1 Are neutrinos Dirac or Majorana particles?

Invent novel experimental approaches to determine whether neutrinos are Dirac or Majorana particles.

Focus: Neutrino physics
Requirements: Analytical calculation
Author: Boris Kayser

Essentially the only approach being actively pursued to determine experimentally whether neutrinos are Dirac or Majorana particles is the search for neutrinoless double beta decay. Without consulting the literature (which would spoil the fun), can you think of other experimental approaches to making this determination? Analyze your proposed approaches quantitatively. Why are they sensitive to whether neutrinos are of Dirac or Majorana character? How sensitive is each of them? For each of them, what would it take, if anything, in the way of forces and/or particles beyond those that are presently known for this approach to work?

2 Atmospheric neutrinos from Earth, Sun and planets

Learn about the physics of atmospheric neutrinos and its dependence on atmospheric properties.

Focus: Atmospheric showers, particle decay and absorption
Requirements: analytical calculations
Author: Lutz Köpke

The physics of atmospheric neutrinos, in particular its energy dependence, is strongly governed by the competition between decay and re-interaction of charged pions and kaons decay (and to a lesser extent D$^{\pm}$ mesons) in the atmosphere. For sufficiently high energies, magnetic effects play a minor role and analytical formulae are available. For this tasks, such a formula such as that of Gaisser should be used:

$$\begin{aligned}\phi_\nu(E_\nu) &= \phi_N(E_\nu) \\ &\times \left\{\frac{A_{\pi\nu}}{1+B_{\pi\nu}\cos(\theta)E_\nu/\epsilon_\pi} + \frac{A_{K\nu}}{1+B_{K\nu}\cos(\theta)E_\nu/\epsilon_K}\right. \\ &\quad \left. + \frac{A_{\mathrm{charm}\,\nu}}{1+B_{\mathrm{charm}\,\nu}\cos(\theta)E_\nu/\epsilon_{\mathrm{charm}}}\right\}, \end{aligned} \tag{1}$$

where $\phi_N(E_\nu) = dN/d\ln(E_\nu)$ is the primary spectrum of nucleons (N) evaluated at the energy of the neutrino . The factors $A_{i\nu}$ contain the physics of meson production weighted by the spectrum and the decay kinematics. As an example,

$$A_{\pi\nu} = \frac{Z_{N\pi}}{1 - Z_{NN}} \frac{(1-r_\pi)^\gamma}{\gamma + 1}.$$

Here

$$Z_{ab} = \frac{1}{\sigma_a}\int_0^1 x^\gamma \frac{\mathrm{d}\sigma_{ab}(x)}{\mathrm{d}x}$$

is the spectrum weighted moment for the interaction process in which a particle a interacts with a nucleus in the atmosphere and produces a secondary particle b that has a fraction x of the lab energy of the projectile. The factor involving $r_\pi = m_\mu^2/m_\pi^2$ is the spectrum weighted kinematic factor for the decay $\pi \to \mu + \nu$ and $\gamma \approx 1.7$ is the integral spectral index in a power-law approximation to the primary cosmic ray spectrum.For each of the main neutrino parents, there is a critical energy,

$$\epsilon_i = m_i c^2 \times \left(\frac{h_0}{c\tau_i}\right), \tag{2}$$

where h_0 is the scale height of an exponential approximation to the atmosphere and m_i and τ_i are, respectively, the mass and rest lifetime of a neutrino parents $\pi^{\pm}, K^{\pm}, D^{\pm}$. When

$$E_\nu > \sec(\theta) \times \epsilon_i \tag{3}$$

re-interaction of the parent hadron is favored over its decay.

The energy dependence should be programmed and its dependence on atmospheric properties should be studied. Of particular relevant is the production of neutrinos in the atmosphere of the sun but one may also look at planets, such as Jupiter.

We suggest to proceed as follows:

1. **Methodology:** Become aquainted with the problem by reading the relevant chapters in Thomas Gaisser's book on *Cosmic rays and particle physics* or preprints that cover the matterm e.g. `arXiv:0104327`. Also check papers on the atmospheric neutrino production in the sun (`arXiv:1706.01290`, `arXiv:1704.02892`, `hep-ph/9604288`) and from Jupiter (`arXiv:1606.01291`).

2. **Analytical approximation:** Implement an analytical approximation (e.g. that of Gaisser) for atmospheric neutrinos from the Earth and vary the critical energy parameters. Find out the values for the critical energies and Z factors for the Earth atmosphere.

3. **Adaptation to Sun and Jupiter:** Try to understand what will change in case of the Sun and a large planet, such as Jupiter (see references above). Adapt the analytical formula accordingly. You may try to discuss other planets if you wish.

4. **Conclusion:** Summarize the investigation by summarizing its main results depending on the atmospheric properties and its shortcomings.

3 CP violation from flavor fractions

Analyze the structure of the leptonic mixing matrix and of neutrino oscillation probabilities to understand the conditions under which CP is violated in the neutrino sector.

Focus: Oscillation physics
Requirements: Analytical calculation
Author: Boris Kayser

Suppose there are only three neutrino flavors, and three neutrino mass eigenstates, and that the $3x3$ leptonic mixing matrix U is unitary. Suppose further that, with shrinking experimental uncertainties, we learn that the neutrino mass eigenstate ν_3 is exactly 49% ν_μ and exactly 49% ν_τ, and that the mass eigenstate ν_2 is exactly 33% ν_μ and exactly 33% ν_τ. By carrying out the following steps, prove that the CP-violating difference must then be nonzero.

First, find the magnitudes of all of the 9 elements of U. Now, the three terms on the left-hand side of the unitarity constraint $\sum_{i=1}^{3} U_{\mu i}^* U_{ei} = 0$ can be pictured as forming the three sides of a closed triangle in the complex plane. This triangle is known as a unitarity triangle. From the given data, find the area, A, of this triangle. As you will see, A is not zero.

From the expressions given in the lectures for the probabilities $P(\nu_\alpha \to \nu_\beta)$ and $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$, and the assumed unitarity of U, find an expression for $\Delta_{\mu e}$ in terms of A and the mass-squared splittings Δm_{ij}^2. In particular, show that $\Delta_{\mu e} \equiv P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ is proportional to A. Since our A is not zero, the CP-violating difference $\Delta_{\mu e}$ is not zero -— CP is violated.

You may find the trigonometric identity

$$\sin x + \sin y - \sin(x+y) = 4 \sin \tfrac{x}{2} \sin \tfrac{y}{2} \sin \tfrac{x+y}{2} \tag{4}$$

useful in the above derivation.

Now what if we assume not the idealized flavor fractions of the mass eigenstates given at the start of this problem, but the measured leptonic mixing angles, including their uncertainties. Disregarding the present hint that the CP-violating phase δ is nonzero, can we already say that CP is violated?

4 Coherence in neutrino oscillations

A project about the subtle quantum mechanics of neutrino oscillations, including several potential brain-teasers.

Focus: Neutrino oscillations
Requirements: Analytical calculation
Author: Joachim Kopp

Neutrino oscillations are an interference effect. They can occur only if different neutrino mass eigenstates evolve coherently (i.e. their relative phases are well-defined and evolve smoothly with time) and if the detector is unable to distinguish different mass eigenstates. In understanding the conditions for coherence, it is often useful to picture the propagating neutrino as a superposition of three Gaussian wave packets, one for each mass eigenstate.

1. Consider pion decay at rest, $\pi^+ \to \mu^+ + \nu_\mu$. Compute the energy and momentum of the emitted neutrino. You will find that the result depends on the neutrino mass.

2. Oscillations of ν_μ produced in pion decay can occur if the detector is unable to distinguish the different momentum eigenstates corresponding to the mass eigenstates ν_1, ν_2, ν_3. Use the Heisenberg principle to derive a condition on the size of the detector.

3. Because of their different masses and momenta, different neutrino mass eigenstates propagate with different group velocities. Eventually, the wave packets corresponding to different mass eigenstates will be separated in space and time. They will no longer overlap, and coherence will be lost. Estimate the propagation distance L^{coh} (as a function of the neutrino mass, energy, and the wave packet width σ) at which wave packets become separated. For which neutrino sources is decoherence relevant? How far away does a source need to be for two mass eigenstates $m_1 = 0$ eV and $m_2 = 0.05$ eV to arrive at the detector with a separation of 1 sec?

4. Supernova neutrinos arrive at Earth as an incoherent superposition of mass eigenstates. Derive an expression for the probability for observing a ν_2 as a ν_e, assuming neutrinos do *not* travel through significant amounts of Earth matter prior to detection.

