Computational Physics Section 10: Introduction to Particle Physics

UNIVERSITY of HOUSTON

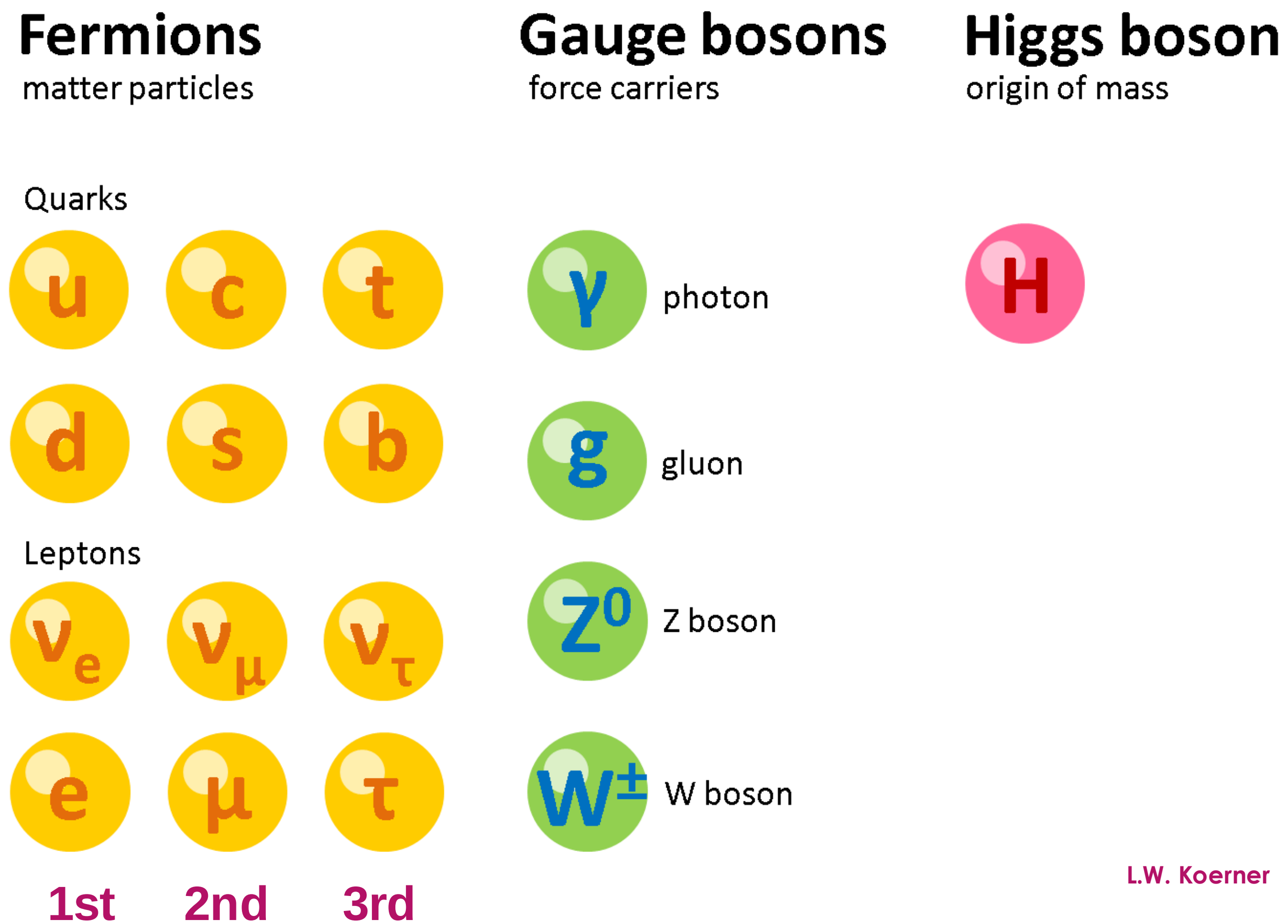
Introduction

- We're going to go over some examples of how computational methods are used in experimental particle physics, in particular the field of neutrino physics (which is what I study)
- Before we do that, I'd like to give you an overview of the field, so you can better understand the examples we work on
- Section 10, Exercise 1

The Standard Model of Particle Physics

All the known elementary particles

3 “generations” of matter



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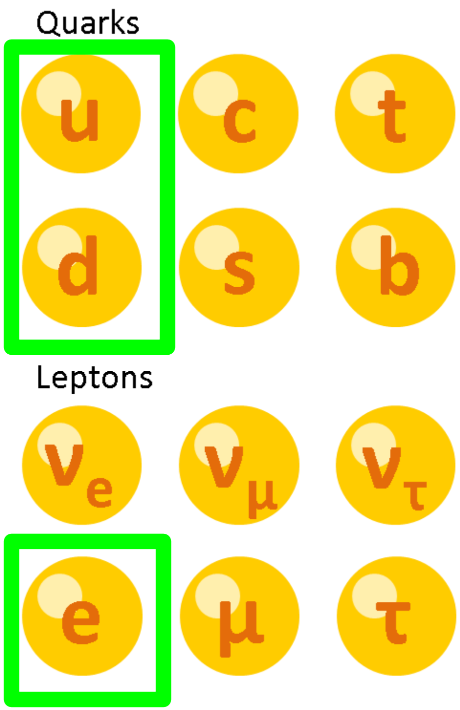
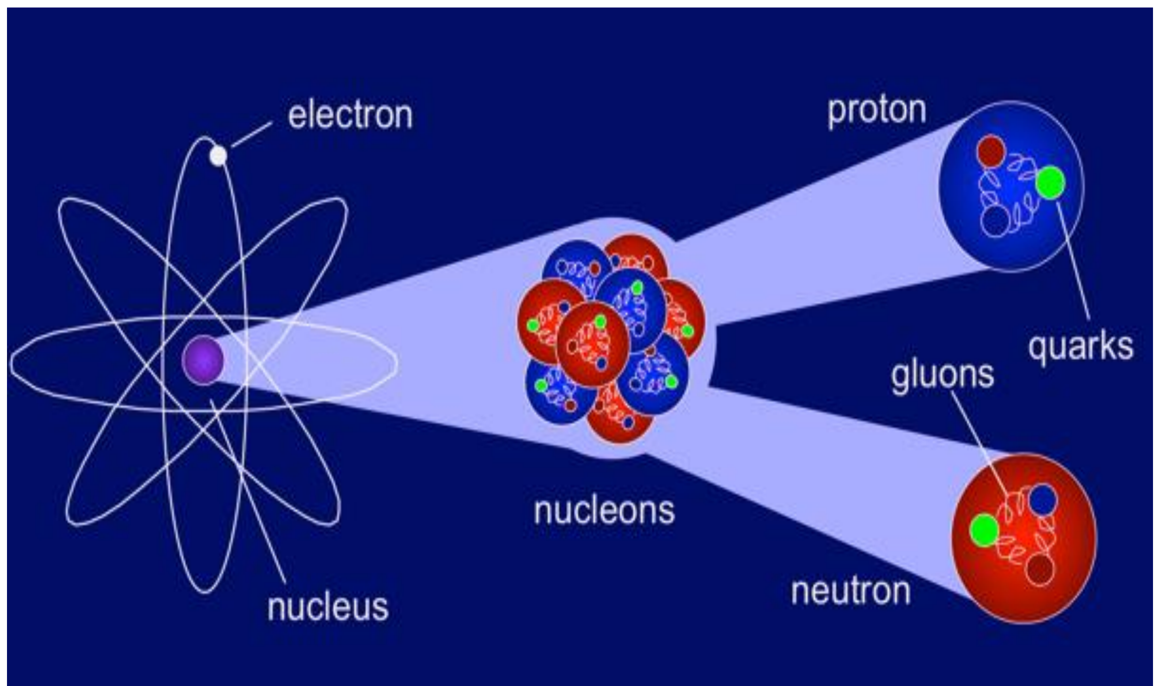
The Standard Model of Particle Physics

