Precise Measurement of Neutrino Interactions & Oscillation Parameters and Long-baseline Neutrino Experiments

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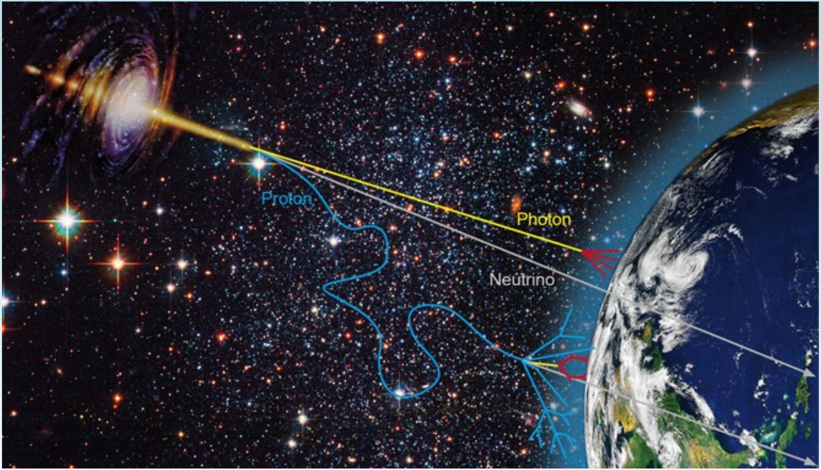
19 January 2021
Particle Physics Seminar at BNL

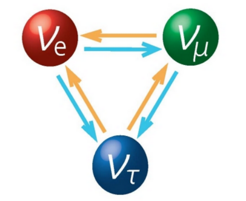
Introduction:

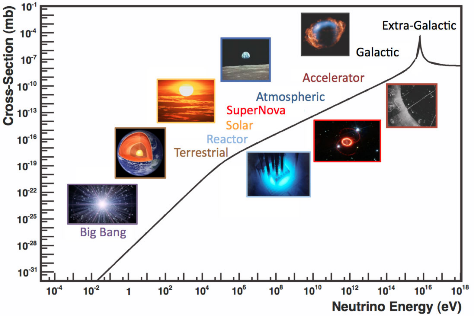


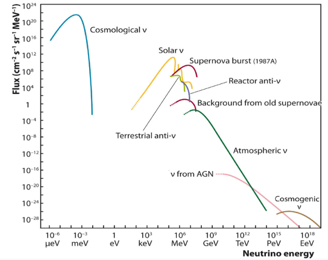
- Neutrinos: the second most abundant particle in the universe.
- Least Interactive, hence most directional w.r.t. its source
- Great source of information, if tapped rightly

Yet least understood wrt photon !!

- Very weakly interacting nature.
- Oscillates into Three Active flavors
- Identified from leptons on interaction.







- Natural and Artificial Sources available over a wide energy range.

Neutrino Oscillation:

- Oscillation described by the PMNS matrix:

$$U_{3\times3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric + accelerator disapp | SBL reactor + accelerator app | solar + KamLAND

- Look for the survival probability of the initial flavor, and the disapperance probability.
- To observe $P_{\mu\mu}$,$P_{\mu e}$,P_{ee}, and so on to measure the different parameters.
- Accelerator and Reactor experiments have been doing significant progress. (Solar/Atmospheric contributed too.) Most parameters determined
- T2K, Super-K, SNO, Nova, Daya-Bay, Reno, Double-Chooz are few such experiments, and many more contribute too.

Where we stand now *Globally*...

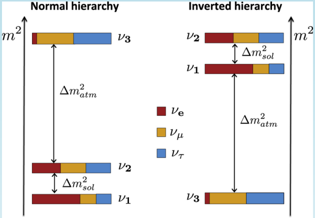
de Salas et al, arXiv:2006.11237

parameter	best fit $\pm 1\sigma$	3σ range	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	6.94–8.14	2.7%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	$2.56^{+0.03}_{-0.04}$	2.46–2.65	1.2%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	2.46 ± 0.03	2.37–2.55	
$\sin^2\theta_{12}$ $/10^{-1}$	3.18 ± 0.16	2.71–3.70	5.2%
$\sin^2\theta_{23}$ $/10^{-1}$ (NO)	$5.66^{+0.16}_{-0.22}$	4.41–6.09	4.9%
$\sin^2\theta_{23}$ $/10^{-1}$ (IO)	$5.66^{+0.18}_{-0.23}$	4.46–6.09	4.8%
$\sin^2\theta_{13}$ $/10^{-2}$ (NO)	$2.225^{+0.055}_{-0.078}$	2.015–2.417	3.0%
$\sin^2\theta_{13}$ $/10^{-2}$ (IO)	$2.250^{+0.056}_{-0.076}$	2.039–2.441	

Courtesy: referred to presentation at the ICHEP2020.

Still to look for...

(in 3-active-flavor scenario)



- Delta CP and ordering of MH are the most important questions still waiting to be answered.
- Neutrino Experiments providing intense beam of neutrinos and detecting them before and after flavor oscillations are the only option for such rigorous measurements.
- **Improved Detection Strategies** and **Signal Selection techniques** are the crucial cornerstones in such neutrino experiments

Approx. Outline for today:

- § To highlight the importance and methods of signal selections in measuring neutrino interactions, and oscillations, referring examples: T2K, INO.
    - Role of the detectors
    - Role of variables, cuts, methods in the analysis
- § To cite a quick overview of the DUNE detectors

Results are not the focus of this presentation, but will be referred to, as/when needed.

