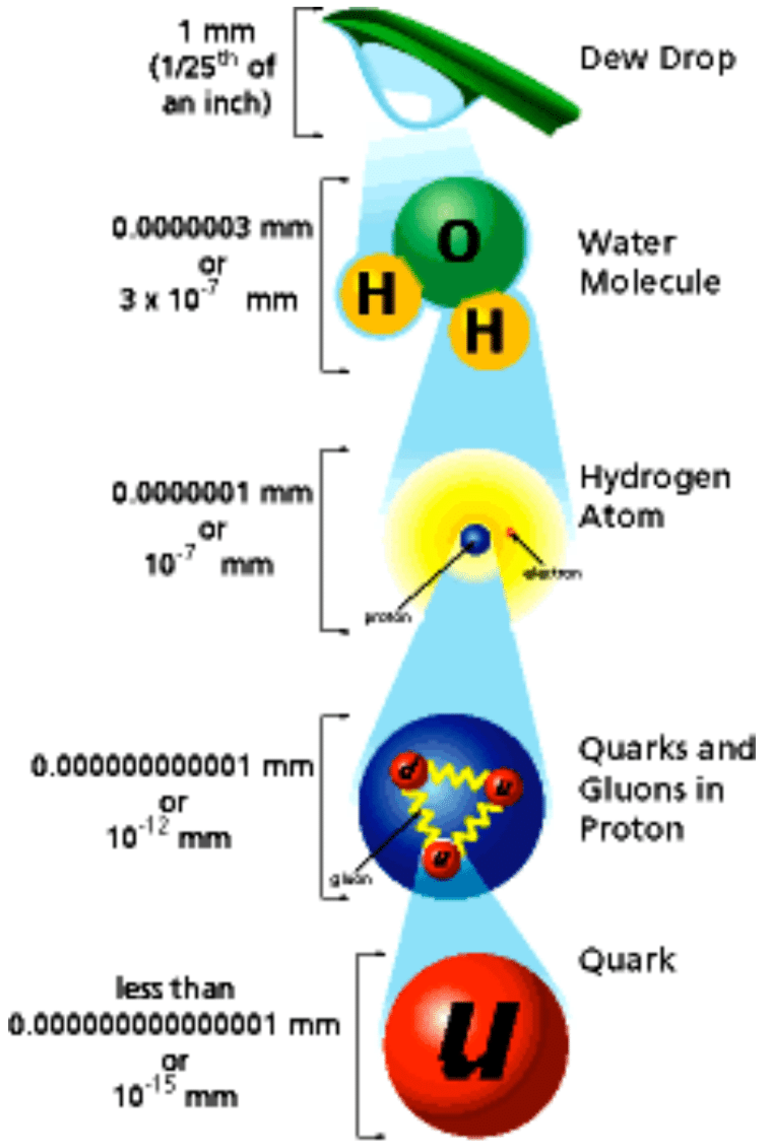
Neutrinos and particle detectors

Jeff Nelson

Outline

- Particle physics overview
  - > Forces, particles
  - > Accelerators
  - > Particle detectors
- Neutrinos & Neutrino Oscillations
- Neutrino experiments
  - > Beams
  - > Detectors
  - > Data
- W&M HEP group

Sizes: Lets go smaller first



The 4 fundamental forces

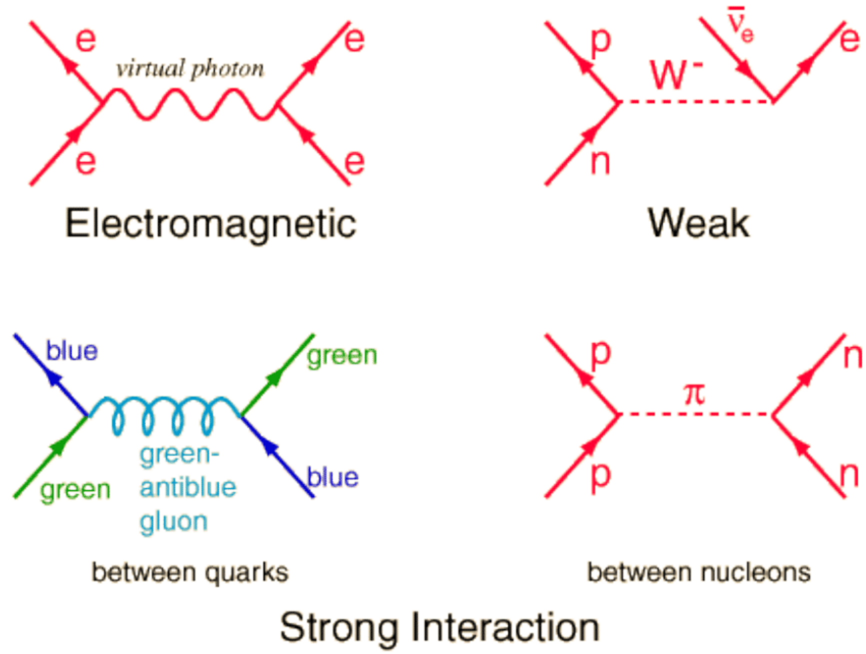
1. Gravity
   - It is the primary physics of objects in the Universe
   - Is created by mass
   - Always attractive
   - The weakest force
2. Electromagnetic force
   - Electricity and magnetism are part of the same force
   - It is created by electric charge
   - Can be attractive or repulsive (opposites attract !!!)
   - Responsible for holding electrons to atoms, chemical bonds, and the sizes of objects
   - The 2nd strongest force

The 4 fundamental forces

3. Strong nuclear force
   - Binds the quarks into protons and neutrons
   - Also for holding protons and neutrons into nuclei
     - Must be a lot stronger than E&M since it easily overcomes the electric repulsion and binds more strongly
     - Nuclei are much smaller than atoms
   - Cancels out over distances larger than a proton or nucleus
   - The strongest force
4. The weak force
   - Only seen in some types radioactive decay, Solar fusion, and in the earliest times at the beginning of the Universe
   - Only force that can change a particle's type
     - e.g. decay of a neutron to a proton
   - 2nd weakest force

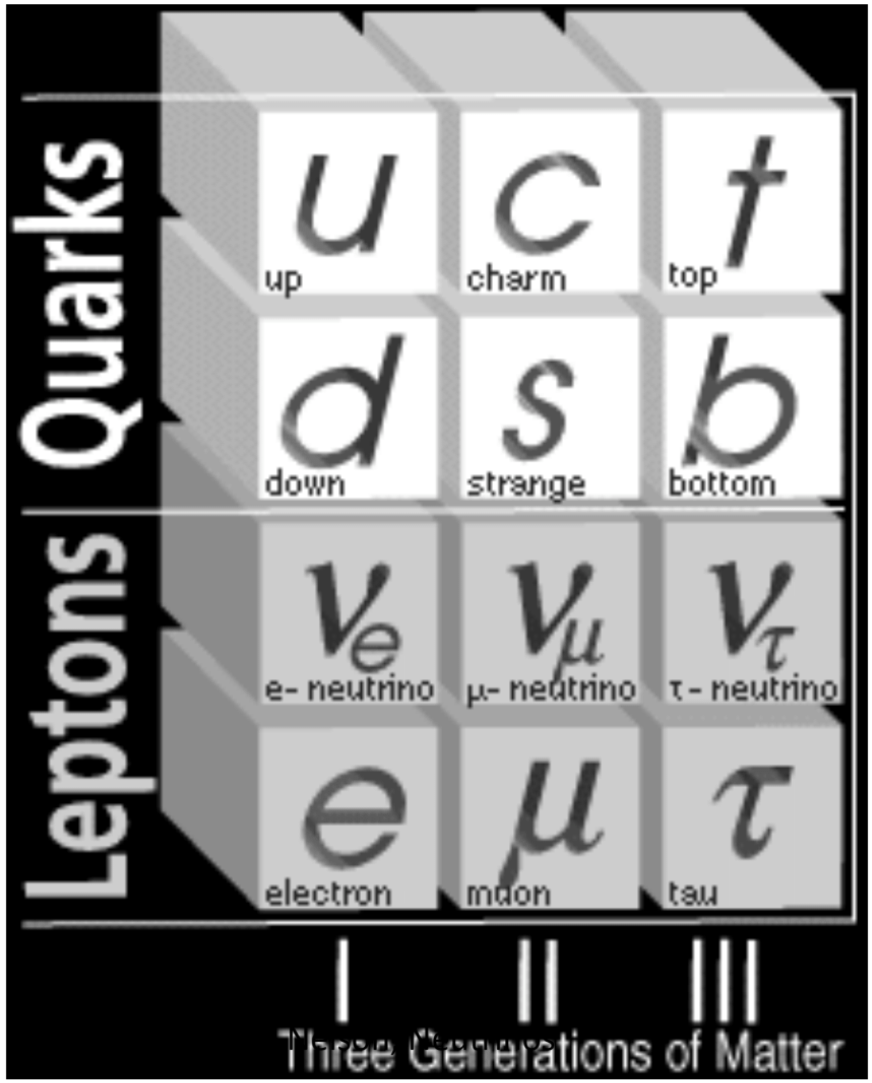
Forces in field theory

- In modern physics we do not think of a force at a distance
- We think of it as the exchange of particles
  > Photon for E&M
  > Gluon for the strong force
  > W/Z particles for the weak force



