Experimental Questions in Neutrino Physics

*part 1: The Known Knowns*

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University of Manchester
Outline

• In this lecture I will talk about the history of experimental neutrino physics and where we are now.

• Tomorrow I will talk about measurements that are ongoing or proposed that will expand our understanding of the model.

• I tried to avoid explaining experimental techniques as much as possible – which is not that much.
Neutrinos in the Standard Model

- Interact only weakly
- Maximal breaking of C and P symmetries (no R-handed neutrinos and L-handed antineutrinos.)

Charged Current (CC) Interaction – how we define a neutrino flavor:
How neutrinos interact

CC:
\[ \nu_l \rightarrow \text{Nucleon} \rightarrow W^\pm \nu_l \]

NC:
\[ \nu_l \rightarrow \text{Nucleon} \rightarrow Z^0 \pi^0 \gamma \nu_l \]

I am deliberately not specifying single nucleons.

ES:
\[ \nu_l \rightarrow e \rightarrow Z^0 \nu_l \]

No “new” lepton in final state – cannot distinguish \( \nu \) flavor.

Neutral Current

Neutral Current

Elastic Scattering

No “new” lepton in final state – cannot distinguish \( \nu \) flavor.
Sources of Neutrinos

We have discovered many sources of neutrinos:

- Nuclear Reactors
- The Sun
- Cosmic Rays
- SuperNova stars
- The Earth Core
- Radioactive Sources

We can even create beams of neutrinos!
A Bit of History

β-decay spectrum

2-body decay:
Centre of Mass frame

\[ p_1 = p_2 = p \]

- W. Pauli proposes the neutrino (then called neutron) to solve this problem:
- "I have done a terrible thing, I have postulated a particle that cannot be detected."

\[ \text{Expected from 2-body decay:} \]

\[ \text{Observed:} \]

\[ \text{electron kinetic energy (MeV)} \]
Experimental detection

• Fortunately, he was proven right (per theory prediction) and wrong (per experimental prediction) by Reines and Cowan in 1956.
• A clever signature: Inverse Beta Decay (IBD):

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

Prompt annihilation
2x 511keV γ

Unique signature of neutrino

Delayed (5x10^{-6} s)
γ capture on Cd

---

WESTERN UNION

June 14, 1956

Dear Professor Pauli,

We are happy to inform you that we have definitely detected neutrinos. . .

Fred Reines
Clyde Cowan
Detection of the $\mu$ and $\tau$ neutrinos

- Discovery of the muon neutrino
  - Discovery of the muon neutrino ($\nu_\mu$)
  - Brookhaven 1962
  - Shoot a 15 GeV beryllium target
  - Pions
  - $\nu_\mu$
  - A spark chamber

- Discovery of the tau neutrino ($\nu_\tau$)
  - Tau neutrino observed by DONUT at FNAL in 2000
  - 800 GeV proton beam at a tungsten beam dump
  - $D_s$ mesons,
  - $\nu_\tau$
  - Neutrinos and detect them using emulsion detector.
“known” Questions in $\nu$-physics
(answered or being answered)

- Experimental neutrino physics in the last decades was driven by the following questions:

  - why do we see less neutrinos from the sun?
  - where are the atmospheric $\nu$s?
  - could this be due to oscillations?
  - What are the parameters of oscillation?
    - Especially, is $\theta_{13}$ non-zero?
  - Is the $\theta_{23}$ mixing maximal?
  - what is going on with neutrino interactions?!
Solar Neutrinos

Things to note:
All neutrinos are $\nu_e$
Majority of $\nu$'s have lowest energy

"Proton proton cycle" by Dorottya Szam
Observing Solar Neutrinos

- Used neutrino capture on \(^{37}\text{Cl}\), which results in \(^{37}\text{Ar}\) which is radioactive. (0.814 MeV thresh.)

- Via ingenious chemical methods the \(^{37}\text{Ar}\) was extracted and measured (~0.5 atoms produced/day!)