The "Assembled Detector" Strategy:

§ Moving to the generation: more of different types of detectors taking data in sync, rather than single detectors, even in *neutrino experiments*.

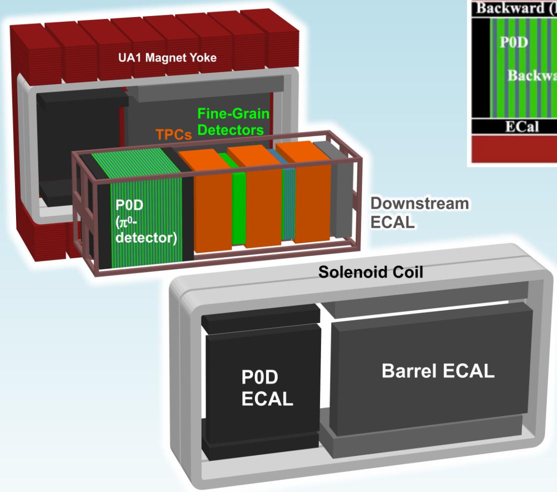
§ Better utilisation of resources, realisable because of intense neutrino beams available

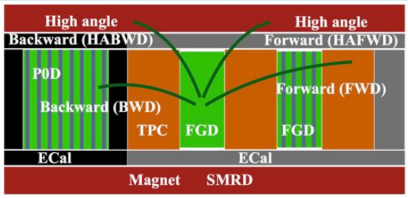
§ Particle identification abilities improve, given different detector types ⇒ better signal identification

§ Better kinematics measurement, applying appropriate vetos and constraints

- Target, Tracker, Calorimeter are the primary components
- Additional veto-detectors to reduce background.
- Particle ID from dE/dx measurements must distinguish protons and, muons & pions.
- Magnetic field for Charge identification $(\mu^+/\mu^-, \pi^+/\pi^-)$

For example the T2K ND280 detector: off axis





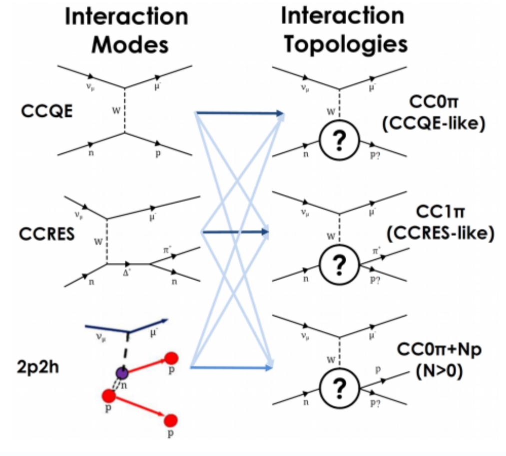
- 2 Fine Grained Detectors sandwiched in the 3 TPCs form the primary tracker. FGD1: CH, FGD2: CH+water
- Surrounding ECAL serves as Calorimeter and tracker, recording the em showers
- Magnetic field of 0.3 T provide for CID

Water target in P0D

In upgrade: finer granularity detectors

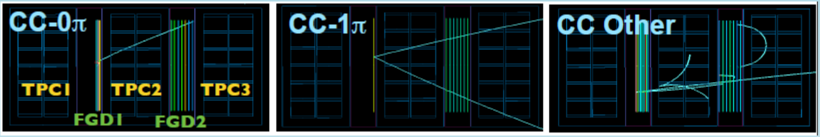
The Topology Reminder:

- Nuclear & Detector effects obscure true interaction mode of the neutrinos
- Sample w.r.t visible outgoing hadron (π) content (PIDs and CIDs are hence very crucial)



- So, event samples classified as
  - $\nu - 0\pi$
  - $\nu - 1\pi$
  - $\nu - others$
  - Single-track
  - Multi-track

  and so on...

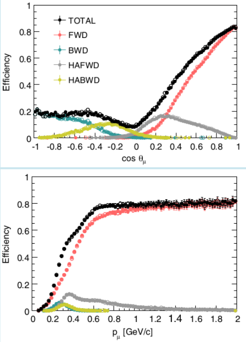


- FGDs: scintillator bars, designed s.t.
  - capable of detecting almost all charged particles produced at the interaction vertex with good efficiency to determine the type of interaction.
  - thin enough that charged leptons will penetrate into the TPCs where their momenta and flavor can be determined
  - electronics must provide for acceptance of late hits such as those due to Michel electrons.
  - Particle ID from dE/dx measurements must distinguish protons from muons and pions.
- TPC PID likelihood discriminates pions and muons
- ECAL acts as tracker calorimeter, also provides for detailed reconstruction of em shower, optimised for periphery, downstream etc.

Courtesy: 10.1016/j.nima.2012.08.020

- Selection criteria devised, considering possible combinations of the constraints from each detector type.
- Primary observables: Reconstructed particle (mostly muon) momentum and direction.
- Multi-targets available simultaneously, like CH and CH+H2O, Fe, H2O at the T2K-ND.
- Multi-beam-energy peaks: Off-axis: 2.5° ~0.6 GeV; On-axis:0° ~1 GeV
- Multiple sets of interactions w.r.t. the phase space can be selected with varied efficiency: forward, backward, 4π directions. Better coverage of phase space.