The Periodic Table of Elementary Particles

Strong Force



Q = 2/3e

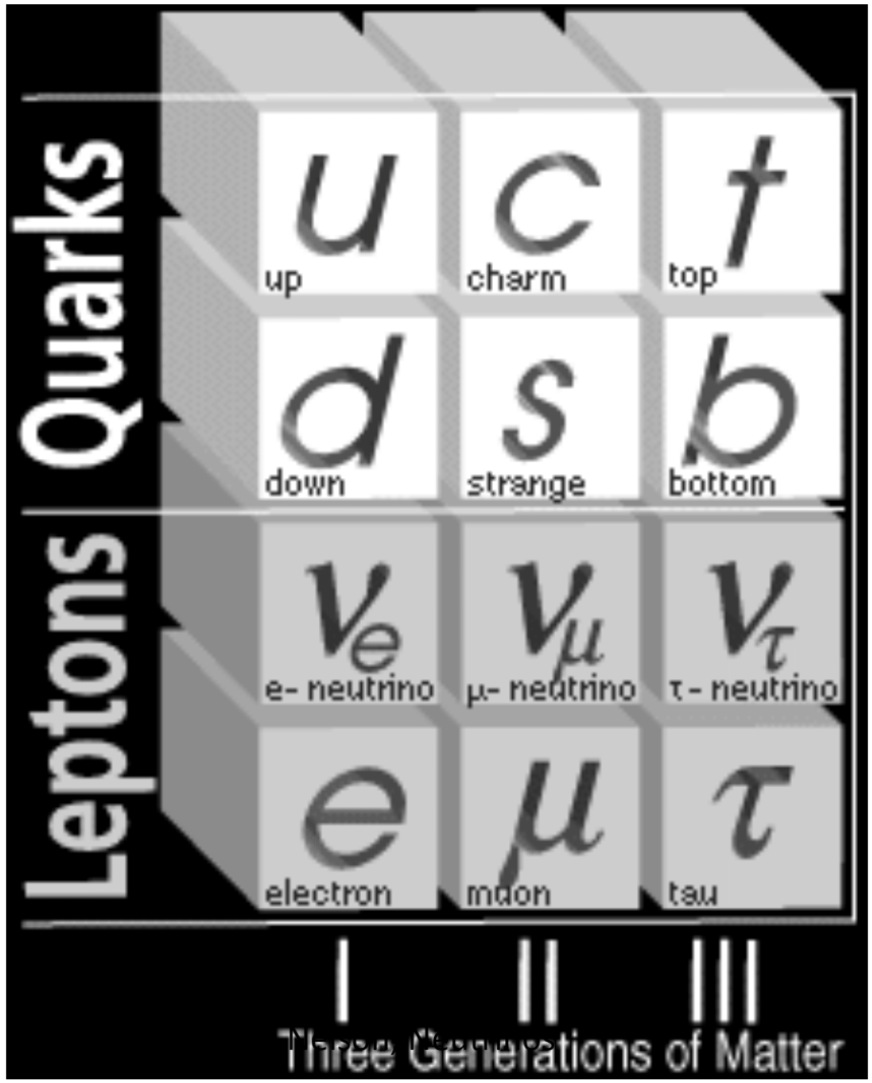
Q = -1/3e

Q = 0

Q = -1e

The Periodic Table of Elementary Particles

Electromagnetic Force



Q = 2/3e

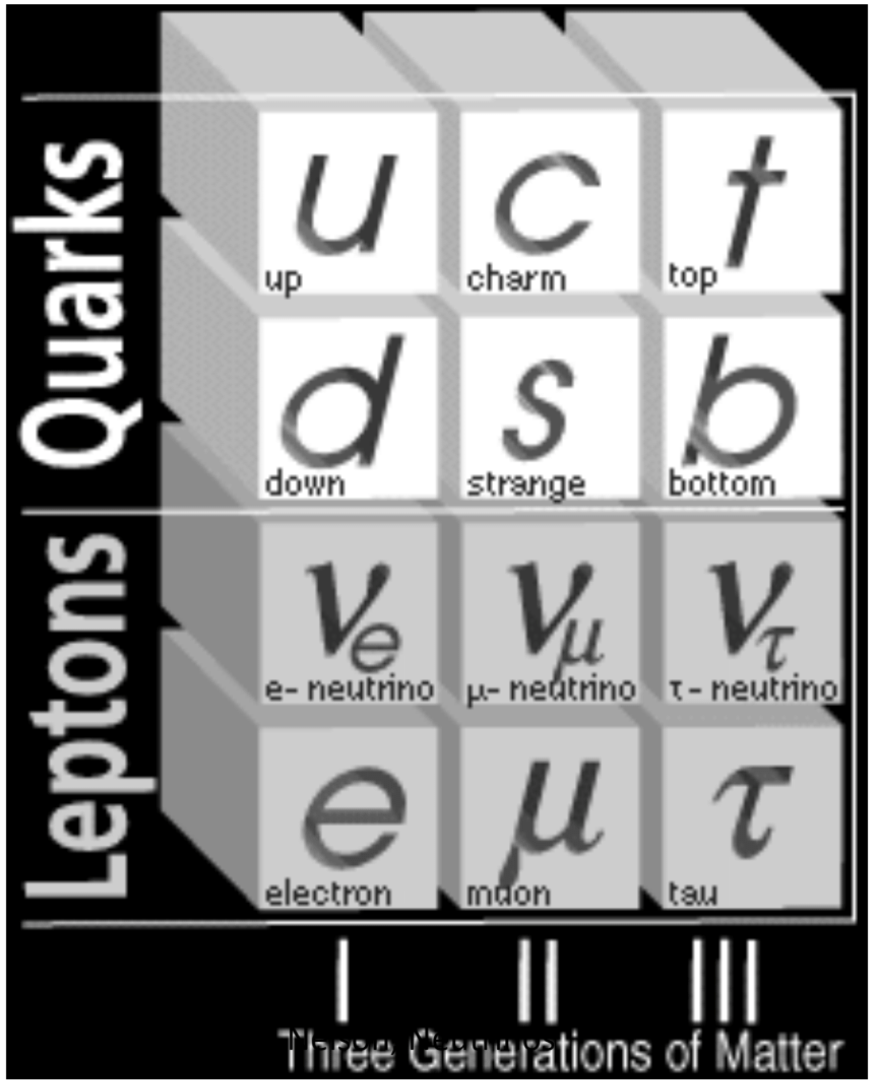
Q = -1/3e

Q = 0

Q = -1e

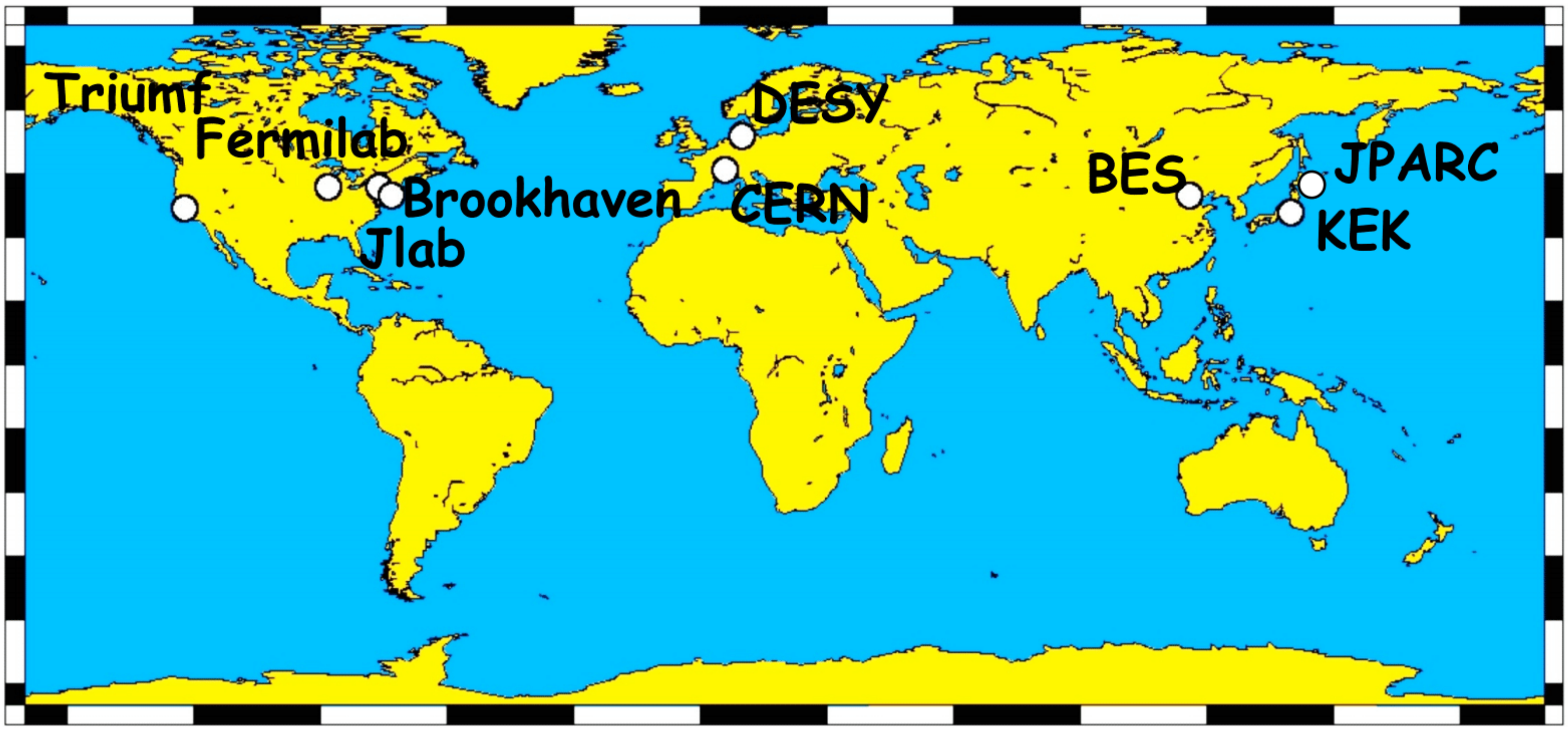
The Periodic Table of Elementary Particles

Weak Force

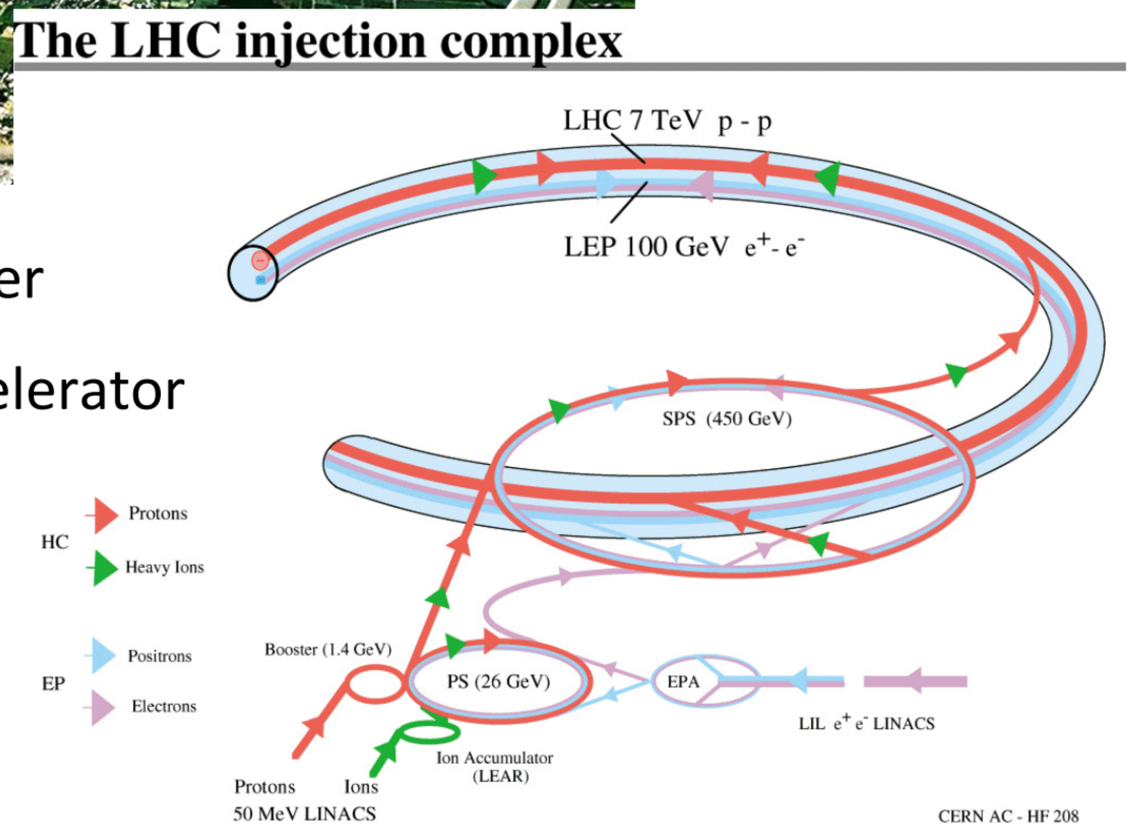


Making high energy beams of particle

Some High-Energy Accelerator Facilities



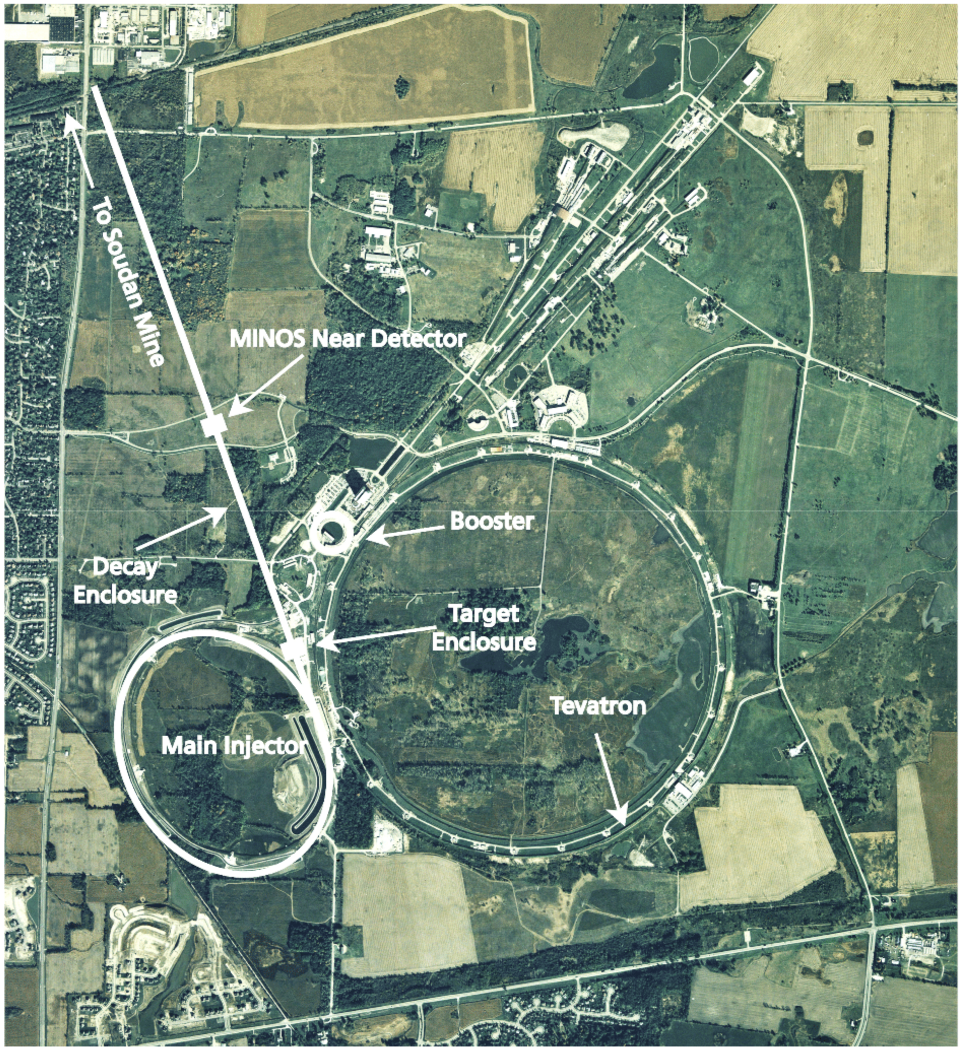
Particle Accelerators



CERN – Large Hadron Collider

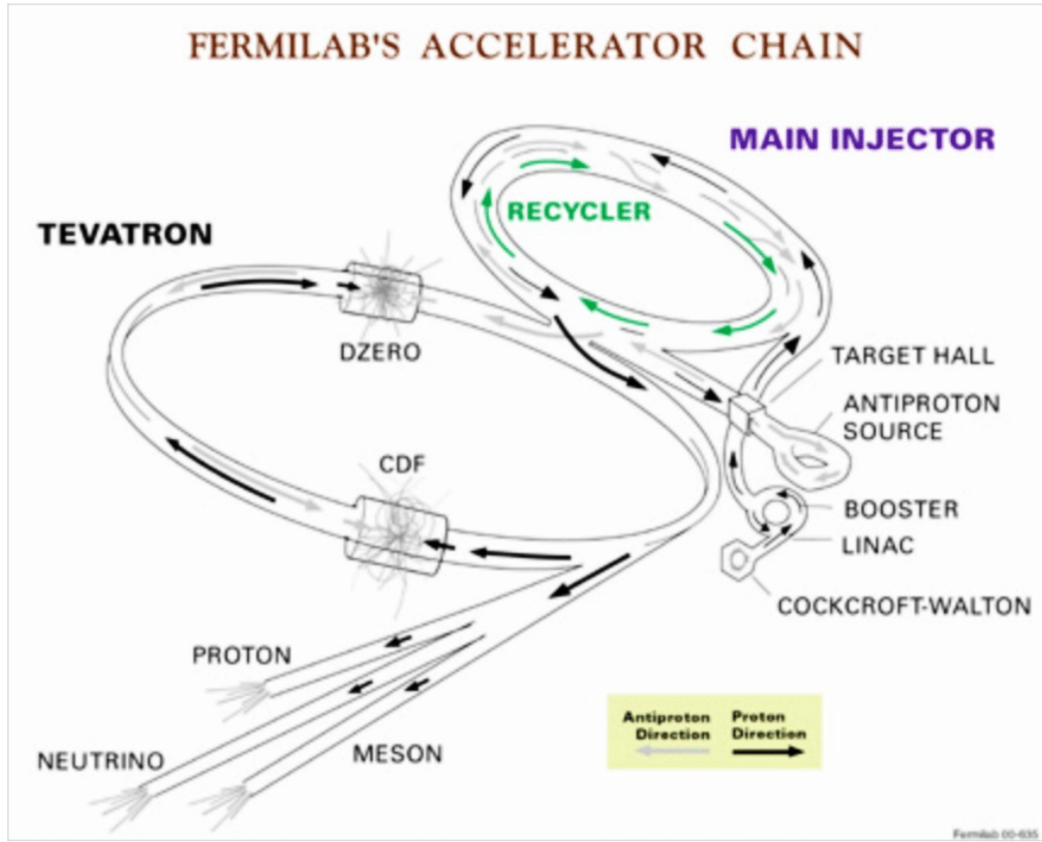
7+7 TeV proton-proton accelerator

Fermilab


To Soudan Mine
MINOS Near Detector
Booster
Decay Enclosure
Target Enclosure
Main Injector
Tevatron

