Neutrino Physics

CTEQ Summer School 2011

Madison, Wisconsin

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David Schmitz

Fermilab

Introductions First

Who am I?

- A neutrino physicist working at Fermilab
- An experimentalist
- Research background in neutrino oscillation experiments (MiniBooNE) and low-energy neutrino interaction experiments (MINERνA)

As an experimentalist, will tend to focus on an experimental history of the field and a qualitative understanding of key effects

Introductions First

Who is a neutrino?

- Most abundant matter particle in the universe, outnumbering protons, neutrons and electrons by a huge factor ($\sim 10^8$)
- The only known component of dark matter in the universe (a few %)
- Neutrinos are critical to the dynamics of stars. Flux at earth produced by the sun about $66 \times 10^9\ cm^{-2}s^{-1}$
- Carry 99% of the energy produced in a supernova
- Large numbers produced at the Big Bang still whizzing around the universe, "relic neutrinos" $\sim 400/cm^3$
- Even a banana is a prolific contributer to the neutrino content of the universe at the rate of ~1 million per day (radioactive potassium decay)

In order to understand the universe that we live in, it looks like we'll need to understand the neutrino

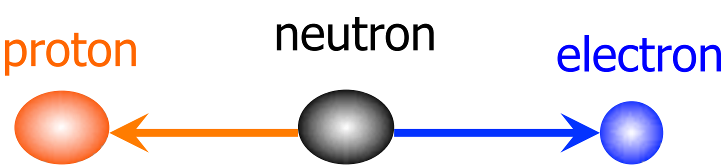
What's Our Plan?

- Lecture I
  - Birth of Neutrino Physics
  - Some Basics of the Weak Interaction
  - Neutrinos as a Probe of Matter
- Lecture II
  - Early Experimental History – Big Challenges and Bigger Surprises
  - Neutrino Oscillations, Masses and Mixing
  - Open Questions in the Neutrino Sector

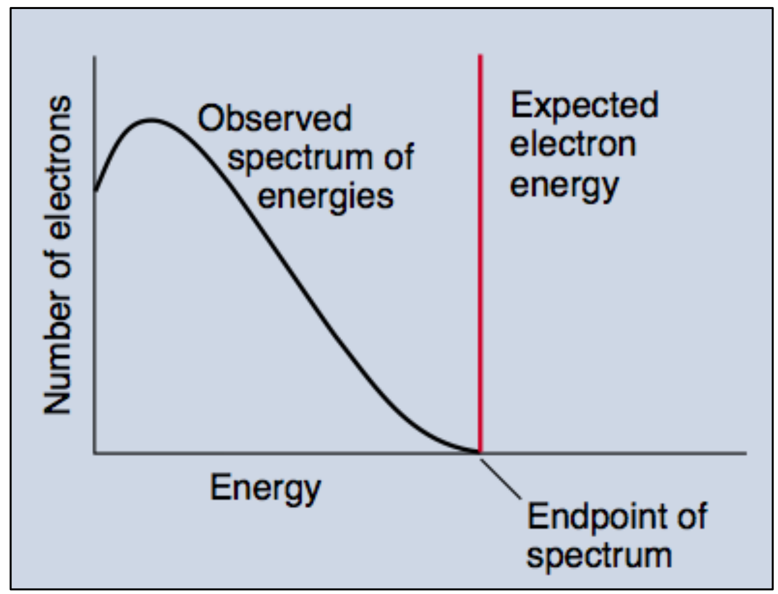
General Goal: To provide you an introduction to the basic vocabulary and concepts needed to understand current efforts and future results in neutrino physics

1930s: A Crisis in Particle Physics

- By 1931, it was well known that nuclei could change from one variety to another by emitting a “beta particle” (electron)
- But a 2-body decay should yield a monochromatic β spectrum
- Some even considered abandoning the conservation of energy!



$$(A,Z) \rightarrow (A,Z+1) + e^{-}$$



A “Desperate Remedy”

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

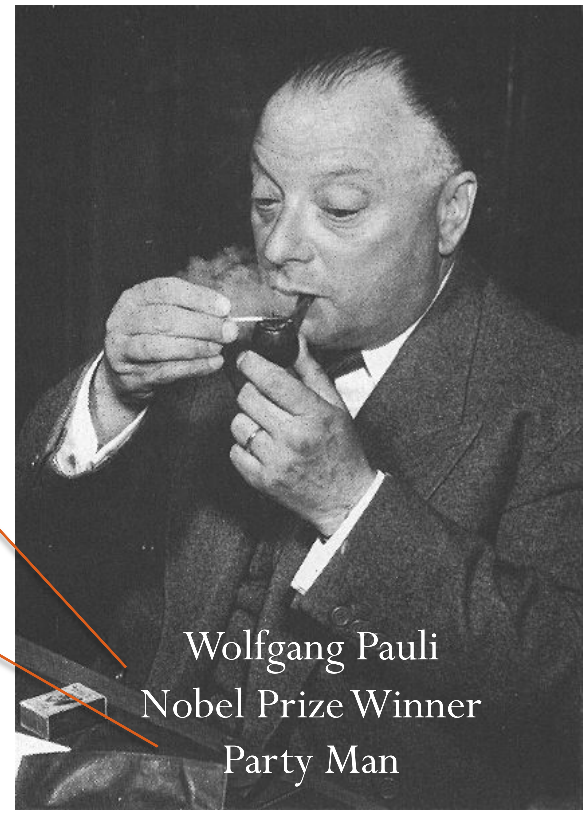
Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant,

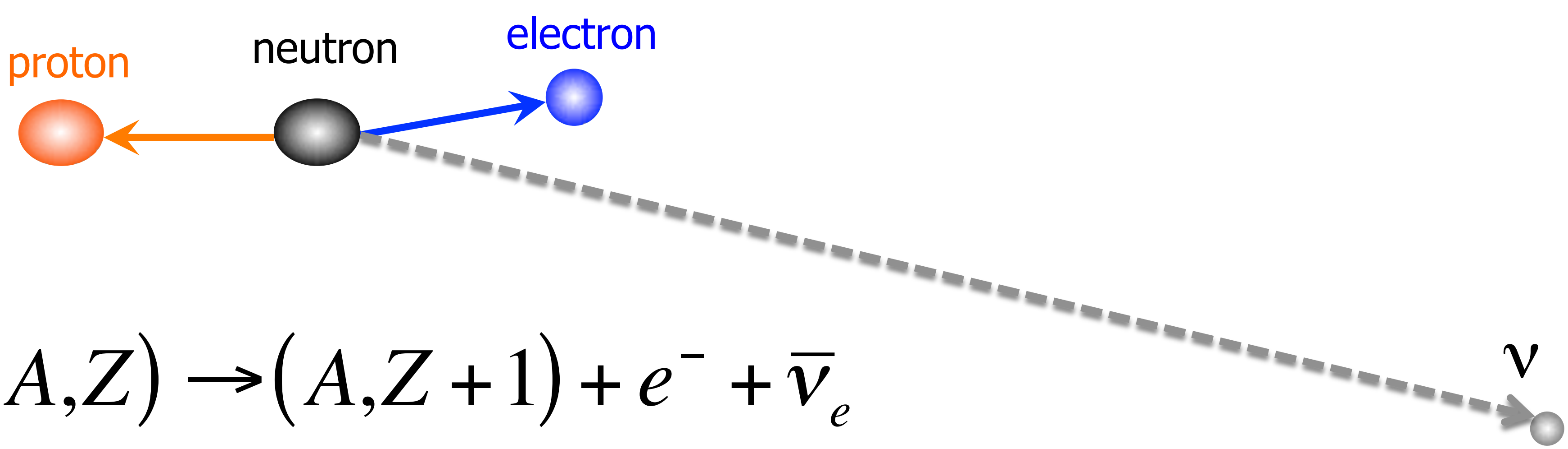
W. Pauli

“wrong statistics” and “exchange theorem” refers to a second problem that:

$$n_{spin-1/2} \not\to p_{spin-1/2} + e_{spin-1/2}$$



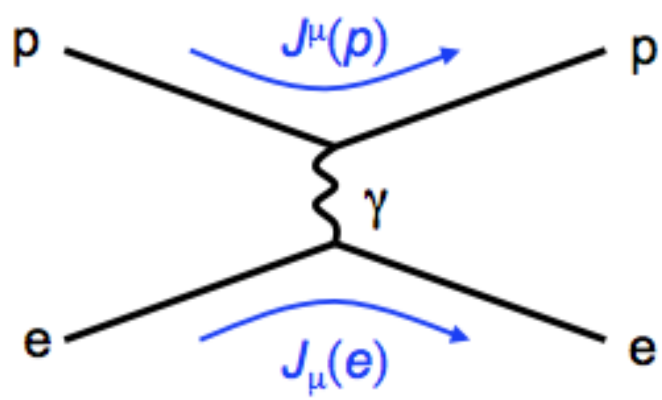
A “Desperate Remedy”

- Of course, we now know Pauli’s “neutron” to be the electron antineutrino
- Spin-1/2 fermion, solves both the statistics and energy problems
- But can we detect it?
- 

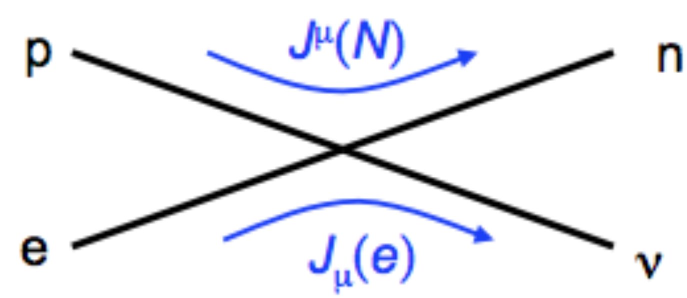
$$(A,Z) \rightarrow (A,Z+1) + e^{-} + \overline{\nu}_e$$

Fermi's Weak Interaction

- Enrico Fermi (1932), to explain the observed β-decay, developed the first model for weak interactions inspired by the success of the "current-current" description of electromagnetic interactions:



A point interaction of
four spin-1/2 fields



$$M_{em} = \left(e\bar{u}_p\gamma^\mu u_p\right)\left(\frac{-1}{q^2}\right)\left(-e\bar{u}_e\gamma_\mu u_e\right) \qquad M_{weak-CC} = G_F\left(\bar{u}_n\gamma^\mu u_p\right)\left(\bar{u}_\nu\gamma_\mu u_e\right)$$

Fermi's Weak Interaction

- Note the inclusion of Fermi's coupling constant, G_F

$$M_{weak-CC} = G_F\left(\bar{u}_n\gamma^\mu u_p\right)\left(\bar{u}_\nu\gamma_\mu u_e\right)$$

- G_F is not dimensionless (GeV^{-2}) and would need to be experimentally determined in β-decay and μ-decay experiments

$$\frac{G_F}{(\hbar c)^3} = \sqrt{\frac{\hbar}{\tau_\mu}\cdot\frac{192\pi^3}{(m_\mu c)^5}} \approx 1.166\times 10^{-5}/GeV^2$$

Fermi's Weak Interaction

- Bethe-Peierls (1934), using Fermi's original theory and the experimental value of G_F, were able to calculate the expected cross-section for inverse beta decay of few MeV neutrinos:

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

$$\boxed{\sigma_{\bar{\nu}p} \approx 5 \times 10^{-44}\, cm^2 \quad for \quad (E_{\bar{\nu}} \sim 2\ MeV)}$$

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atomic mass unit

$$\boxed{d_{lead} = \frac{1.66\text{x}10^{-27}\ \text{kg}}{(\sigma_{x\text{-}N}\ \text{m}^2)(11400\ \text{kg/m}^3)}}$$

ν-N cross-section

density of lead

Hmmm… that looks small

What's the mean free path of a neutrino in lead?

Fermi's Weak Interaction

A typical neutrino produced in a power reactor or the core of the sun has 1-10 MeV of energy:

$$\sigma \sim 10^{-44}\ cm^2, \quad d_{lead} \sim 10^{16}\ m$$

over a light year of lead!

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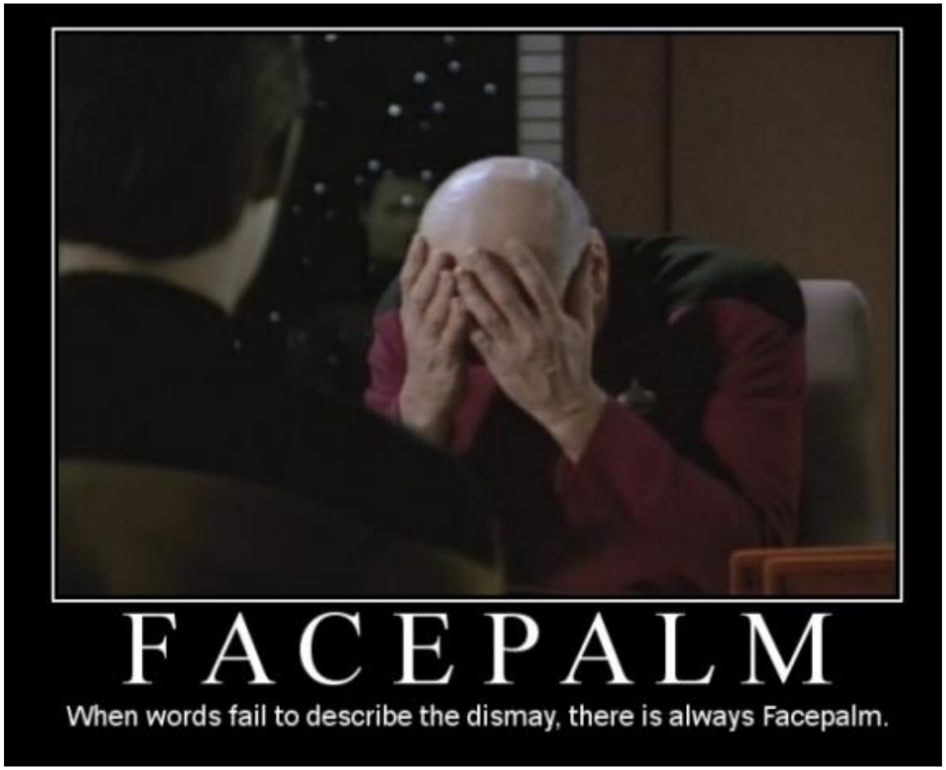
What about a proton with ~1 GeV of energy?

$$\sigma \sim 10^{-25}\ cm^2, \quad d_{lead} \sim \underline{10\ cm}$$

Pauli's Despair

The expected huge difficulty in detecting a neutrino led Pauli to famously quip :



"I have done something very bad by proposing a particle that cannot be detected; it is something no theorist should ever do."

- Wolfgang Pauli (1931)

Could the tiny cross section be overcome?

Project Poltergeist

To detect a neutrino, need an extremely intense source to compensate for the tiny cross section

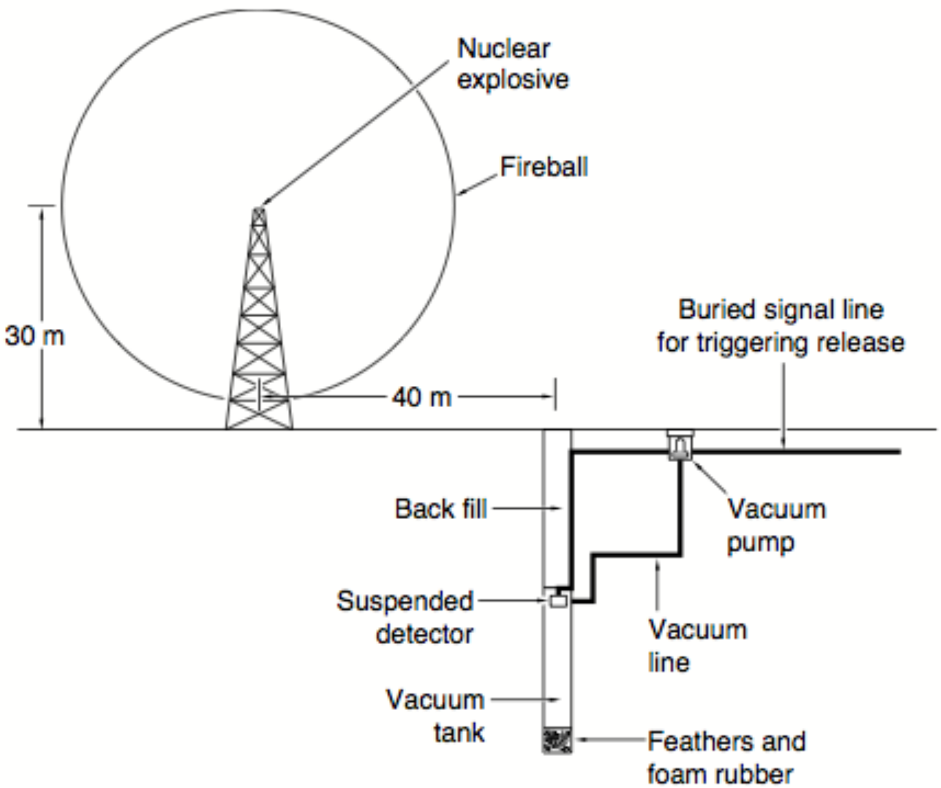


Figure 1. Detecting Neutrinos from a Nuclear Explosion

<u>Straightforward plan</u>

1. Explode nuclear bomb
2. Simultaneously drop detector to feather bed
3. Detect neutrino
4. Repeat??

Persistence Pays Off

To detect a neutrino, need an extremely intense source to compensate for the tiny cross section

- Solution: nuclear power reactor fission chain:

$$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e \rightarrow (A,Z+2) + e^- + \bar{\nu}_e \rightarrow \ldots$$

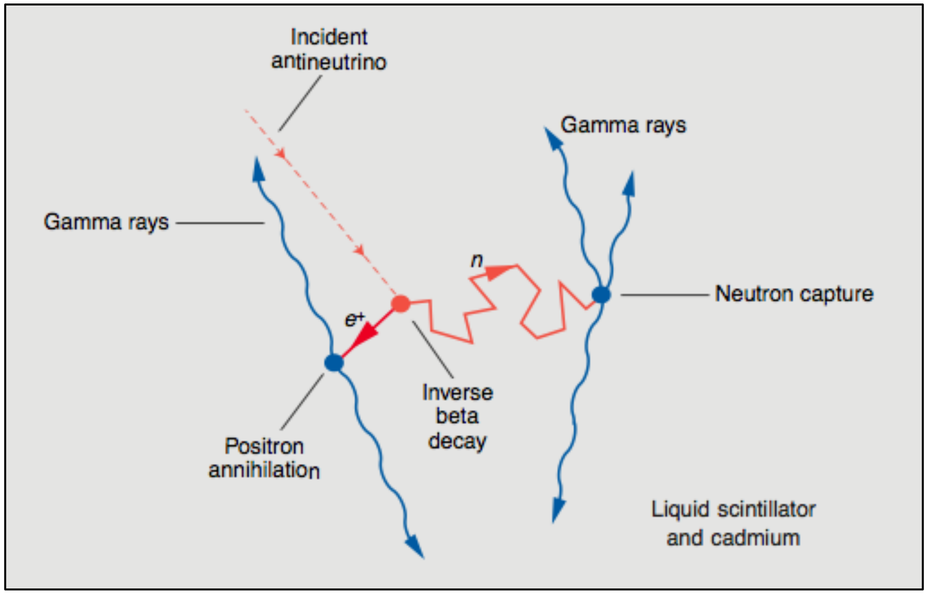
$$N_{\bar{\nu}} \approx 5.6 \times 10^{20} s^{-1} \ in \ 4\pi$$

- Fred Reines and Clyde Cowan used the nuclear power reactor at Savannah River as an intense source and the inverse β-decay reaction to try to detect the ν_e

Persistence Pays Off

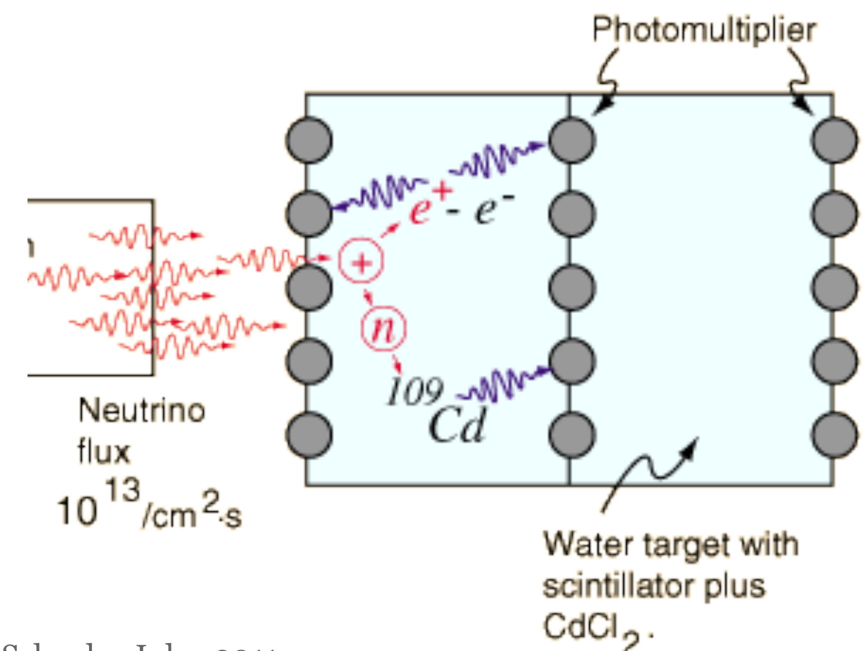
- Finally, confirmation in 1956

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



Positron annihilates promptly on electron to produce two 0.5 MeV Gamma rays

Neutron gets captured by Cadmium nucleus after a delay of ~5 microseconds



Persistence Pays Off

"[Prof. Pauli], we are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons."

- Fred Reines and Clyde Cowan (1956)

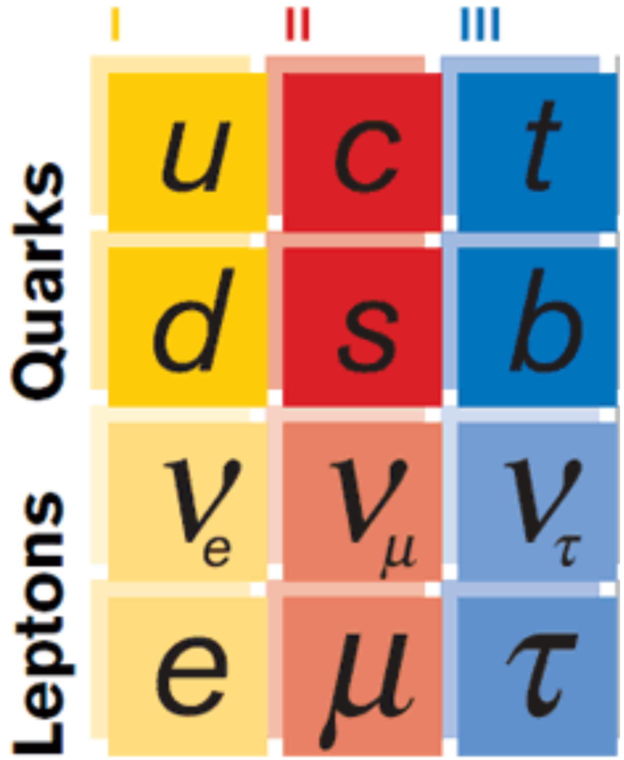
"Everything comes to him who knows how to wait."

- Wolfgang Pauli (1956)

It took 25 years to detect the first of Pauli's neutrino!

Flavor and Families in the SM

- In 1962 Schwartz, Lederman and Steinberger established the existence of a second, distinct type of neutrino that made muons instead of electrons when they interact
- This discovery was really the first indication of the "family" structure in the Standard Model
- The third (and last?) neutrino was not directly detected until 2000 by the DONUT experiment at Fermilab (70 years after the Pauli hypothesis)



Three Generations of Matter

The Modern Weak Interaction

- Taking another look at Fermi's theory of the weak interaction:

$$M_{weak-CC} = G_F\left(\bar{u}_n\gamma^{\mu}u_p\right)\left(\bar{u}_\nu\gamma_{\mu}u_e\right)$$

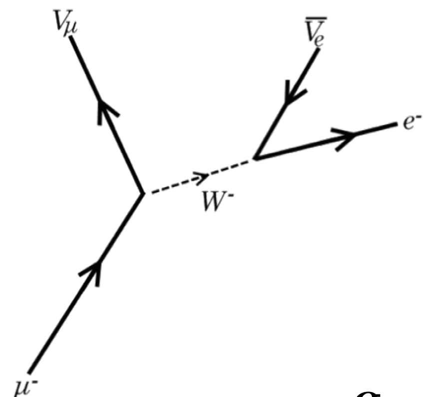
- Note the absence of a propagator term. Of course, we now know that the weak force, like the EM one, is mediated by the exchange of weak bosons, the $W^{\pm}$ and Z

- We also know that the assumption of current-current was incorrect, the weak force violates parity and so the vertex factors are not simply γ_μ, but include both vector and vector-axial coupling contributions (V-A)

$$\gamma_\mu \to \gamma_\mu\left(1-\gamma^5\right)$$

The Modern Weak Interaction

- An example, the decay of muons:



$$\mu^- \to e^- + \overline{\nu}_e + \nu_\mu$$

q^2: 4-momentum carried by the exchange particle

M: mass of exchange particle

$$M_{\mu-decay} = \frac{g_W}{\sqrt{2}}\left[\overline{u}_{\nu_\mu}\gamma^\mu\left(1-\gamma^5\right)u_\mu\right]\left(\frac{1}{M_W^2-q^2}\right)\left[\overline{u}_e\gamma_\mu\left(1-\gamma^5\right)u_{\overline{\nu}_e}\right]$$

- Fermi's original theory essentially buried the propagator, vertex terms, and a dimensionless constant (g_w here) into the constant G_F

- But in many experimental cases $q^2 << M_W{}^2$, making Fermi's theory an excellent approximation

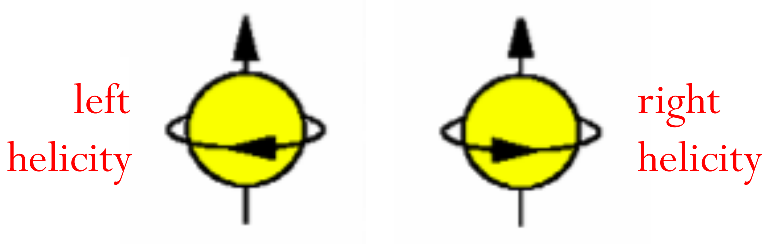
Helicity, Chirality, and Parity

The Weak force is "left-handed"

$$\frac{1}{2}\left(1-\gamma^5\right)\psi = \psi_L$$

(1-γ^5) is projection operator onto the left-handed states for fermions and right-handed states for anti-fermions

- Helicity
  - Projection of spin along the particle's momentum vector



  - Frame dependent for massive particles (can always boost to a frame faster than the particle, reversing helicity)

- Chirality ("Handedness")
  - Lorentz invariant counterpart to helicity
  - Same as helicity for massless particles
  - Since neutrinos created by weak force
    - all neutrinos are left-handed
    - all antineutrinos are right-handed
  - Only left-handed charged leptons participate in weak interactions. Small right-helicity contribution $\propto m/E$

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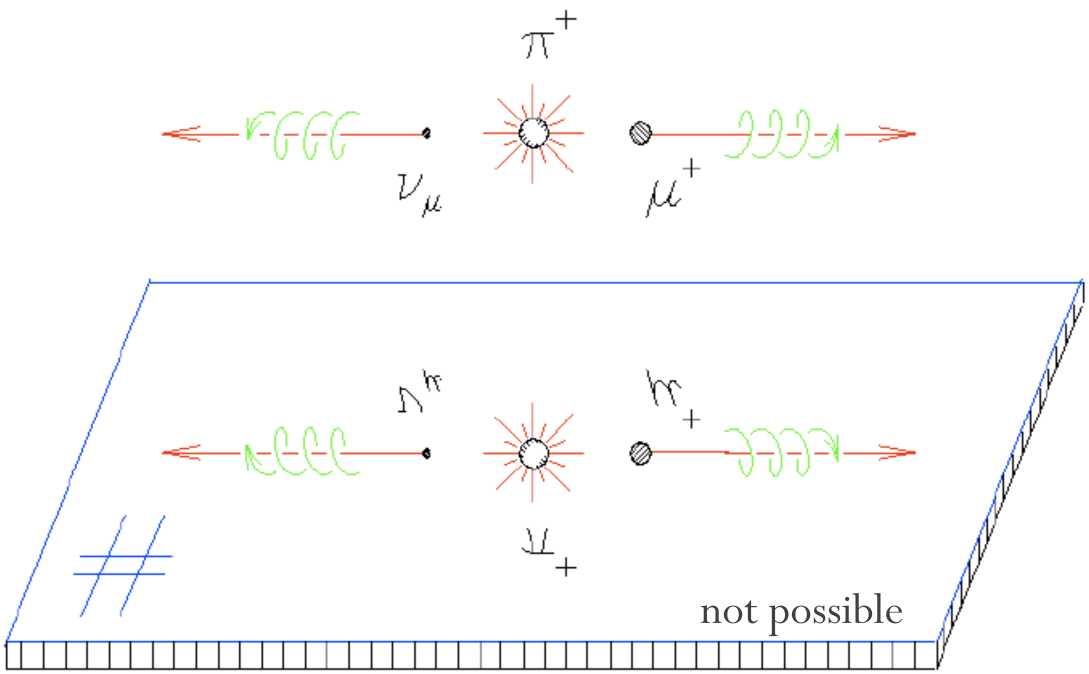

$$R_\pi = \frac{\Gamma\left(\pi^+ \to e^+ \nu_e\right)}{\Gamma\left(\pi^+ \to \mu^+ \nu_\mu\right)}$$

$$R_\pi = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 = 1.23 \times 10^{-4}$$

Strength of the Weak Interaction

- Using the low q^2 approximation and the value of G_F we got from the muon lifetime and mass:

$$\frac{G_F}{(\hbar c)^3} = 1.166 \times 10^{-5} / GeV^2 = \frac{\sqrt{2}}{8}\left(\frac{g_w}{M_W c^2}\right)^2$$

Once it was realized there is a massive propagator, one can calculate the intrinsic strength of the weak interaction…

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$$M_W \approx 80\ GeV/c^2 \quad \Rightarrow \quad g_w \approx 0.7$$

$$if \qquad \alpha = \frac{g_e^2}{4\pi} = \frac{1}{137}, \qquad \alpha_w = \frac{g_w^2}{4\pi} = \frac{1}{29}$$

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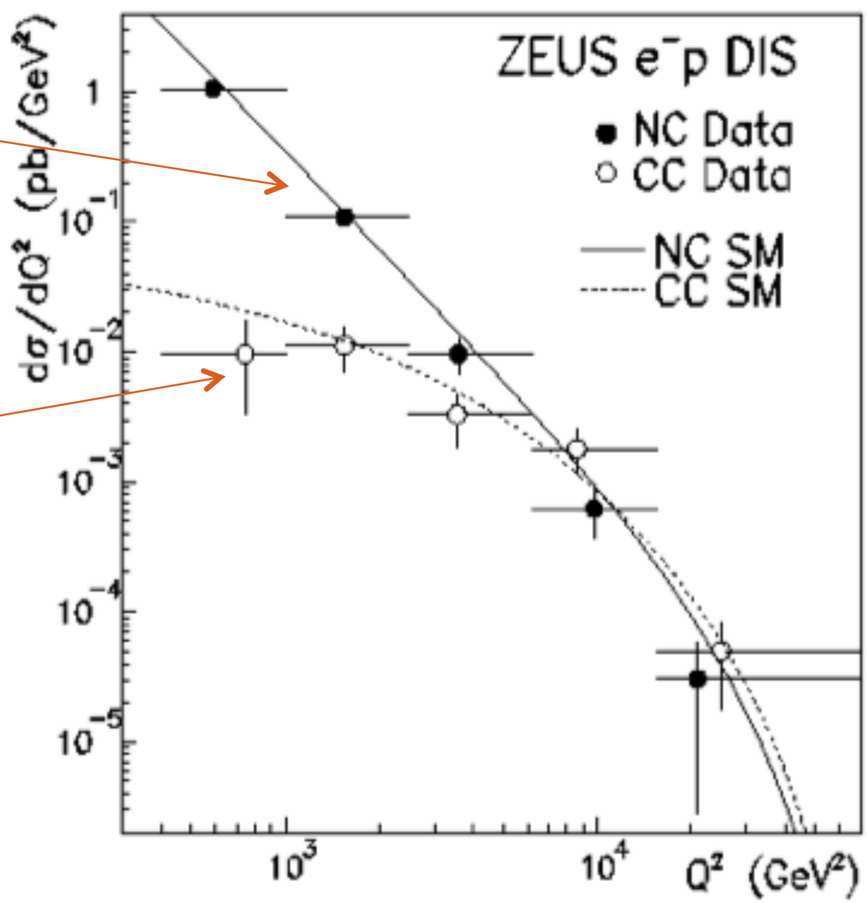
The Weak Interaction coupling constant is <u>the same order</u> as the electromagnetic!!

Strength of the Weak Interaction

- And at sufficiently high center of mass energy, the weak interaction becomes as strong as the EM!

NC dominated by EM interactions (photon exchange) $\sim 1/q^2$

CC due to interaction via W boson $\sim 1/(q^2 - M_W^2)$



ZEUS an experiment at HERA, a high energy electron-proton collider

Electromagnetism / Electroweak

- University of Wisconsin's own F. Halzen makes a very nice analogy in *Quarks and Leptons* between the unification of electromagnetic and weak interactions and the original unification of EM

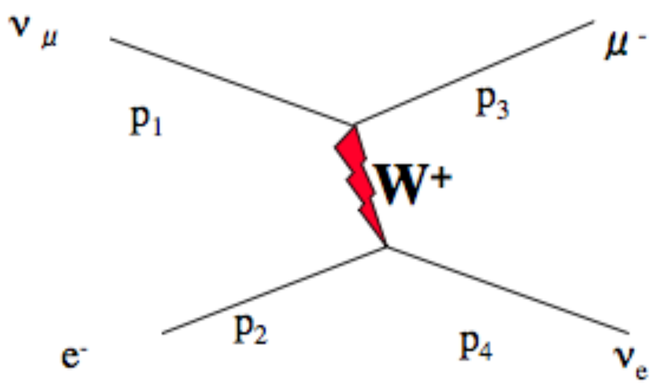
> *"We may think of $g_e \approx g_w$ as a unification of weak and electromagnetic interactions in much the same way as the unification of the electric and magnetic forces in Maxell's theory of electromagnetism, where*
>
> $$\mathbf{F} = e\mathbf{E} + e_M\, \mathbf{v}\, x\, \mathbf{B}$$
>
> *with $e_M = e$. At low velocities, the magnetic forces are very weak, whereas for high-velocity particles, the electric and magnetic forces play a comparable role. The velocity of light c is the scale which governs the relative strength. The analogue for the electroweak force is M_W on the energy scale."*

What happens when we are at energies significantly below the M_W scale?

