Thoughts on Neutrino Detectors for NuStorm

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Physics Goals

Measure exclusive neutrino cross sections at the 1% level

- Support the long baseline programme (DUNE, HK).
- Measure electron neutrino cross sections
- Measure cross sections with multi particle final states + full kinematics
- Constrain the elements of neutrino-nucleus scattering models

Search for Sterile neutrinos

- Or improve measurements following positive results at Fermilab SBL programme
- Multiple baselines
- Excellent neutrino energy reconstruction

Reminder: Oscillation experiments

The idea is simple: compare the rates at near and far detector

We measure the results of the neutrino interactions, but oscillations affect the neutrinos themselves.

- The spectrum is different at near and far detectors
- Neutrino cross sections are essential to understand the effect on the measurements
- We have to estimate neutrino energy or a proxy for it
  - CCQE
  - Calorimetric

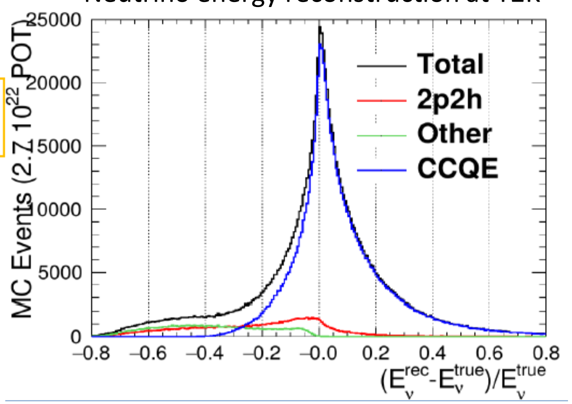
Convolution of cross section and nuclear effects

Near detector

Event Rate: $N(x) = \phi(E_\nu) \times \sigma\,(E_\nu) \times \epsilon(E_\nu) \times P_{\nu_\mu \to \nu_e}$

Far detector

Neutrino energy reconstruction at T2K

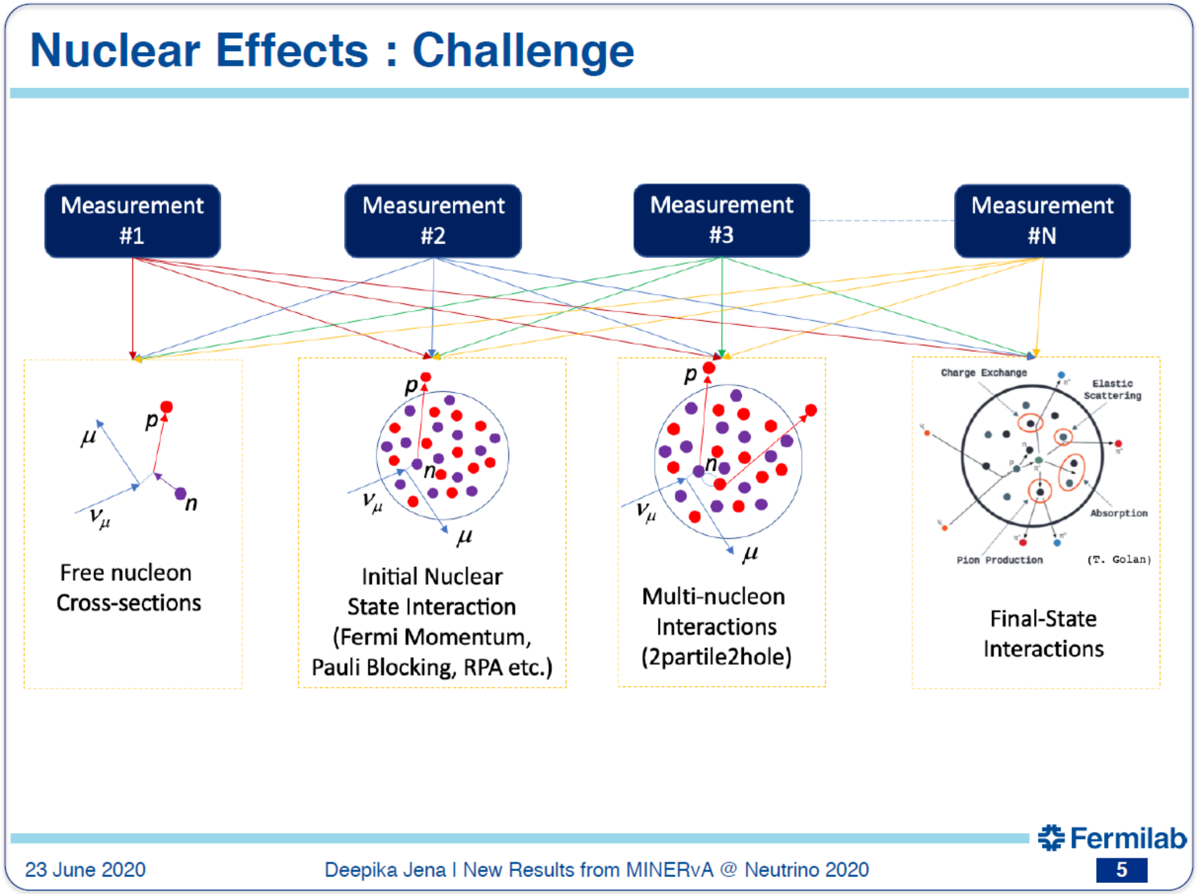


Breaking apart cross sections

Cross section models are combinations of several parts

- Free nucleons
  - CCQE, Resonant, DIS
- Initial states, including state correlations
- Final state interactions

Measurements that can decouple these will help build better models



Detector Requirements

We need to reconstruct the products of the neutrino interactions. Our detector is also our target.