Plots for example:



Courtesy: PRD 98, 012004 (2018)

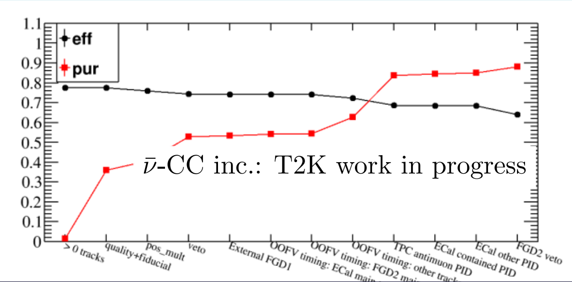
Several cross section results published by the T2K Collab. and other experiments.

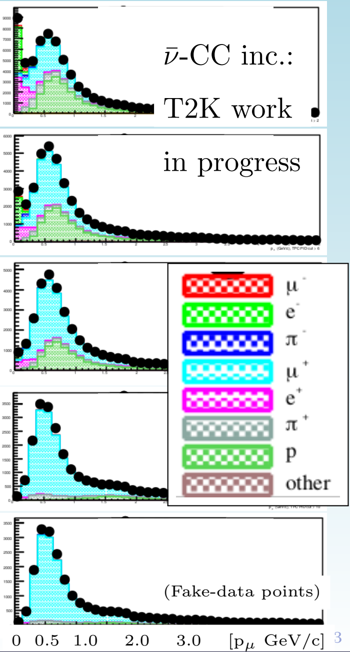
(Not discussing them here.)

Sample Selection

As for example in the following sample in FGD1 (T2K-ND280):

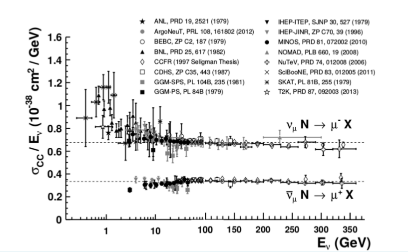
- Constraints from TPC and vetoing with FGD2 applied, reducing p-bkg.
- Additional constraints from the ECAL improve the selection
- Max. Signal efficiency & purity in the p_μ and $\cos\theta_\mu$ ensured

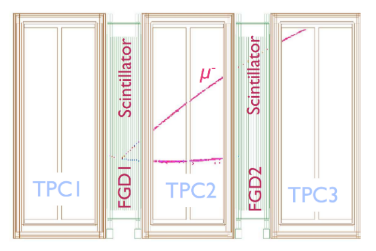




Measuring neutrino interactions

(at the T2K near detector): *"A brief overview of the methodology"*



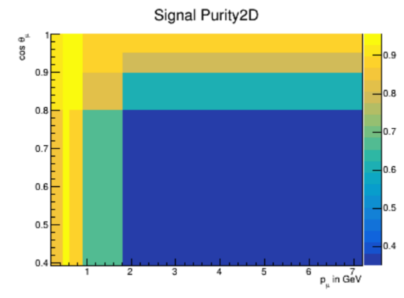


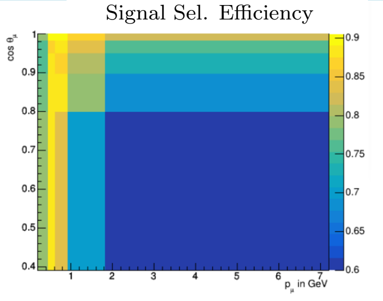
- Selection of the sample to ensure maximum purity, efficiency.
- Binning and Unfolding with the reconstructed MC and fake data checks
- Systematics (Detector-related, Flux, Cross-section-Parameters*)
- Final Cross Section Results with MC

◯ Unblinding data

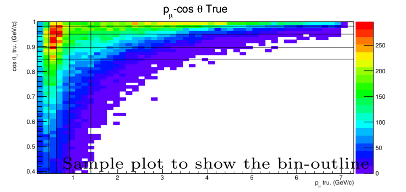
Signal Selection Purity and Efficiency:

Anti-muon neutrino CC-inclusive (MC plots shown) [T2K-work-in-progress]

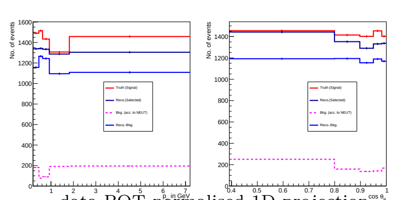




Optimised binning scheme used.



Sample plot to show the bin-outline



data-POT normalised 1D-projection

Unfolding the Reconstructed Events:

- An unfolding method used aiming to remove the detector effects in the measurement
- The flux-avg./int. xsec. is calculated from the **unfolded** events N in each bin,

$$For\ e.g.\ ,\ \langle\frac{\delta^2\sigma}{\delta p_\mu \delta \cos\theta_\mu}\rangle_{\alpha\beta} = \frac{\hat{N}_{\alpha\beta}}{T\Phi\Delta p_{\mu,\alpha}\Delta\cos\theta_{\mu,\beta}}$$

  And finally also obtain total cross section σ.
- So choice of the **Unfolding method** to be used must be checked to ensure min. MC bias, and convergence of the unfolding process.
- **Unfolding Techniques:** D'Agostini, SVD, TUnfold or binned-likelihood fit, many more available. Data-driven regularisation implemented. (Not discussing details in this presentation)
- Checks with lots of pseudo data sets. After several checks and reviews: to apply in the analysis.