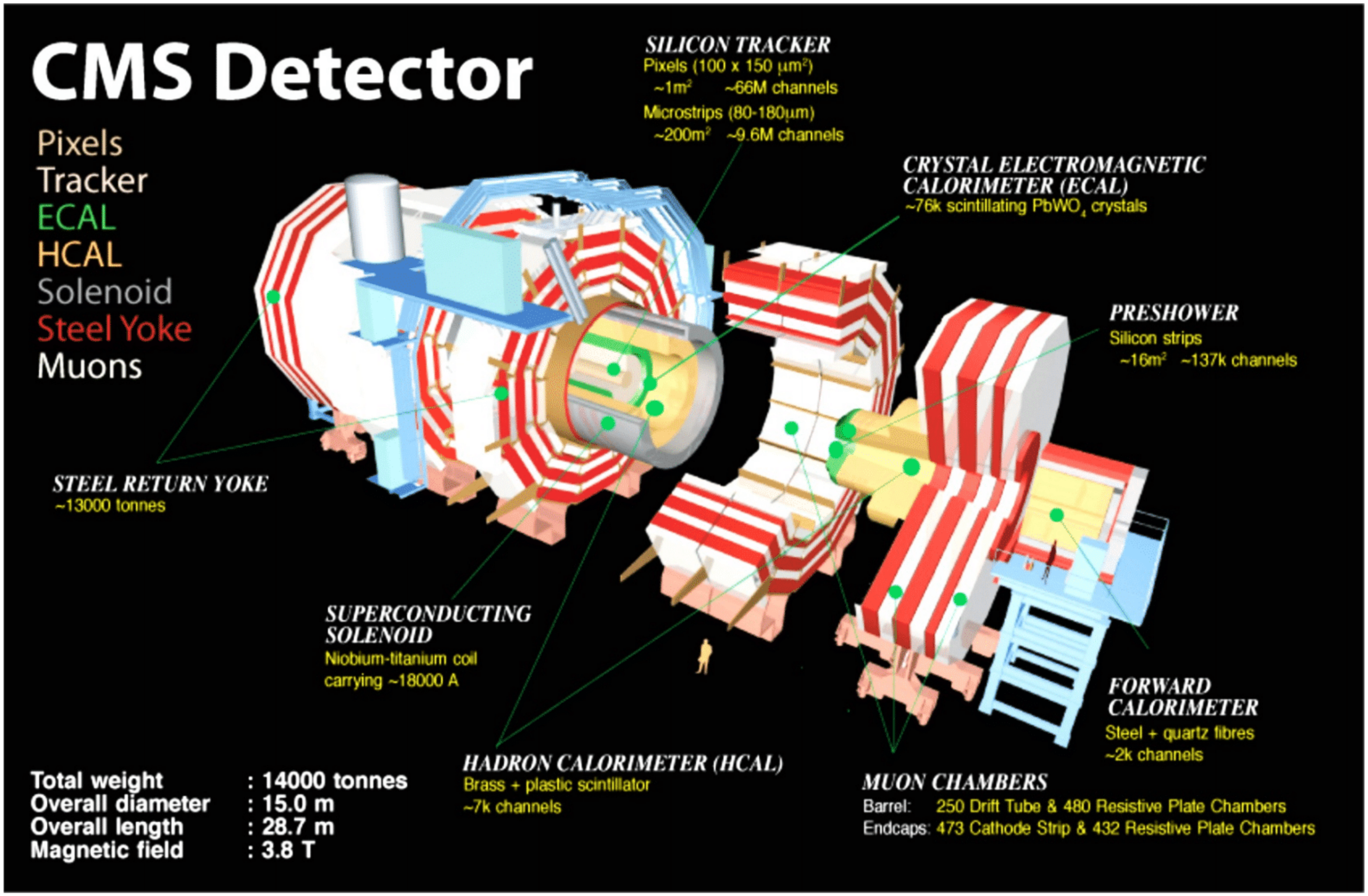
Fermilab's Accelerator Complex

- Energy increased in steps kinda like a transmission



Detecting particles

Detecting Collision Products



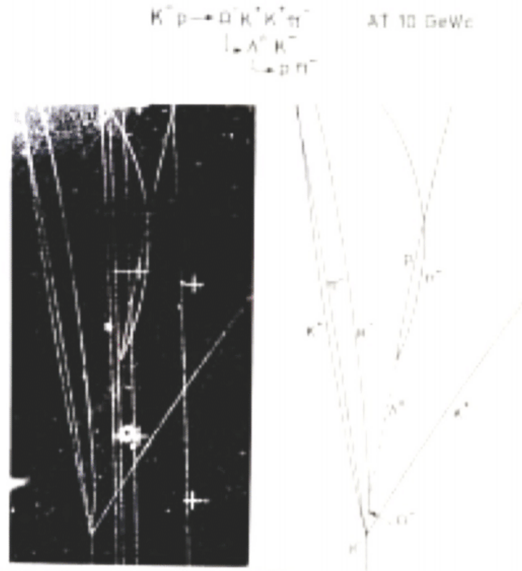
Experimental Goals

- We'd like to get the four vectors for each of the particles in the final states of an interaction
  - > Mass & momentum
  - > Requires at least two measurements of the particle
  - > Some of them need to be "non-destructive"
- Complications due to
  - > Most particles decay before they can be detected
    - Most common things to try to actually detect ➔
  - > Background from other interactions
  - > Ambiguities
  - > Not all particles are created equal: some are harder to detect than others!

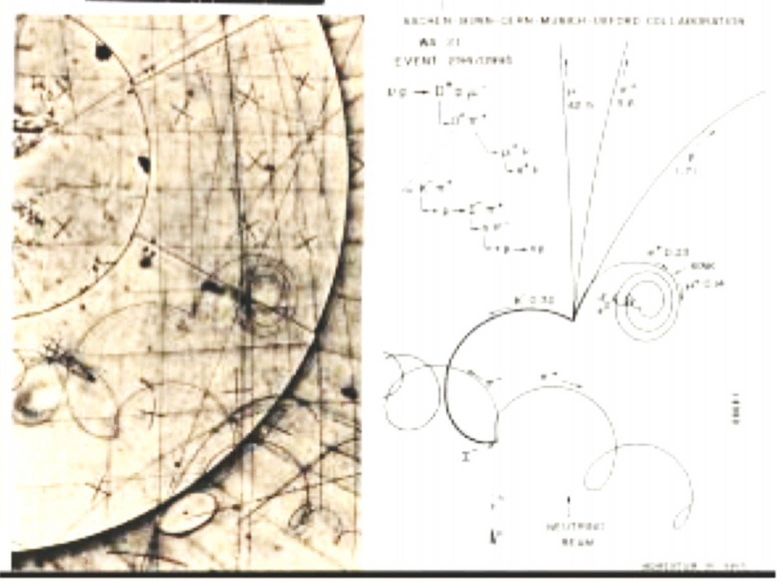
Particle	Mass (MeV/c^2)
p	938.27
n	939.57
π^+	139.57
π^0	134.96
e^+	0.511
μ^+	105.7
K^+	493.7
K^0	497.7

A Look at the Past

E.Nappi
INFN-Bari



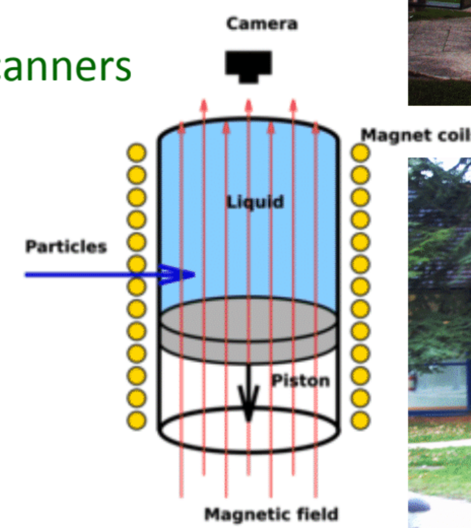
70's: Hydrogen bubble chamber



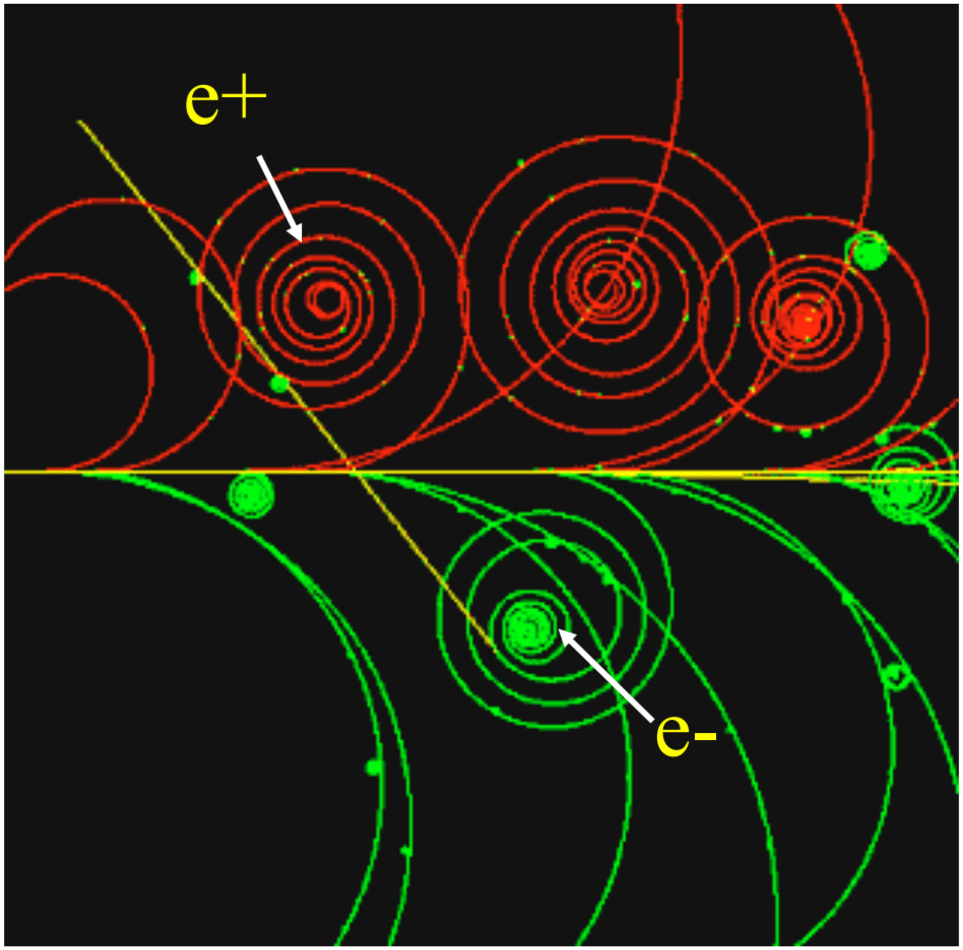
1978: BEBC

Bubble chambers

- Make a superheated liquefied gas & put it in a magnetic field
  - > Near boiling point & a large piston to put it past
- Particles would dump energy into the liquid and make bubbles
- Literally take a picture
  - > Make measurements on the printed photos
  - > Very precise
  - > Very labor intensive – fleets of scanners
- Particle identification possible
  - > Decay modes
  - > Lifetimes
  - > Some particle identification
    - More on this later



A track in a magnetic field gives us the momentum and the charge



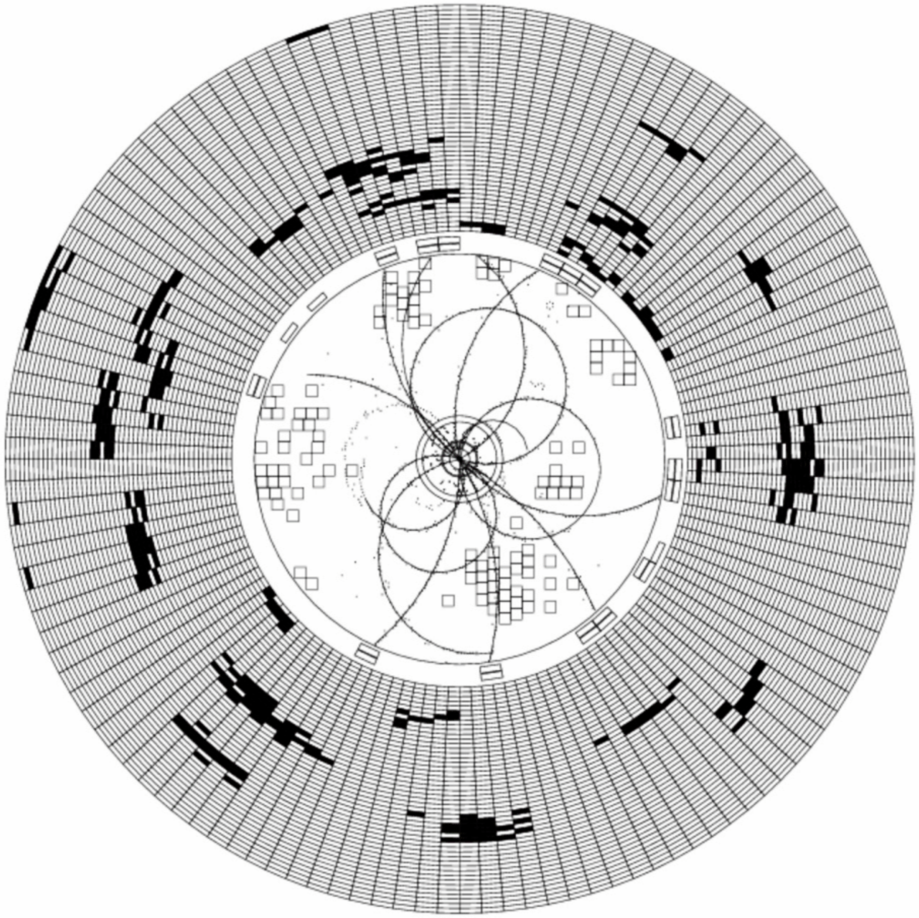
$$\vec{F} = q\vec{v} \times \vec{B}$$

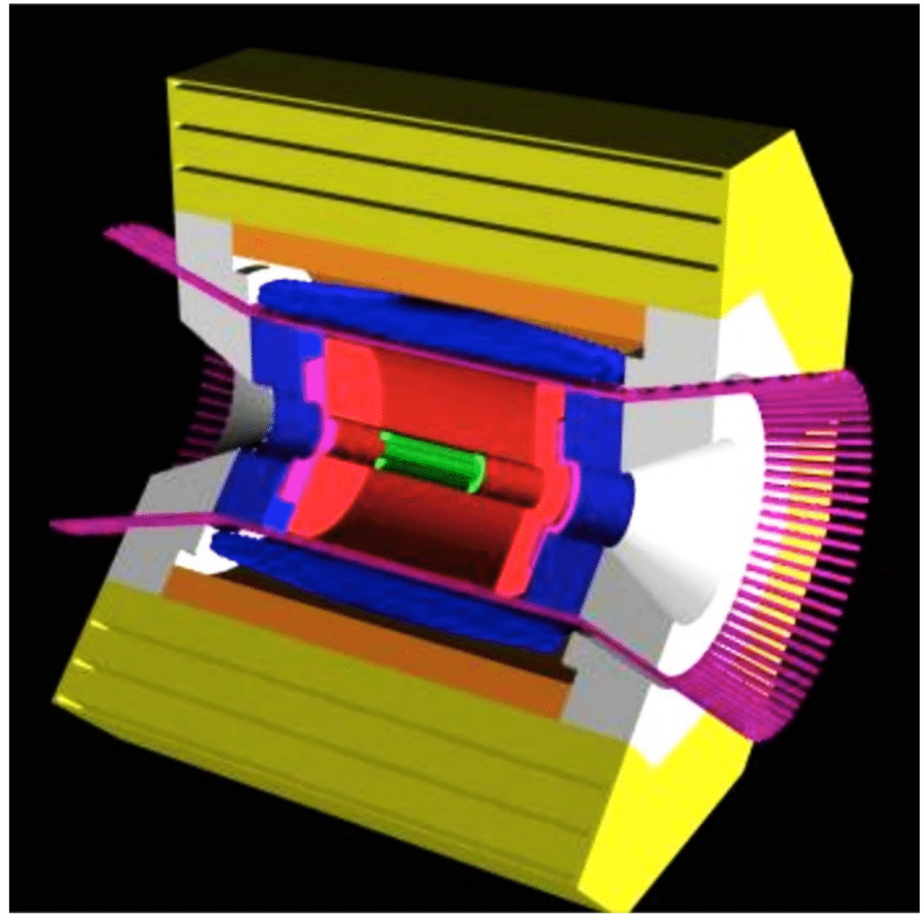
r = 0.3Bp where r [m], B [T], p [GeV/c]

