Overview of Neutrino Physics

History, As a Probe and Mass?
HUGS 2004

Introduction to Concepts and the Vocabulary

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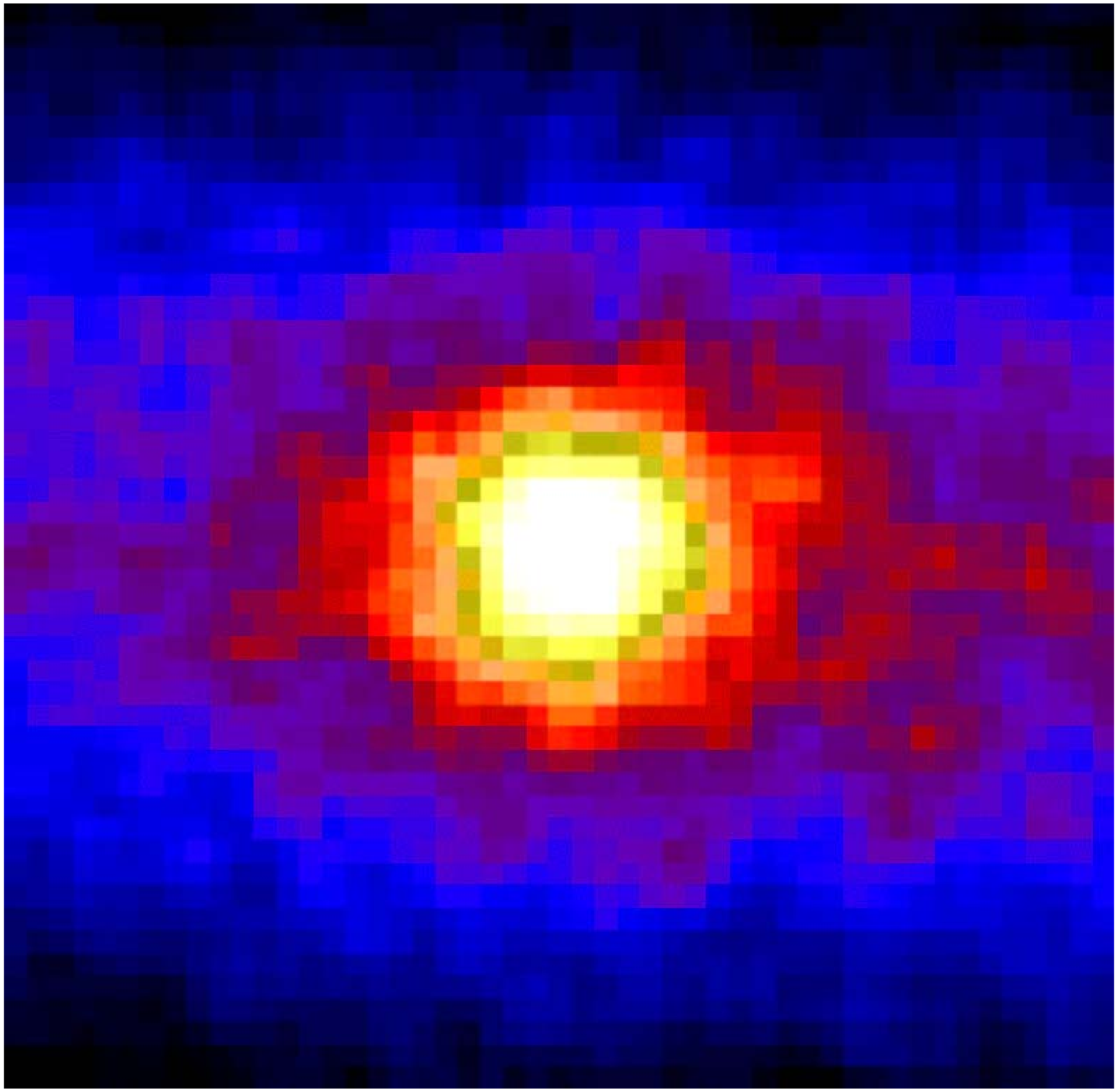
With thanks to Peter Shanahan, Fermilab and Hitoshi Murayama, LBL

Neutrinos are Everywhere

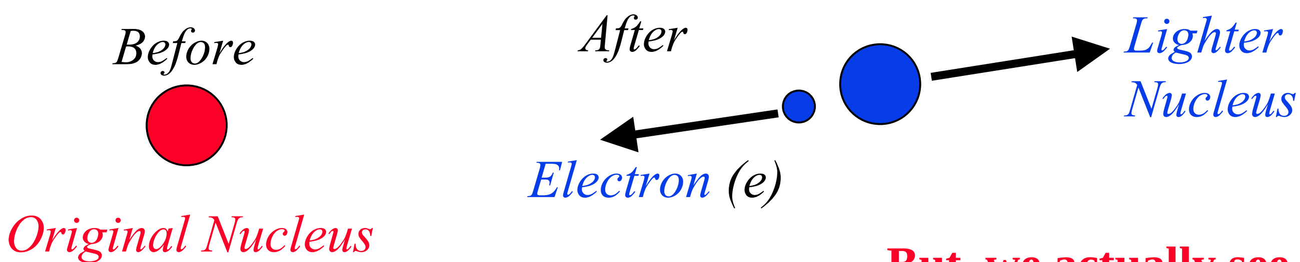
- They come from the Big Bang
  - When the Universe was hot, neutrinos were created equally with any other particles. There are still over: ~ 300 neutrinos per cm^3
- They come from the Sun
  - 10^{11} neutrinos going through your body every second
- They are reluctant to interact
  - If you want to stop them, you need to stack lead shielding up to three light-years thick.

The Sun as a Neutrino Source

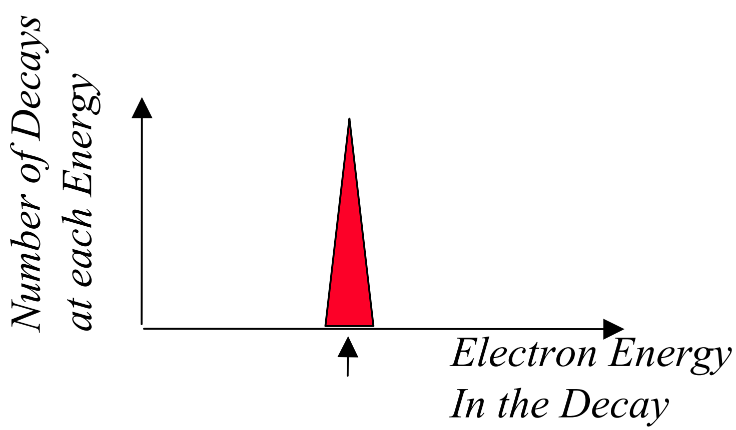


The Conception of the Neutrino

The historical path to neutrinos… Beta decay of atomic nuclei:



Conservation of energy and momentum ⇒ electron should have a fixed energy



But, we actually see a wide range of energies…what is going on here??

F. A. Scott, *Phys. Rev.* **48**, 391 (1935)

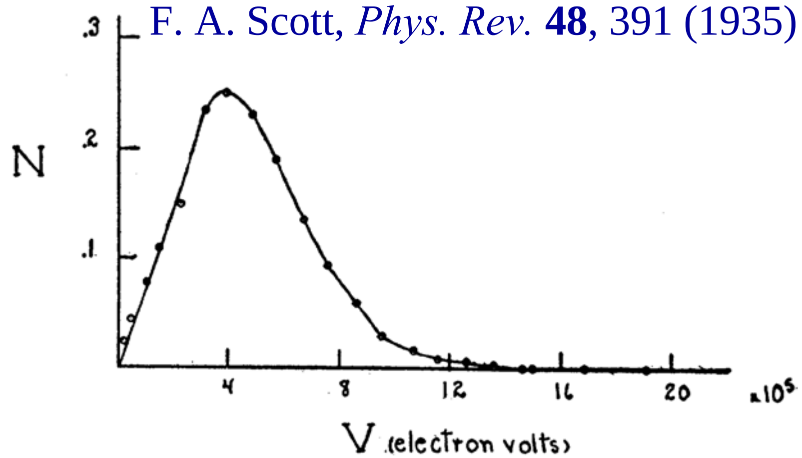


FIG. 5. Energy distribution curve of the beta-rays.

Non-conservation of Energy?

Bohr: **At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β-ray disintegrations.**

4th December 1930

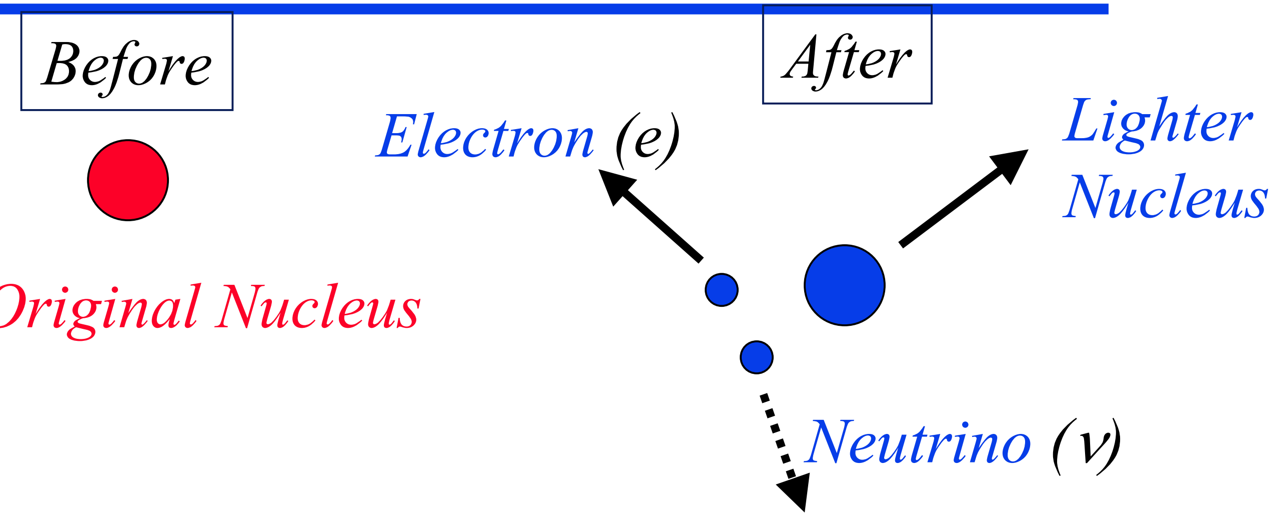
Pauli:

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 Li^6 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 in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

The Neutrino's Conception is Complete

Pauli and Fermi
Early 1930's



This must be a very different particle from the known ones:

- Max electron energy is what we expect for 2 body $\Rightarrow$ *(nearly) massless*
- We don't see it along with electron $\Rightarrow$ *very weakly interacting*

The neutrino: "Little Neutral one" – massless, no electric charge, new *Weak Force* Charge

Neutrinos are Left-handed

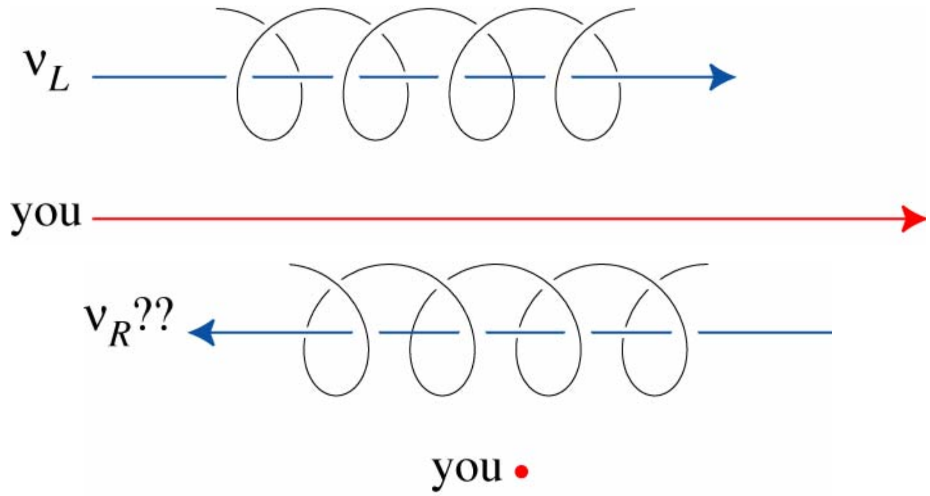
Helicity of Neutrinos*

M. GOLDHABER, L. GRODZINS, AND A. W. SUNYAR
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

Neutrinos must be Massless

All neutrinos left-handed ⇒ massless
If they have mass, can't go at speed of light.

