Neutrino Physics

What’s a “Neutrino” and How does it Interact?

CTEQ SS09

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Objectives of this Lecture

- Birth of Neutrino Physics
- Growing Pains - the puzzles come much more rapidly than the solutions
- Vocabulary of Neutrino Oscillation Physics
- Where do we stand today with neutrino oscillations - the current challenges
- Now that we know - pretty much - what a neutrino is, how do neutrinos interact with matter and contribute to QCD studies

Neutrinos Are Everywhere!

Neutrinos outnumber ordinary matter particles in the Universe (electrons, protons, neutrons) by a huge factor.

- Depending on their masses they may account for a fraction (% or two?) of the "dark matter"
- Neutrinos are important for stellar dynamics: $\sim 6.6\times10^{10}$ $cm^{-2}s^{-1}$ stream through the Earth from the sun. Neutrinos also govern Supernovae dynamics, and hence heavy element production.
- **To understand the nature of the Universe in which we live we must understand the properties of the neutrino.**

A bit of history… 1930 - Wolfgang Pauli

Dear Radioactive Ladies and Gentlemen….

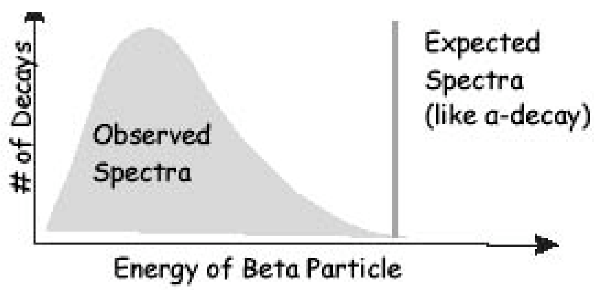
Dear Radioactive Ladies and Gentlemen,

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



Within a year Pauli was under analysis with C. Jung

N. Bohr suggested energy not conserved in β decays

L. Meitner proposed β^- loses energy through secondary interactions in nulceus yielding gamma rays

First Calculation of Neutrino Cross Sections

Bethe-Peierls (1934): calculation of first cross-section for inverse beta reaction using Fermi's theory for:

$$\bar{\nu}_e + p \rightarrow n + e^+ \quad \text{or} \quad \nu_e + n \rightarrow p + e^-$$

yields:

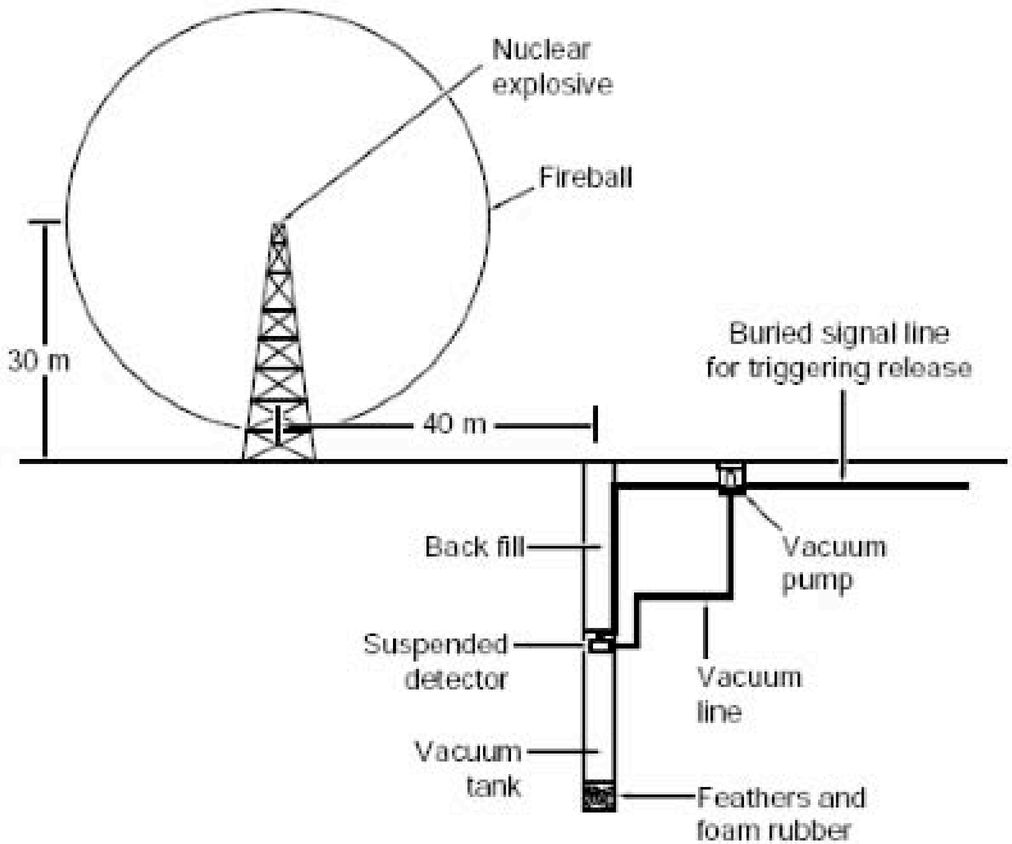
$$\sigma \approx 10^{-44}\ cm^2 \quad \text{for} \quad E(\bar{\nu}) = 2\ MeV$$