Modern world

- Use a gas, liquid, or solid and look for electrons kicked out of the gas by charged particles
- Electronic readout
  - > Much faster rates
  - > Automated analysis and reconstruction
  - > Mostly lower resolution

An event display from a detector (CLEO2) electron-positron collision (5+5 GeV)



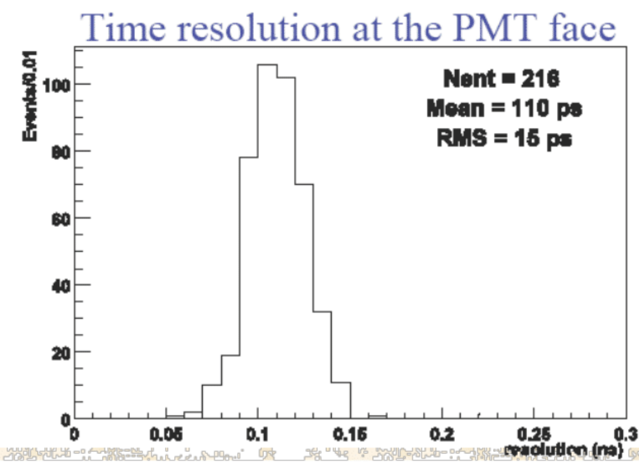


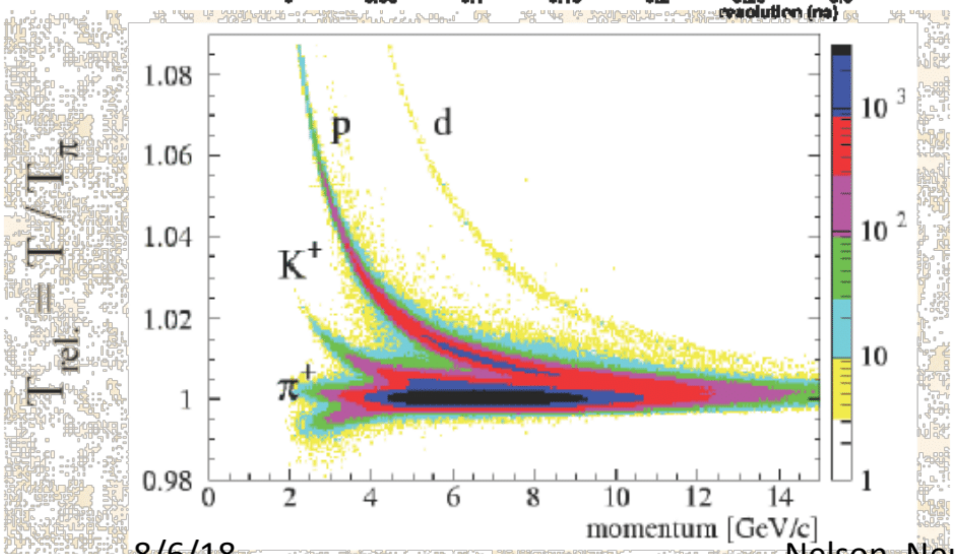
Particle Identification

- Need something in addition to momentum
- Mass is good…
  - > Electrons knocked off of atoms by high speed charged particle
    - Rate of ionization (dE/dx) is a function of velocity
  - > Time of flight
    - velocity vs momentum to get mass
  - > Cherenkov radiation
    - Threshold and ring size depend on velocity
  - > A few others later
    - Radiation damage in a solid
    - Penetrating power
    - Transition radiation
    - Decay kinematics
    - Distribution of deposited energy

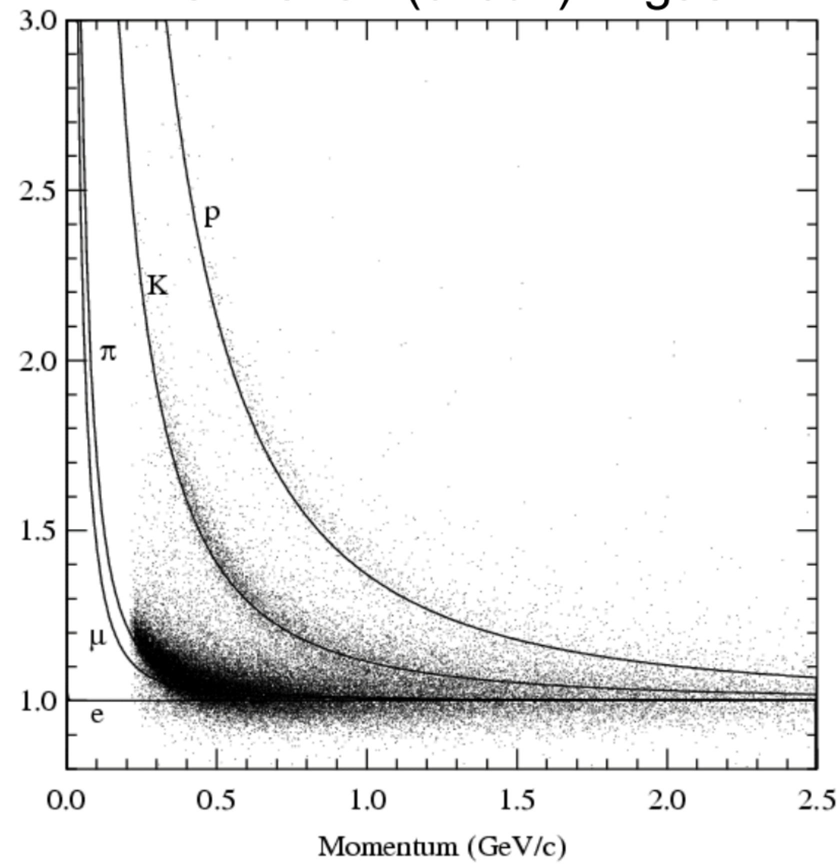
Examples

Time of flight



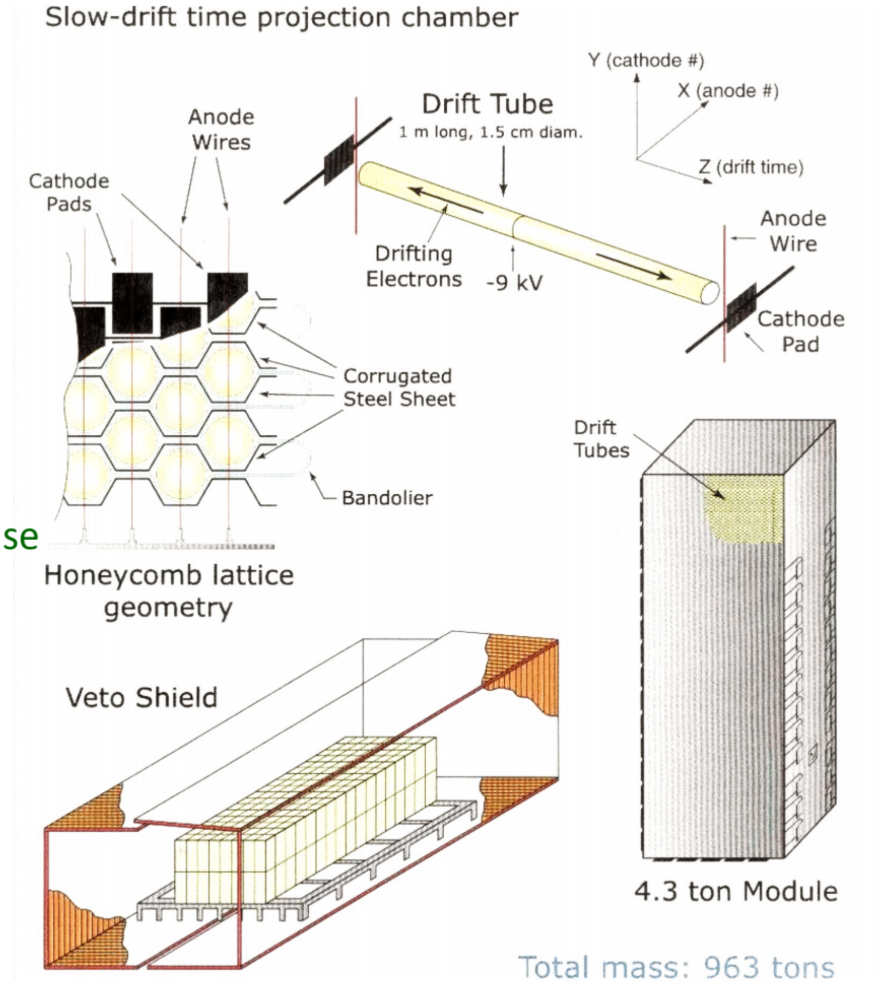


Ionization (dE/dx) in gas



Other options for tracking

- Time projection chamber
  - > Use long drifts to measure 3rd dimension with time of electron drift
  - > Slower & less readout channels
- Ionization in a solid
  - > Use silicon to do the same thing
  - > Can use typically 10 um side strips or pixels
    - Very low gain ~3000 electrons because we do not have the gas gain
  - > Many millions of pixels in typical modern detectors
- Molecular damage
  - > Photo plates
  - > Acid etch



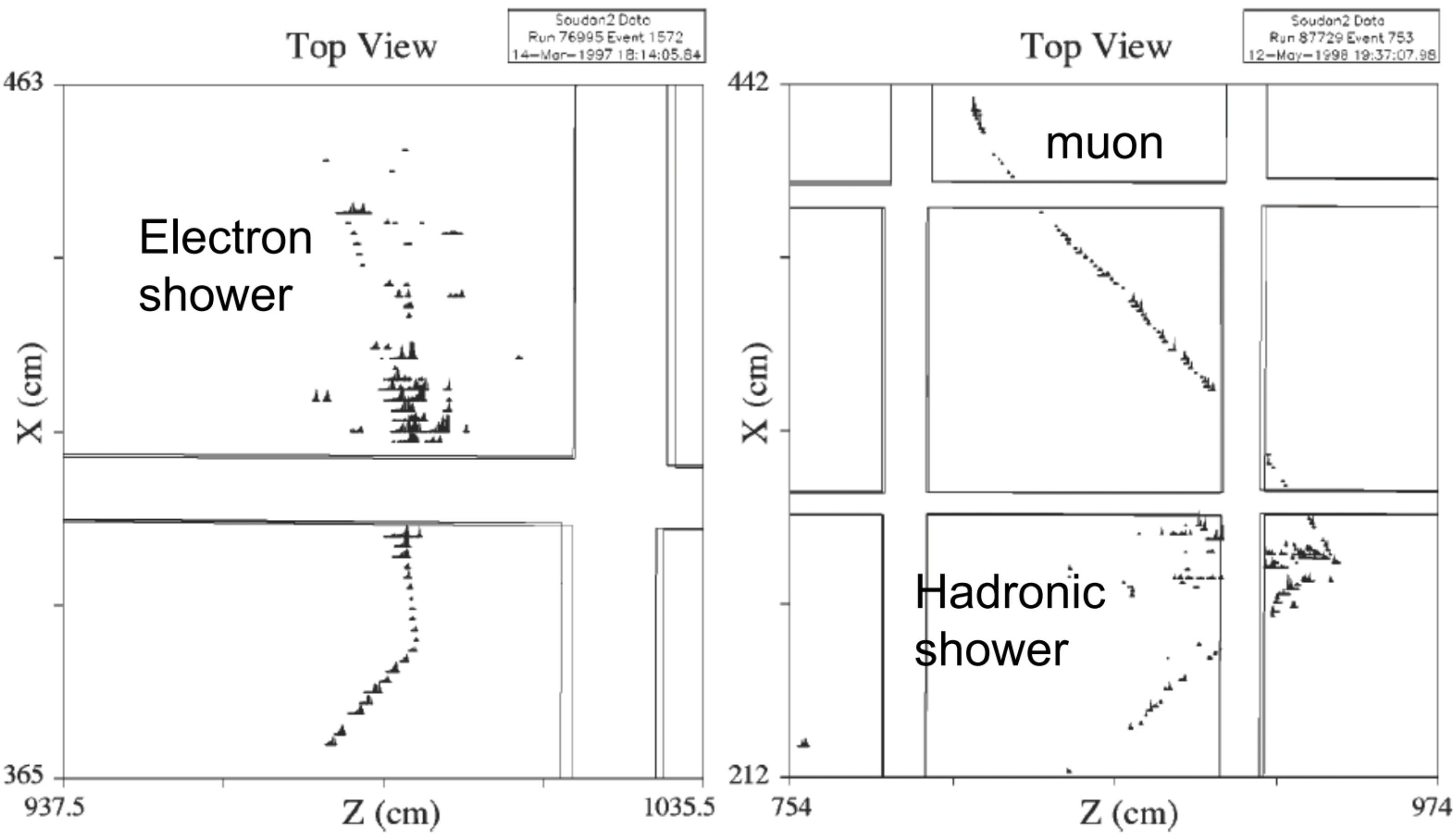
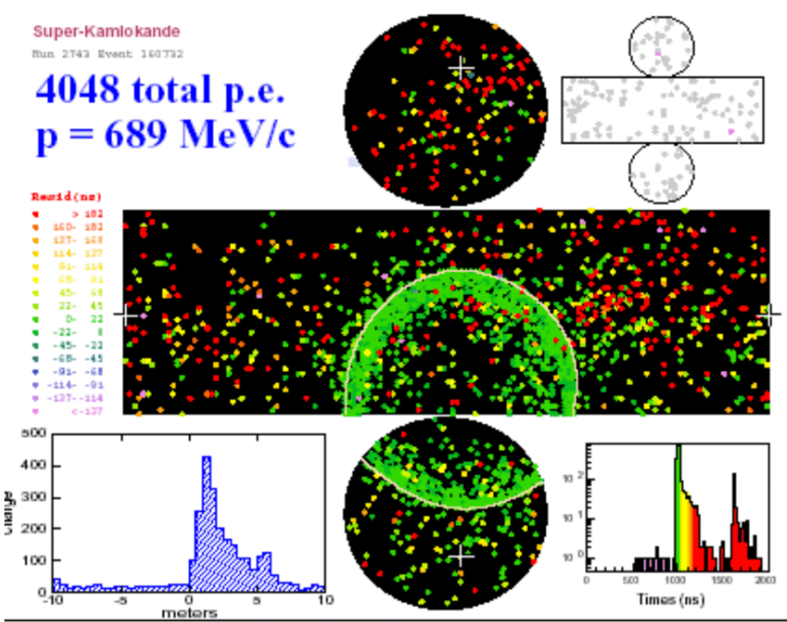
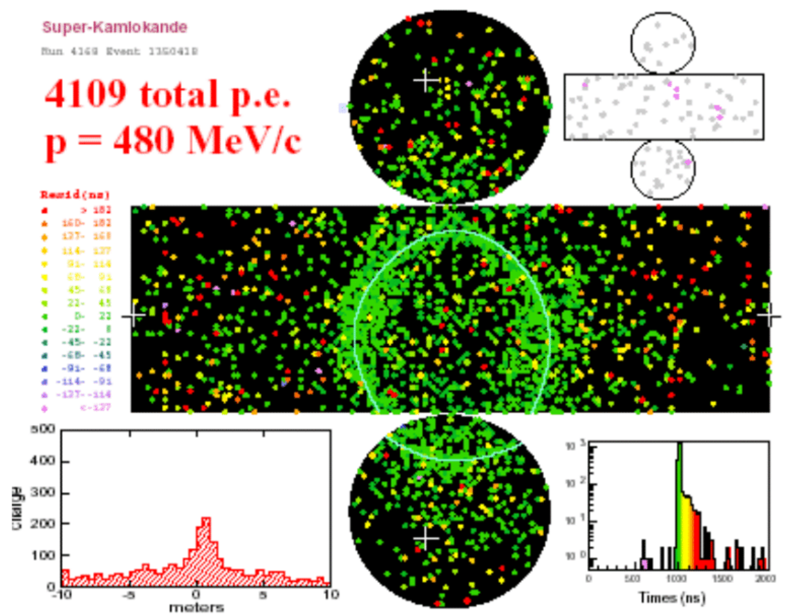


FIG. 1. Two neutrino interactions in Soudan 2. The event on the left is a quasielastic ν_e interaction producing a proton and an electron. The electron travels about one radiation length before showering. The proton is easily recognizable by its heavy ionization (large symbols) and its lack of Coulomb scattering. The event on the right has a long noninteracting muon track, which shows typical Coulomb scattering, and a hadronic shower at the vertex. The shower contains a charged pion and at least two electromagnetic showers.