Systematics

Following systematic uncertainties are mainly considered.

- ☑ statistical uncertainty of the collected data and simulated MC events.
- ☑ uncertainties in the neutrino flux measurement. (the better the flux simulations done, and the covariance matrix provided thus, the less is the uncertainty contribution)
- ☑ uncertainties in detector reconstruction of the variables (dedicated studies with control-set of data necessary for each case)
- ☑ uncertainty in the cross section model parameters used to simulate the signal and background processes. (Reweighting tool used/developed as Collab.)

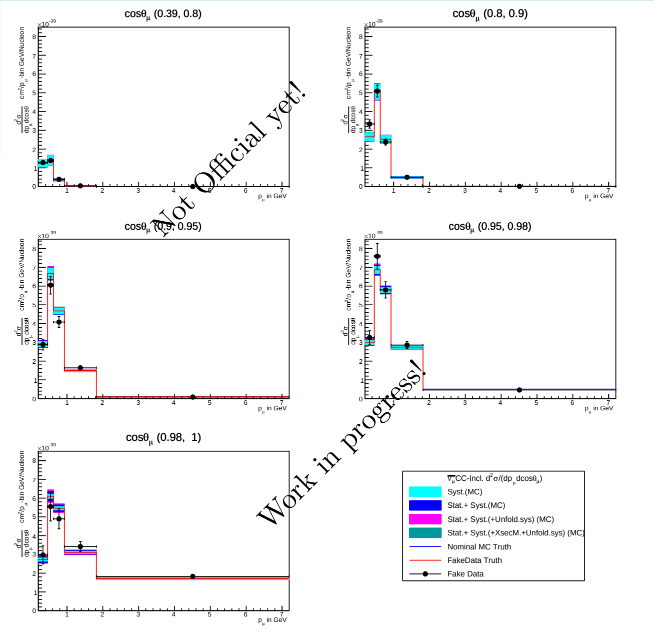
Flux and detector related sys. and cross section parameterisation systematics implemented by T2K built software tools (as shown here).

Final Cross sections:

Showing an example of double differential cross section measurement here:

Nominal MC= NEUT; fake data= NEUT toy MC; (used FD POT ≈Data POT)

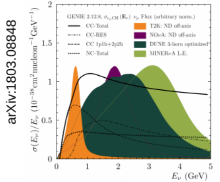
χ^2 distribution



Neutrino Cross Sections and Neutrino Oscillations

$$\mathbf{N}(\vec{x}) = \boxed{\boxed{\Phi(E_\nu) \cdot \sigma(E_\nu, \vec{x}) \cdot \epsilon(E_\nu)} \cdot P_{ab}(E_\nu, \Delta m^2_{ij}, \theta_{ij})}$$

- Cross Sections necessary to measure oscillated neutrinos (from any source: accelerators or atmosphere etc.)
- Systematic uncertainty important for precision in oscillation results.
- $\sigma(E_\nu, \vec{x})$ relate E_ν with observables
- **Events** ratios at **Near** (accelerator) and **Far** detectors do not cancel systematics: owing to diff. Flux, Cross-sections, Detector-smearing, and Osc. Probability.

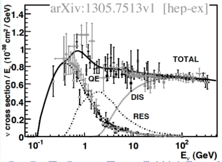


✠ Measurement of σ with minimal uncertainty imp.

$\Rightarrow$ Several measurements needed to constrain and improve ν-interaction models

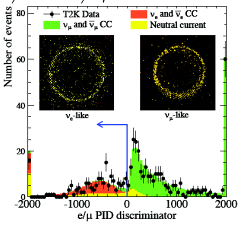
$\Rightarrow$ Reduced Systematics in Osc. analysis

$\Rightarrow$ Better goals-designing of future experiments



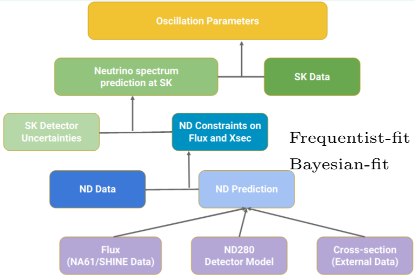
Detecting Neutrinos after Oscillations:

Courtesy: *https://www.nature.com/articles/s41586-020-2177-0*



- Long-baseline neutrino experiments have a dedicated far detector to detect oscillated neutrinos.
- As for example, T2K has Super-K as its far-detector
- A 50kt Water Cherenkov Detector, 295km far from source; diffused e-rings, sharp μ-rings

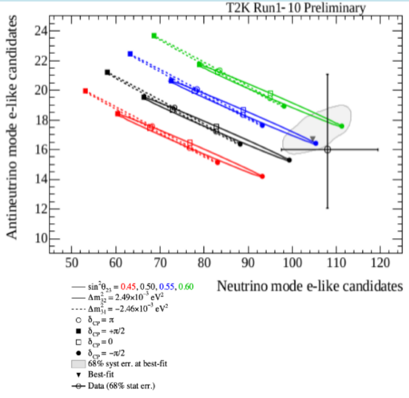
Conceptual Flowchart:



- Select samples with no pions (& $\nu_e 1\pi^+$) (based on topology again: 1-ring CCQE μ-like, 1-ring CCQE e-like, 1-ring CC$1\pi^+$ e-like etc)
- Fit is done simultaneously to all selected data samples, to get the oscillation results.