- The number of neutrinos observed was way off from expectation.

- Experiment is wrong?
- Theory is wrong?
- Something fishy is going on here?

ASTROPHYS JOURN., 496:505526, 1998

R. Davis Jr constructing his experiment in the Homestake mine
A deficit of Solar Neutrinos?

- Other experiments radiochemical using Gallium (0.2 MeV threshold) also saw a deficit.
- As did Water Cherenkov.
- But at a different rate?
- Other measurements of the Sun agree with the Solar Theoretical Model.
Cherenkov Detectors

- Originally developed to look for proton-decay, but appropriated for neutrino physics.
- Cherenkov light is emitted when a particle travels faster than the speed of light (in the medium).
- Hard to see heavier particles like protons etc...
- But has directionality!

\[
\cos \theta = \frac{AB}{AC} = \frac{1}{n\beta} = \frac{1}{n}
\]
Discovery of atmospheric neutrinos and their asymmetry

Primary cosmic ray (p, He ..)

atmosphere

Generation height
10~30km

\( \nu_\mu / \nu_e \sim 2 \)  
\(< \sim 1 \text{ GeV } \)

\( \nu_\mu / \nu_e > 2 \)  
\( > \sim 1 \text{ GeV } \)

Super Kamiokande detector misses muon neutrinos from the bottom (but not from the top).

Neutrinos are disappearing. What is happening to them?
SNO – resolving the Solar problem

Extremely clever idea: try to observe electron and other neutrinos separately using properties of Heavy Water.

Different reactions have different signatures:
CC – isotropic Cherenkov Rings
NC – delayed neutron capture (≈6.25 MeV)
ES – Cherenkov Rings pointing back to the sun

<table>
<thead>
<tr>
<th>Charged Current</th>
<th>$\nu_e + d \rightarrow p + p + e^-$</th>
<th>$E_{th} = 1.4$ MeV</th>
<th>$CC \text{ Rate} \propto \Phi(\nu_e)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral Current</td>
<td>$\nu_x + d \rightarrow \nu_x + p + n$</td>
<td>$E_{th} = 2.2$ MeV</td>
<td>$NC \text{ Rate} \propto \Phi(\nu_x)$</td>
</tr>
<tr>
<td>Elastic Scattering</td>
<td>$\nu_x + e^- \rightarrow \nu_x + e^-$</td>
<td>$E_{th} \sim 0$</td>
<td>$ES \text{ Rate} \propto \Phi(\nu_e) + 0.154 \Phi(\nu_\mu + \nu_\tau)$</td>
</tr>
</tbody>
</table>
SNO (2)

Total flux from the sun agrees with the model. But, we know that the sun only produces $\nu_e$. 
"known" Questions in $\nu$-physics  
(answered or being answered)  

• Experimental neutrino physics in the last decades was driven by the following questions:

- why do we see less neutrinos from the sun?  
- where are the atmospheric $\nu$s?  
- could this be due to oscillations?  
- What are the parameters of oscillation?  
  - Especially, is $\theta_{13}$ non-zero?  
  - Is the $\theta_{23}$ mixing maximal?  
- what is going on with neutrino interactions?!

Knowing that neutrinos oscillate has opened a whole new field of experimental physics.
Neutrino Oscillations

- We know three neutrino flavors: $\nu_e$, $\nu_\mu$ and $\nu_\tau$.

- SNO and Super-K tell us that neutrinos are not disappearing. They're changing into one another. Oscillating.

- Then $\nu_1$, $\nu_2$ - mass eigenstates = eigenstates of free Hamiltonian.

- $\nu_e$, $\nu_\mu$ eigenstates of interaction Hamiltonian

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu
\end{pmatrix} =
\begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]
Measuring Neutrino Oscillations

- In oscillation physics we usually start with one type of neutrino and measure how it changes into another type.
- We can do this by detecting the new neutrinos (appearance) or registering the loss of original (disappearance).
- We can tell neutrinos apart by the effect of their “Charged Current” interactions.