Strength of the Weak Interaction

- Why so "weak" for neutrino interactions?

- For example, neutrino-electron scattering: $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$



$$
\begin{aligned}
s &\equiv (p_1 + p_2)^2 \\
&= (E_\nu + m_e)^2 - (\vec{p}_\nu)^2 \\
&= E_\nu^2 - p_\nu^2 + m_e^2 + 2E_\nu m_e \approx 2E_\nu m_e
\end{aligned}
$$

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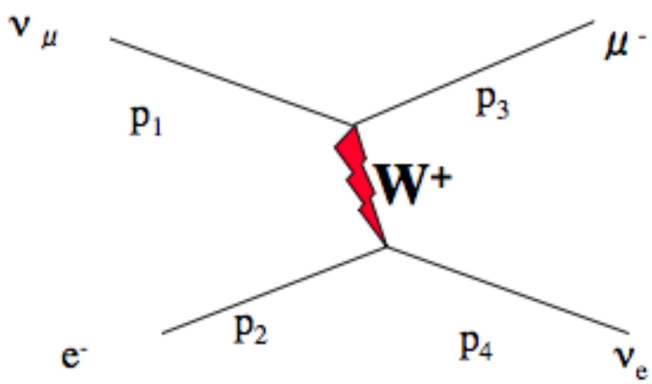

$$s \equiv (p_1 + p_2)^2$$
$$= (E_\nu + m_e)^2 - (\vec{p}_\nu)^2$$
$$= E_\nu^2 - p_\nu^2 + m_e^2 + 2E_\nu m_e \approx 2E_\nu m_e$$

- For a real experiment, neutrino energy may be order 100 GeV:

$$E_{CM} = s \approx 2E_\nu m_e = 2 * 100 * .000511 \approx \boxed{0.1\,GeV}$$

Strength of the Weak Interaction

- Why so "weak" for neutrino interactions?

$$\frac{d\sigma}{dq^2} \propto \frac{1}{(M^2 - q^2)^2}$$

q^2 is 4-momentum carried by the exchange particle

M is mass of the exchange particle

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Need to create this to mediate the interaction, but only had 0.1 GeV

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Where to get the additional needed energy from?

Take out a loan…

Strength of the Weak Interaction

At low center of mass energies, we borrow it from the vacuum for a short time!

$$\Delta E \Delta t \geq \frac{\hbar}{2} \qquad t \sim \frac{\hbar}{\Delta E}$$

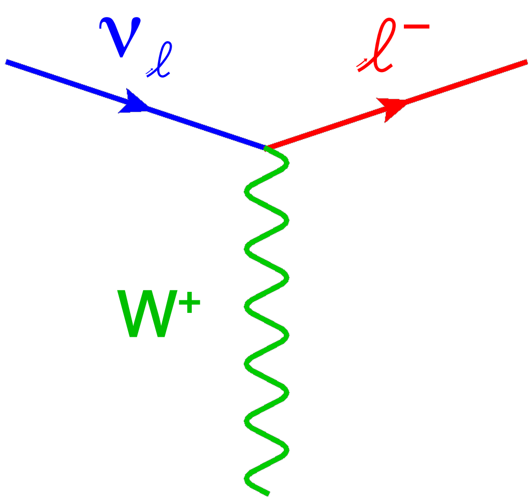
To make a W boson, we'll need to borrow $80\ GeV/c^2$, $t \sim 8 \times 10^{-27}\ s$

Which explains the very short range of the weak interaction at low energies, $d = tc \sim 2.4 \times 10^{-18}\ m$

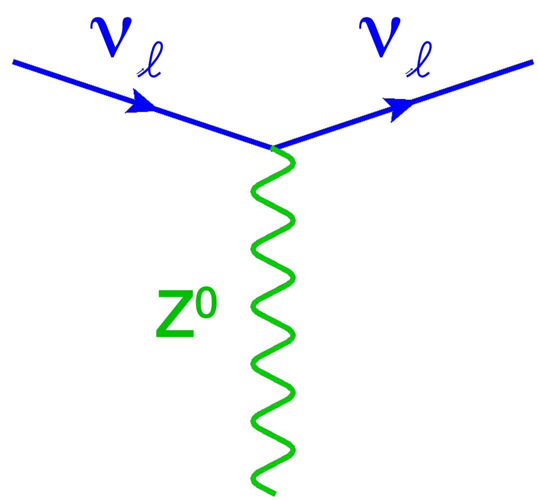
Two Types of Weak Interactions

$W^{\pm}$ exchange constitutes a "charged-current" interaction

Z^0 exchange constitutes a "neutral-current" interaction



Charged-Current (CC)



Neutral-Current (NC)

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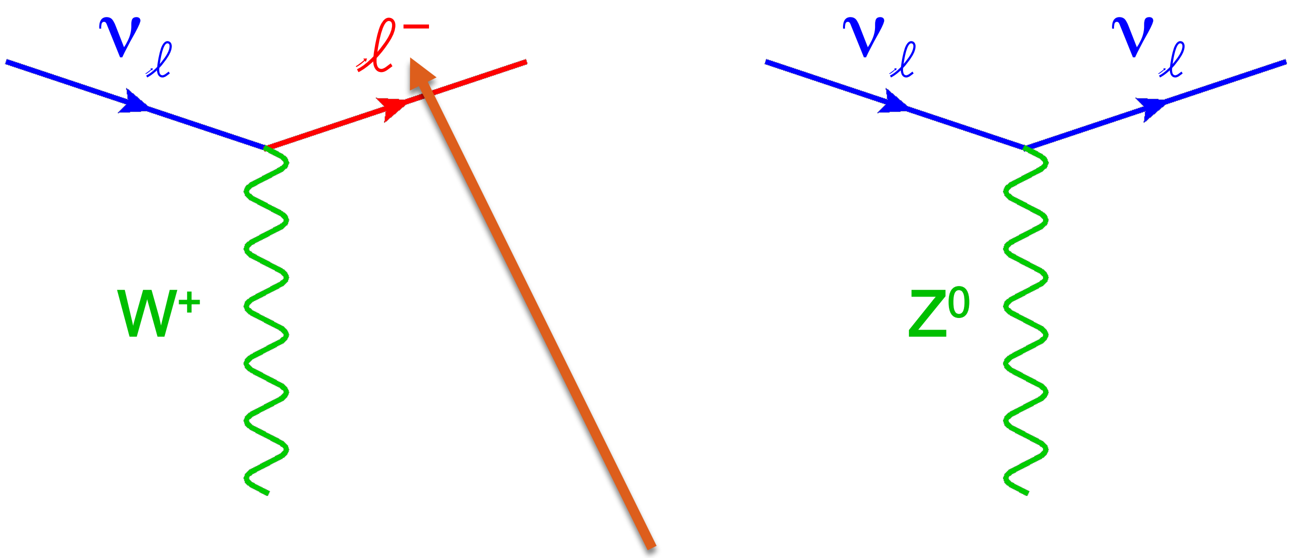

Flavor of outgoing
charged lepton determines
flavor of neutrino

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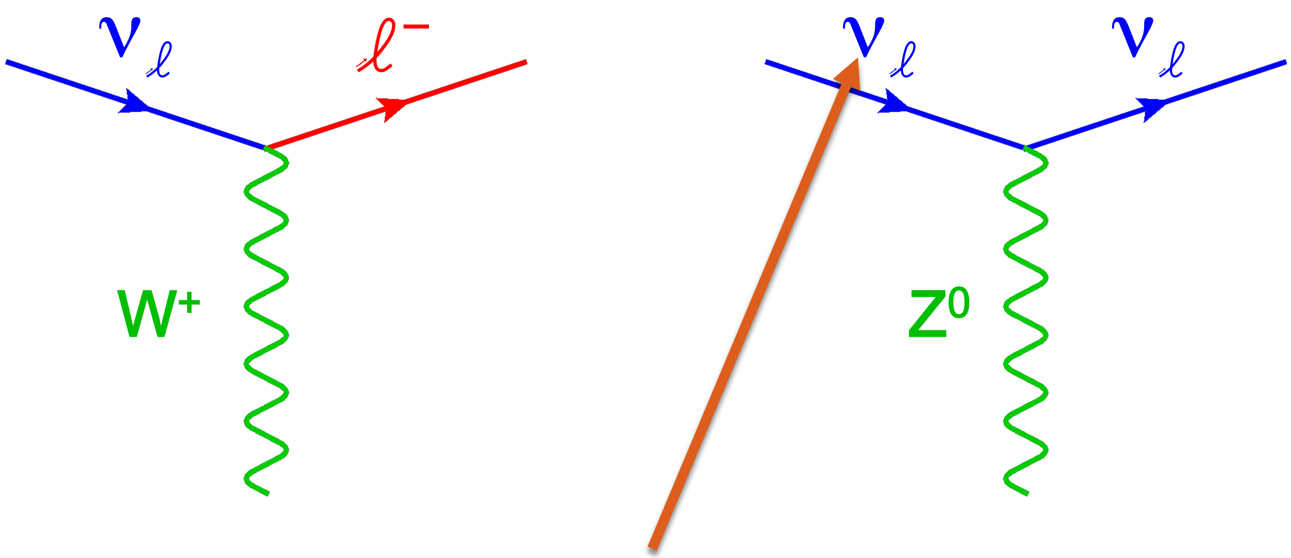

No way to determine flavor in neutral-current interaction

Two Types of Weak Interactions

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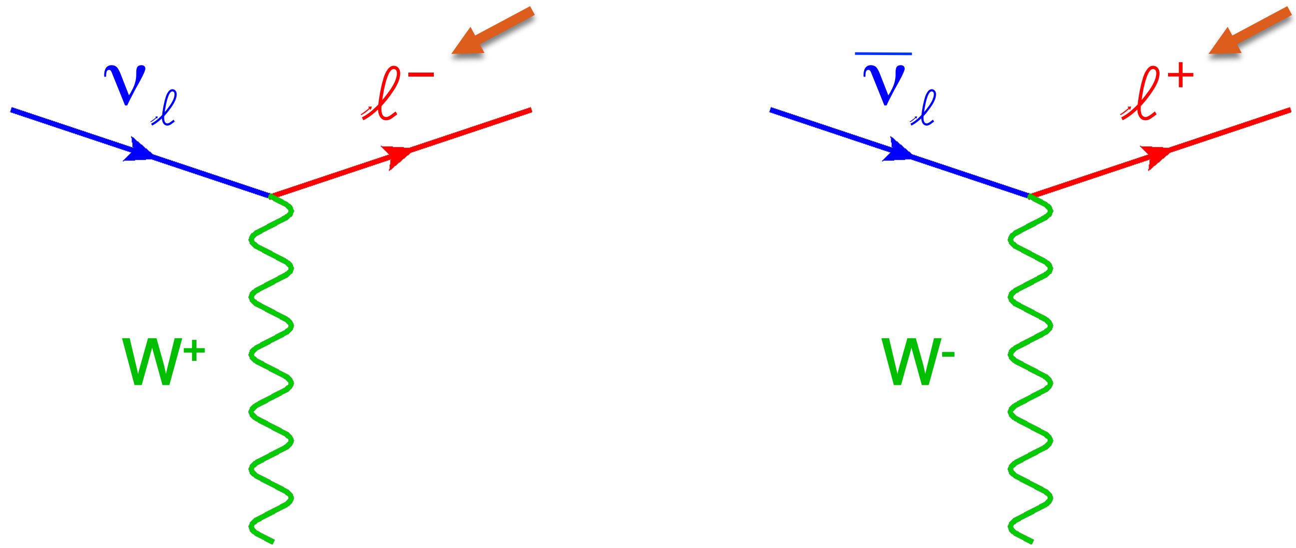
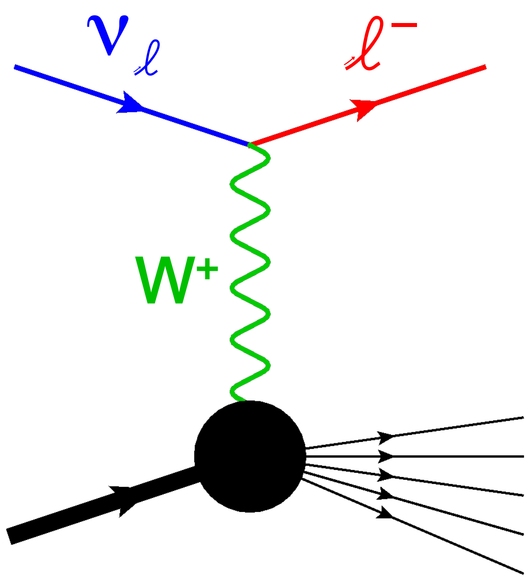


Sign of outgoing
charged lepton determines
<u>neutrino vs. antineutrino</u>

Neutrino-Nucleon Interactions

- The lepton vertex was pretty simple. Of course, it's the hadronic vertex in ν-N scattering that contains all the complication



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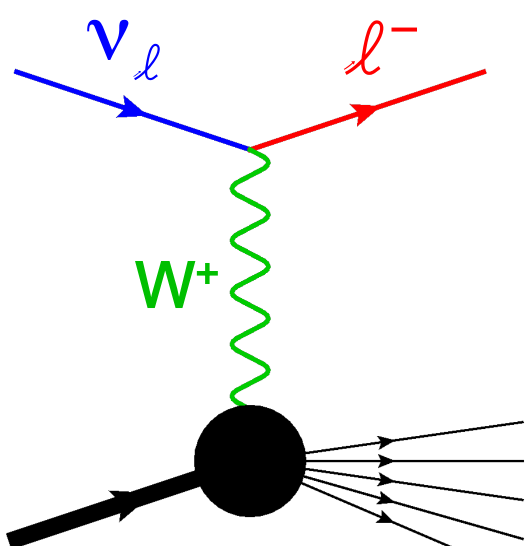

✓ Quasi-Elastic Scattering (QE)

- target changes (CC) but no break up

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

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

✓ Nuclear Resonance Production

- target goes to excited state

$$\nu_\mu + N \rightarrow N^*(\Delta) \rightarrow \mu + N + \pi$$

✓ Deep-Inelastic Scattering (DIS)

- nucleon breaks up completely

$$\nu_\mu + quark \rightarrow \mu + \mathrm{X}$$

Neutrino-Nucleon Interactions

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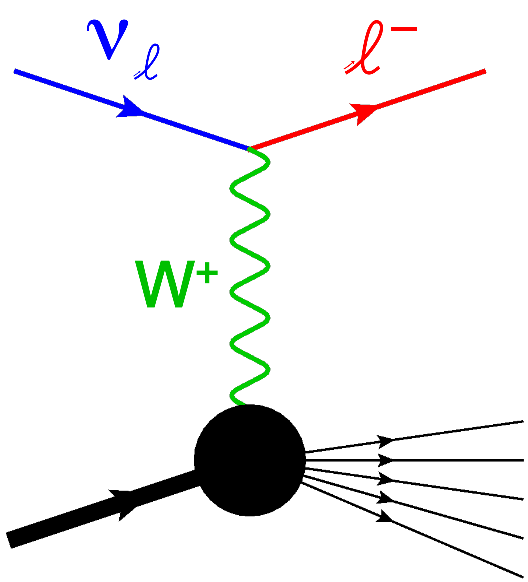
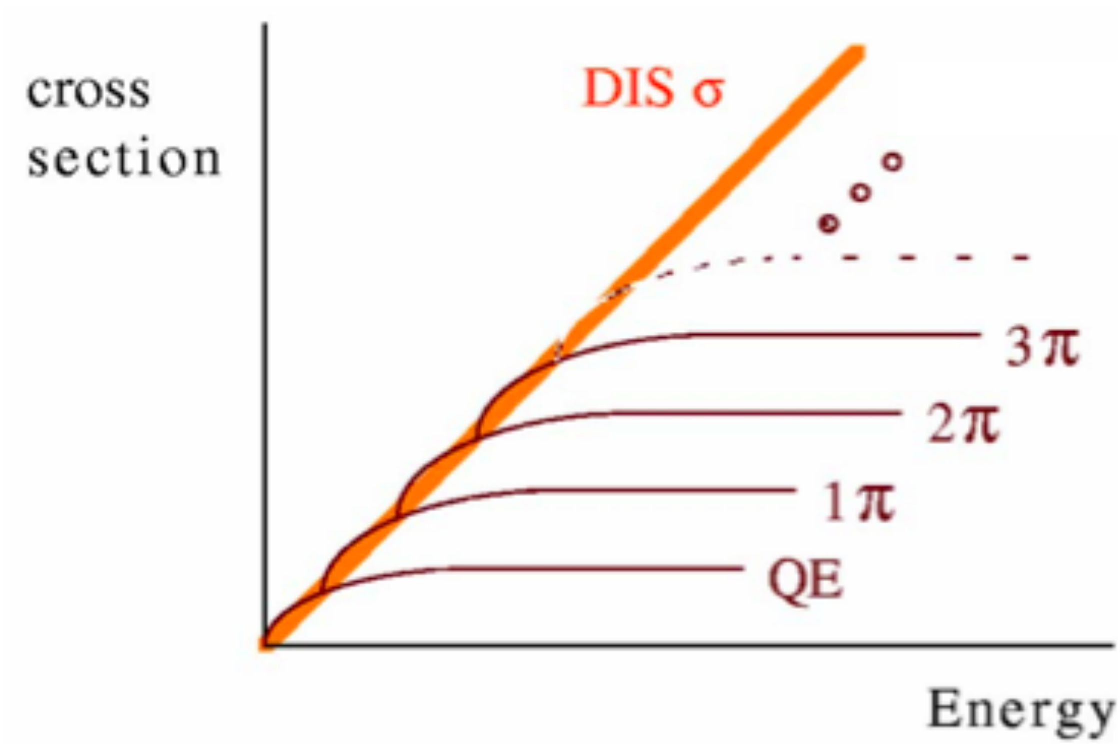
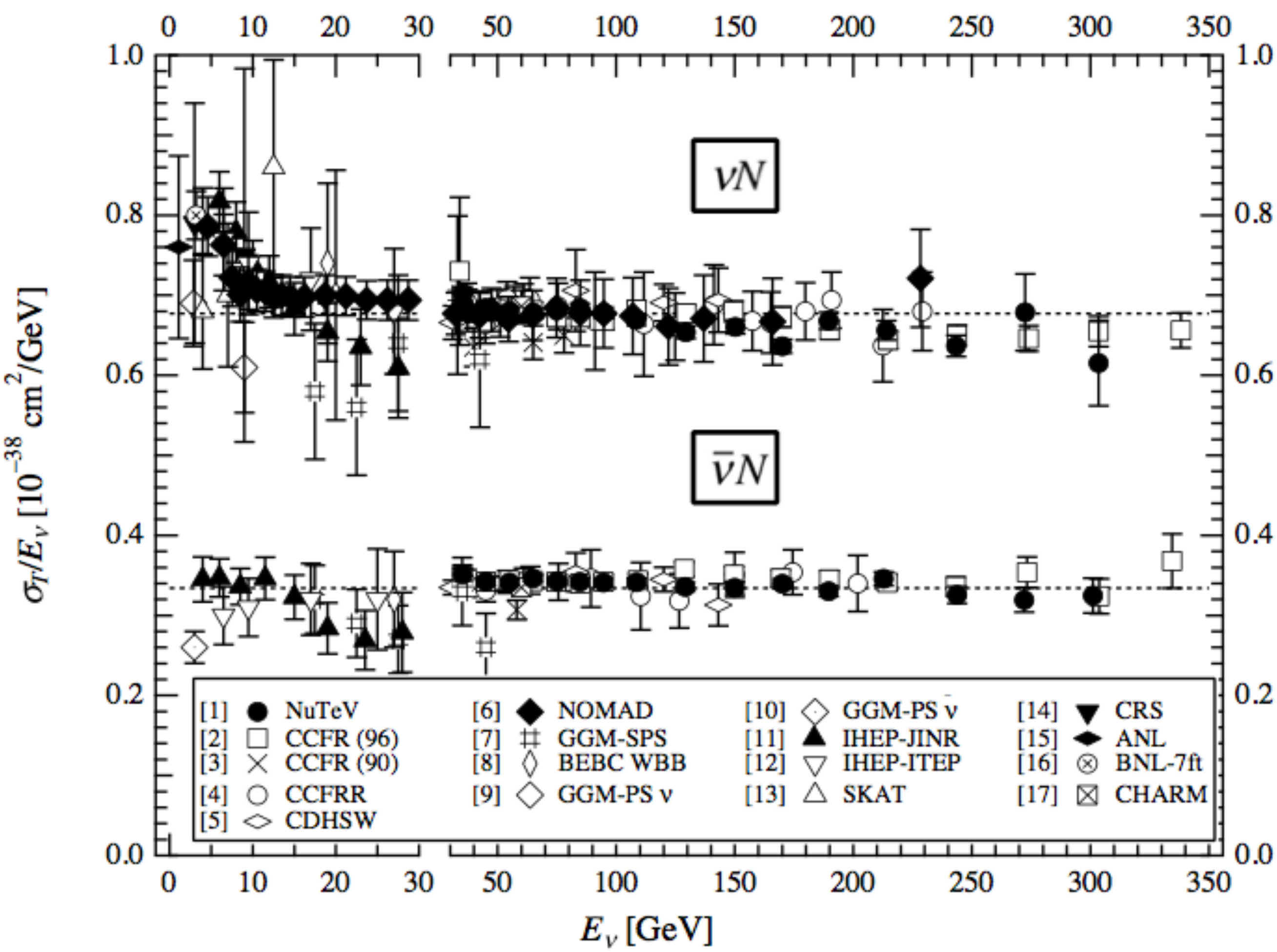




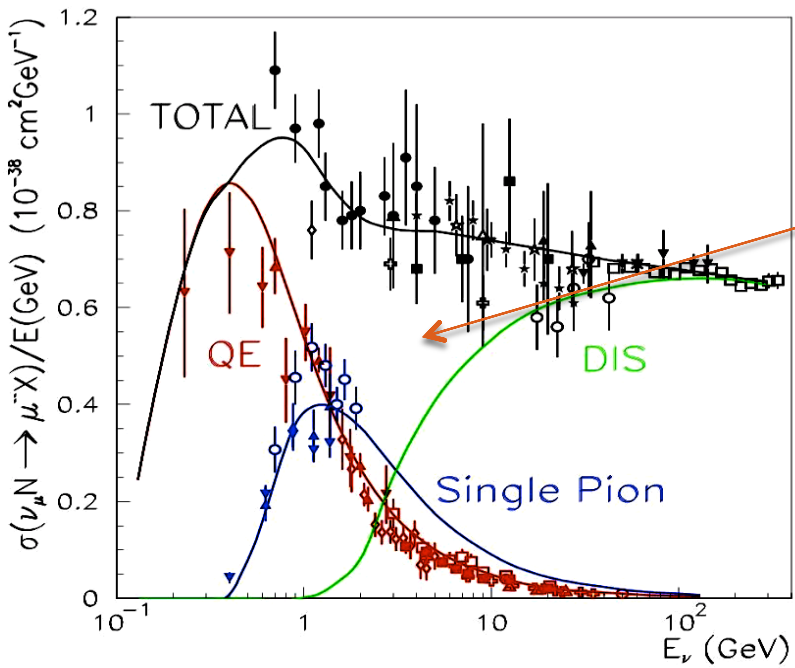
ν_μ Total CC/NC Cross Sections

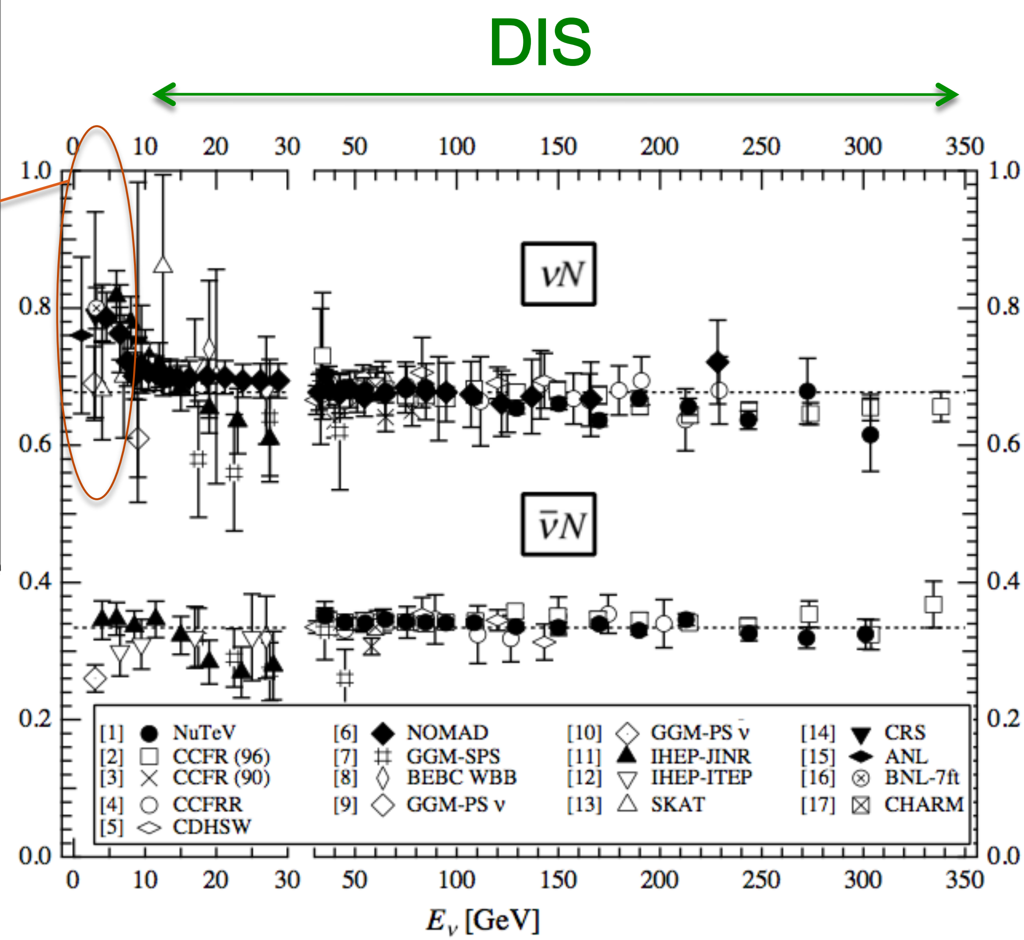
- Indeed the cross section rises linearly with energy

Note the division by E_ν on this axis: σ/E_ν



ν_μ Total CC/NC Cross Sections



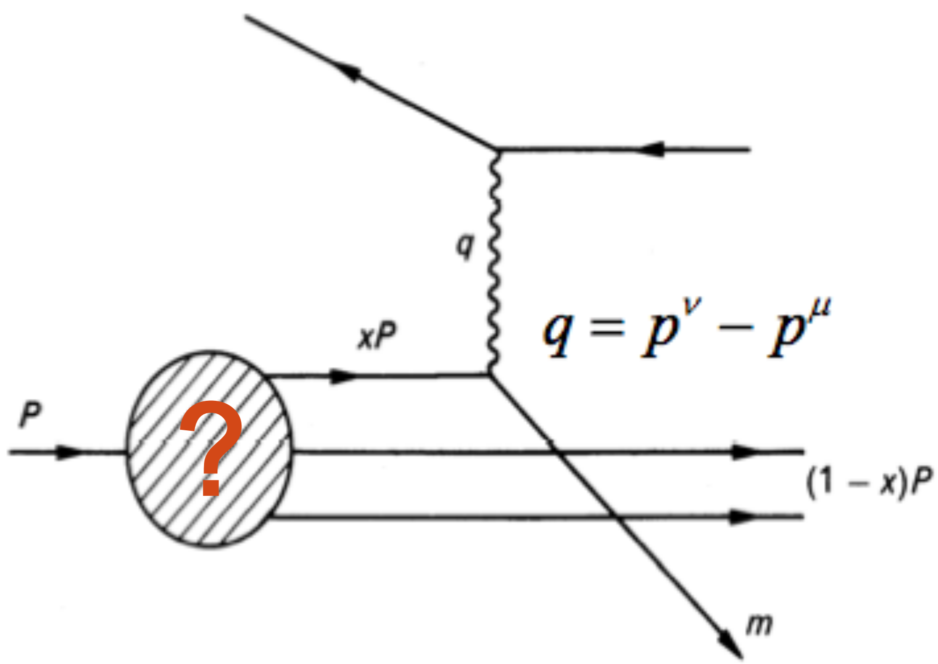


Only in lowest energy region (few GeV) does non-DIS cross section dominate

Probing Nucleon Structure with Neutrinos

Neutrinos provide a unique weak probe complimentary to the wealth of charged lepton DIS data (Cynthia Keppel's lecture last week)

In the quark parton model, the neutrino scatters off an individual parton inside the nucleon, which carries a fraction, x, of the nucleon's total momentum



$$q = p^{\nu} - p^{\mu}$$

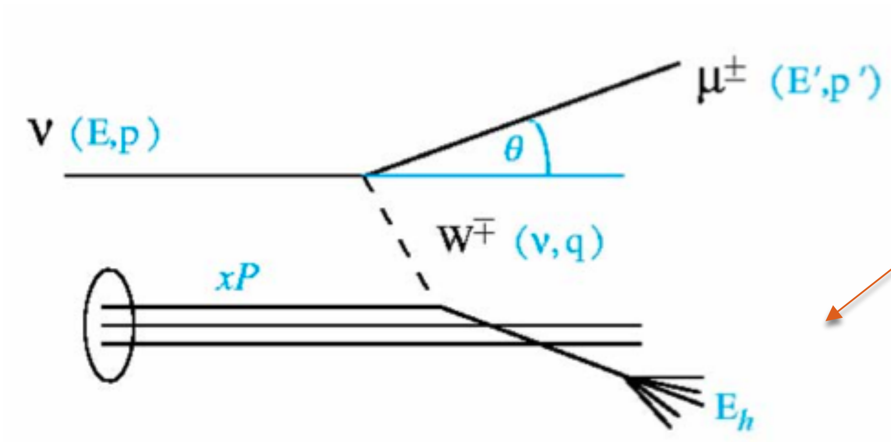
mass of target quark:

$$m_q^2 = x^2 P^2 = x^2 M_T^2$$

mass of final state quark:

$$m_{q'}^2 = \left(xP + q\right)^2$$

Kinematic Variables of Neutrino DIS



observables:

E_μ, θ, E_h

$E_\nu = E_\mu + E_h - M_T$

momentum transfered between ν and quark, Q^2: $Q^2 = -q^2 = -(p-p')^2 = 4E_\nu E_\mu \sin^2\left(\frac{\theta}{2}\right)$

energy transfered from ν to quark, ν : $\nu = E_\nu - E_\mu = E_h - M_T$

fraction of nucleon momentum carried by quark, x : $x = \dfrac{Q^2}{2M_T\nu}$

fraction of available energy transfered to quark, y : $y = \dfrac{\nu}{E_\nu} = 1 - \dfrac{E_\mu}{E_\nu} = \dfrac{Q^2}{2M_T E_\nu x} \approx \dfrac{1}{2}(1-\cos\theta)$

recoil mass squared, W^2: $W^2 = -Q^2 + 2M_T\nu + M_T^2$

Parton Distribution Functions $q(x)$

- Charge and helicity considerations impose important restrictions on possible neutrino-quark interactions
- Key point is that neutrinos and antineutrinos sample different quark flavor content of nucleon substructure
  - neutrinos only interact with : $d,\ s,\ \bar{u},\ \bar{c}$
  - antineutrinos only interact with : $u,\ c,\ \bar{d},\ \bar{s}$

$$\frac{d\sigma}{dxdy}(\nu + proton) = \frac{G_F^2 s}{\pi} x\left[d(x) + s(x) + \left[\bar{u}(x) + \bar{c}(x)\right](1-y)^2\right]$$

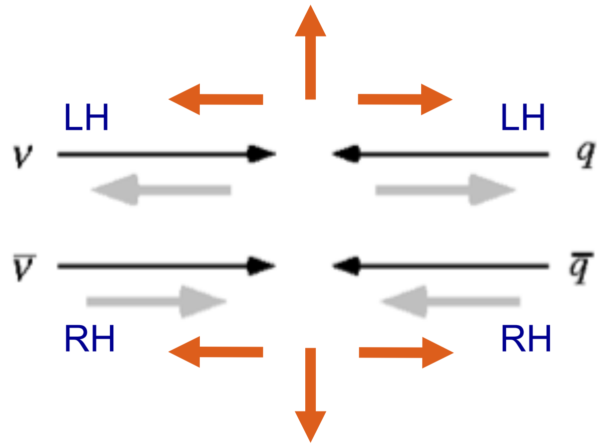
$$\frac{d\sigma}{dxdy}(\bar{\nu} + proton) = \frac{G_F^2 s}{\pi} x\left[\bar{d}(x) + \bar{s}(x) + \left[u(x) + c(x)\right](1-y)^2\right]$$