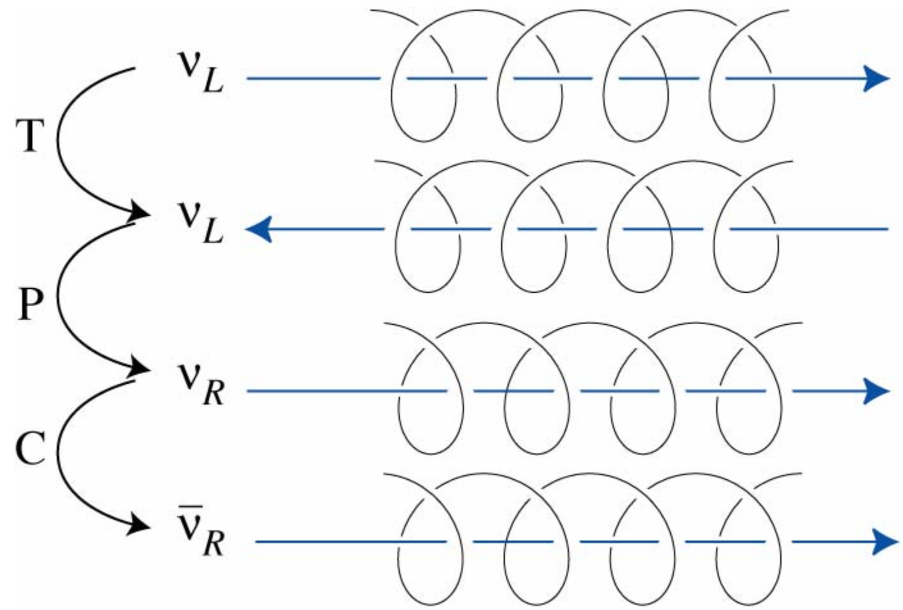


Now neutrino right-handed??
⇒ contradiction ⇒ can't be massive

Anti-Neutrinos are Right-handed

CPT theorem in quantum field theory

- C: interchange particles & anti-particles
- P: parity
- T: time-reversal



State obtained by CPT from ν_L must exist: $\overline{\nu}_R$

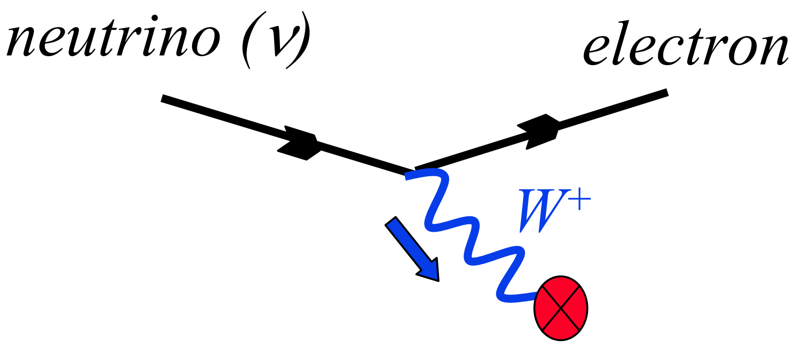
Standard Model

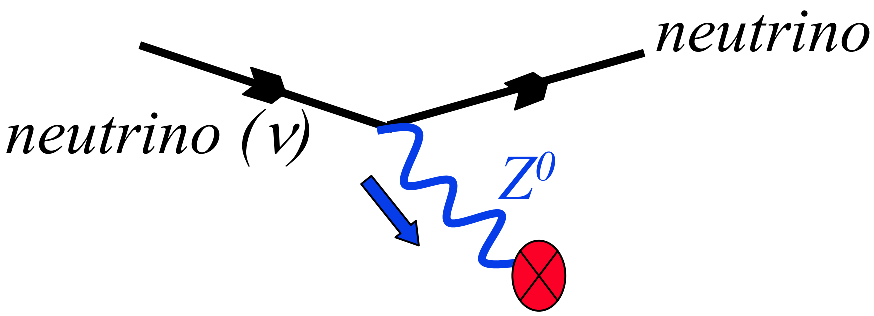
Therefore, neutrinos are strictly massless in the Standard Model of particle physics

If neutrinos have mass, then the Standard Model is incomplete!

Neutrinos and the Weak Force

- Weak force carried by W and Z bosons
  - W – “Charged current”   Z – “Neutral current”
  - $W^{\pm}$ and Z^0 are very massive – ~ 80 and 91 GeV/c^2 compare photon – massless





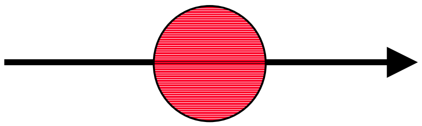
Neutrinos are Non-trivial to Detect

- Neutrino interactions are extremely rare
  - The weak force is… weak…
- Comparison:
  - Electrons from beta decay can be stopped by aluminum foil
  - X-rays (photons) are stopped by a thin piece of lead
  - 5GeV Muons are stopped by meters of Iron
  - Neutrinos from Sun can pass through

    light-years of water…

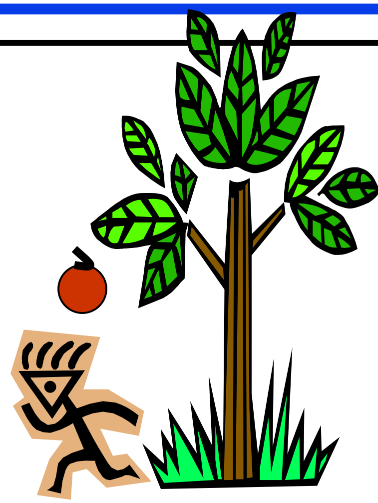
Only about 1 in 10^{18} neutrinos passing through a proton will interact with it

- Why is the weak force so weak?

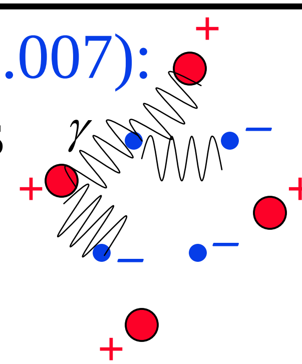


"4" Fundamental Forces

Gravity (10^{-38}):
Felt by all particles, but very, very weak



Electromagnetic (0.007):
Felt by all particles with an electric Charge. Carried by photons (γ)



Strong Nuclear Force (1):
Felt only by "nuclear" particles (quarks, gluons)
Carried by the gluon (g)

Weak Nuclear Force (10^{-6}):
Closely related to electromagnetism… really one "electroweak force"
But very different in our lives

Neutrino Cross Sections

$$G_F = \frac{\sqrt{2}}{8}\left(\frac{g_W}{M_W}\right)^2 = 1.166\times 10^{-5}/GeV^2 \quad (g_W \approx 0.7)$$

$1/(Q^2 - M_B^2)^2$

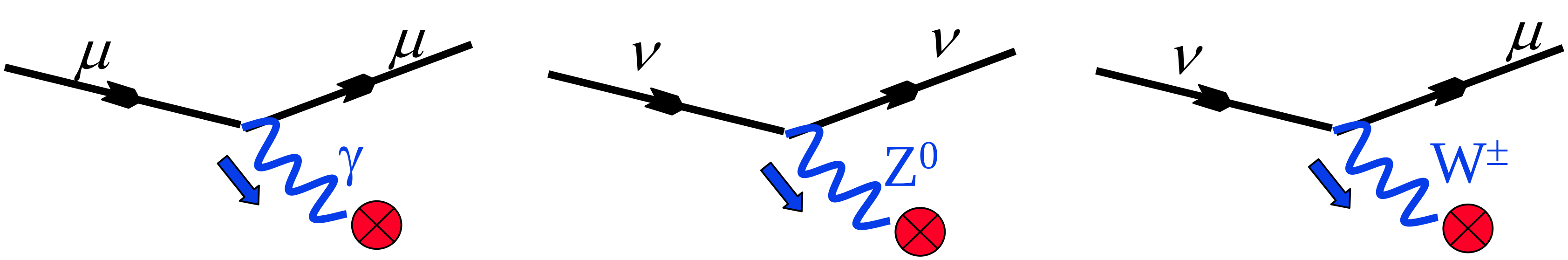
$\sigma \propto \{(\text{couplings}) \times (\text{propagator})\}^2 \times$ (details of participants)

At typical lab energies:

$M_\gamma = 0 \Rightarrow 1/Q^4$

$M_W = 80.1\text{GeV} \Rightarrow 1/M_W^4$

For $Q \approx 2\text{GeV}$, $\sigma_{EM}/\sigma_{Wk} \sim 2.5 \times 10^6$!



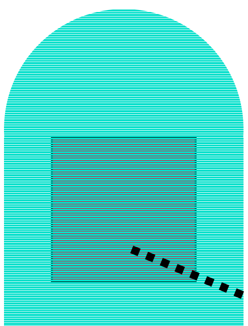
The Discovery of the Neutrino

Direct detection of the neutrino had to wait more than 20 years after its conception…

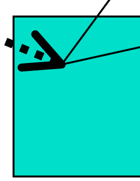
1st idea – nuclear bomb blast…

2nd idea – nuclear reactor

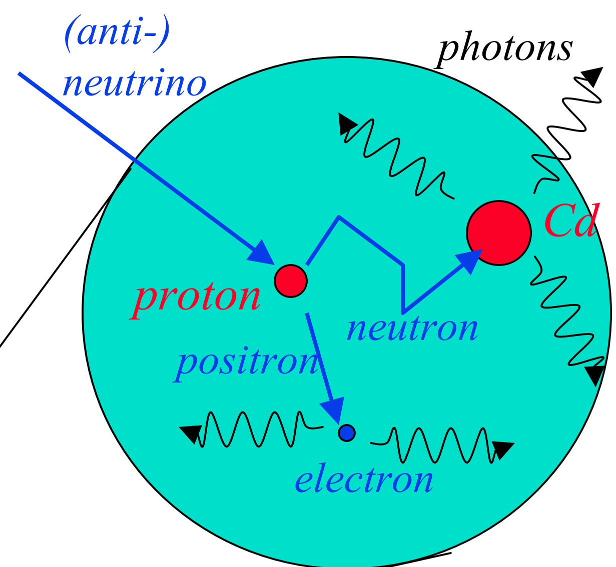
Reines and Cowen - 1956
Savannah River Plant



10^{12} antineutrinos per square inch per second



50 gal water with some Cd to detect neutrons



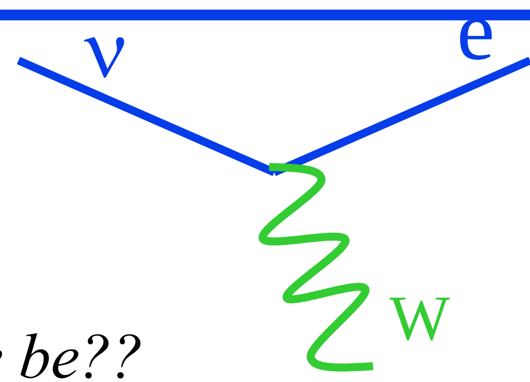
Inverse beta decay

A few neutrinos per hour were detected!

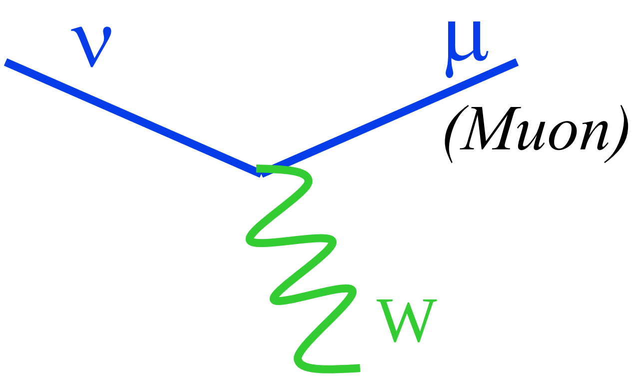
$\sigma \approx 6x10^{-44}cm^2$

Neutrino Flavor

We've already seen



But could there be??



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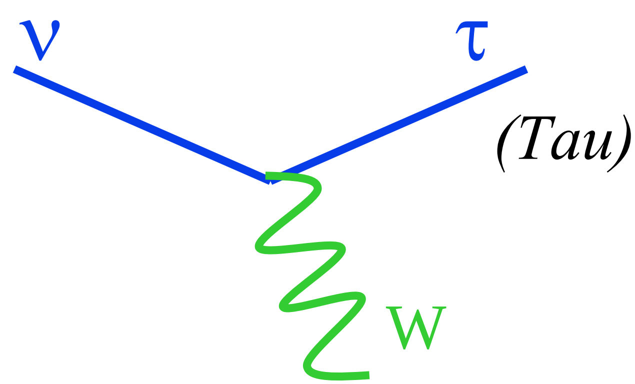
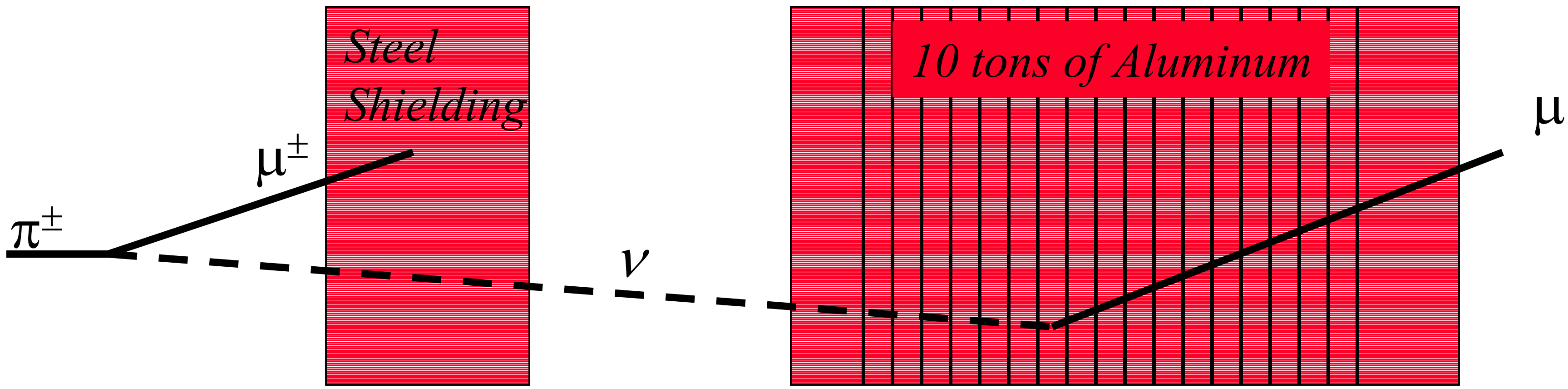


Are there different flavors of neutrinos, for electrons, muons, and taus…?