In a two neutrino model, the probability of this oscillation looks like this:

\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2_{12} L}{4E_\nu} \right) \]
Things to note

• Oscillations are only possible if neutrinos have mass

• But we don't know what it is, only the squared difference (a parameter).

• Mixing angles are another parameter.

• Adjusting L/E allows us to measure different mixings.

\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]

\[ \Delta m_{12}^2 = m_1^2 - m_2^2 \]

\[ \frac{\Delta m^2 L}{4E} \ll 1 \]

Oscillations did not have a chance to happen

\[ \frac{\Delta m^2 L}{4E} \gg 1 \]

Oscillations averaged out – only sensitive to mixing angle
Expanding to three flavours

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

\[ V_{MNS} \approx \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \]

\[ V_{CKM} \approx \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix} \]

\[ \mu \Rightarrow \tau \quad \mu \Leftrightarrow e \quad e \Leftrightarrow \mu \]
Filling out the PMNS mixing matrix

• For precise measurements we need:
  - Large detectors (statistics)
  - Control of flux (how many neutrinos do we have?)
  - Energy resolution – both at source and in detector
  - Patience

Change L/E in order to probe different $\Delta m^2$ and mixing angles.

Create neutrinos to our specifications.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>L/E [km/MeV]</th>
<th>$\Delta m^2$ sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor LBL</td>
<td>~1</td>
<td>$\sim 10^{-3}$ eV$^2$</td>
</tr>
<tr>
<td>Reactor VLBL</td>
<td>~100</td>
<td>$\sim 10^{-5}$ eV$^2$</td>
</tr>
<tr>
<td>Accelerator SBL</td>
<td>$\sim 10^{-3}$</td>
<td>$\sim 10^{-5}$ eV$^2$</td>
</tr>
<tr>
<td>Accelerator LBL</td>
<td>~1</td>
<td>$\sim 10^{-3}$ eV$^2$</td>
</tr>
<tr>
<td>Atmospheric</td>
<td>~10</td>
<td>$\sim 10^{-4}$ eV$^2$</td>
</tr>
</tbody>
</table>
Man-Made Neutrinos: Reactor

- Used to discover first neutrinos.
- Cheap (apparently people use them for other things.)

- Energy range is fixed.
- The neutrino spectrum is a result of a complicated system.
Man-Made Neutrinos: Reactor

Nuclear reactor fuel and subsequent fission fragments are neutron rich and decay by turning neutrons to protons and emitting antineutrinos.

99% of neutrinos comes from 4 isotopes $^{235}$U, $^{239}$Pu, $^{238}$U and $^{241}$Pu.

- **Ab Initio approach:**
  Calculate spectrum branch-by-branch using beta branch databases: endpoints, decay schemes → needs some guessing with rare beta decays.

- **Conversion approach**
  Measure beta spectra directly, convert to $\nu_e$ using ‘virtual beta branches’. → This is not that well defined.

  King and Perkins, Phys. Rev. 113 (1958)

In general, anti-neutrino flux follows the heat emission of the reactor.
Man-Made neutrinos: Accelerator

• Need:
  – Beam of protons
  – Target
  – Focusing horn (magnetic field)
  – Decay pipe

Costs more, but have more control over energy.
Calculating spectra is also difficult.
Man-Made neutrinos: Accelerator (2)

Off-axis give better energy resolution, But less events.
Minos/Minos+

A. Blake
Tokai to Kamioka (T2K)

Super-Kamiokande
(ICRR, Univ. Tokyo)

J-PARC Main Ring
(KEK-JAEA, Tokai)

6/26/15
A. M. Szlec, LV Krakow School of Theoretic
$\theta_{23}$ measurements

**MINOS**

*Normal hierarchy*

$|\Delta m_{32}^2| = 2.34^{+0.09}_{-0.09} \times 10^{-3}\text{eV}^2$

$\sin^2 \theta_{23} = 0.43^{+0.16}_{-0.04}$

$0.37 < \sin^2 \theta_{23} < 0.64$ (90% C.L.)