Keep in mind the physics goals and beam composition

Detectors should provide

- Charge Identification - Magnetise
- Momentum Reconstruction – Curvature/Path length
- Particle Identification - muons/electrons/pions/protons/photons
- Reconstruction of multiple particles – most interactions will produce at least 2
  - Requirement for any kind of calorimetric neutrino energy reconstruction
- Detection of protons and neutrons at low threshold – nuclear effects
- Variety of nuclear targets
  - Minimum of Ar and H_2O. Also C (HK and DUNE ND comparisons). Strong case for H & D if possible.

Detector Systems

Meeting all requirements with a single detector looks challenging.

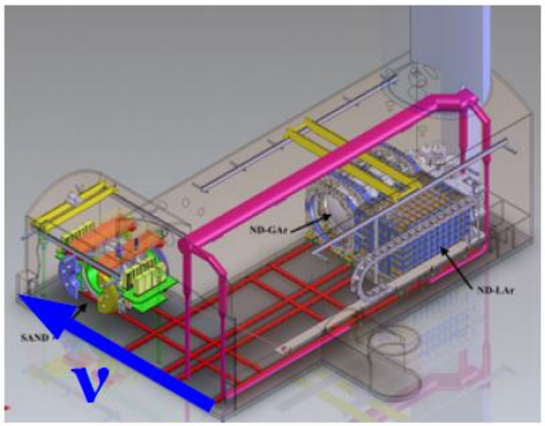
Take inspiration from HK + DUNE ND systems + experience from T2K, Minerva, MiniBooNe, MicroBooNe etc.

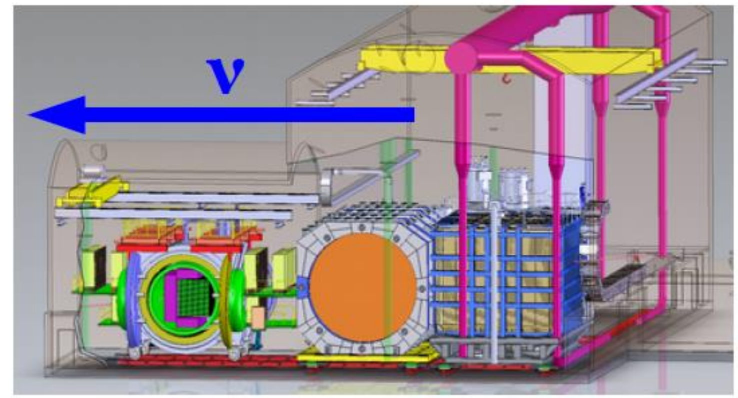
For oscillation measurement multiple detectors with multiple baselines are essential.

General point, I assume beam timing is sufficient to remove cosmic backgrounds, but some minimal overhead, is likely desirable.

Reminder DUNE ND System

DUNE ND Complex

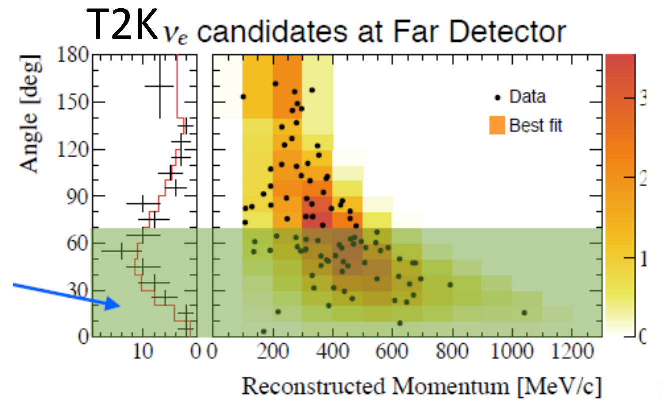




SAND ND-GAr ND-LAr

- DUNE ND complex: multiple complementary systems
  - <u>ND-LAr</u>: modular, pixelated LArTPC
    - Acts as primary target and is most similar to FD (both contain LAr)
  - <u>ND-GAr</u>: high-pressure GArTPC surrounded by ECAL and magnet
    - Constrains nuclear interaction model; muon spectrometer
  - <u>SAND</u>: tracker surrounded by ECAL and magnet
    - On-axis monitor of beam spectrum
- ND-LAr/ND-GAr can move off-axis (DUNE-PRISM)

Reminder HK ND/ND280 Upgrade

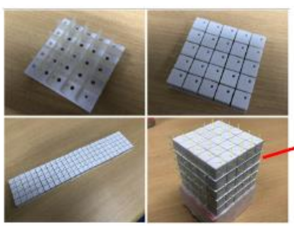


ND280 upgrade plan for T2K

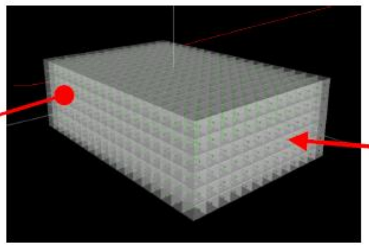
arXiv:1901.03750

There will be talk by Patrick Dunne on July 2nd "Latest Neutrino Oscillation Results from T2K"

- **Large angle acceptance** to constrain neutrino interaction models
- Measurement of **short tracks** to identify non-QE, NC γ etc.