The Muon Neutrino

Lederman (Leon), Schwartz, and Steinberger at Brookhaven (1962):

Do neutrinos produced along with muons make electrons when they interact, or only muons?



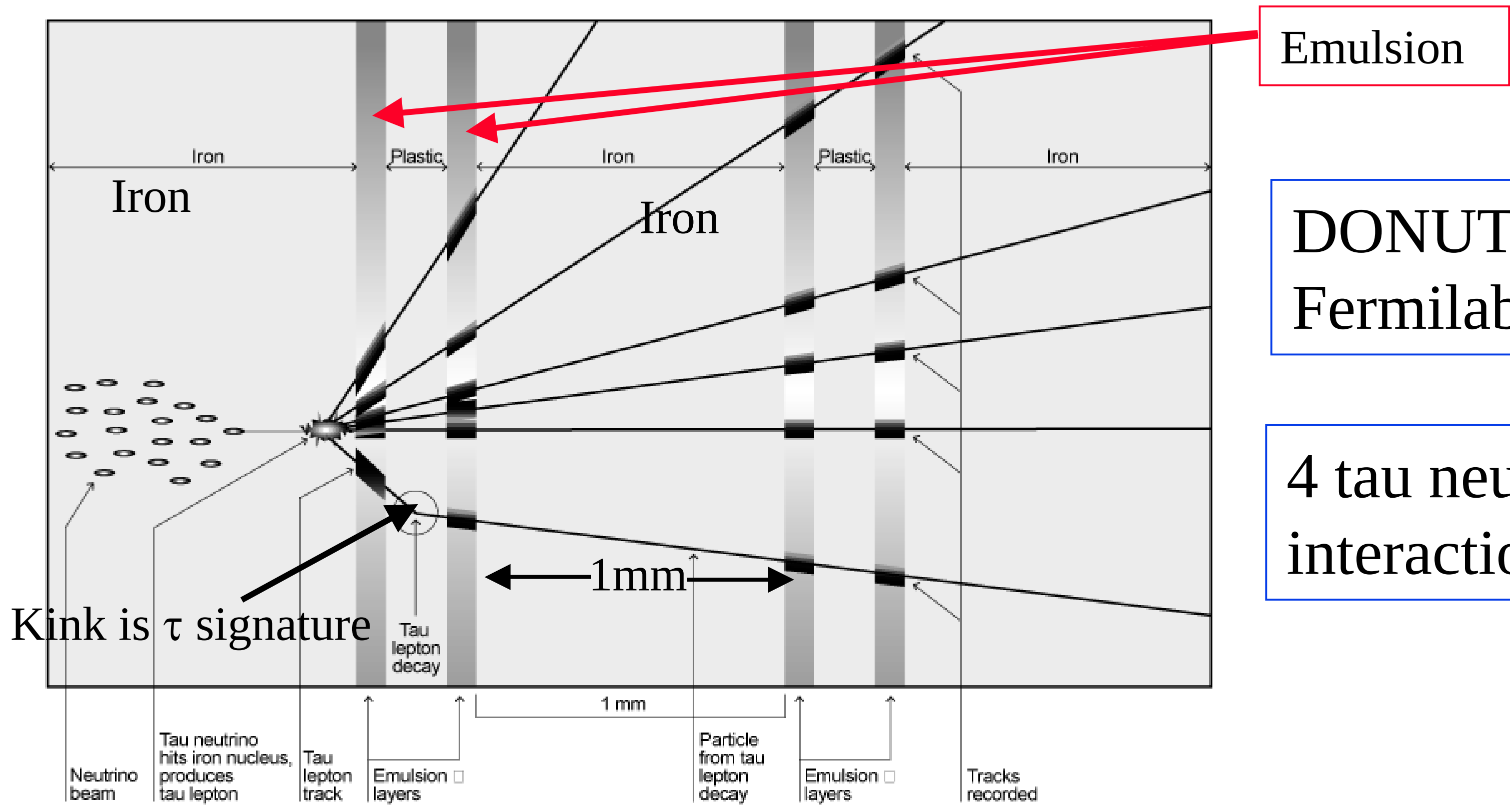
10^{14} neutrinos
51 interactions seen!

There are distinct *muon* and *electron* neutrinos
(Won the Nobel Prize in 1988)

Tau Neutrino

Is there a neutrino that only makes tau (τ) leptons?

Detecting a Tau Neutrino

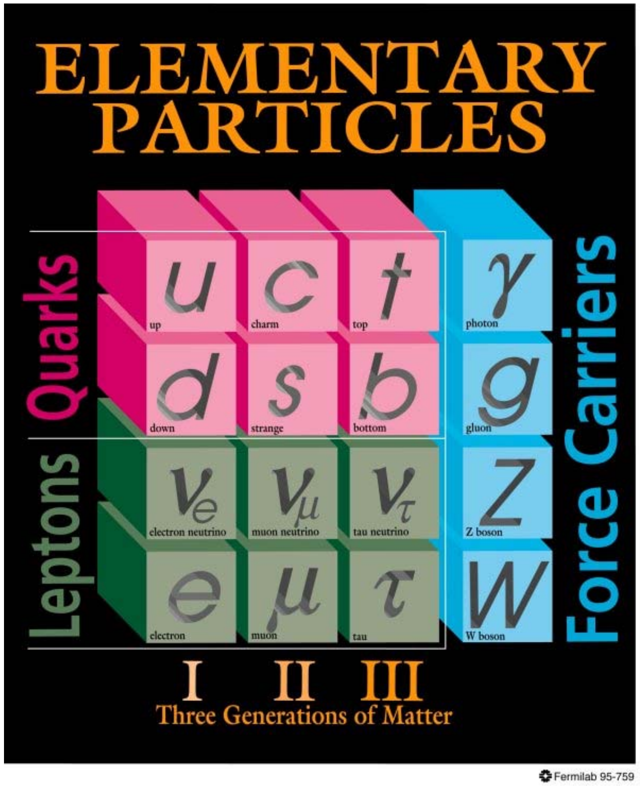


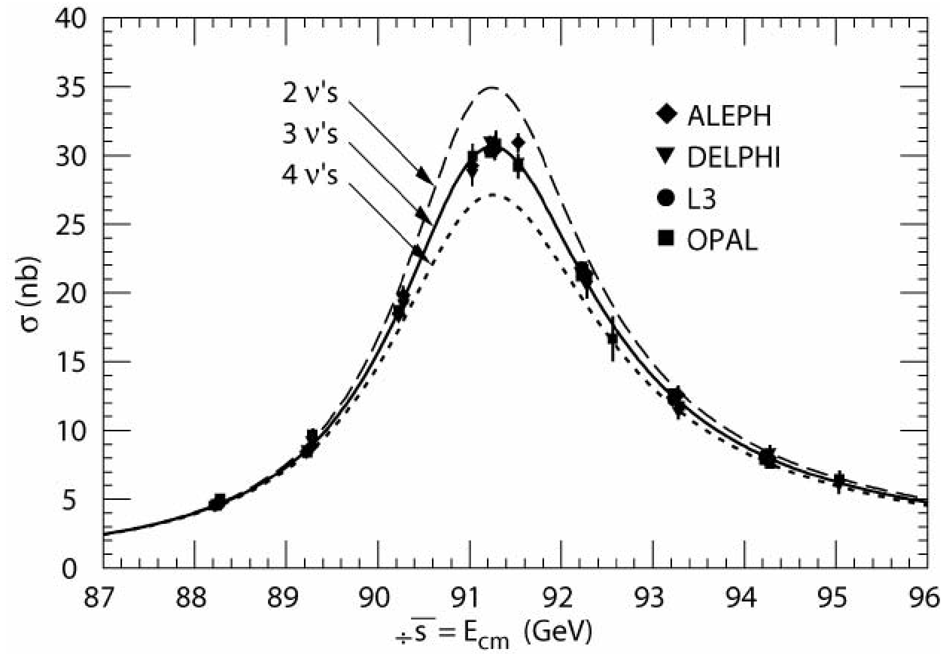
Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.

DONUT (E872) at Fermilab -1997….

4 tau neutrino interactions observed!

How Many Neutrinos?





Also have anti-matter: Each particle type has a corresponding *anti-particle*

*There are three - **and only three** - neutrinos*

What Can You do with a Neutrino?

By studying neutrino interactions, you can learn about

Electroweak force: unification of electromagnetic and weak forces

W and Z bosons

Structure of protons and neutrons $\Rightarrow$ details of the Strong Nuclear Force (QCD)

$$\sigma \propto (\text{couplings})^2 \text{ x } (\text{propagator})^2 \text{ x } (\text{details of participants})$$

And, more recently, you can learn about the nature of mass, and possibly get insight into Grand Unification of EW and QCD!

(Quasi)-Elastic Scattering

C.H. Llewellyn Smith Phys.Rept.3:261,1972

$$\nu + n \rightarrow \mu^- + p$$

$$\frac{d\sigma^{\nu,\bar{\nu}}}{dq^2} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2} \times \left[A(q^2) \mp \frac{(s-u)B(q^2)}{M^2} + \frac{C(q^2)(s-u)^2}{M^4} \right],$$

$$G_F = \frac{\sqrt{2}}{8}\left(\frac{g_W}{M_W}\right)^2 = 1.166\times 10^{-5}/GeV^2 \quad (g_W \approx 0.7)$$

$$A(q^2) = \frac{m^2 - q^2}{4M^2}\left[\left(4 - \frac{q^2}{M^2}\right)|F_A|^2 - \left(4 + \frac{q^2}{M^2}\right)|F_V^1|^2 - \frac{q^2}{M^2}|\xi F_V^2|^2\left(1 + \frac{q^2}{4M^2}\right) - \frac{4q^2 Re F_V^{1*}\xi F_V^2}{M^2}\right];$$

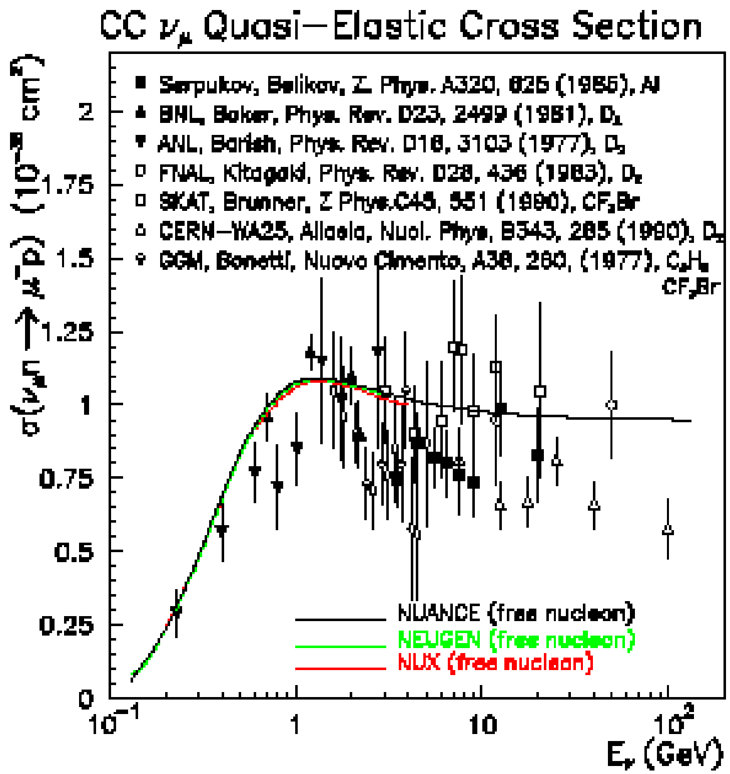
$$B(q^2) = -\frac{q^2}{M^2} Re F_A^*(F_V^1 + \xi F_V^2), \quad C(q^2) = \frac{1}{4}\left(|F_A|^2 + |F_V^1|^2 - \frac{q^2}{M^2}\left|\frac{\xi F_V^2}{2}\right|^2\right).$$

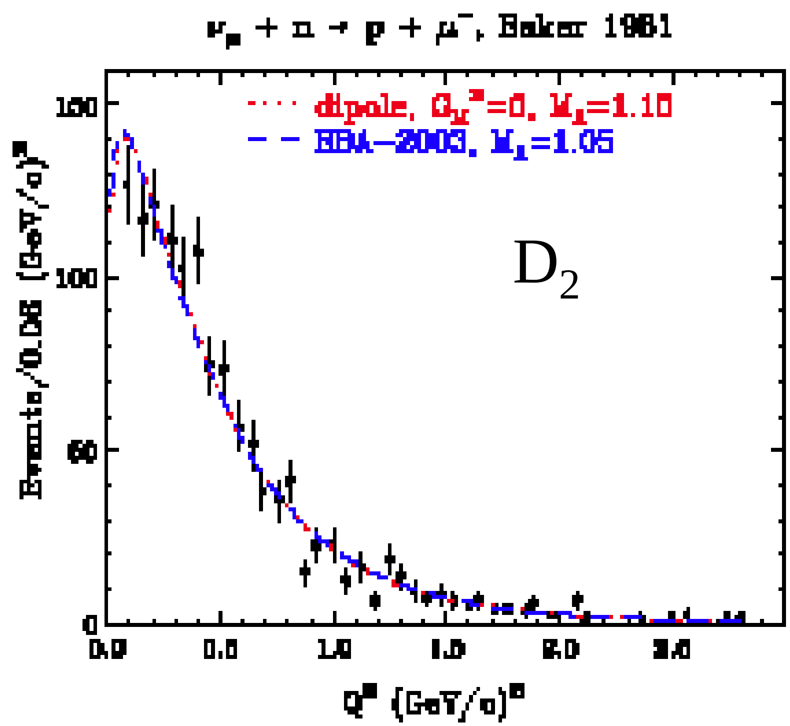
$$F_V^1(q^2) = \frac{G_E^V(q^2) - \frac{q^2}{4M^2}G_M^V(q^2)}{1 - \frac{q^2}{4M^2}}, \quad \xi F_V^2(q^2) = \frac{G_M^V(q^2) - G_E^V(q^2)}{1 - \frac{q^2}{4M^2}}.$$