A quick look at the Collaboration results:

(Glimpses included just for completion)



- $\nu/\bar{\nu}$ measurements at ND, reduce uncertainties in the 1e/μ SK-samples from 13-17% to 4-9%, while 22% to 19% for the $\nu_e 1\pi^+$ sample.
- T2K completed taking Run 10 data in Feb. 2020, with beam intensity $\gtrsim$500kW.

[Quoted numbers and Picture from https://www.nature.com/articles/s4158 020-2177-0 and T2K results presented @IICHEP2020]

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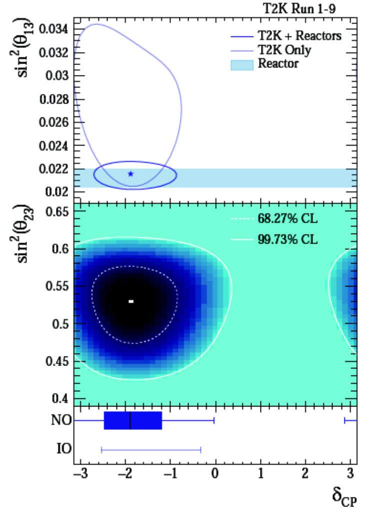

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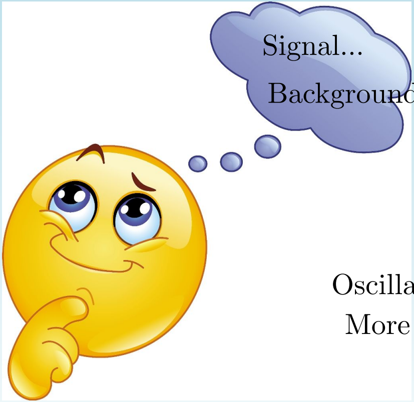
So...

Interaction Model
Constraints

Systematic
Uncertainty
Reduction



Signal...

Background...

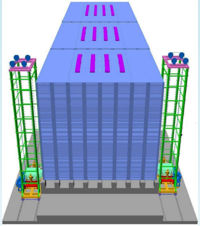
Oscillation Measurement
More Precise !!

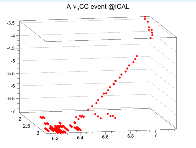
Wait... more of the tale...

Appopriate Signal Selection Still Important!

- Signal Selection **techniques** are still very crucial for any experiment aiming to study neutrino oscillations, besides the systematics discussed so far.

Atmospheric neutrino detectors also detect neutrinos after oscillation.
As for example, INO-ICAL, an upcoming atmospheric neutrino experiment.

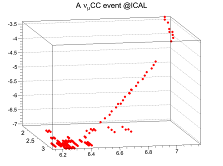


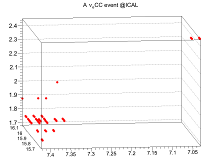


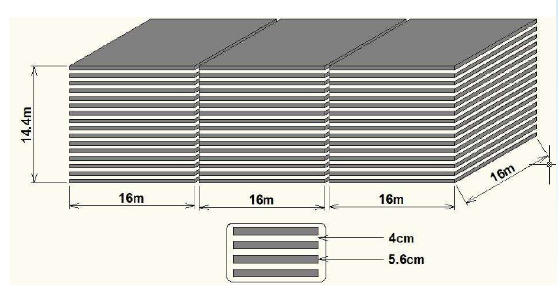
- 50kt iron layers interleaved with 150 layers of RPCs.
- $\vec{B}$ ~1.3T: to tell apart the μ^+s and μ^-s: to determine the ordering of ν-mass hierarchy.
- Events may be classified: w. μ-tracks and w/o.
- Muon/Antimuon-neutrino events are the required signal events to measure the oscillation, hence only the former to be discussed here.

The ICAL detector:

- Events may be classified: w. μ-tracks and w/o.
- 5.6cm of iron layers ensure cleaner muon tracks, and the field to tell CID.
- RPC gas mixture optimised to run on avalanche-mode
- "Muon(Track)less" events = ν_e**CC** + [others(all NCs & ν_τCC) + ν_μCC(Low energy or Horizontal)].



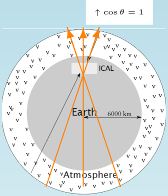




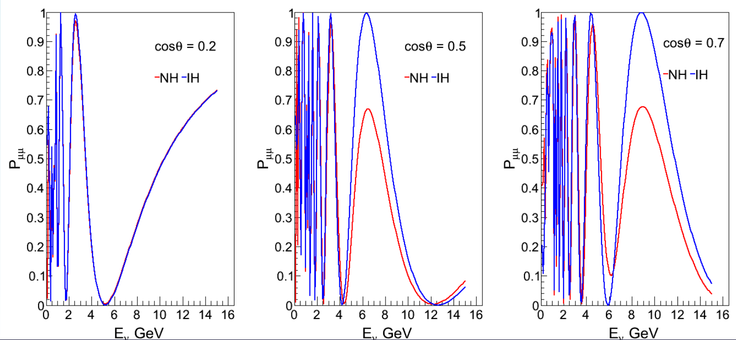
Studies also done to devise selection of nueCC events to as good as >50% purity.