This means that the mean free path of a neutrino in water is:

$$\lambda = \frac{1}{n\sigma} \approx 1.5 \times 10^{21}\ cm \approx 1600 \quad light - years$$

Experimentalists groaned - need a very intense source of ν's to detect inverse Beta decay

Project Poltergeist from 1951



I. Explode bomb
II.At same time let detector fall in vacuum tank
III. Detect neutrinos
IV. Collect Nobel prize

OK – but repeatability is a bit of a problem

They Finally Found the Right Source - Experimental Detection of the Neutrino

In nuclear reactors fission of $_{92}U^{235}$ produces chain of beta reactions

1

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

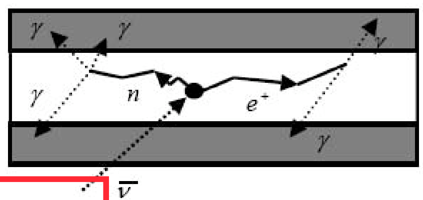
$$N_{\bar{\nu}} \approx 5.6 \times 10^{20}\ s^{-1}\ in\ 4\pi$$

26 YEARS LATER!!

Reines and Cowan detect in 1953 (Hanford) (discovery confirmed 1956 in Savannah River)

1) Detection of two back-to-back γ's from prompt signal e+e-->γγ at t=0.

2) Neutron thermalization: neutron capture in Cd, emission of late γ's



$\sigma = (11 \pm 2.6) \times 10^{-44}\ cm^2$ (within 5% of expected)

2 Existence of "second" neutrino ν_μ established in 1962 by Schwartz, Lederman and Steinberger at Brookhaven National Laboratory

3 First direct evidence for the third (and last?) neutrino - ν_τ - by the DONUT collaboration at Fermilab in 2000

Where the Puzzles Start…Solar Neutrinos

10^{12} solar ν's/sec pass through your brain

Nuclear reactions in the core of the sun produce ν_e and only ν_e.

In 1968, Ray Davis' Homestake experiment measured the higher-E part of the ν_e flux ϕ_{ν_e} that arrives at earth using a huge tank of "cleaning fluid" and $\nu_e + {}^{37}Cl \longrightarrow {}^{37}Ar + e^-$

Theorists, especially John Bahcall, calculated the produced ν_e solar flux vs. E and predicted that Davis should see

36 Ar **atoms** per **month**.

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

What was going on?

The Possible Solutions:

The theory was wrong.

The experiment was wrong.

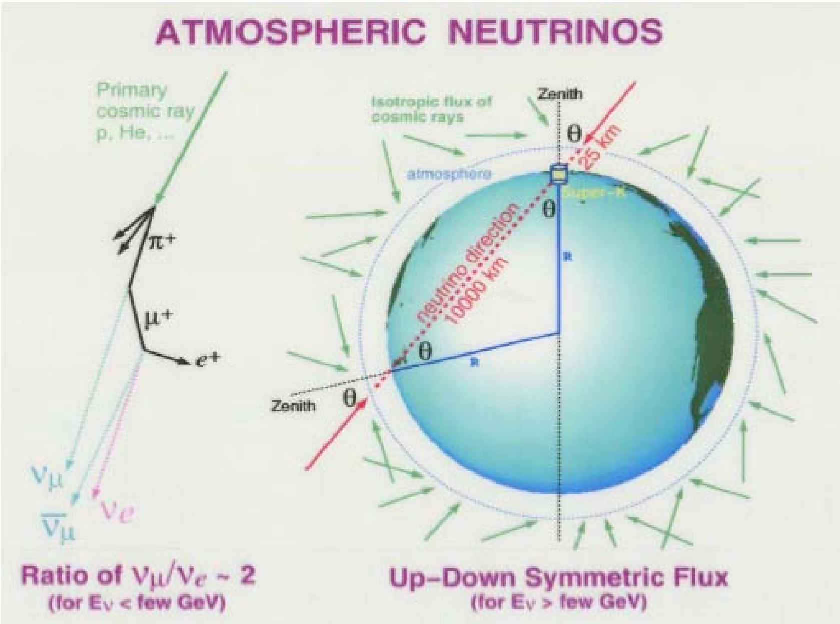
Both were wrong.