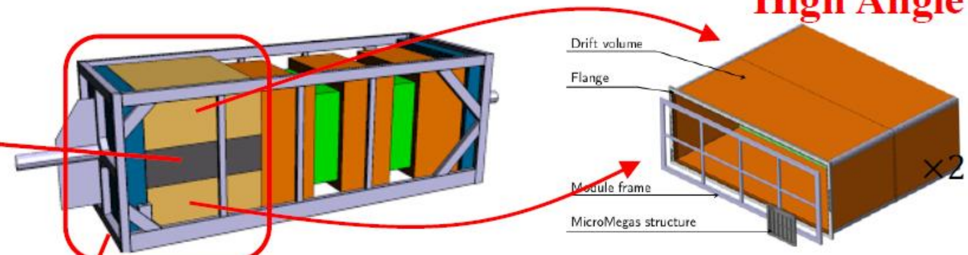
Improve reconstruction of hadron (short) tracks

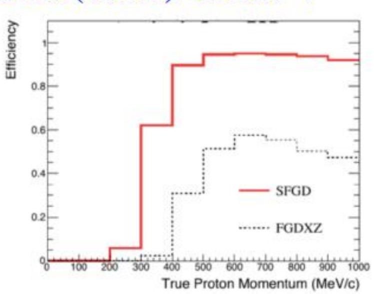


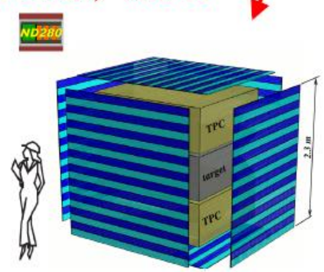
SuperFGD

(scintillator target tracker)
~2m^3, ~2M cubes, ~60k ch

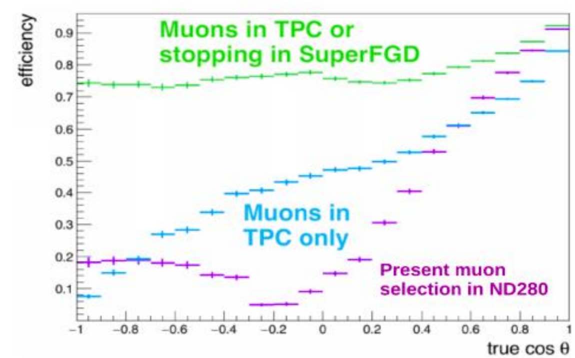
High Angle TPC







TOF



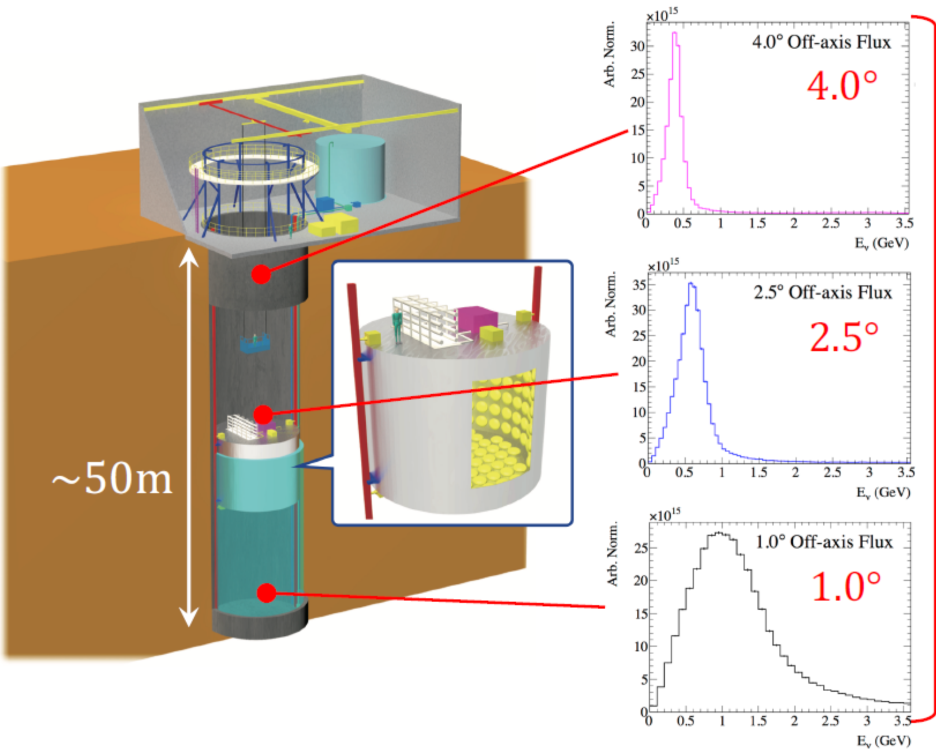
Hyper-K is planning to use ND280 after T2K has finished

