Neutrinos @U Minn

Daniel Cronin-Hennessy

Introduction to Research Seminar

Nov 16 2007

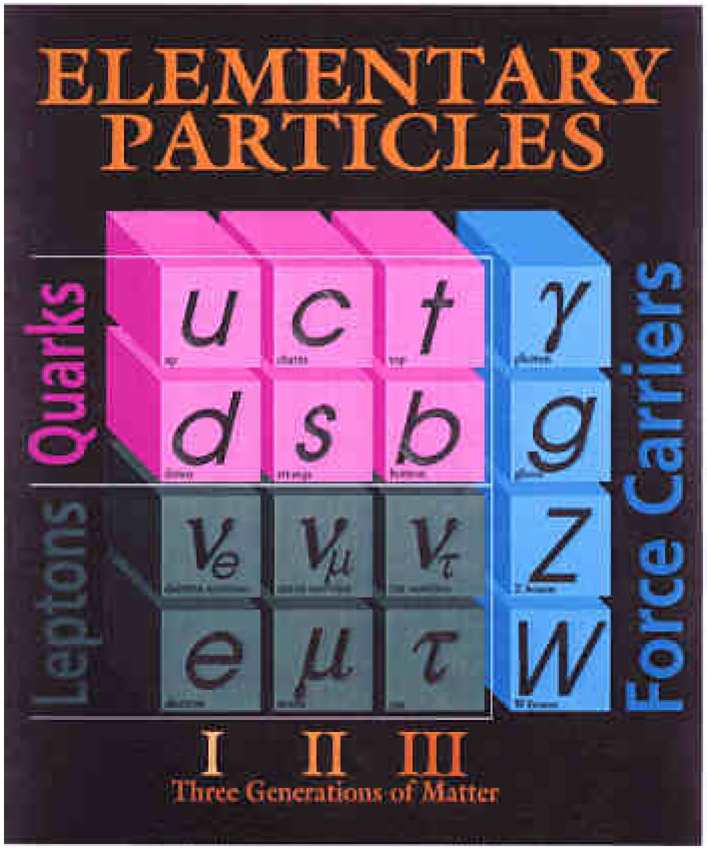
Outline

- Introductions
- Physics Overview (The bigger picture).
  - Mass, Handedness, and Asymmetries
- Neutrinos and Oscillations
- NOνA
- Summary

Neutrino Group

- Dan Cronin-Hennessy
- Ken Heller
- Marvin Marshak
- Ron Poling
- 5 PDs
- 5 GS
- N Staff

The Standard Model



Four fundamental forces:

Strong: gluons
Weak: W+, W-, Z0
Electromagnetic: photons
Gravity: gravitons

Fundamental particles come two types:

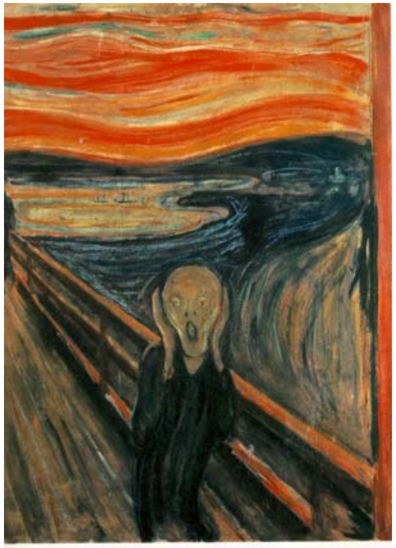
Leptons: electron and heavier cousins
Quarks: which carry an additional charge (color).

3 generations of each.

The "stable" (lowest quark mass) are the constituents of protons/neutrons.

Our interest is neutrino oscillations: eg $\nu_\mu \rightarrow \nu_\tau$

Fundamental Forces



- Electromagnetic
- Strong
- Weak

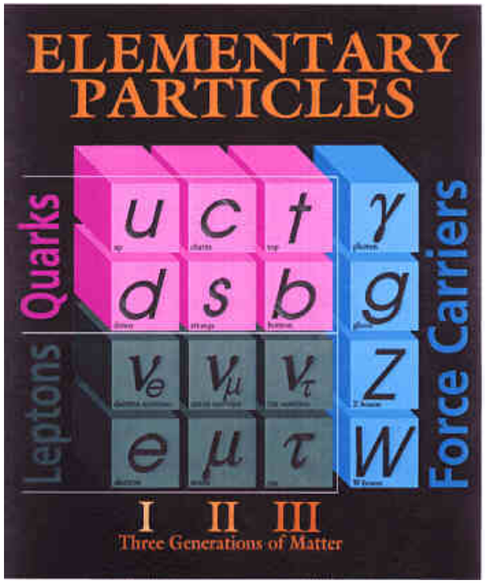
Electromagnetic

- Recall Stern-Gerlach Experiment
  - B gradient distinguishes alternative spin orientations
  - Still, we do not think of spin-up and spin-down electrons as different particles.

$|\uparrow\rangle$ Electron spin up $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$

$|\downarrow\rangle$ Electron spin down $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$

Weak



- Weak Isospin or T: Weak Charge
  - Double valued charge.
  - Mathematically equivalent to spin (SU(2))

$\begin{pmatrix} 1 \\ 0 \end{pmatrix}$ Weak Isospin up, T_3=+1/2: neutrino

$\begin{pmatrix} 0 \\ 1 \end{pmatrix}$ Weak Isospin down, T_3=-1/2: electron $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$

Can we seriously view the electron and neutrino as substates of one particle? Is the weak isospin symmetry a good symmetry?

Note: Left-handed particle states have T=1/2 and Right-handed states T=0

Standard Model Pre-Y2K

- Neutrinos massless
  - Gravitational charge = 0 (mass=0)
  - Electric charge = 0
  - Strong charge = 0 (no color)
  - Weak charge for RH states = 0

*** A true “ghost”.

Quick and Dirty Interpretation of Neutrino Oscillations

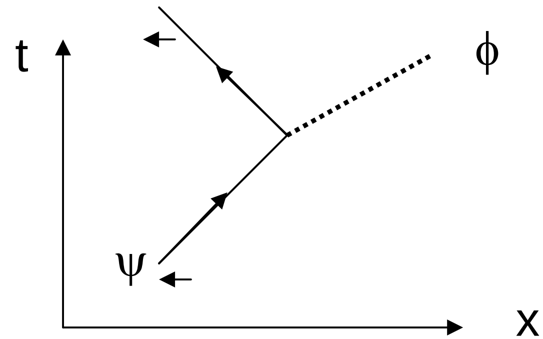
- Particles that move at the speed of light (massless) have “stopped clocks” ➔ No change possible
- Neutrinos change (oscillation)➔ Neutrinos move slower than light ➔ Some types of neutrinos must have non-zero mass.
- I can change the direction of a moving neutrino by changing my frame of reference. Momentum changes but spin does not. LH ←→ RH.