Quasi-elastic Scattering

$$G_E^V(q^2) = G_E^p(q^2) - G_E^n(q^2), \quad G_M^V(q^2) = G_M^p(q^2) - G_M^n(q^2).$$

$$F_A(q^2) = \frac{g_A}{\left(1 - \frac{q^2}{M_A^2}\right)^2}, \quad F_P(q^2) = \frac{2M^2 F_A(q^2)}{M_\pi^2 - q^2}.$$





Neutrino induced Resonance Production

7 possible channels (3 CC, 4 NC):

$$\begin{aligned} \nu_\mu p &\rightarrow \mu^- p \pi^+ \\ \nu_\mu n &\rightarrow \mu^- n \pi^+ \\ \nu_\mu n &\rightarrow \mu^- p \pi^0 \end{aligned} \qquad \begin{aligned} \nu_\mu p &\rightarrow \nu_\mu n \pi^+ \\ \nu_\mu p &\rightarrow \nu_\mu p \pi^0 \\ \nu_\mu n &\rightarrow \nu_\mu n \pi^0 \\ \nu_\mu n &\rightarrow \nu_\mu p \pi^- \end{aligned}$$

Main contribution is from $\Delta(1232)$ (but others can contribute)

ν Monte Carlos covering this kinematic region have been using early theoretical predictions by Rein–Sehgal

Rein and Sehgal, Annals Phys 133, 79 (1981)

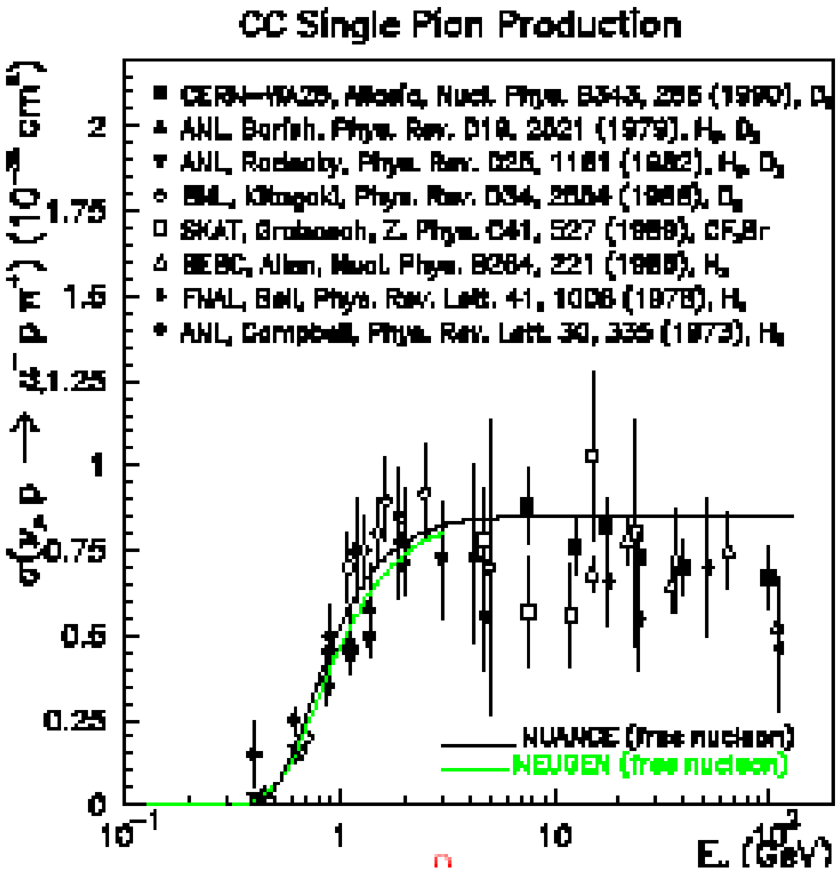
Also recent work by Harry Lee (ANL) and collaborators

Contributions from 16–18 baryonic resonances (N^*, Δ)

Recent calcs on nuclear effects (π absorption, CE)

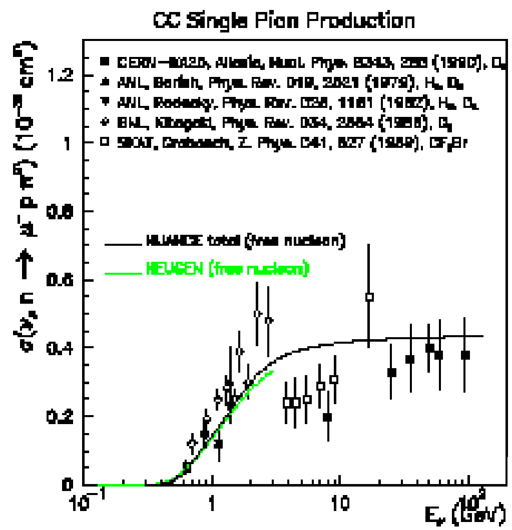
Paschos, Nucl. Phys. B588, 263 (2000)

Existing 1 π Data - pre-current experiments

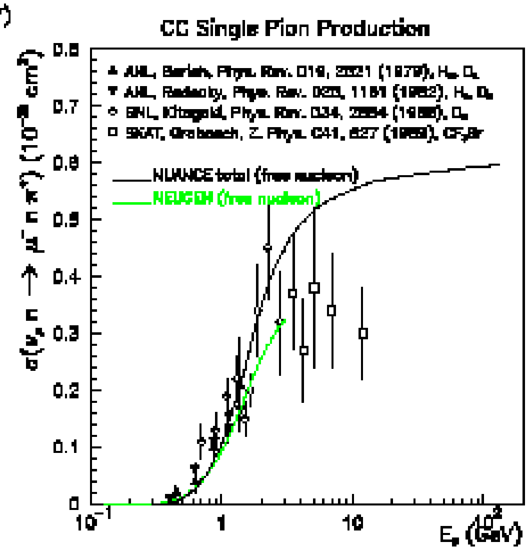


$\nu_\mu p \rightarrow \mu^- p \pi^+$

$\nu_\mu n \rightarrow \mu^- p \pi^0$



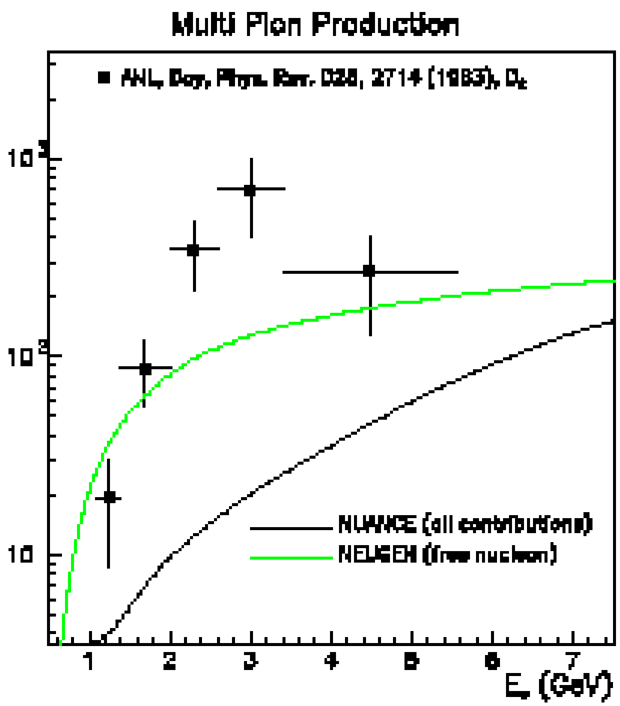
$\nu_\mu n \rightarrow \mu^- n \pi^+$

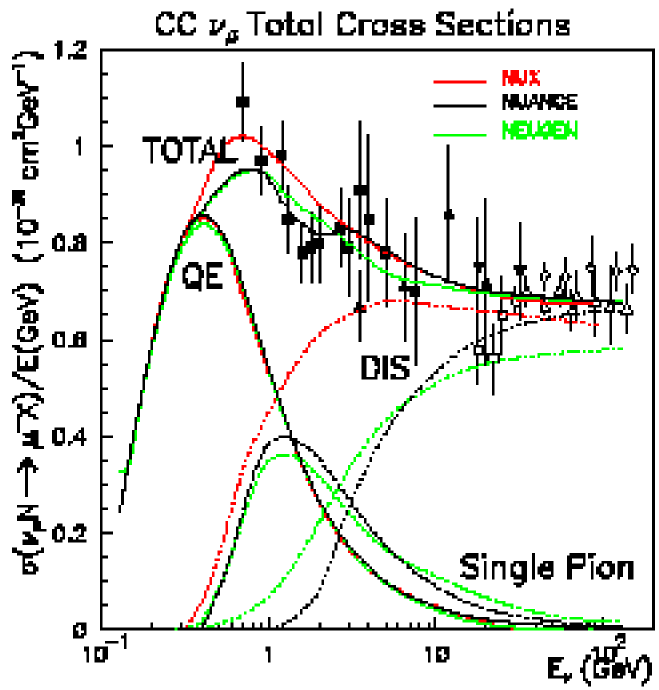


S. Zeller, NuInt04

Neutrino Multi-pi and Total Cross Section

$\nu_\mu p \rightarrow \mu^- n \pi^+ \pi^+$





Cross Section	Present Knowledge	ν Data	Theor. Models
DIS	Excellent ★★★★	many exps	parton model
Quasi–Elastic	Good ★★★	bc	form factors
Resonant 1π	Fair ★★	bc	Rein–Sehgal
Coherent π	Poor (low E) ★1/2	bc, counter	several
Combining σ's	Poor ★	little	several +
Nuclear Targets	Poor ★1/2	very limited	variety

S. Zeller, NuInt04

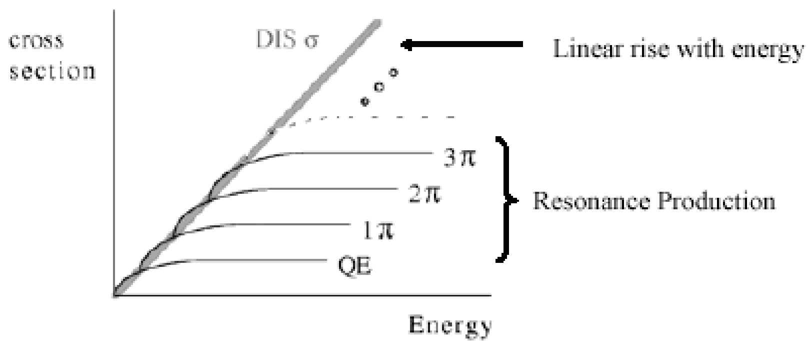
Neutrino Scattering as a Probe of DIS

Neutrinos have the ability to directly resolve flavor of the nucleon's constituents: ν interacts with d, s, $\bar{u}$, and $\bar{c}$ while $\bar{\nu}$ interacts with u, c, $\bar{d}$ and $\bar{s}$.

$$\frac{d\sigma^{\nu A}}{dxdQ^2} = \frac{G_F^2}{2\pi x}\left[\frac{1}{2}\left(F_2^{\nu A}(x,Q^2) + xF_3^{\nu A}(x,Q^2)\right) + \frac{(1-y)^2}{2}\left(F_2^{\nu A}(x,Q^2) - xF_3^{\nu A}(x,Q^2)\right)\right]$$

$$\frac{d\sigma^{\bar{\nu} A}}{dxdQ^2} = \frac{G_F^2}{2\pi x}\left[\frac{1}{2}\left(F_2^{\bar{\nu} A}(x,Q^2) - xF_3^{\bar{\nu} A}(x,Q^2)\right) + \frac{(1-y)^2}{2}\left(F_2^{\bar{\nu} A}(x,Q^2) + xF_3^{\bar{\nu} A}(x,Q^2)\right)\right]$$

$+ y^2 F_L$



$$\frac{\sigma_T}{\overline{\sigma_T}} = \frac{1 + \varepsilon/3}{1/3 + \varepsilon}$$

$$\overline{\sigma_T} = 0.5\ \sigma_T$$

$$\varepsilon = \overline{q}\,/\,q \approx 0.2$$

Extracting Parton Distribution Functions: What Can We Learn With All Six Structure Functions?

Using Leading order expressions:

$$F_2^{\bar{\nu}N}(x,Q^2) = x\left[u + \bar{u} + d + \bar{d} + 2\bar{s} + 2c\right]$$

$$F_2^{\nu N}(x,Q^2) = x\left[u + \bar{u} + d + \bar{d} + 2s + 2\bar{c}\right]$$

$$xF_3^{\bar{\nu}N}(x,Q^2) = x\left[u + d - \bar{u} - \bar{d} - 2\bar{s} + 2c\right]$$

$$xF_3^{\nu N}(x,Q^2) = x\left[u + d - \bar{u} - \bar{d} + 2s - 2\bar{c}\right]$$

Does $s = \bar{s}$ and $c = \bar{c}$ over all x?