(Not discussed here. See A. Ajmi et al., DOI: 10.1088/1748-0221/10/04/P04006)

Improving MH-sensitivity of ICAL using neural network

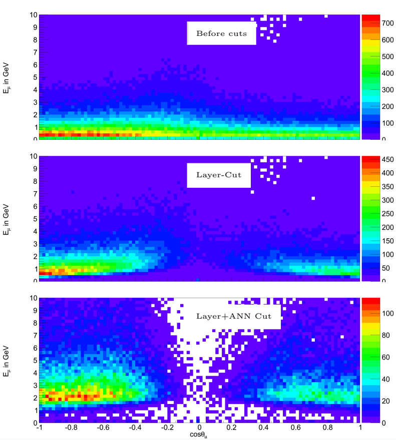


- Hierarchy signature most visible for $E_{\nu_\mu} \gtrsim 3$ GeV and for up-going (through earth) ν's in vertical cone ($1 < \cos\theta < 0.5$).
- Multivariate tools used to select signal with high efficiency & high purity. Multiple options studied: Neural network chosen
- ν_μCC events with $E_\nu > 2$(opt.3-4 GeV) and with $|\cos\theta| > 0.2$ (opt:0.4-0.5): designated as signal. All others: background.



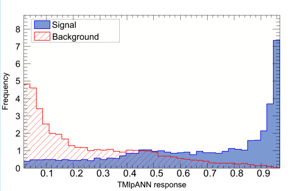
Effects of Selection Parameters:

- Additional selection variables devised during the muless study.
- Careful studies to observe the signal and bkg. behavior for each.
- Appropriate ones chosen for training the multi variate tools.
- Var1(Hits), Var2(layers) distinguish the low energy from the high energy ν events.
- Var3(Maxdist) distinguishes the horizontal high energy events from the rest.
- The high energy vertical ν_μCC events contain significantly higher Var4 (singlets) than the low energy/ horizontal events.
- The hits-pattern across the layers for the high energy vertical ν_μCC events form higher Var5 (triplets) than the the other three categories of ν_μCC events considered.



(MC distr.: Nuance gen., Geant4 reco. evts)

- The NH and the IH set of events so chosen are then binned in E_μ and $\cos\theta_\mu$.
- For final signal def.: $E_\nu > 2$ GeV and $|\cos\theta| > 0.2$, ANNcut of 0.7 selects such events with an efficiency 55% and a purity of 93%.



Now, looking at the osc. results...

- For uniform binning, use of ANN improves $< \Delta\chi^2 >$ from 3.5 to 8.
- Differential binning inherently extracts differences between the event spectra of NH and IH. ANN leads to small improvement in $< \Delta\chi^2 >$ from 7 to 9.
- For a 10 year exposure, ICAL@INO can obtain a hierarchy discrimination $\Delta\chi^2$ of 9.5 (after marginalisation and systematics).
- Inclusion of NC and ν_eCC events lowers the $\Delta\chi^2$ (from ν_μCC events only) by $\sim$1, but the ANNCut rejects such background contaminations.
- Therefore, **ICAL@INO can observe 3σ hierarchy discrimination with 10 years of exposure**.

For details see A. Ajmi et al., DOI: 10.1088/1742-6596/888/1/012151

Well then...

So, what do I finally take home...

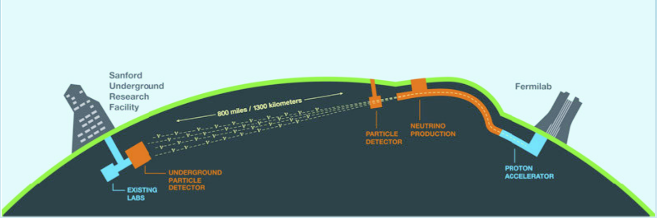
Comments on Selection Techniques:

- Scope of improving on the definition of Selection variables present/provided through newer detector additions/vetoes, or analytical approaches.
- Threshold optimisation, low noise/signal electronics are the mandatory steps
- Several analytic methods from the Multi-variate Tools like the CNN, BDT, Neural Network, etc. are currently very popular means of use. But deciding the input variables is still the most important.
- Most of the above so-called "machine-learning" tools are available in ROOT, package or stand-alone. Use of the chosen method subject to justification. For hard-sought signal selection, combining the algorithms inclusively or exclusively would lead to further evolution.

Inference so far:

- ✠ Consistent efforts necessary to improve signal selection methods, be it for neutrino interaction measurement or oscillation-studies, to derive the best possible outputs.
- ✠ Detector assemblies of multiple types at the near detector site, where intense neutrino flux present, provide for better event sampling, flux and interaction measurements. (In addition, vetoing newer detectors will be a good scope of R&D for future.)
- ✠ Detectors at the far end of the oscillation will not only benefit from the reduced cross section systematics provided by the near detectors' studies, but enhancing the signal selection methods can yield improved results.
- ✠ Both the above points apply to **long baseline neutrino experiments**, where prior knowledge of the neutrino energy and the oscillation pathlength are the keypoints to aid any such neutrino study.