Parton Distribution Functions $q(x)$

- Charge and helicity considerations impose important restrictions on possible neutrino-quark interactions

neutrino
+quark

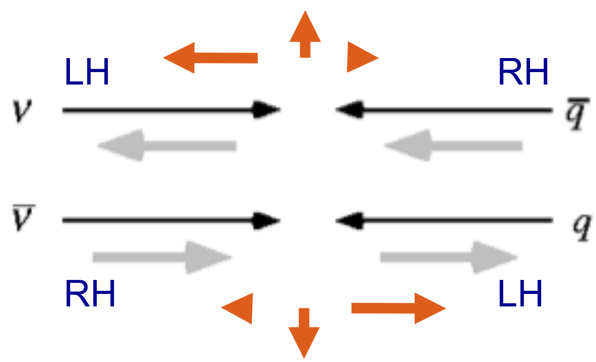
antineutrino
+antiquark



$$\frac{d\sigma}{dy}(\nu q) = \frac{d\sigma}{dy}(\bar{\nu}\,\bar{q}) = \boxed{\frac{G_F^2 s x}{\pi}}$$

neutrino
+antiquark

antineutrino
+quark

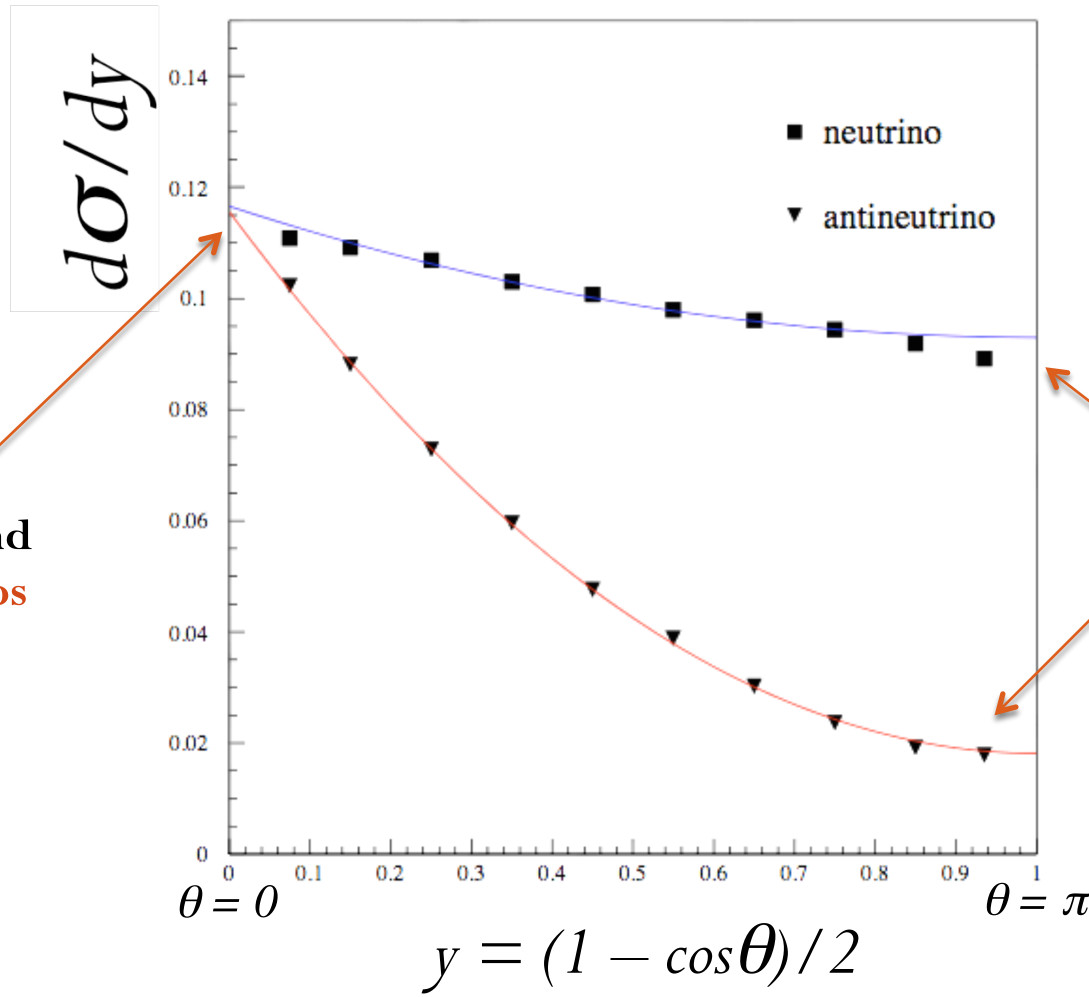


$$\frac{d\sigma}{dy}(\bar{\nu} q) = \frac{d\sigma}{dy}(\nu\,\bar{q}) = \boxed{\frac{G_F^2 s x}{\pi}(1-y)^2}$$

$$1 - y \approx \frac{1}{2}(1+\cos\theta)$$

Parton Distribution Functions $q(x)$

Neutrino CC DIS cross section vs. y



y = 0
neutrinos and
antineutrinos
the same

y = 1
neutrinos
only see quarks
antineutrinos
only see antiquarks

Nucleon Structure Functions

- Can also write the ν-N cross section in a model-independent way using three "nucleon structure functions", F_1, F_2, and xF_3 :

$$\frac{d^2\sigma^{\nu,\bar{\nu}}}{dxdy} = \frac{G_F^2 M_T E}{\pi}\left[xy^2 \underline{F_1(x,Q^2)} + \left(1 - y - \frac{xyM_T}{2E}\right)\underline{F_2(x,Q^2)} \pm y\left(1 - \frac{y}{2}\right)\underline{xF_3(x,Q^2)}\right]$$

- We'll use the Callan-Gross relation to rewrite the expression

$$R \equiv \left(1 + \frac{4M_T^2 x^2}{Q^2}\right)\frac{F_2}{2xF_1} - 1$$

- The functions $F_2(x,Q^2)$, $xF_3(x,Q^2)$, and $R(x,Q^2)$ can then be mapped out experimentally from the measured DIS differential cross section:

$d\sigma/dy$ in bins of (x,Q^2)

Nucleon Structure Functions

neutrino

$$\frac{d^2\sigma^{\nu A}}{dxdy} \propto \left[F_2^{\nu A}(x,Q^2) + xF_3^{\nu A}(x,Q^2)\right] + (1-y)^2\left[F_2^{\nu A}(x,Q^2) - xF_3^{\nu A}(x,Q^2)\right] + f(R)$$

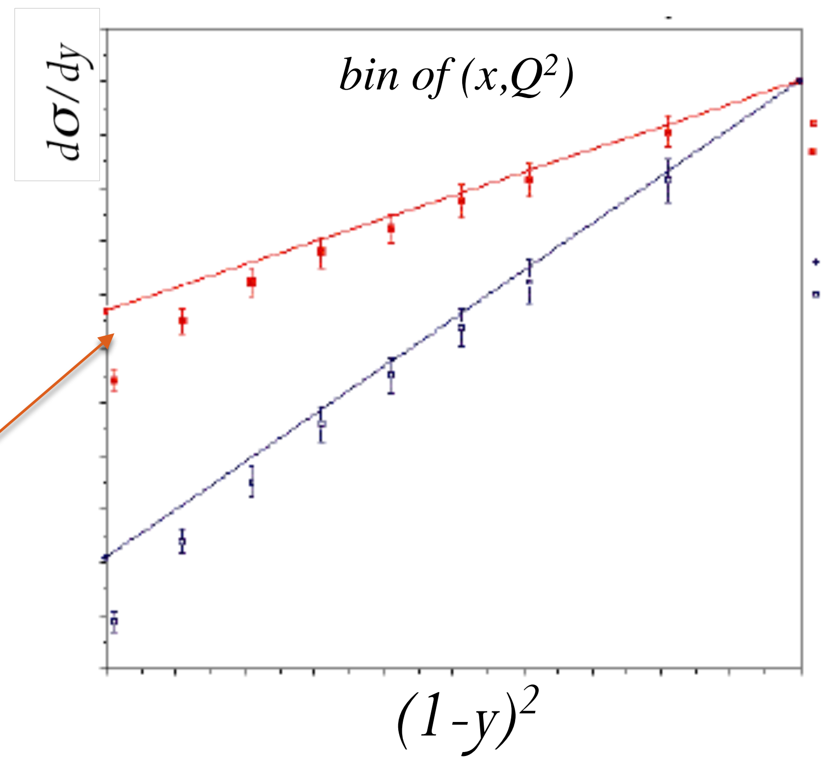
antineutrino

$$\frac{d^2\sigma^{\bar{\nu} A}}{dxdy} \propto \left[F_2^{\bar{\nu} A}(x,Q^2) - xF_3^{\bar{\nu} A}(x,Q^2)\right] + (1-y)^2\left[F_2^{\bar{\nu} A}(x,Q^2) + xF_3^{\bar{\nu} A}(x,Q^2)\right] + f(R)$$

Equations of lines!

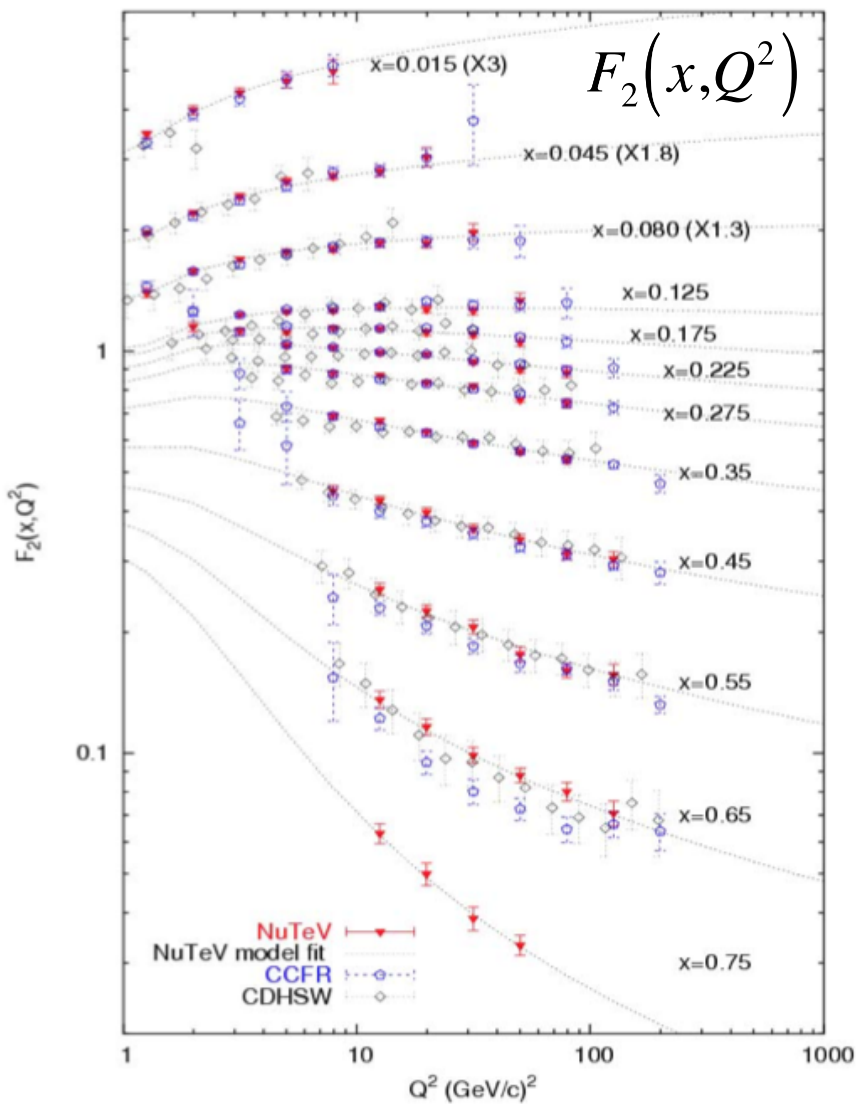
$$y \propto b + mx$$

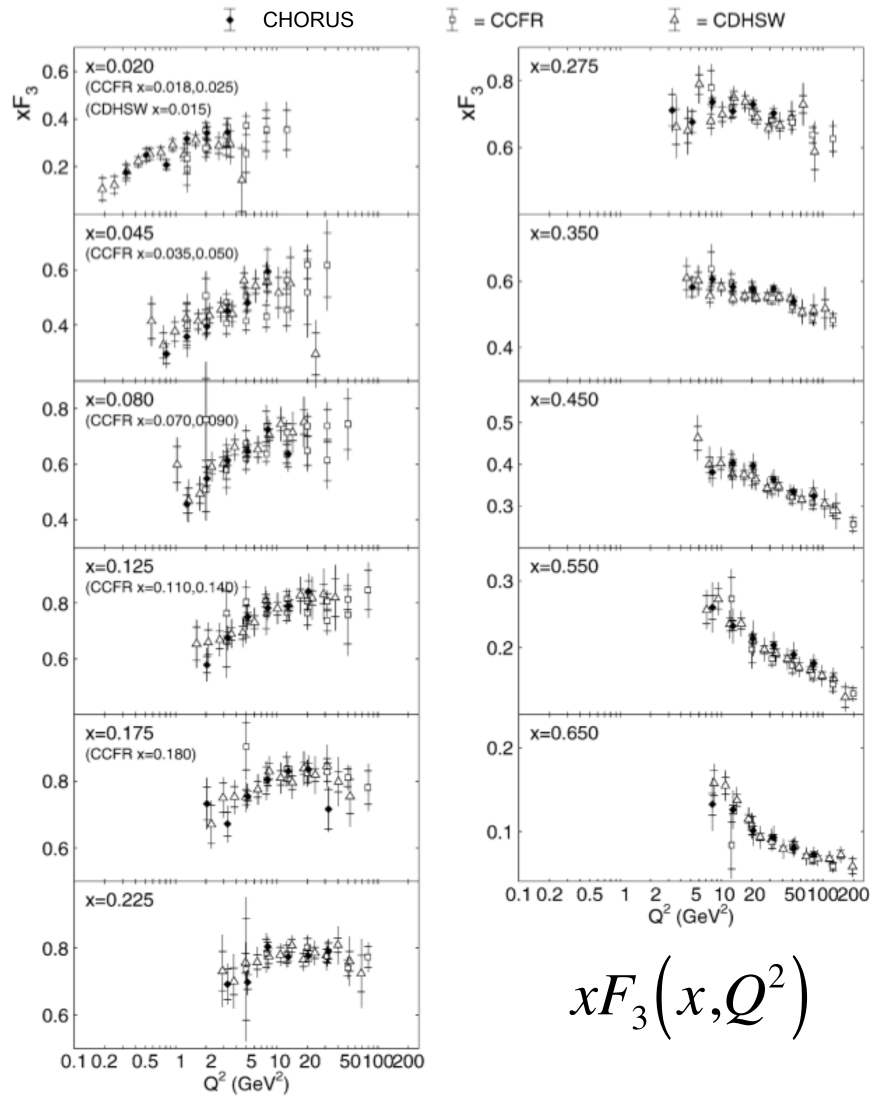
Fit for parameters F_2, xF_3 in bins of (x,Q^2)



R related to excursions from a straight line shape

Nucleon Structure Functions





Relating SFs to PDFs

- Using leading order expressions can relate the structure functions (SFs) to the parton distribution functions (PDFs)

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

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

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

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

- Assuming c = $\bar{\text{c}}$ and s = $\bar{\text{s}}$

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

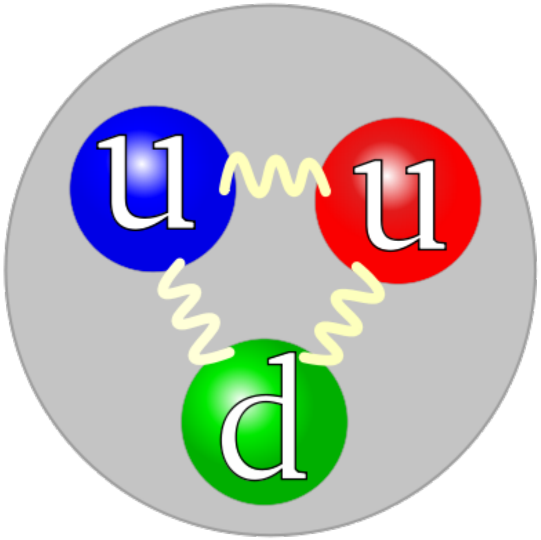
$$F_2^{\bar{\nu}} - xF_3^{\bar{\nu}} = 2\left(\bar{u} + \bar{d} + 2\bar{s}\right) = 2U + 4\bar{s}$$

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

Parton Distribution Functions $q(x)$

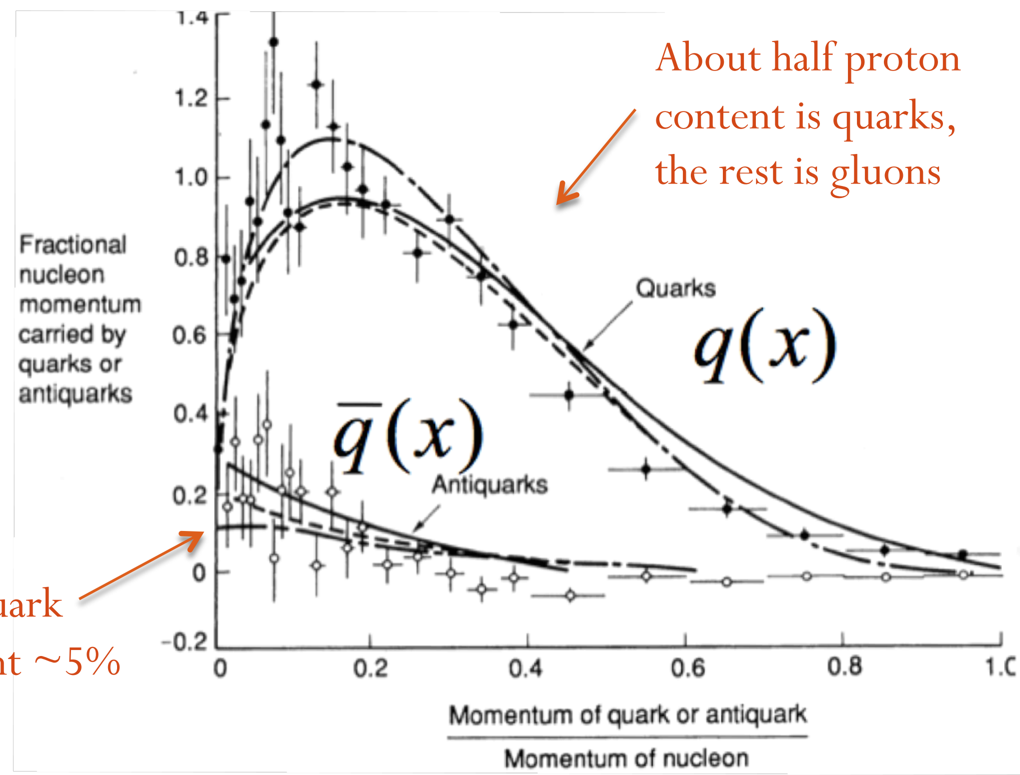
$$\frac{d\sigma}{dxdy}(\nu + proton) = \frac{G_F^2 xs}{2\pi}\left[Q(x) + (1-y)^2 \overline{Q}(x)\right]$$

$$\frac{d\sigma}{dxdy}(\overline{\nu} + proton) = \frac{G_F^2 xs}{2\pi}\left[\overline{Q}(x) + (1-y)^2 Q(x)\right]$$



If there were only the valence quarks ($\overline{Q}$=0)

$$\frac{\sigma(\overline{\nu})}{\sigma(\nu)} = \frac{\int_0^1 dy(1-y)^2}{\int_0^1 dy} = \frac{1}{3}$$

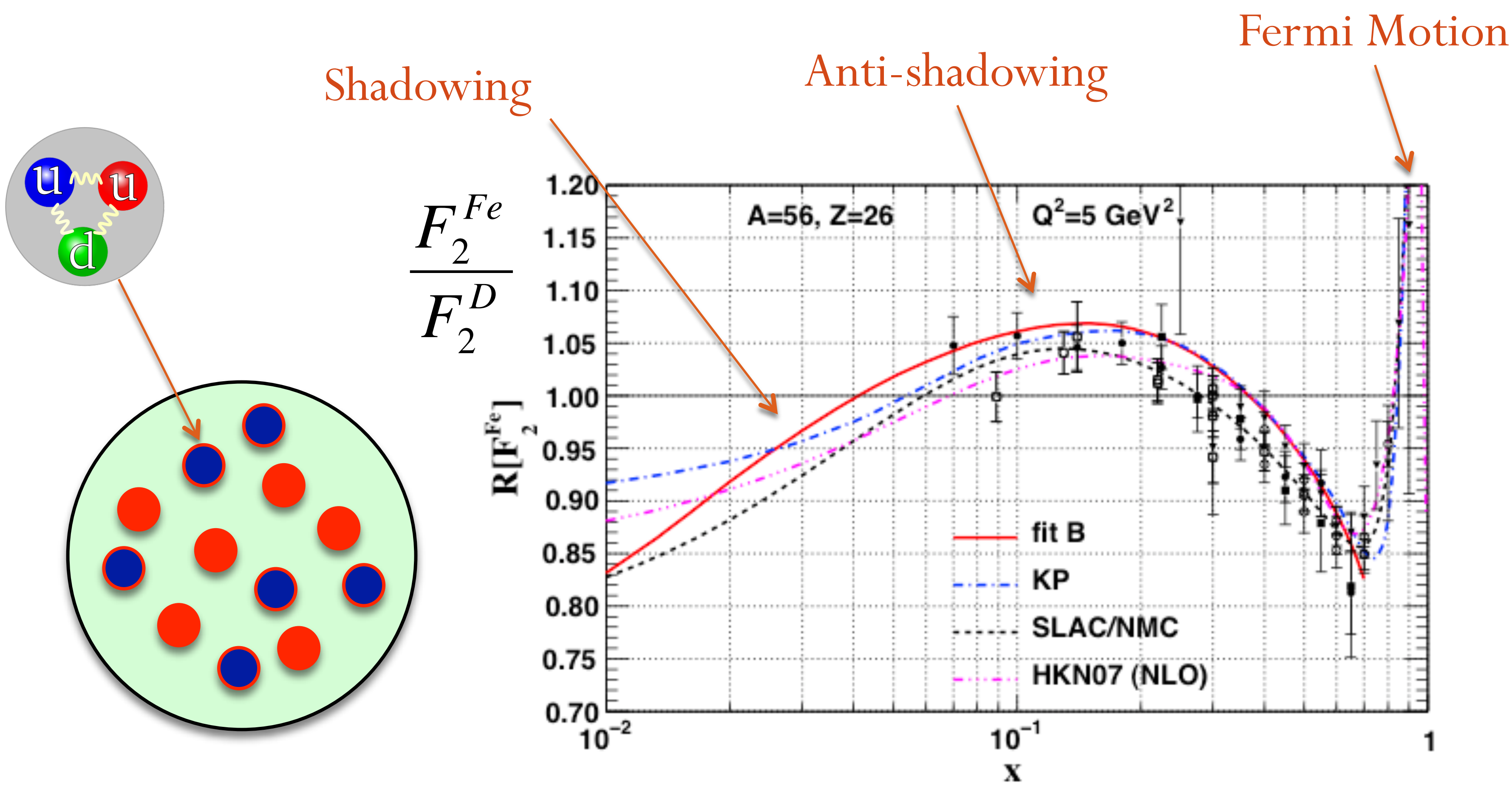


About half proton content is quarks, the rest is gluons

Antiquark content ~5%

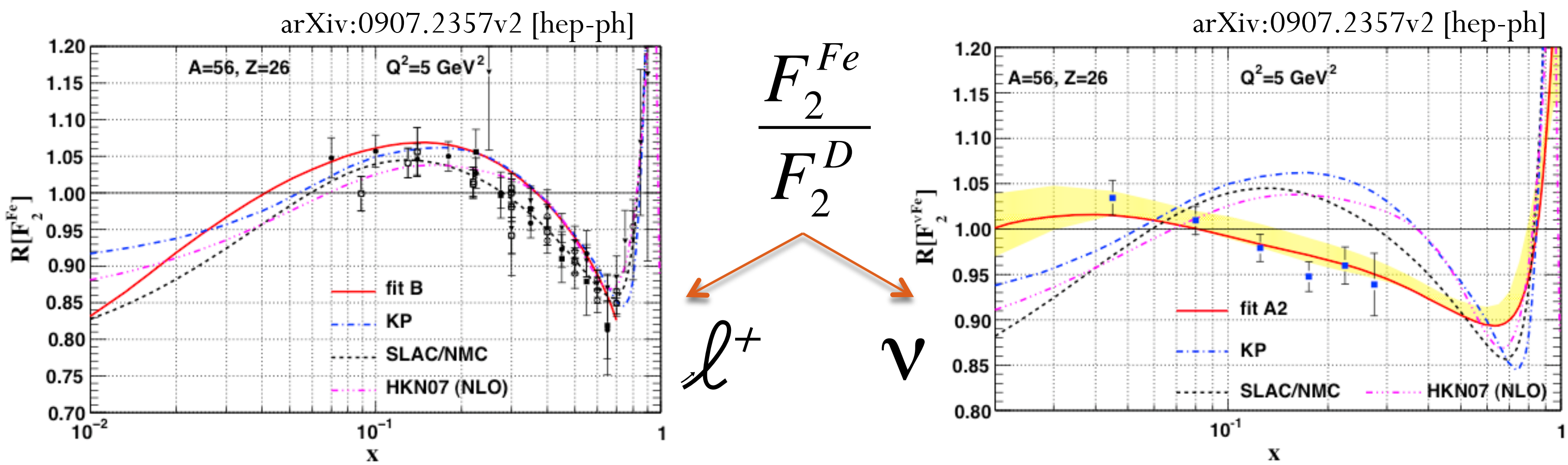
Probing Nuclear Effects with Neutrinos

- Effects of the nuclear medium accessed by comparing structure functions measured on high and low A targets



Probing Nuclear Effects with Neutrinos

- Most neutrino scattering data data off targets of large A (Ca,Fe)
- Recent studies indicate that nuclear corrections in ℓ^+-A (charged lepton) and ν-A (neutrino) scattering <u>may not be the same</u>



- Need data across a range of A to extract nuclear effects (MINERνA)

Summary I

- Neutrinos provide an important weak force probe of matter
  - Neutrinos and antineutrinos “taste” different quark flavor content
    - neutrinos only interact with : $d, s, \bar{u}, \bar{c}$
    - antineutrinos only interact with : $u, c, \bar{d}, \bar{s}$
  - Angular distributions of neutrino/antineutrino DIS interactions affected by left-handedness of weak interaction
    - $\sigma(\bar{\nu}q) = \sigma(\nu q)(1-y)^2$
- Neutrinos and the weak interaction are critical players in many processes in the universe
- But what do we know about the neutrino itself….?

What's Our Plan?

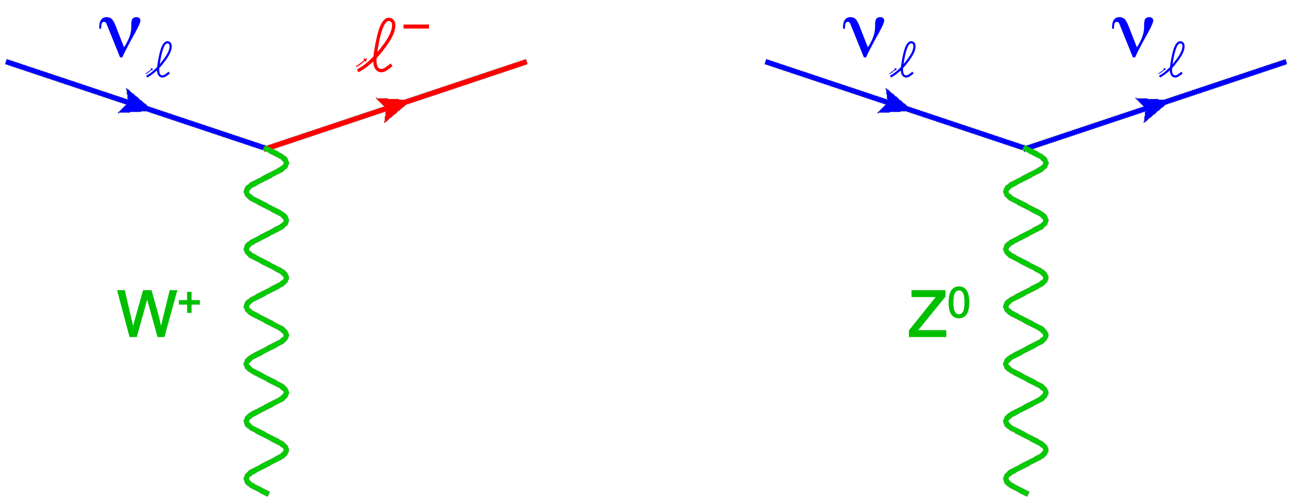
- Lecture I
  - Birth of Neutrino Physics
  - Some Basics of the Weak Interaction
  - Neutrinos as a Probe of Matter
- Lecture II
  - Early Experimental History – Big Challenges and Bigger Surprises
  - Neutrino Oscillations, Masses and Mixing
  - Open Questions in the Neutrino Sector

General Goal: To provide you an introduction to the basic vocabulary and concepts needed to understand current efforts and future results in neutrino physics

Two Types of Weak Interactions

$W^{\pm}$ exchange constitutes a "charged-current" interaction

Z^0 exchange constitutes a "neutral-current" interaction

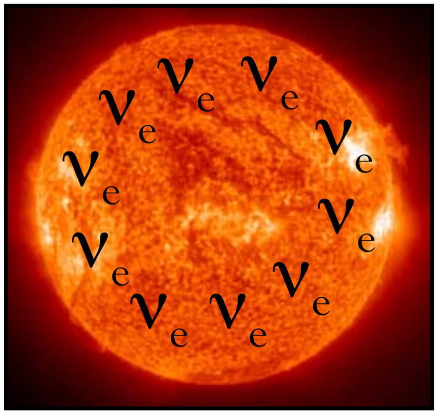


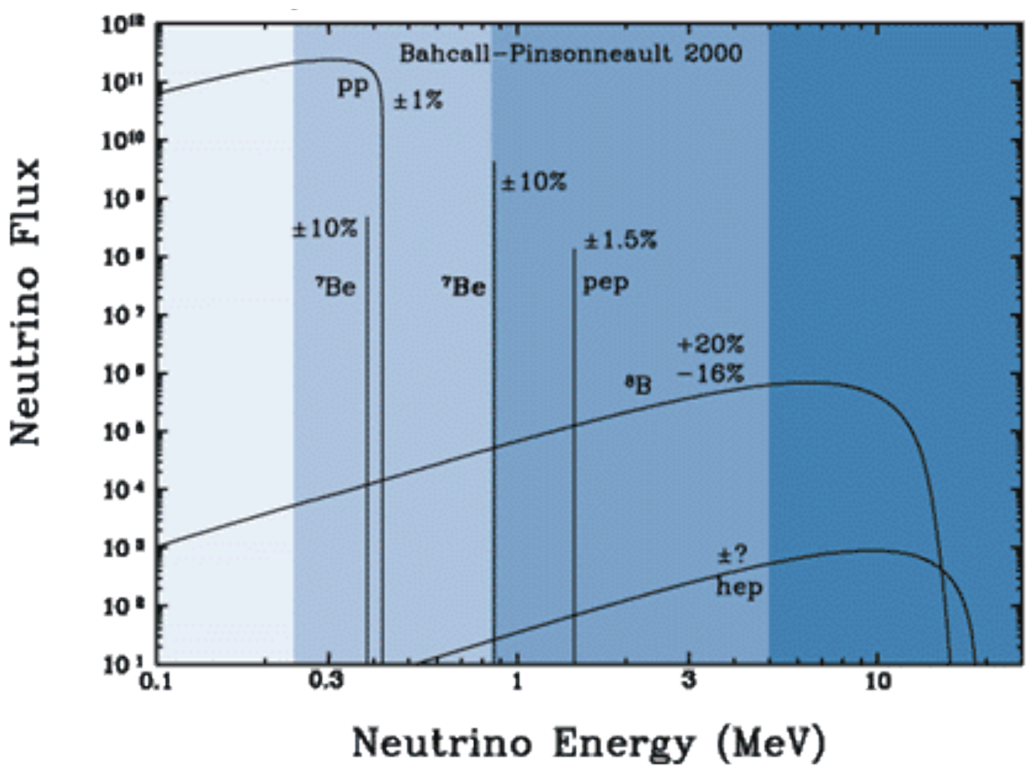
Charged-Current (CC)   Neutral-Current (NC)

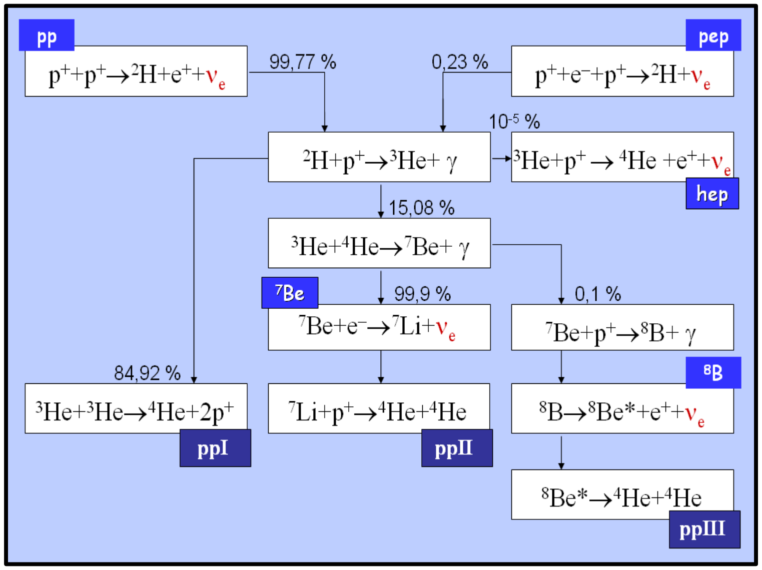
Can detect neutrinos through their CC and NC interactions

Let's Give it a Try: ν_e from the Sun

- Nuclear reactions in the sun produce electron neutrinos <u>ONLY</u>
- If can detect them, can test the model of the sun
  - Look deep into the sun using neutrinos!