International contributions for further upgrades are welcome

Reminder HK intermediate detector

Intermediate water Cherenkov detector (IWCD)

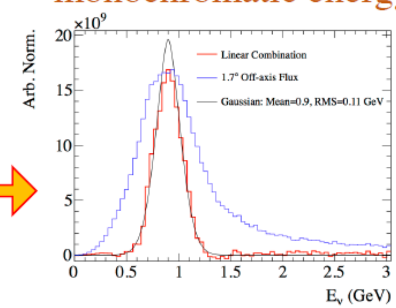
- 1kton scale water Cherenkov detector at ~1km baseline
- Detector can vertically move ⇒ measurement at different off-axis angles



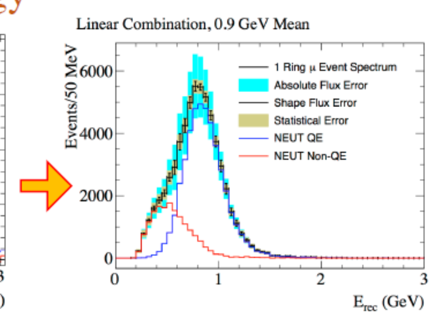
Physics target

- ν-int. measurement by off-axis scanning
- ν_e cross section (3-5% for $\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\nu_e)/\sigma(\nu_\mu)$)
- NC and intrinsic ν_e BG measurement (3-4%)
- Neutron multiplicity with Gd loading

Linear sum to make monochromatic energy



Reconstruction

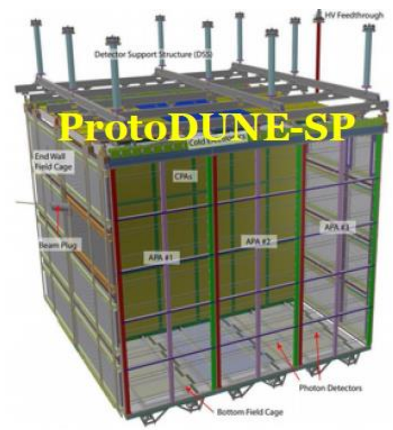


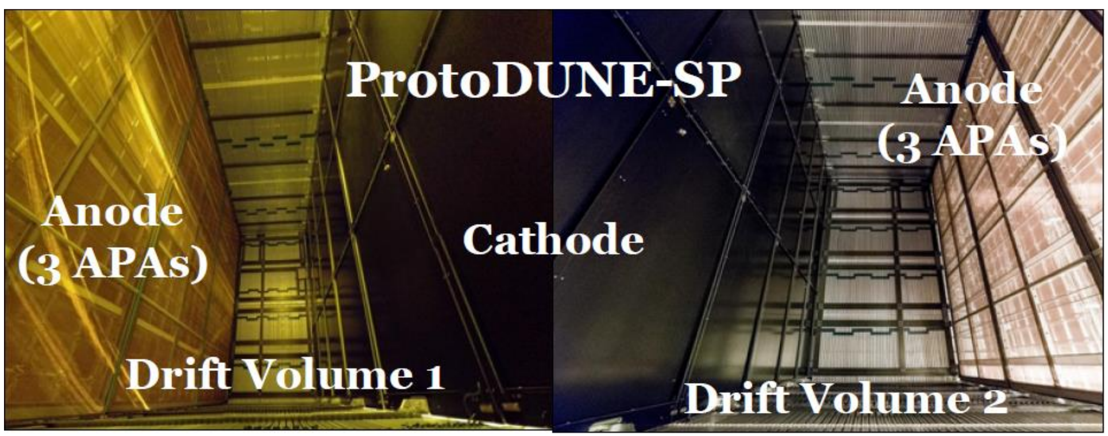
Detector 1 – Liquid Argon TPC

Two concepts to consider, single phase and dual phase

Single Phase – wire detection – think ProtoDune SP, MicroBooNe, SBND, DUNE

- Ar target
- Excellent track reconstruction
- Should be a proven technology in time for nuStorm
- No magnetic field, relatively high proton threshold, neutron detection?