*Inverted hierarchy*

$|\Delta m_{32}^2| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\text{eV}^2$

$\sin^2 \theta_{23} = 0.43^{+0.19}_{-0.05}$

$0.36 < \sin^2 \theta_{23} < 0.65$ (90% C.L.)

**T2K**

T2K favours maximum disappearance

In contrast to SK atmospheric and MINOS

6/26/15

A. M. Szelc, LV Krakow School of Theoretical Physics
$\nu_\tau$ extremely hard to detect – need high energy to create $\tau$ and great resolution to see it.

Emulsion detectors.

Neutrinos found to switch to elusive ‘tau’ flavour
Experiment that once claimed faster-than-light observation achieves its original goal.

Davide Castelvecchi
16 June 2015

Now a 5 sigma measurement.
Solar neutrinos

- The best measurement of the Solar Mixing angle comes from a reactor experiment (KamLand).

L is the effective baseline taken as a flux-weighted average (L=180km);
We are still looking at the Sun

- Was able to reduce natural radioactivity enough to lower their threshold to ~100 keV
Observation of the pp-cycle in Borexino

\[ \chi^2/d.o.f. = 172.3/147 \]

- \textbf{pp }\nu\textbf{: }144 \pm 13 \text{ (free)}
- \textbf{7Be }\nu\textbf{: }46.2 \pm 2.1 \text{ (constrained)}
- \textbf{pep }\nu\textbf{: }2.8 \text{ (fixed)}
- \textbf{CNO }\nu\textbf{: }5.36 \text{ (fixed)}
- \textbf{210Pb: }0.06 \text{ (fixed)}
- \textbf{210Po: }583 \pm 2 \text{ (free)}
- \textbf{14C: }39.8 \pm 0.9 \text{ (constrained)}
- \textbf{Pile-up: }321 \pm 7 \text{ (constrained)}
- \textbf{210Bi: }27 \pm 8 \text{ (free)}
- \textbf{85Kr: }1 \pm 9 \text{ (free)}

\[ P(v_e - v_\nu) \]

\[ \Delta m^2_{21} \]

\[ \sin^2 \theta_{12} \]

Global fit:
\[ \begin{array}{|c|c|}
\hline
\sin^2 \theta_{12} & 0.304^{+0.013}_{-0.012} \\
\Delta m^2_{21}/10^{-5} \text{ eV}^2 & 7.50^{+0.19}_{-0.17} \\
\hline
\end{array} \]

JHEP 1411:052, 2014

6/26/15

A. M. Szelić, LV Krakow School of Theoretical Physics
The state of affairs as of 2011

- We knew that 3 neutrinos exist.
- Two mass splittings $\Delta m^2_{\text{sol}}$, $\Delta m^2_{\text{atm}}$ and mixing angles measured.
- We do not know the mass hierarchy (normal or inverted?).
- We do know the neutrino masses are very small.
- Biting our nails, hoping the mixing angle: $\theta_{13}$ is big enough so that a measurement of the CP violation phase is possible (tomorrow's lecture).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$\sim 0.45$</td>
<td>LBL Acc</td>
</tr>
<tr>
<td>$\Delta m^2_{32}$</td>
<td>$\sim 2.4 \times 10^{-3} \text{eV}^2$</td>
<td>LBL Acc</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>$\sim 0.3$</td>
<td>VLBL react.</td>
</tr>
<tr>
<td>$\Delta m^2_{32}$</td>
<td>$\sim 7.5 \times 10^{-5} \text{eV}^2$</td>
<td>VLBL Reac, SNO</td>
</tr>
</tbody>
</table>
Daya-Bay – an example of an LBL reactor neutrino experiment.