Let's Give it a Try: ν_e from the Sun

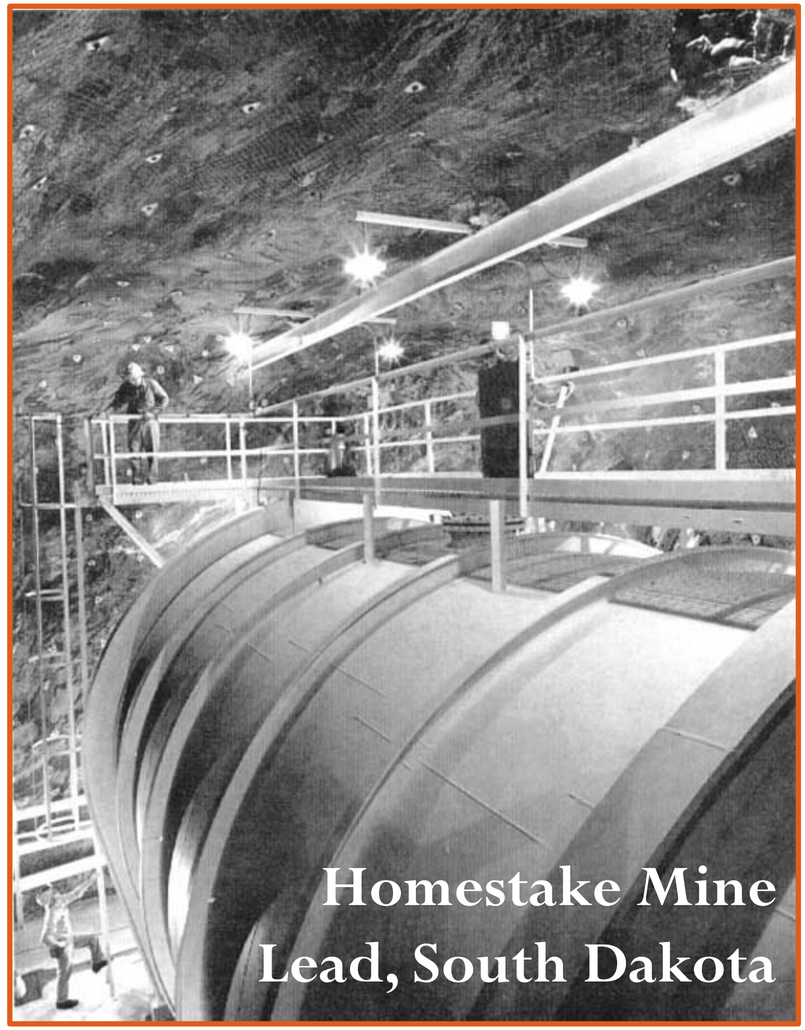
- Ray Davis set out to detect ν_e from the sun using a tank of cleaning fluid buried deep underground

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

- Every once in a while Davis would extract and count the number of argon atoms in the tank

- John Bahcall had calculated how many to expect:

$$\sim 36\ Ar\ atoms/month$$



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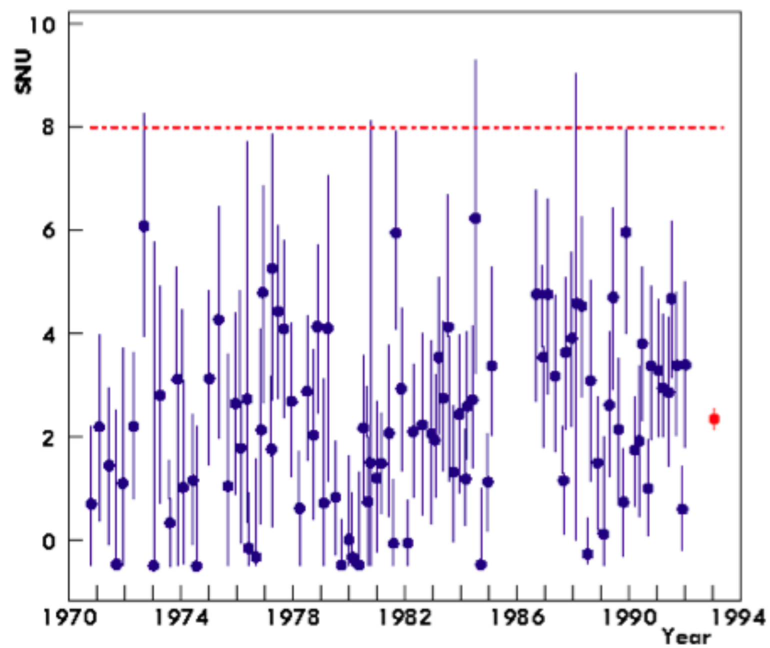


$$\frac{\phi_{\nu_e}(Homestake)}{\phi_{\nu_e}(Theory)} = 0.34 \pm 0.06$$

Let's Give it a Try: ν_e from the Sun

What could possibly explain this?

The theory was wrong

The experiment was wrong

They were both wrong

Let's Give it a Try: ν_e from the Sun

What could possibly explain this?

The theory was wrong

The experiment was wrong

They were both wrong

But what if neither was wrong?

Would imply ~2/3 of the solar ν_e flux "disappears" on the way to earth!

A Definitive Solar Neutrino Result

- Major drawback of Davis' experiment was could only see electron neutrino interactions. The Sudbury Neutrino Observatory (SNO) could see interactions involving all three flavors (ν_e, ν_μ, ν_τ)

$$\nu_e + d \rightarrow p + p + e^- \quad (CC)$$

CC interactions sample $\phi_{\nu e}$ only

$$\nu_x + d \rightarrow p + n + \nu_x \quad (NC)$$

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad (ES)$$

NC interactions sample total $\phi_{\nu e} + \phi_{\nu\mu} + \phi_{\nu\tau}$

$$\frac{\phi_{\nu_e}}{\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}} = 0.340 \pm 0.023(stat) \pm 0.030(syst)$$

ν_e fraction agrees with Davis!

SNO: $\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} = (4.94 \pm 0.21 \pm 0.36) \times 10^6 cm^{-2} s^{-1}$

Theory: $\phi_{total} = (5.69 \pm 0.91) \times 10^6 cm^{-2} s^{-1}$

Total flux agrees with Bahcall!

Try Again: ν_μ / ν_e from Atmosphere

- Neutrinos created by decay of pions in particle showers initiated when energetic cosmic rays interact in the atmosphere

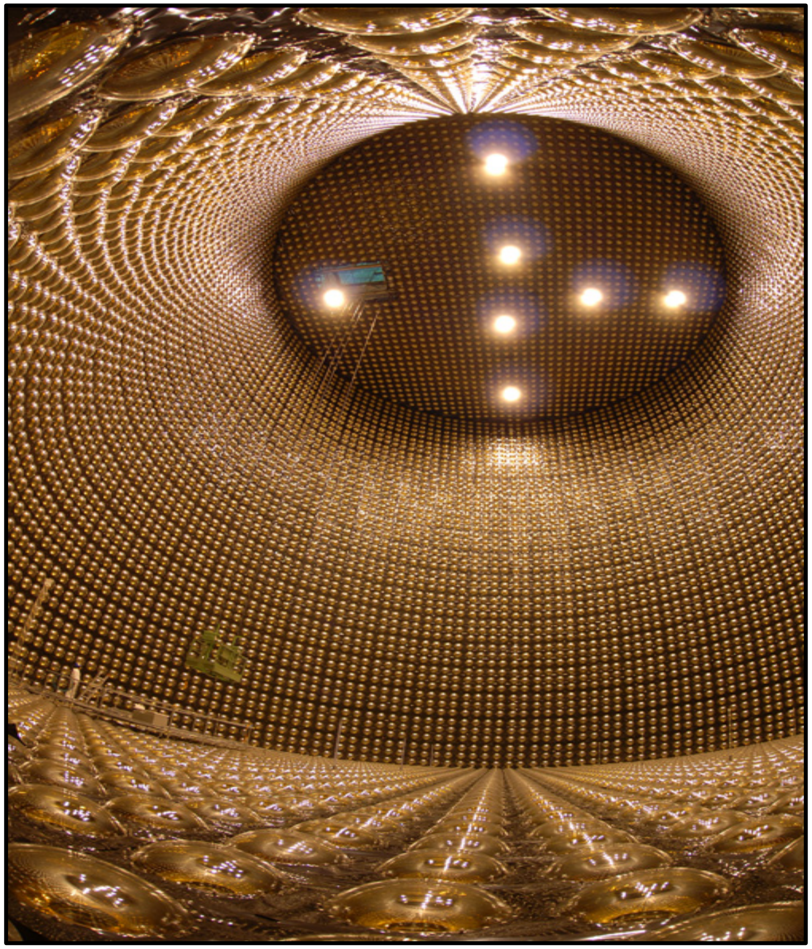
$$\text{Expect: } \frac{\phi_{\nu_\mu}}{\phi_{\nu_e}} \approx 2$$

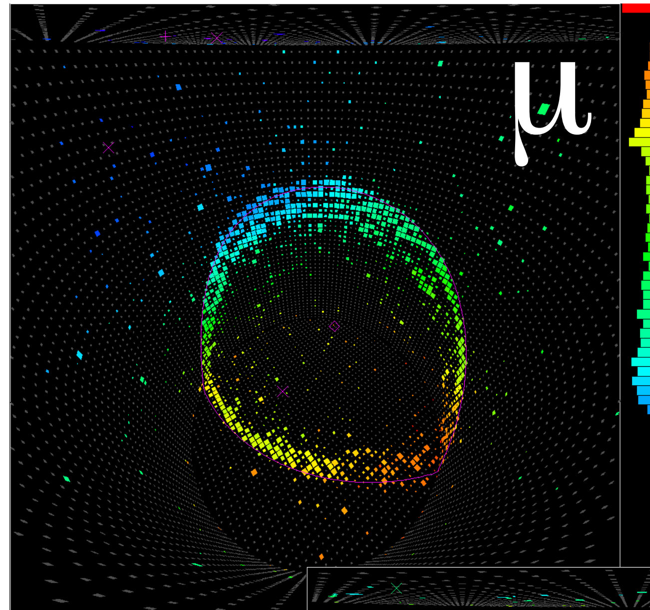
INFN-Notizie N.1 giugno 1999

Try Again: ν_μ / ν_e from Atmosphere

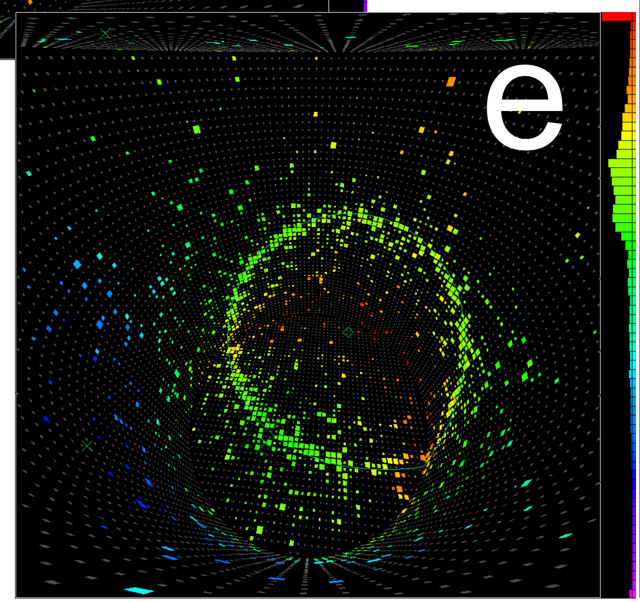
Super-Kamiokande

50kT water Cherenkov detector



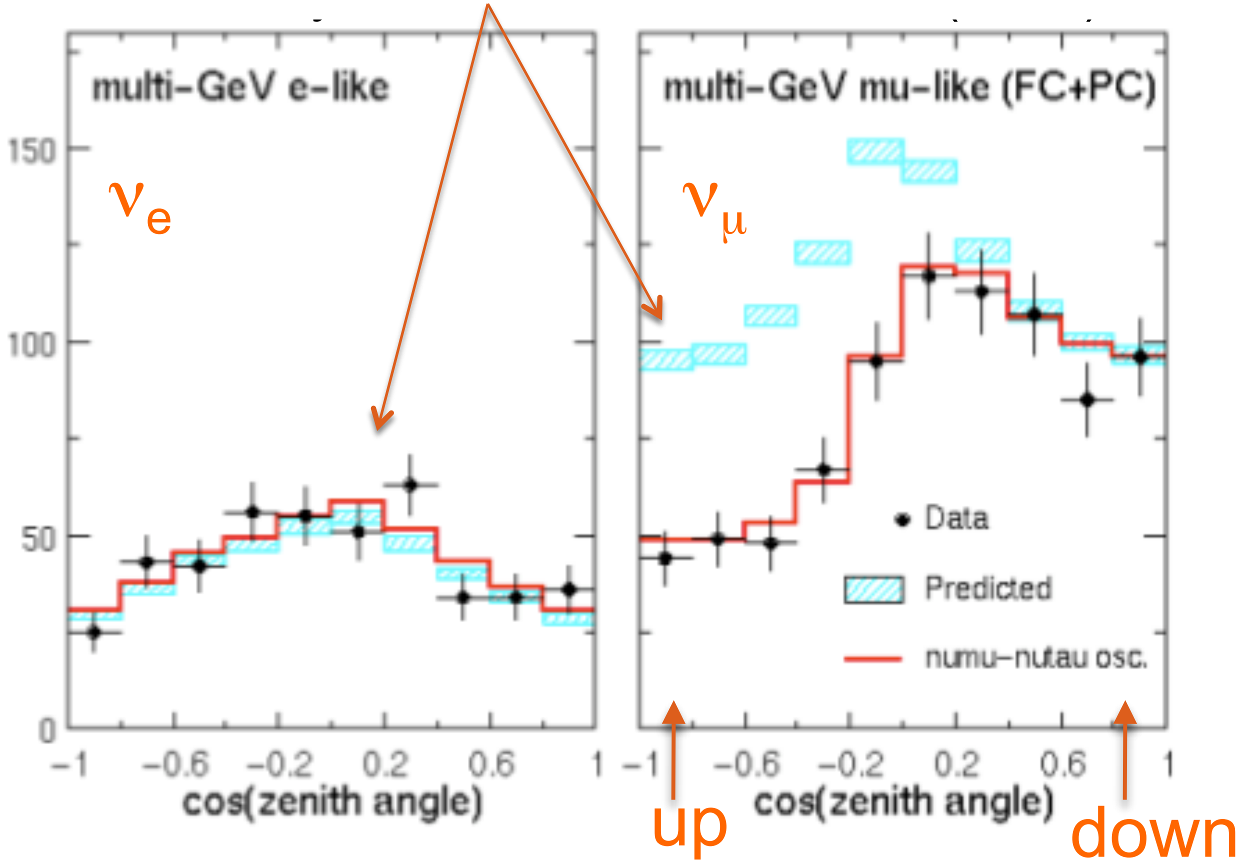


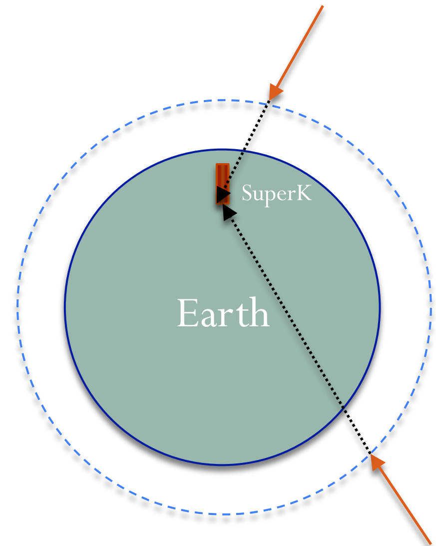
Originally built to search for proton decay. Still waiting for one of those, but won a Nobel Prize for study of atmospheric neutrinos in the mean time.



Try Again: ν_μ / ν_e from Atmosphere

Expect: $\dfrac{\phi_{\nu_\mu}}{\phi_{\nu_e}} \approx 2$





Expect:

$$\frac{\phi_{\nu_\mu}(Up)}{\phi_{\nu_\mu}(Down)} \approx 1$$

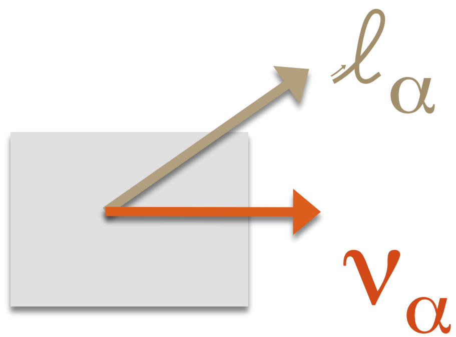
Another "Desperate Remedy"

Where are the disappearing neutrinos disappearing to? Another dilema that persisted for more than <u>two decades!</u>

- It was realized that if neutrinos indeed have small non-zero masses, then quantum mechanics allows that they could be disappearing into other kinds of neutrinos…
  - ν_e from the sun ➔ ν_μ / ν_τ
  - ν_μ from atmosphere ➔ ν_τ

and tiny masses can have HUGE effects

What is Neutrino Flavor?



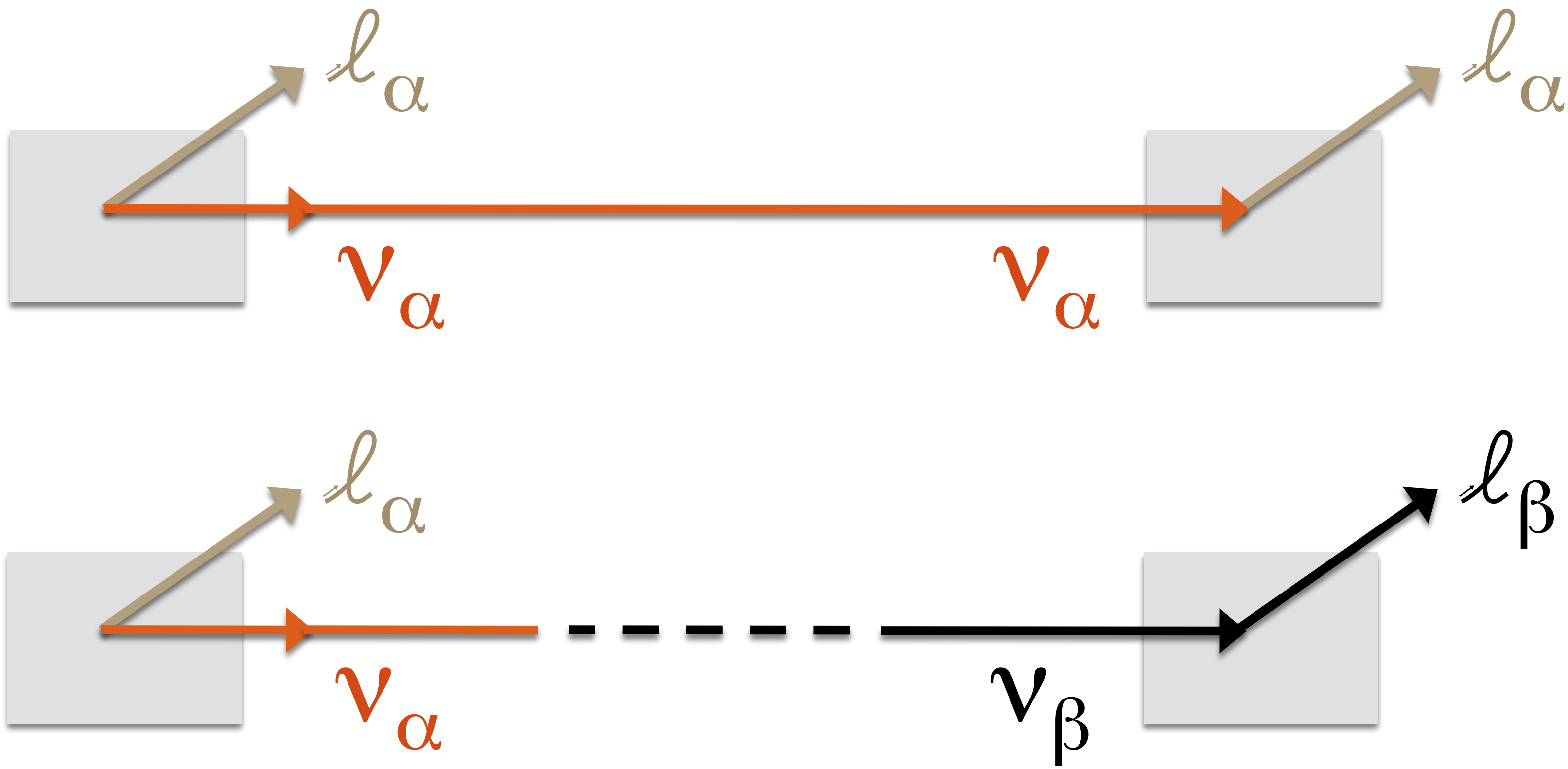
The neutrino of flavor α is the one created in W boson decay together with the charged lepton of flavor α

What is Neutrino Flavor?

The neutrino of flavor α is the one created in W boson decay together with the charged lepton of flavor α

And which creates a charged lepton of flavor α when it undergoes a charged-current interaction

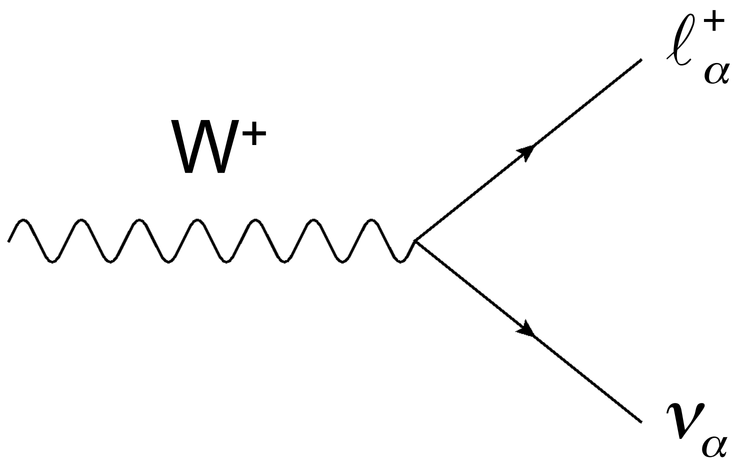
What is Neutrino Flavor Change?



Which could be possible if
neutrinos have mass and leptons mix

Flavor ⟷ Mass

- We know the initial weak flavor, $\nu_\alpha = (\nu_e, \nu_\mu, \nu_\tau, \ldots)$ through identification of the charged lepton partner $\ell_\alpha = (e, \mu, \tau, \ldots)$ when the neutrino is created
- But suppose that weak flavor eigenstate is actually a superposition of pure mass eigenstates



Mixing matrix describing mass state content of flavor states

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$$

Neutrinos of definite flavor

Neutrinos of definite mass

Flavor ⟷ Mass

Leptonic Mixing Matrix

flavor states participating in standard weak interactions

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

neutrino mass states

Flavor ⟷ Mass

Leptonic Mixing Matrix

flavor states participating in standard weak interactions

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

neutrino mass states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

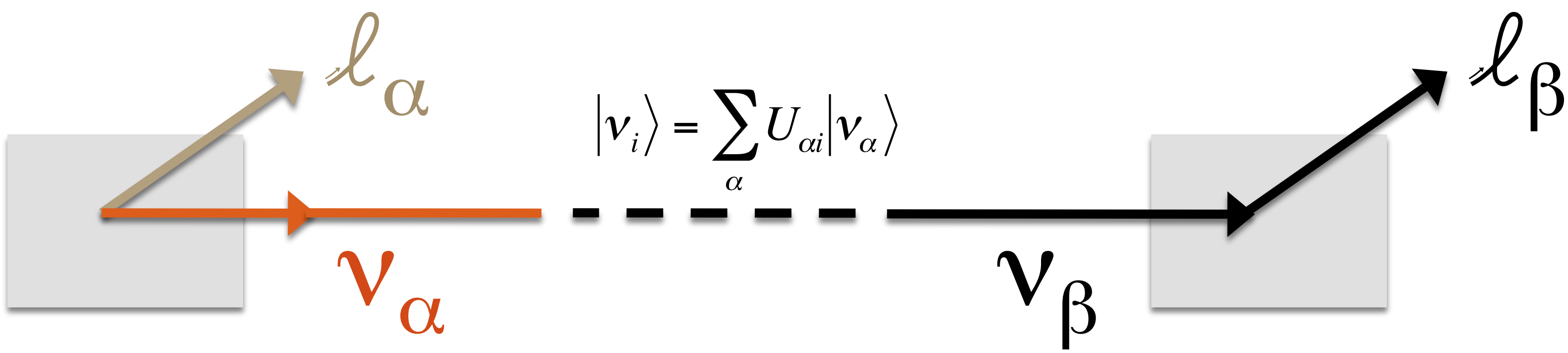
mass eigenstates == flavor eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 0.58 & 0.58 & 0.58 \\ 0.58 & 0.58 & 0.58 \\ 0.58 & 0.58 & 0.58 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor eigenstates = equal mix of mass states

Flavor ⟷ Mass

- And a <u>neutrino's propagation through space</u> (from production to detection) is dictated by the free Hamiltonian whose eigenstates are the states of <u>definite mass</u>, $\nu_i = (\nu_1, \nu_2, \nu_3, \ldots)$, not flavor, and whose time evolution is described by the Schrodinger equation:



$$i \frac{\partial}{\partial t} |\nu_i(t)\rangle = E_i |\nu_i(t)\rangle \approx \left(E_i + \frac{m_i^2}{2E_i} \right) |\nu_i(t)\rangle$$

The Oscillation Formula

- The trivial solution to this Schrodinger equation tells us how the ν_i propagate in time:

$$\left|\nu_i(t)\right\rangle = e^{-i\left(E_i + m_i^2/2E_i\right)t}\left|\nu_i(0)\right\rangle$$

  - The mass eigenstates which contribute coherently to an experimental beam are those with a common energy, E
  - Since neutrino is ultra-relativistic, L ≈ t (for c = 1)

$$\left|\nu_\alpha\right\rangle \rightarrow \left|\nu(L)\right\rangle = \sum_i U_{\alpha i}^* e^{-i\left(m_i^2/2E\right)L}$$

at production point

after traveling a distance L

The Oscillation Formula

- The probability that a neutrino created as weak eigenstate α being detected as weak eigenstate β after traveling a distance L is:

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu \ (L) \rangle|^2 = \left| \sum_i U^*_{\alpha i} e^{-i(m_i^2 L/2E)} U_{\beta i} \right|^2$$

The Oscillation Formula

- The probability that a neutrino created as weak eigenstate α being detected as weak eigenstate β after traveling a distance L is:

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu \;\; (L)\rangle|^2 = \left| \sum_i U^*_{\alpha i} e^{-i(m_i^2 L/2E)} U_{\beta i} \right|^2$$

$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re \left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \right) \sin^2 \left(\Delta m^2_{ij} \frac{L}{4E} \right)$$

$$+ 2 \sum_{i>j} \Im \left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \right) \sin \left(\Delta m^2_{ij} \frac{L}{2E} \right)$$

$$\Delta m^2_{ij} \equiv m^2_j - m^2_i$$

mass-squared difference of two mass eigenstates

The Oscillation Formula

1. The periodic nature of the oscillation probability formula ($\sin^2 \omega x$) has earned the phenomenon the name "neutrino oscillations".

2. If neutrinos do not have masses so that all $\Delta m^2 = 0$, then the probability reduces to $\delta_{\alpha\beta}$, and neutrinos cannot change flavor through oscillations. On the other hand, if neutrinos are found to oscillate, then one or more neutrino masses are necessarily non-zero and not identical.

3. If the mixing matrix is diagonal, such that eigenstates do not mix, then again the probability reduces to $\delta_{\alpha\beta}$, oscillations ➔ mixing

4. To determine the oscillation probability of antineutrinos, one must change the sign of the third term to (-). Because antineutrino transmutation is the CP mirror image of neutrino transmutation, evidence that $P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$ would be evidence of CP violation in the lepton sector.

The Mixing Matrix

Leptonic Mixing Matrix

flavor states participating in standard weak interactions

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

neutrino mass states

By analogy with CKM matrix for quark mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3 mixing angles and 1 CP violation phase $c_{ij} \equiv \cos\theta_{ij}$ $s_{ij} \equiv \sin\theta_{ij}$

Verifying the Oscillation Explanation

- Recall, we laid out the oscillation scenario with neutrino masses and mixings as an explanation for the solar and atmospheric neutrino puzzles:
  - What happened to all the ν_e from the sun?
  - What happened to the ν_μ created in the atmosphere which traveled through the earth?

If this is the correct explanation, then we should be able to construct a set of <u>laboratory experiments</u> to test it and make precision measurements

The Mixing Matrix

Leptonic Mixing Matrix

flavor states participating in standard weak interactions

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

neutrino mass states

Very instructive to factorize matrix that we wrote down before:

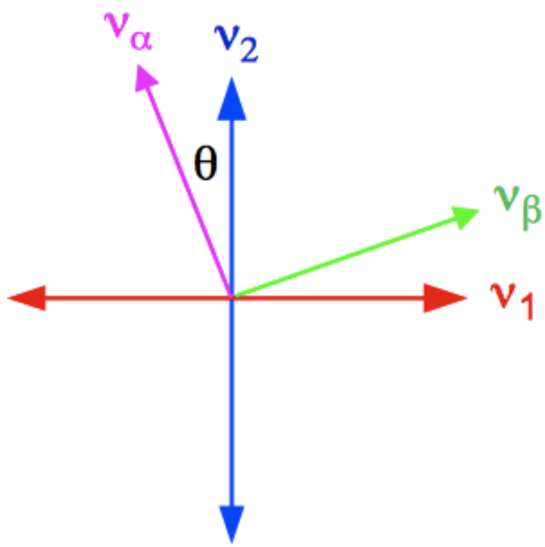
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

factor responsible for atmospheric neutrino anomaly ($\Delta m_{23}^2, \theta_{23}$)

Quasi 2-neutrino mixing

factor responsible for solar neutrino anomaly ($\Delta m_{12}^2, \theta_{12}$)

Two Neutrino Mixing



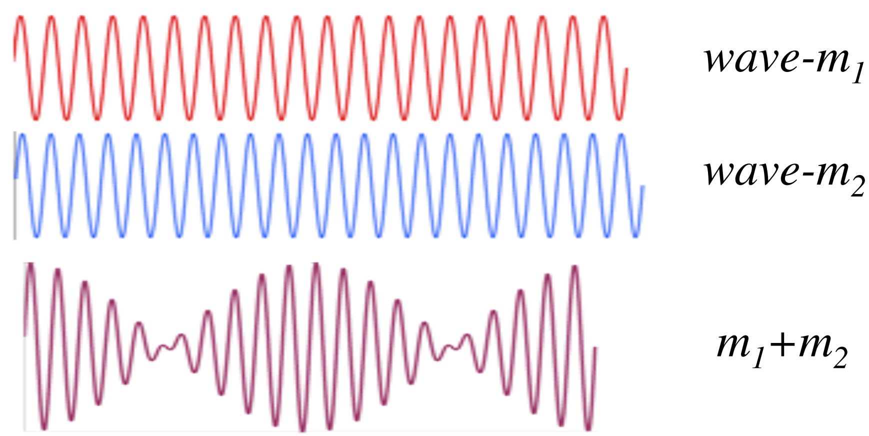
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\,\Delta m_{ij}^2 \frac{L}{E}\right)$$

The mixing angle, θ, determines the amplitude of the oscillation

Δm^2 determines the shape of the oscillation as a function of L (or E)

$$\Delta m_{ij}^2 \equiv m_j^2 - m_i^2$$

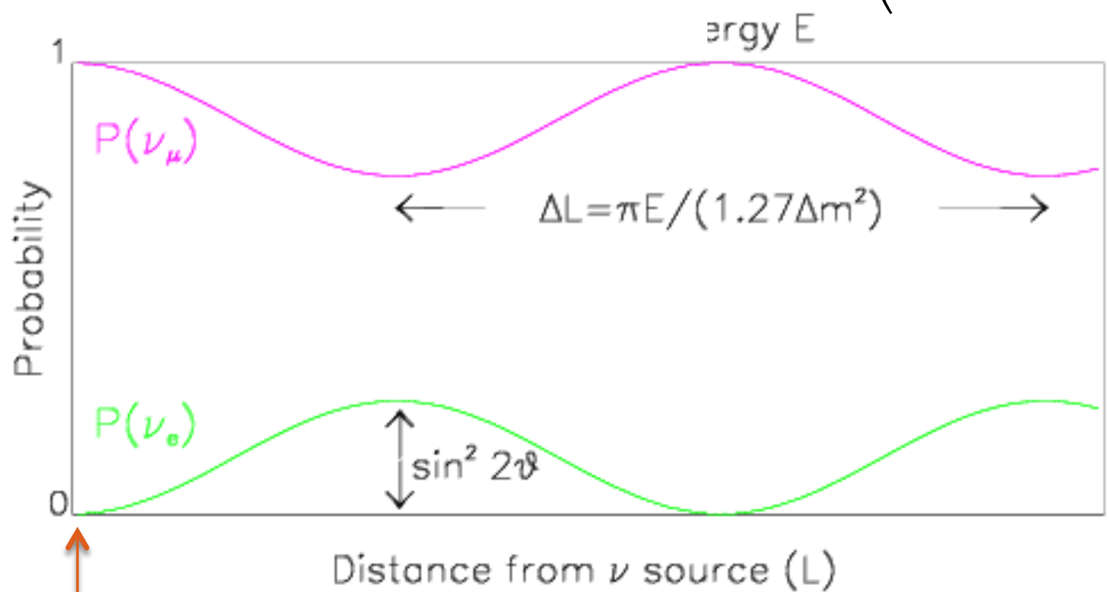
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta_{ij} & \sin\theta_{ij} \\ -\sin\theta_{ij} & \cos\theta_{ij} \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$



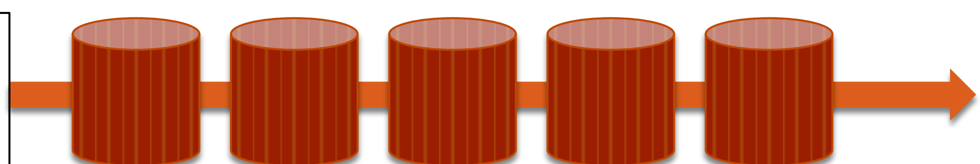
Two Neutrino Mixing

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\,\Delta m_{ij}^2 \frac{L}{E}\right)$$

Fixed E
Variable L



Begin with mono-energetic beam of ν_α



A bunch of detectors to measure ν_α / ν_β content along path

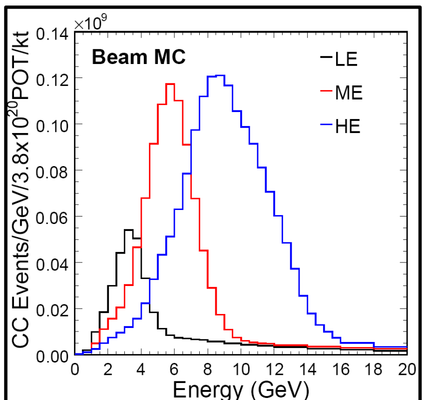
Wouldn't that be awesome!!
Alas…

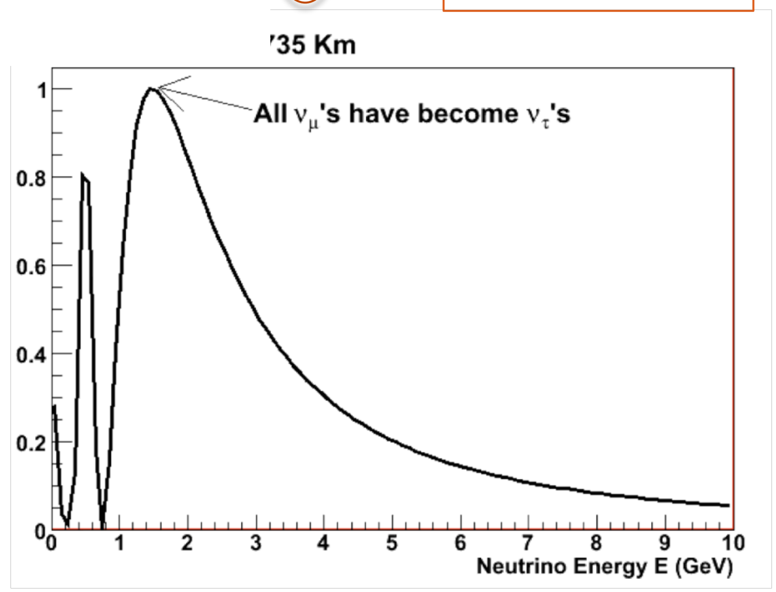
Two Neutrino Mixing

$$P\left(\nu_\alpha \to \nu_\beta\right) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\Delta m_{ij}^2 \frac{L}{E}\right)$$