Inigo: *I admit it. You are better than I am.*
Man in Black: *Then why are you smiling?*
Inigo: *Because I know something you don't know.*
Man in Black: *And what is that?*
Inigo: *I am not left handed! [switches sword to his right hand]*

Man in Black: *Get used to disappointment.*
Inigo: *Okay.*

Mass

Interaction



$$m\overline{\Psi}\Psi$$

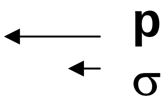
$$m(\overline{\Psi_L}\Psi_R + \overline{\Psi_R}\Psi_L)$$

$$\sim g\overline{\Psi}\phi\Psi$$

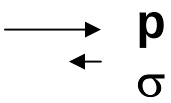
$$\sim \overline{g\Psi}(H + v)\Psi$$

$$\sim g\overline{\Psi}H\Psi + g v\overline{\Psi}\Psi$$

Particle in one frame:

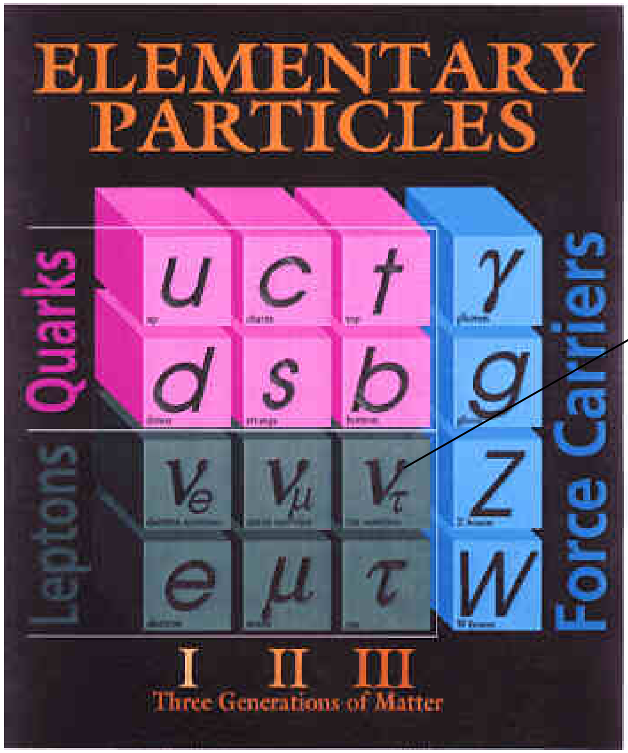


And in another:



Does the neutrino fit into this clever fermion mass generation scheme?

Comparable masses



No. Neutino masses (eV) Are off-scale compared to variations within a generation

Low Mass

Med Mass

High Mass

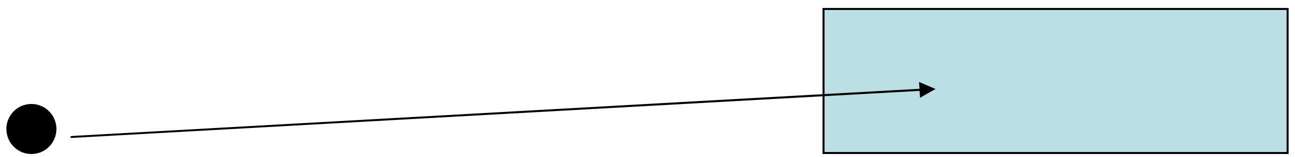
Summary: Why is the study of neutrinos a high priority?

- We know less about neutrinos than other particles.
- Neutrinos oscillate → mass
  - Mass generation may be different for neutrinos.
  - Neutrino could be a fundamentally different type of particle (Majorana) compared to other fermions.
  - The neutrino is the only fundamental fermion without electric charge (could be its own anti-particle).
- Is the study of neutrinos a path to new physics?
  - Possibly, the feeble mass may suggests a new high energy scale.

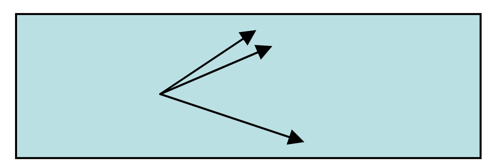
A “typical” experiment

Produce a particle that interest you

Build a detector to monitor the various interactions of the particle



Free particle propagates to detector: just wait



This is the interesting part for neutrinos.

Study weak interactions

Propagation depends on states of definite mass.
Interactions depend on Weak eigenstates

Neutrino Oscillations

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha,i} |\nu_i\rangle,$$

The matrix has **3 mixing angles** (θ_{12}, θ_{23}, θ_{13}) and one phase (δ).

$$\begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}c_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Two-neutrino oscillation formula. $\nu_\mu \rightarrow \nu_\tau$