Fermions

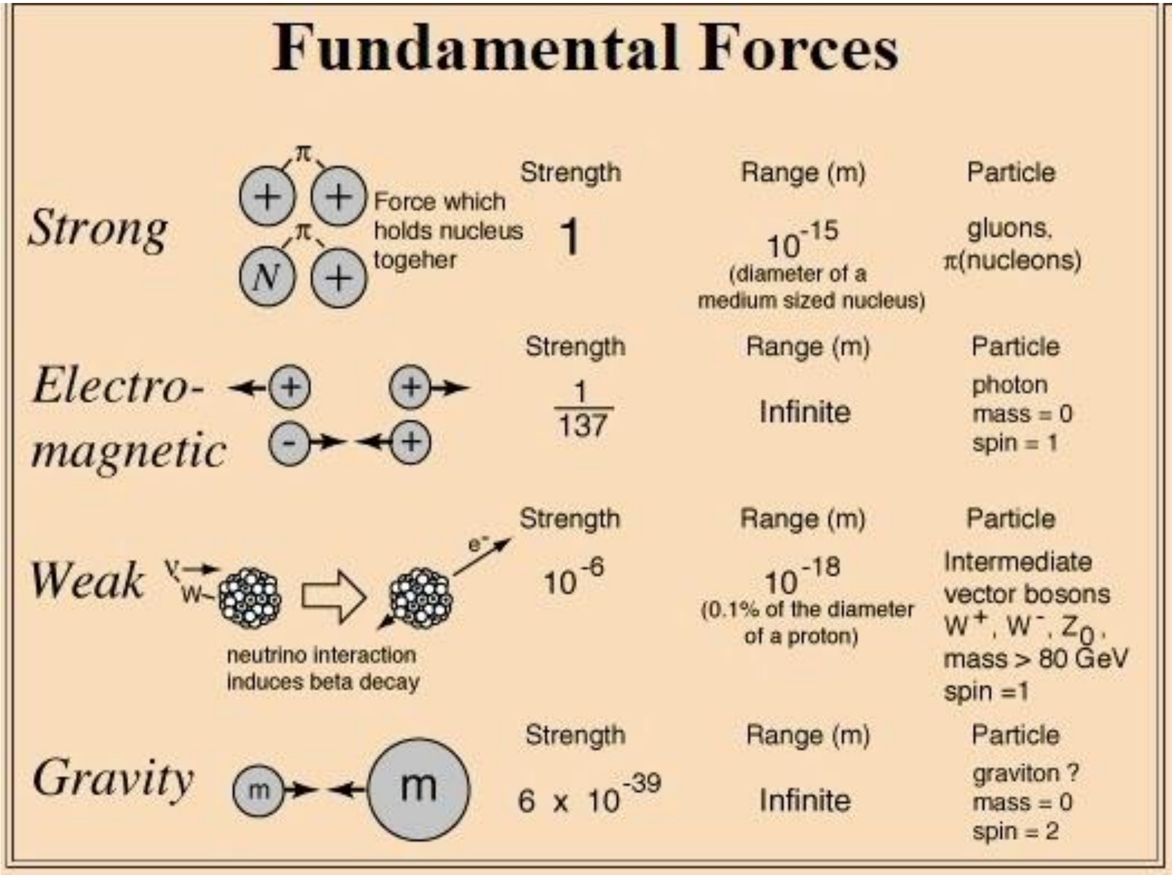
matter particles



All ordinary matter is made up of up and down quarks and electrons

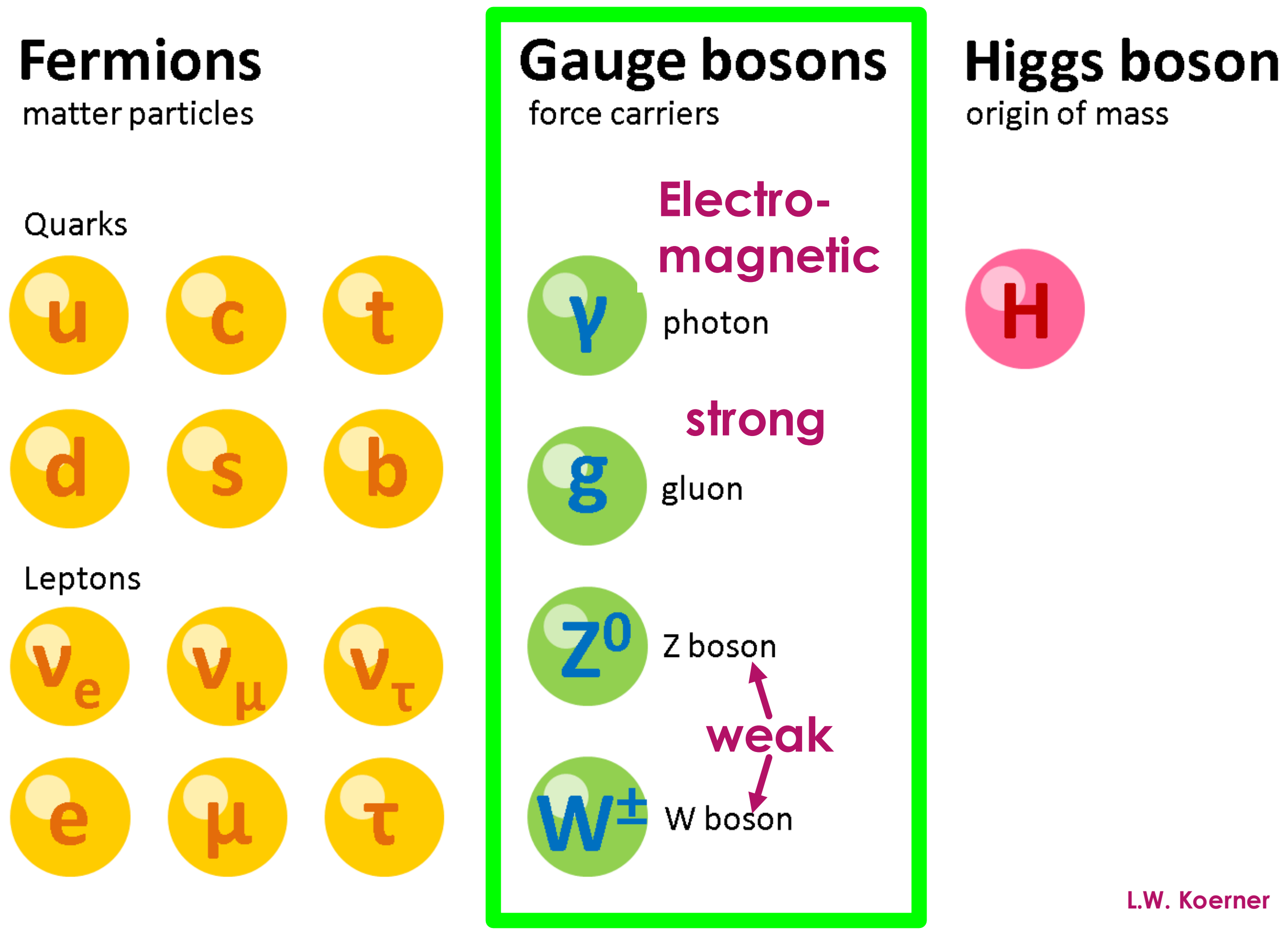


Fundamental Forces



http://hyperphysics.phy-astr.gsu.edu/hbase/forces/funfor.html

