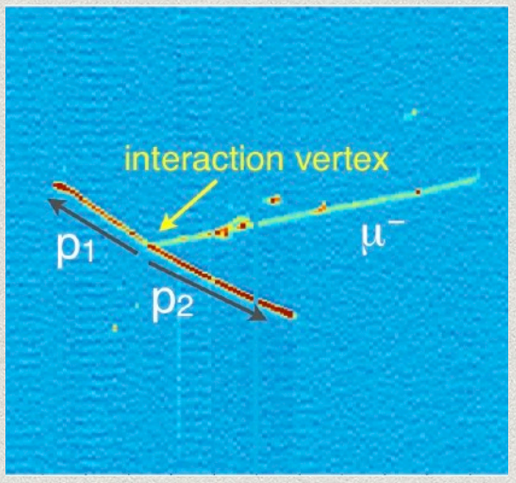
Quasielastic (QE) scattering produces the simplest final state and it is a **golden channel for neutrino oscillation searches**.



Profound disagreement between data and models based on single-nucleon interactions.

Demonstrates **importance of multi-nucleon effects**.

Supported by recent ab-initio calculations.



Proton kinetic energy (MeV)	Proton track length (cm)
20	≈ 0.4
50	≈ 2
100	≈ 8
200	≈ 26

QE-like events with **multiple nucleons** in the final state can shed light on nuclear dynamics.

Need to detect nucleons with KE ~ 20 MeV

Challenging for conventional reconstruction.

Opportunity for a DL approach?

PhD Project

Tom

Júlia

Rhiannon

1. Assemble and commission an awesome detector (wearing hats and all)

PhD Project

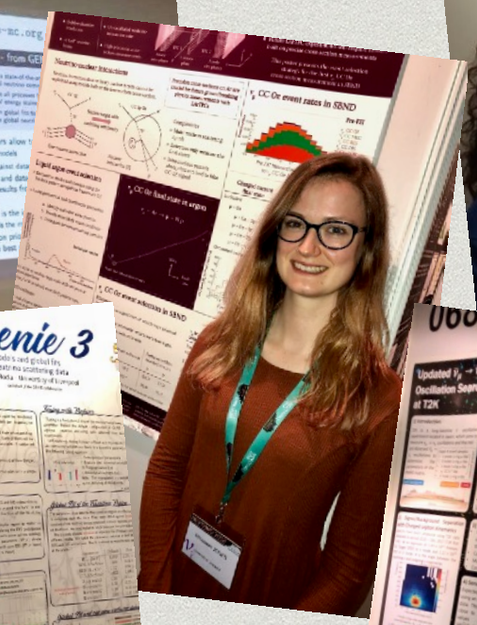
Rhiannon and Júlia

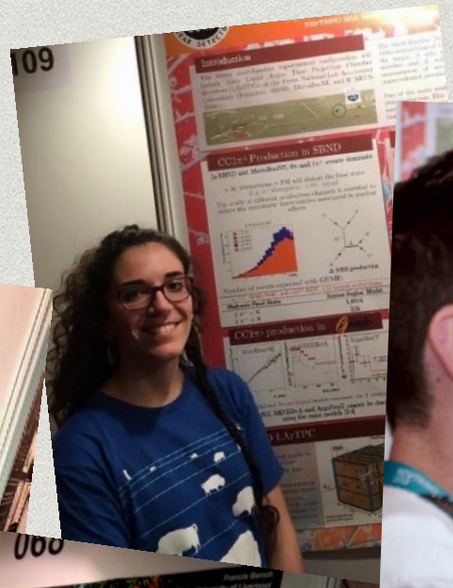
Entire group

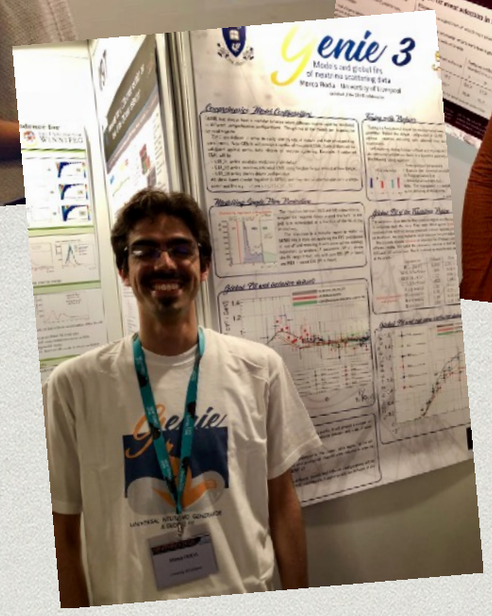
1. Assemble and commission an awesome detector