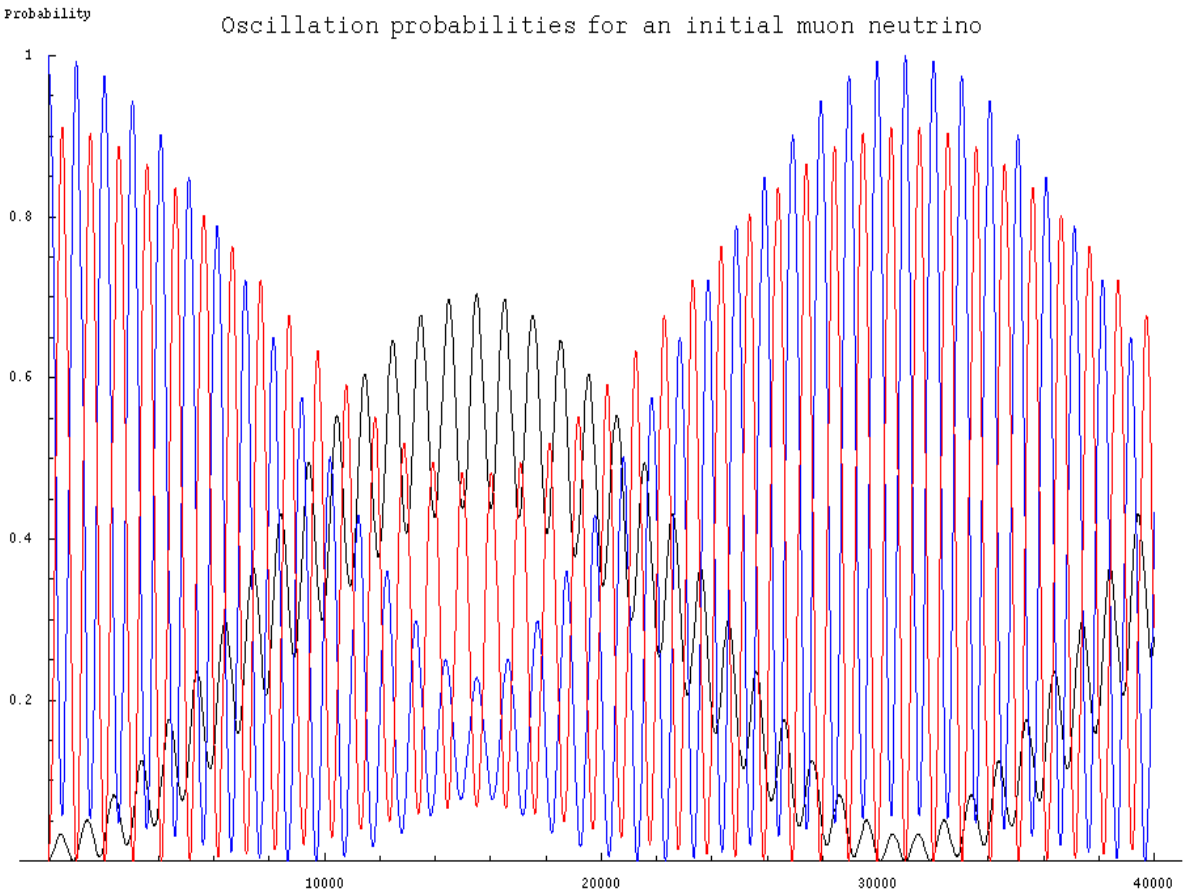
$$P_{vac}(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2\theta_{23}\sin^2(1.27\frac{|\Delta M^2_{32}|}{eV^2}\frac{L}{km}\frac{GeV}{E})$$

MINOS

Dependence on 4 parameters:
Two are tunable: L and E.
Two nature has chosen and we want to know: θ and Δm^2

We live in a three neutrino flavor world not two.
Three mixing angles and two mass differences.
Three amplitudes and two frequencies two measure.

Atmospheric ν_μ's (GeV) and **Solar** neutrinos ν_e's (MeV)



L/E (km/GeV)

Blue = ν_μ **Red= ν_τ** **Black = ν_e**

2 distinct periods are seen.

Fast oscillation large $\Delta m^2 \sim \Delta m_{23}^2$ (atmospheric – θ_{23})

Slow oscillation small $\Delta m^2 \sim \Delta m_{12}^2$ (solar- θ_{12})

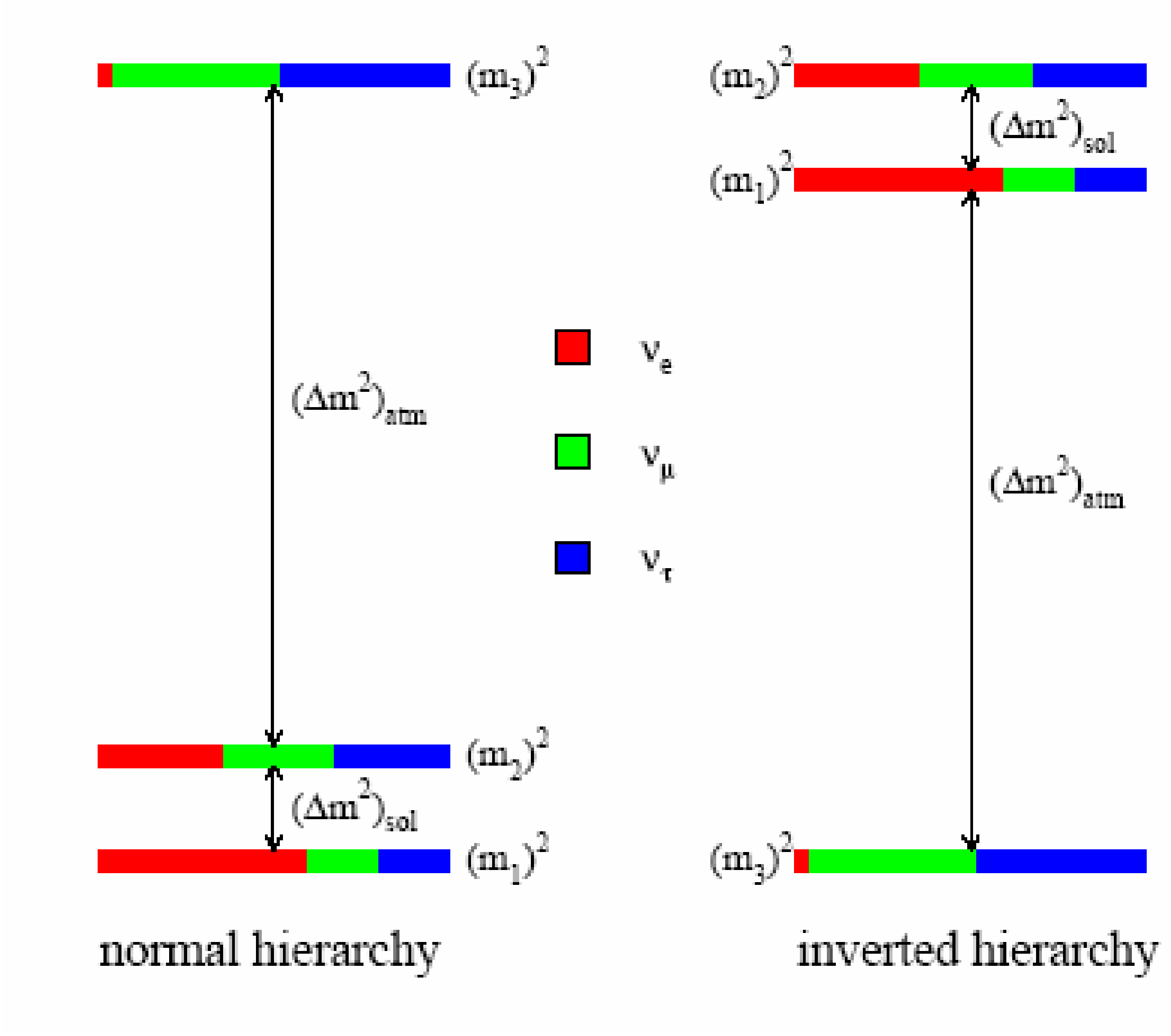
MINOS measure the disappearance of the muon neutrino (blue)