The Standard Model of Particle Physics



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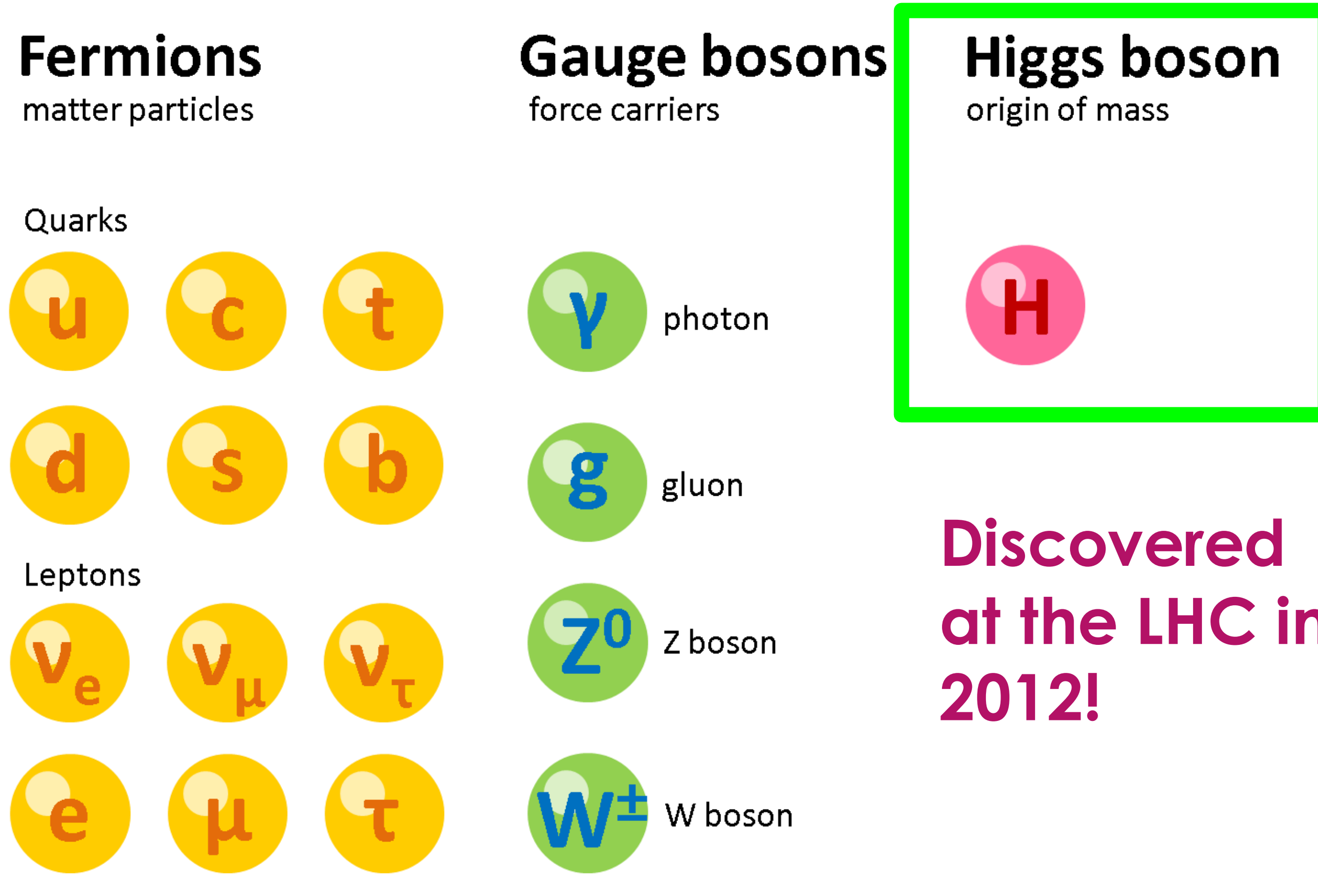
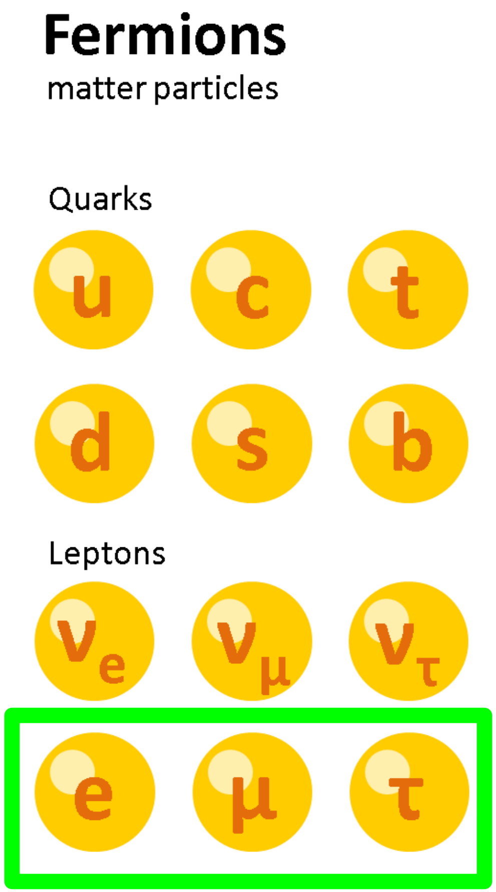
The Standard Model of Particle Physics