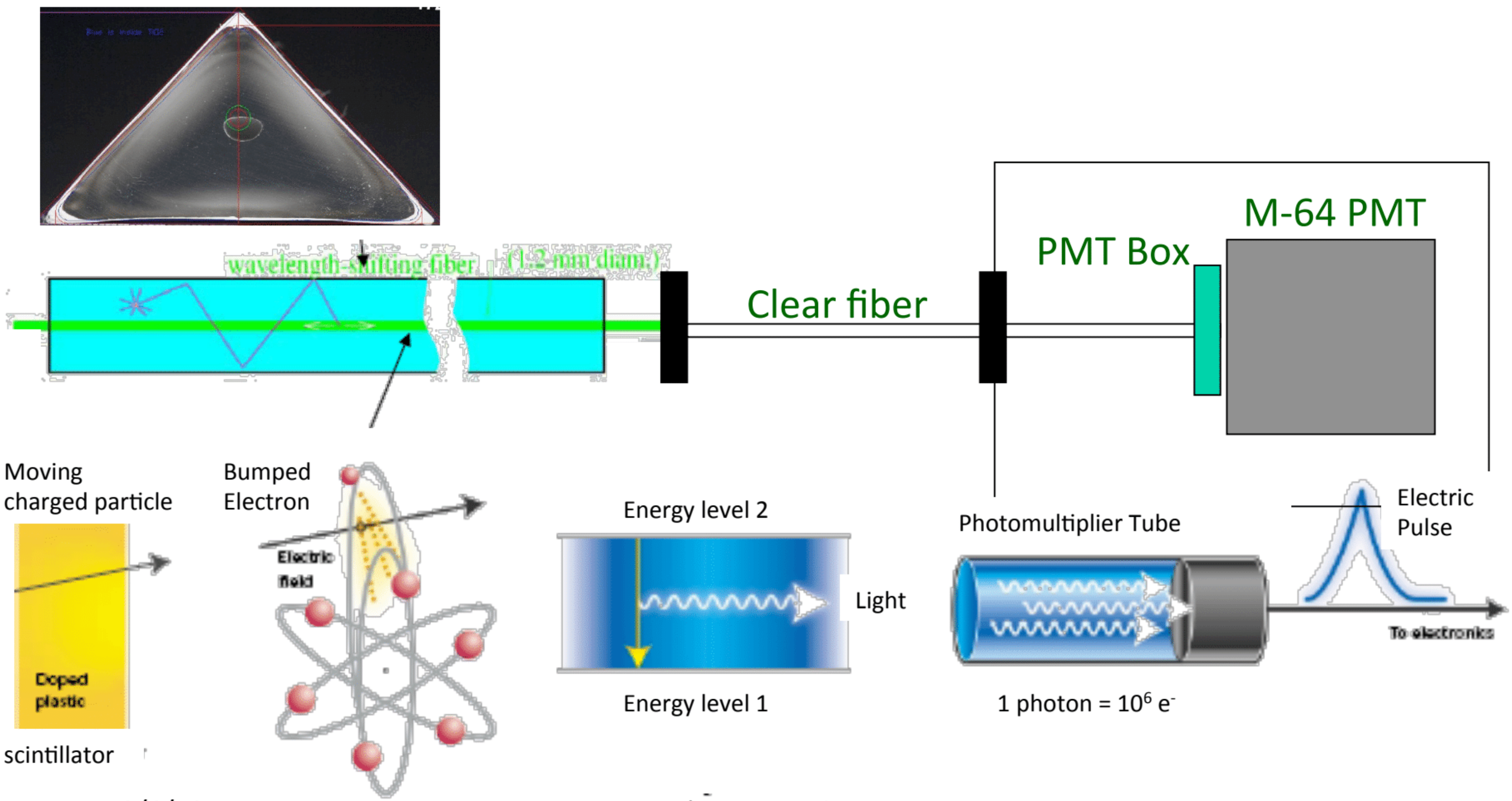
Cerenkov Rings in SuperK

- Note fuzzy vs clear outer edge

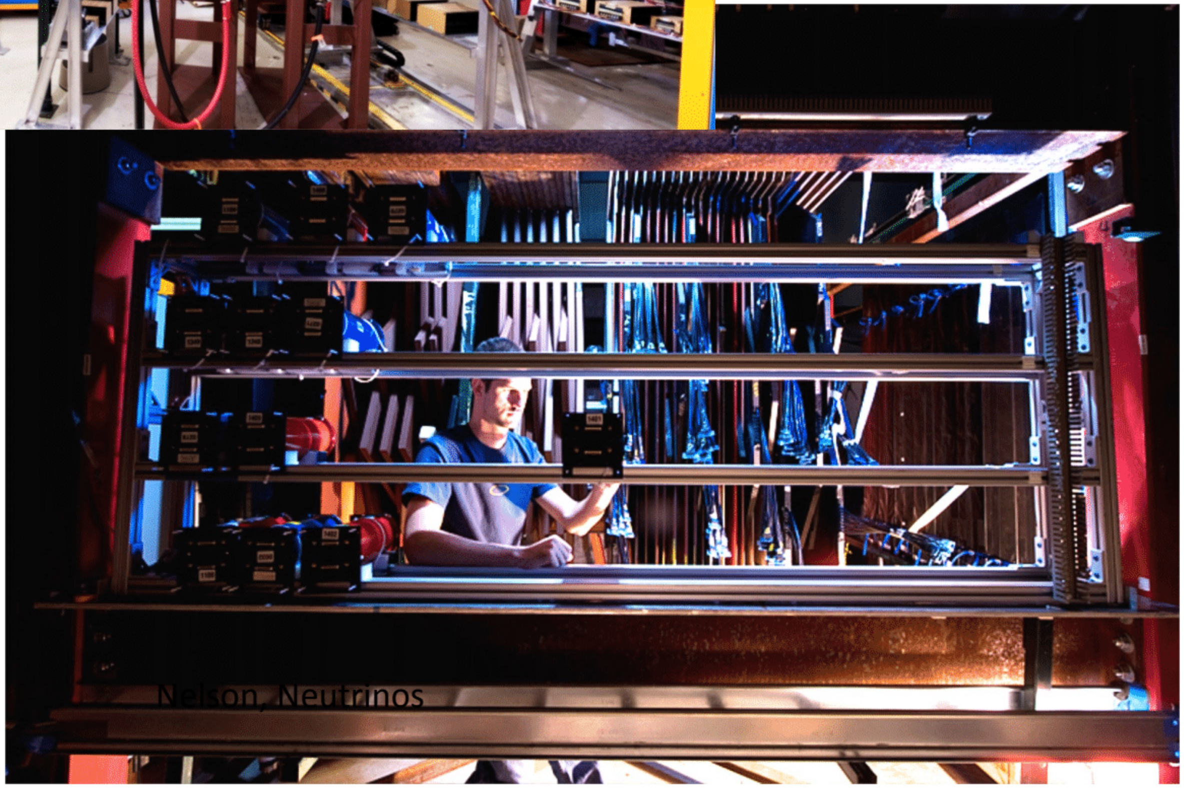




Scintillation



A small experiment: the MINERvA test beam experiment



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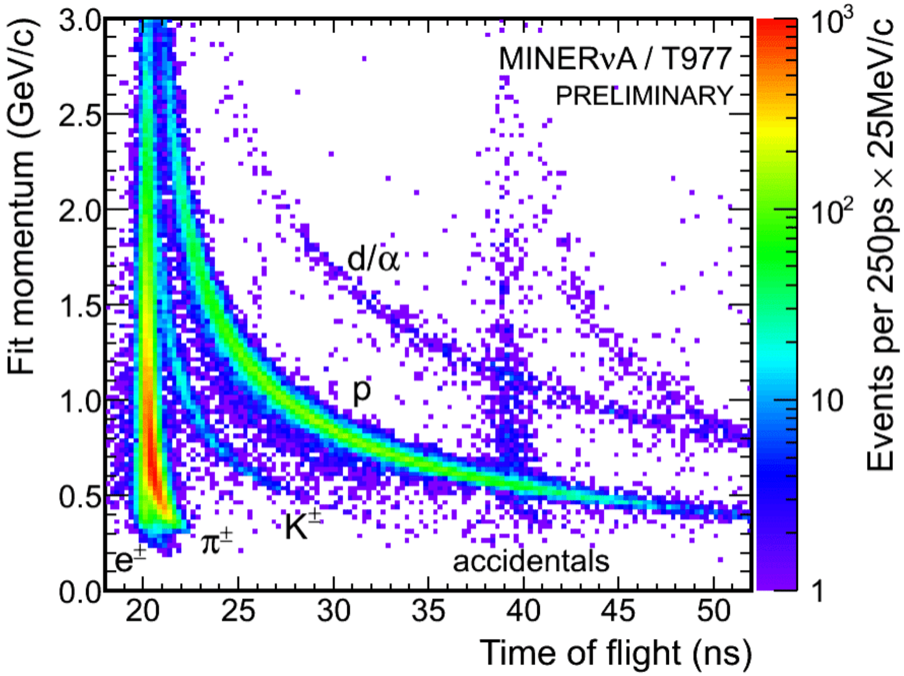
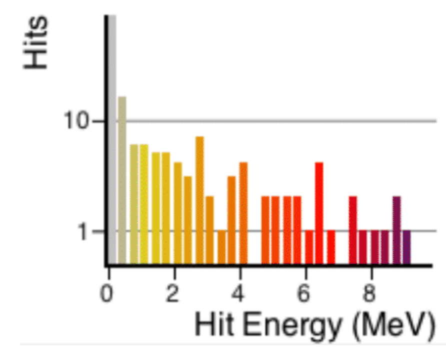
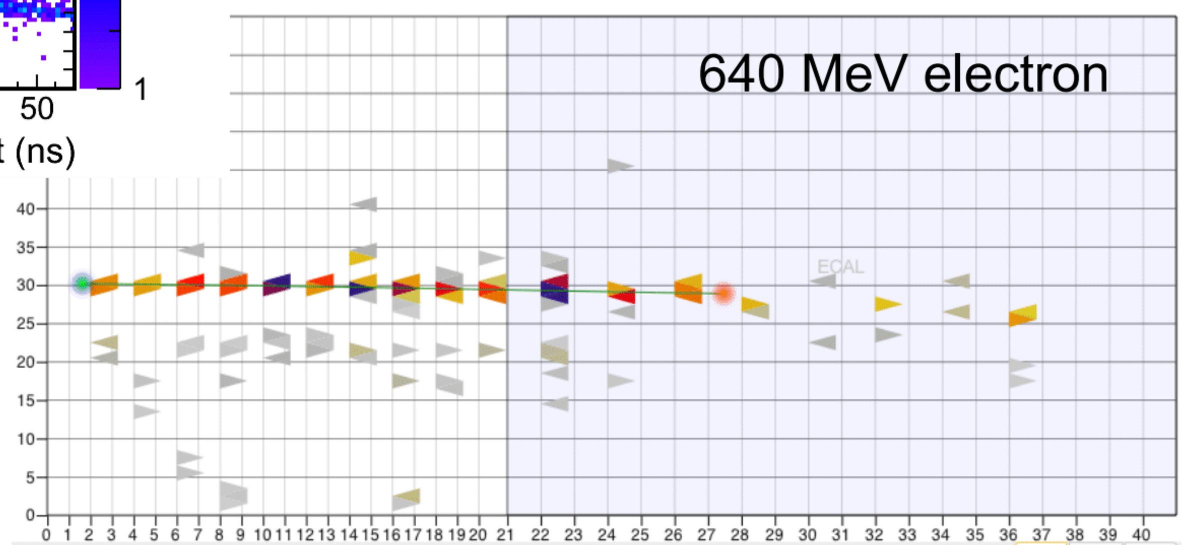


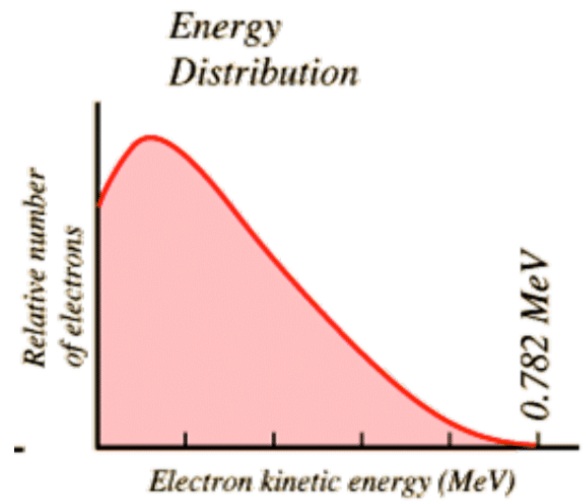


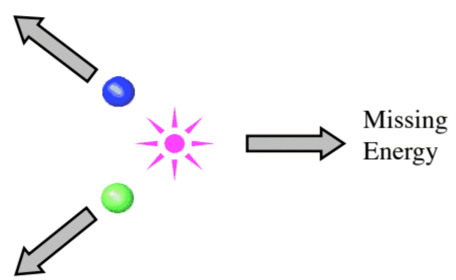


The neutrino story

The Missing Energy Problem

- Isolated neutrons have a 13min half life
  - > They were observed to decay to a proton and an electron
- The problem
  - > They should have been back to back and mono-energetic if it was a two-body decay
  - > A continuous spectrum was observed
  - > When adding up the momenta of the observed decay products, **energy was missing**