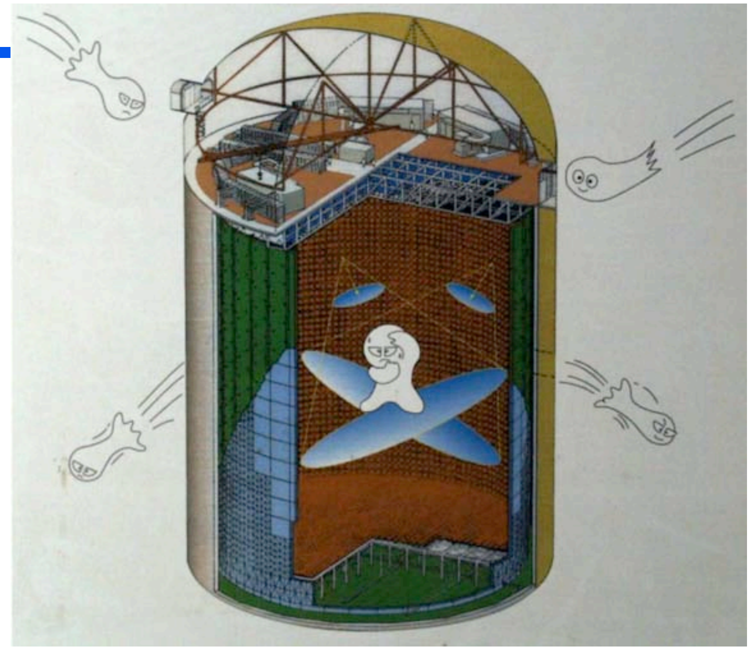
The most radical - NEITHER was wrong.

2/3 of the solar ν_e flux “disappears” on the way to earth

(changes into something that the Homestake experiment could not see).

Next Puzzle - Atmospheric Neutrinos





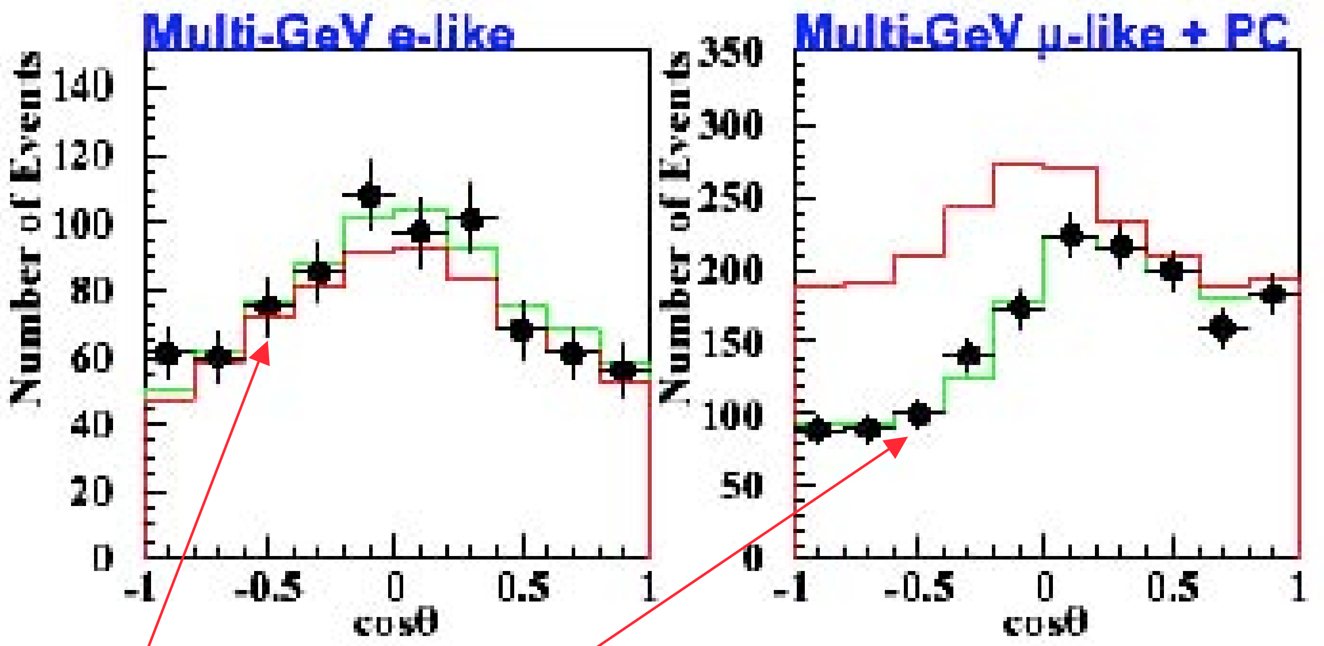
2 GeV cosmic rays hit the earth isotropically, and we expect:

$$\Rightarrow \frac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} \approx 1.0$$

However, Super-Kamiokande (50 kT water) found for $E_\nu > 1.3$ GeV

$$\frac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} = 0.54 \pm 0.04 \,.$$

Resolution of the Atmospheric Neutrino Anomaly



Upward-going muon neutrinos depleted, while upward-going electron neutrinos slightly higher than expected

VERY suggestive of Neutrino Oscillations

Green curve in above figures

Resolution of Solar Neutrino Puzzle:

Neutrinos Change Flavor Between the Sun and the Earth

Sudbury Neutrino Observatory (SNO) measures (high E part):

$$\nu_{sol}\, d \rightarrow e\, p\, p \;\Rightarrow\; \phi_{\nu_e}$$

$$\nu_{sol}\, d \rightarrow \nu\, n\, p \;\Rightarrow\; \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} \quad \text{Total } \nu_{sol} \text{ flux}$$

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

Smiling John

Total Flux of Neutrinos

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

Theory: $\phi_{total} = (5.69 \pm 0.91) \times 10^6/\text{cm}^2\text{sec}$

BOTH RAY DAVIS AND JOHN BAHCALL WERE RIGHT

Oscillation Hypothesis confirmed by KamLAND Reactor Results

What are Neutrino Oscillations ?

- Difference between:
  - flavor states; ν_L interacts with matter it yields a charged lepton of flavor L and
  - Mass states; ν_L need not be a mass eigenstate but rather a superposition of mass eigenstates, at least 3 mass eigenstates and perhaps more.

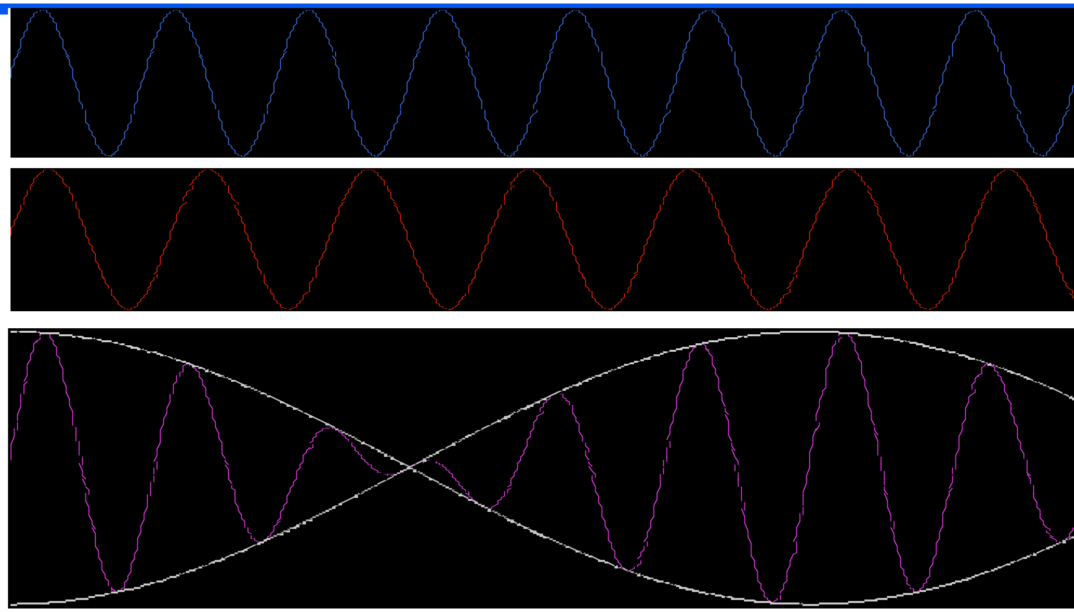
$$|\nu_l\rangle = \sum_m U_{lm} |\nu_m\rangle$$