5. What changes if neutrinos travel through the Earth before being detected?

6. Discuss whether neutrinos produced in Z boson decays oscillate, and what it would take to observe these oscillations.

Cross Section Calculation Activity

Activity Summary

In this activity, you will learn the steps needed to calculate the neutrino interaction total cross section as a function of E_ν based on the experimental definition

$$\sigma_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N_{data,j}^{bkgd})}{A_\alpha \phi_\alpha T} \tag{1}$$

where j is the index of a reconstructed E_ν bin, $U_{j\alpha}$ is a function that accounts for unfolding from reconstructed bin j to true bin α, $N_{data,j}$ is the number of selected events, $N_{data,j}^{bkgd}$ is the estimated number of background events, A_α is the efficiency for reconstructing signal events, T is the number of target nucleons, and ϕ_α is the flux in bin i.

We will perform this calculation on a charged current neutrino interaction. This interaction has a charged lepton with matching lepton number in the final state. For ν_μ scattering, there will be a μ^- in the final state.

The background to this event sample are neutrino events of the wrong channel. These include neutral current events and wrong sign events (antineutrinos). A wrong sign (WS) event can be falsely accepted in the event sample when a charged-current interaction produces a muon whose charge is reconstructed as negative. Although a ν_μ event can lead to a μ^- through charm production, the vast majority of the WS background is the result of a reconstruction failure in MINOS. If the interaction is mediated by a $W^\pm(Z0)$ it is called a charged (neutral) current interaction. In neutral current interactions, the final state lepton is a neutrino that has the same favor as the incident neutrino.

There are three dominant interaction channels for neutrino-nucleon scattering neutrino energies: QuasiElastic scattering, Resonance production, and Deep Inelastic Scattering.

Figure 1 shows an event display of a CCQE two track interaction, where the muon is matched to MINOS and the short track is a proton.

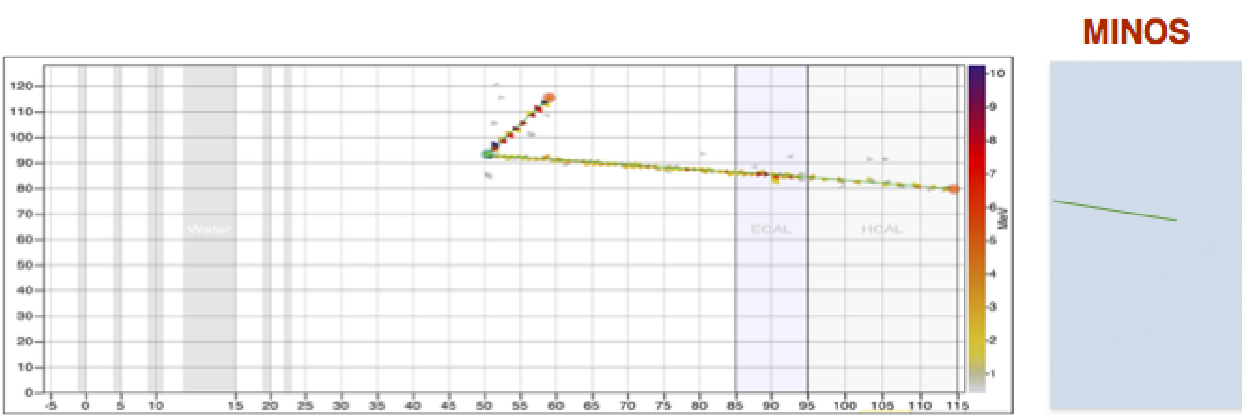

Figure 1: Event Display of CCQE Event

The input files for this activity can be found at
`https://www.dropbox.com/home/Files_Cross_Section_Activity`
The Monte Carlo `CCInclusiveReco_MC_AnaTuple_minerva1.root`
The efficiency `myEfficiencyAndPurity.root` and the flux `Flux_v10r6p13_resurrection.root`

Event Selection

Select events for the muon neutrino Charged-Current interactions (quasi-elastic, resonance and deep inelastic). Fill a histogram of the MC for the reconstructed neutrino energy (`CCInclusiveReco_E`)

HINT 1! The reconstruction cut used in this analysis:

- `CCInclusiveReco_nuHelicity == 1` (Event has the right helicity)
- `pass_canonical_cut==1` (Event has a fiducial vertex, an analyzable muon, significant curvature, matched to MINOS, plausible energy)
- `1 > phys_n_dead_discr_pair_upstream_prim_track_proj` (At least there's only 1 dead discr pairs upstream of the vertex of interaction/it removes event that can't be reconstructed due to the dead time)
- `CCInclusiveReco_E > 22.0` (Event has neutrino energy below 22 GeV)

The event sample distribution should look like Figure 2.

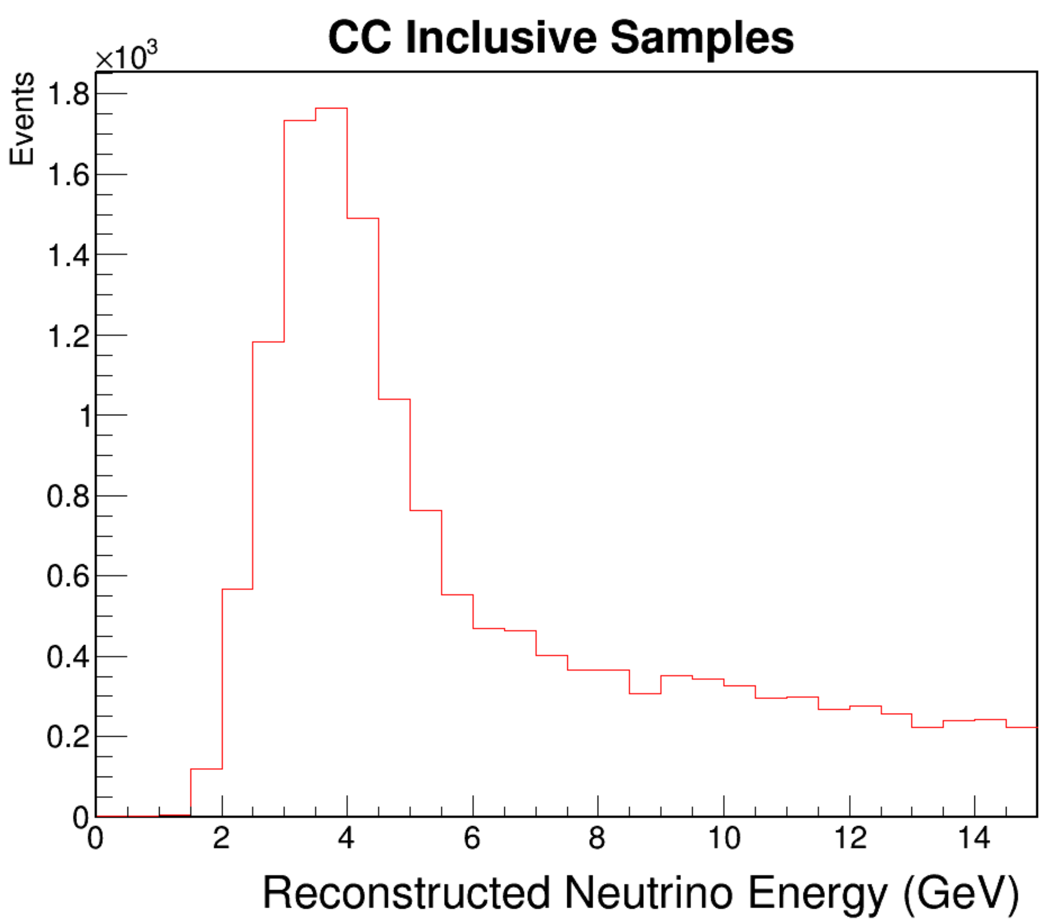

Figure 2: Event Sample Distribution

Background Subtraction

Any selected sample contains certain background, in this case the background is the neutral current events and wrong sign events (antineutrinos). We MUST constraint the background and subtract it from the data. Since the background for this sample is very small we do not have time do perform a background constraint, we are going to subtract the background prediction from genie simulation.

Fill a histogram with the prediction of the background events for the events passing the reconstruction cut (see Activity 1) but didn't pass the signal cuts according to the true information from the MC.

HINT!

- True energy cut is the same as the reco E cut: `mc_incomingE < 22.0`
- For MC, you can subtract the background from samples:

The background subtracted distribution for MC should look like Figure 3.