If so.....

$$F_2^{\nu} - xF_3^{\nu} = 2\left(\bar{u} + \bar{d} + 2\bar{c}\right) = 2U + 4\bar{c}$$

$$F_2^{\bar{\nu}} - xF_3^{\bar{\nu}} = 2\left(\bar{u} + \bar{d} + 2\bar{s}\right) = 2U + 4\bar{s}$$

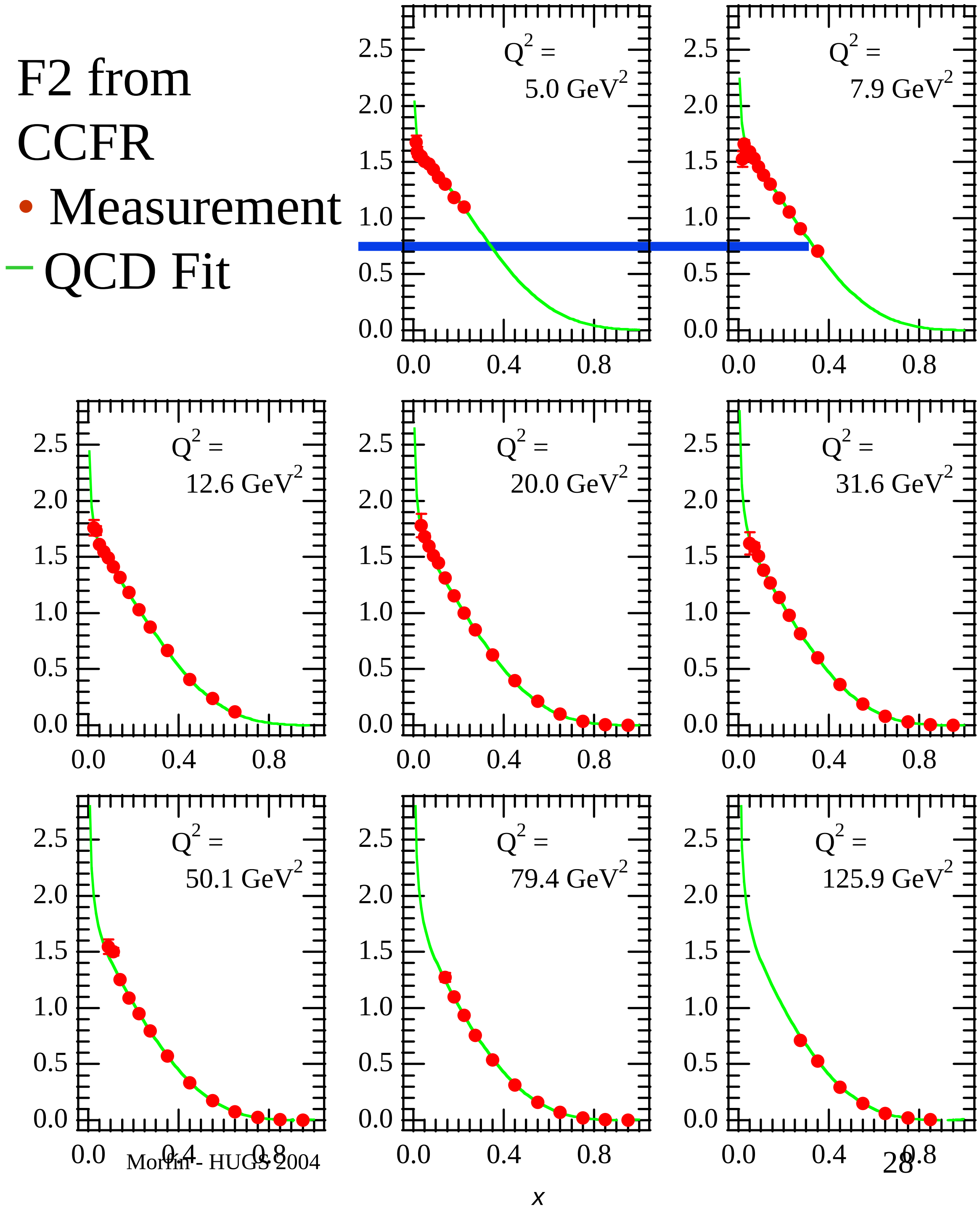
$$xF_3^{\nu} - xF_3^{\bar{\nu}} = 2\left[(s + \bar{s}) - (\bar{c} + c)\right] = 4\bar{s} - 4\bar{c}$$

Sample of Scattering Results

CCFR experiment – took data at Fermilab in 1980s and early 90's.

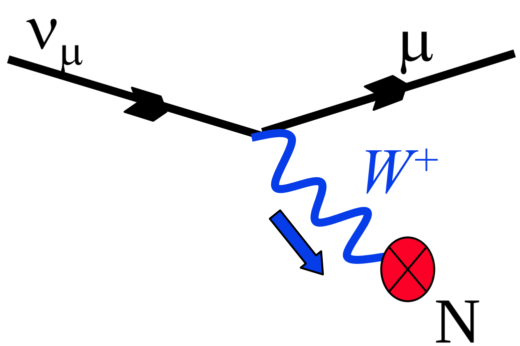
Evolution of quark structure vs. Q^2 agrees well with QCD theory

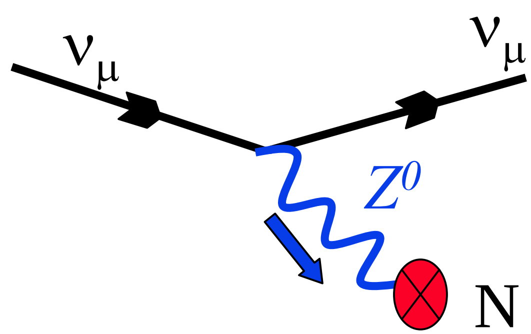
Much newer results exists, but are still preliminary



Electroweak Studies

- Unification of electromagnetic and weak forces leads to an interesting prediction for relative coupling of W's and Z's:





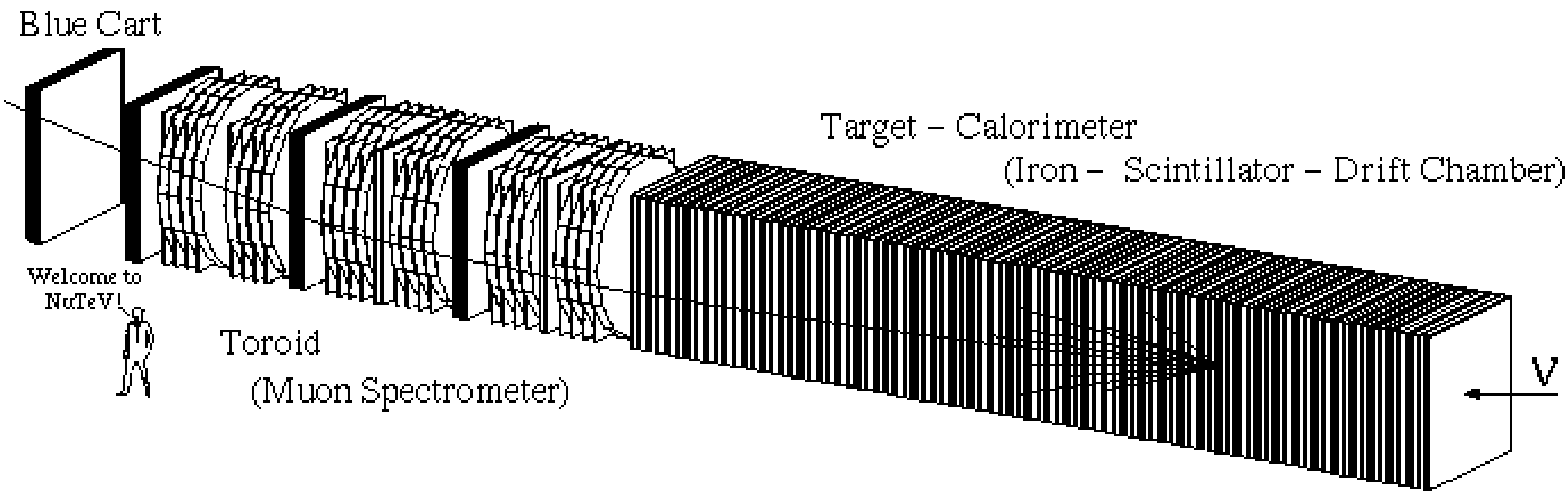
$$R^- \equiv \frac{\sigma(\nu_\mu N \to \nu_\mu X) - \sigma(\bar{\nu}_\mu N \to \bar{\nu}_\mu X)}{\sigma(\nu_\mu N \to \mu^- X) - \sigma(\bar{\nu}_\mu N \to \mu^+ X)} = \rho\left(\frac{1}{2} - \sin^2\theta_W\right)$$

$$where\ \ \rho = 1 \quad and\ \ \sin^2\theta_W \equiv 1 - \frac{M_W^2}{M_Z^2}$$

To measure $\sin^2\theta_W$, need ν and $\bar{\nu}$ beams, and ability to distinguish charged and neutral currents

NuTeV

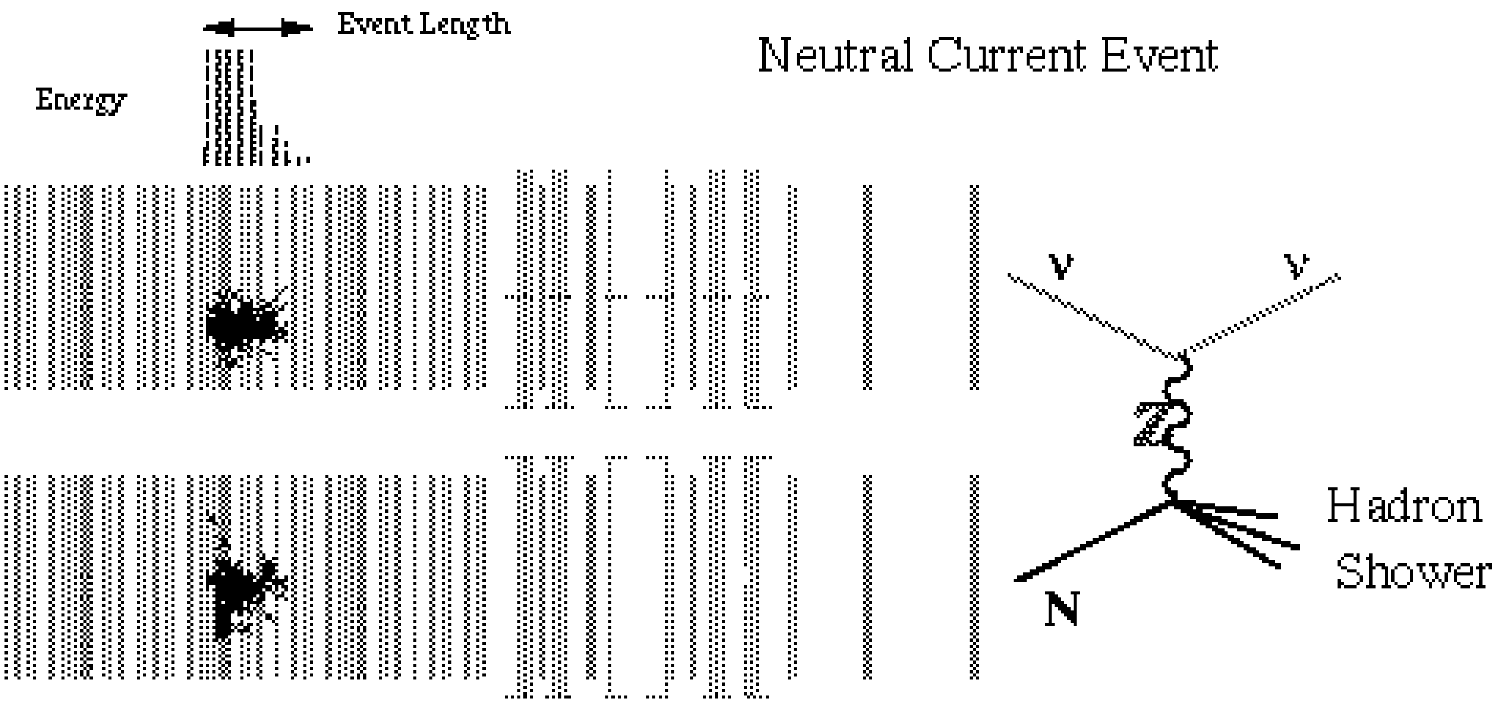
- Neutrinos at the TeVatron – successor to CCFR