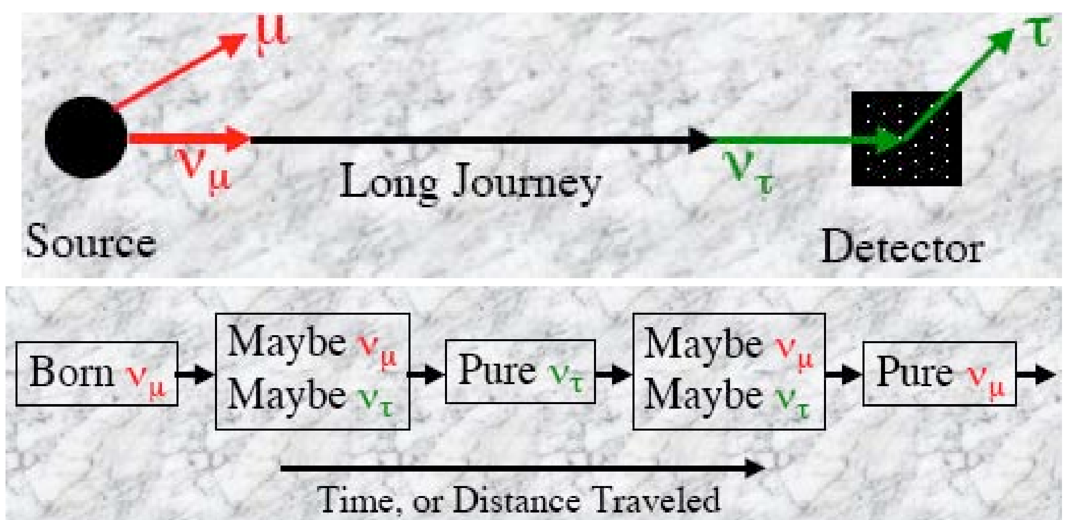
- The U_{lm} are known as the leptonic mixing matrix U.
- If ν_l is a superposition of several mass states with differing masses which cause them to propagate differently, we have neutrino oscillations.
- The amplitude for the transformation $\nu_L \dashrightarrow \nu_{L'}$ is:

$$A(\nu_l \rightarrow \nu_{l'}) = \sum A(\nu_l \text{ is } \nu_m) A(\nu_m \text{ propagates}) A(\nu_m \text{ is } \nu_{l'})$$

$$A(\nu_m \text{ propagates}) = \exp\left(-i \frac{M_m^2}{2} \frac{L}{E}\right)$$

Oscillating between two different types of ν





Neutrino Oscillation: continued

- As an example, if there are only two flavors involved in the oscillations then the U matrix takes on the following form and the probability (square of the amplitude) can be expressed as:

$$U = \begin{pmatrix} \cos\theta & e^{i\delta}\sin\theta \\ -e^{-i\delta}\sin\theta & \cos\theta \end{pmatrix} \quad \text{and}$$

$$P(\nu_1 \to \nu_{1'}) = \boxed{\sin^2 2\theta} \sin^2\left[1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right]$$

$$\text{with} \quad \boxed{\Delta m^2 \equiv M_2^2 - M_1^2}$$

- Life is more complicated with 3 flavors, but the principle is the same and we get bonus of possible CP violations as in the quark sector $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$.

- The components of U now involve θ_{13} , θ_{23} ,θ_{12} and δ and the probabilities involve Δm_{13} , Δm_{23} and Δm_{12} .

Basic 3-flavor Oscillation Phenomenology

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$ $s_{ij} = \sin\theta_{ij}$

"Solar" "Atmospheric CP Violation "????"