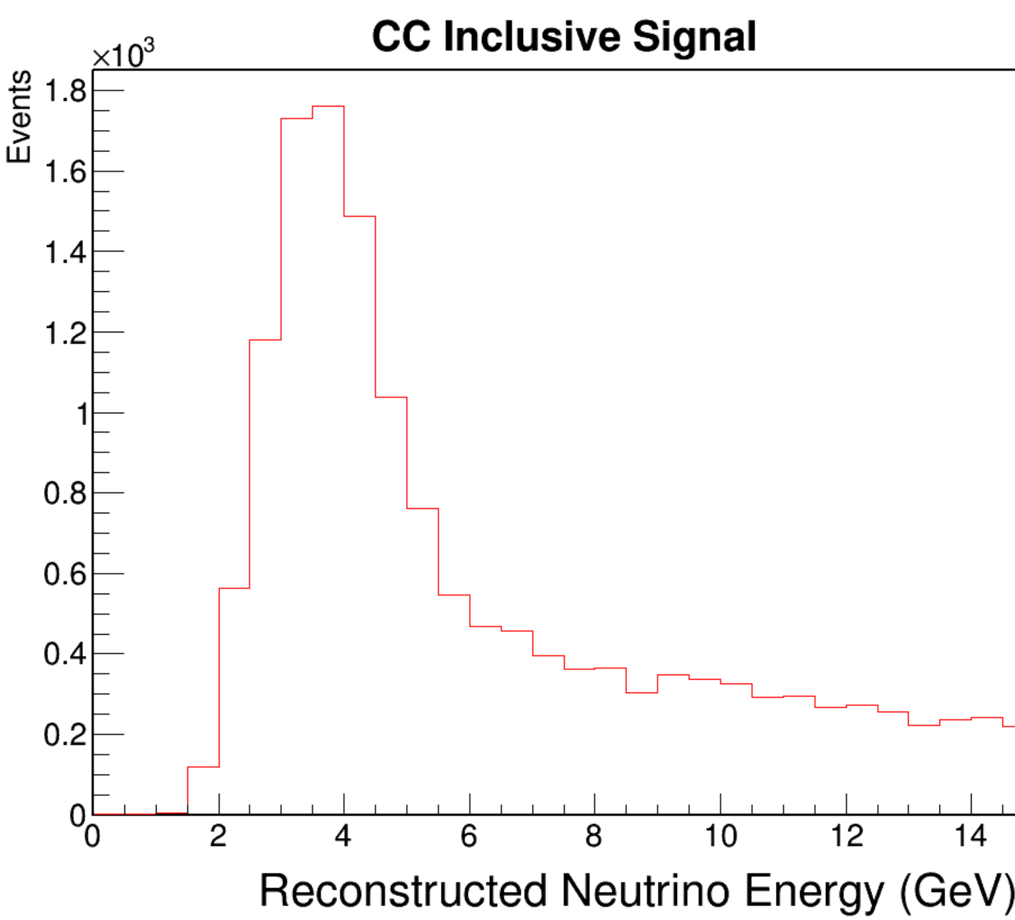

Figure 3: Background Sbtracted Distribution

Migration Matrix and True Neutrino Energy Distribution

$$\sigma_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha \phi_\alpha T} \tag{2}$$

The migration matrix is used for the unfolding, to fill the migration matrix define a 2 dimensional histogram, where x axis is the reconstructed neutrino energy `CCInclusiveReco_E` and the y is the true neutrino energy `mc_incomingE`. Fill the migration matrix with events that passed both the reconstruction cut and signal cut. Next, define a histogram for a true neutrino energy distribution, that also passed the reconstruction cut and signal cut. You will need these two histograms to unfold the reconstructed distribution to true distribution. The migration matrix of your event sample, should look like Figure 4.

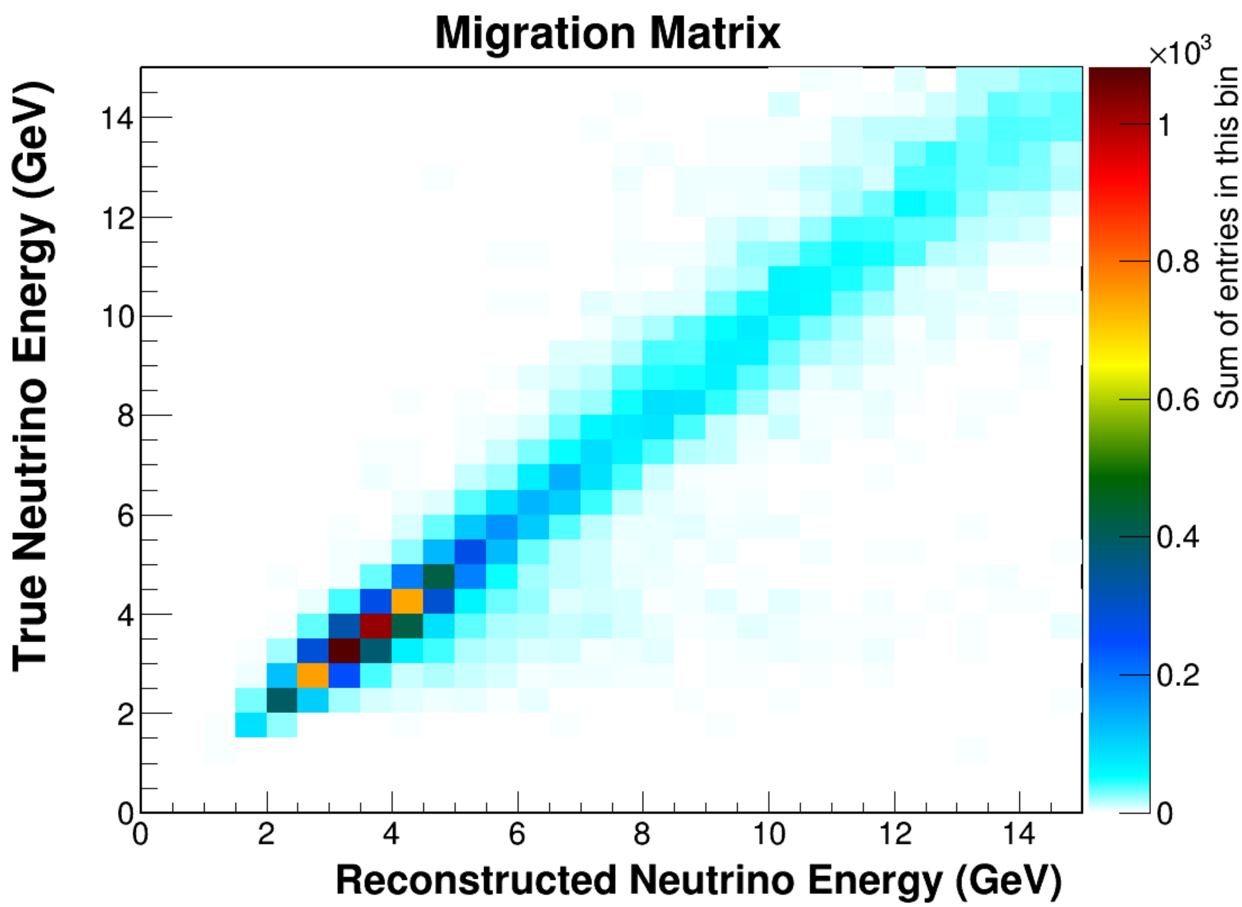

Figure 4: Migration Matrix

Unfolding

The unfolding uses the migration matrix, the reconstructed histogram, the true histogram and the background subtracted histogram.

HINT! To unfold the distribution use

$RooUnfold * unfold = RooUnfold :: New(RooUnfold :: kBayes, response, h_data, 4, "unfold");$

The unfolded distribution should look like Figure 5.