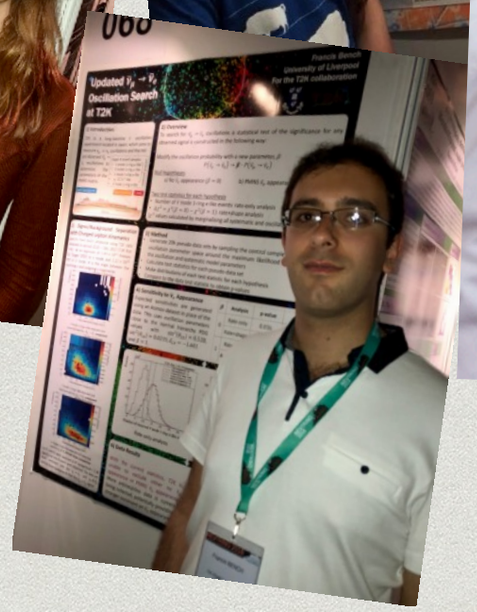
2. Analyse lots of detailed neutrino interaction data using modern ML techniques

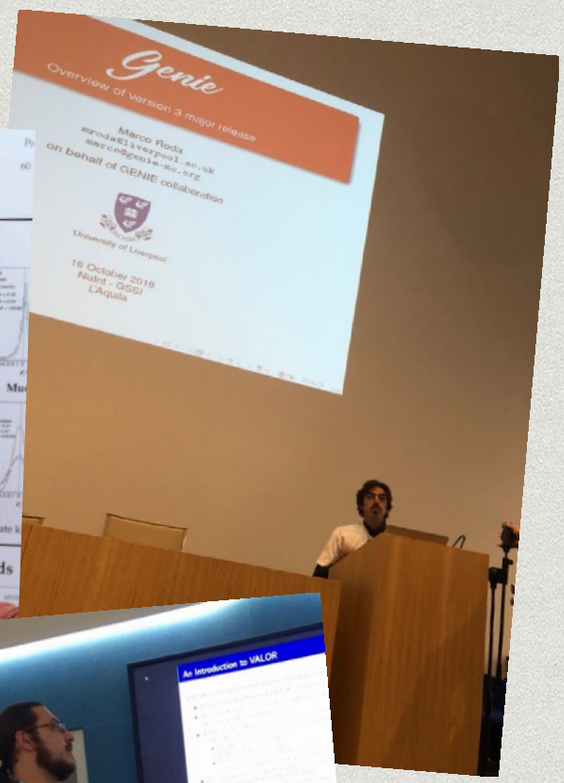
PhD Project

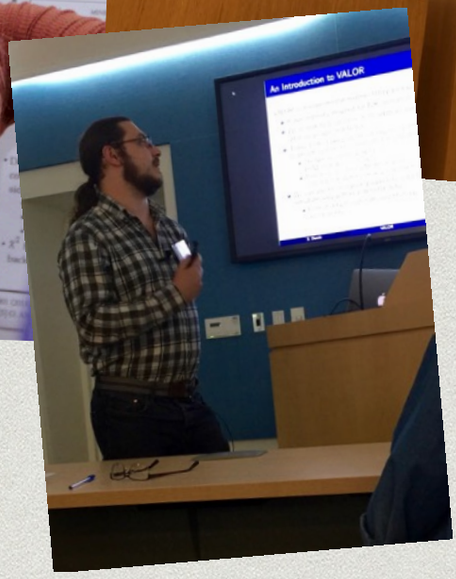












1. Assemble and commission an awesome detector
2. Analyse lots of detailed neutrino interaction data using modern ML techniques
3. Produce leading v+Ar physics measurements, publish and present prolifically

All within the duration of your PhD!