NuTeV uses magnets to select π^+,K^+ for ν_μ, π^-, K^- for $\overline{\nu}_\mu$

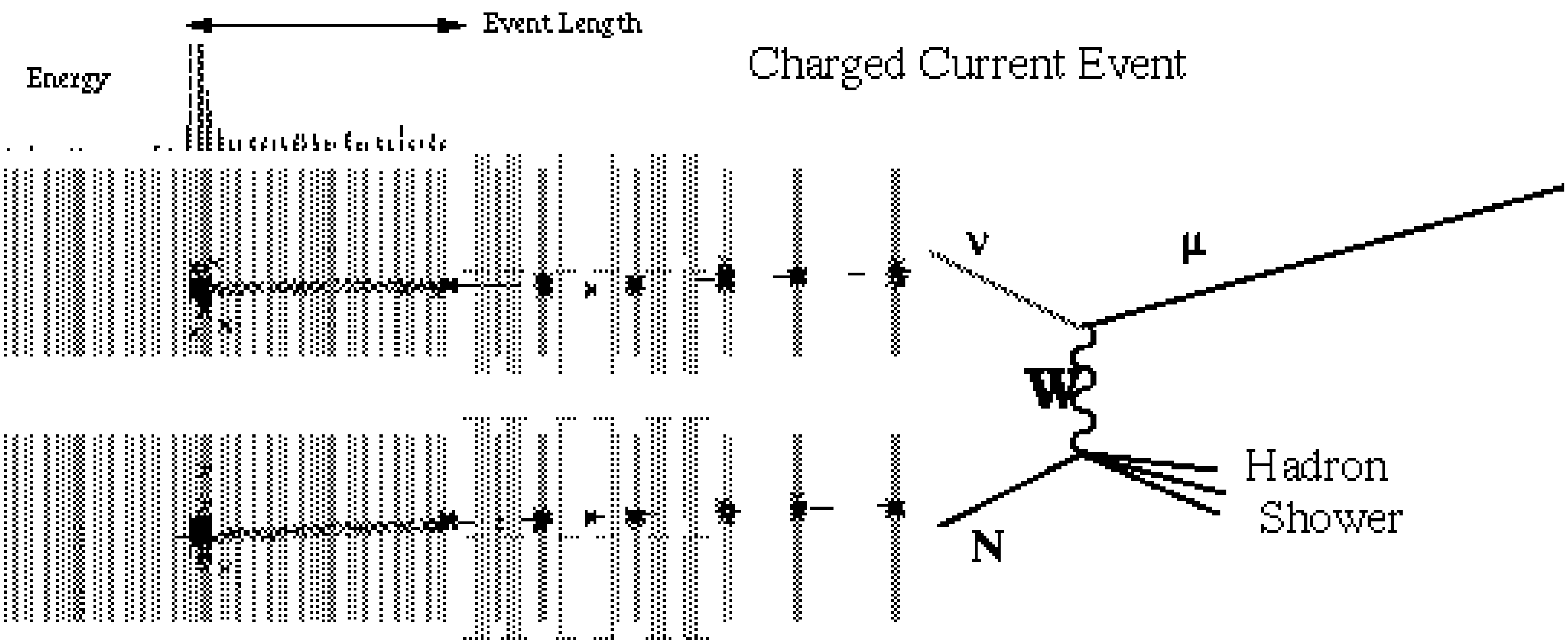
NuTeV Analysis

NuTeV distinguishes charged current ($\nu \rightarrow \mu$) from neutral current ($\nu \rightarrow \nu$) by "event length"



NuTeV Charged Current

Muons traverse meters of steel – easy signature for charged current interaction



NuTeV $\sin^2\theta_W$ Result

Measured:

$\sin^2\theta_W = 0.22773$

± 0.00135

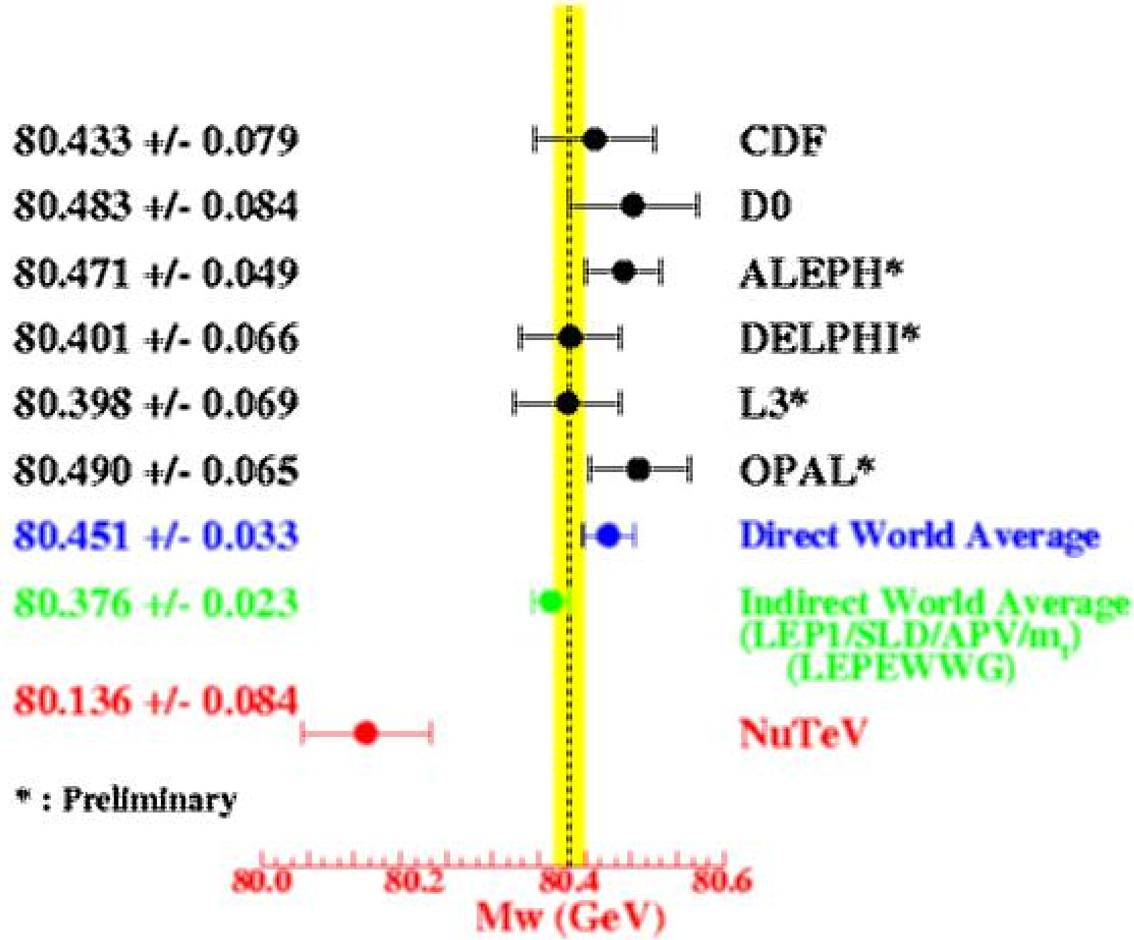
± 0.00093

Expected:

$\sin^2\theta_W = 0.2227$

± 0.00037

"3 σ" deviation:
1 in 400 chance of
being just a fluctuation



$\sin^2\theta_W$ Interpreted as M_W measurement

Interpretation

- Z boson interacts 1% weaker
- Bigger QCD effects than anticipated?
  - Unlikely, based on analysis of possible effects.
- Could it be destructive interference with another boson of mass ~1.2 TeV?
  - Great example of lower energy experiments having possible impact on very high energy physics.

We’ve skirted the issue long enough….

Do Neutrinos have Mass?

$$m_{\nu_1} < 2.5 \text{ eV at } 95\% \text{ c.l. (Troitsk)}; < 6 \text{ eV at } 95\% \text{ c.l. (Mainz)};$$

$$m_{\nu_2} < 170 \text{ keV at } 90\% \text{ c.l. (PSI; } \pi^+ \rightarrow \mu^+ + \nu_\mu);$$

$$m_{\nu_3} < 18.2 \text{ MeV at } 95\% \text{ c.l. (ALEPH; } \tau^- \rightarrow 5\pi + \nu_\tau)$$

Neutrinos and Mass

- We know neutrinos must be very light –
  - Lighter than we can detect in beta decay
  - This makes neutrinos very different from other particles.

Electron neutrino has at most 10^{-5} the mass of the electron

Compare to quarks: top quark is "only" about 50 times more massive than its partner, the b-quark

What can it tell us about how particles get mass?

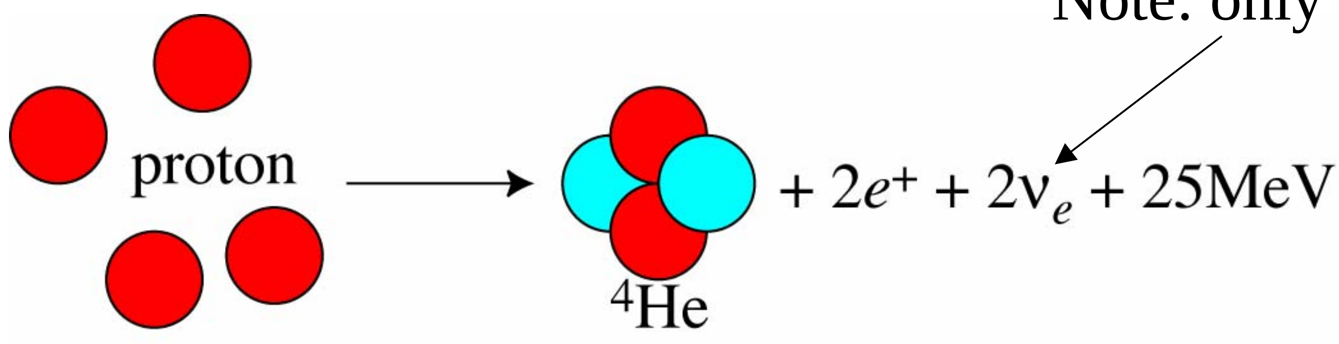
Higgs mechanism…

Evidence for Neutrino Mass

How the Sun burns

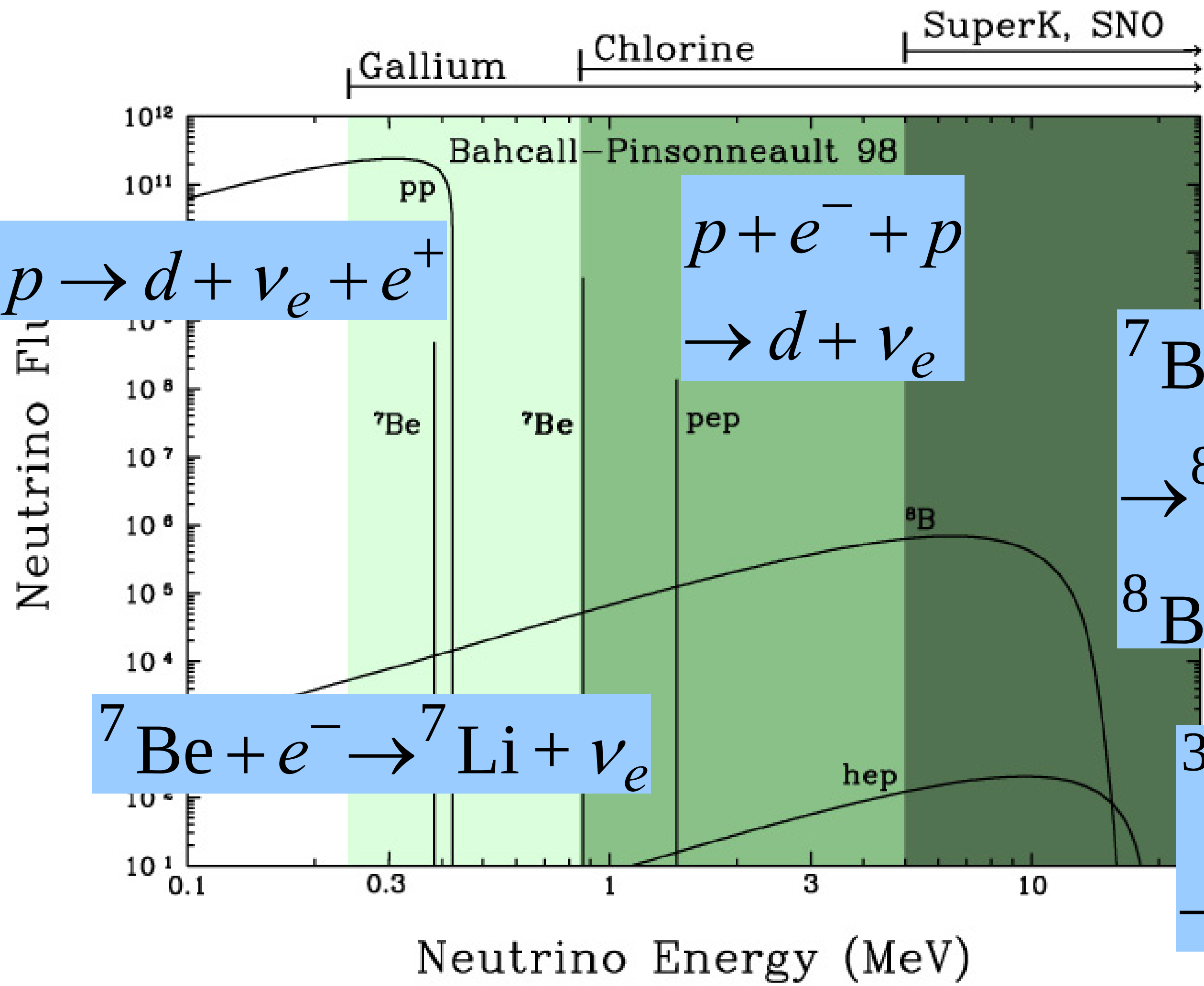
- The Sun emits light because nuclear fusion produces a lot of energy

Note: only ν_e!!



$$\Phi_\nu = \frac{2L_{\text{sun}}}{25\text{MeV}} \frac{1}{4\pi(1\text{AU})^2} = 7 \cdot 10^{10}\,\text{sec}^{-1}\,\text{cm}^{-2}$$