NOvA will measure the appearance of the electron neutrino (black)

Electron appearance depends on θ_{13} and Δm_{23}^2

Mass Hierarchy

Dm122~10-3 ev2
Dm232~10-5 eV2

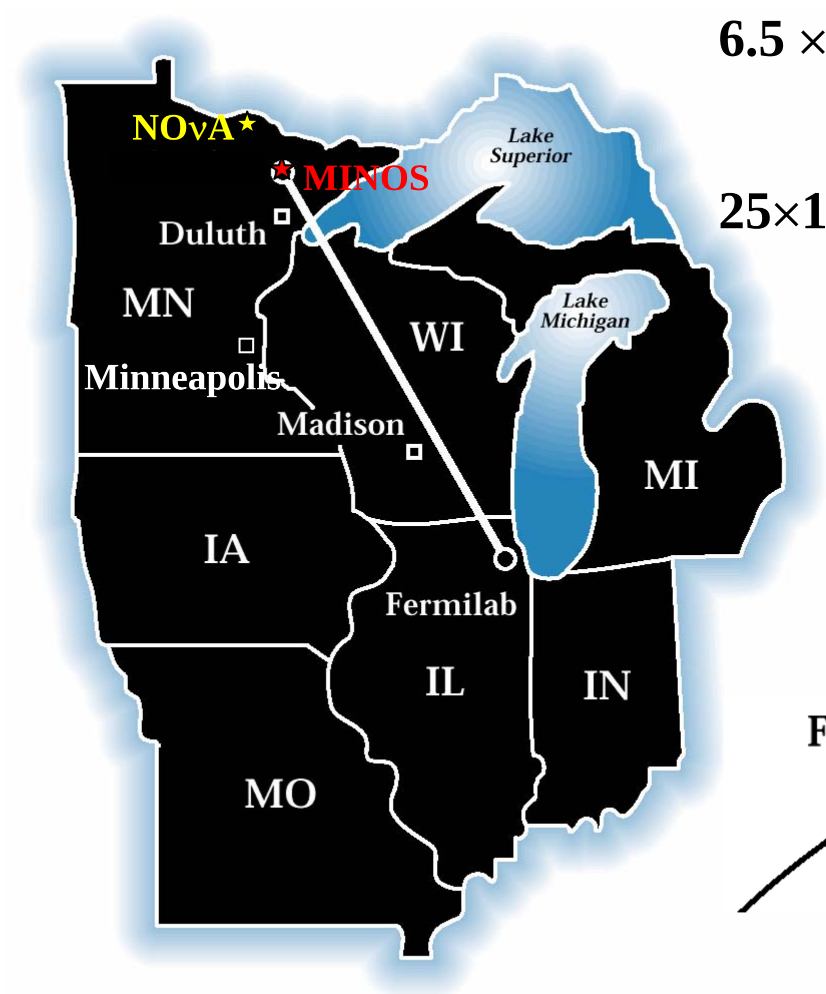


CP-Violation

- The phase δ in the mixing matrix provides the opportunity for CP violation.
- Compare $P(\nu_\mu \rightarrow \nu_e)$ to $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$.
- Understanding the weak interaction is the key to understanding the matter bias of our universe, mass generation, parity violation … all the interesting stuff!

Mama, don't let your babies grow up to be strong interaction physicists.