We'll do interesting science, **and enjoy every sec!**

What do we offer?

The opportunity to assemble/commission/understand a wonderful detector, and follow this through to leading physics publications! (within your PhD!)

The opportunity to join **elite research institutions** and **outstanding research teams** with **internationally recognised expertise and leadership**

Outstanding training opportunities (eg via LIV.DAT etc)

An exciting research project, at the heart of the world neutrino programme!

Unparalleled support structure within a vibrant and friendly team!

You can become a super-employable all-around expert: **A future research leader!**

What am I looking for?

Only the very best student, that can raise up to the challenge!

A students with the personal attributes to fit in our close-knit research environment and become a future leader!

I am confident that such stellar students exist within this room.

Are YOU up for the challenge?

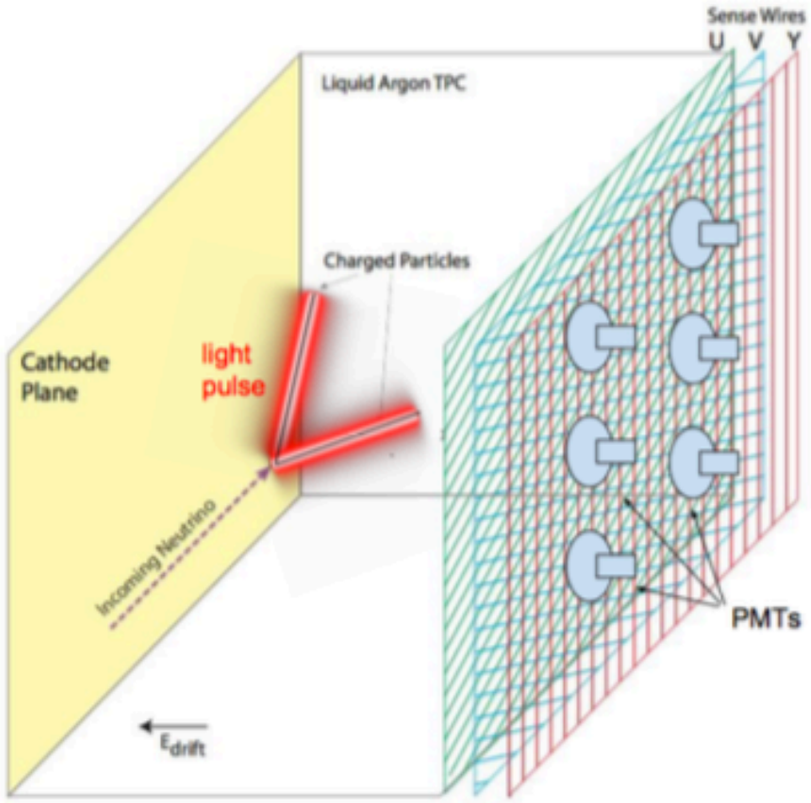
Formal interviews held today.

Glória DSP: 14:35; [**Chris T**: 15:00;] **Adam H**: 15:25; **Charlotte C**: 15:50

If you are not in this list but want to be considered, please come and find me NOW!