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)}(x) = s_{23}^2 \sin^2 2\theta_{13} \sin^2\left[\frac{\Delta m_{23}^2}{4E}x\right]$$

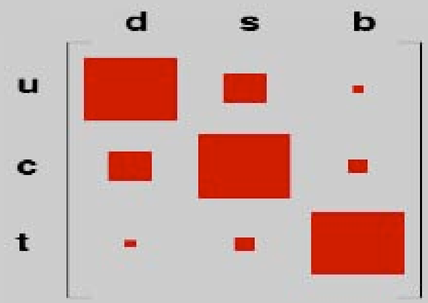
$$P_{\nu_e\nu_\tau(\bar{\nu}_e\bar{\nu}_\tau)}(x) = c_{23}^2 \sin^2 2\theta_{13} \sin^2\left[\frac{\Delta m_{23}^2}{4E}x\right]$$

$$P_{\nu_\mu\nu_\tau(\bar{\nu}_\mu\bar{\nu}_\tau)}(x) = c_{13}^4 \sin^2 2\theta_{23} \sin^2\left[\frac{\Delta m_{23}^2}{4E}x\right]$$

$$\left|\Delta m_{12}^2\right| << \left|\Delta m_{23}^2\right|, \left|\Delta m_{13}^2\right| \approx \left|\Delta m_{23}^2\right|$$

The Neutrino Mixing matrix is quite different than the standard quark mixing matrix - why?

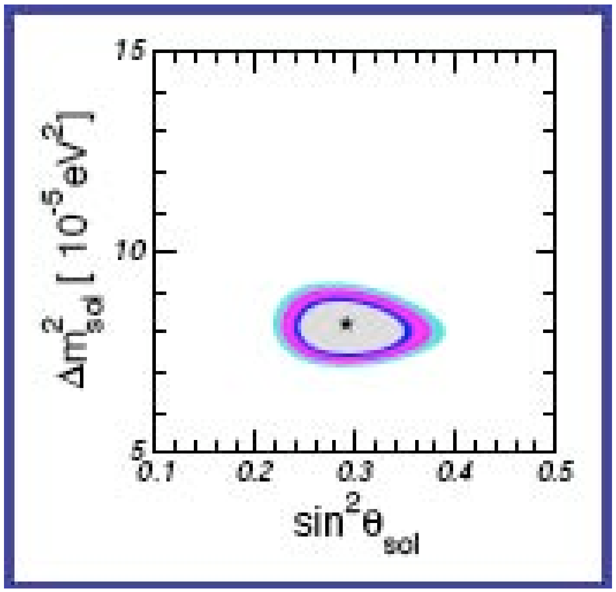
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

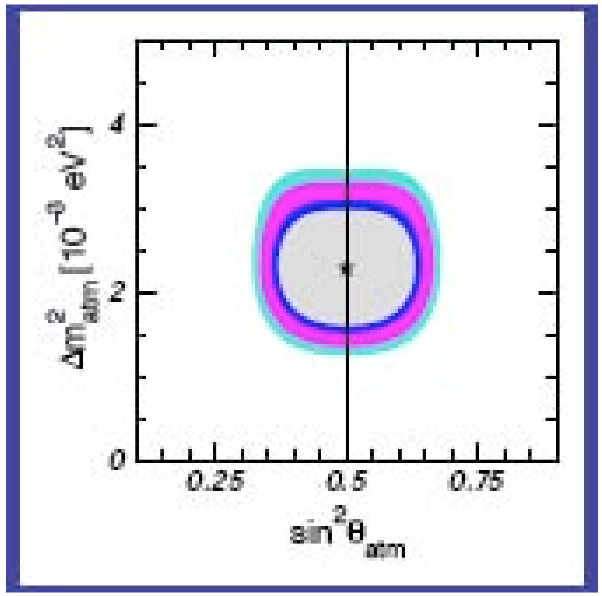


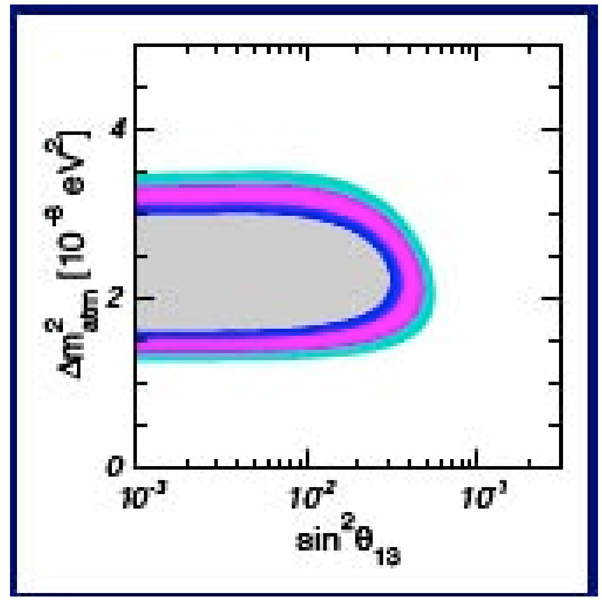
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & >0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

How are experimental neutrino oscillation results presented?