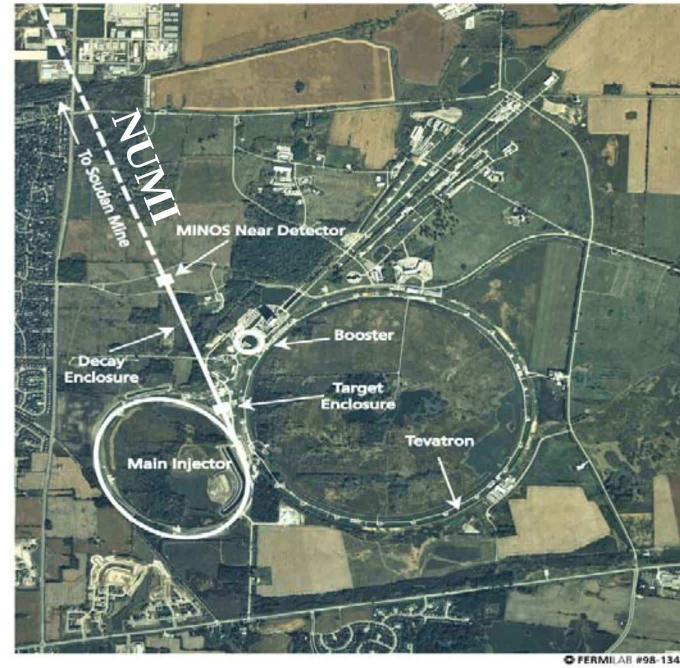
The NuMI Beam



3.4×10^{20} protons/yr

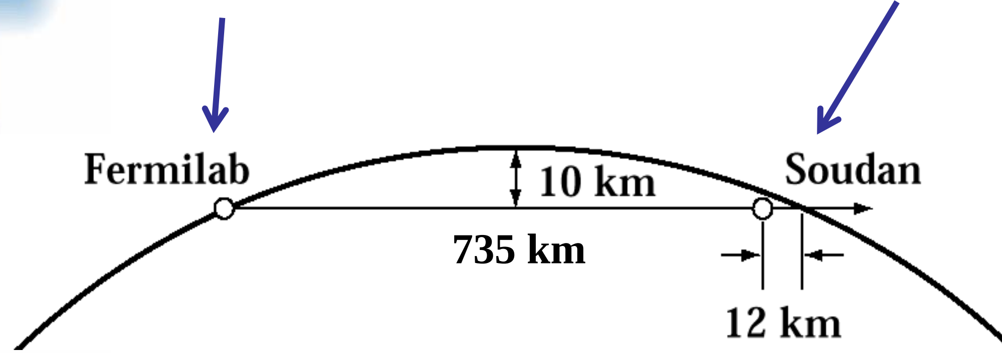
6.5×10^{20} protons/yr post collider

25×10^{20} protons/yr proton driver



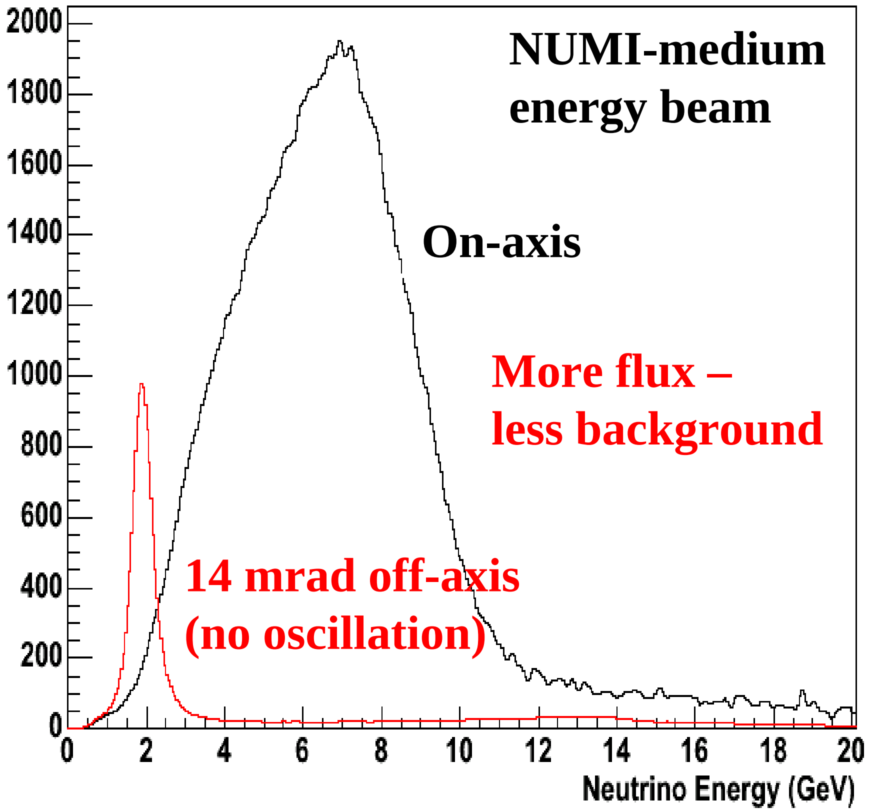
Neutrinos produced

Far Detector

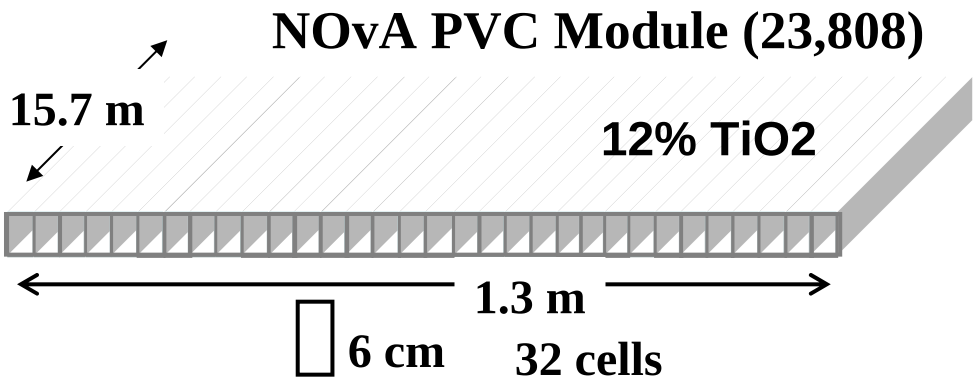


The NuMI Beam

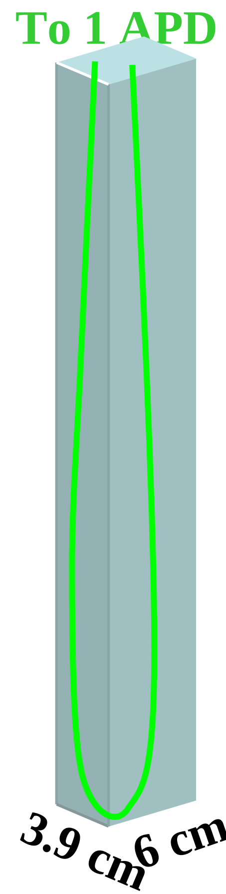
- Narrow energy distribution.
- Higher intensity at desired energy.
- Below tau threshold.
- Suppressed high energy tail.
  - Reduces NC contamination.



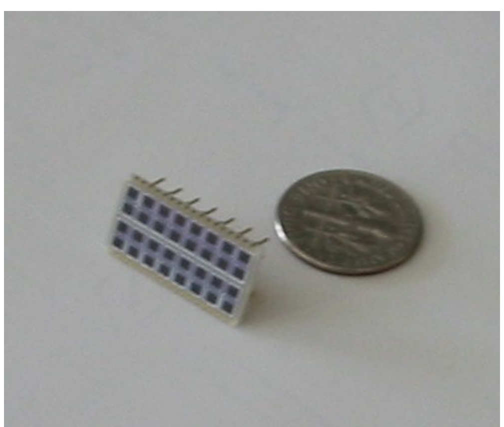
NOνA Detector Technology



Extruded PVC dimensions typical of commercially available products.