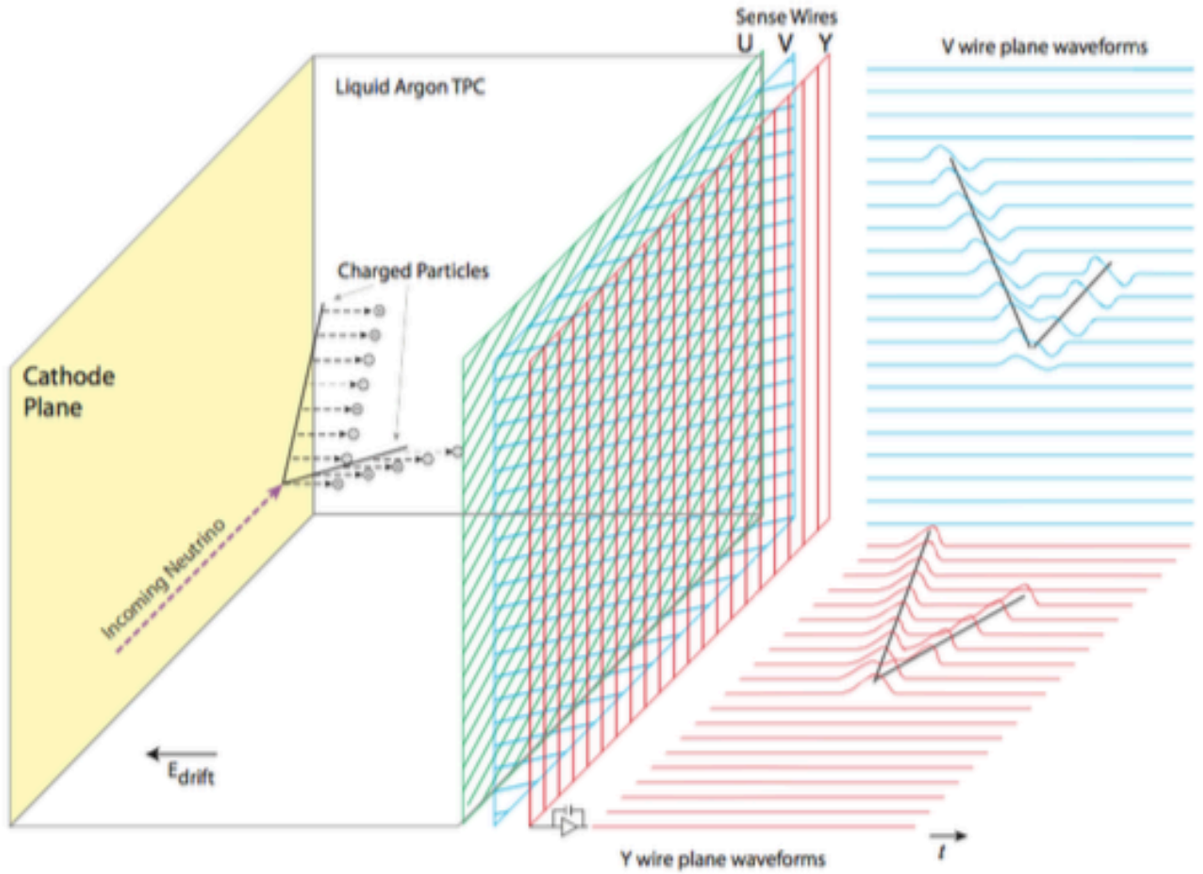
Extra slides

LArTPC detector technology



- Charged particles excite Argon atoms.
- Prompt scintillation light
  - 6 nsec characteristic time constant (fast component)
  - $\approx$ 40k photons/MeV (E=0)
  - emission at $\approx$ 128 nm (VUV)
- Allows determination of t_0