The Complete Solar Neutrino Flux



$$p + p \rightarrow d + \nu_e + e^+$$

$$p + e^- + p \rightarrow d + \nu_e$$

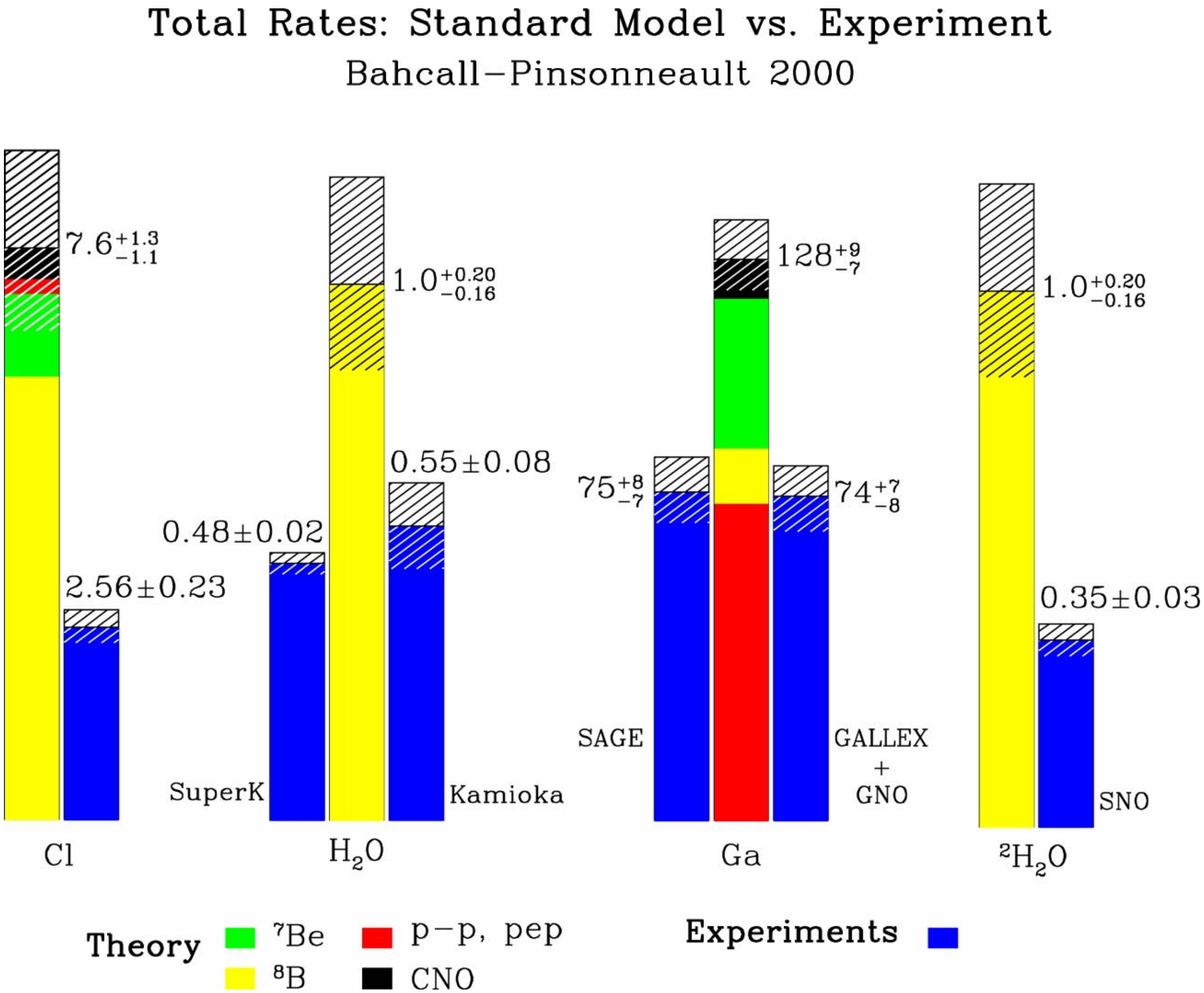
$$^7\text{Be} + p \rightarrow {}^8\text{B} \rightarrow {}^8\text{Be} + e^+ + \nu_e$$

$$^8\text{Be} \rightarrow 2\alpha$$

$$^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$$

$$^3\text{He} + p \rightarrow {}^4\text{He} + \nu_e + e^+$$

Something is missing….or the Solar model is wrong



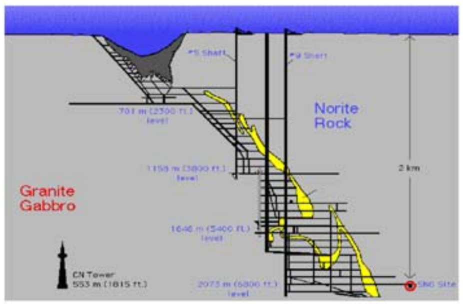
Implies survival probabilities of

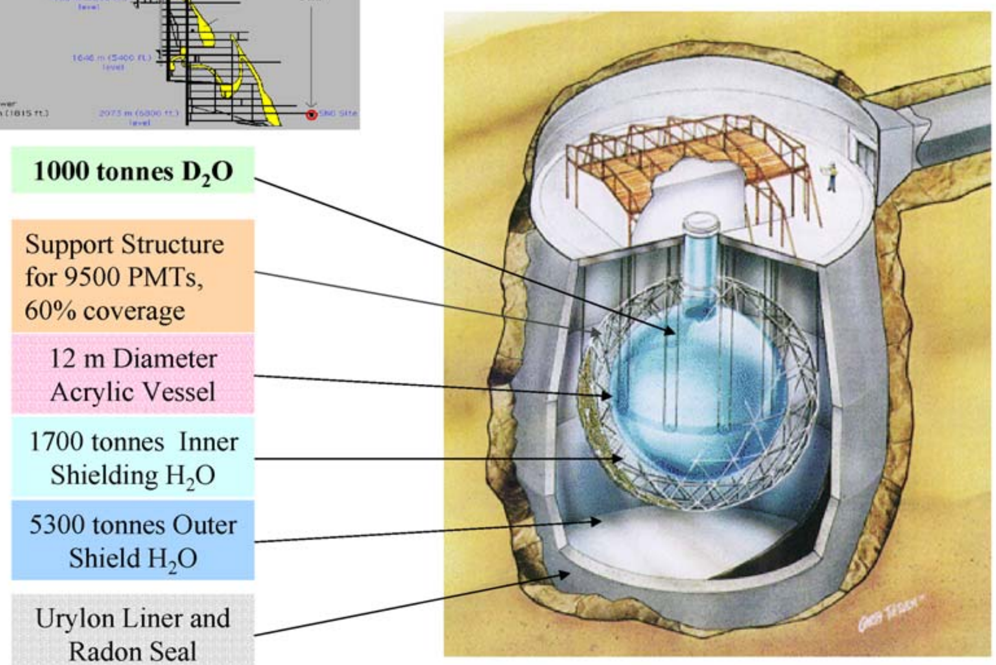
^{8}B: ~1/3

^{7}Be: <1/3

pp: ~2/3

The SNO Experiment





SNO comes to the rescue

- Charged Current: ν_e

$$\Phi_{CC} = 1.76 \pm 0.05 \pm 0.09 \cdot 10^6 \, \mathrm{cm}^{-2} \, \mathrm{sec}^{-1}$$

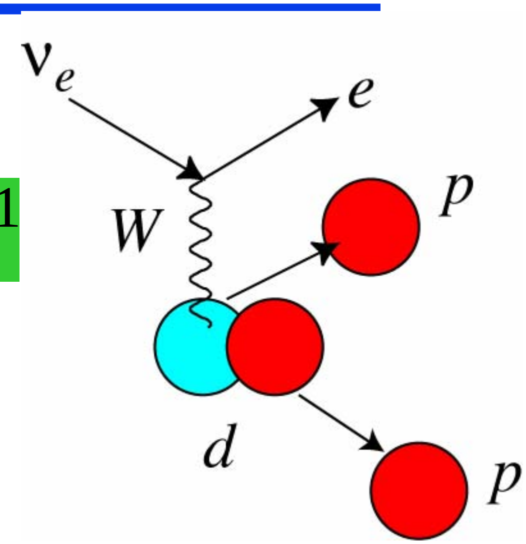
- Neutral Current: $\nu_e + \nu_\mu + \nu_\tau$

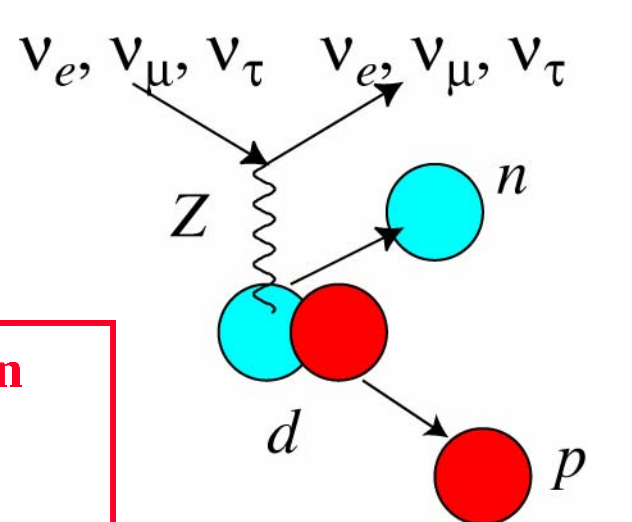
$$\Phi_{NC} = 5.09 \begin{smallmatrix} +0.44 \\ -0.43 \end{smallmatrix} \begin{smallmatrix} +0.46 \\ -0.43 \end{smallmatrix} \cdot 10^6 \, \mathrm{cm}^{-2} \, \mathrm{sec}^{-1}$$

- 5.3σ difference

$\Rightarrow$ **$\nu_{\mu,\tau}$ are arriving from the Sun!**

The electron neutrinos are changing flavor between being created in the sun, and reaching earth $\Rightarrow$ Evidence of neutrino mass…

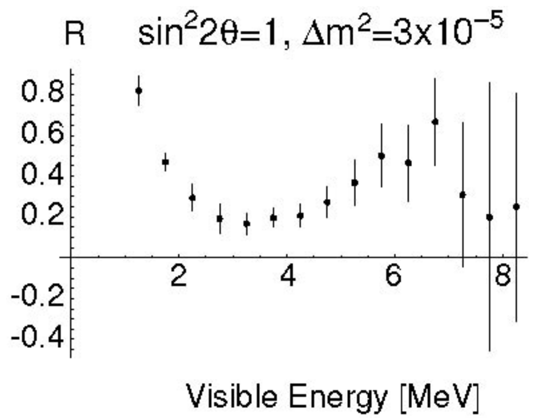




KamLAND result

- First terrestrial experiment relevant to solar neutrino problem. Reactor produced $\bar{\nu}_e$
- Can see the dip when $\Delta m^2 > 2\times 10^{-5}$ eV^2

(Pierce, HM)