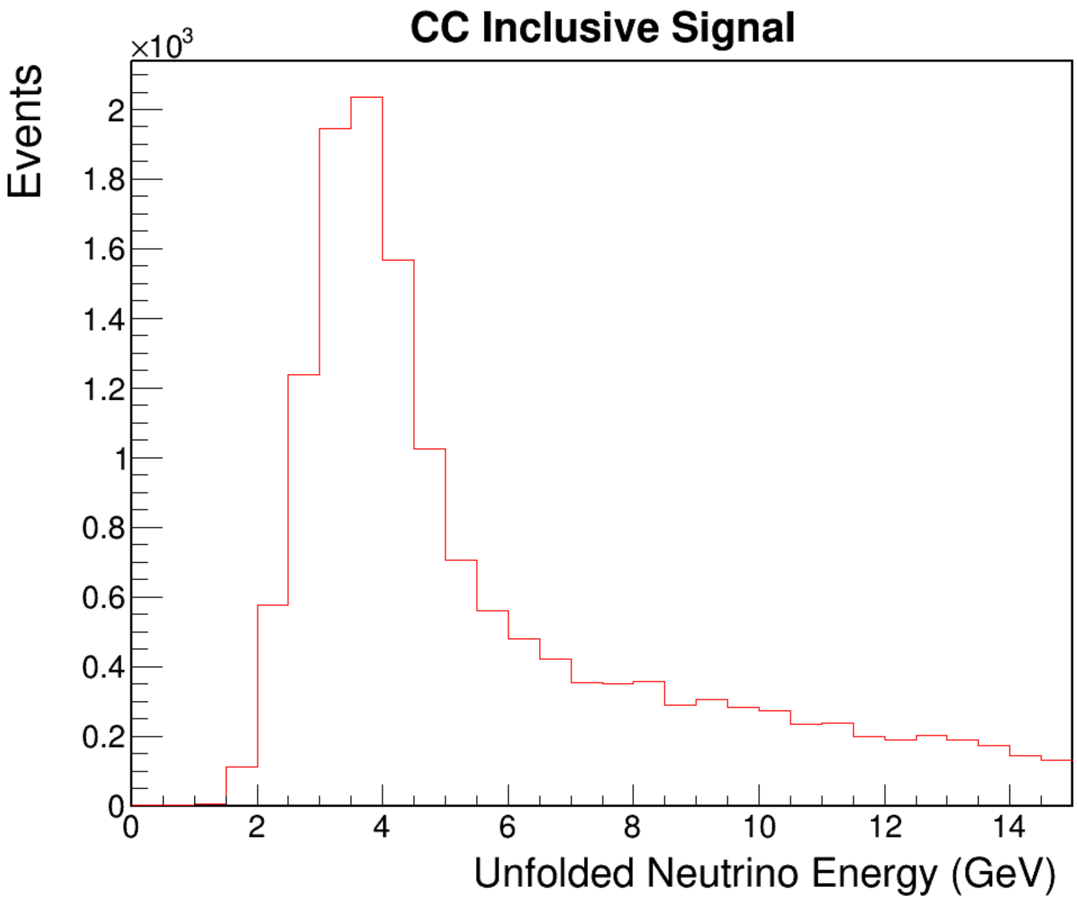

Figure 5: Unfolded Neutrino Energy Distribution

Efficiency Correction

Due to the limitations of our detector technology and geometry and also because the neutrino event signature is difficult and challenging to identify, the signal cuts that we use are unable to reconstruct some fraction of our signal. Therefore, the cross section calculation needs to be corrected for its efficiency. The efficiency for true kinematics is measured in simulation as :

$$A_\alpha = Efficiency = \frac{N^{selected}_{CCInclusive,\alpha}}{N^{Total}_{CCInclusive,\alpha}} \tag{3}$$

where,

- $N^{selected}_{CCInclusive,\alpha}$ is the number of MC CC Inclusive signal events in the selected sample in the $\alpha - th$ neutrino energy bin. To get number of events for $N^{selected}_{CCInclusive,\alpha}$, apply the event selection cut described in Activity 1 and signal cut: `mc_current==1 and mc_incoming==14`

- $N^{selected}_{CCInclusive,\alpha}$ is the total number of CC Inclusive MC signal events generated in the $\alpha - th$ neutrino energy bin. To get the number of events for $N^{selected}_{CCInclusive,\alpha}$, apply the signal cuts and true energy cut: `mc_incomingE < 22`

HINT! Since we have to loop over the Truth tree entries to get $N^{selected}_{CCInclusive,\alpha}$, the code will take some time to run. To save time, we have provided the Efficiency histogram inside the code and you can use it to correct the unfolded neutrino energy histogram by: `h_CrossSection->Divide(h_unfold,h_Efficiency);`

The efficiency of the neutrino energy should look like Figure 6.

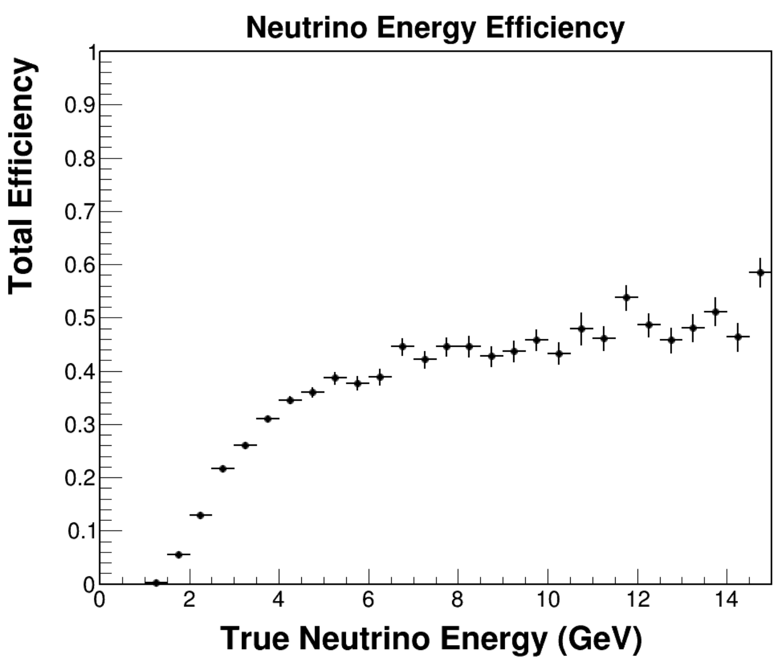

Figure 6: Neutrino Efficiency

Flux

The next step in calculating the cross section is dividing the efficiency corrected distribution by the flux in each neutrino energy bin and the width of the E_ν.

The flux we use for this calculation has finer binning compared to the E_ν binning that we have used so far. Since we need to divide the cross section by the flux, we need to rebin the original flux histogram to the binning we use for the E_ν histogram.

HINT! Rebin the flux histogram to the neutrino energy bins:

```
for(int j=1; j < h_flux_rebinned->GetNbinsX()+1; ++j ){
    double e_min = h_Eff_NeutrinoEnergy->GetBinLowEdge( j );
    double e_max = h_Eff_NeutrinoEnergy->GetBinLowEdge( j+1 );
    int b_min = flux->FindBin( e_min );
    int b_max = flux->FindBin( e_max ) - 1;
    double flux_cv =  flux->Integral( b_min, b_max, "width" );
    h_flux_rebinned->SetBinContent( j, flux_cv );
}
```

The rebinned flux distribution should look like Figure 7 .

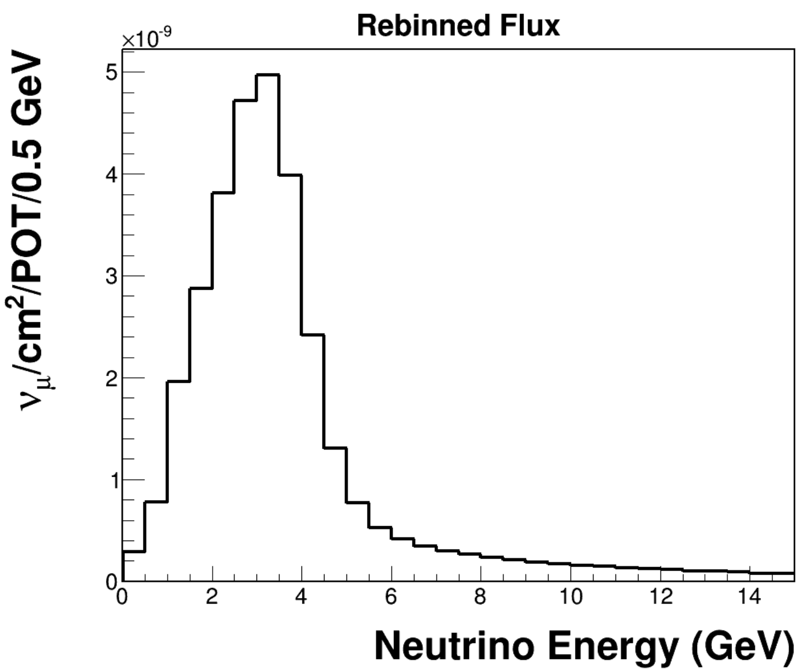

Figure 7: Rebinned Flux Histogram

Target Normalization and Cross Section Calculation

$$\sigma_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha \phi_\alpha T} \tag{4}$$

The last step in calculating the cross section is dividing the unfolded, efficiency corrected distribution with the number of targets in CC Inclusive channel. The number of targets (nucleons) in the fiducial volume for the MINERvA experiment is 3.17846e+30