Fixed L

Variable E

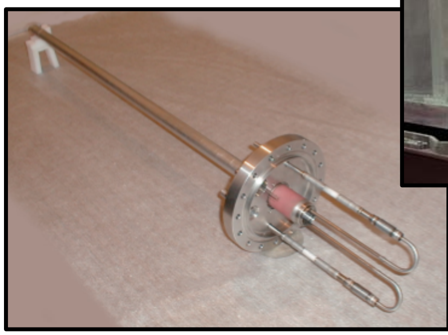


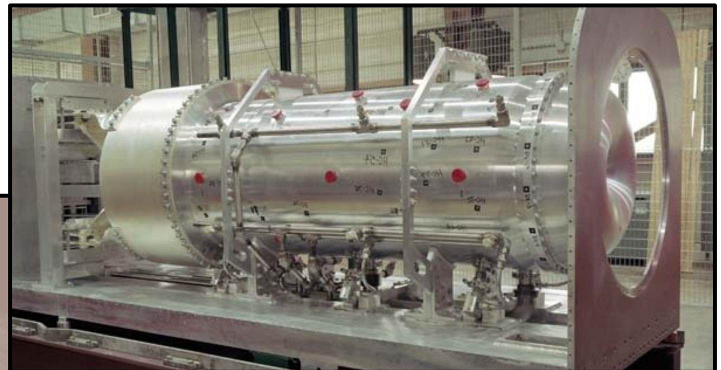


Begin with broad energy spectrum beam of ν_α

Measure ν_α / ν_β energy spectrum at origin and again after traveling distance L

Building a Neutrino Beam



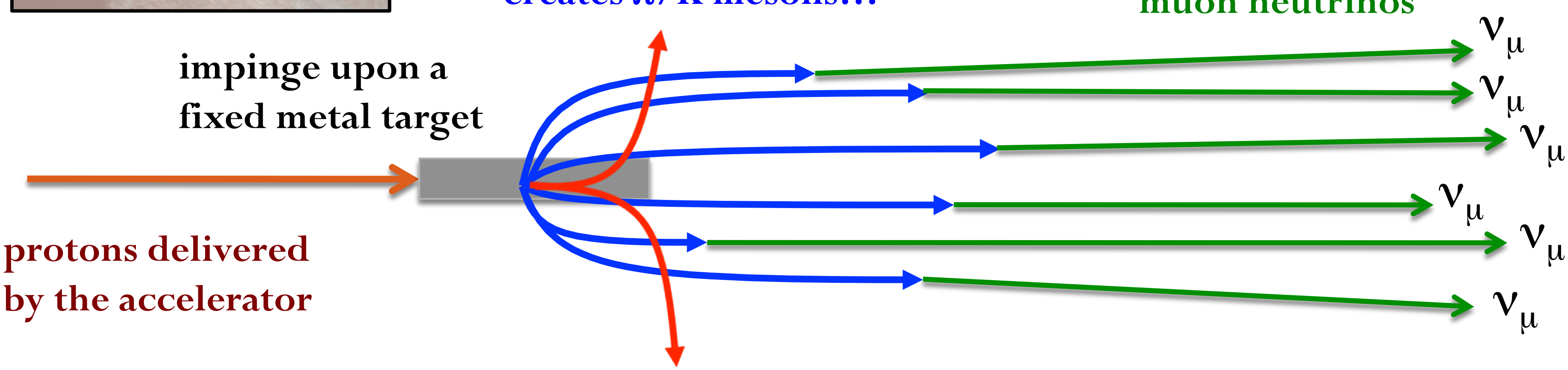


This is the basic concept first invented by Schwartz, Lederman and Steinberger when they discovered the ν_μ in 1962

pions decay into muon neutrinos

creates π/K mesons…

impinge upon a fixed metal target

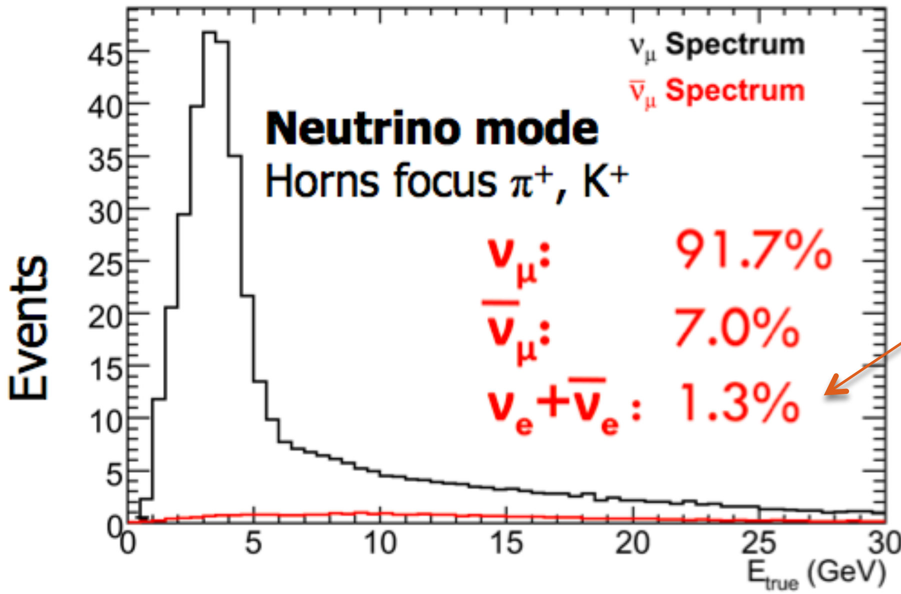


protons delivered by the accelerator

…which are focused (defocused) by a strong magnetic field created by a "focusing horn"

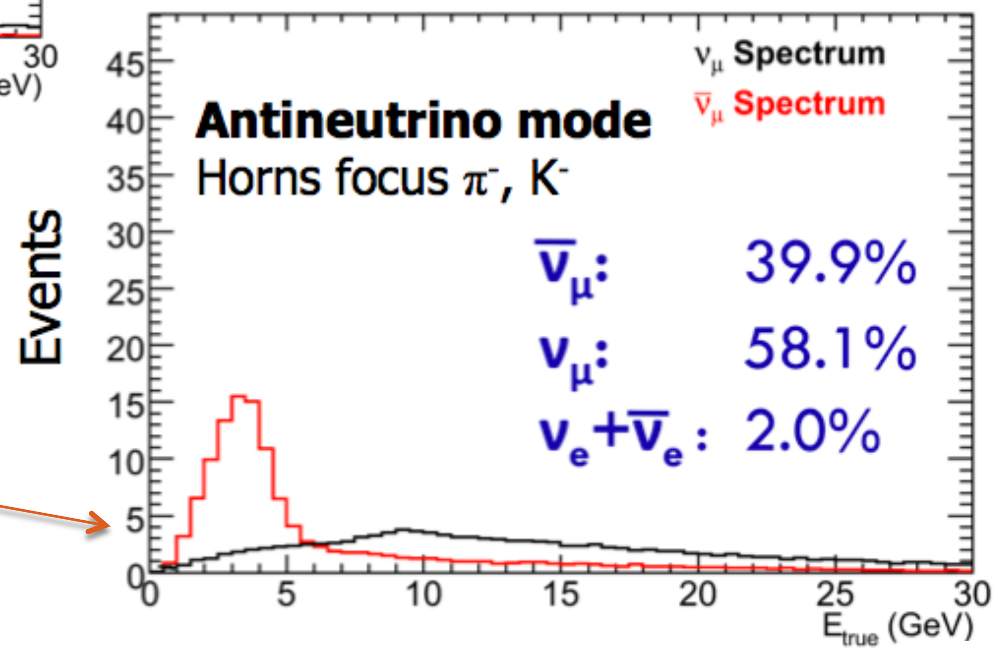
reversing current creates antineutrino beam

The NuMI Beamline at Fermilab



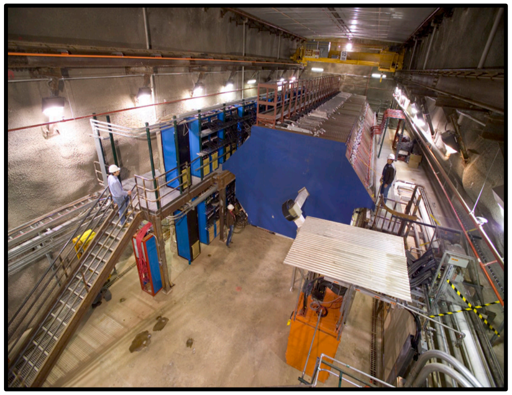
Beamline of the MINOS and MINERνA experiments

electron neutrinos from kaon and muon decays

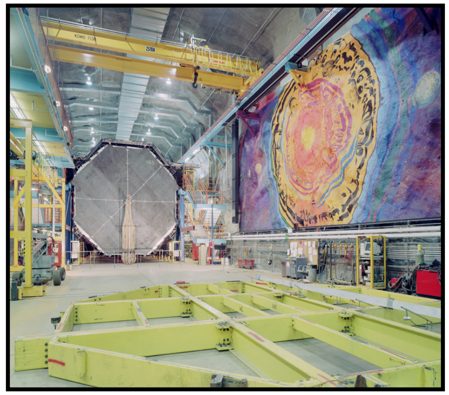


"wrong sign" contamination much worse in antineutrino mode due to differences in π^+/π^- spectra off target and neutrino/antineutrino cross sections

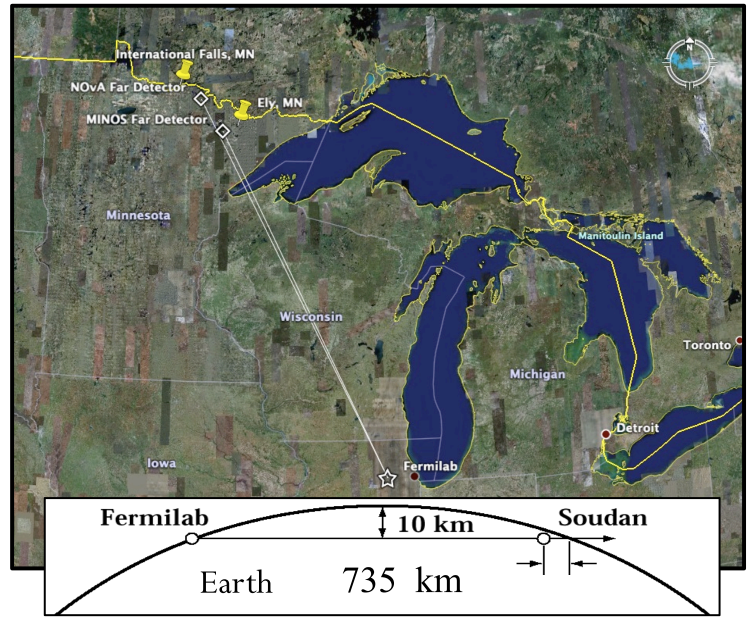
The MINOS Experiment

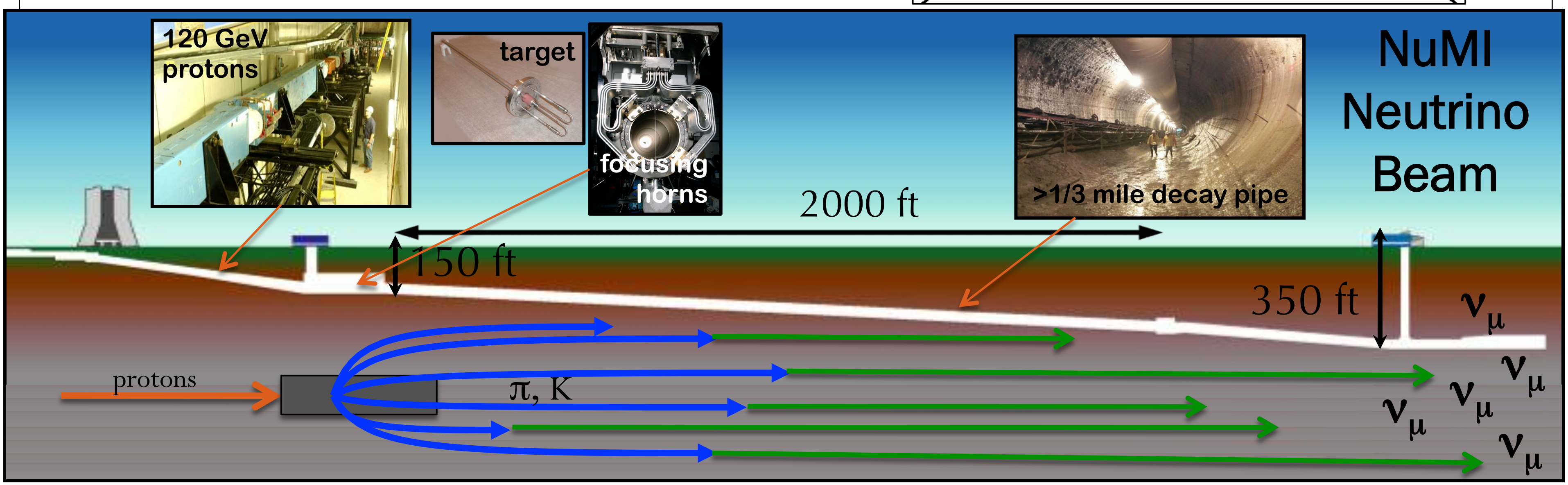


1k ton near detector
at Fermilab

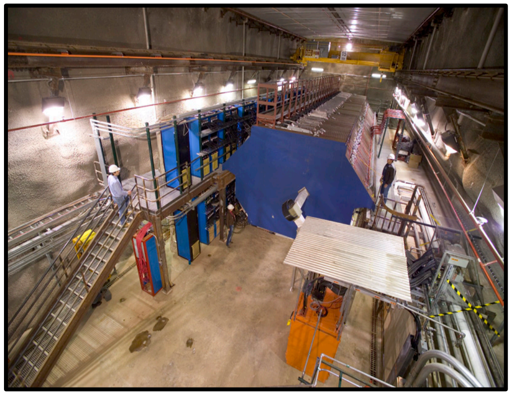


5 kton far detector
at Soudan, MN

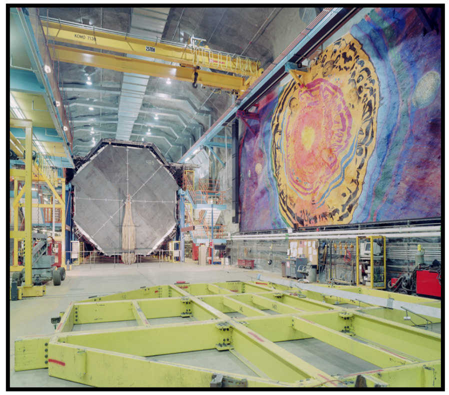




The MINOS Experiment



1k ton near detector
at Fermilab



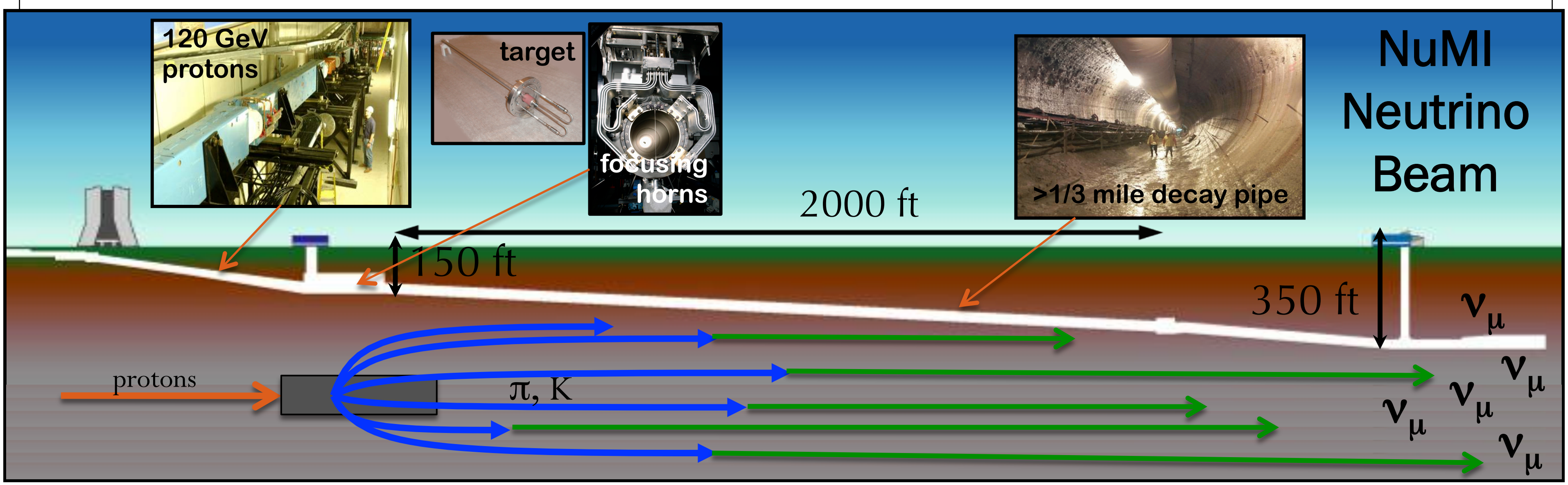
5 kton far detector
at Soudan, MN

$$\langle E \rangle_{MINOS} \approx 3\,GeV$$

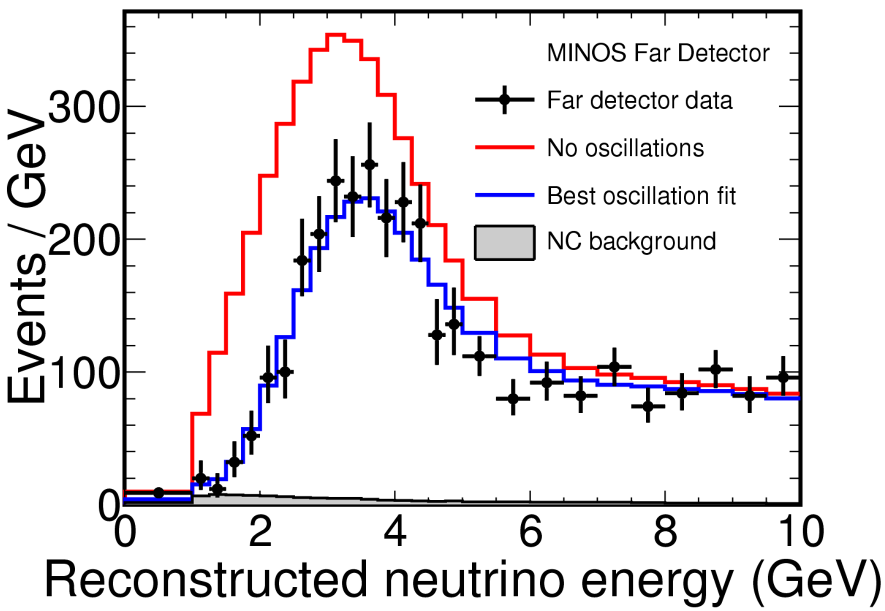
$$\langle L \rangle_{MINOS} \approx 735\,km$$

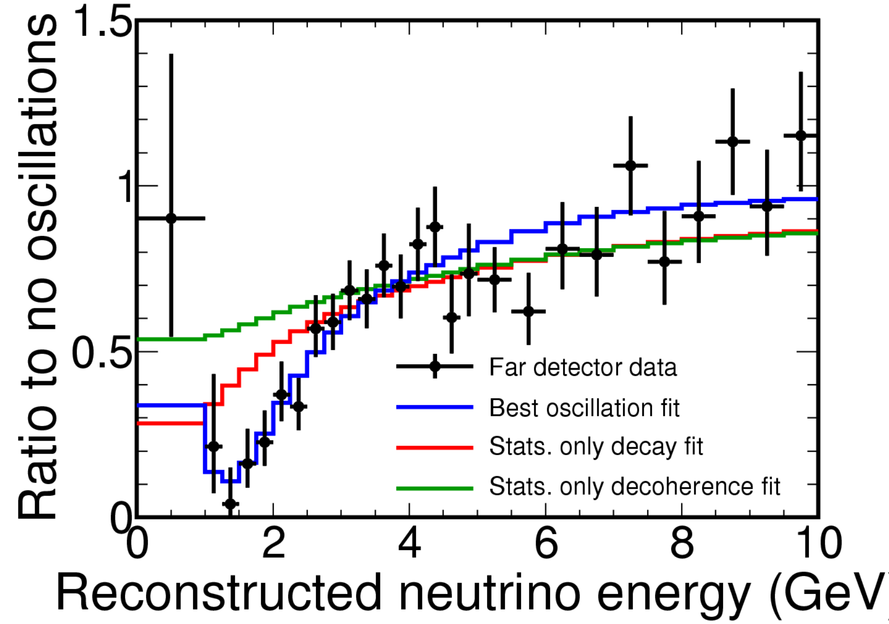
$$for\ \ \sin^2(x) \sim 1$$

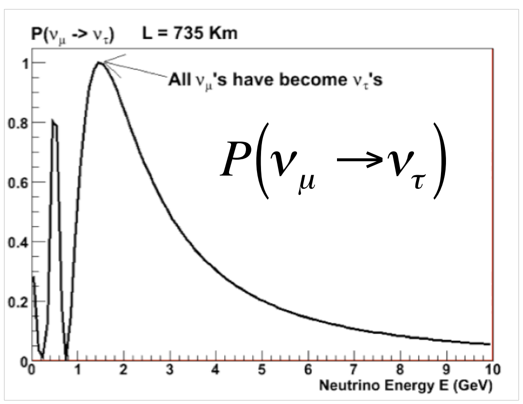
$$\Delta m^2 \geq 1 / \left(1.27 * \frac{735\,km}{3\,GeV}\right) \sim 10^{-3}\,eV^2$$



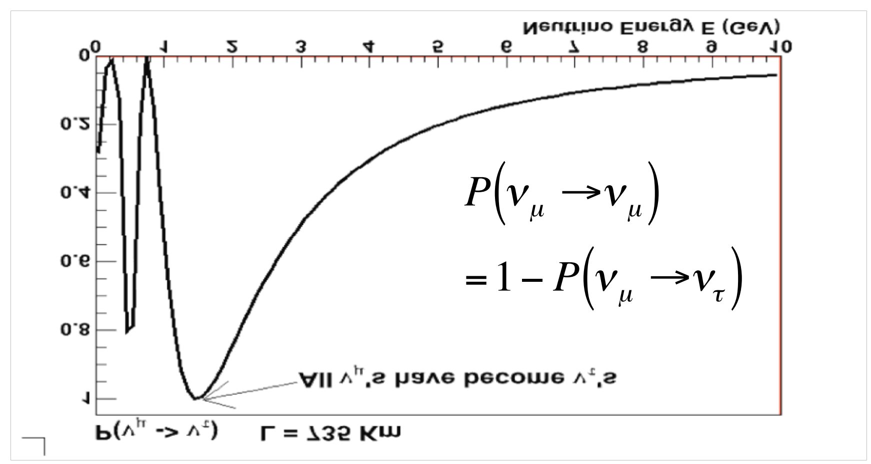
The MINOS Experiment



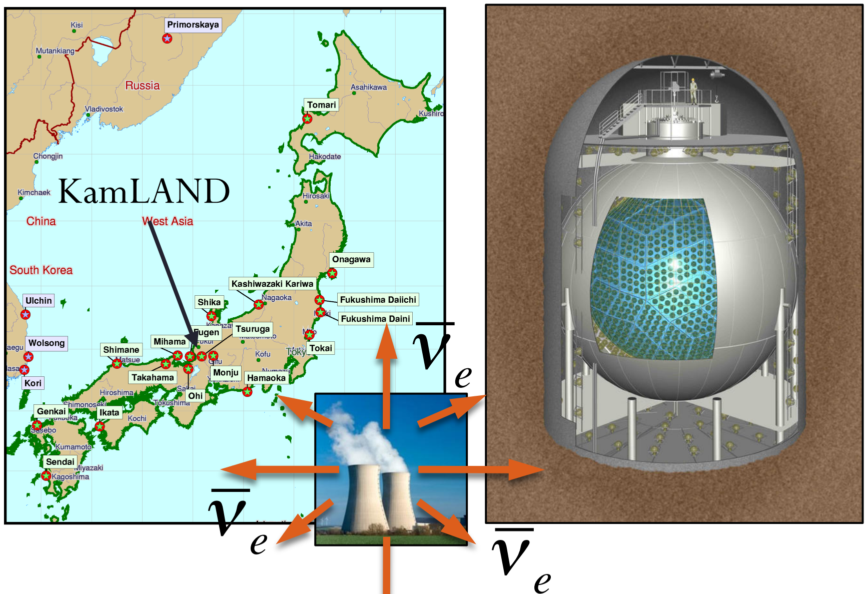




MINOS measures the <u>disappearance</u> of muon neutrinos



The KamLAND Experiment



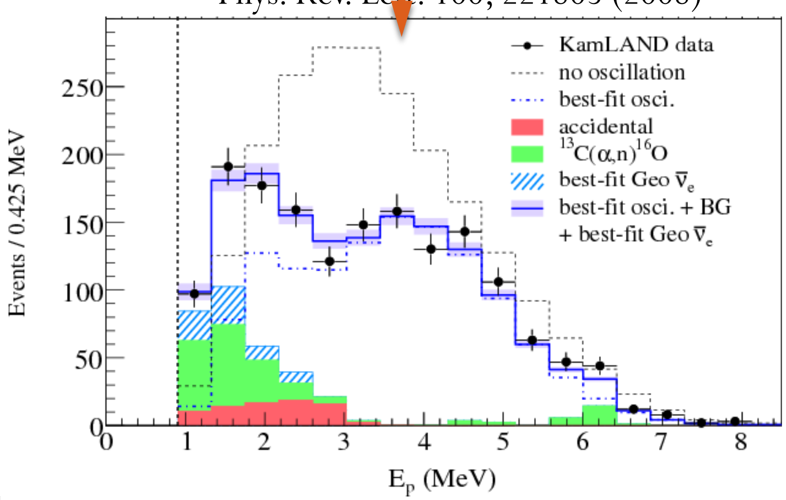
$$\langle E \rangle_{KamLAND} \approx 5\ MeV$$

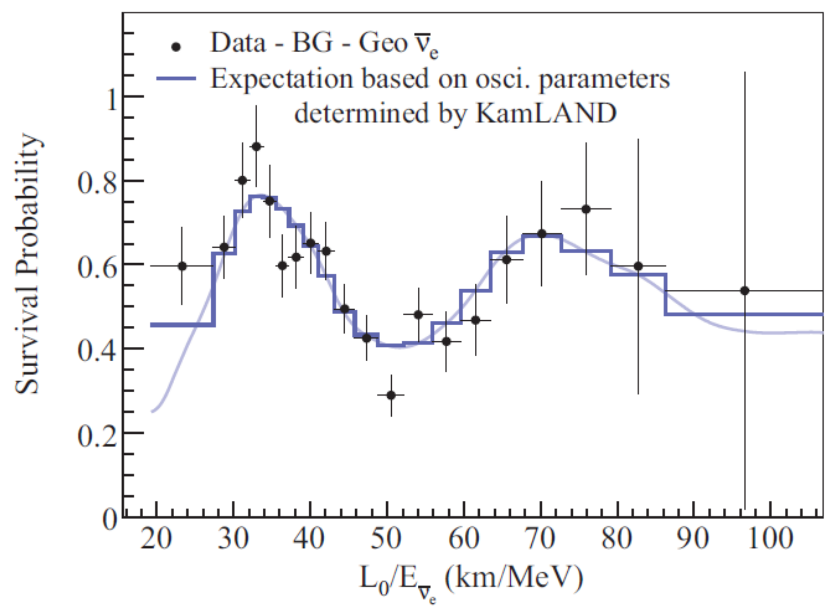
$$\langle L \rangle_{KamLAND} \approx 180\ km$$

$$for\ \ \sin^2(x) \sim 1$$

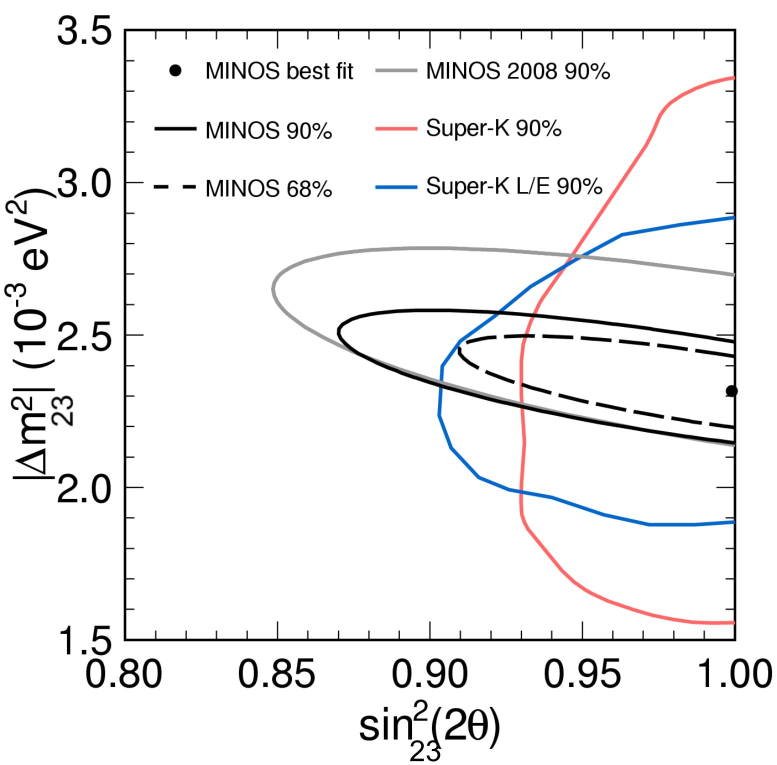
$$\Delta m^2 \geq 1 / \left(1.27 * \frac{180\ km}{0.005\ GeV} \right) \sim \underline{10^{-5} eV^2}$$

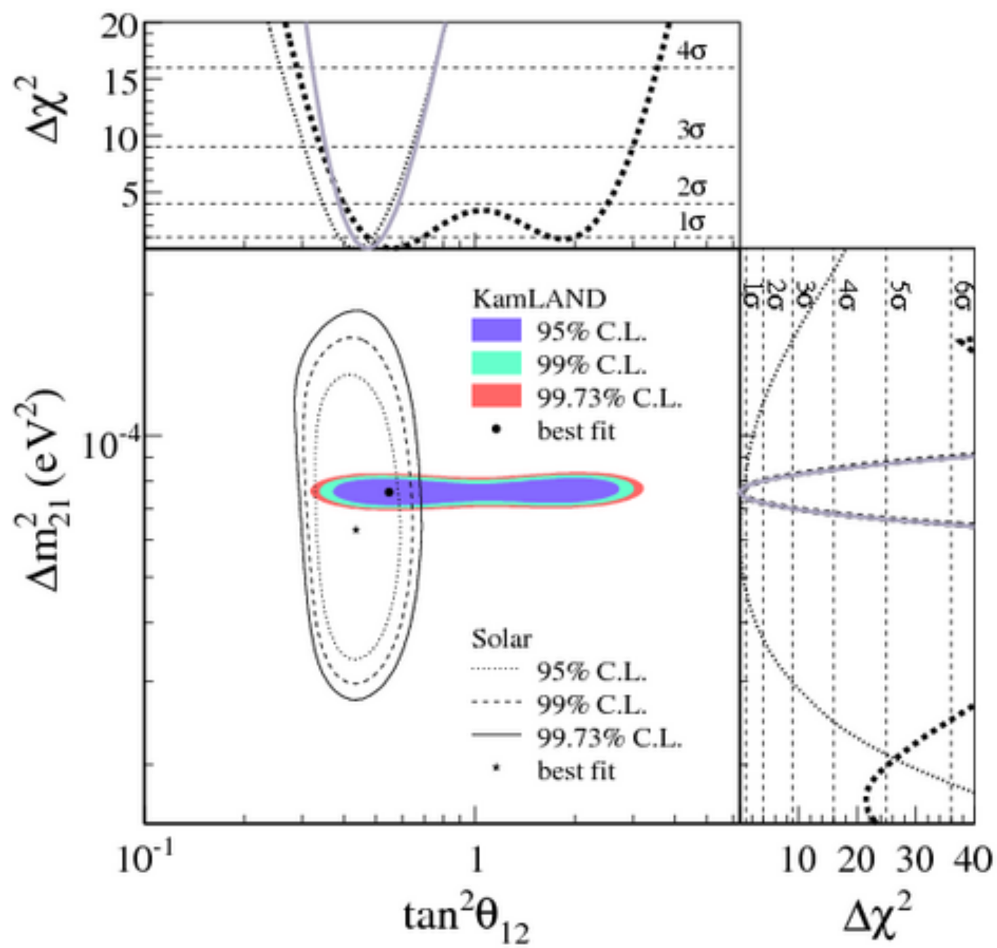
Phys. Rev. Lett. 100, 221803 (2008)