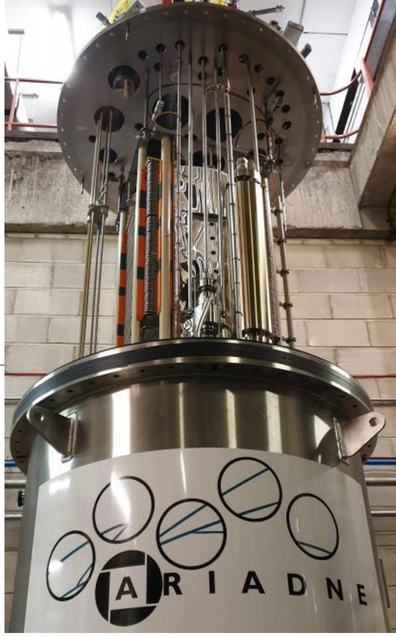


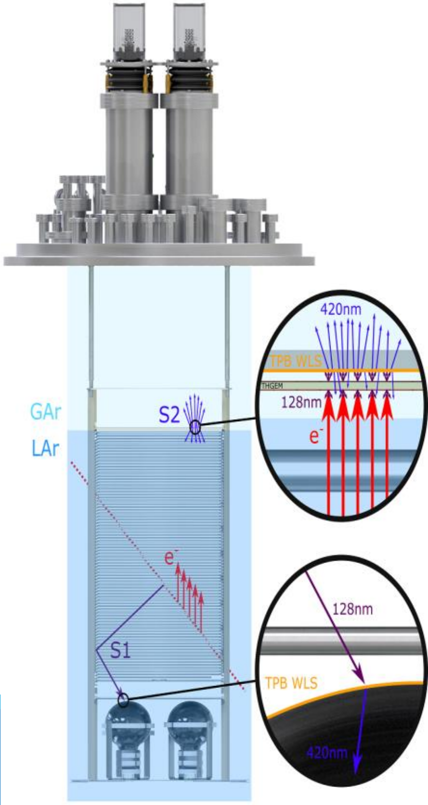
Dual Phase Options

Multiple read out options for dual phase, optical readout is one interesting option

Ariadne:

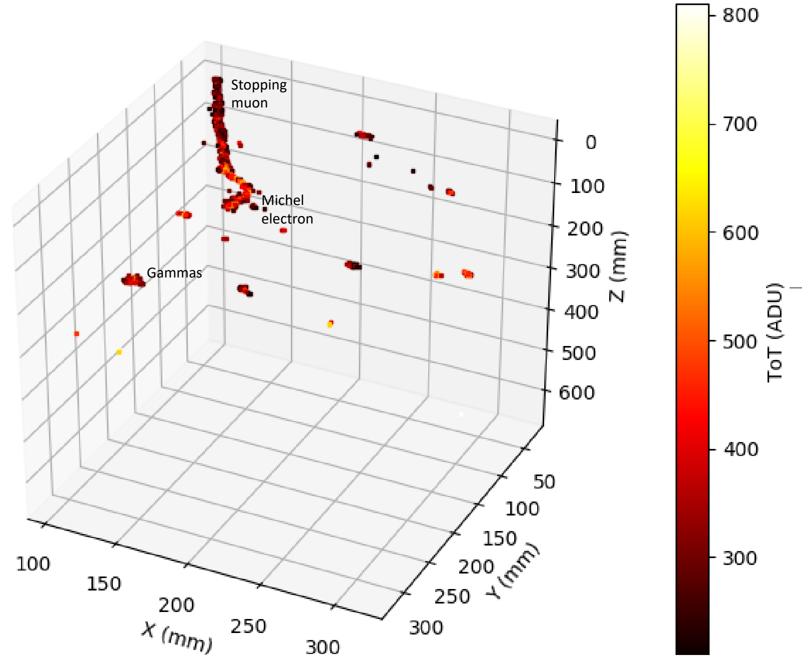
- Fast optical imaging
- High resolution (~mm pixels) Low threshold (~100 keV)
- Small number of channels compared to wires
- Use image intensifiers and cameras to measure secondary scintillation light from THGEM holes
  - Use TPX3Cam fast cameras for readout
    - Accurate calorimetry
    - Accurate timing (1.6 ns) for full 3D reconstruction
    - Zero suppressed readout