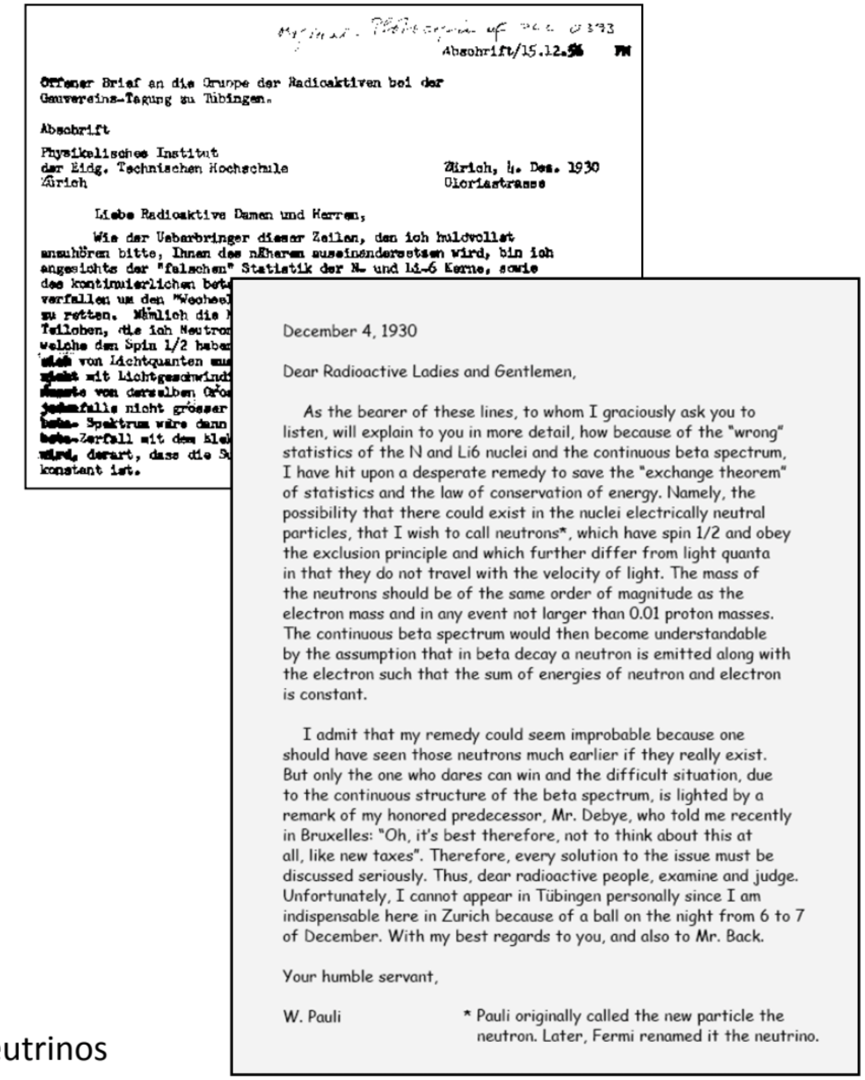




"I have hit upon a desperate remedy…"

- Pauli proposes that a
  - > New
  - > Chargeless,
  - > Massless,
  - > Weakly interacting

  particle is also being produced



Abschrift/15.12.56

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen bet…
verfallen um den "Wechsel…
zu retten. Nämlich die …
Teilchen, die ich Neutron…
welche den Spin 1/2 haben…
sich von Lichtquanten aus…
nicht mit Lichtgeschwindi…
müsste von derselben Grö…
jedenfalls nicht grösser …
beta- Spektrum wäre dann …
beta-Zerfall mit dem Ele…
wird, derart, dass die Su…
konstant ist.

December 4, 1930

Dear Radioactive Ladies and Gentlemen,

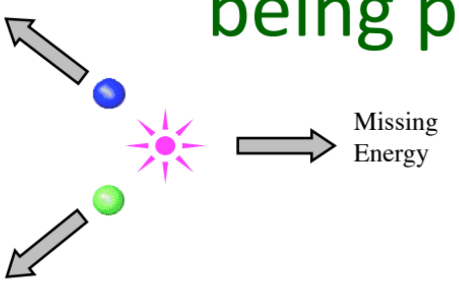
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons*, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted along with the electron such that the sum of energies of neutron and electron is constant.

I admit that my remedy could seem improbable because one should have seen those neutrons much earlier if they really exist. But only the one who dares can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honored predecessor, Mr. Debye, who told me recently in Bruxelles: "Oh, it's best therefore, not to think about this at all, like new taxes". Therefore, every solution to the issue must be discussed seriously. Thus, dear radioactive people, examine and judge. Unfortunately, I cannot appear in Tübingen personally since I am indispensable here in Zurich because of a ball on the night from 6 to 7 of December. With my best regards to you, and also to Mr. Back.

Your humble servant,

W. Pauli

* Pauli originally called the new particle the neutron. Later, Fermi renamed it the neutrino.



Their original experimental concept

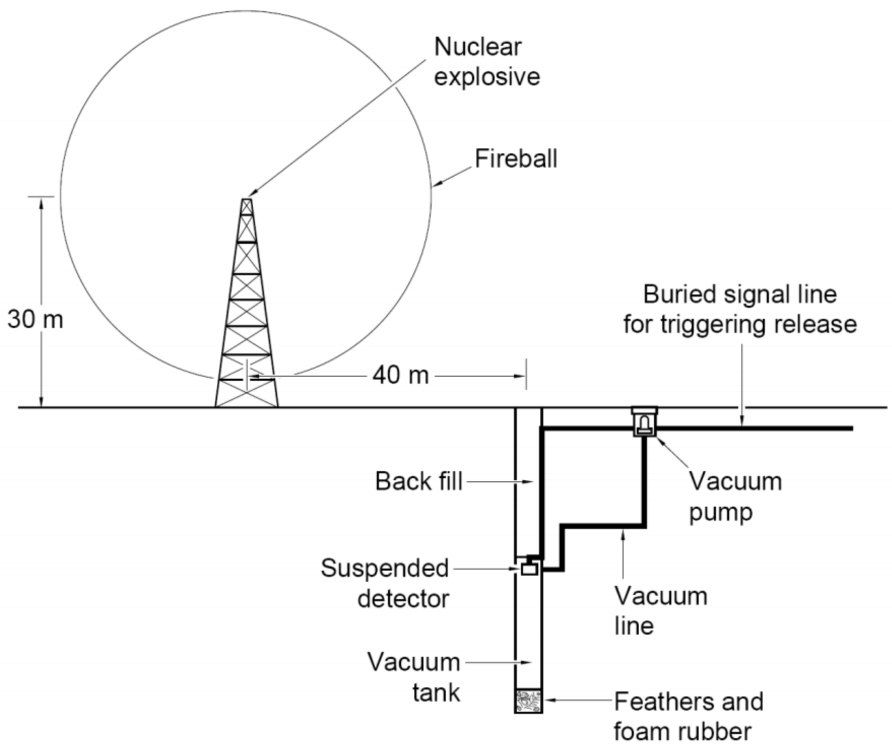
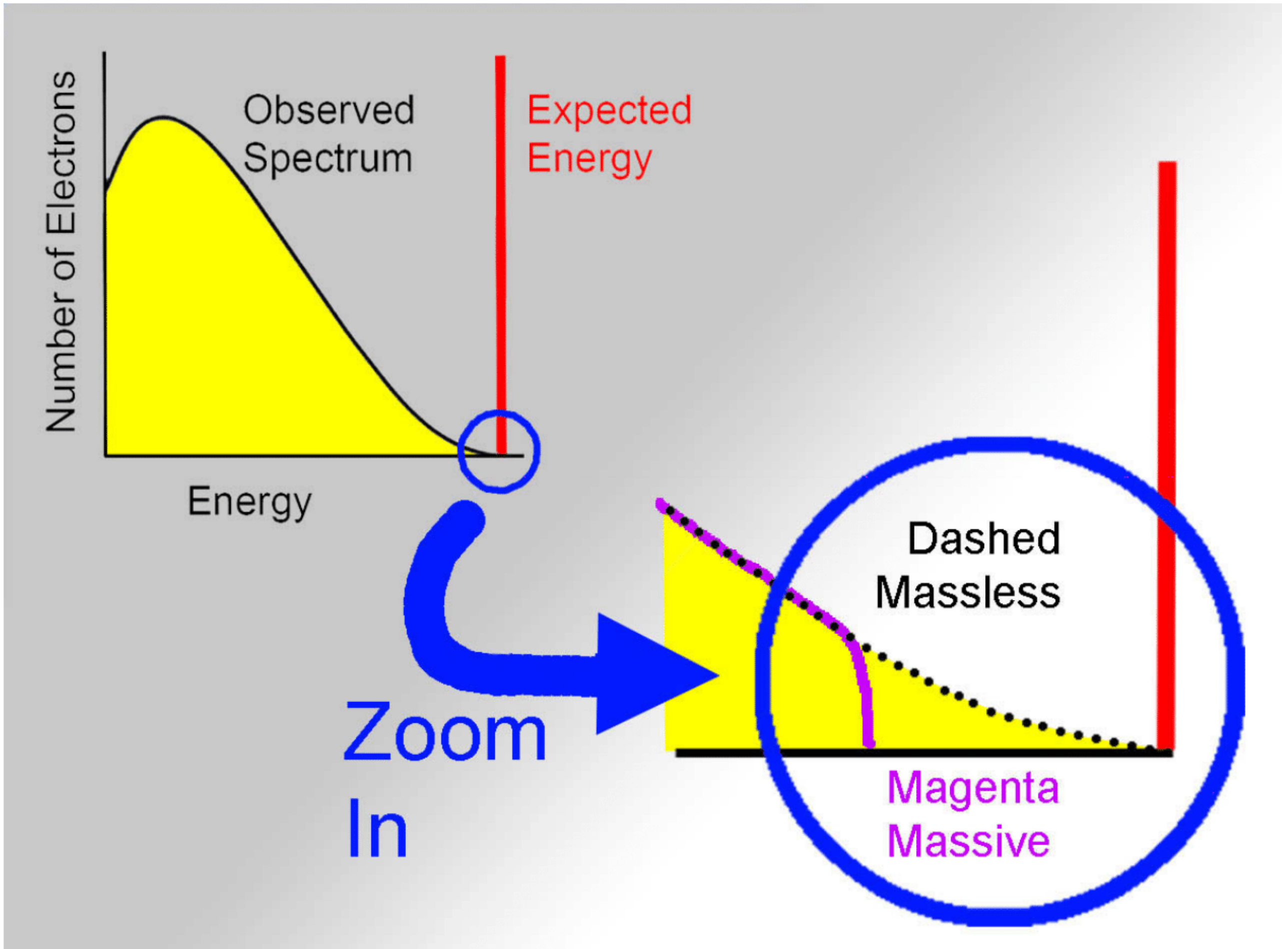


Figure 1. Detecting Neutrinos from a Nuclear Explosion
Antineutrinos from the fireball of a nuclear device would impinge on a liquid scintillation detector suspended in the hole dug below ground at a distance of about 40 meters from the 30-meter-high tower. In the original scheme of Reines and Cowan, the antineutrinos would induce inverse beta decay, and the detector would record the positrons produced in that process. This figure was redrawn courtesy of Smithsonian Institution.

Later they were seen

- In the 1930 nuclear reactors were not in the forefront of people minds
- As they came to being, people tried to see the reactor's neutrinos in scintillator counters
- In 1956, Frederick Reines and Clyde Cowan, report the first evidence for neutrinos

Neutrino mass from the end-point method



Neutrinos

- Little or no mass
  - > Cosmology & direct evidence say $M_\nu < 1eV$
  - > The most numerous particle of matter in the universe
  - > Energy density of Big Bang neutrinos is comparable to all matter in the Universe
  - > Produced in radioactive decays, nuclear reactions, the Sun, & supernova explosions

- Only interact using the weak nuclear force
  - > This doesn't happen very often

Neutrino experiments: exercises in forensics

- We cannot see the neutrino
- We only know they are there by looking for the results of their interactions
- We take the final state particles and infer the energy and type of the incoming neutrino
  - > Forensics
- Can also the "missing energy" technique to infer a neutrino was produced

2-Flavor Oscillation Formalism

- What if there 2 neutrino basis (weak force & mass)?

$$|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$$

- The probability that a neutrino (e.g. ν_μ) will look like another variety (e.g. ν_τ) will be

$$P(\nu_\mu \rightarrow \nu_\tau; t) = |\langle\nu_\tau|\nu_\mu(t)\rangle|^2$$

- A 2-component unitary admixture characterized by θ results in

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \, \sin^2(1.27\, \Delta m^2\, L/E)$$

- Experimental parameters

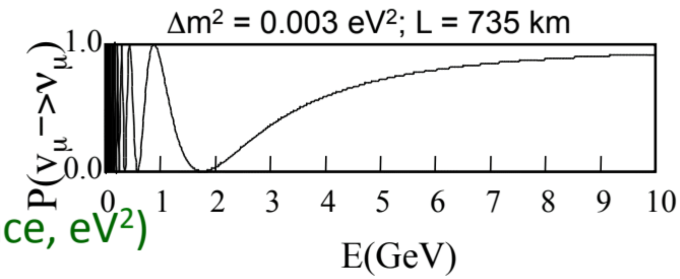
L (distance from source to detection, km)

E (particle energy, GeV)

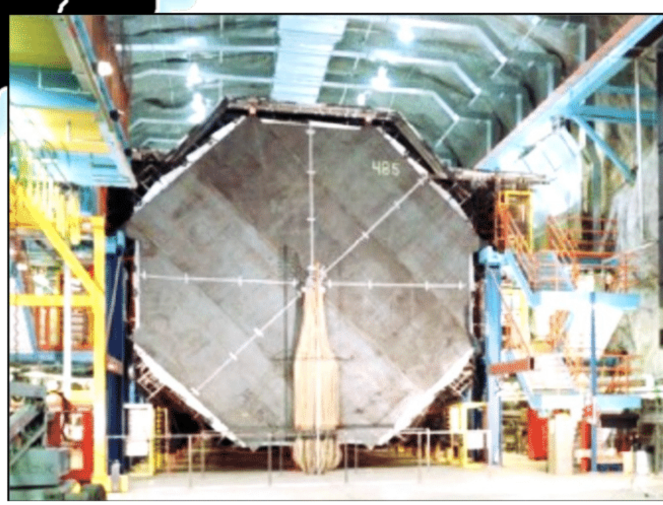
- Oscillation (physics) parameters

$\sin^2 2\theta$ (mixing angle)

$\Delta m^2 = m_\tau^2 - m_\mu^2$ (mass squared difference, eV^2)