The cross section plot should look like Figure 8

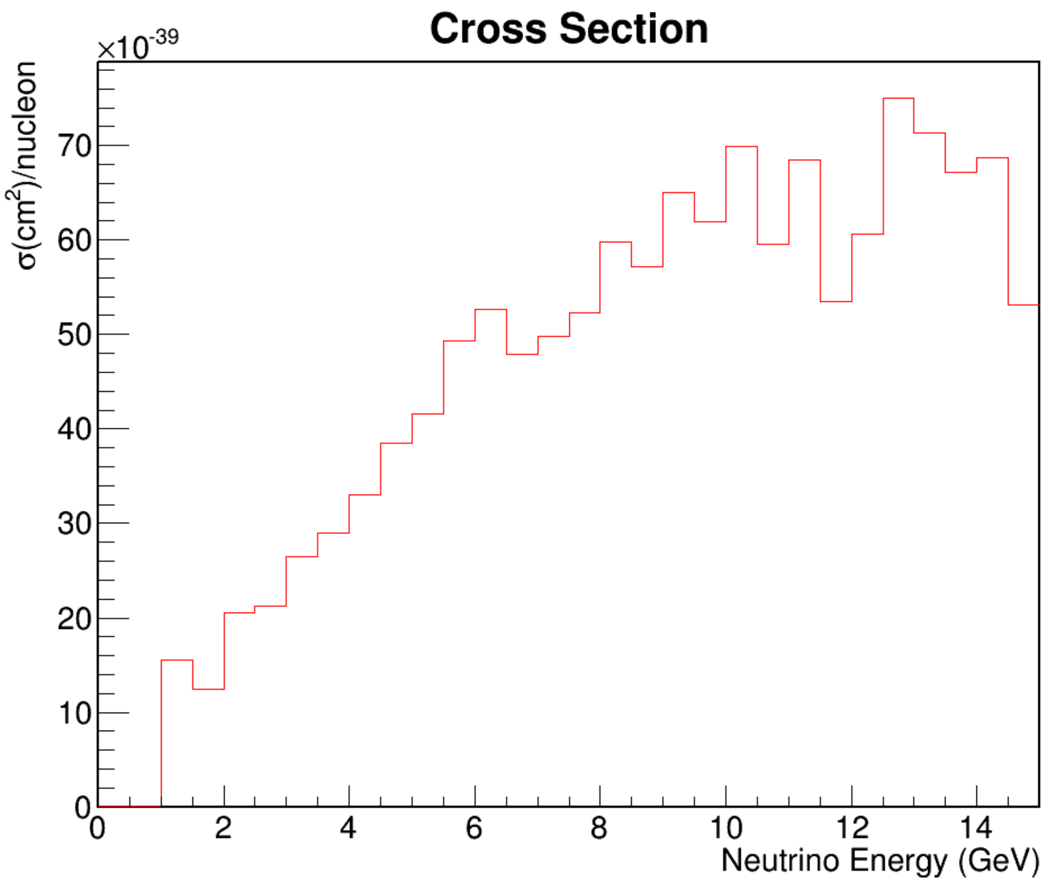

Figure 8: The cross section of CC Inclusive Interaction

Image credit: https://www.zerochan.net/1609600

Find the Supernova!

How well can a neutrino experiment locate a supernova on the sky? What modifications would you like to make to a detector, say Super-Kamiokande, to do a better job? Making reasonable assumptions, what's the best that one can do? Can multiple experiments do a better job? How should we go about doing this?

MOTIVATION AND GOALS

The neutrinos from a supernova exploding in our galaxy are likely to arrive at Earth *before* the light does! Of course, this is not because neutrinos travel faster than light, but because they are emitted a little bit earlier. As you can imagine, this early neutrino signal can be used to warn astronomers of an impending supernova in our galaxy, so that they can all point their telescopes in the correct direction. But wait! Most existing neutrino detectors, including the largest detectors such as Super-K and IceCube, largely employ the inverse beta reaction to detect neutrinos, and this reaction does not allow us to infer the original neutrino direction very well. You are tasked with developing a strategy to improve upon this state of affairs! The international neutrino community has set forth the following goals for your team:

- Identify at least one experimentally observable feature of the potential neutrino signal at a large water Cherenkov detector that can be used to extract directional information on incoming neutrinos. Construct a numerical experiment that simulates the events and perform the analysis that is required to determine the supernova direction. Quantify the accuracy to which you can predict the supernova location based on detector size, properties, number of neutrino events observed, etc.

  Hint: There is a reaction through which neutrinos interact in the detector and the final visible particle tracks the original neutrino direction quite faithfully.

- Can you improve your strategy if you could tag each event as occurring due to one of the two different reactions? Quantify the improvement you can obtain.

  Hint: What if you are told that dissolving some Gd salt in the detector allows one to tag the inverse beta events with some known efficiency?

- Bonus: If you have more than 1 detector can you use a different strategy? How many detectors will you need to uniquely find a location in the sky? Construct a numerical model that employs this strategy.

  Hint: How does LIGO find locations of the events it hears?

- Bonus: Where on the sky is a galactic core-collapse supernova likely to happen? What does this depend on? Make a heat-map of the potential sky locations.

  Hint: This depends on the distribution of massive stars in our galaxy. The GAIA satellite has recently provided a lot of new data that will allow us to make better maps of these kind.

No references to literature have been provided. This is deliberate. Finding the relevant papers using http://inspirehep.net/ is an important part of this project. Similarly, the goals are left imprecisely stated without specific numbers being provided; it is part of the project to find out what these are.

All the best!
Basu Dasgupta

7 Low-energy neutrino target isotopes

Select a suitable target isotope for a low-energy neutrino detector.

Focus: Low-energy neutrinos, nuclear physics
Requirements: Analytical calculation Author: Jonathan Link

In 1976, Raju Raghavan proposed using ^{115}In as the neutrino target for the detection of pp solar neutrinos (Phys.Rev.Lett. 37 (1976) 259-262). Dr. Raghavan used the published tables of nuclides to identify a possible charged current reaction, with a threshold of 115 keV, which changes the neutrino to an electron ($E_e = E_\nu - 1.15\,\mathrm{keV}$) and transforms ^{115}In to a metastable excited state of ^{115}In. The ^{115}In* state decays to its ground state by emitting two gammas with a half-life of 3.26 µs. The two gammas of fixed energy from the delayed decay can be used to tag the primary electron as having come from a neutrino interaction. Use the online nuclear data tables (`http://www.nndc.bnl.gov/`) to identify other isotopes that might be useful for tagging neutrino (or antineutrino) interactions. Try to think about how a detector could be constructed with the isotope. It's worth noting that no ^{115}In detector has ever been built. Dr. Raghavan did go on to invent procedures for metal loaded liquid scintillators which were used by Daya Bay and other reactor neutrino experiments to measure θ_{13}. Also, consider the natural abundance of the isotope. Is there enough to build a useful detector, and would the detector require isotopic enrichment?

8 Neutrino telescopes meet neutrino beams

Explore the potential of the future low-energy neutrino telescopes PINGU and ORCA to study neutrino oscillations from atmospheric and beam neutrinos.

Focus: Oscillation physics
Requirements: Numerical calculation / PISA software
Author: Sebastian Böser

Initially designed to detect extra-galactic neutrino sources, it has been realized over the last decade that using the ubiquitous flux of atmospheric neutrinos, neutrinos telescopes can such as IceCube/DeepCore or Antares can perform precision measurements of the *atmospheric* neutrino oscillation parameters. Building on this success, a new generation of telescopes with lower energy threshold is being proposed both in the Mediterranean (ORCA) as well as at the South Pole (PINGU), specifically targeted to precision oscillation measurements.

In this exercise we will use the PISA analysis framework - a fast yet precise simulation package to explore the capabilities of these next-generation detectors. Three steps are suggested for this tutorial:

1. Acquaint yourself with the **PISA software package** and how it works, by working through the provided tutorials. Particularly have a look at the **effect of the earth matter density on the oscillation pattern**.
2. While there are essentially not τ-neutrinos generated in the atmospheric flux, they appear through neutrinos oscillations. PINGU and ORCA will have the best sensitivity to this ν_τ **appearance** effect, which is important to study unitarity - i.e. make sure that neutrinos don't disappear while they oscillate.
3. If shoot at by a neutrino beam, ORCA and PINGU can also be used to **determine the CP-violating phase** δ_{CP}. Estimate the best baseline from where to shoot such a beam and find out how well δ_{CP} can be measured.

PISA is a python based framework - basic python programming skills are required.

9 Pre-Supernova Neutrinos

Be the first one to see the next Supernova coming! Learn to distinguish the faint neutrino signal of remote silicon-burning stars from other neutrino background fluxes.

Focus: Low-energy neutrinos, stellar physics
Requirements: Analytical calculation/toy MC
Author: Michael Wurm

Towards, the ends of their lives, heavy stars begin to burn ever heavier elements in thermonuclear fusion reactions. In this process, the stellar core becomes continuously hotter and denser, until neutrino cooling (from thermal $\nu\bar{\nu}$-production) overtakes photon emission as the main cooling mechanism of the stellar interior. This offers the exciting possibility to observe a substantive neutrino signal from a nearby giant stars months or days before it ends in an even more spectacular core-collapse Supernova explosion!

In this project, you will investigate the possibility to detect such an event in a large-volume neutrino observatory like Super-Kamiokande and JUNO. Based on the data on late-burning stage neutrino emission given below (taken from `arXiv:astro-ph/0311012`), calculate the event rates and spectra for electron scattering and inverse beta decay expected in a 20 kt water or liquid scintillator detector. Compare this to other, continuous neutrino signals (solar neutrinos, geoneutrinos, reactors) that might pose a background to these searches. What is the best chance of detection? What is the maximum distance at which such an event could be detected? Discuss how current-day detectors could be improved to detect pre-Supernova neutrinos from a progenitor star located at the galactic center ($d = 10\,\mathrm{kpc}$).