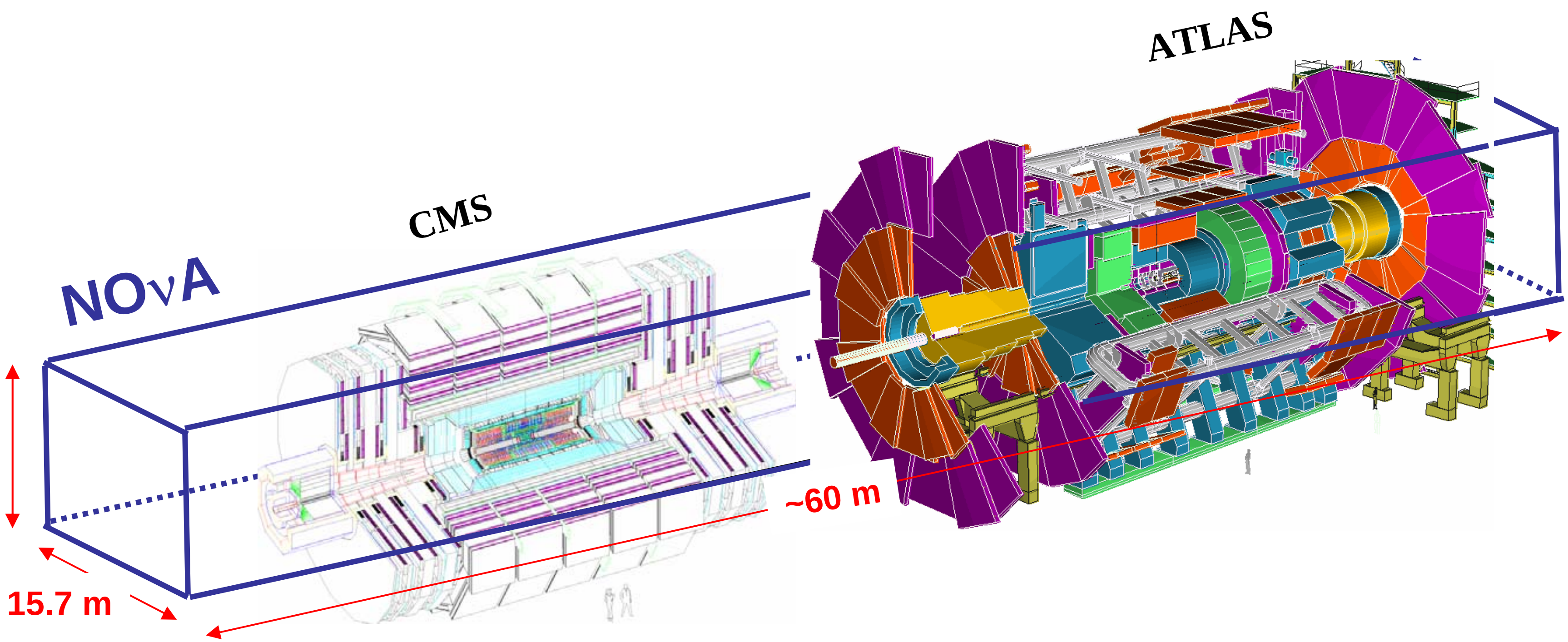


Looped WLS fiber design.



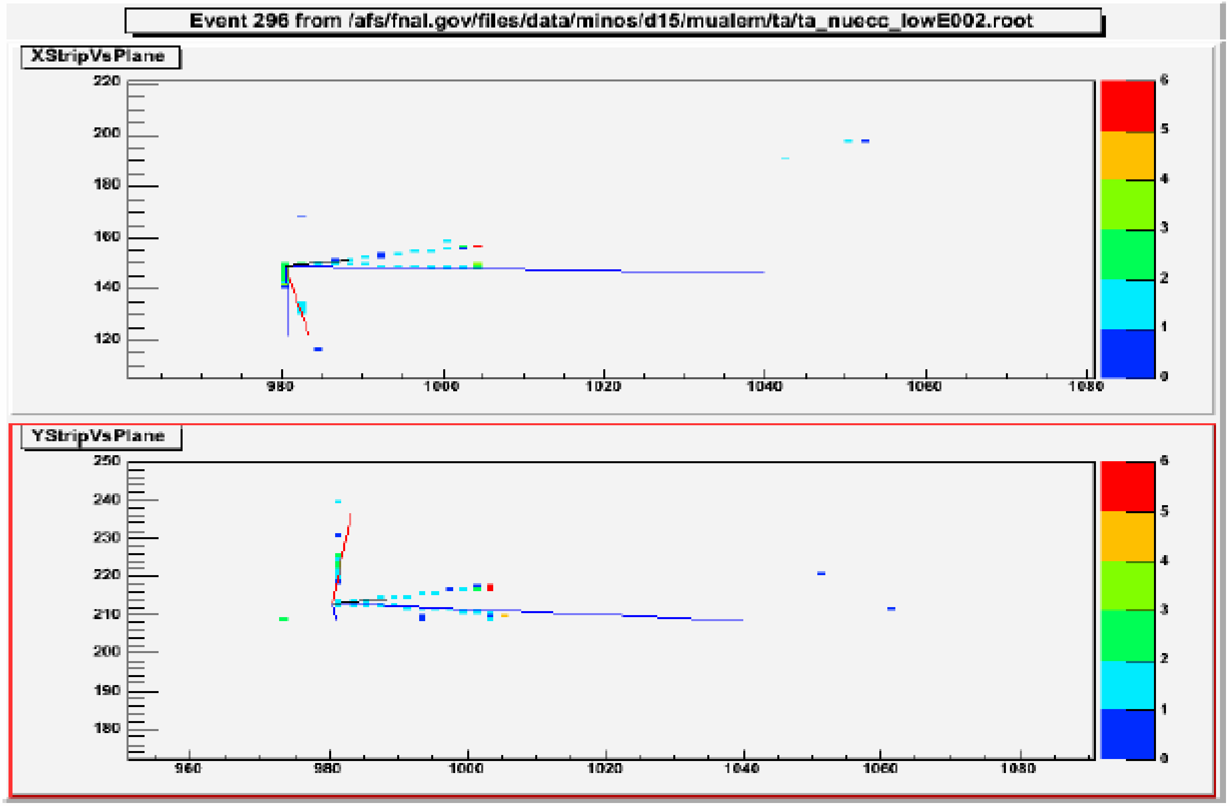
Inexpensive APD
High quantum efficiency.