The upcoming Long baseline ν-experiment: DUNE

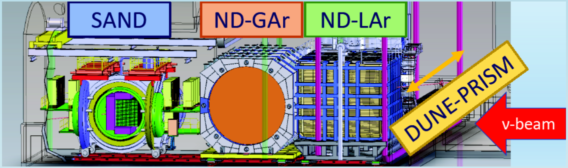


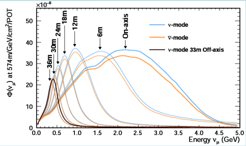
- 1300km baseline: significant matter effects along beam from the accelerator.
- ON-axis 1.2MW ν-beam (upgradable to 2.4 MW power), expecting 1.1e21 POT/year
- Aims to reach an exposure of 120 kt.MW.year by $\sim$2035
- Near detectors: On-axis and off-axis triplet detector assemblies: multifaceted benefits
- Far detector: 4 modules LArTPC 17.5(10) kt each. SP-DP combination. Efforts to maximize fiducial target volume.
- Open to receive natural source ν's as well.

Primary Objectives:

- To obtain a sensitivity to measuring CPV of $> 3\sigma$ over more than 75% of the possible δ_{CP} range.
- To achieve a 5σ determination of the ordering of the neutrino mass hierarchy (the sign of Δm^2_{31})
- measurement of the mixing angle θ_{23} and the determination of the octant in which this angle lies, and sensitive tests of the three-neutrino paradigm.
- Measurements of neutrino oscillation phenomena using atmospheric neutrinos
- To search for proton decay in several modes
- To detect any other galactic neutrinos in the range if any, SNBs etc.

Near Detectors:



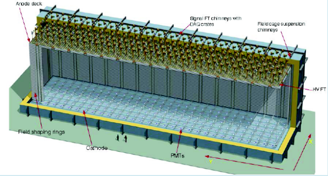


Courtesy: Pictures from DUNE-tdr and presentations @ICHEP2020.

- On-axis SAND, & LArTPC, GArTPC+ECal+0.5T: movable off-axis
- Monitor the neutrino beam. Predict the neutrino spectrum at the FD, with minimum systematic uncertainties
- Measure interactions on argon to reduce uncertainties due to nuclear modeling. measure the full kinematic range of the interactions to be seen at the FD.
- Measure neutrino cross sections precisely to constrain and modify the interaction models, to use in OA and others.
- Obtain data with different fluxes to disentangle flux and cross section, and systematic uncertainties on ν-energy reconstruction.

Far-Detectors:

- LArTPC detectors 20kt + 10kt + 10kt
- high-performance event imaging, calorimetry and particle identification capabilities
- good neutrino energy reconstruction capability: a crucial factor for wide-band beams



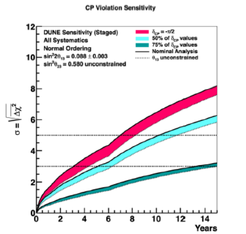
Courtesy: Pictures and numbers from DUNE-tdr.

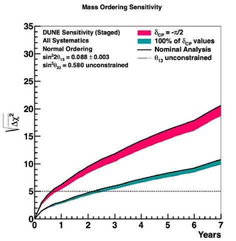
  - Single Phase: no amplification, low noise, smaller drift length
  - Double Phase: amplified signals, interaction identifications enhanced, larger drift length.
  - LArTPC (just for estimation): In ν_e events, the leptonic energy resolution (spectrum averaged) is 8%, the hadronic energy resolution is 49%, and the neutrino energy resolution is 13%, for ν_μ-CC track-contained events: 18%.

On the quest to achieve ...

Physics Milestone	Exposure (staged years, $\sin^2\theta_{23} = 0.580$)
5σ Mass Ordering δ_{CP} = $-\pi/2$	1
5σ Mass Ordering 100% of δ_{CP} values	2
3σ CP Violation δ_{CP} = $-\pi/2$	3
3σ CP Violation 50% of δ_{CP} values	5
5σ CP Violation δ_{CP} = $-\pi/2$	7
5σ CP Violation 50% of δ_{CP} values	10
3σ CP Violation 75% of δ_{CP} values	13
δ_{CP} Resolution of 10 degrees $\delta_{CP} = 0$	8
δ_{CP} Resolution of 20 degrees δ_{CP} = $-\pi/2$	12
$\sin^2 2\theta_{13}$ Resolution of 0.004	15

Courtesy: Pictures and numbers from DUNE-tdr/cdr





- Needs systematic uncertainties reduced to ~1-5%
- Improvements in the selection of events always important. (for cross section measurement hence/and oscillation measurement)

Conclusion

- The need and importance for improved Signal Selection techniques will always be dominant
- Designing of the multiple type of detectors, their organisation and synchronised signal retrieval adds to backround elimination apart from their acceptance and basic role.
- Cross section measurement: an elaborate process, high purity selected events sample essential, to lead in modifying interaction models, thus reduce related uncertainties.
- Multi variate tools or machine learning methods: a generic tool very popular now, can also help in choosing events with physics signature, as long as the training is sketched right, and "meaningful" input variables are fed in. Lots of scope to go beyond the currently applied concept.
- Success of the neutrino long baseline experiments heavily rests on such evolution, which will also lead for future. DUNE is such an opportunity while expecting to measure CPV, MH ordering and many more.