Presenting Oscillation Results





SuperK atmospheric data + MINOS

Solar data + KamLAND

Neutrino Mass and Mixing Summary

- <u>"Atmospheric" Osc. Parameters</u>

$$\Delta m^2_{23} = 2.51\times 10^{-3}\,eV^2 \qquad (\pm 4.8\%)$$

$$\theta_{23} = 42.3^{\circ}{}^{+5.3}_{-2.8} \qquad (+12.5\%)$$

- <u>"Solar" Osc. Parameters</u>

$$\Delta m^2_{12} = 7.59\times 10^{-5}\,eV^2 \qquad (\pm 2.6\%)$$

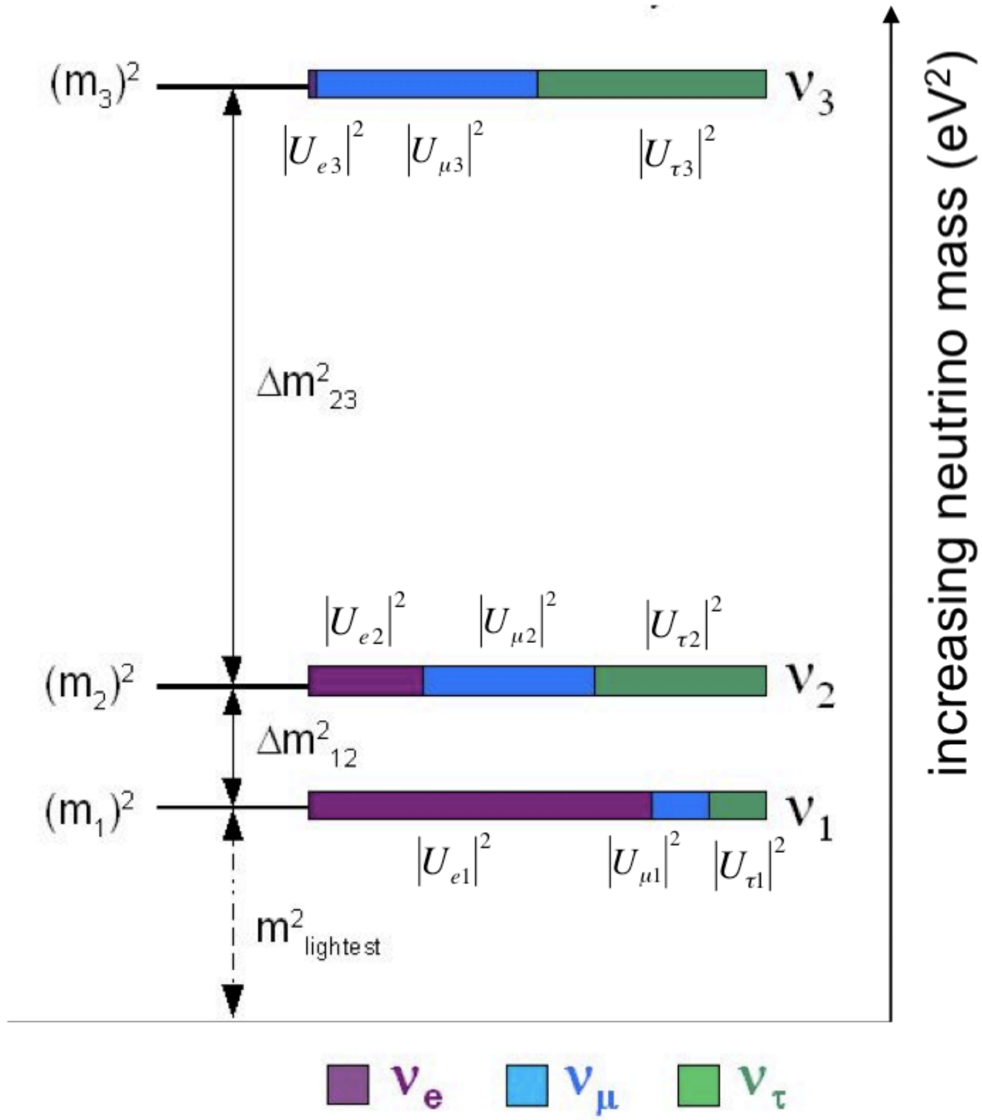
$$\theta_{23} = 34.4^{\circ}{}^{+1.0}_{-1.0} \qquad (\pm 2.9\%)$$

- <u>Other Osc. Parameters</u>

$$\theta_{13} < 9.4^{\circ} \qquad (1\sigma)$$

δ_{CP} unknown

$$U_{MNS} \sim \begin{pmatrix} 0.8 & 0.6 & <0.1 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$



* parameter values from global fits to data, hep-ph 1001.4524

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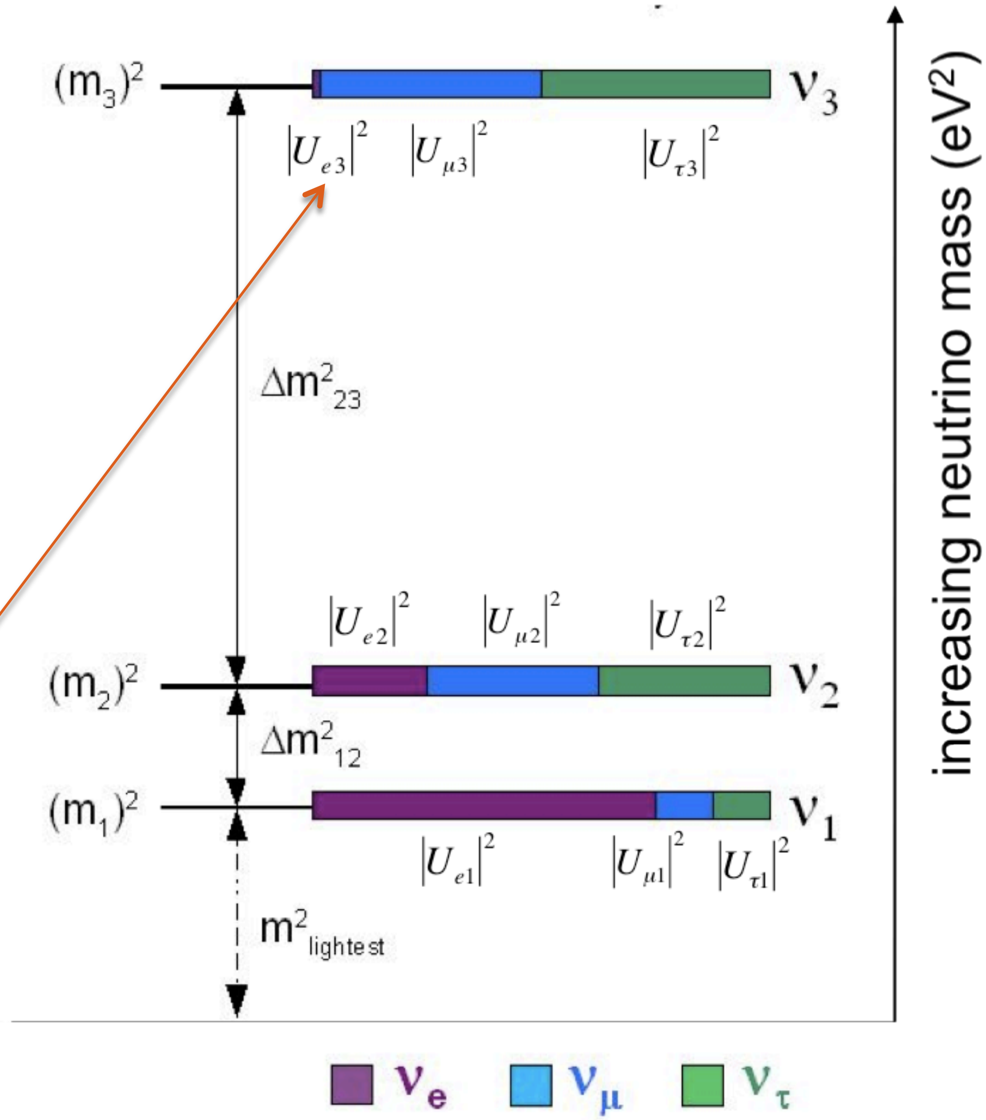


* parameter values from global fits to data, hep-ph 1001.4524

Still Many Open Questions

What is the **absolute mass scale** of the neutrinos?

What is the **mass mechanism** for neutrinos? Dirac vs. Majorana particles. Are neutrinos their own antiparticles?

Are there **additional neutrino** states, or only three?

Why is neutrino **mixing so different** from quark mixing?

Is θ_{23} maximal?

What is θ_{13}? Why is it so small?

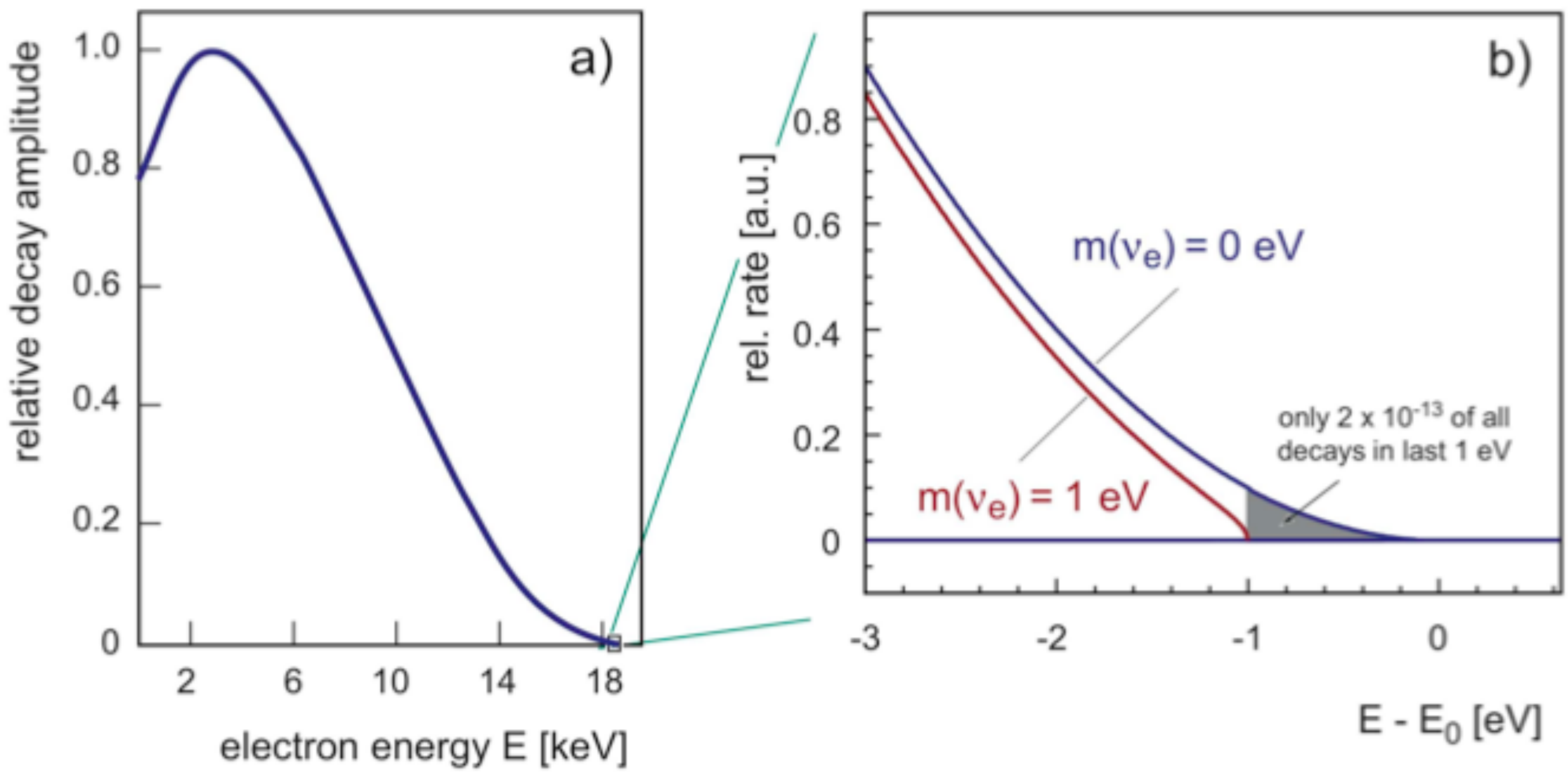
Is there **CP violation** in the neutrino sector (what is δ)?

What is the **hierarchy** of the neutrino masses (sign of Δm_{23}^2)?

Still Many Open Questions

What is the absolute mass scale of the neutrinos?

Best known laboratory method is to look at endpoint of electron energy spectrum in tritium decay



Still Many Open Questions

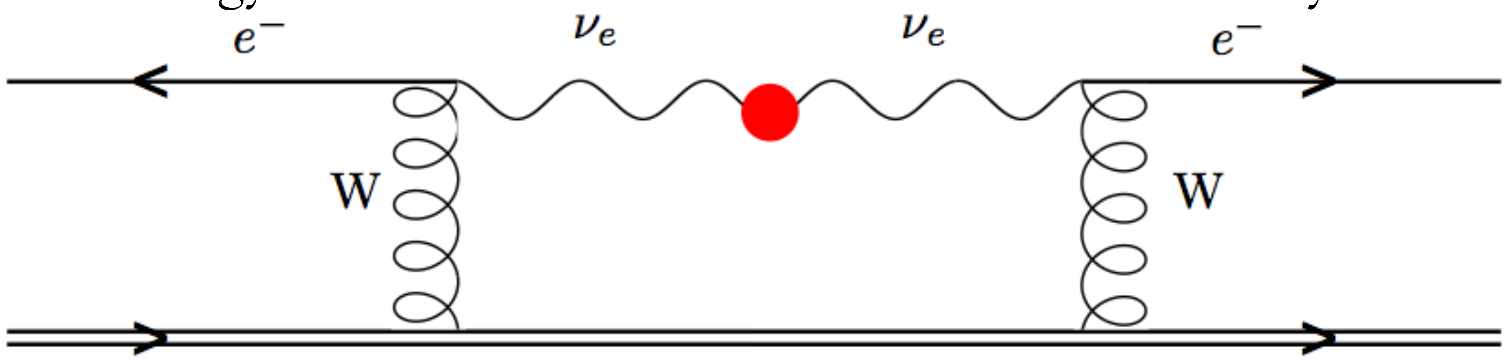
What is the absolute mass scale of the neutrinos?

KATRIN's goal is to reach 250 meV sensitivity

Still Many Open Questions

What is the mass mechanism for neutrinos? Dirac vs. Majorana particles. Are neutrinos their own antiparticles?

Strategy is to search for neutrinoless double beta decay



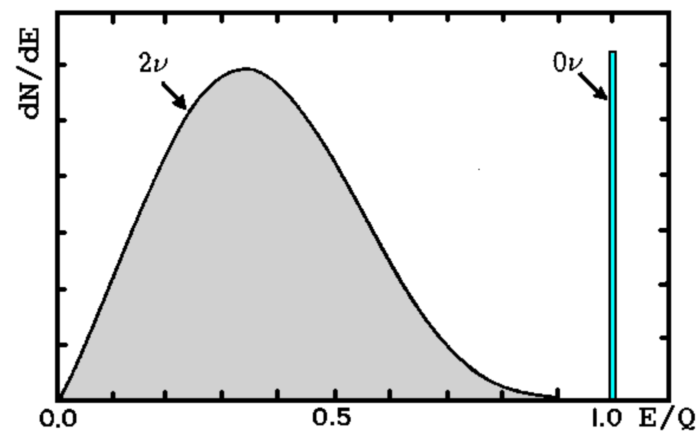
<u>Many experiments:</u>

CUORE (^{130}Te)

GERDA (^{76}Ge)

NEMO (^{100}Mo, ^{82}Se)

…



Still Many Open Questions

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accessible through oscillations

Is θ_{23} maximal?

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Is there CP violation in the neutrino sector (what is δ)?

What is the hierarchy of the neutrino masses (sign of Δm_{23}^2)?

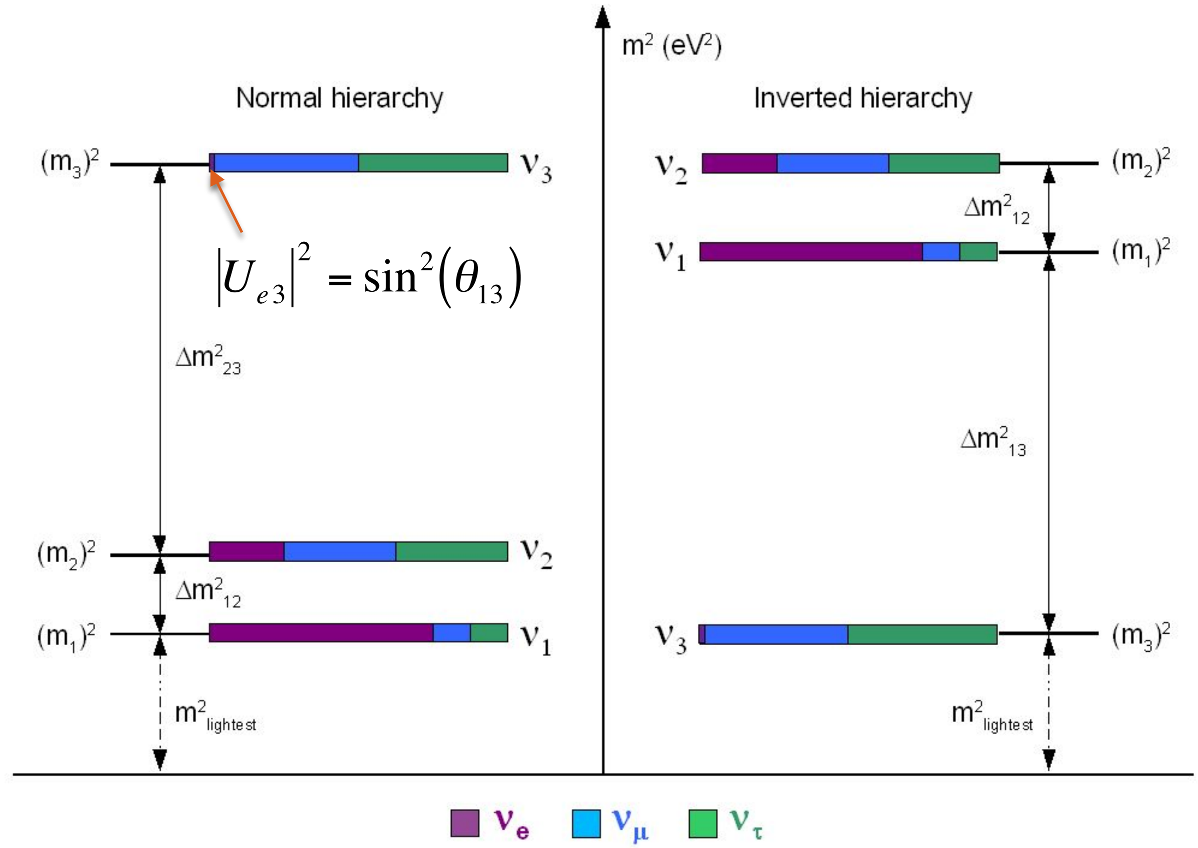
Still Many Open Questions

Quarks

$$U_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0 \\ 0.2 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrinos

$$U_{MNS} \sim \begin{pmatrix} 0.8 & 0.6 & <0.1 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$



Key to accessing the mass hierarchy and CP violation is $\nu_\mu \rightarrow \nu_e$ oscillations at the atmospheric (Δm_{23}^2) mass splitting

θ_{13} is the Gate Keeper

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} T_1 - \alpha \sin 2\theta_{13} T_2 - \alpha \sin 2\theta_{13} T_3 + \alpha^2 T_4$$

$$\alpha = \frac{\Delta m^2{}_{21}}{\Delta m^2{}_{31}}$$

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

$$T_2 = \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

CP Violating terms

$$T_3 = \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

$$\Delta = \frac{\Delta m^2{}_{31} L}{4E_\nu} \qquad x = \frac{2\sqrt{2} G_F N_e E_\nu}{\Delta m^2{}_{31}}$$

Matter Effects

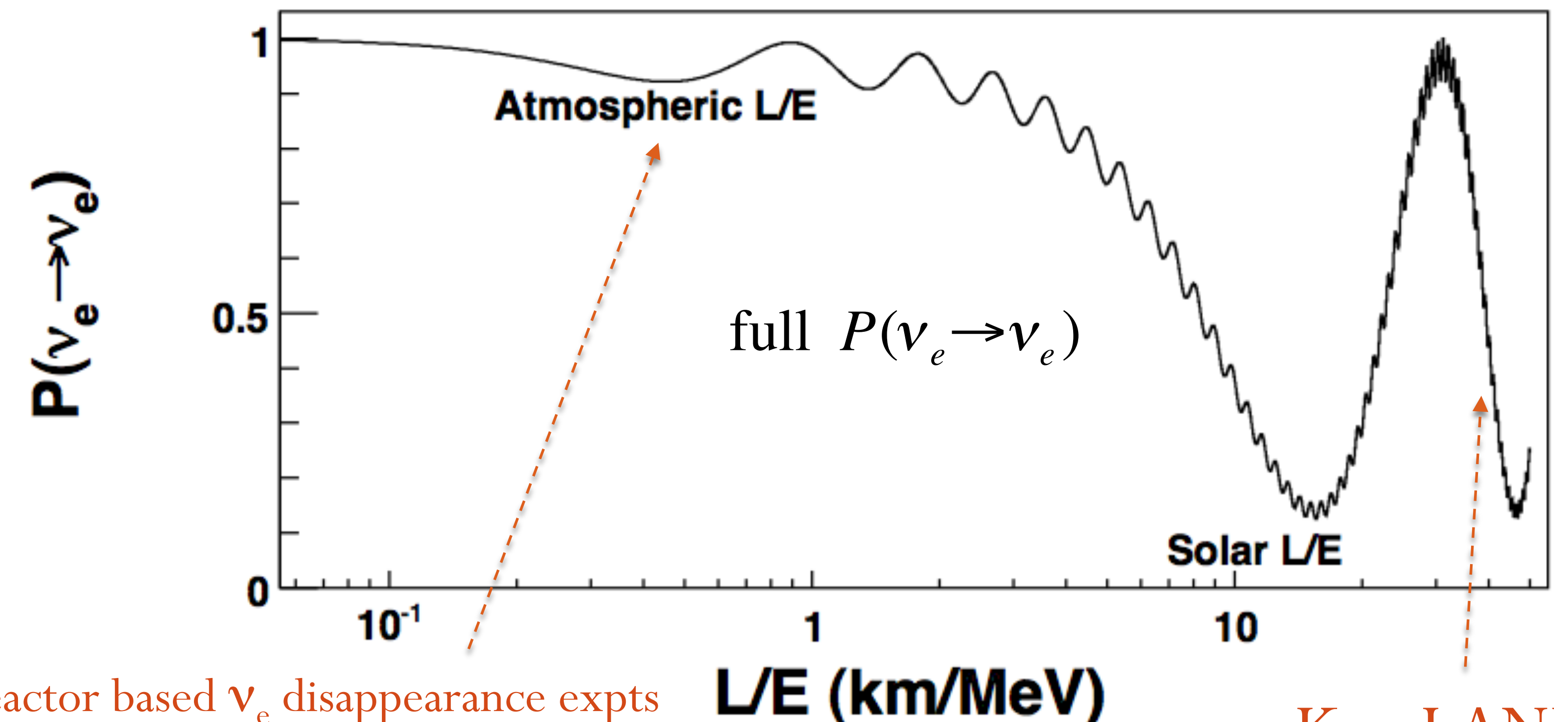
Rich physics in this next stage!!

Is there CP violation in the neutrino sector?

What is the mass hierarchy?

θ_{13} from ν_e Disappearance

- θ_{13} can be directly probed through ν_e disappearance at the right L/E
- Note, no sensitivity to mass hierarchy or CP violation



Reactor based ν_e disappearance expts such as Double Chooz and Daya Bay

KamLAND

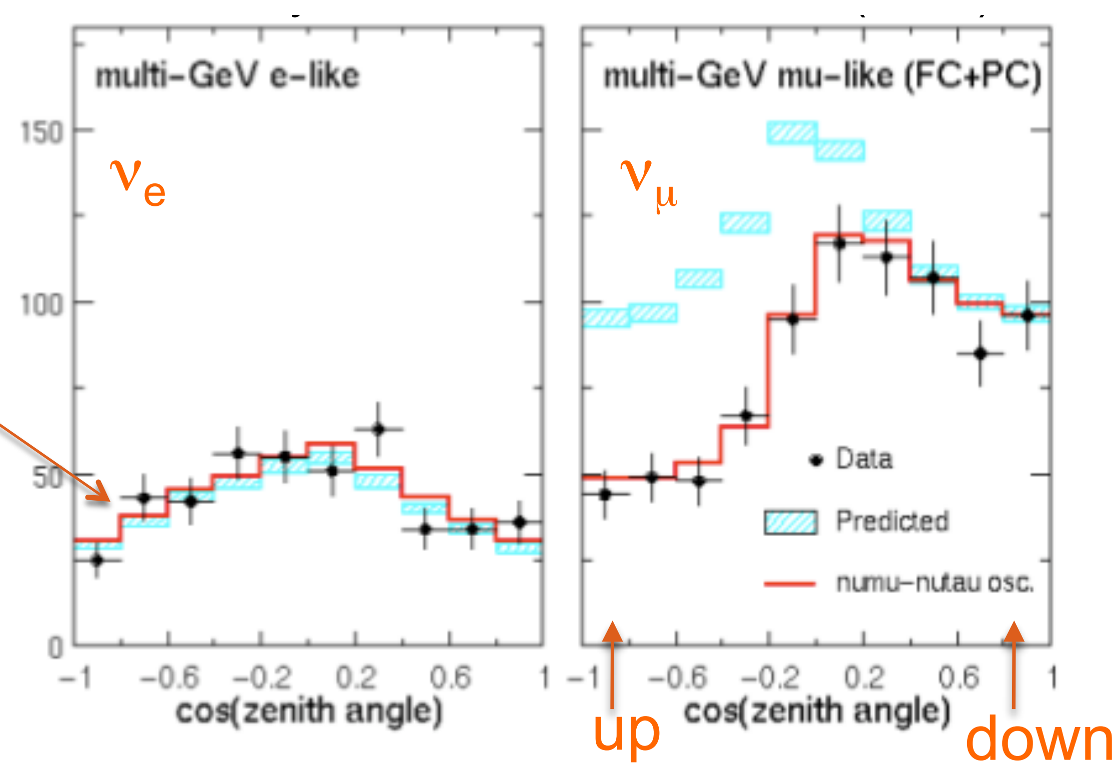
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2(1.27 \cdot \Delta m^2_{23} \cdot L/E)$$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{12} \cdot \sin^2(1.27 \cdot \Delta m^2_{12} \cdot L/E)$$

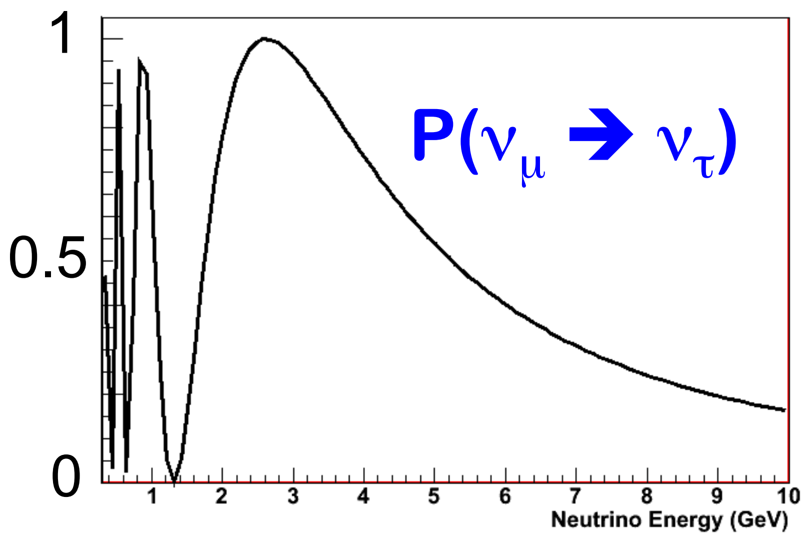
ν_μ Disappearance vs. ν_e Appearance

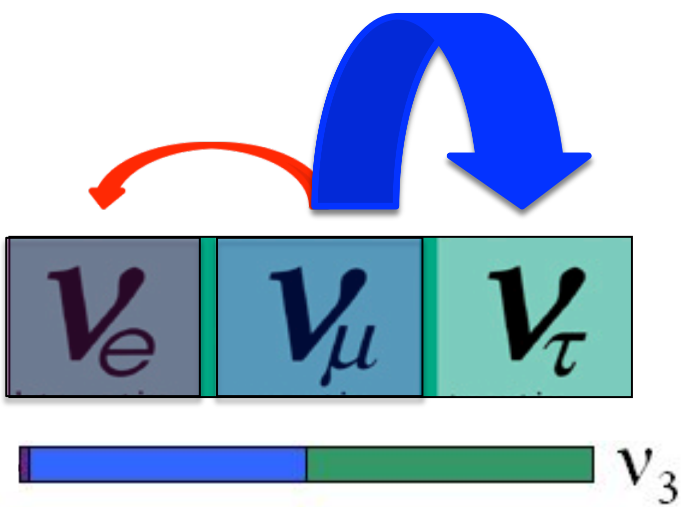
SuperK / MINOS ν_μ disappearance mostly due to $\nu_\mu \rightarrow \nu_\tau$

No noticeable excess of ν_e in upward direction in SuperK atmospheric data

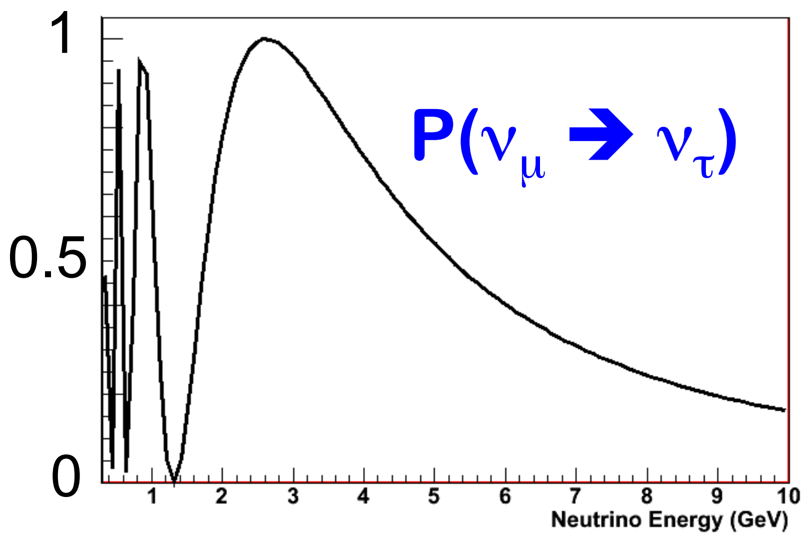


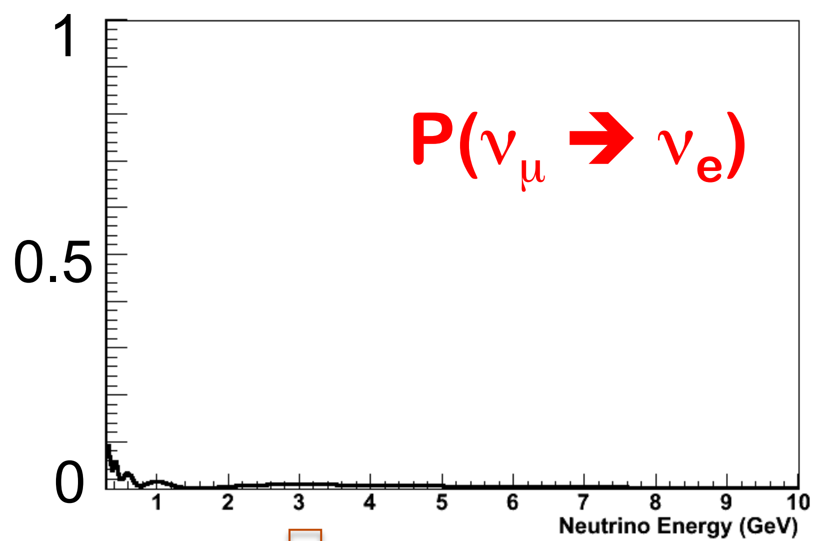
ν_μ Disappearance vs. ν_e Appearance

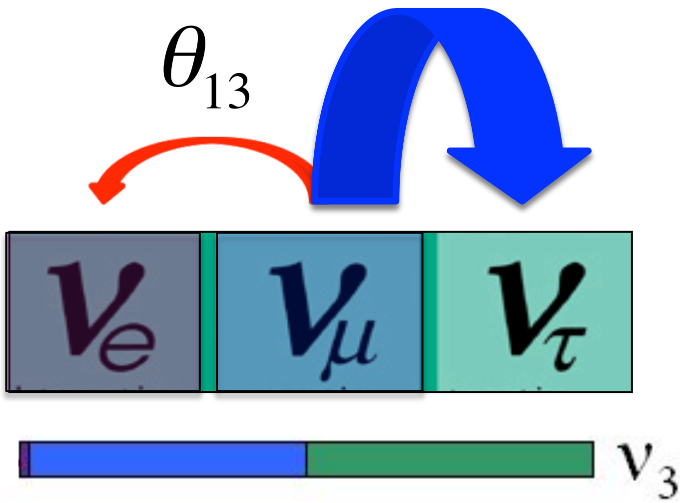




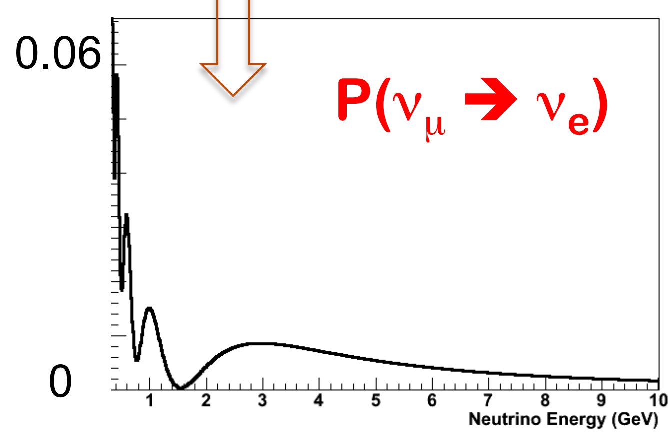
ν_μ Disappearance vs. ν_e Appearance





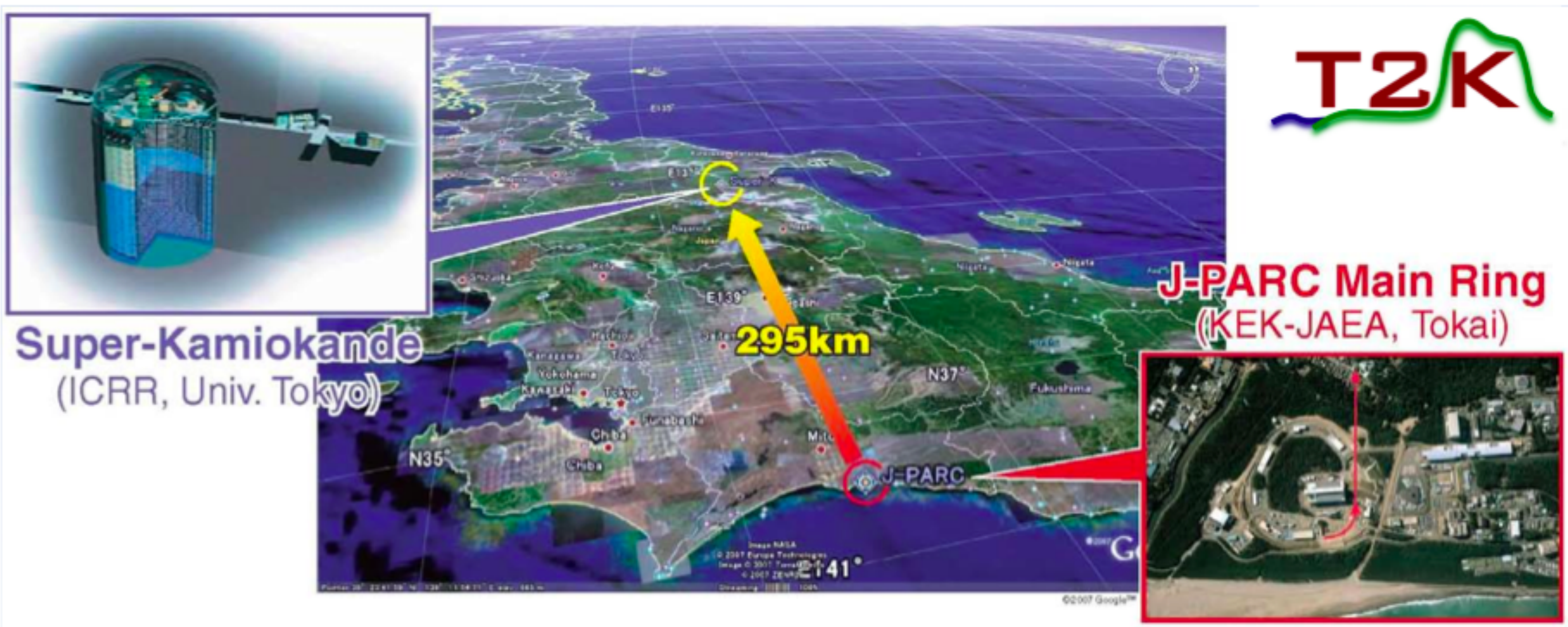


ZOOM IN



Long Baseline ν_e Appearance Searches

- MINOS detectors not optimized for electron detection, but have collected lots of data (8.2e20 POT)
- T2K uses Super Kamiokande detector with excellent electron reconstruction, but just started data collection (1.4e20 POT)