Note: The authors of `arXiv:astro-ph/0311012` *have of course investigated the possibility for detection of pre-SN neutrinos. While it will be instructive to read the first two chapters of the paper, you should stop there in order not to spoil the fun.*

Burning Phase	T_c [MeV]	ρ_c [g/cc]	μ_e [MeV]	L_ν [erg/s]	Duration τ	Total energy emitted [erg]
C	0.07	$2.7 \cdot 10^5$	0.0	$7.4 \cdot 10^{39}$	300 yrs	$7 \cdot 10^{49}$
Ne	0.146	$4.0 \cdot 10^6$	0.20	$1.2 \cdot 10^{43}$	140 days	$1.4 \cdot 10^{50}$
O	0.181	$6.0 \cdot 10^6$	0.24	$7.4 \cdot 10^{43}$	180 days	$1.2 \cdot 10^{51}$
Si	0.319	$4.9 \cdot 10^7$	0.84	$3.1 \cdot 10^{45}$	2 days	$5.4 \cdot 10^{50}$

Table 2
Properties of a 20 $M_\odot$ star according to Ref. [6]. We have calculated the total energy radiated in neutrinos as a product τL_ν. Actually, the neutrino emission is expected to be a function of time.

Burning phase	ν_e ($\bar{\nu}_e$) fraction	$\nu_{\mu,\tau}/\nu_e$ ratio	Average ν_x energy
C	42.5 %	1:11.4	0.71 MeV
Ne	39.8 %	1:7.8	0.99 MeV
O	38.9 %	1:6.9	1.13 MeV
Si	36.3 %	1:5.4	1.85 MeV

Table 3
Fraction of given neutrino flavor emitted by pair-annihilation, used in formula (9). One can notice increasing with temperature fraction of muon and tau neutrinos.

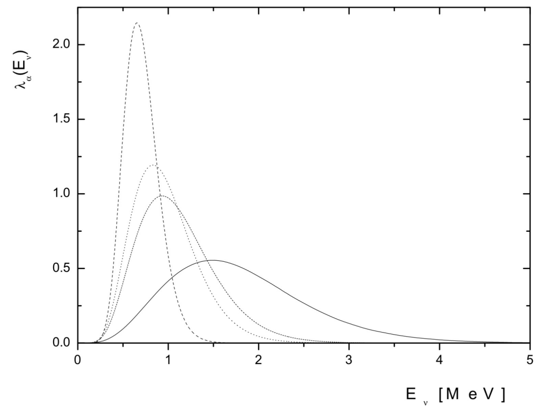

Fig. 1. Normalized spectrum of pair-annihilation anti-neutrinos emitted by 20 $M_\odot$ star during carbon (dashed line), neon (dotted line), oxygen (short-dashed line) and silicon (solid line) burning stage. The spectrum shape for all flavors of neutrinos and anti-neutrinos is very similar. However, relative fluxes of given neutrino flavors (cf. Table 3) are different. There is equal amount of neutrinos and anti-neutrinos. The average anti-neutrino energy is 1.80 MeV, 1.11 MeV, 0.97 MeV, 0.71 MeV for Si, O, Ne, and C burning stage, respectively. As we expect, for $T \to 0$ the spectrum shape approaches the $E_{\bar{\nu}} = m_e$ =0.51 MeV annihilation line.

10 Sensitivity studies with GLoBES

Learn to use the software package GLoBES and study the sensitivity of current and future experiments.

Focus: Neutrino oscillations
Requirements: Numerical calculation/GLoBES software
Author: Joachim Kopp

In planning neutrino oscillation experiments and in analyzing their data, simulations play a crucial role. One of the most powerful software tools for phenomenological studies in neutrino physics is GLoBES, which will be the topic of this tutorial.

Download GLoBES from `http://www.mpi-hd.mpg.de/~globes/` (we recommend to download the latest development version) and install it. GLoBES runs best on Linux machines, but usually works also on Macs, provided that a build environment is available. GLoBES depends on the GNU Scientific Library.

Next, download the GLoBES tutorials from the Documentation section of the webpage. There are four tutorials available:

1. **Simulating T2K.** In this entry-level tutorial, you will learn about the basic features of GLoBES, and you will study the sensitivity of the T2K experiment. (Note that this simulation is based on the T2K Letter of Intent, so results will differ from the performance of the actual T2K experiment.)

2. **AEDL featurea.** In this intermediate level tutorial, you will learn how to implement a new experiment in GLoBES.

3. **Advanced features.** In this advanced tutorial, you will learn how to control the treatment of systematic uncertainties in GLoBES and how to change the way oscillation probabilities are computed (relevant for instance for the implementation of scenarios beyond the Standard Model).

4. **Degeneracy Finding.** A common problem in fitting neutrino oscillation data is that several disjoint regions of parameter space can all give a good fit (for instance normal vs. inverted mass ordering). In this advanced tutorial, you will learn about strategies to make sure a fitting algorithm doesn't miss any of these regions.

Choose a tutorial that matches your interests and previous experience. All tutorials contain GNUPlot scripts for plotting results. Of course, you are welcome to use your own favorite plotting tool instead.

G. Cowan / INSS 2018
25,26 May 2018

INSS Statistics Project

The purpose of this exercise is to design a statistical test to discover a signal process such as dark matter by counting events in a detector. Suppose the detector can for each event measure a quantity x with $0 \leq x \leq 1$, for which probability density functions (pdfs) are for signal (s) and background (b),

$$f(x|s) = 3(1-x)^2 \,, \tag{1}$$

$$f(x|b) = 3x^2 \,. \tag{2}$$

1(a) Suppose for each event we test the hypothesis that it is background. We reject this hypothesis if the observed value of x is less than a specified cut value $x_{\rm cut}$. Find the value of $x_{\rm cut}$ such that the probability to reject the background hypothesis (i.e., accept as signal) if it is background is $\alpha = 0.05$. (The value α is the *size* or significance level of the test.)

1(b) For the value of $x_{\rm cut}$ that you find, what is the probability to accept an event with $x < x_{\rm cut}$ given that it is signal. (This is the *power* of the test with respect to the signal hypothesis or equivalently the signal efficiency.)

1(c) Suppose that the expected number of background events is $b_{\rm tot} = 100$ and for a given signal model one expects $s_{\rm tot} = 10$ signal events. Find the expected numbers of events s and b of signal and background events that will satisfy $x < x_{\rm cut}$ using the value of $x_{\rm cut} = 0.1$.

1(d) Assuming the numbers from 1(c), the prior probabilities for an event to be signal or background are

$$\pi_s = \frac{s_{\rm tot}}{s_{\rm tot} + b_{\rm tot}} = 0.09 \,, \tag{3}$$

$$\pi_b = \frac{b_{\rm tot}}{s_{\rm tot} + b_{\rm tot}} = 0.91 \,. \tag{4}$$

Based on these values, what is the probability for an event to be signal given that one finds $x < x_{\rm cut}$. (Recall Bayes' theorem or consult `arXiv:1307.2487`.)

1(e) Now suppose we do the experiment and observe $n_{\rm obs}$ events in the search region $x < x_{\rm cut}$. We now want to test the hypothesis that $s = 0$ (the background-only hypothesis or "b"), against the alternative that signal is present with $s \neq 0$ (the "$s + b$" hypothesis).

The actual number of events n found in the experiment with $x < x_{\rm cut}$ can be modeled as following a Poisson distribution with a mean value of $s + b$. That is, the probability to find n events is

$$P(n|s,b) = \frac{(s+b)^n}{n!} e^{-(s+b)} \,. \tag{5}$$

Suppose for a certain $x_{\rm cut}$ one has $b = 0.5$ and we find there $n_{\rm obs} = 3$ events. The p-value of the background-only hypothesis is the probability, assuming $s = 0$, to find $n \geq n_{\rm obs}$.

$$p = P(n \geq n_{\rm obs}|s=0,b) = \sum_{n=n_{\rm obs}}^{\infty} \frac{b^n}{n!} e^{-b} = 1 - \sum_{n=0}^{n_{\rm obs}-1} \frac{b^n}{n!} e^{-b} \; . \tag{6}$$

Find the p-value and from this find the *significance* with which one can reject the $s = 0$ hypothesis, defined as

$$Z = \Phi^{-1}(1-p) \; , \tag{7}$$

where Φ is the standard cumulative Gaussian distribution and Φ^{-1} is its inverse (the standard Gaussian quantile). For more information see Sec. 10 of `arXiv:1307.2487`. You will need the cumulative chi-square distribution and the quantile of the Gaussian distribution, which from ROOT are available as `1 - TMath::Prob` and `TMath::NormQuantile`.

1(f) The expected (median) significance assuming the $s+b$ hypothesis of the test of the $s = 0$ hypothesis is a measure of sensitivity and this is what one tries to maximize when designing an experiment. It can be approximated with a number of different formulas. For $s \ll b$ one can use $\mathrm{med}[Z_b|s+b] = s/\sqrt{b}$. If $s \ll b$ does not hold, a better approximation is

$$\mathrm{med}[Z_b|s+b] = \sqrt{2\left((s+b)\ln\left(1+\frac{s}{b}\right) - s\right)} \; . \tag{8}$$

Using Eq. (8), find me median significance for $x_{\rm cut} = 0.1$. Write a program that scans over values of $x_{\rm cut}$ between 0 and 1 and plots s, b and $\mathrm{med}[Z_b|s+b]$ (using the different approximations) versus $x_{\rm cut}$ and thus find the value of $x_{\rm cut}$ that maximizes the median significance.