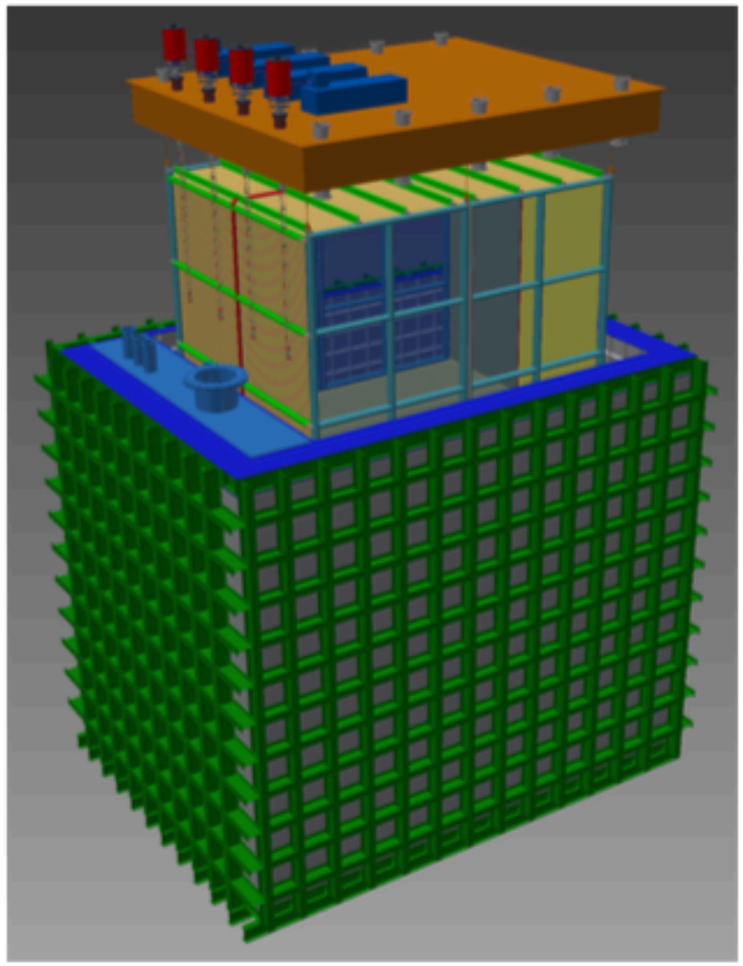
- Charged particles ionize Argon atoms.
- Charge drifts to segmented anode (wire planes)
  - Drift velocity ≈ 1.6 mm/μs at 500 V/cm
  - Max drift time at SBND $\approx$ 1.25 ms
- Projected (2-D) view of ionization tracks by each wire plane. Combination of multiple projected views (from wire planes of different orientations) forms stereoscopic images!



SBND TPC

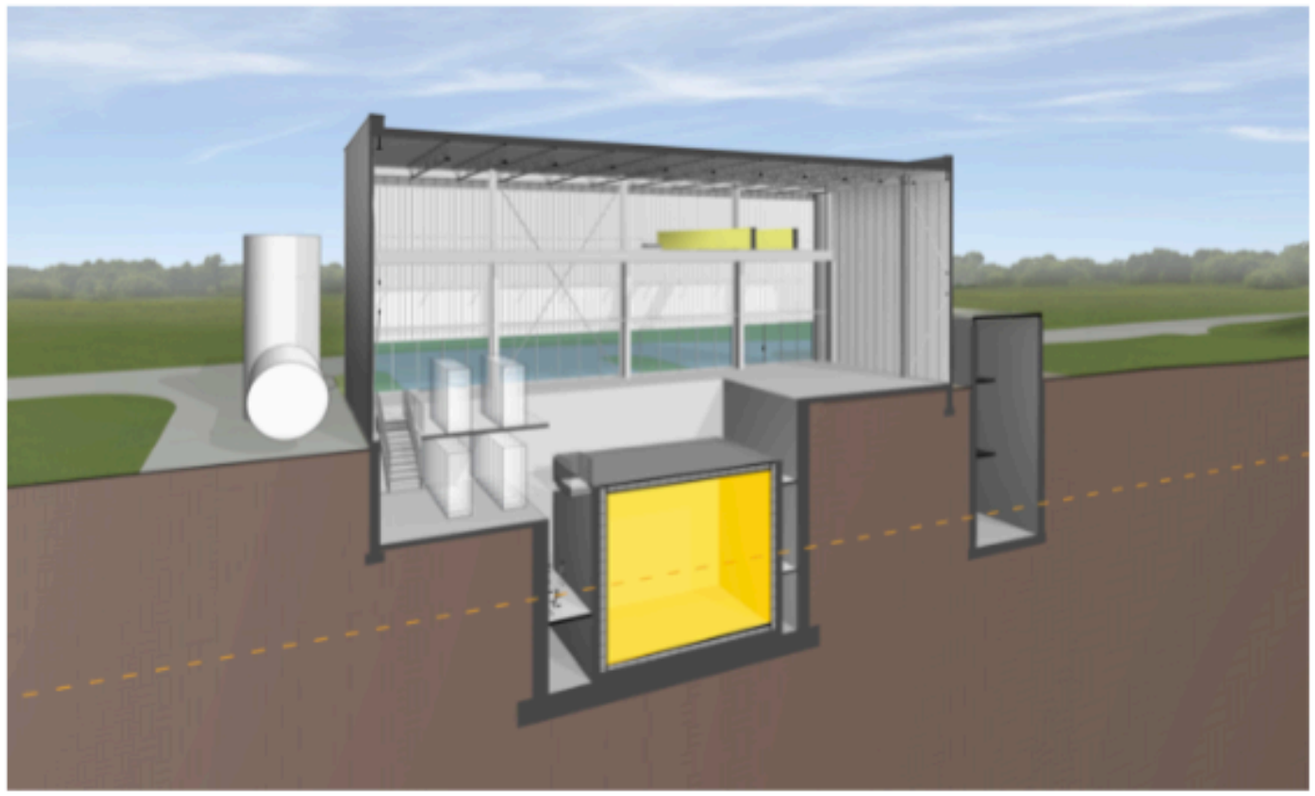
Liquid Argon Time Projection Chamber (LArTPC) detector in membrane cryostat.