Dec 2002

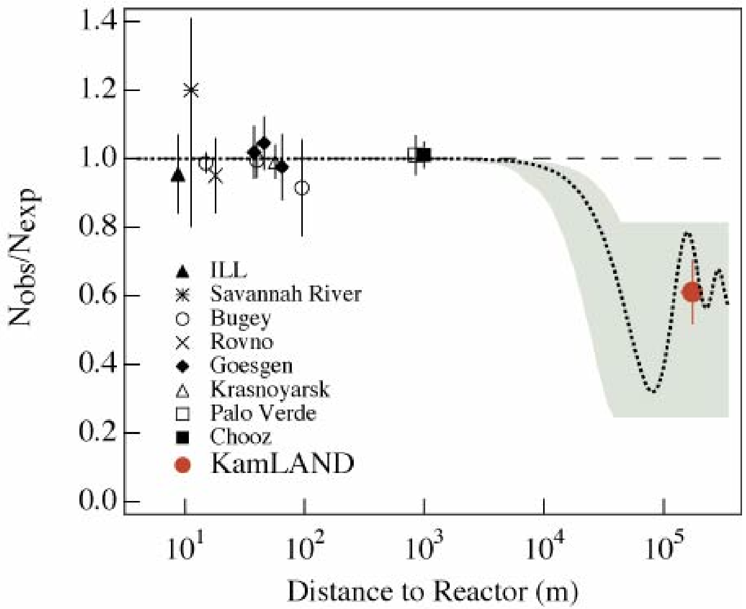
Expected #events: 86.8±5.6

Background #events: 0.95±0.99

Observed # events: 54

No oscillation hypothesis

Excluded at 99.95%



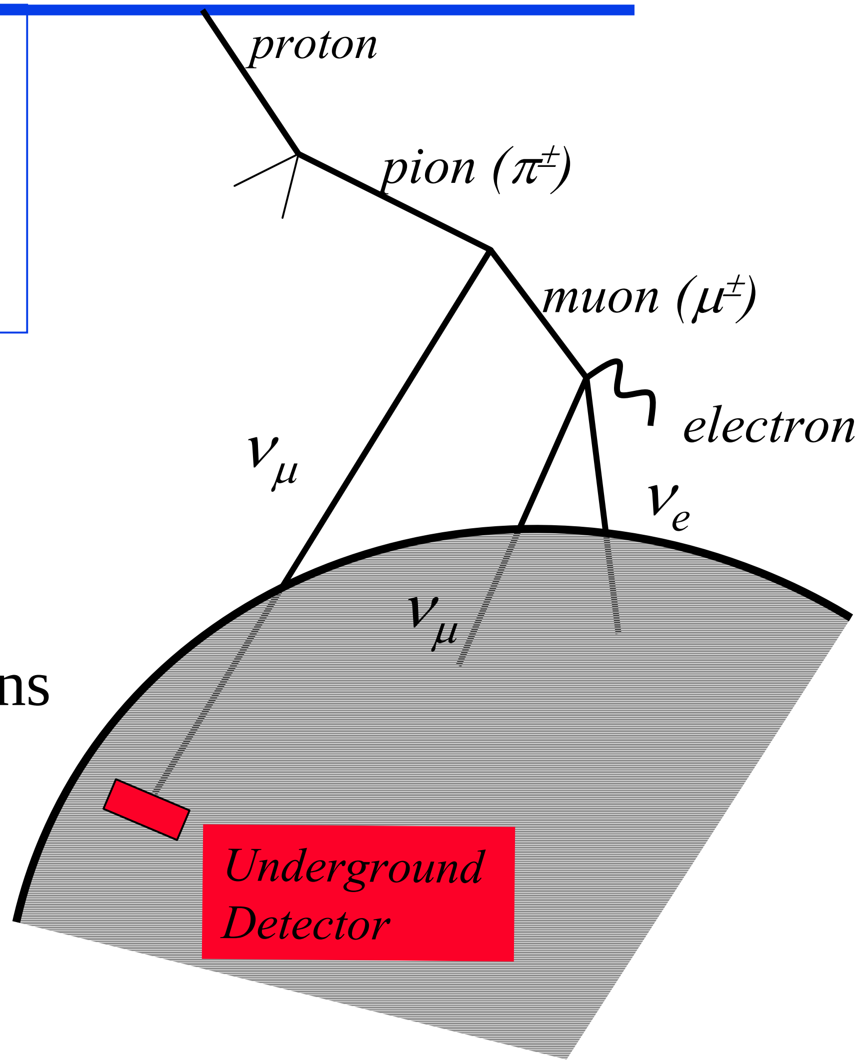
Data/theory

Atmospheric Neutrinos

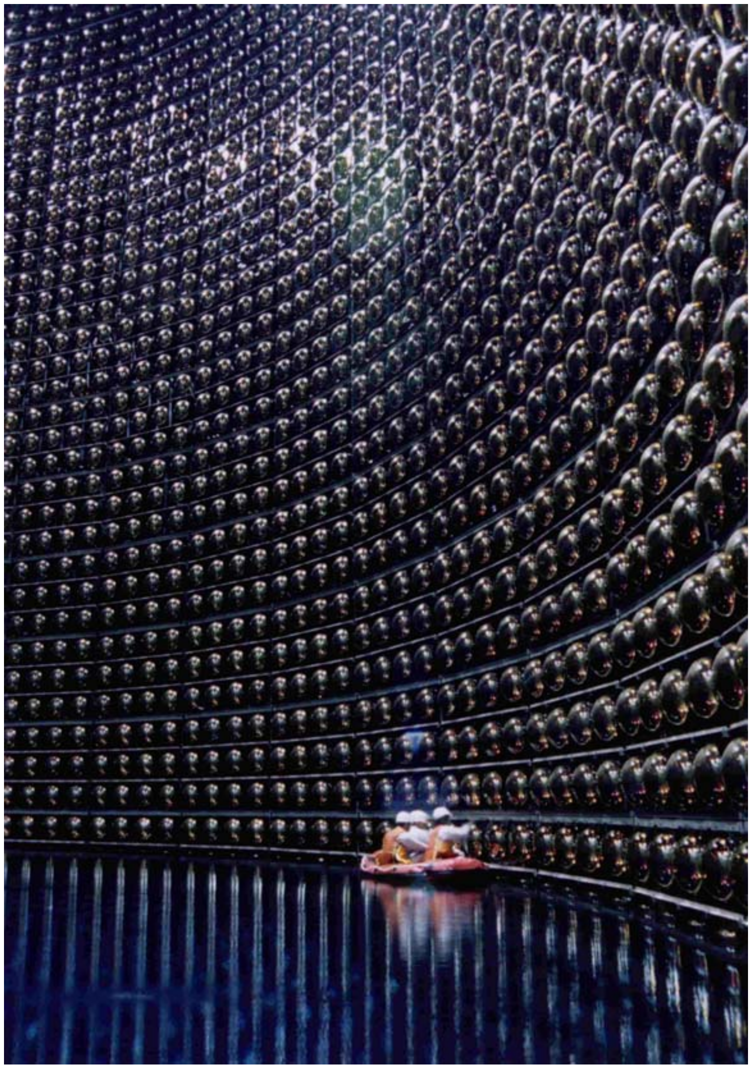
Look for neutrinos produced by cosmic rays in atmosphere – probe different Δm^2 scales than solar neutrinos

If no oscillations….

- Expect about twice as many muon neutrinos as electron neutrinos
- Can make reasonably solid predictions for distribution of neutrino angles



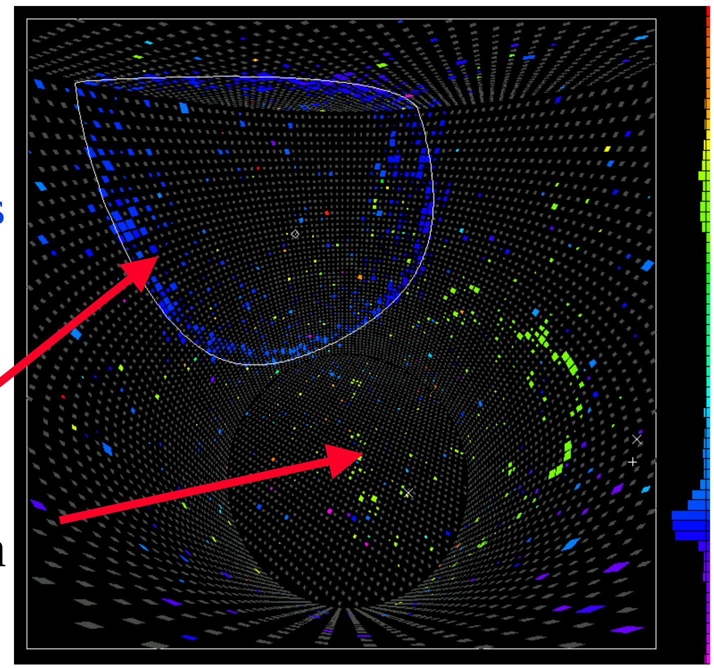
Super Kamiokande (Super-K)



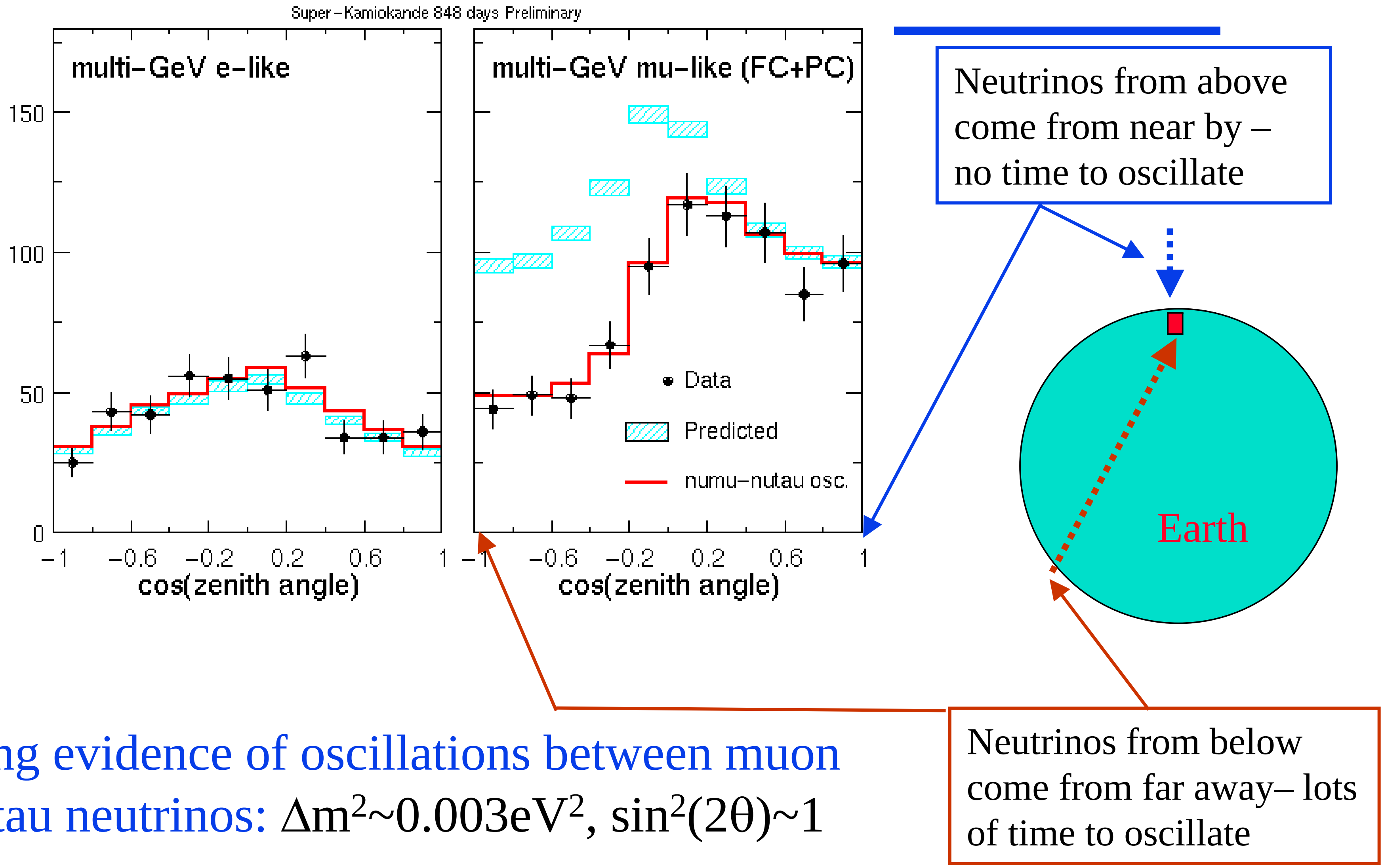
- Kamioka mine in Japan - 3300 feet underground - 50,000 tons of water!
- 12000 + very sensitive light detectors
- Look for Cerenkov light

Pattern of light hitting detectors gives type and energy

Muon and its decay electron



Super-K Oscillation Evidence



Strong evidence of oscillations between muon and tau neutrinos: $\Delta m^2 \sim 0.003 eV^2$, $\sin^2(2\theta) \sim 1$

Obvious Public Interest in this Experiment!

LSND

- Atmospheric and Solar neutrino oscillation evidence are both *disappearance*
  - Too few of the expected neutrino types are seen
- One experiment claims *appearance* of unexpected neutrinos – Liquid Scintillator Neutrino Detector at Los Alamos
  - See 1 in 400 very low energy muon neutrinos turn into electron neutrinos
  - Very short distance – possibly "large" mass difference
  - Very important to verify or refute.
- **Awkward Discovery!**
  - Solar Oscillations give us m_2 - m_1
  - Atmospheric Oscillations give us m_3 - m_2
  - LSND Appearance result gives us m_4 - m_3 OOPS, need a fourth neutrino!

The LSND Experiment

- Excess positron events over calculated BG
- LSND Result: 3.3σ Signal

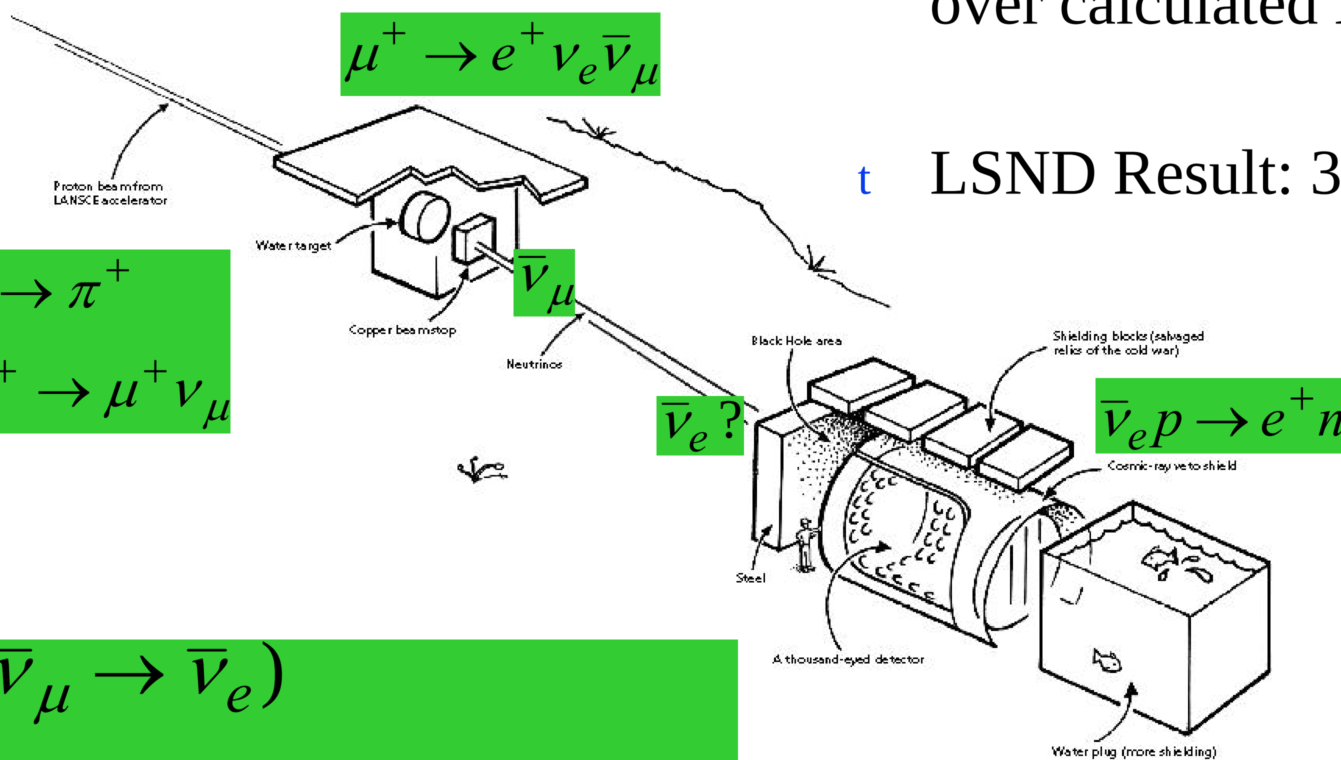
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$p \rightarrow \pi^+$$
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$\bar{\nu}_\mu$

$\bar{\nu}_e$?

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



$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$
$$= (0.264 \pm 0.067 \pm 0.045)\%$$

MiniBooNe Experiment at Fermilab to check this!

What is going on here?
Why are neutrinos changing flavor from creation to detection?