1(g) Now suppose that for each event we do not simply count the events having x in a certain region but we design a test that exploits each measured value in the entire range $0 \leq x \leq 1$. The data thus consist of the number n of events, which follows a Poisson distribution with mean of $s + b$, and the n values $x_1, \ldots, x_n$.

We can define a test statistic to test the background-only hypothesis that is a monotonic function of the likelihood ratio L_{s+b}/L_b,

$$q = -2\sum_{i=1}^{n}\left[1 + \frac{s_{\rm tot}}{b_{\rm tot}}\frac{f(x_i|s)}{f(x_i|b)}\right] \tag{9}$$

The motivation for this statistic is described further in Sec. 5.1 of `arXiv:1307.2487`.

From `http://www.pp.rhul.ac.uk/~cowan/stat/mainz2018/project/mc/` download the program `invisibleMC.cc` and the makefile. Build and run the program. This will produce histograms of q under the $s + b$ hypothesis, and also a histogram of q (called `h_q_sb`) and it will find the median q, $\mathrm{med}[q|s + b]$.

You should add code in analogy with this that generates data according to the background-only ($s = 0$) hypothesis. Generate 10^7 experiments and count how many have $q < \mathrm{med}[q|s+b]$. The fraction with $q < \mathrm{med}[q|s + b]$ is the median p-value of the background-only hypothesis. Find this and from it find the median significance Z (the sensitivity). Compare to the values you found from Eq. (8).

The Hunt for Red October

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(Dated: May 15, 2018)

Nuclear-powered submarines are useful only as long as their position is unknown to the enemy. However, they emit a steady flux of electron antineutrinos resulting from the beta-decays of the fission fragments. Your task is, to either come up with a neutrino-based scheme which can pinpoint the location of a submerged nuclear-powered submarine or to convince the admirals that their submarines are safe from this threat.

Nuclear energy has revolutionized submarine warfare. Military submarines can stay submerged for months and move stealthily at high speeds through the oceans. Submarine-launched ballistic missiles (SLBM) are the backbone of nuclear deterrence since they offer an assured retaliatory capability. A submarine whose location has been uncovered by an adversary is usually relatively defenseless and thus avoiding detection is the operational priority of any submarine captain. Any major breakthrough in either avoiding detection or improving detection would have major consequences for naval and nuclear doctrine, see Ref. [1].

Conventional means to detect submarines center on acoustic signatures, but also electro-magnetic, temperature and chemical signatures have been proposed. Even exotic means outside of the realm of science like extrasensorial perception have been seriously investigated.

For the purpose of this mission, assume that a nuclear-powered submarine has a reactor with a thermal power of 150 MW. Its submerged top speed is 45 knots and its maximum diving depth is 300 m. The reactor power is proportional to the speed, a rough but useful approximation.

The antineutrino spectrum per fission from a submarine reactor can be approximated to stem only from fission in uranium-235, neutrino fluxes can be found in Ref. [2]. Neutrinos from reactors can interact via both charged current and neutral current reactions, for a review see [3]. Common detector types for charged current neutrino reactions are either liquid scintillator, *e.g.* KamLAND [4], or water Cerenkov types, *e.g.* Super-Kamiokande [5]. Both detector types profit from the addition of gadolinium to improve neutron tagging [6, 7]. Also neutral current reactions of low-energy neutrinos have been measured, for a recent results see Ref. [8].

During the Cold War the focus was on finding or concealing SLBM carrying submarines in the open, deep blue ocean and a detailed analysis of neutrino detection can be found in a JASON report [9]. The conclusion is rather negative, however the basic concepts how to approach the problem are sound. Neutrino detector technology has however made great progress in the past 30 years.

In your analysis focus on scenarios not involving the open ocean and not necessarily involving SLBMs. Think of current political events. Your task is, to either come up with a neutrino-based scheme which can pinpoint the location of a submerged nuclear-powered submarine or to convince the admirals that their submarines are safe from this threat.

You will need to come up with a detection reaction, a detector technology and then be able to compute event rates as a function of distance and speed of the submarine. Based on the specific application your thinking of, you will need come up with a search strategy or avoidance strategy. Statistical analysis would be useful, you can resort to the PDG review of statistics (written by G. Cowan who is lecturing at this school). Think of backgrounds, if you can. Note, that a submarine costs about as much as the LHC, that is 10^{10} USD/EUR. Some reactions allow to reconstruct neutrino direction. Imagine future technologies.

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13 Vertex reconstruction in scintillator

Build your own virtual solar neutrino detector! Learn to reconstruct the position of neutrino events in your liquid scintillator target to reject external background.

Focus: Low-energy neutrinos, event reconstruction algorithms
Requirements: Toy Monte Carlo
Author: Michael Wurm

Solar neutrino detectors are constantly fighting radioactive background to extract the faint neutrino signal from their data. One of the most important tools is the definition of a Fiducial Volume (FV) in the central region of the liquid scintillator target. In this way, the otherwise overwhelming external background of gamma-rays emitted from the detector and outside materials can be substantially reduced, greatly improving the signal-to-noise ratio. A basic prerequisite to this analysis approach is a reconstruction algorithm for the position of the (neutrino or gamma) event vertex. This information can be extracted from the position and arrival time pattern of scintillation photons on the photosensors (PMTs) surrounding the scintillator volume.

The project can be divided in two tasks (and, potentially, two teams): The composition of a toy MC for a generic liquid scintillator detector plus the programming of a reconstruction algorithm, and the generation of signal and background event distributions as well as an optimization of the fiducial volume definition.

Toy MC and reco: Assume a generic spherical detector of 5 m radius with perfect photodetection capabilities, i.e. 100 % photocoverage and photoefficiency. Now,

1. Write a photon generator for a point-like event vertex: Assume isotropic light emission and an exponentially decaying time profile ($\tau = 3\,\mathrm{ns}$). Use an effective light yield of 600 photons per MeV (taking into account typical photocoverage and photoefficiency values).

2. Prepare an algorithm to save photon hit positions and times on the active surface of your detector.

3. Write a basic reconstruction algorithm based on the barycenter of photon hits as a seed for the algorithm of step 4

4. Conceive a minimization routine that uses the time-of-flight (TOF) differences between individual photon hits to reconstruct the position of light emission. For this you will first need a generic PDF for photon arrival time at a given photosensor depending on the TOF, and then do a combined fit of all registered hits that minimizes PDFs vs. measured arrival times based on the vertex position.

5. Congratulations, you have arrived at a state-of-the-art reconstruction algorithm! Now, you can start to add all the detector effects that make life

interesting: For instance, the photosensors will feature finite time resolution ($\Delta t \approx 1\,\mathrm{ns}$), there will be light absorption and scattering processes in the liquid scintillator etc.

Event distributions and FV: Start again with a spherical detector ($r = 5\,\mathrm{m}$).

1. Determine the rate of ^{208}Tl gamma rays ($E_\gamma = 2.6\,\mathrm{MeV}$) emitted by a steel sphere of 3 cm thickness. For this, assume a contamination level of 8 mBq/kg of ^{232}Th decays inside the steel and assume secular equilibrium along the thorium decay chain.

2. Create a toy MC to determine the background event distribution: Start the gamma rays on the steel sphere in random directions, assuming the propagate straight and following an exponential absorption law ($\lambda_{\mathrm{abs}} = 16\,\mathrm{cm}$). Save the coordinates of absorption inside the scintillator volume.

3. In all state-of-the-art scintillator experiments, the outer part of the detection volume is formed by an inactive buffer layer (e.g. non-scintillating oil). How thick do you have to choose the layer in order to reduce the gamma background rate to $\sim 1\,\mathrm{s}^{-1}$?

4. Assume a neutrino interaction rate of $\sim$0.5 per day and ton (corresponding to elastic scattering of solar ^{7}Be neutrinos. Define a volume in which the signal-to-background ratio is better than 1:1.

5. Within this volume, how long do you have to measure to obtain a 5σ evidence of the solar neutrino signal? Study whether you would obtain evidence sooner for a different FV definition.

6. Based on the maximum energy transfer of ^{7}Be neutrinos ($E_\nu = 866\,\mathrm{keV}$), smear your event distributions for spatial reconstruction uncertainty. How does this affect your fiducial volume definition?

The Future of Long Baseline Neutrino Physics

May 20, 2018

1 Introduction

There's a lot of hype about the future of the long baseline neutrino physics program with rapid progress by T2K and NOvA and the next generation of experiments, DUNE and Hyper-Kamiokande, coming along. Let's take the future into our own hands and see what's in store for the next several years as T2K and NOvA continue to run in advance of DUNE and HK. In what follows, we will focus on T2K, given the publicly information available on both neutrino and antineutrino mode running.