NOνA Dimensions

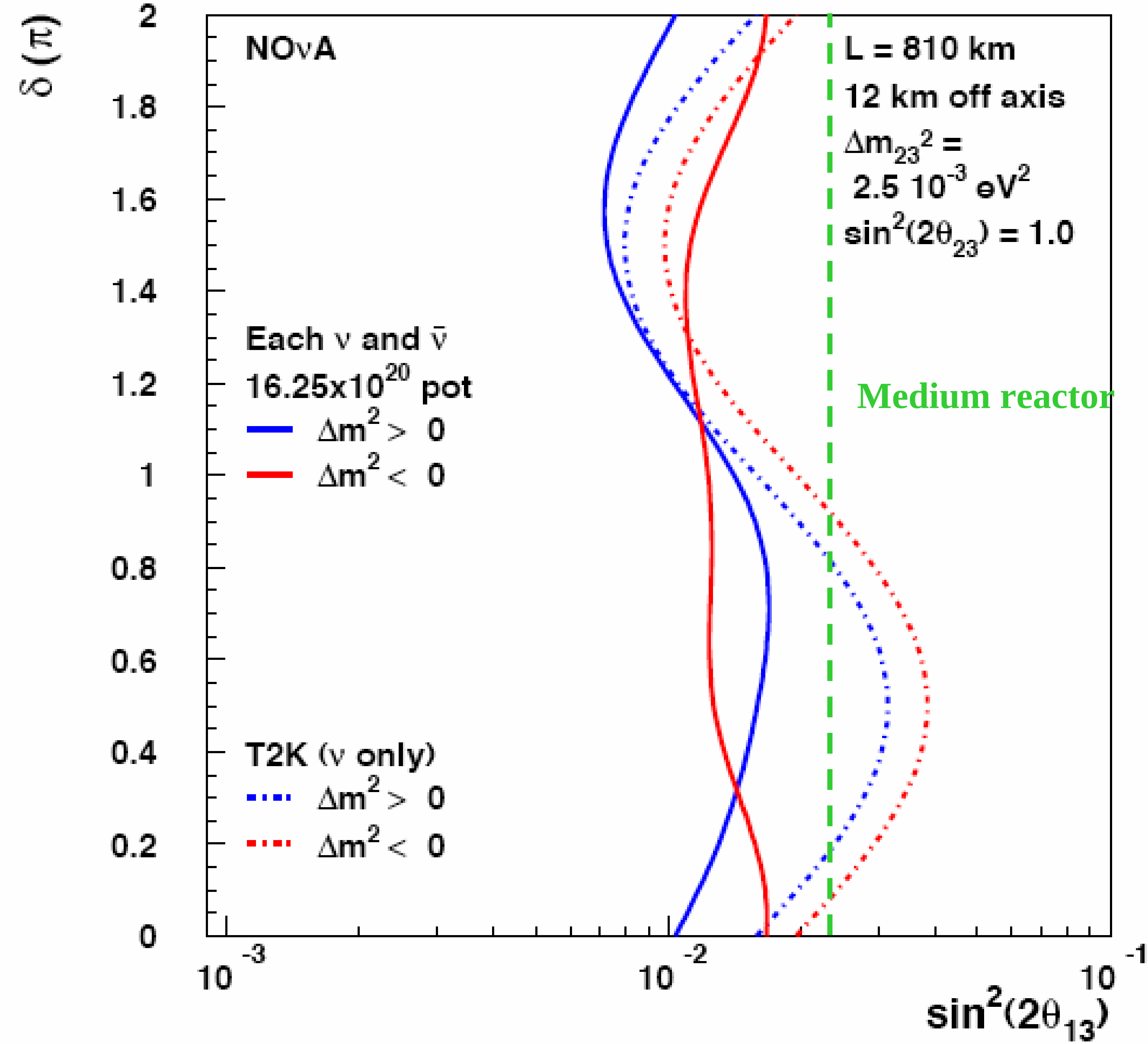


12 000 modules, 1000 planes.
Planes are alternated in orientation for obtaining x and y positions.
3-d recontruction of tracks.