"Solar"

$\Delta m_{12} = (7.9 \pm 0.3) \times 10^{-5}\ eV^2$

$\sin^2\Theta_{12} = (0.31 \pm .03)$

Solar + KamLAND

"Atmospheric

$\Delta m_{23} = (2.2\ ^{+.37}_{-.27}) \times 10^{-3}\ eV^2$

$\sin^2\Theta_{23} = (0.50 \pm .06)$

SuperK + K2K

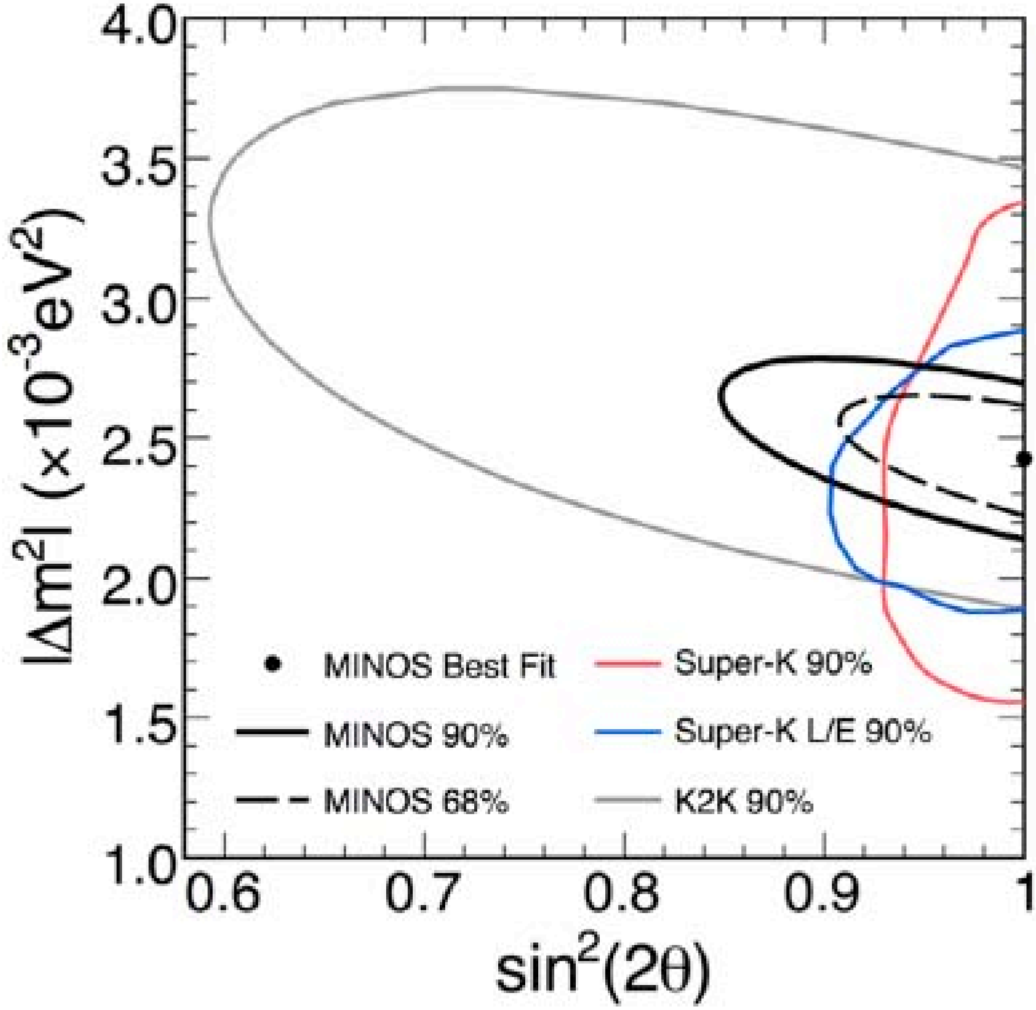
$\nu_e \longleftrightarrow \nu_{\mu/\tau}$ Osc.