A **key prototype for DUNE**. Similar design / construction procedures for many components.



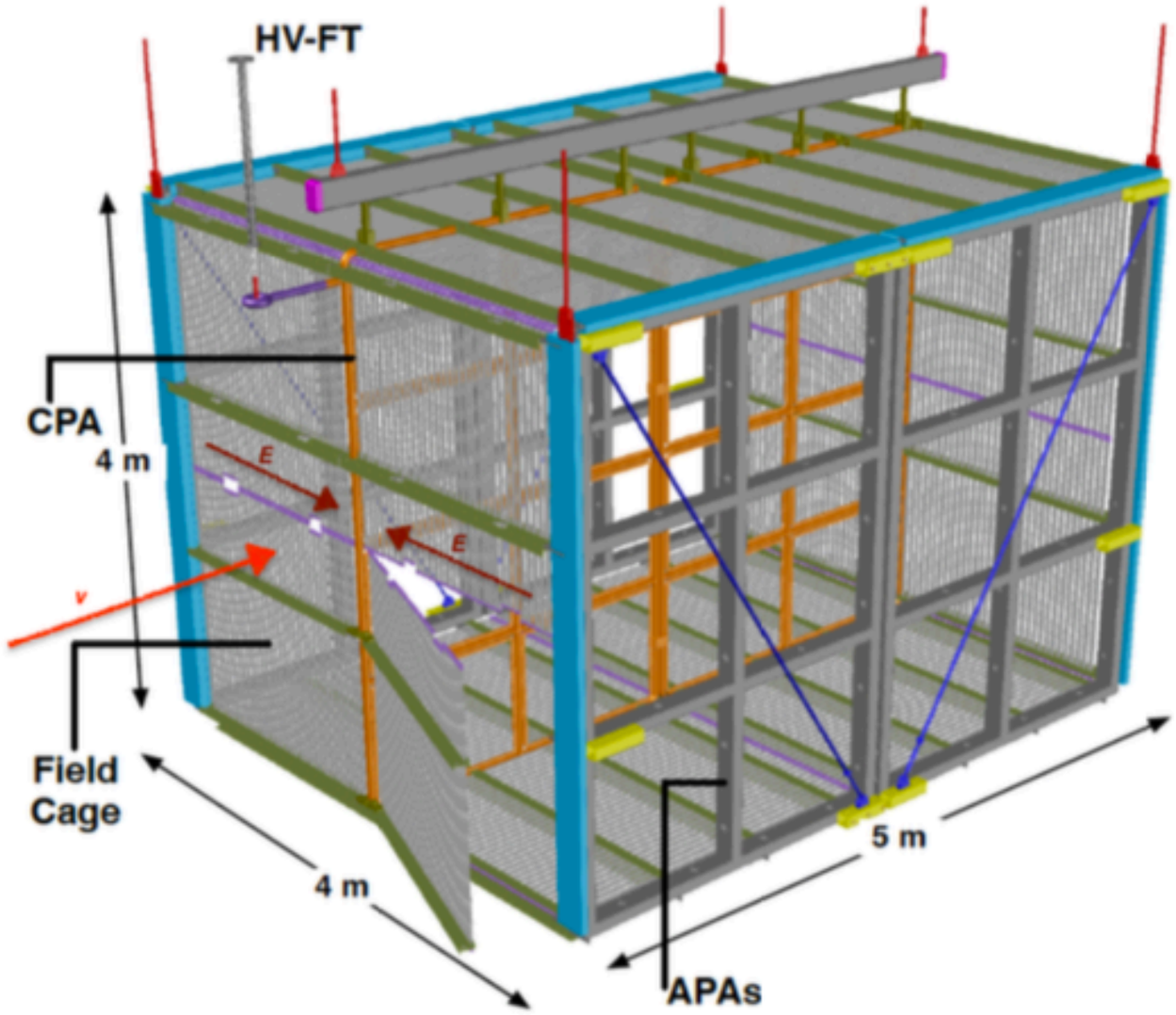
Membrane cryostat:
3rd generation DUNE prototype
with lighter support structure.