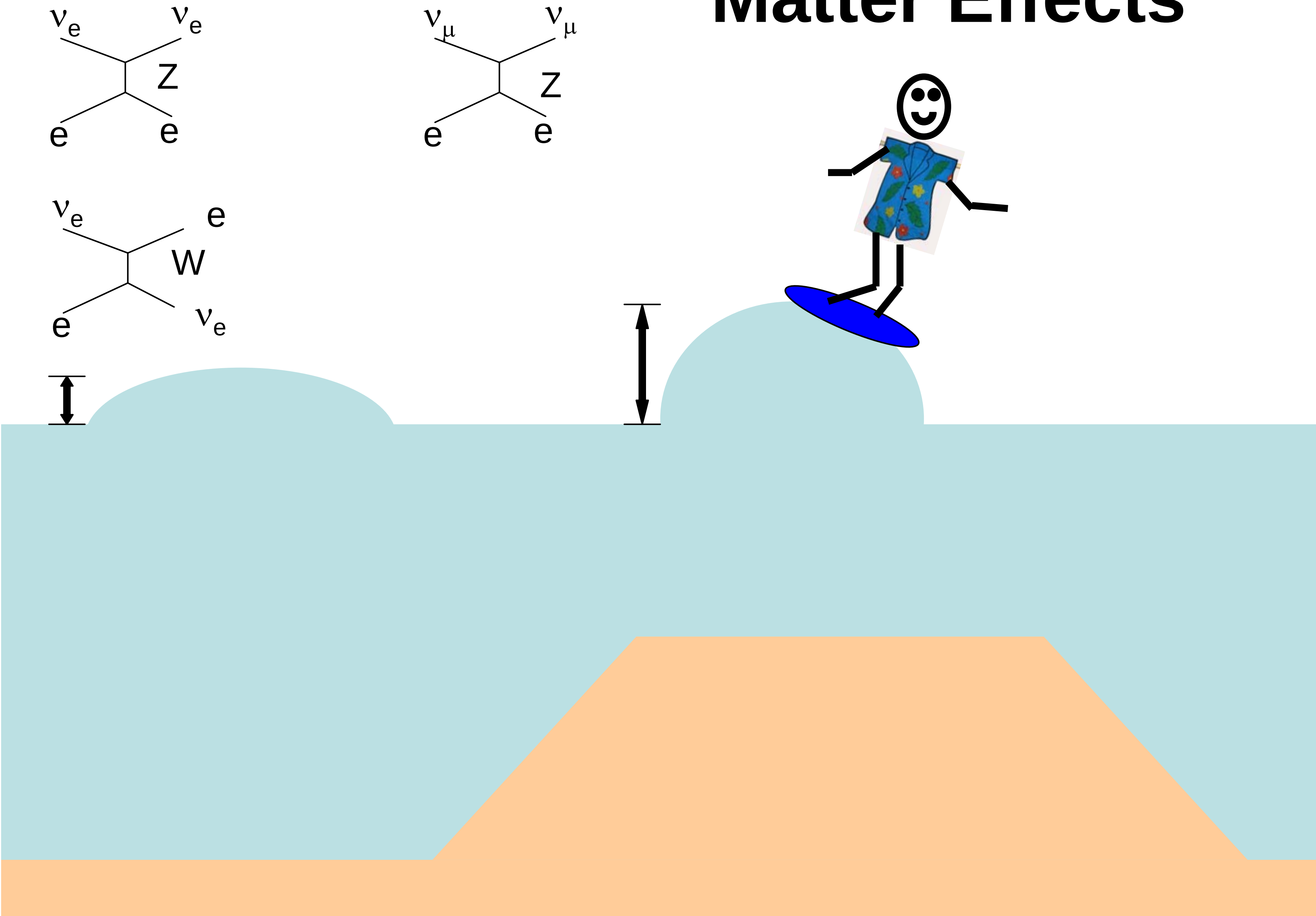
Event Picture



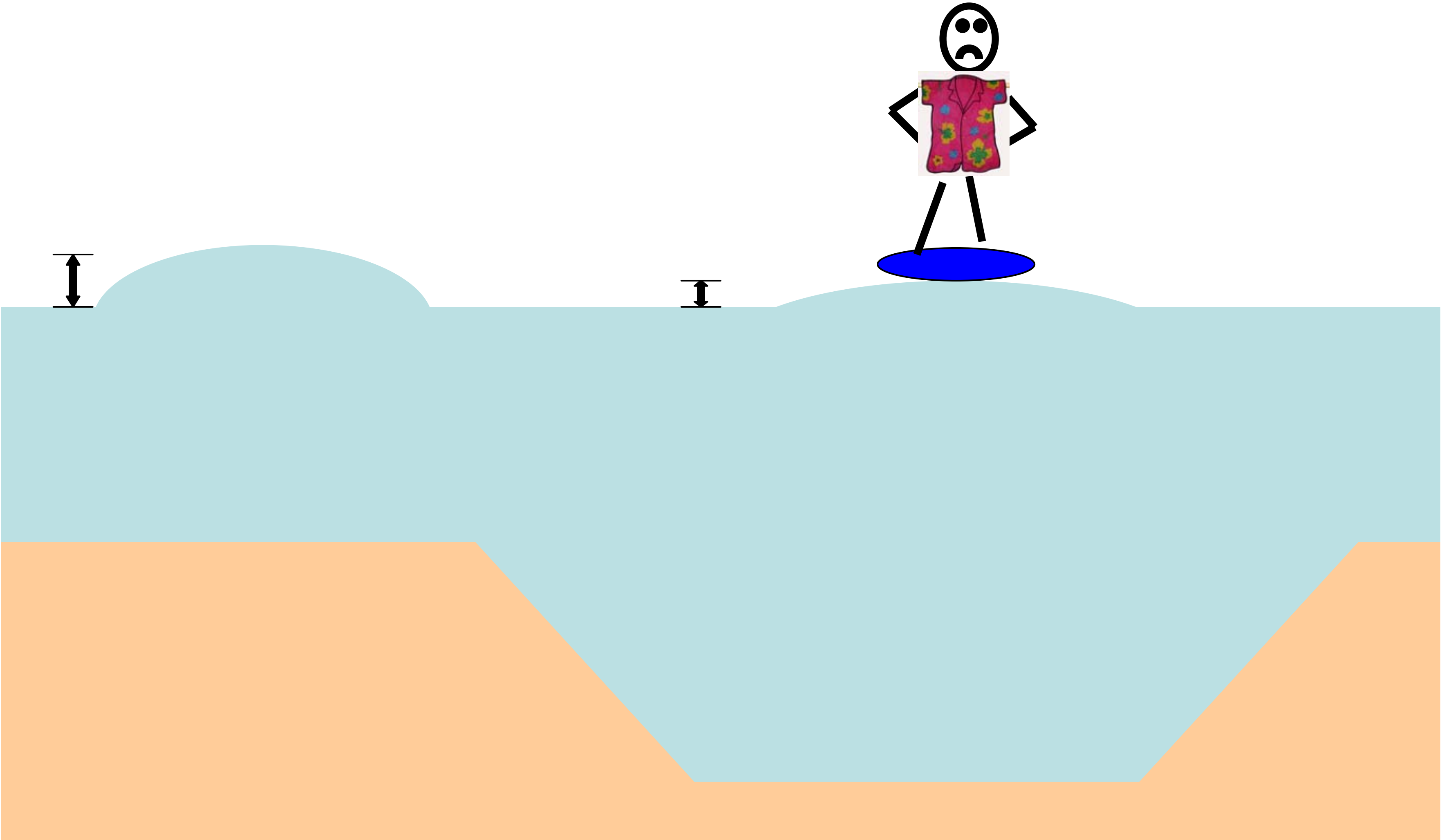
3 σ Discovery Potential for $\nu_\mu \rightarrow \nu_e$



Matter Effects



Matter Effects



Summary

- The primary goal of NOνA is the observation of $\nu_\mu \rightarrow \nu_e$ oscillations.
  - Determine θ_{13}
  - If θ_{13} is large other experiments may observe this oscillation before NOνA begins acquiring data.
- The unique feature of NOνA is access to information on the mass hierarchy.
  - Our sensitivity is due to having the highest energy neutrinos and longest baseline.
- CP violation is most likely a longer term goal but mathematically possible with the combined data of NOνA, T2K and the reactor experiments.