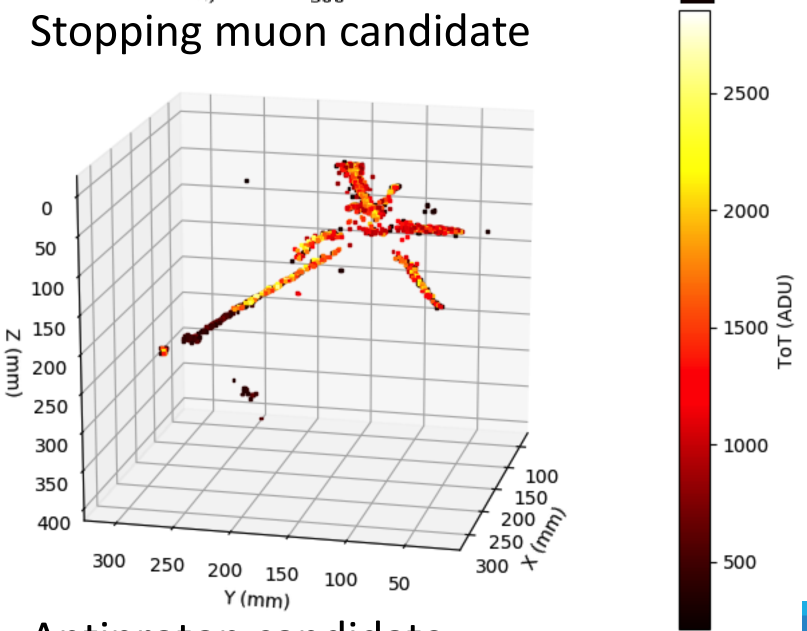


Gallery and video of Cosmics interacting in LAr

THGEM field 29kV/cm
Resolution 1.1mm/pixel

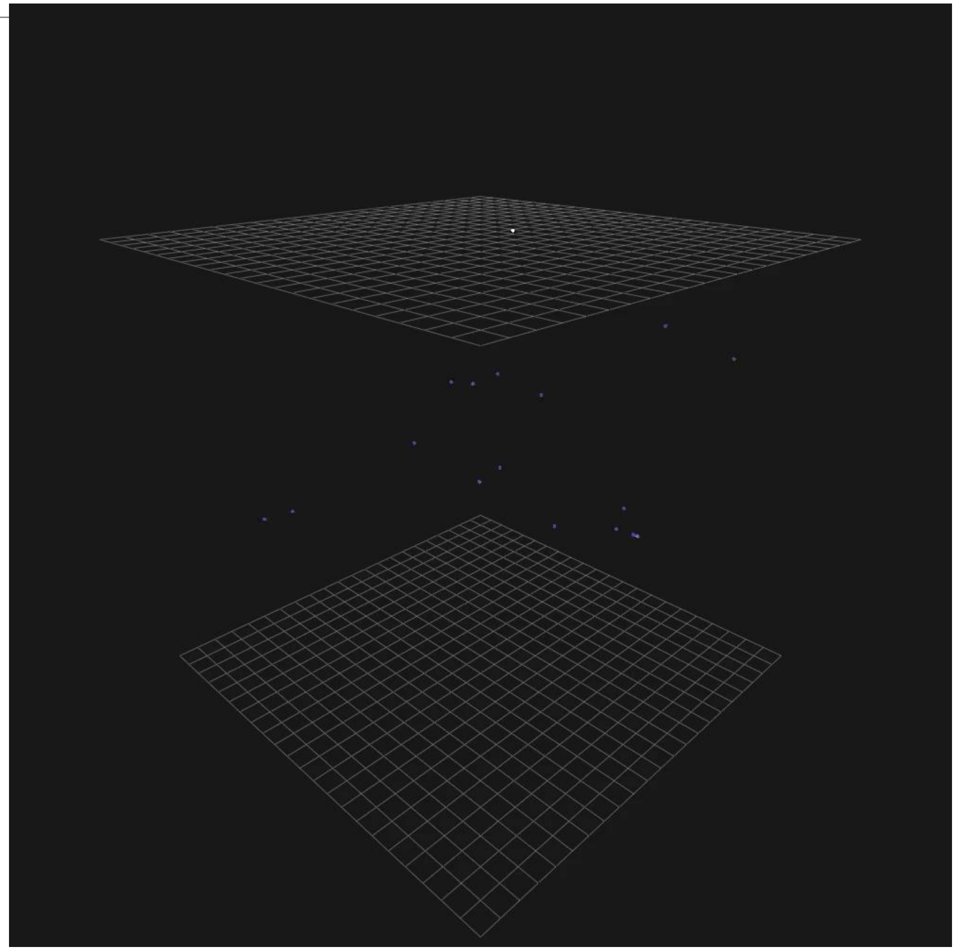


Stopping muon candidate



Antiproton candidate

Continuous streaming, 10 msec slice



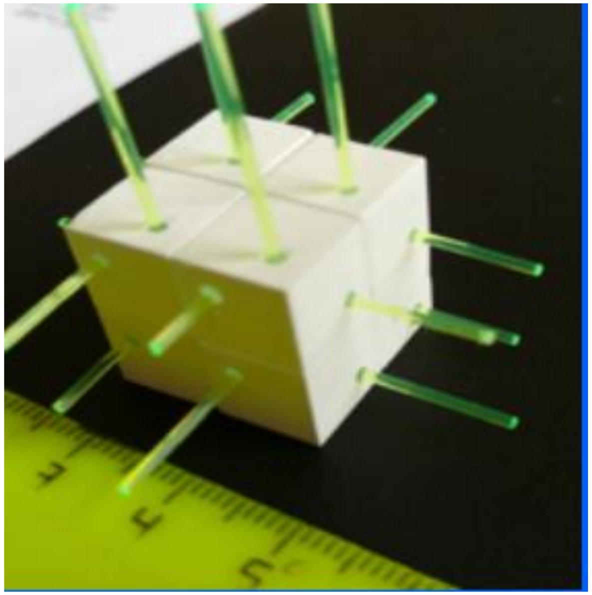
Detector 2 ND280UP/ Sand inspired

Tracking detectors have led current cross section measurement programmes and can continue to do so in the liquid argon era.

- Especially for alternative nuclei.

Super FGD style detectors are currently leading way here.