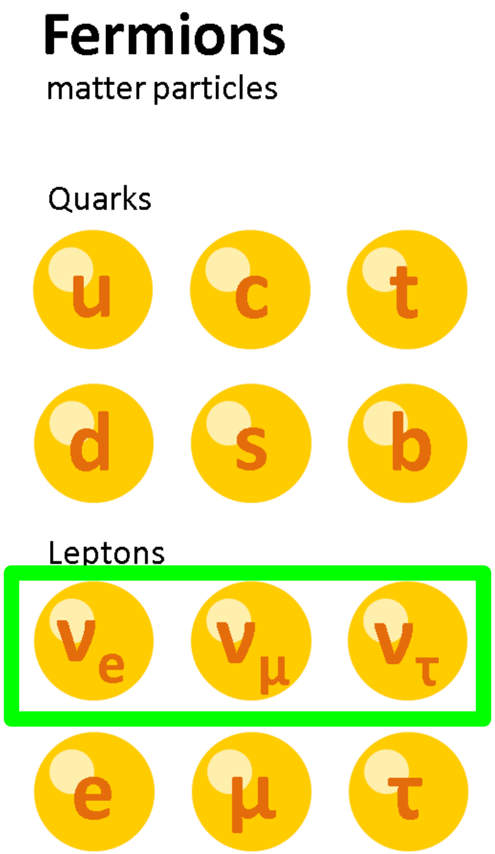
Discovered at the LHC in 2012!

Charged Leptons



- Electron (e-)
  - aka ‘beta’ particle; emitted in nuclear beta decay
- Muon (μ-) and Tau (τ-): basically heavier versions of the electron
- Antiparticles: e+ (positron), μ+, τ+

Neutrinos (Neutral Leptons)



- Each charged lepton has an associated neutrino
  - 3 "flavors"
- ν_e, ν_μ, ν_τ
- Antiparticles $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$
- Natural sources: solar neutrinos, atmospheric neutrinos, geoneutrinos
- Flux of neutrinos from Sun at Earth: 70,000,000,000 per second per square cm!

The “Ghost Particle”

- Neutrino interactions with matter are very rare
  - Only interact via weak force (and gravity)
- “Mean free path” of a 1 MeV neutrino in lead is > 1 light year! (Compare to mean free path of typical medical x-rays ~10-100's of micrometers)
- To observe a significant number of neutrino interactions, you need: 1) large amount of target material 2) high intensity source of neutrinos 3) lots of time

Number of observed interactions

Cross-section: m^2 per nucleon

Number of target nucleons

$$n_{obs} = \Phi \times \sigma \times \epsilon \times N \times t$$

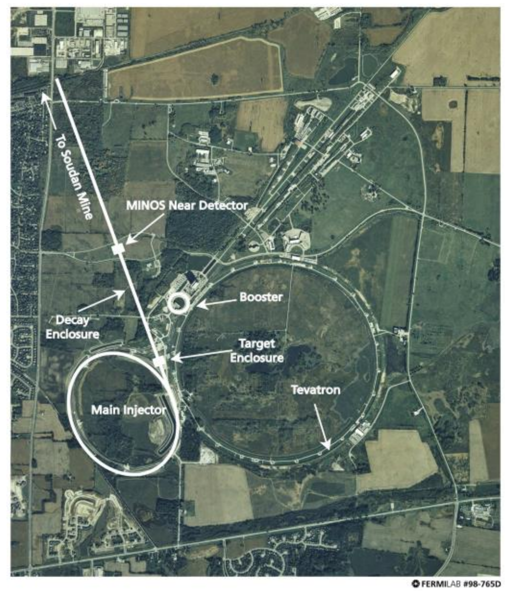
Flux: neutrinos from source per s per m^2

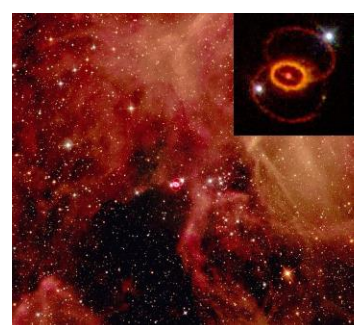
Detection efficiency

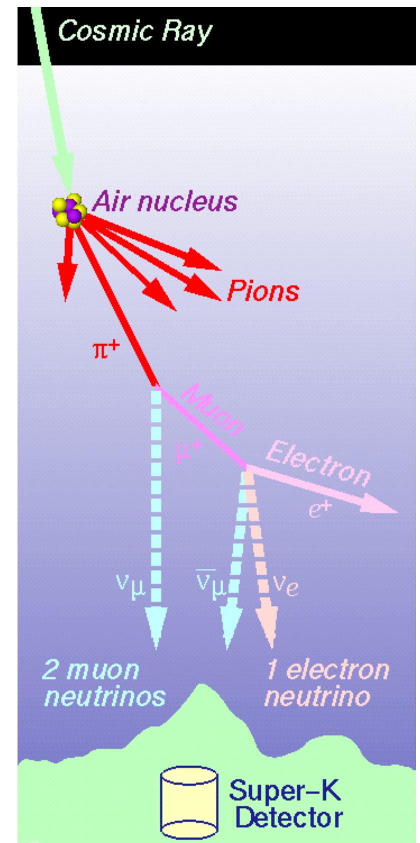
Time in s

Neutrino Sources

- Natural sources:
  - The Sun and other stars
  - Atmospheric neutrinos
  - Geo-neutrinos
  - Supernovae
  - Big Bang
  - Astrophysical neutrinos
- Produced by people using
  - Reactors
  - Accelerators