- Detection via scintillation light (liquid scintillator)
- Use Inverse Beta Decay signature.
- Doped with Gd to increase neutron capture.
Daya-Bay/Reno/Double Chooz

\[ \sin^2 2\theta_{13} = 0.084 \pm 0.005 \] (Daya-Bay)

\[ \sin^2 2\theta_{13} = 0.09 \pm 0.03 \] (D-Chooz)

\[ \sin^2 2\theta_{13} = 0.088 \pm 0.011 \] (RENO)
The 5 MeV bump

Day Bay

Entries / 250 keV

Prompt Positron Energy (MeV)

Data/Prediction

Prompt Energy [MeV]

RENO

Near detector

Data
Prediction

$\sin^2 2\theta_{13} = 0.103$
$|\Delta m^2_{31}| = 2.32 \times 10^{-3} \text{ eV}^2$
Ab-initio calculations

- Making different assumptions can reproduce bump.
- But has problems with the beta spectra.
- There are other things that are fishy with the fluxes (more on that tomorrow).
\[ \theta_{13} \text{ by } \nu_e \text{ appearance} \]

In parallel, long baseline neutrino experiments have measured \( \nu_e \) appearance

- 7.3 sigma evidence for electron neutrino appearance in T2K.
- First ever conclusive evidence of neutrino flavour appearance

MINOS
“known” Questions in ν-physics (answered or being answered)

- Experimental neutrino physics in the last decades was driven by the following questions:

- why do we see less neutrinos from the sun?
- where are the atmospheric νs?
- could this be due to oscillations?
- What are the parameters of Oscillation?
  - Especially, is $\theta_{13}$ non-zero?
  - Is the $\theta_{23}$ mixing maximal?
- what is going on with neutrino interactions?!
The Current State of Knowledge
The neutrino model

- Our picture of Neutrinos in the standard model is almost complete.
- Large “mixing” angle $\theta_{13}$ opens the way to measurements of CP violation in the neutrino sector (not guaranteed).
- The mixings are very different than in the quark sector.
- We do not know the absolute neutrino mass.

“Known” physics

“Unknown” physics
“known” Questions in $\nu$-physics
(answered or being answered)

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How to measure $\nu$ interactions in a LArTPC

- The LArTPC and its bubble chamber like-data gives us strong background rejection tools.
- As well as extremely powerful tools to see e.g. nuclear effects.

\[
\begin{align*}
\nu_l &\rightarrow \nu_l \\
Z^0 &\rightarrow \pi^0 \\
\gamma &\rightarrow \\
\text{Nucleon} &\rightarrow \text{proton} \\
\text{Muon} &\rightarrow \text{Charged }\pi
\end{align*}
\]
LArTPC Operation

Liquid Argon TPC

Anode wire planes: U, V, Y

Cathode Plane

$E_{\text{drift}} \approx 500 \text{V/cm}$

PMT
Final State Interactions

- LArTPCs, and their resolution and calorimetric capabilities of allow us to reconstruct exclusive topologies.
- We can see if nuclear effects play a key role in neutrino-nucleus interactions in nuclear targets.
- Due to intra-nuclear re-scattering (FSI) Final State interactions additional nucleons, many de-excitation γ’s and and soft pions appear in the Final State.
- ArgoNeuT was one of the first detectors to be able to observe these effects.
Observing proton multiplicities

• The granularity of the LArTPC allows seeing actual final state topologies.

• Measuring cross sections as a function of proton multiplicity.
Back-to-Back Protons

4 back-to-back 2-proton events observed in Lab frame.

Possible mechanism is CC RES pionless reactions involving pre-existing SRC np pairs.

We can see nuclear effects!