The MINOS Experiment



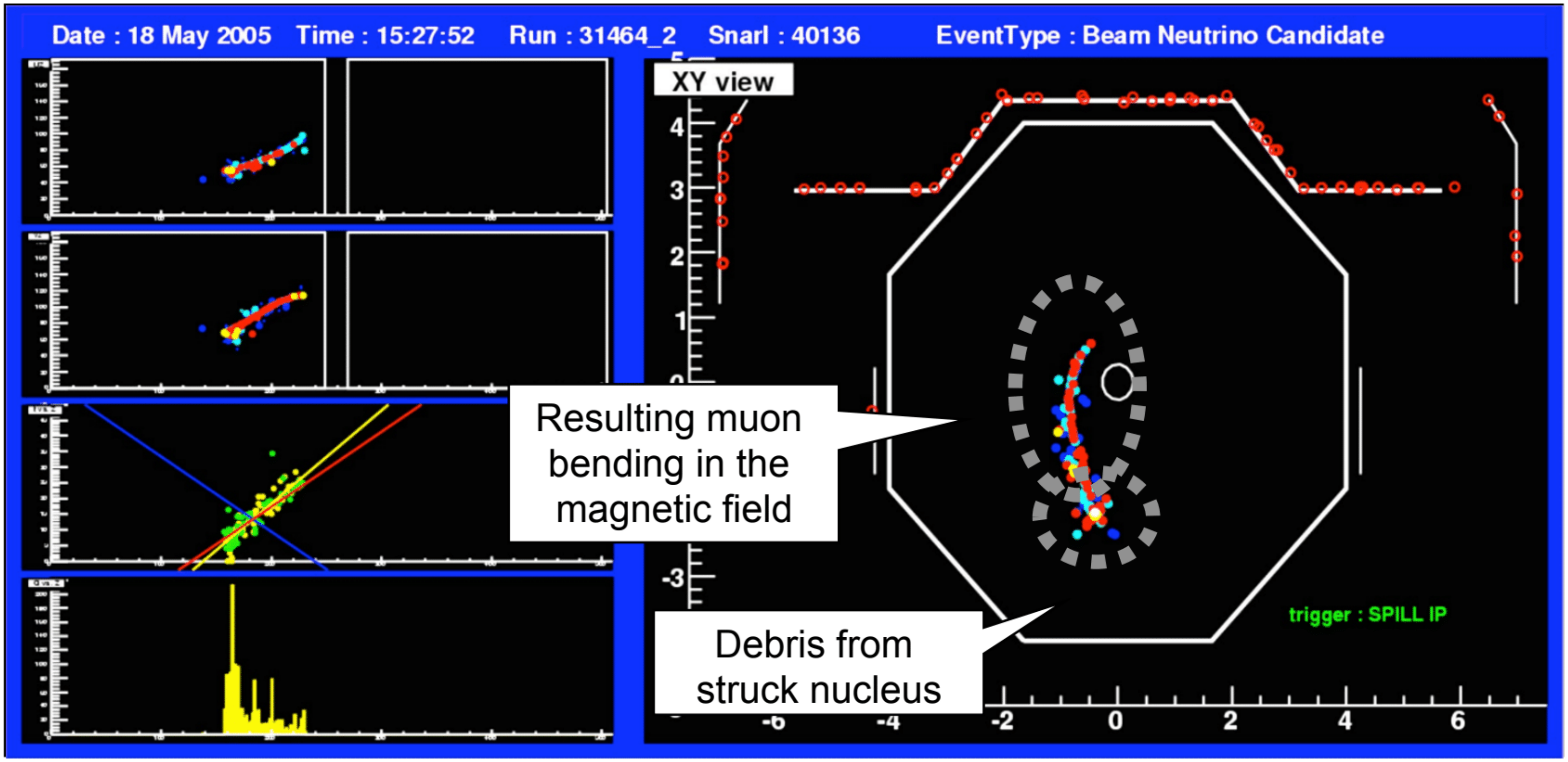
Send neutrinos 735 km from Fermilab to Soudan

- There's no tunnel — just solid rock
- Their journey takes only 0.0024 sec

2 neutrino detectors

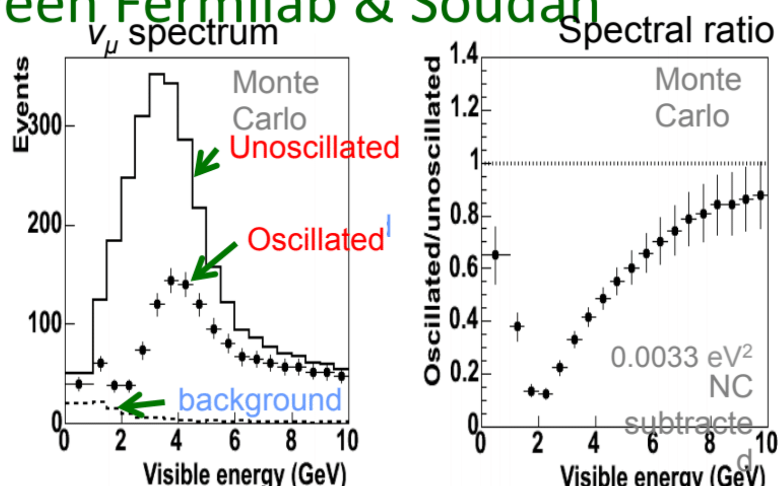
- A small detector at Fermilab ("near detector")
- A large detector at Soudan ("far detector")

A Neutrino Interaction
("An Event")



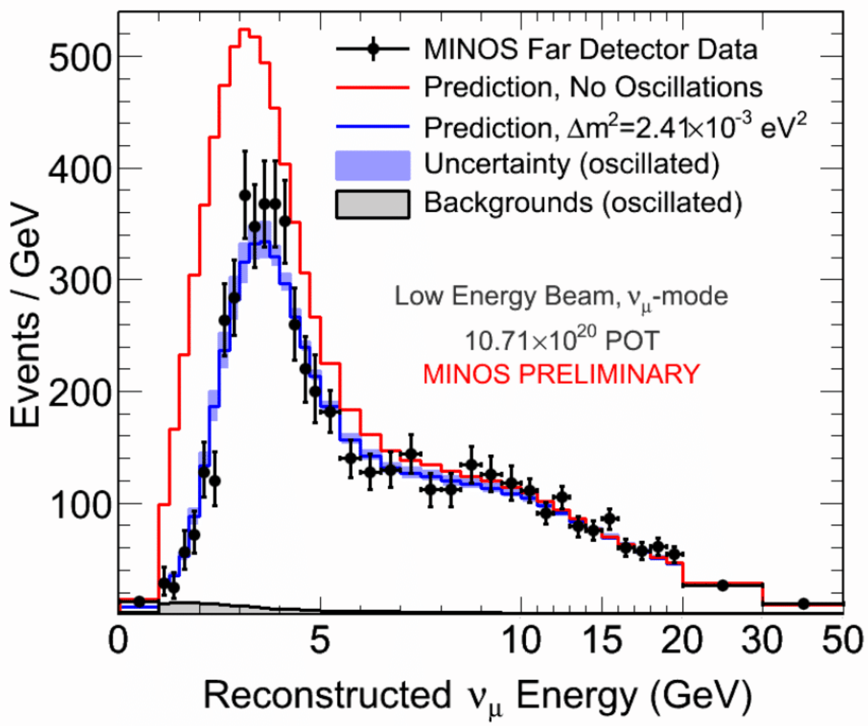
Neutrino Data Analysis

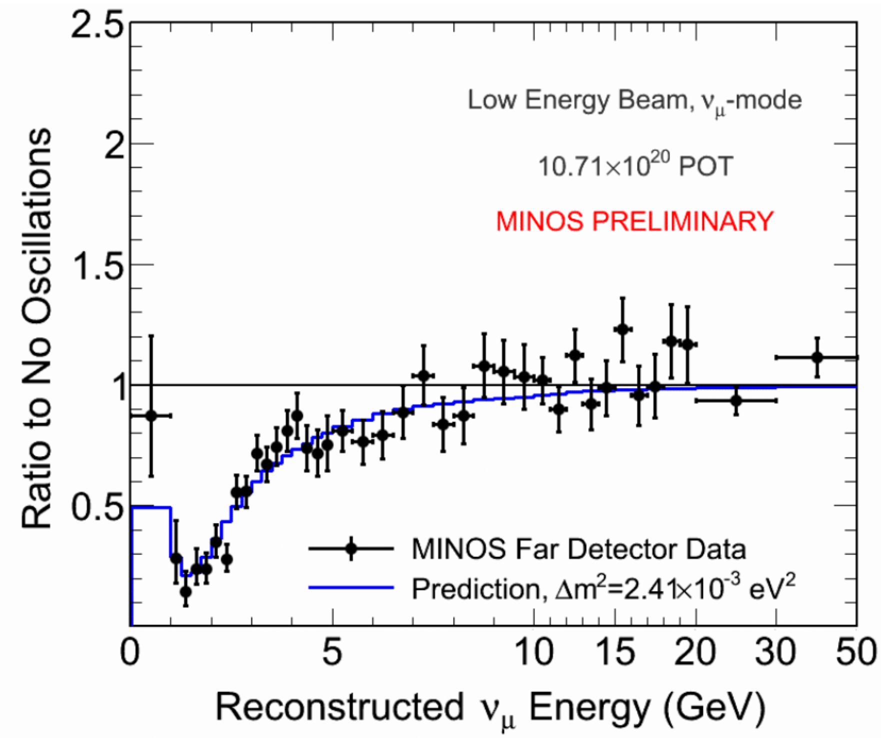
- We run with a muon neutrino beam
  - > Look for muons & measure their momentum
    - From curvature of the muons in the magnetic field or range
  - > Look at energy recoiling form the struck nucleon
  - > Compute the total energy & plot the energy spectrum
- Oscillations result in…
  - > Spectral differences between Fermilab & Soudan
  - > Dip position & depth give us the oscillation parameters
  - > Goal is few percent measurement



Nelson, MINOS

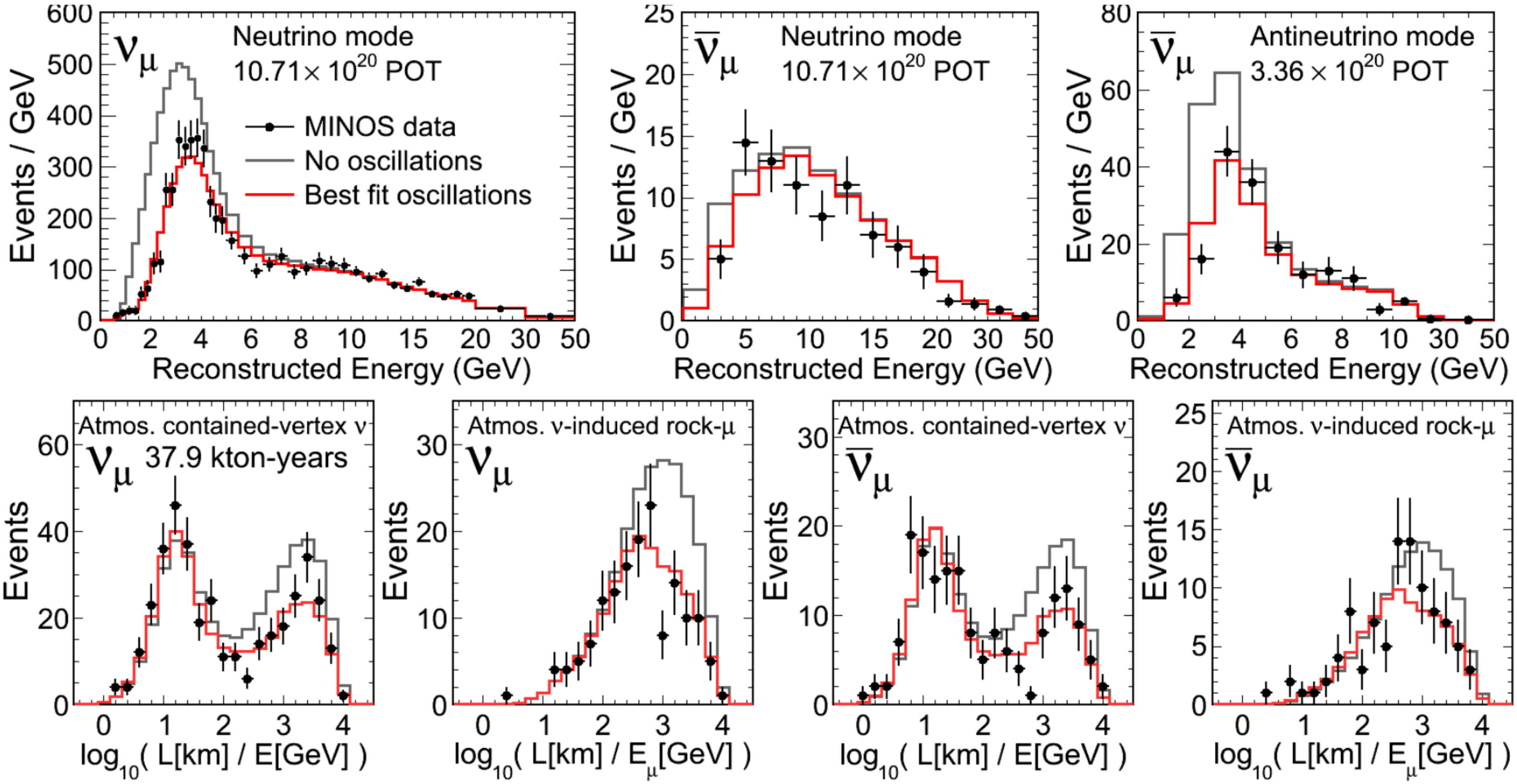
MINOS long-baseline neutrino oscillation results





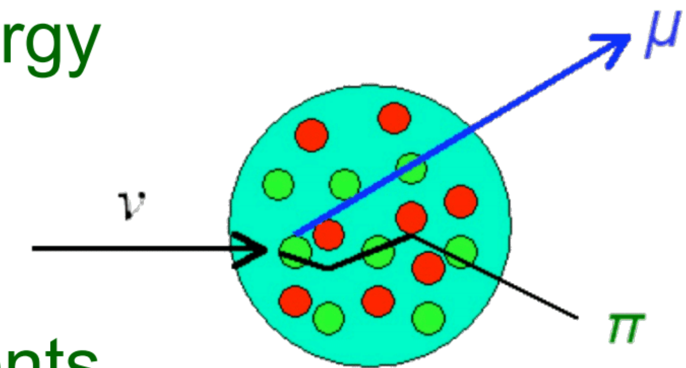
Category	Observed	Predicted (w/o oscillations)
Beam neutrinos	6028	7074
Atmospheric neutrinos	2072	2397