Long Baseline ν_e Appearance Searches

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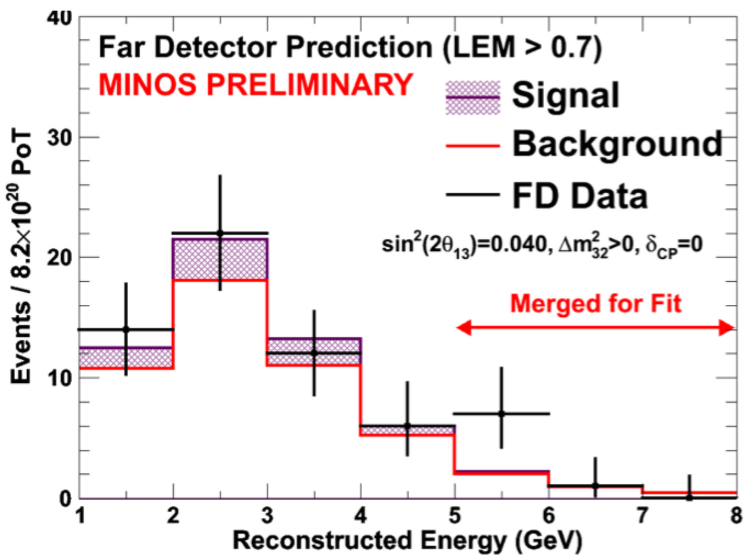
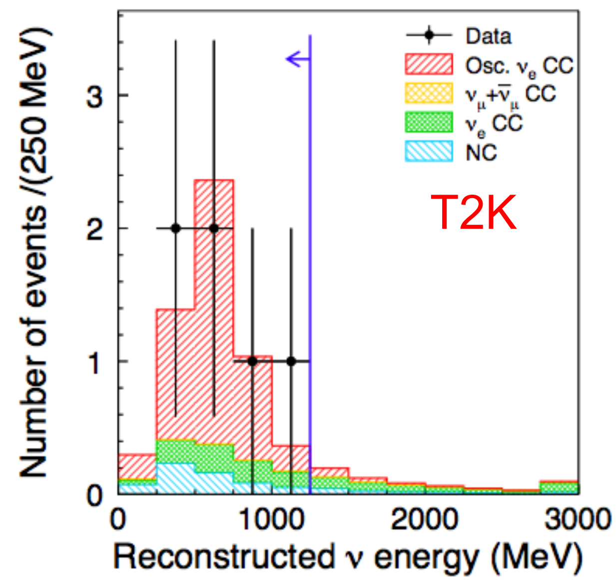




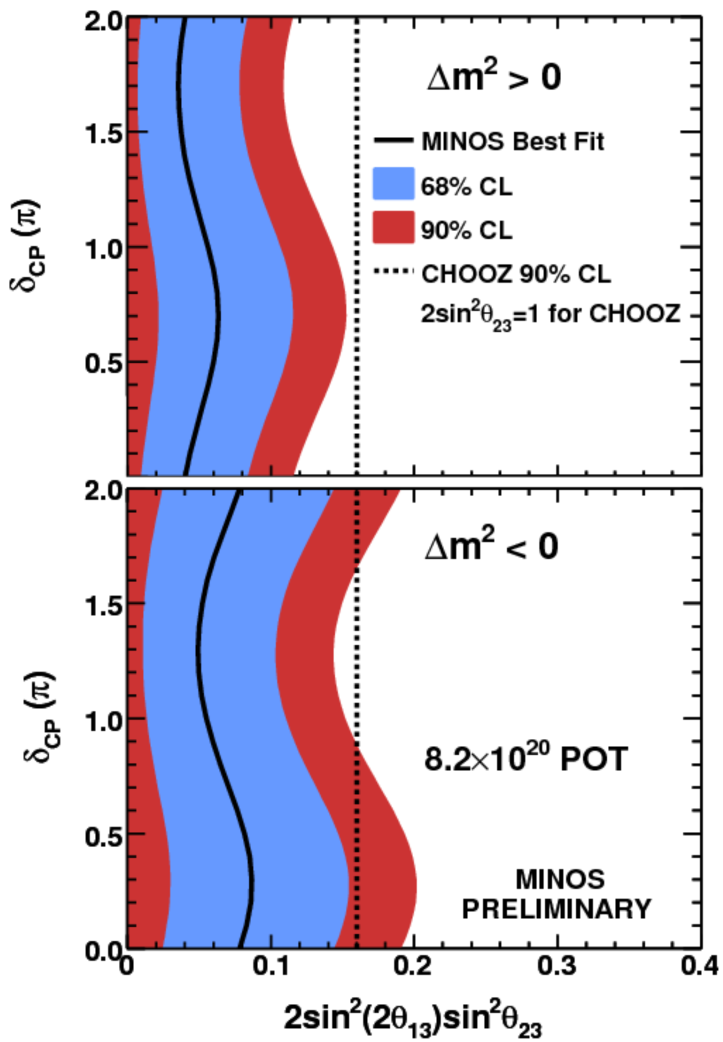
N_{ν_e} expected: $49.5 \pm 2.8(syst) \pm 7.0(stat)$

N_{ν_e} observed: 62

N_{ν_e} expected: $1.5 \pm 0.3(syst)$

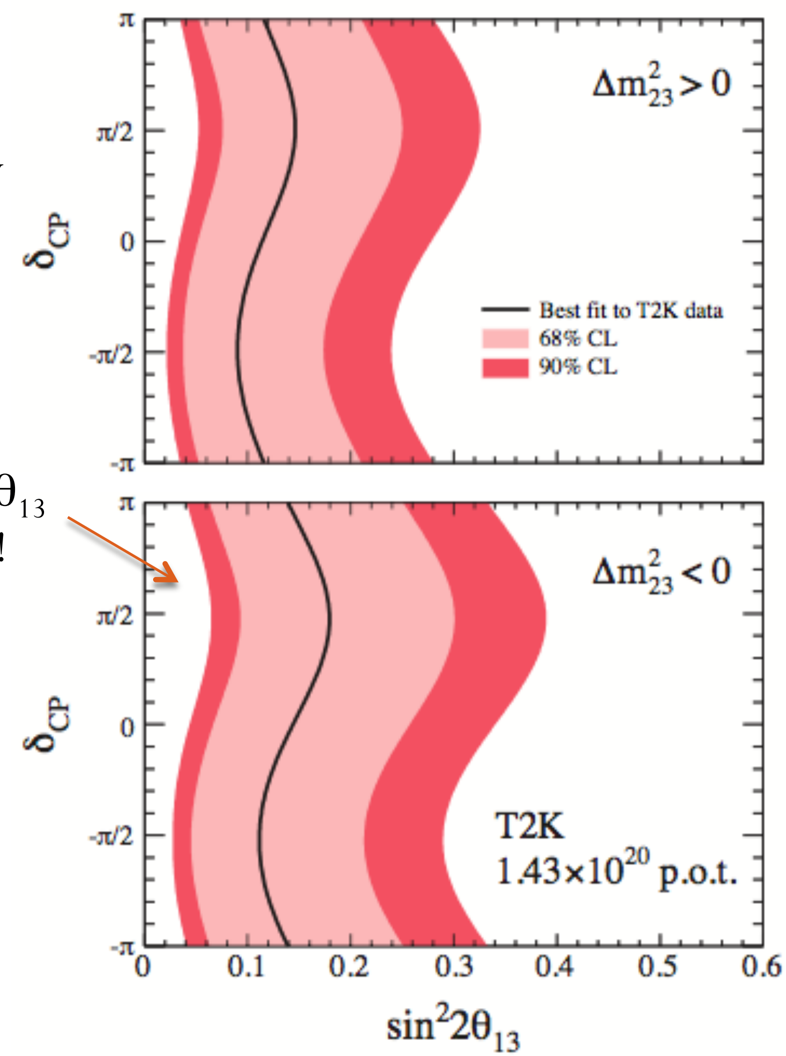
N_{ν_e} observed: 6

MINOS and T2K ν_e Results

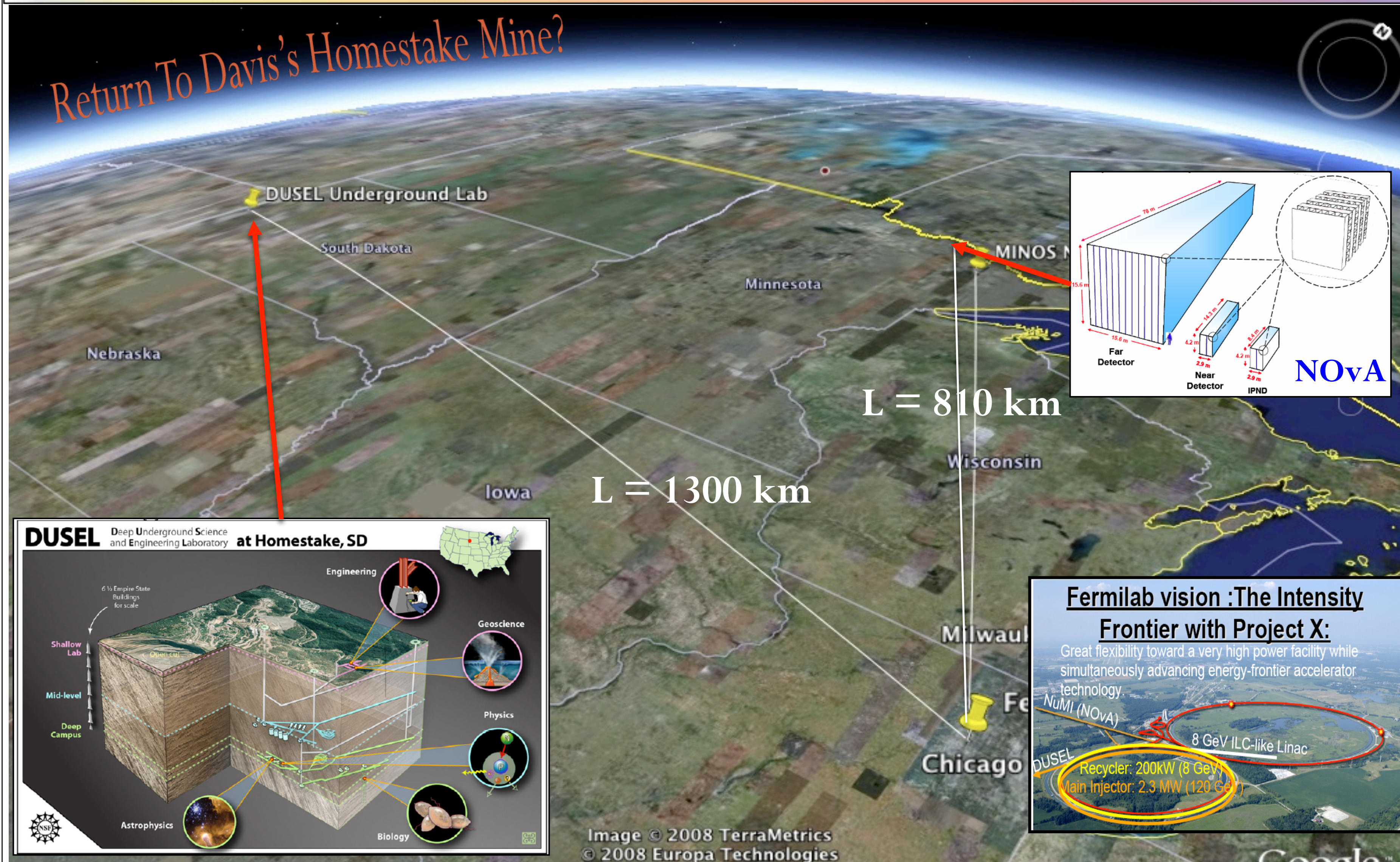


Value of θ_{13} depends on mass hierarchy and δ_{CP}

A hint at non-zero θ_{13} from T2K!



Future Long Baseline Experiments



Long Baseline Neutrino Experiment (LBNE)

- Baseline designs involve 100 kton water Cherenkov detector(s) AND/OR 17 kton liquid argon TPC neutrino detectors(s)

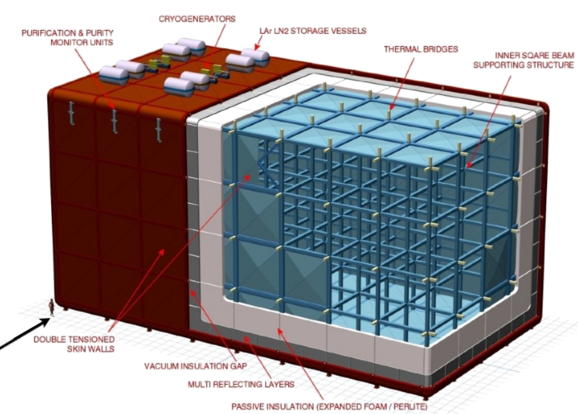
Long Baseline ν Physics
- θ_{13}, Mass Hierarchy, and CP violation
- Osc. parameters precision measurements

Proton Decay

Supernova Burst/Relic neutrinos

Atmospheric/Solar/UHE neutrinos

neutrino physicists



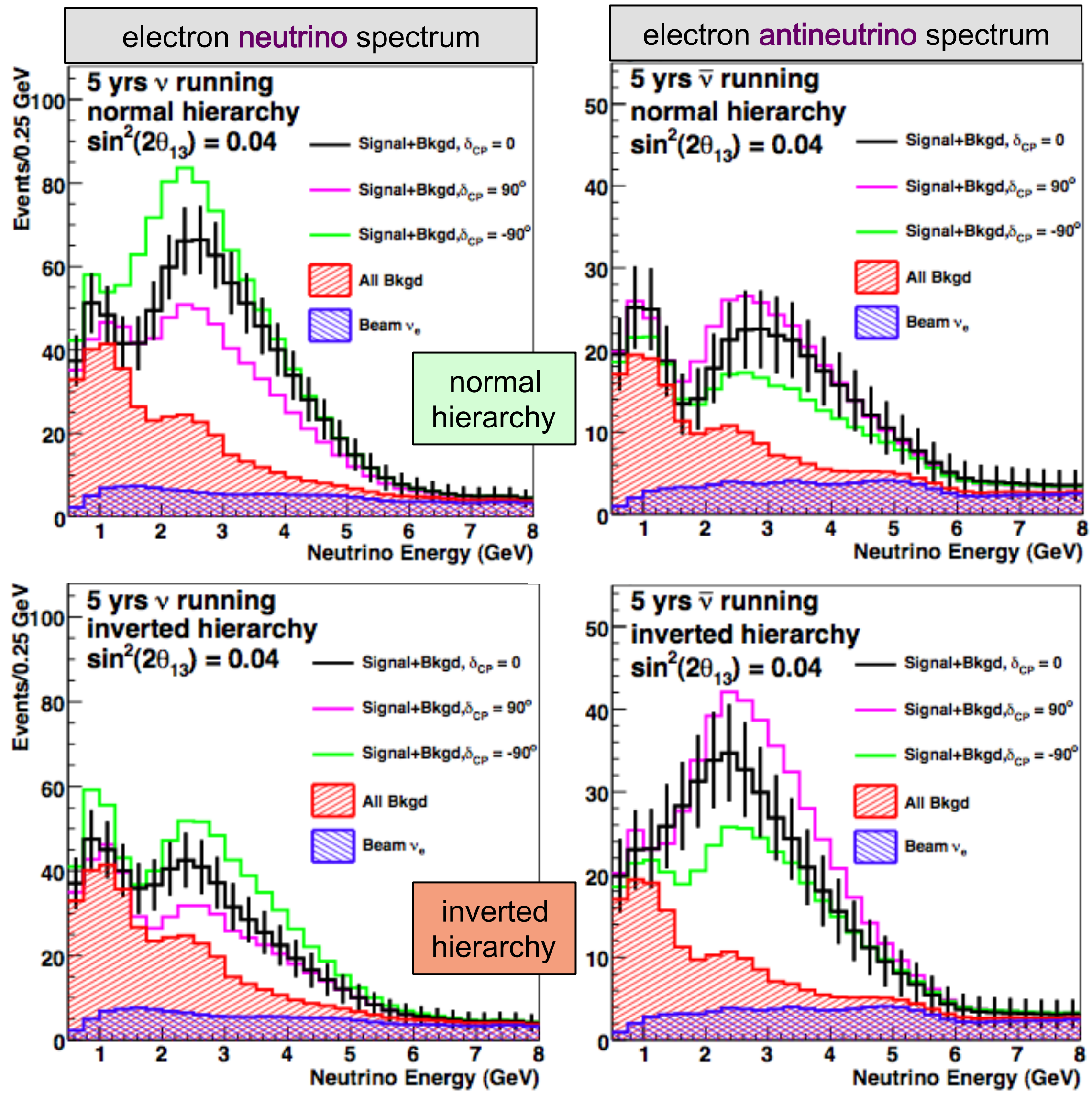
Long Baseline Neutrino Experiment (LBNE)

Comparison between neutrino and antineutrino oscillations is the key to extracting mass hierarchy and CP violation

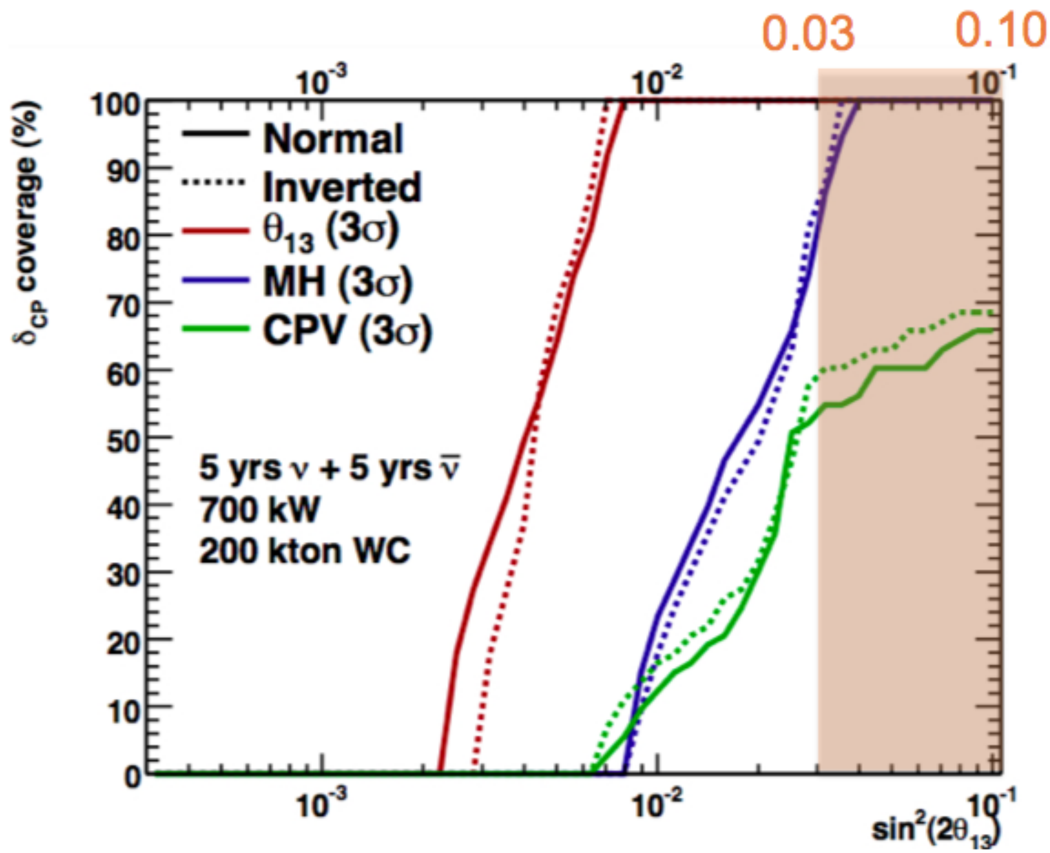
$$P(\nu_\mu \rightarrow \nu_e)$$

vs.

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$



Long Baseline Neutrino Experiment (LBNE)



Right of red curve are values of δ_{CP} and $\sin^2(2\theta_{13})$ for which LBNE can resolve non-zero θ_{13} at 3σ

Right of blue curve are values of δ_{CP} and $\sin^2(2\theta_{13})$ for which LBNE can determine mass hierarchy at 3σ

Right of green curve are values of δ_{CP} and $\sin^2(2\theta_{13})$ for which LBNE can establish CP violation at 3σ

Summary II

- Neutrino mass and mixing has been firmly established as the solution to the solar and atmospheric neutrino puzzles
- However, still many open questions yet to answer:

What is the absolute mass scale of the neutrinos?

Heaviest one heavier than $\sqrt{\Delta m^2_{23}} \approx 50\ meV$

What is the mass mechanism for neutrinos? Dirac vs. Majorana particles. Are neutrinos their own antiparticles?

Are there additional neutrino states, or only three?

LSND and MiniBooNE

Why is neutrino mixing so different from quark mixing?

accessible through oscillations

Is θ_{23} maximal?

What is θ_{13}? Why is it so small?

Is there CP violation in the neutrino sector (what is δ)?

Could the leptons hold the key to understanding the matter dominated universe?

What is the hierarchy of the neutrino masses (sign of $\Delta m_{23}{}^2$)?

- Plus the unknown unknowns. Neutrinos have a reputation for surprises requiring "desperate remedies"!

Acknowledgements

- Many thanks to those from whom I liberally borrowed slides and ideas, especially:
  - Jorge Morfin (Fermilab)
  - Boris Kayser (Fermilab)
  - Stephen Parke (Fermilab)
  - Sam Zeller (Fermilab)
  - Kevin McFarland (University of Rochester)
  - Bonnie Fleming (Yale)
- Useful references for further reading:
  - K. Zuber, *Neutrino Physics*, 2004
  - J. Thomas, P. Vahle, *Neutrino Oscillations: Present Status and Future Plans*, 2008
  - F. Close, *Neutrino*, 2010
  - F. Halzen, *Quarks and Leptons*, 1984

Extras

MINOS Antineutrinos

Expect 156 events with no oscillations

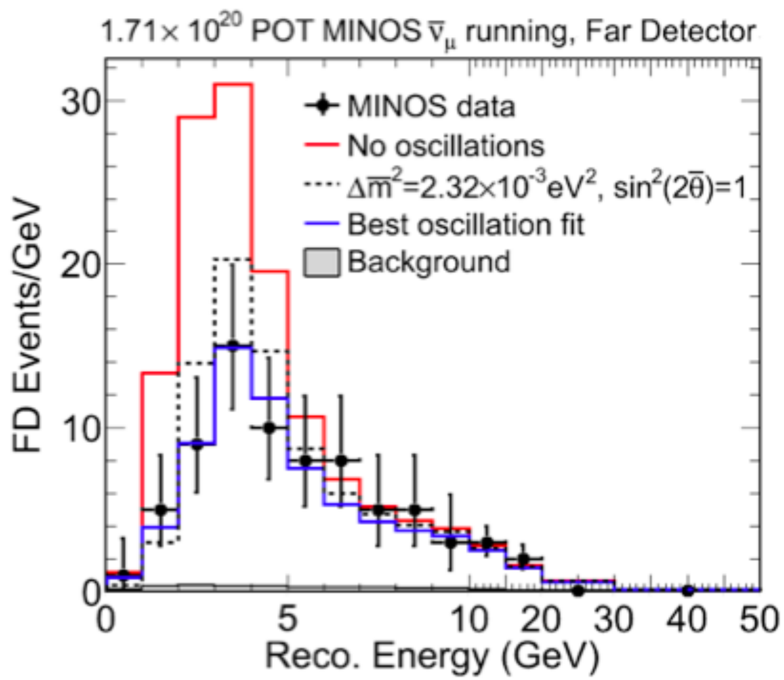
Observe 97 events

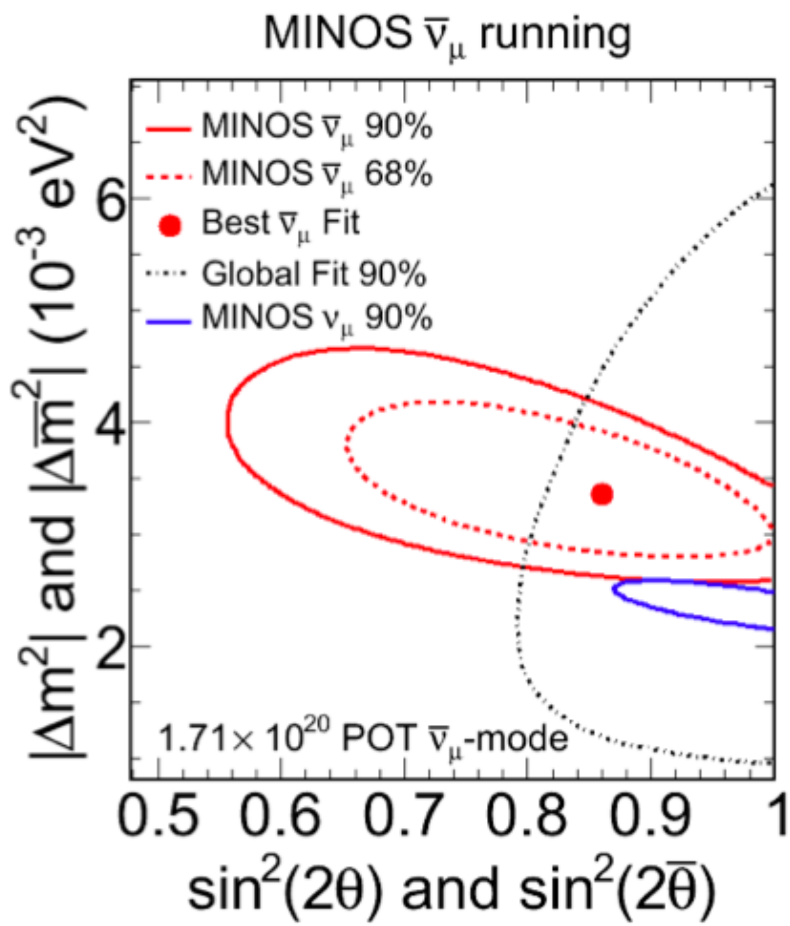
- No oscillations disfavoured at 6.3σ

Best fit to oscillations:

$$|\Delta\overline{m}^2| = (3.36^{+0.46}_{-0.40}(\text{stat.}) \pm 0.06(\text{syst.})) \times 10^{-3}\,\text{eV}^2$$

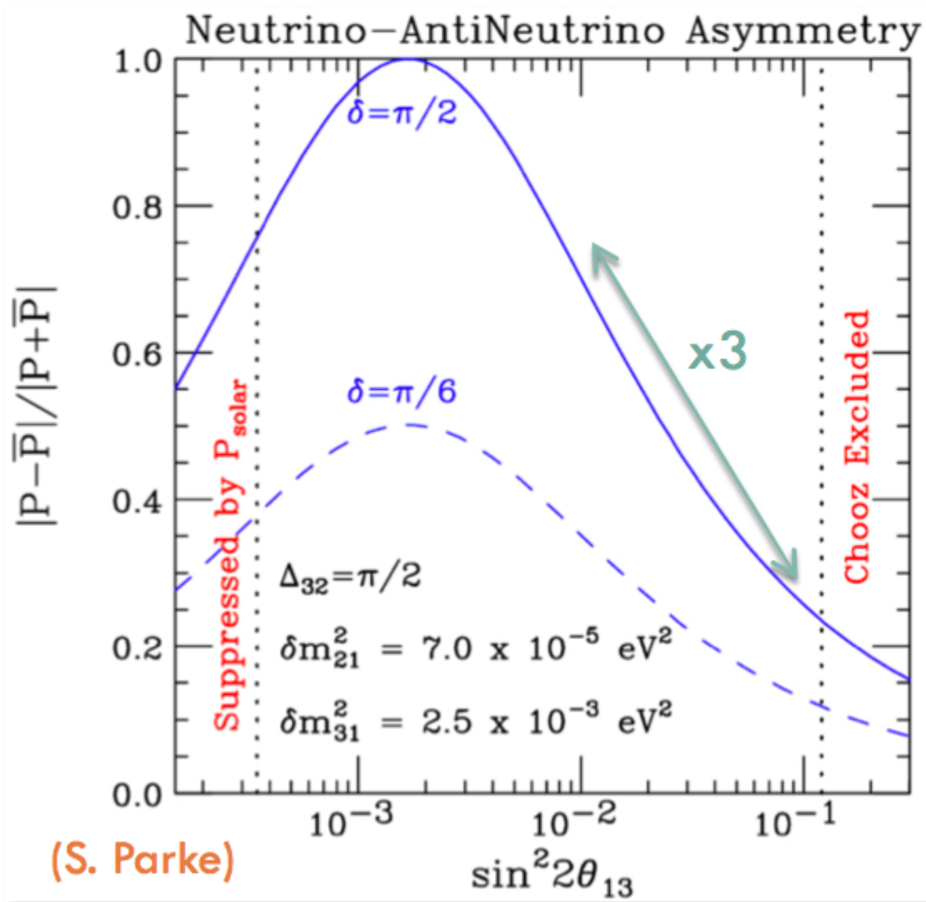
$$\sin^2(2\overline{\theta}) = 0.86^{+0.11}_{-0.12}(\text{stat.}) \pm 0.01(\text{syst.})$$





Global fit from Gonzalez-Garcia & Maltoni, *Phys. Rept.* 460 (2008), SK data dominates

$P(\nu) / P(\bar{\nu})$ Asymmetry



(ignoring matter effects & backgrounds for now)

- the asymmetry

$$\frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

is proportional to $\sim 1/\sin\theta_{13}$

- **the asymmetry gets smaller as θ_{13} increases**

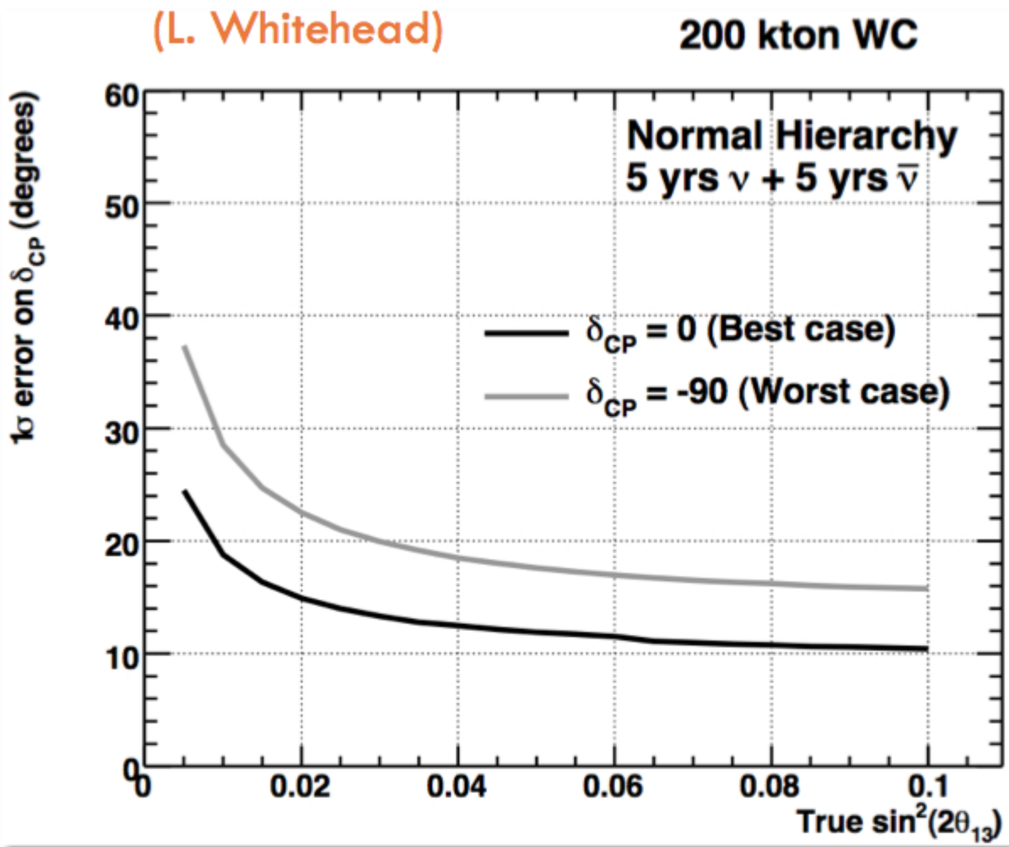
$\sim$75% for $\sin^2 2\theta_{13}$=0.01
$\sim$25% for $\sin^2 2\theta_{13}$=0.10
$\delta_{CP}=\pi/2$

factor ~3 reduction in CP asymmetry (independent of baseline)