- Scintillating cubes read out by wavelength shifting fibres.
- C target. Can investigate using hollow cubes filled with water and WBLS for water target.
  - Alternatively use water layers
  - WAGASCI concept
  - Would desire a fully plastic scintillator region as well.
- Good proton detection and some neutron detection as well

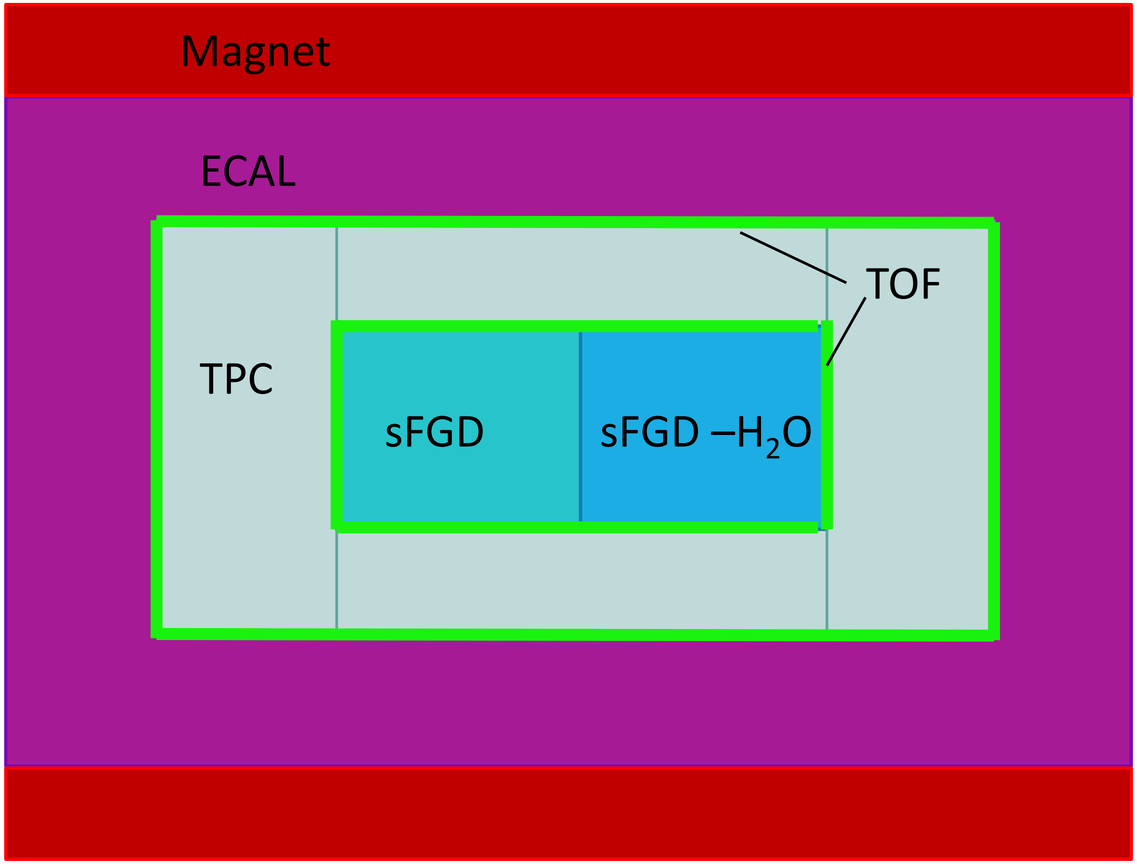


Fitting this into the rest of the detector

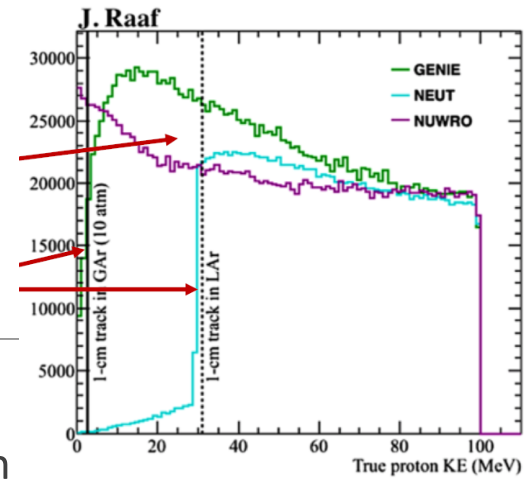
Surround the sFGD with TPC

- Lack of high angle tracks in ND280 has been a major issue
  - Need to extrapolate models to unmeasured parts of phase space and match far detector acceptance
  - Major part of ND280 upgrade
- TPC will have excellent momentum resolution for charged tracks and excellent PID (with some exceptions)
- Surround this with ECAL
  - Similar to but more sophisticated than ND280
  - Gamma catcher at front (no lead) – Detector low energy (c. 50 MeV) photons
  - HCAL at rear- (thicker lead or iron) pions to shower to improve PID
  - Overall can catch everything that leaves the interaction and patch PID inefficiencies in TPC
- Time of Flight
  - Could be part of electronics for sFGD and ECAL or dedicated detector.
  - Sense of tracks must be known to reduce backgrounds
  - Further PID
- Magnet to surround entire detector
  - Yoke could form part of HCAL, but must be designed in
  - Momentum in TPC and track sign