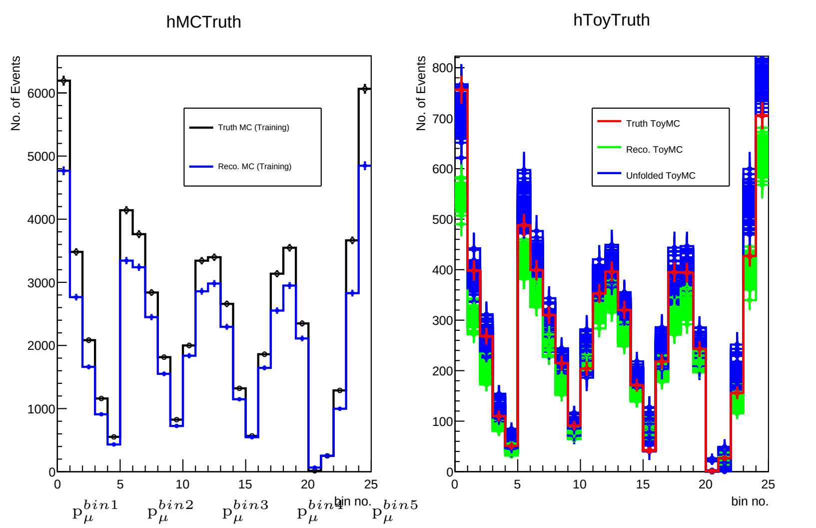
Looking forward to many more new neutrino fundamental surprises, and the emerging concepts, techniques and definitely enjoy the curiosity and excitement all the way!!

Thank you !

Back ups:

Unfolding check with several fake toys:

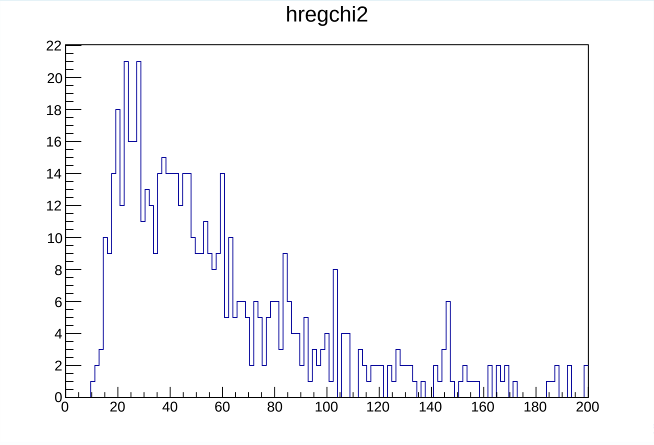
Nominal MC: NEUT , fake toys from NEUT MC



χ^2 Distribution:

NEUT Nom. MC with 1000fakedata toys (NEUT, hL2 variated sets): NDF = 25.

$$\chi^2 = (Unfolded - Truth)V^{-1}(Unfolded - Truth)^T \quad (1)$$



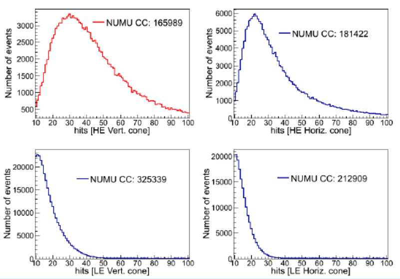
Results from my Trackless Events ("Muonless") studies:

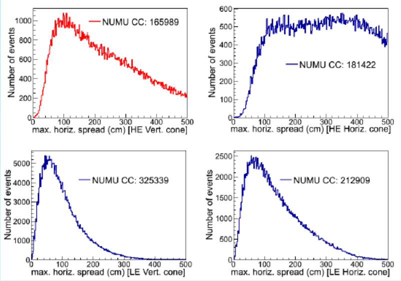
- **Devised** various selection criteria to select a sample rich in ν_eCC events with varying efficiency and purity, only few mentioned here.

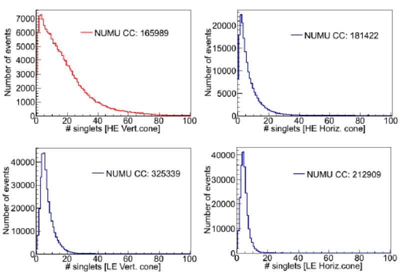
Selection Criteria	$\#\nu_e$ CC Purity	~Exp.evts/yr(MC)
Maximum Hits diff.	53%	300
Overall Pattern: hits in layers	58%	170
Comparison: hits in layers	60%	100
Single layer hits	68%	15

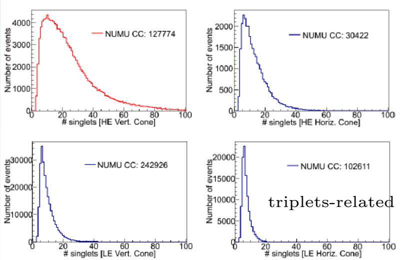
Results in brief: mainly ν_eCC-Extraction:

- ☑ Maximum obtainable ν_e**CC purity:** $\sim$ **60%** with $\sim$ 100 events/yr.
- ☑ Depending on constraints: purity of ν_eCC events in the selected sample varies between 55% to ~70%.
- ☑ Purity of ν_e CC decreases with increasing sample size.
- ☑ Improving on purity depletes vertical events fraction. .
- ☑ An approximate neutrino Energy and Direction Estimation also made for these muonless events.









triplets-related