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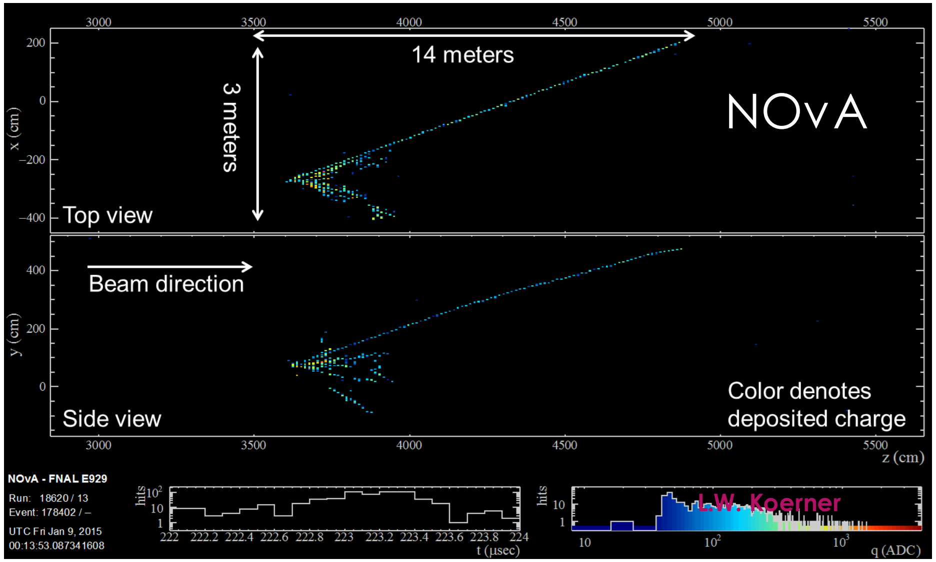
Detecting Neutrinos

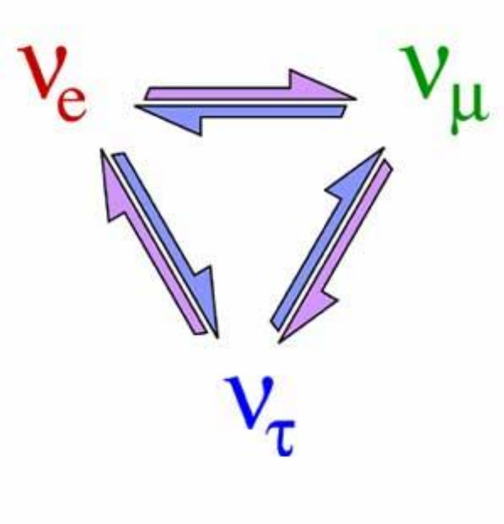
- We build massive detectors to detect charged particles via
  - Ionization (electrons)
  - Scintillation (light)
  - Cherenkov light (directed light)
- But… Neutrinos are neutral!
  - Don't leave tracks in our detectors
- Neutrinos interact with the atoms in our detectors
  - Those interactions destroy the neutrino and create charged particles that we can detect
- We can identify the neutrino flavor based on the charged particles that are produced in the interaction:
  - Electron neutrinos produce electrons, and so on



Neutrino Oscillations

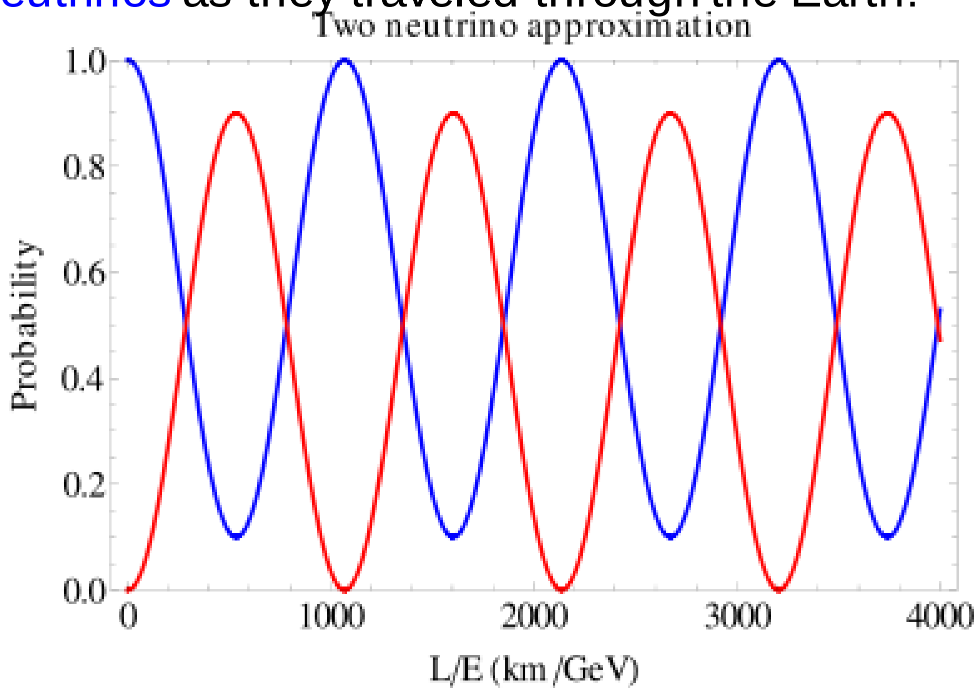
Neutrinos change from one flavor to another as they travel along.

Discovered when muon neutrinos from the atmosphere were observed to "disappear," changing into tau neutrinos as they traveled through the Earth!



The periodic change of neutrino flavor from one type into another is referred to as neutrino oscillations.

http://scienceblogs.com/startswithabang/2010/09/27/the-new-nu-news/



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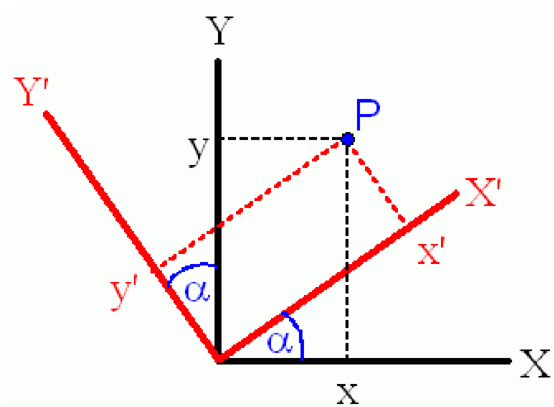
https://en.wikipedia.org/wiki/Neutrino_oscillation

Why do neutrinos oscillate?



- Quantum Mechanics!
- We can define the 3 neutrinos in terms of their flavors or in terms of their masses (think different coordinate systems)
- A neutrino with a particular mass is actually a combination of the 3 different flavors
- We call this neutrino mixing – a mass state is a mixture of flavor states

Neutrino Mixing (2-flavor case)

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = U \begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} \qquad U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Mixing (mass states are linear combinations of flavor states)

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} \, |\nu_\alpha\rangle$$

Propagation of mass states

$$|\nu_i(t)\rangle = e^{-i(E_i t - \vec{p}_i \cdot \vec{x})} \mid \nu_i(0)\rangle$$

Probability for flavor change

$$P_{\alpha\to\beta} = |\langle \nu_\beta(t) | \nu_\alpha \rangle|^2$$

A neutrino produced in one flavor state can be detected later in a different flavor state!