- **signal rate increases w/ θ_{13}**

factor ~10 increase from 0.01 to 0.1
so x3 improvement in stat sig of signal

$P(\nu)$ / $P(\bar{\nu})$ Asymmetry

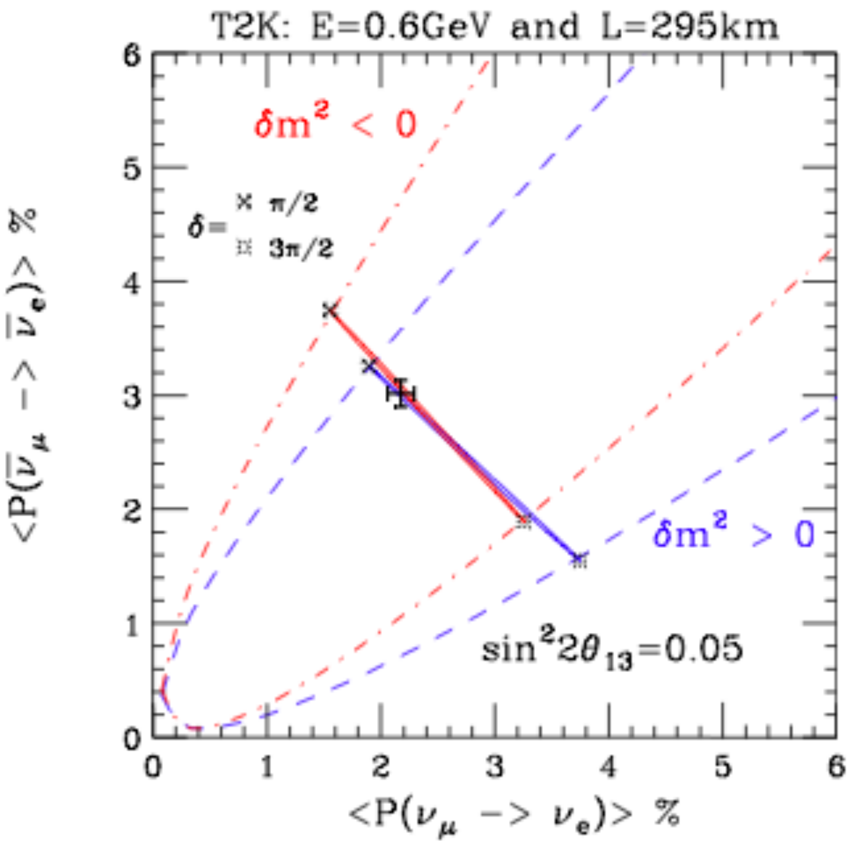


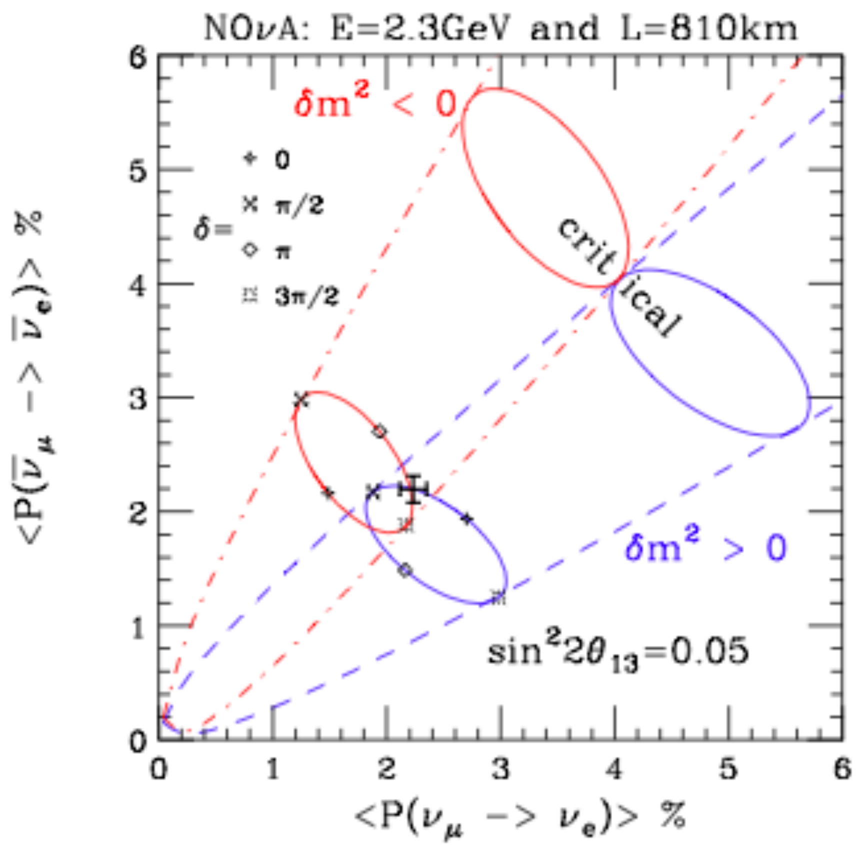
(calculation includes backgrounds, background uncertainties, and matter effects)

- as a result, the error on the CP asymmetry and thus how well can measure δ_{CP} is essentially independent of the value of θ_{13}
- can provide an excellent measurement of δ_{CP} over a very broad range of θ_{13}

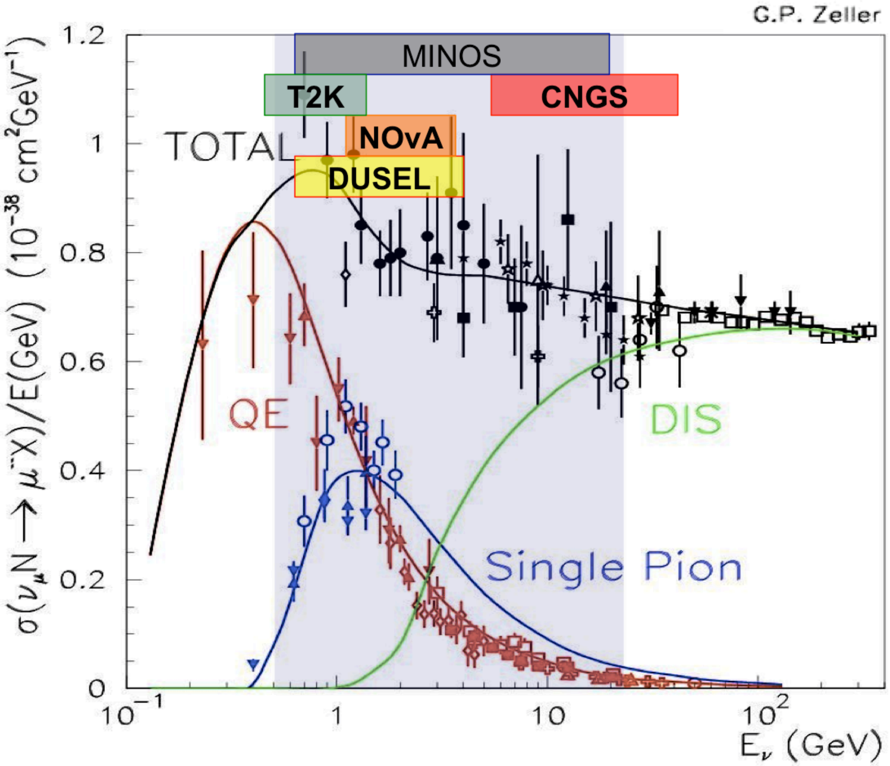
(10-20^0 for $\sin^2 2\theta_{13}$~0.03-0.10; gets a little worse for smaller θ_{13})

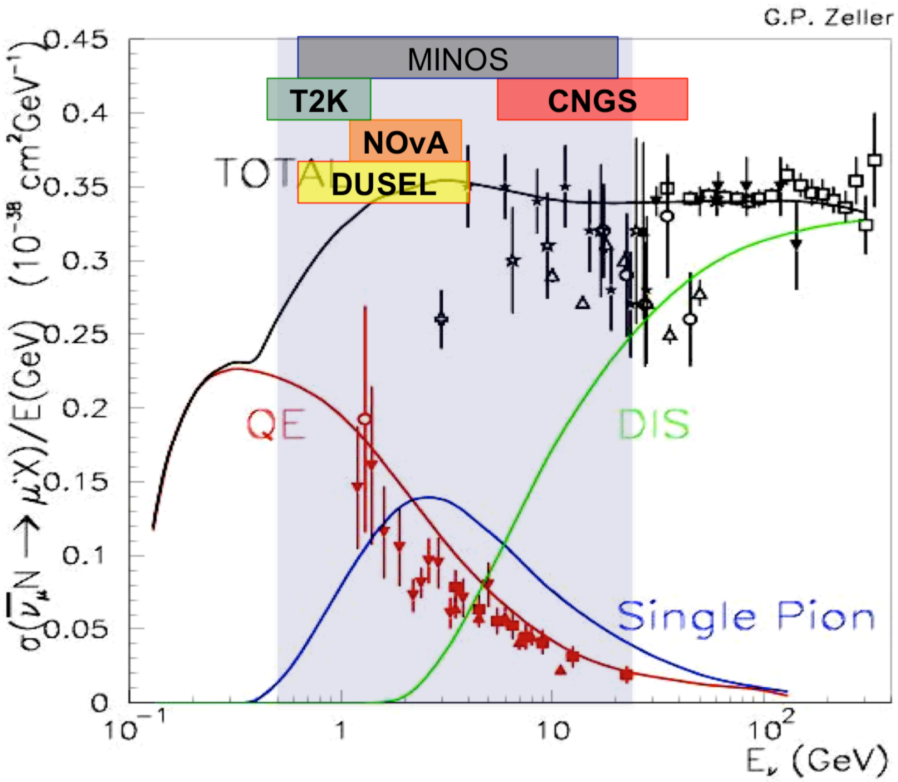
P(ν) / P($\bar{\nu}$) Asymmetry





Cross Sections

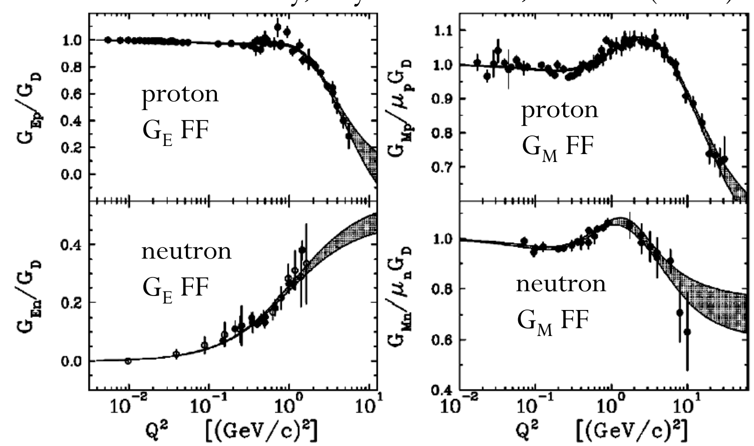




CCQE Scattering

- Charged-Current Quasi-Elastic Scattering

Kelly, Phys. Rev. **C70**, 068202 (2004)



- **Vector Form Factors**
  - well known from e⁻ scattering
  - deviations from dipole form at high Q^2
- **Axial-Vector Form Factor** dominates uncertainty in CCQE cross-section. Assume dipole form:

$$\boxed{F_A(Q^2) = F_A(0)\left(1 + \frac{Q^2}{M_A^2}\right)^{-2}}$$

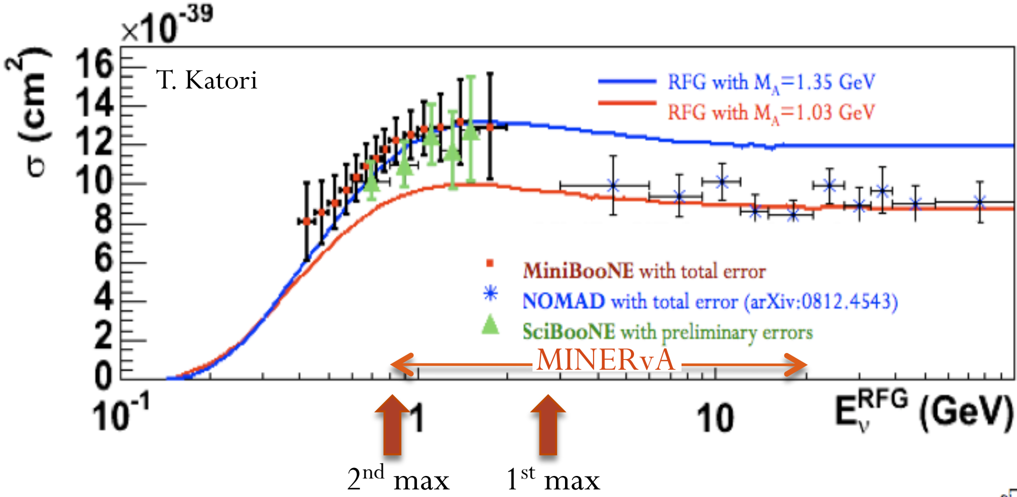
well known from β decay experiments ($Q^2 = 0$)

measured from Q^2 distribution of QE neutrino-nucleon events

- **Nuclear effects** – simulated with Relativistic Fermi Gas Model "RFG" formalism of Smith and Moniz, NP B43, 605 (1972).

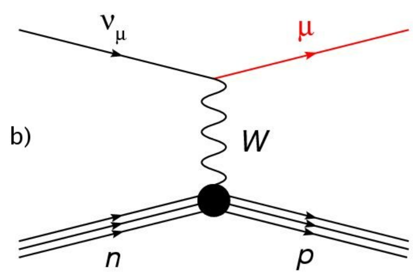
CCQE Scattering

- **How much of CC cross section is quasi-elastic like?**

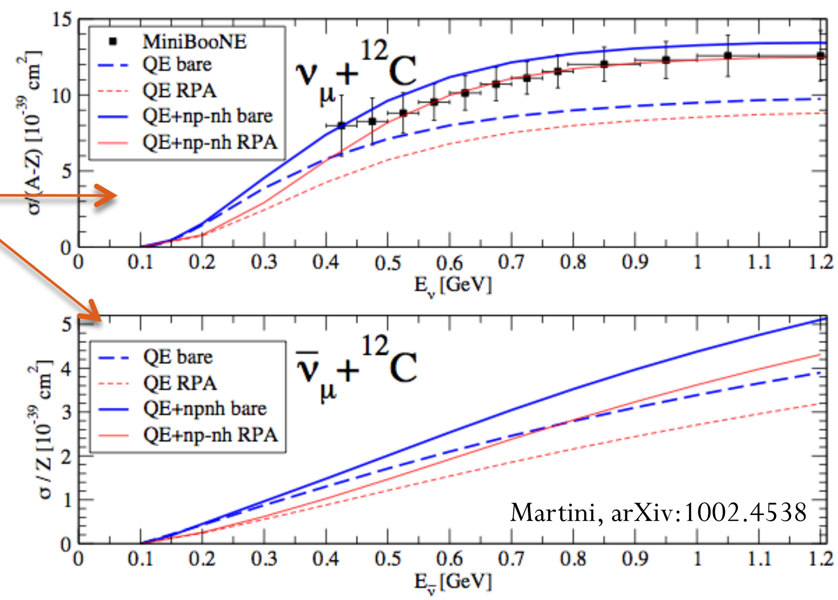


Tension in different data sets not understood (~30% difference)

Much recent theoretical effort to explain Mini/SciBooNE data



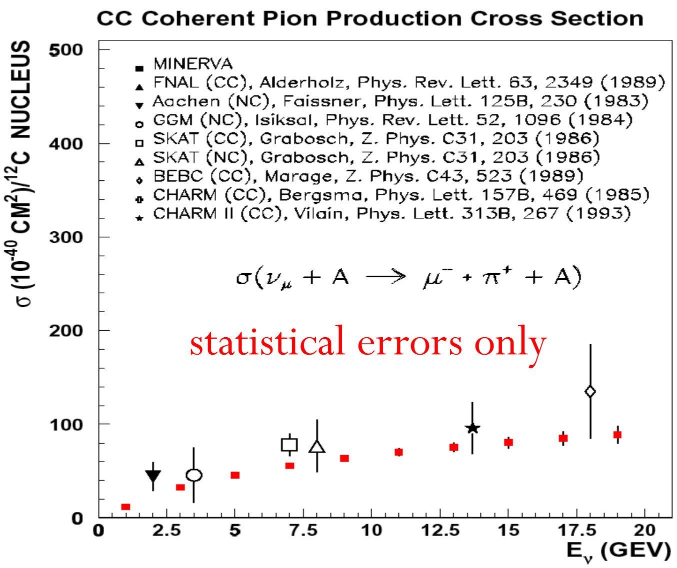
Often explanations have different effects on neutrino/antineutrino cross sections

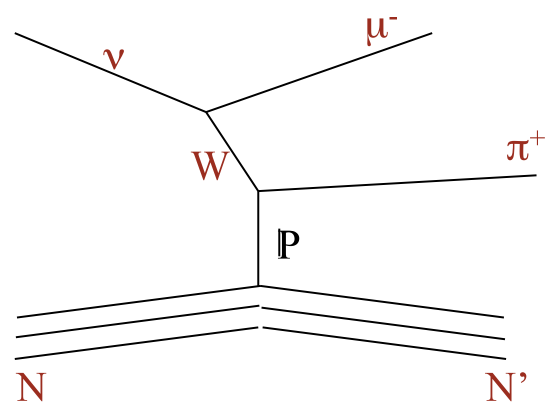


This is the exclusive channel for which we have the most data and understand the best

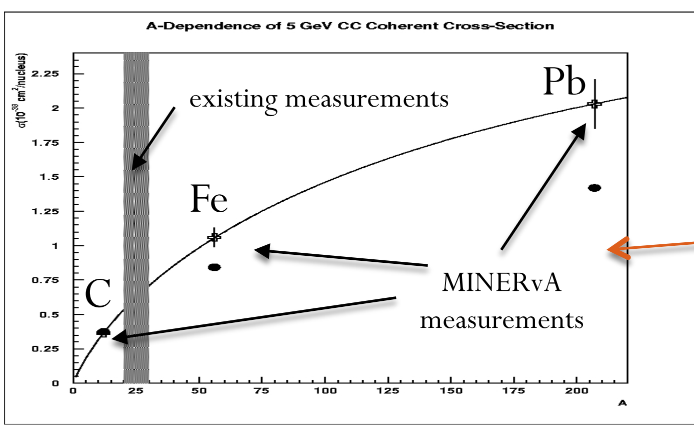
Coherent Scattering

- Coherent pion production (CC/NC) off the nucleus





- Scatters off the nucleus as a whole, leaving nucleus in the ground state.
- Comparison with theoretical models

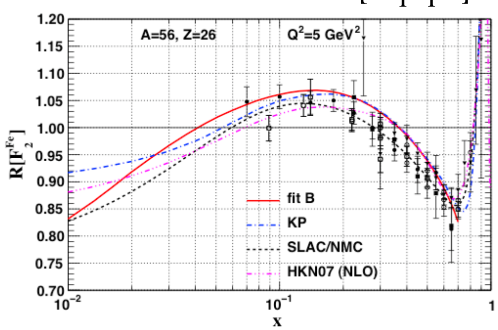


- MINERνA's nuclear targets allow the first measurement of the A-dependence of σ_{coh} across a wide range in a single experiment

Neutrino DIS Data on Nuclear Targets

- Deep Inelastic Scattering Physics: PDFs and Nuclear Effects

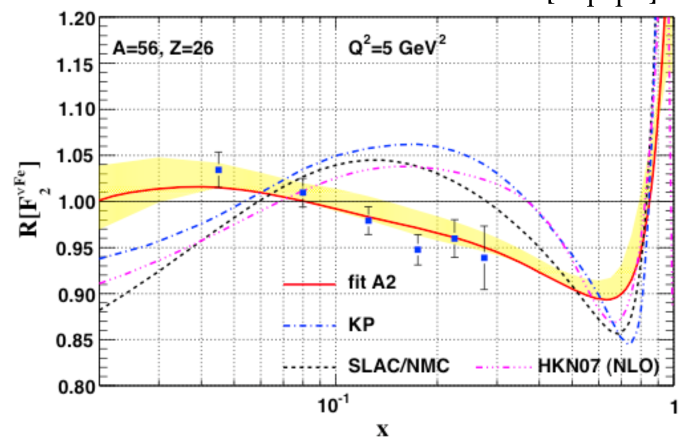
arXiv:0907.2357v2 [hep-ph]



- Combined many charged lepton data sets on many different nuclei
- Added **A**-dependent terms to the parameterization to include effects within model

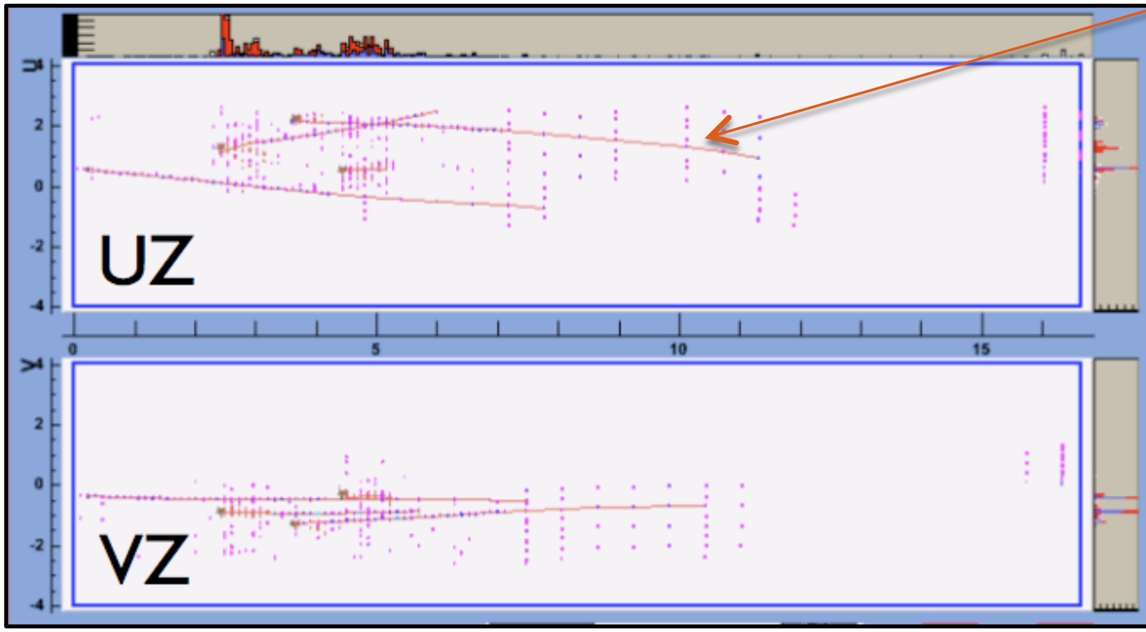
F_2^A/F_2^D : Observable	Experiment	Ref.	# data
D	NMC-97	[31]	275
He/D	SLAC-E139	[18]	18
	NMC-95,re	[32]	16
	Hermes	[33]	92
Li/D	NMC-95	[34]	15
Be/D	SLAC-E139	[18]	17
C/D	EMC-88	[35]	9
	EMC-90	[36]	2
	SLAC-E139	[18]	7
	NMC-95,re	[32]	16
	NMC-95	[34]	15
	FNAL-E665-95	[37]	4
N/D	BCDMS-85	[19]	9
	Hermes	[33]	92
Al/D	SLAC-E049	[38]	18
	SLAC-E139	[18]	17
Ca/D	EMC-90	[36]	2
	SLAC-E139	[18]	7
	NMC-95,re	[32]	15
	FNAL-E665-95	[37]	4
Fe/D	BCDMS-85	[19]	6
	BCDMS-87	[20]	10
	SLAC-E049	[21]	14
	SLAC-E139	[18]	23
	SLAC-E140	[22]	6
Cu/D	EMC-88	[35]	9
	EMC-93(addendum)	[39]	10
	EMC-93(chariot)	[39]	9
Kr/D	Hermes	[33]	84
Ag/D	SLAC-E139	[18]	7
Sn/D	EMC-88	[35]	8
Xe/D	FNAL-E665-92(em cut)	[40]	4
Au/D	SLAC-E139	[18]	18
Pb/D	FNAL-E665-95	[37]	4
Total:			862

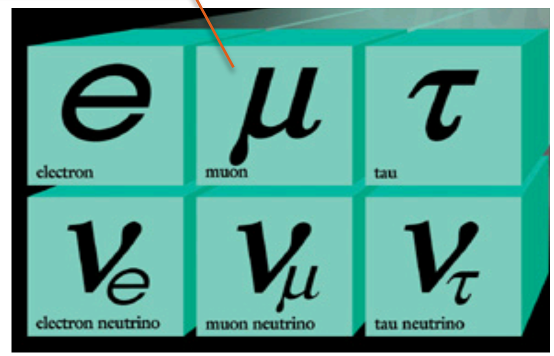
arXiv:0907.2357v2 [hep-ph]



- Only NuTeV iron neutrino data
- Would like to use a similar table of data to properly compare charged and neutral lepton data
- MINERvA provides **<u>He, C, Fe, Pb</u>**

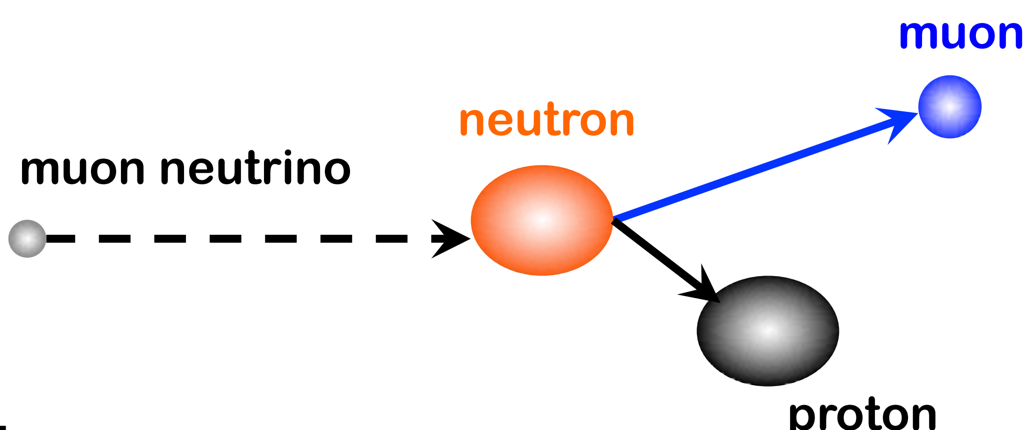
Detecting Neutrinos



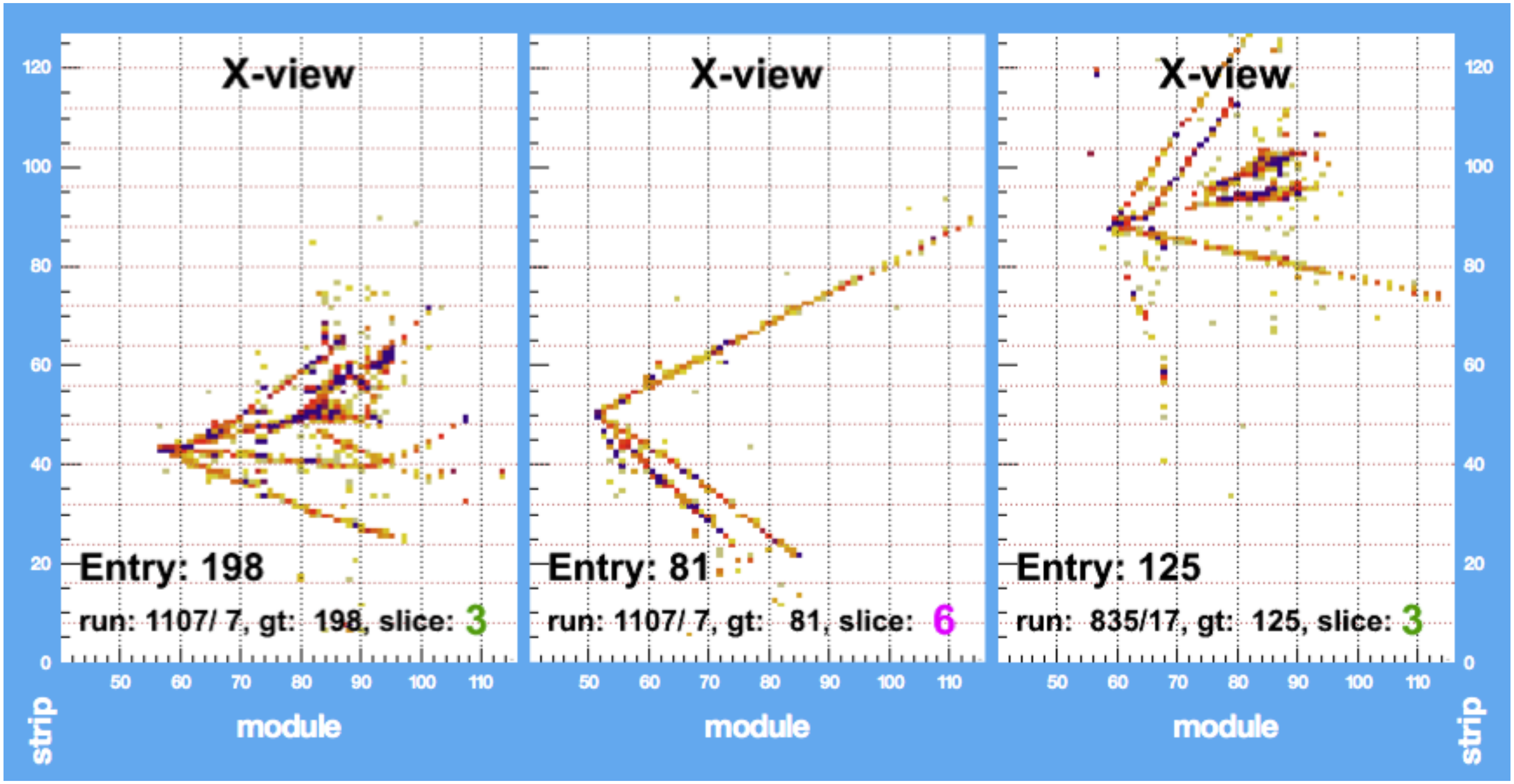


don't see the neutrino directly, but when one interacts with a nucleus in the detector it creates its **charged lepton partner**

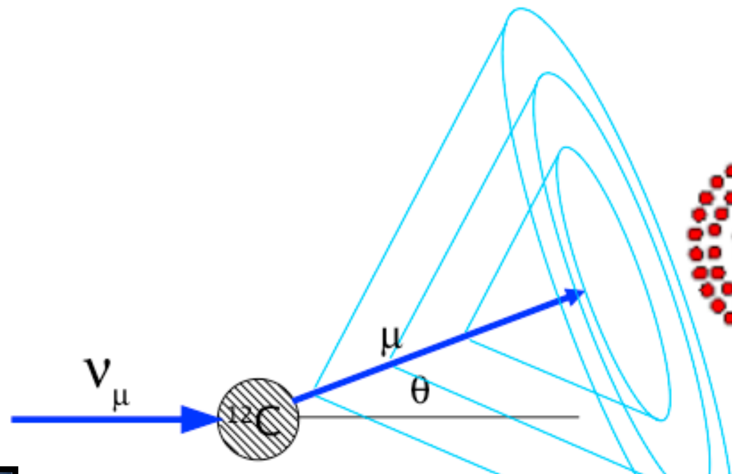
can distinguish the charged leptons in the detector



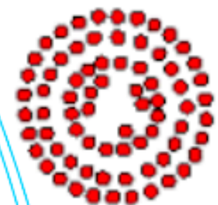
Detecting Neutrinos

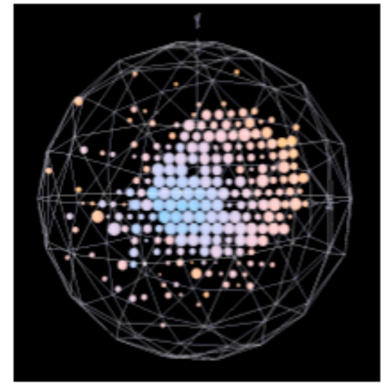


Detecting Neutrinos

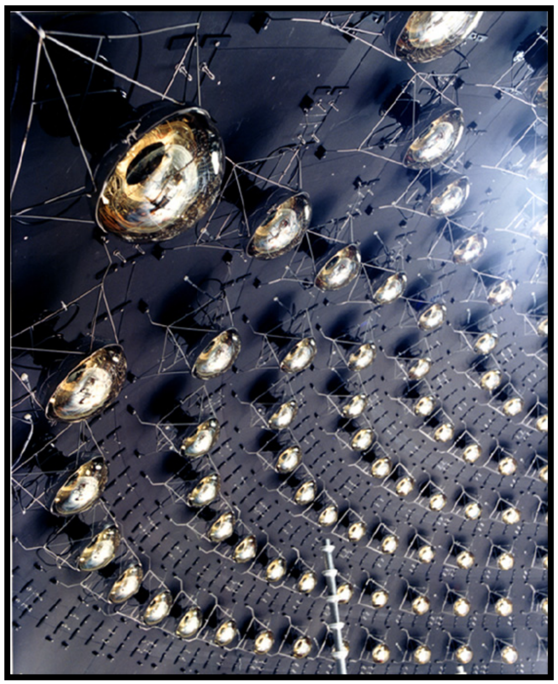


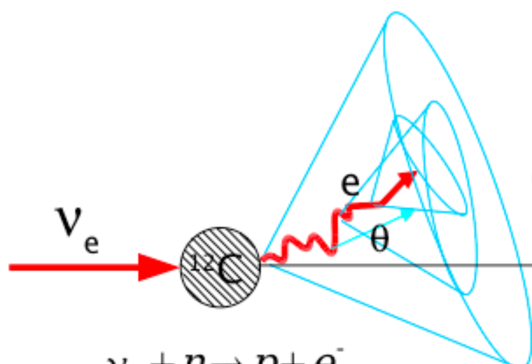
$$\nu_\mu + n \rightarrow p + \mu^-$$



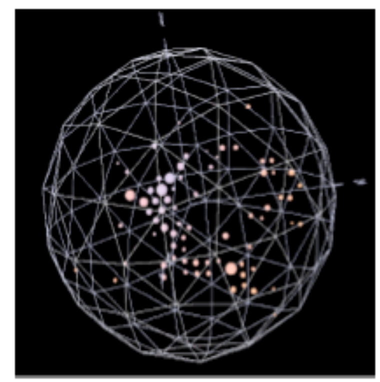


$$E_\nu^{QE} = \frac{1}{2}\frac{2ME_l - m_l^2}{M - E_l + P_l \cos\theta_e}$$





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



$$E_\nu^{QE} = \frac{1}{2}\frac{2ME_l - m_l^2}{M - E_l + P_l \cos\theta_e}$$