Cartoon of such a detector

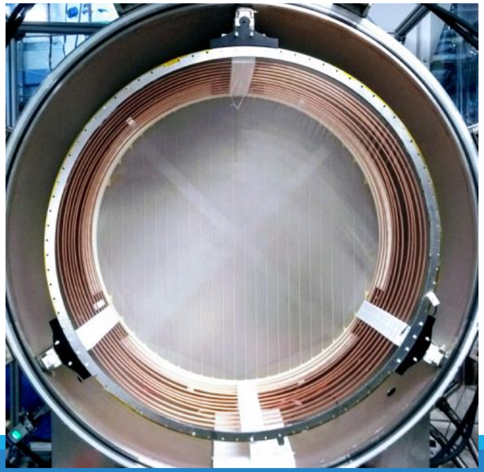


Extra Options



HPTPC

- Similar to detector 2 but replace sFGD and TPC with a high pressure TPC
- Third detector option for DUNE
- Advantage of lower proton threshold
  - Allows improved measurements of various nuclear effects
- Fewer pile up concerns than other detectors
- Gas mixture changes allow measurement on different nuclei
  - Oxygen may be a problem
  - Theoretical opportunity for H and D measurements.
    - Additional safety factors to overcome
- Current research on such detectors is active in the UK



Extra Options

Water Cherenkov

- Well understood technology – provides a water taget

- Better matched to energies slightly lower than nustorm
- Issues with amount of overburden.
- Muon momentum reconstruction is problematic
  - Need to range out in detector, but such a large detector will have pile up and overburden problems

Extra Options

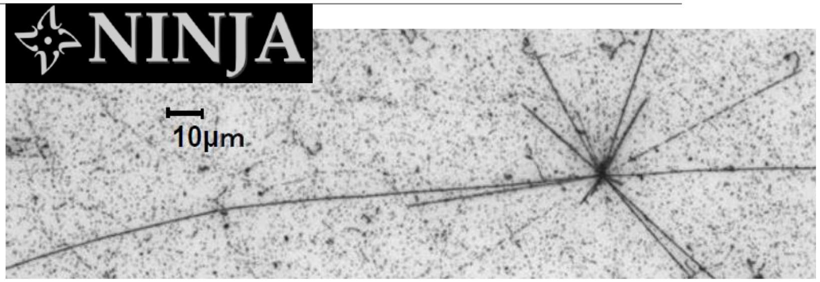
Emulsion detectors

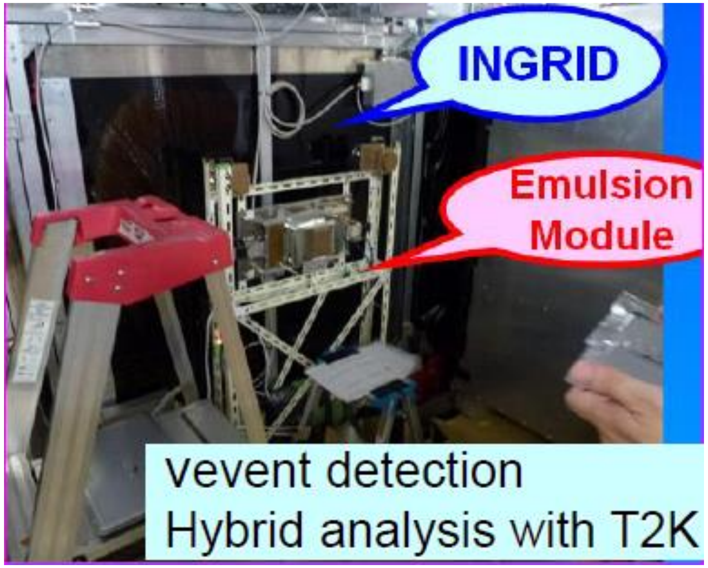
Very fine scale tracking

- Have to backup emulsion with additional detectors to find vertex
- Need to photograph and scan emulsion
  - Speed of this process has been increasing

Potentially the cleanest way to detect ν_τ if this become an important physics goal

Most recent example is Ninja at JPARC





Extra Options

Magnetised Iron Spectrometer

- Most likely to act a companion to another technology to provide muon momentum reconstruction
  - Emulsion, Water Cherenkov
- Does not provide 4π measurement

Baby MIND at JPARC is a prime example

- Spectrometer for WAGASCI and Ninja

Baby Mind @ JPARC

Oscillation Detection

For an idealised oscillation experiment you would prefer the same target in near and far detectors

- Not achieved in LarTPC and tracker plan

Moveable detectors are part of HK and DUNE ND plans

- Use off axis angle to change the neutrino spectrum and improve physics extraction through the extra controls.

For oscillations the same idea can be used to control L

- For example imagine putting one of the detectors in rail track inside a tunnel.
- Excellent cancelation of systematics for high precision sterile neutrino experiment.

Summary

I've discussed my personal thoughts on possible detectors for nustorm

- Detector choices will have been missed or glossed over.

Extraction of the full potential of the beam will require multiple detectors

We should aim to collect detailed cross section data on at least Ar and O

A serious consideration of H and D targets should be made to get to bare nucleon cross sections

A Liquid Argon TPC and an improved magnetised tracker are two clear detector choices that can be made.

Additional detector technologies are available and should also be pursed