Neutrino Oscillations (2-flavor case)

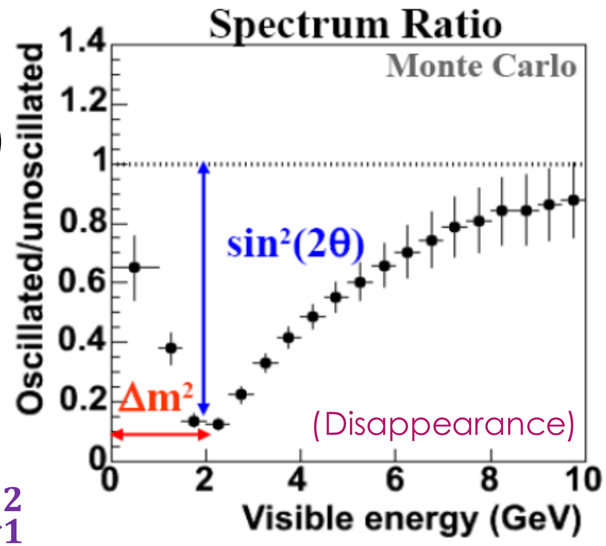
Look for disappearance of a flavor

$$P_{\alpha\to\alpha} = 1 - \sin^2 2\theta \sin^2(1.27\,\Delta m^2 L/E)$$

Look for appearance of a flavor

$$P_{\alpha\to\beta} = \sin^2 2\theta \sin^2(1.27\,\Delta m^2 L/E)$$

(2-flavor approximation) 1.27 GeV/(ev^2 km)



L **= baseline,** ***E*** **= neutrino energy,** $\Delta m^2 = m_2^2 - m_1^2$

Usual strategy:

- **Put a detector a known distance away from a well-known neutrino source**
- **Measure the energy spectrum of neutrinos in your detector**
- **The ratio of what you observe to what you expect (with no oscillations) depends on the oscillation probability**

How to observe oscillations?

Look for disappearance of a flavor component

$$P_{\alpha\rightarrow\alpha} = 1 - \sin^2 2\theta \, \sin^2(1.27\,\Delta m^2 L/E)$$

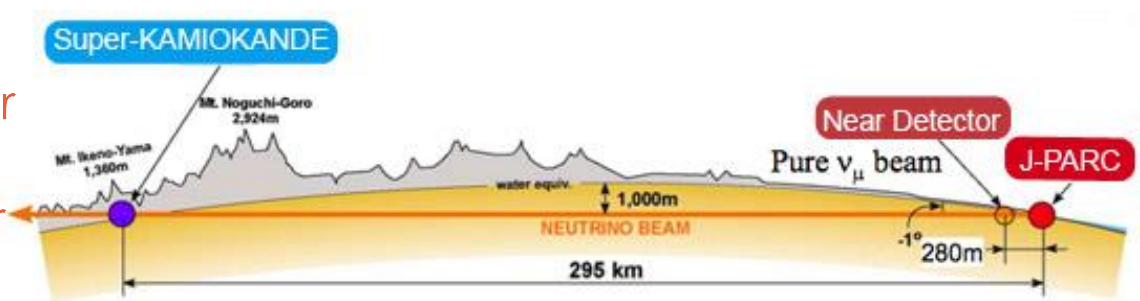
Look for appearance of a flavor component

$$P_{\alpha\rightarrow\beta} = \sin^2 2\theta \, \sin^2(1.27\,\Delta m^2 L/E)$$

Optimize L/E (distance between source and detector / neutrino energy)

Relative (2 detector) measurement allows cancellation of flux uncertainties (and detector and interaction uncertainties if detectors are of similar design):

Far detector measures flavor component of the beam after oscillations



Near detector: Measures flavor component of beam before oscillations

(T2K)

http://www.quantumdiaries.org/tag/standard-model/#LSND

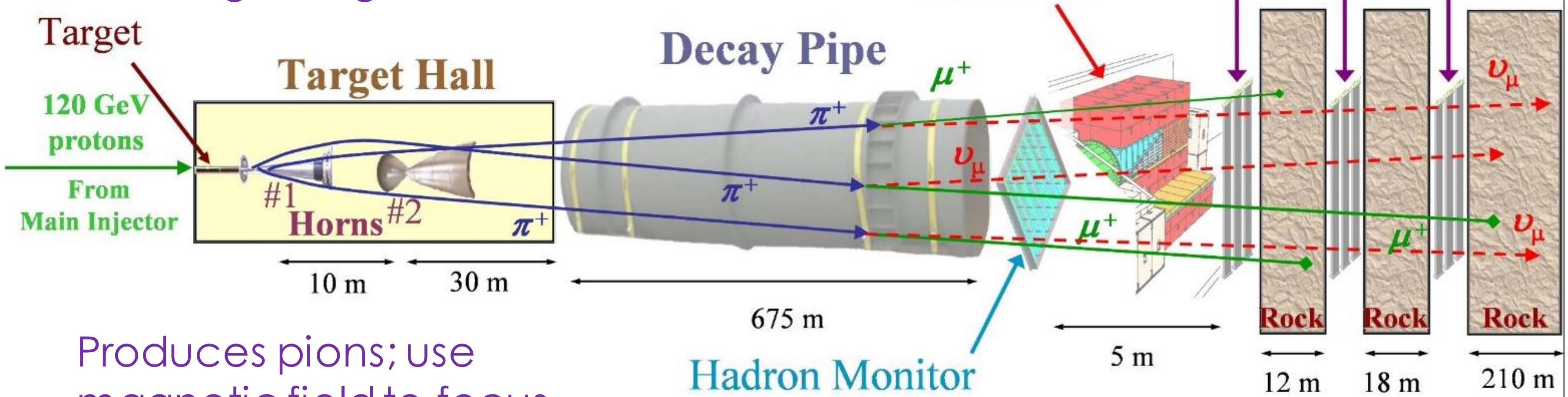
Accelerator Neutrinos

NuMI at Fermilab

(Change magnetic field polarity for neutrino beam or antineutrino beam)

Let pions decay into $\mu^{\pm}$ and neutrinos or antineutrinos

Start with a proton beam hitting a target

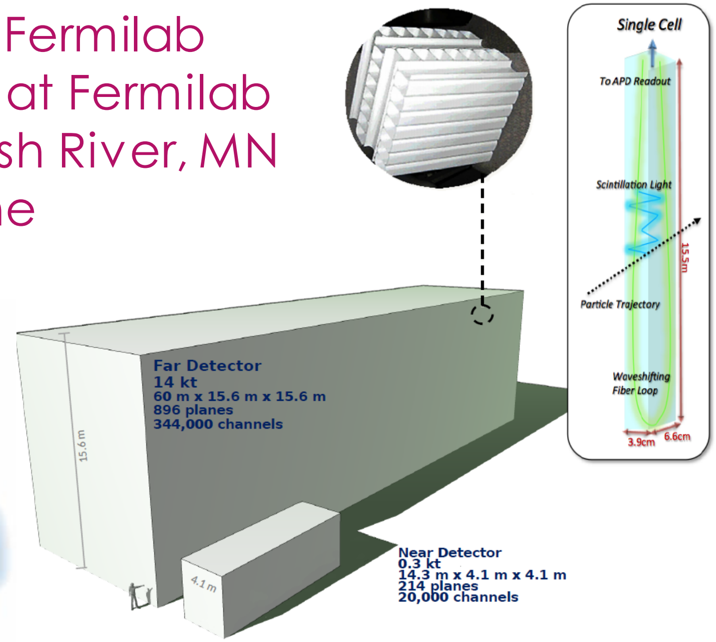


Produces pions; use magnetic field to focus them in forward direction

Dense materials stop $\mu^{\pm}$ and leftover pions; neutrinos travel through the earth to detector