ArXiv:1405.4261

PRD90, 012008 (2014)
Summary of Part 1

• The 3 neutrino model seems almost sorted out.
• We have understood many of the first questions in experimental neutrino physics thanks to the phenomenon of oscillations.
• There are interesting things happening in the neutrino-nucleus interactions.
• Tomorrow: what are the experimental questions that are driving the field today and in the future.
The $\nu$-interaction conundrums

Low energy coherent pion production

Quasi-elastic "high-MA" puzzle

Resonant pion production

Low energy coherent pion production

Quasi-elastic "high-MA" puzzle

Resonant pion production

A. M. Szél, LV Krakow School of Theoretical Physics
Coherent Pion Production

\[ \nu_\mu + A_{g.s.} \rightarrow \mu^- + \pi^+ + A_{g.s.} \]

\[ \bar{\nu}_\mu + A_{g.s.} \rightarrow \mu^+ + \pi^- + A_{g.s.} \]

Both ArgoNeuT and MINERVA measured coherent pion production.
Particles Passing Through Matter

Non-charged particles (e.g. neutrinos and photons) are invisible to our detectors until they interact.

Charged particles ionize the medium along their path – charge and scintillation light which we can detect!

### Charged Particles in Matter:

**(very simplified)**

- **e^−**: electron
- **μ^−/+**: muon

- **ionization**
- **scintillation**

### Photons in Matter:

- **photoelectric effect**
- **Compton scattering**
- **pair production**
New MINOS+ Data

- Combined MINOS and MINOS+ beam data are well-described by standard neutrino oscillations:

- MINOS+ data provide significant statistical improvement at multi-GeV energies.
  - Full MINOS+ data set ($>10 \times 10^{20}$ POT) will further improve precision of $\Delta m^2_{32}$ measurement.
Reactor SBL oscillation

\[ P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m^2_{ee} L}{4E} \right) - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \left( \frac{\Delta m^2_{21} L}{4E} \right) \]

\[ \Delta m^2_{\text{atm}} \]

\[ \Delta m^2_{\text{sol}} \]

\[ L \sim 1-2 \text{ km} \]

\[ L \sim 60 \text{ km} \]

Baseline (km)
The IceCube Neutrino Observatory

IceCube:
- 78 strings, 125 m/17 m spacing
- Energy range: $\sim$ 100 GeV to $\approx$ 10 PeV
- 1 km³ volume of south pole ice as $\nu$ target, and medium for Cherenkov light production.

DeepCore:
- 8 additional strings, $\sim$ 40 - 70 m / 7 m spacing
- Spans $\sim$ 10 - 100 GeV
- Targets atmospheric $\nu$ oscillations and dark matter searches
Atmospheric Neutrino Oscillations

- Neutrinos available over a wide range of energies and baselines
  - Oscillations produce a distinctive pattern in energy-angle space
  - $\nu_\mu$ 1st survival minimum $\sim 25$ GeV, and hierarchy-dependent matter effects below $\sim 12$ GeV.
- Large detector required to provide sufficient statistics to make this approach feasible
  - DeepCore event rates

<table>
<thead>
<tr>
<th>type</th>
<th>triggered</th>
<th>analysis level</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>$\sim 70$ k/yr</td>
<td>$\sim 1-10$ k/yr</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>$\sim 10$ k/yr</td>
<td>$\sim 0.1-3$ k/yr</td>
</tr>
</tbody>
</table>
Atmospheric Oscillations with IceCube-DeepCore

- Projection onto reconstructed $L/E_\nu$ for illustration purposes
- Shaded range shows allowed systematics with constraints from current data

Good agreement in control region

Good description of oscillation region

Observed: 5174 events in 953 days lifetime

UHE neutrinos in IceCube
Coherence of Conventional Neutrino Beams

Neutrinos are finite wave packets. Different masses should travel with different velocities – how long are they coherent?

For Pion DIF it depends on the size of the pion wave packet – calculate that and you know how long the coherence sticks.

Re(ψ)

Source Osc Max

Kicks in sooner with big Δm2 or small packet width

m1 m2 μ e