- SBND hall at O(100) m from the BNB target.
- 112 (270) tonnes active (total) LAr mass.
- Detector at shallow depth (3m of concrete overburden).
- Cosmic veto around cryostat (94% CR flux coverage).



SBND TPC

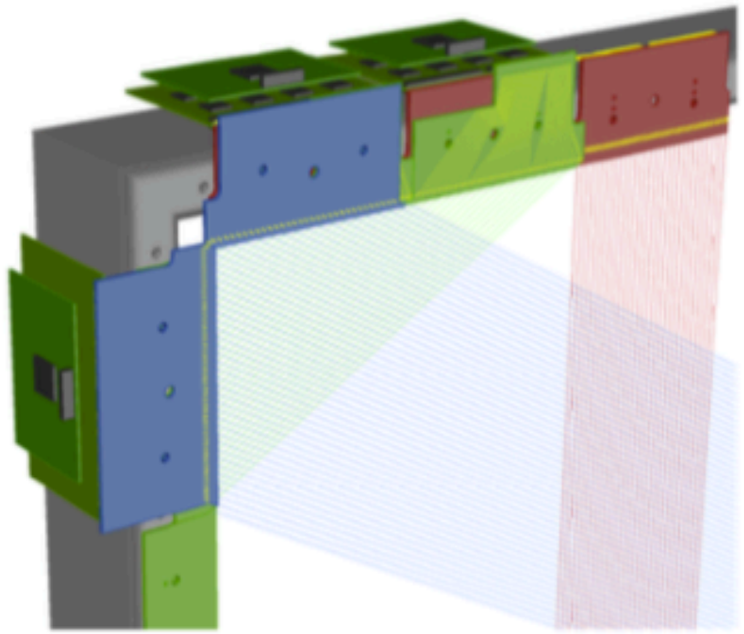
- Active LAr volume: 4m $\times$ 4m $\times$ 5m.
- Cathode Plane Assembly (CPA) in the middle (bias = -100 kV).
- Anode Plane Assemblies (APA) on beam left and right form **two ionization drift volumes**.
- Maximum drift distance: 2 m.
- Drift field $\approx$ 500 V/cm.
- Drift direction perpendicular to the beam direction.
- Charge and light readout.



SBND TPC

Charge readout:

- Two tiled 2.5m-wide Anode Plane Assemblies (APA) on each side of the TPC
- 3 wire planes: Y (vertical) and U/V ($\pm 60^o$).
- 3 mm wire plane spacing.
- 150 μm CuBe wires, 3 mm wire pitch.
- 11,263 channels
- Cold electronics mounted on 2 APA sides.
- S/N for M.I.Ps > 12



Light readout:

- 120 8" Hamamatsu R5912 Cryogenic PMTs
  - 10-stage 10^7 gain, 16% QE (LAr temp), 1 nsec resolution for single p.e.
  - Coated with TPB wavelength shifter
- 24 extra PMTs with no TPB coating
  - Sensitive to prompt Ckv light
- $\sim$15 p.e. per MeV deposited 2 m from PMT plane.