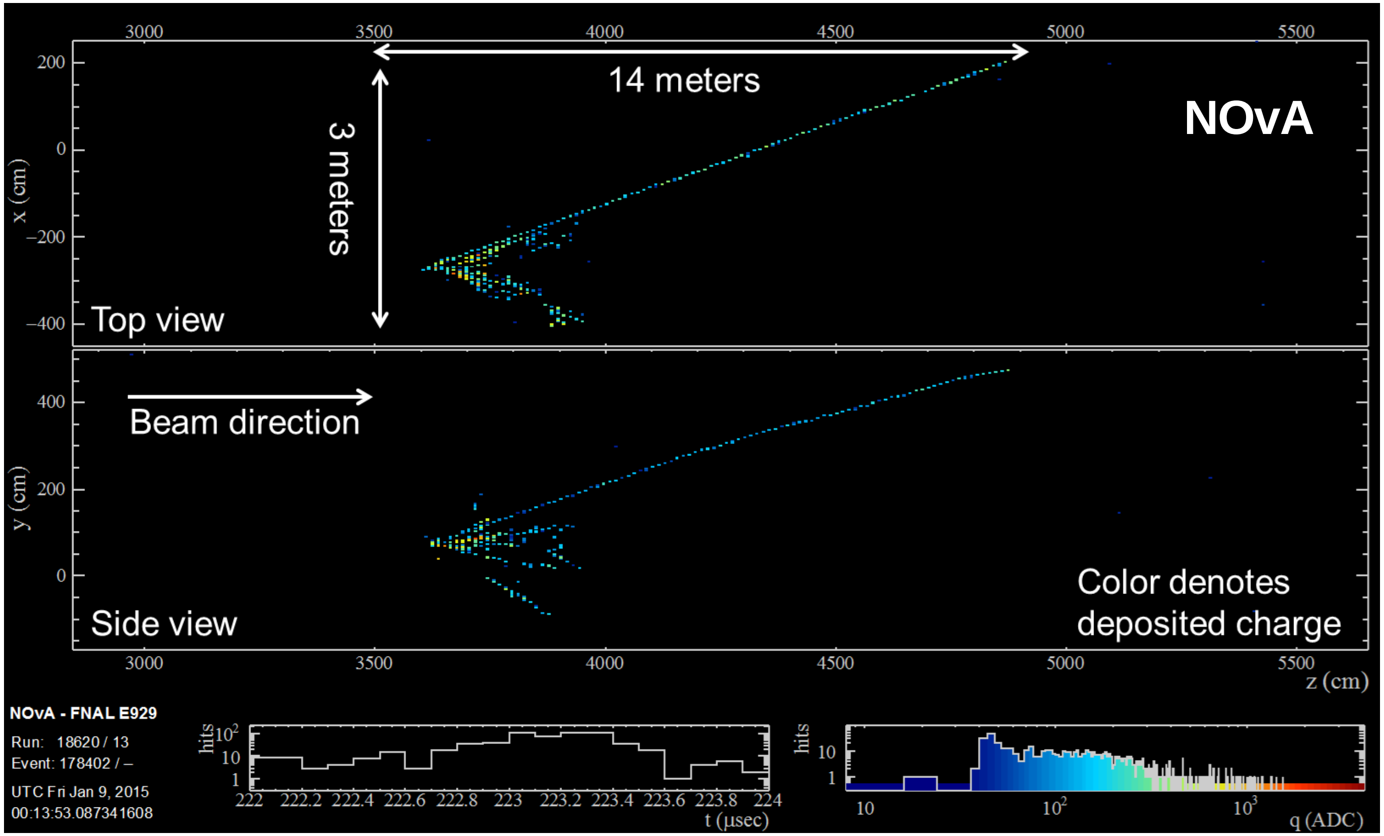
The NOvA Experiment

- NuMI beam @ Fermilab
- Near detector at Fermilab
- Far detector Ash River, MN
- 810 km baseline