MINOS beam & atmospheric neutrinos & antineutrinos combined in a fit



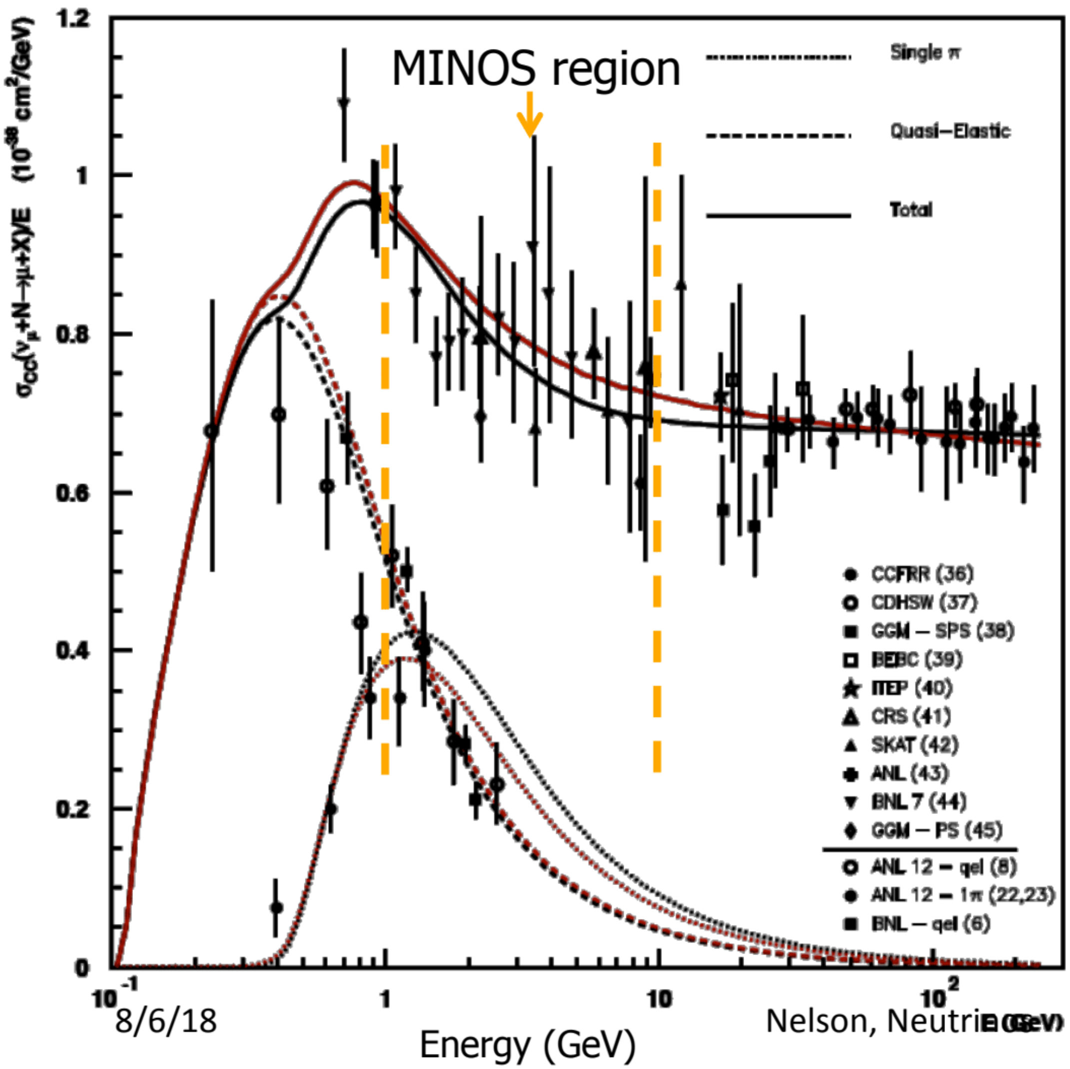
Neutrinos

- We need to estimate the energy of the incoming neutrino
  - > Different from the "visible" energy seen in the detector
- Neutrino oscillation experiments use high Z nuclei as targets (e.g. Fe)
  - > This affects the visible energy …
  - > Number of final state particles
    - We are not sensitive to their rest masses
  - > Intra-nuclear absorption and scattering
  - > Motion of struck nucleon within nucleus



Neutrino-Nucleon Cross Section

cross section = probability of interaction



- Little is known about the region being looked at it (1-10 GeV)
- MINERvA will give us 10-1000 times the statistics as other experiments (largely from the '70s)

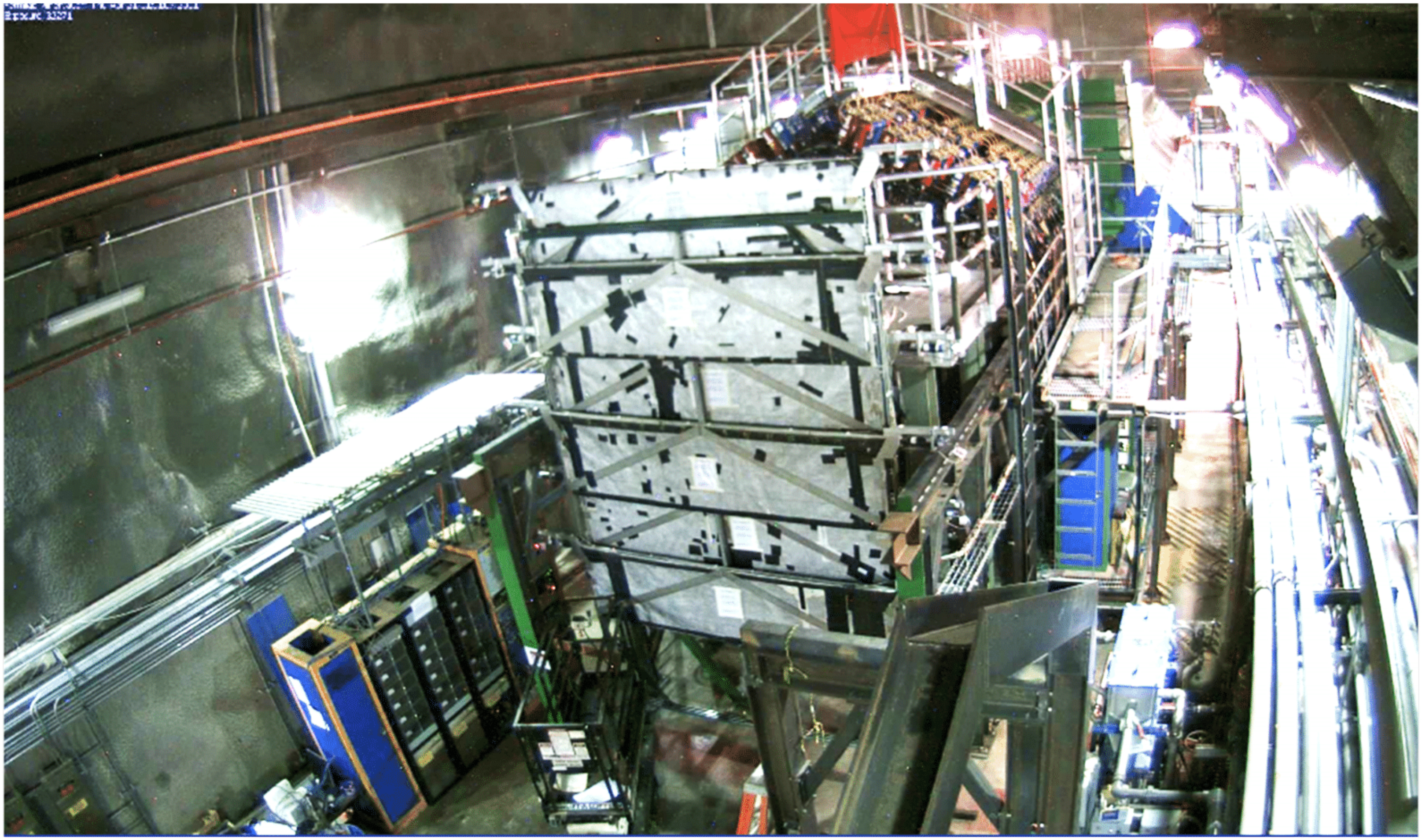
- Types of interactions
  - > Quasielastic

    $\nu_\mu + n \rightarrow \mu^- + p^+$
  - > Single Pion / Resonance

    $\nu_\mu + n \rightarrow \Delta^+ + \mu^- \rightarrow \mu^- + \pi^+ + n$
  - > Deep Inelastic Scattering

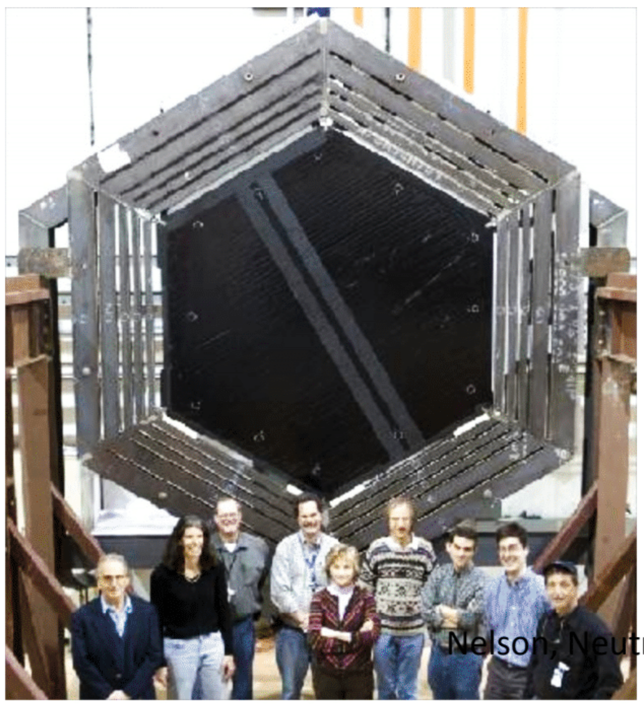
    (many final state particles)

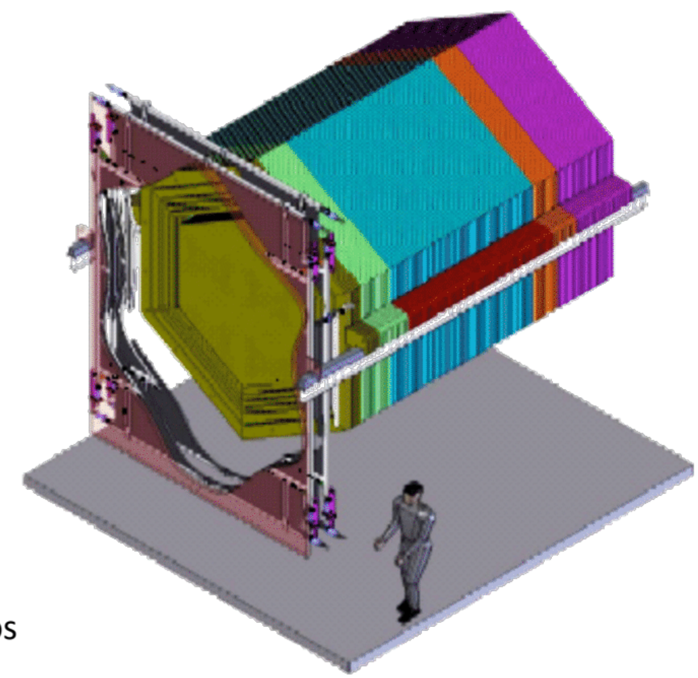
MINERvA detector



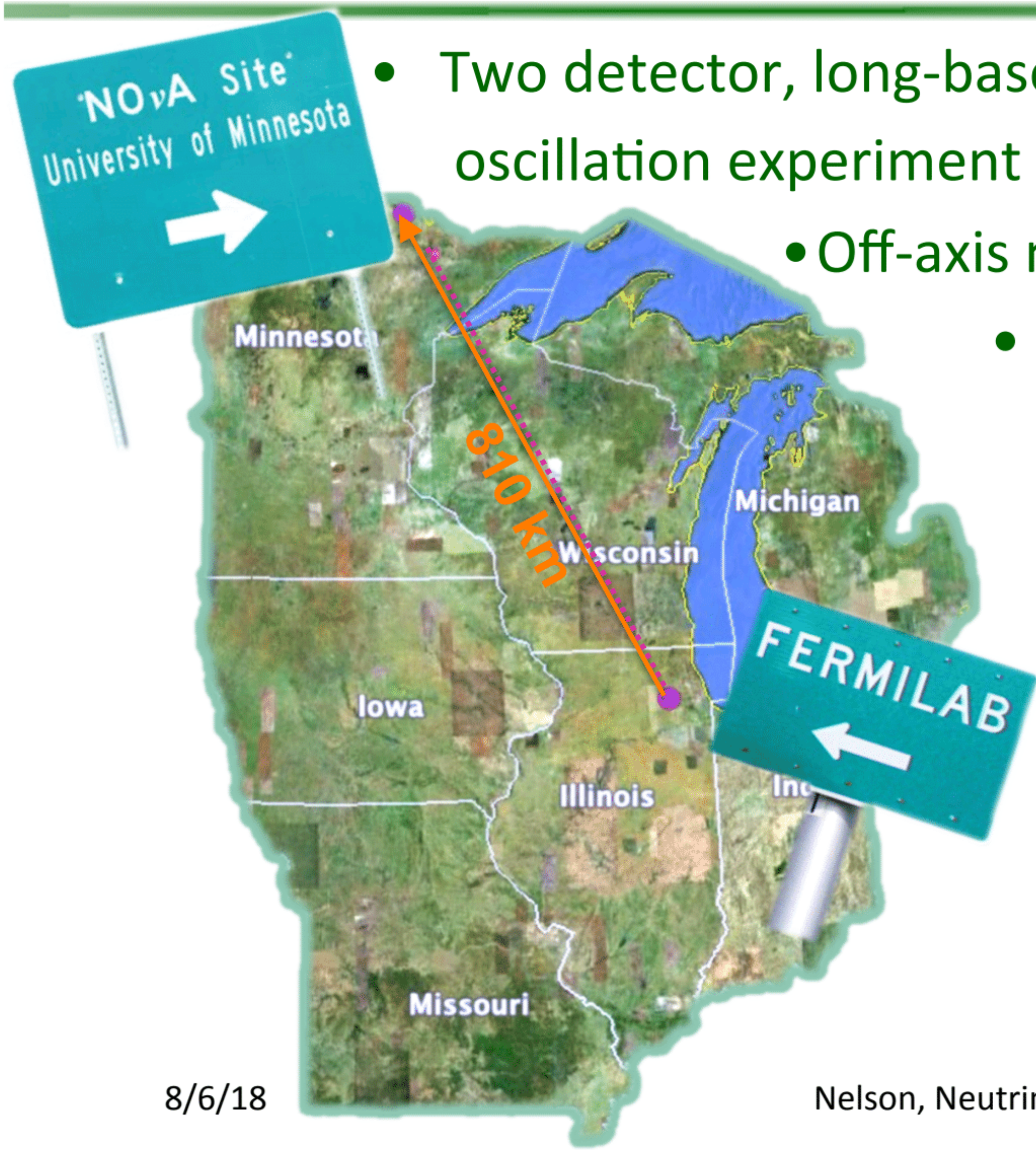
MINERvA Experiment

- Study neutrino nucleus interactions in detail
  - Range of nuclear targets
- Will increase the precision of MINOS data by reducing systematic errors on the Δm^2 measurement
  - No steel so we can see the details
- Pleased in front of the MINOS Near Detector





NOvA – the near future



- Two detector, long-baseline oscillation experiment
  - Off-axis neutrinos from NuMI beam
    - Physics goals:
      - > Search for electron neutrino appearance (with both neutrinos and antineutrinos)
      - > Precision studies of muon neutrino disappearance