2 Basic Physics

The basic formulas for neutrino oscillations at these experiments are very complicated, but a number of approximations exist in the literature.

- For electron (anti)neutrino appearance, there is the approximation of Freund, which can be found as Equation 13.39-13.43 in old editions of the PDG [1].
- for muon (anti)neutrino disappearance, beyond the two-flavor approximation, we have:

$$P(\nu_\mu \to \nu_\mu) = 1 - \left[\cos^4\theta_{13}\ \sin^2 2\theta_{23} + \sin^2 2\theta_{13}\ \sin^2\theta_{23}\right] \sin^2 \Delta m^2_{31} \frac{L}{4E} \tag{1}$$

Write these oscillation probabilities as functions that can be accessed in ROOT or Python, with the neutrino energy in GeV as the argument, and the oscillation parameters and baseline in kilometers as parameters. Note that the equations above use natural units, so be prepared to do the necessary unit conversions. Our current understanding of these parameters is summarized in Table 1. As a sanity check, you might consider evaluating the ν_μ oscillation probability at the peak energy of T2K (0.6 GeV) at its baseline (L=295 km). You should find $P(\nu_\mu \to \nu_\mu) \sim 0$ with current oscillation parameters at this energy and baseline.

[1] `http://pdg.lbl.gov/2008/reviews/rpp2008-rev-neutrino-mixing.pdf`

Parameter	Value
$\sin^2\theta_{12}$	0.307 ± 0.013
$\sin^2\theta_{13}$	0.0210 ± 0.0011
$\sin^2\theta_{23}$	0.51 ± 0.04
Δm^2_{21}	$(7.53 \pm 0.18) \times 10^{-5}\text{eV}^2$
$\lvert\Delta m^2_{31}\rvert$	$(2.45 \pm 0.05) \times 10^{-3}\text{eV}^2$

Table 1: Neutrino oscillation parameters in PDG2017

Experiment	Baseline L (km)	Peak E_ν (GeV)	Mass (kT)	Material	$\epsilon(\nu_\mu)$	$\epsilon(\nu_e)$
T2K(HK)	295	~ 0.6	33(384)	H_2O	~ 0.85	~ 0.7
NOvA	810	~ 2	14	H_2O		
DUNE	1300	~ 3	40	Ar		
T2HKK	1100	~ 1	192	H_2O		

Table 2: Summary of basic parameters for current and future long baseline experiments.

3 The Experiments

Basic parameters of current and future long baseline experiments are summarized in Table 2.

The neutrino fluxes at the far detectors for each experiment are publicly available at:

- T2K: `http://t2k-experiment.org/wp-content/uploads/T2Kflux2016.tar`
- NOvA: `http://nova-docdb.fnal.gov/cgi-bin/ShowDocument?docid=25266`

Pre-computed genie cross sections are also available at:

- Genie: `https://www.hepforge.org/archive/genie/data/2.12.10/`

3.1 Predictions in the absence of oscillations

Let's focus on the T2K experiment. Using the predicted $\nu_\mu/\overline{\nu}_\mu$ flux and the cross section splines for oxygen and hydrogen, predict in the absence of neutrino oscillations:

- The neutrino energy spectrum of ν_μ CC events per 10^{21} protons-on-target when the beam is running in neutrino mode (+250 kA horn operation).

	Normal Ordering				Inverted Ordering			
δ_{CP}	$-\pi/2$	0	$+\pi/2$	π	$-\pi/2$	0	$+\pi/2$	π
$N(\nu_\mu \to \nu_e)$								
$N(\overline{\nu}_\mu \to \overline{\nu}_e)$								

Table 3: Number of $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ per 10^{21} protons-on-target for various configurations of δ_{CP} and mass ordering.

- The neutrino energy spectrum of $\overline{\nu}_\mu$ CC events per 10^{21} protons-on-target when the beam is running antineutrino mode (-250 kA horn operation).
- the total number of events in each case.

at Super-Kamiokande.

The Super-Kamiokande detector uses a single ring selection that to first order selects CCQE and MEC events. So let's focus on these events and recalculate the spectra and event rates above restricting ourselves to the cross section for CCQE and MEC events (I'll collectively call these "single-ring" events).

3.2 Predictions for $\nu_\mu/\overline{\nu}_\mu$ events

Now apply the neutrino oscillation probability for $P(\nu_\mu \to \nu_\mu)$, $P(\overline{\nu}_\mu \to \overline{\nu}_\mu)$ with the current PDG values to these single-ring events as a function of the true neutrino energy and recalculate the spectra and rates in each beam mode. Overlay these predicted oscillated and unoscillated spectra and compare the event rates. As a sanity check, you may want to compare to recent T2K publications, taking note of the selection efficiency $\epsilon(\nu_\mu)$ in Table 2. Note that we have made a number of approximations so agreement at the $\sim 10\%$ can be expected.

3.3 Predictions for $\nu_e/\overline{\nu}_e$ events

Likewise, apply the neutrino oscillation probability $P(\nu_\mu \to \nu_e)$, $P(\overline{\nu}_\mu \to \overline{\nu}_e)$ with normal mass ordering and $\delta_{CP} = 0$ and calculate the spectra and event rate for single-ring $\nu_\mu \to \nu_e$ events in neutrino mode and $\overline{\nu}_\mu \to \overline{\nu}_e$ events in antineutrino mode. For our purposes, you can assume that ν_μ and ν_e have the same cross sections. Then, consider the expected rate of events for $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ in neutrino and antineutrino modes, respectively, for various configurations of δ_{CP} and ordering, according to Table 3. As before, you may want to compare with recent T2K publications, taking into account the selection efficiency $\epsilon\nu_e$ and the fact that we have made a number of approximations.

3.4 Analysis

Armed with the above results, let's investigate the following questions:

- Equation 1 shows that $P(\nu_\mu \to \nu_\mu)$ depends on $\sin^2\theta_{23}$, which in principle is sensitive to the "octant" of θ_{23}, namely whether it is greater or less than $\pi/4$ radians (assuming it isn't exactly $\pi/4$ radians). Is it actually possible to extract the octant of θ_{23}, assuming it has a non-maximal value using just this channel?

- Equation 1 is the same for both ν_μ and $\overline{\nu}_\mu$. Is there a simple reason why this is the case?

- Given an observed number of $\nu_\mu \to \nu_e$ events, what would the "allowed" region in the plane δ_{CP} vs. $\sin^2\theta_{13}$ look like if we assume normal ordering and all the parameters are known? What if we assume inverted ordering?

- Same for $\overline{\nu}_\mu \to \overline{\nu}_e$ events.

- T2K hopes to eventually accumulate 20×10^{21} protons-on-target of data. Assuming this is split evenly between neutrino and antineutrino running, how many $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ events can we expect to observe for the various values of δ_{CP} and mass ordering considered in Table 3? Assuming $\delta_{CP} = -\pi/2$ is the true value and the mass ordering is normal, with what confidence could we exclude the CP-conserving cases of $\delta_{CP} = 0, \pi$. What sources of uncertainty have we neglected?

- Reactor experiments have measured θ_{13} with high precision, as shown in Table 1. How might the strategy of neutrino vs. antineutrino running change if we assume (or do not assume) θ_{13} to be known, in order to maximize sensitivity to CP violation?

- Due to its relatively low energy and short baseline (*i.e.* that α in the Freund approximation is $\ll 1$), matter effects in neutrino oscillations at T2K are relatively small. In what cases can we expect T2K to be able to resolve the mass ordering? In what cases is it maximally degenerate with other (unknown or insufficiently known) parameters?

15 Neutrino detection at 30 PeV

Assess a possible detector design for cosmic neutrinos at the very highest energies.

Focus: High-energy neutrinos, detector physics
Requirements: Analytical and numerical estimates
Author: Dave Seckel

The IceCube astrophysical neutrino flux extends above a PeV, but is uncertain above that. The purpose of this exercise is to assess possible detector designs to obtain a countable number of events. Make estimates of event rate from $N = \phi \cdot A \cdot \Omega \cdot t$, where Area A and Ω are estimated for different detection strategies and technologies. Compare optical and radio techniques. Explicitly consider "ν_τ" channel and transparency of the Earth. Consider cost in design.

16 Separation of hadronic and electromagnetic cascades

Explore methods to separate hadronic from electromagnetic cascades in a high-energy neutrino telescope.

Focus: High-energy neutrinos, detector physics
Requirements: analytical calculations or GEANT
Author: Dave Seckel

Explore methods to separate hadronic from electromagnetic cascades. Include conventional and prompt μ production, μ-echo, n-echo, luminescence, LPM effect. Targeted toward flavor ID in IceCube. Make analytic and/or numerical (GEANT) estimates of μ, neutron yields. Make estimates of detection significance against background noise. Can one separate ν_e cascades from neutral current hadronic recoil cascades? Is there sensitivity to ν_τ cascades, which are intermediate.