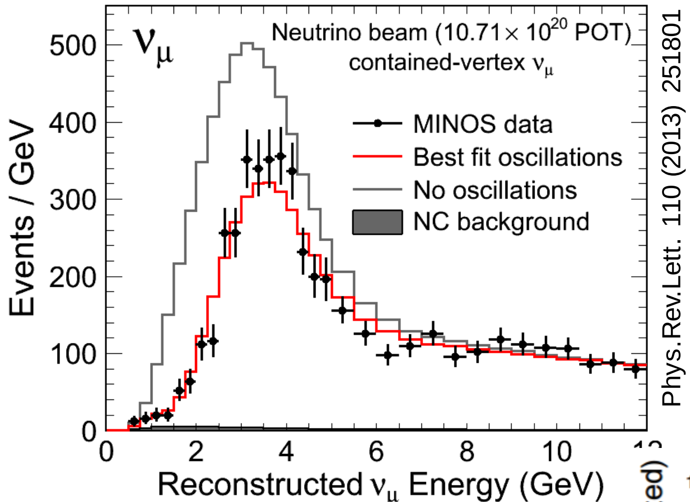


Other long-baseline accelerator neutrino experiments: MINOS, K2K, T2K, OPERA

NOvA Event Display

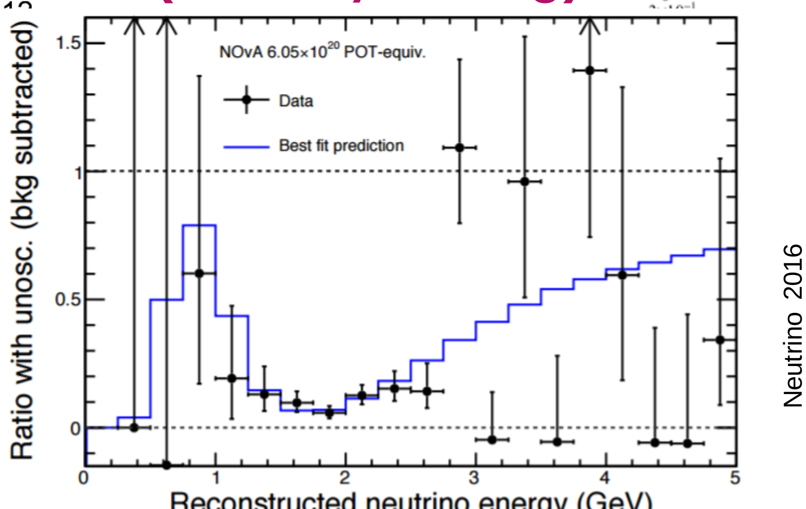


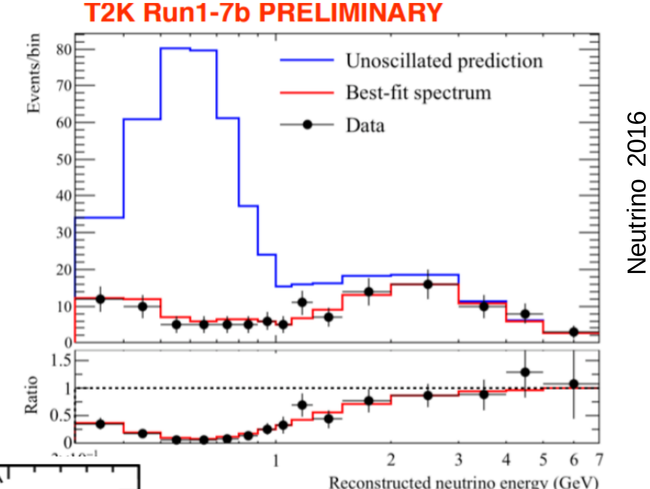
Disappearing Muon Neutrinos from Accelerators



MINOS (finished running)

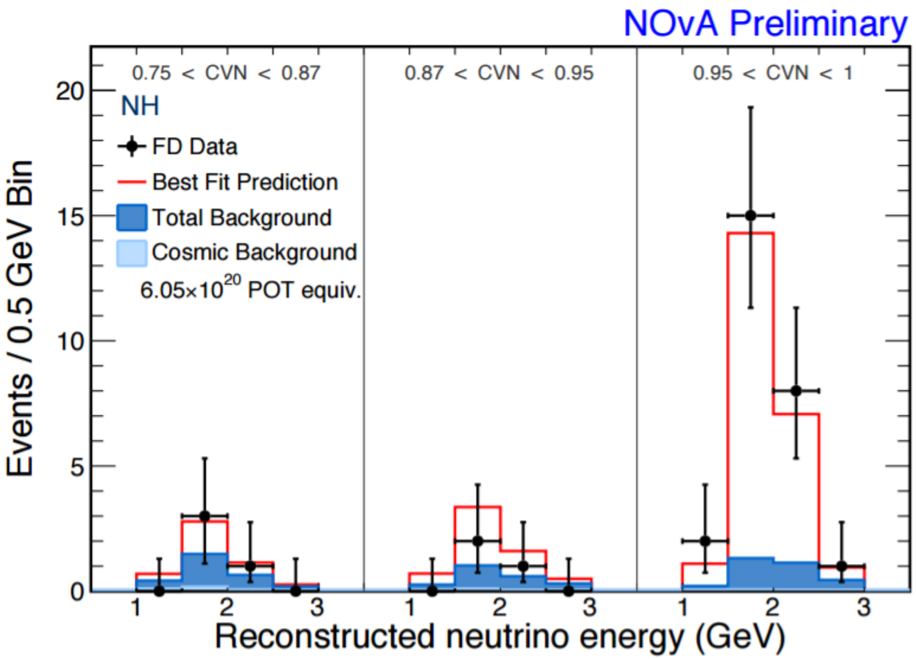
NOvA (currently running)

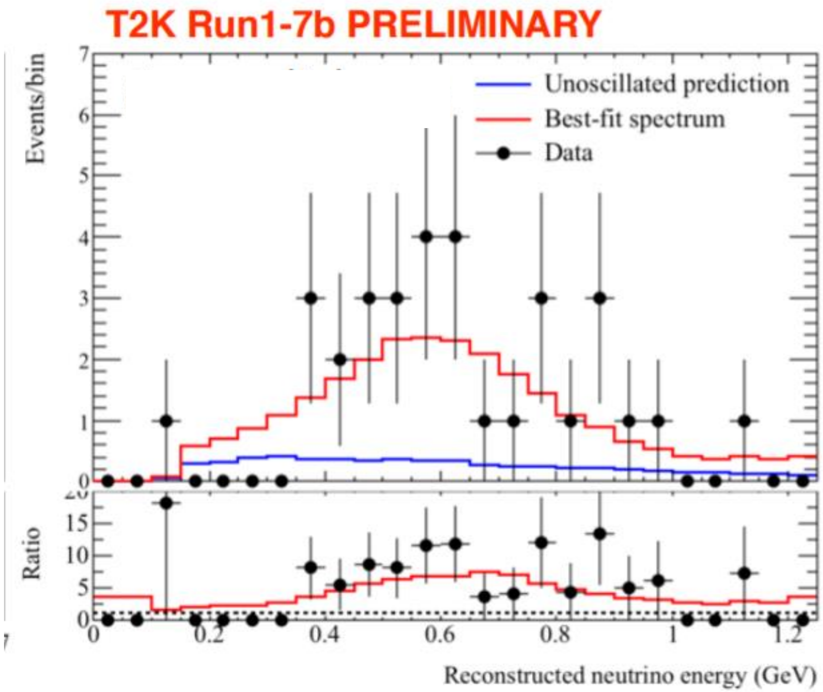




T2K (currently running)

Appearance of Electron Neutrinos





Neutrino 2016

Steps to an Analysis (in NOvA for example)

- Simulations:
  - Source (simulate how the neutrinos are created)
  - Interactions (simulate the neutrino interacting with nucleons in the detector)
  - Outgoing particles (simulate how all the produced particles interact with the detector material, i.e. scintillation, ionization, scattering, etc)
  - Detection (simulate how those interactions get detected, i.e. scintillation light gets detected by photo-multiplier tubes)
- Reconstruction:
  - Treat the simulated data and the real data in the same way
  - Hits → clusters of hits → Tracks and showers
  - Based on tracks and showers determine what kind of interaction happened (was a muon or electron produced in the event?)
  - Reconstruct the neutrino's energy, and any other important quantities

Steps to an Analysis (in NOvA for example)

- Analysis
  - Select the types of events you want to analyze (are you studying muon neutrino interactions? Electron neutrino interactions? Etc)
  - Remove background from your sample (for example, based on time - remove background from cosmic rays by only selecting interactions that happened while the beam was hitting the detector)
  - Analyze to measure a physics quantity
  - Evaluate all the sources of uncertainty that you can think of

Next up… example of computational problems in each category