$\Delta m_{13} \approx \Delta m_{23}$

$\sin^2\Theta_{13} < 0.046\ (3\sigma)$

Chooz

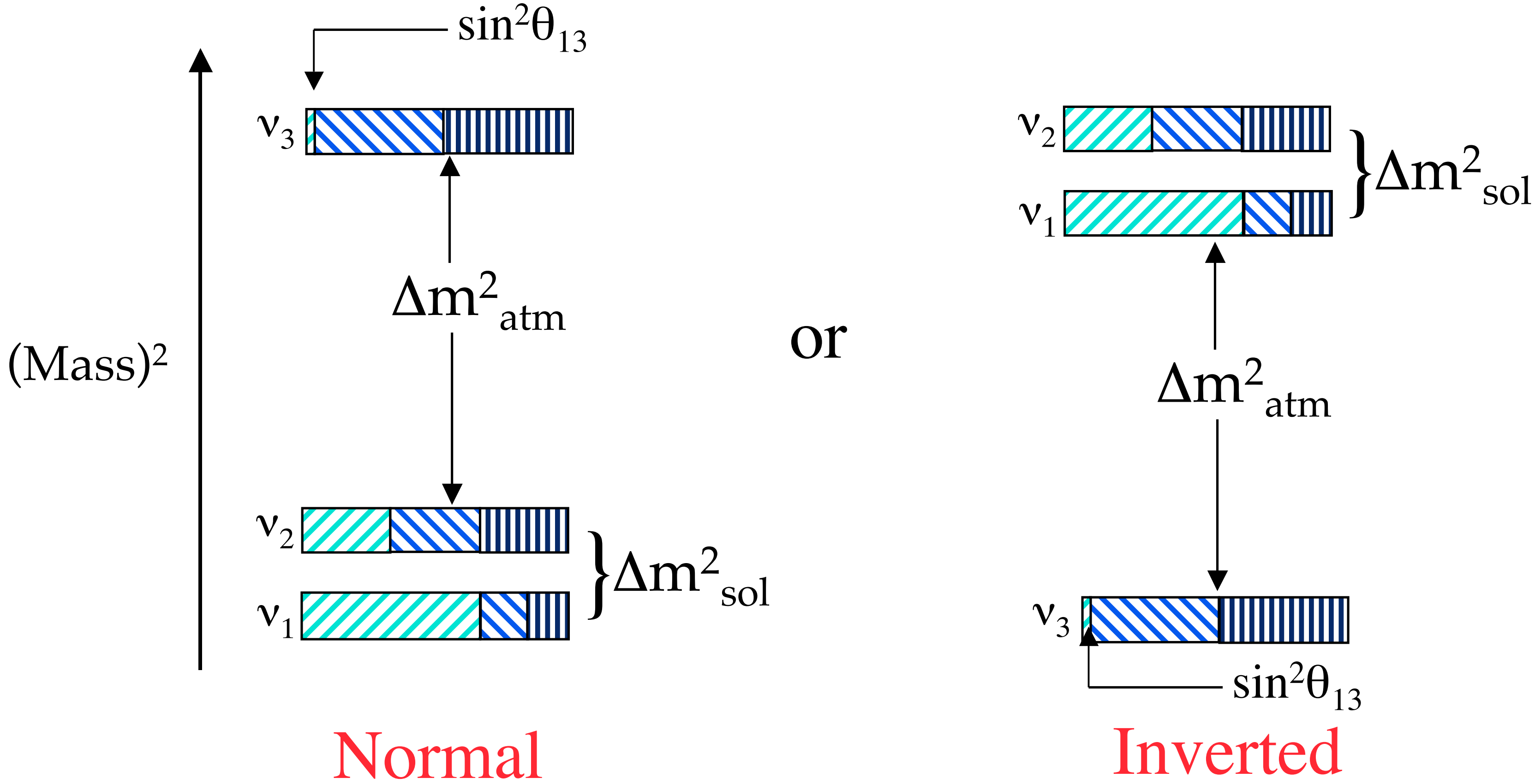
Latest MINOS Results - $3.3x10^{20}$ POT



- Fit includes systematic penalty terms
- Fit is constrained to physical region: $\sin^2(2\theta_{23})\leq 1$
  - Best physical fit: $|\Delta m|^2 = 2.43 \times 10^{-3}$ eV^2 $\sin^2(2\theta)=1.00$
  - Unconstrained: $|\Delta m|^2 = 2.33 \times 10^{-3}$ eV^2 $\sin^2(2\theta)=1.07$ $\Delta\chi^2=-0.6$

In PRL v**101**, 131802. (2008)
(arXiv:hep-ex/0806.2273)

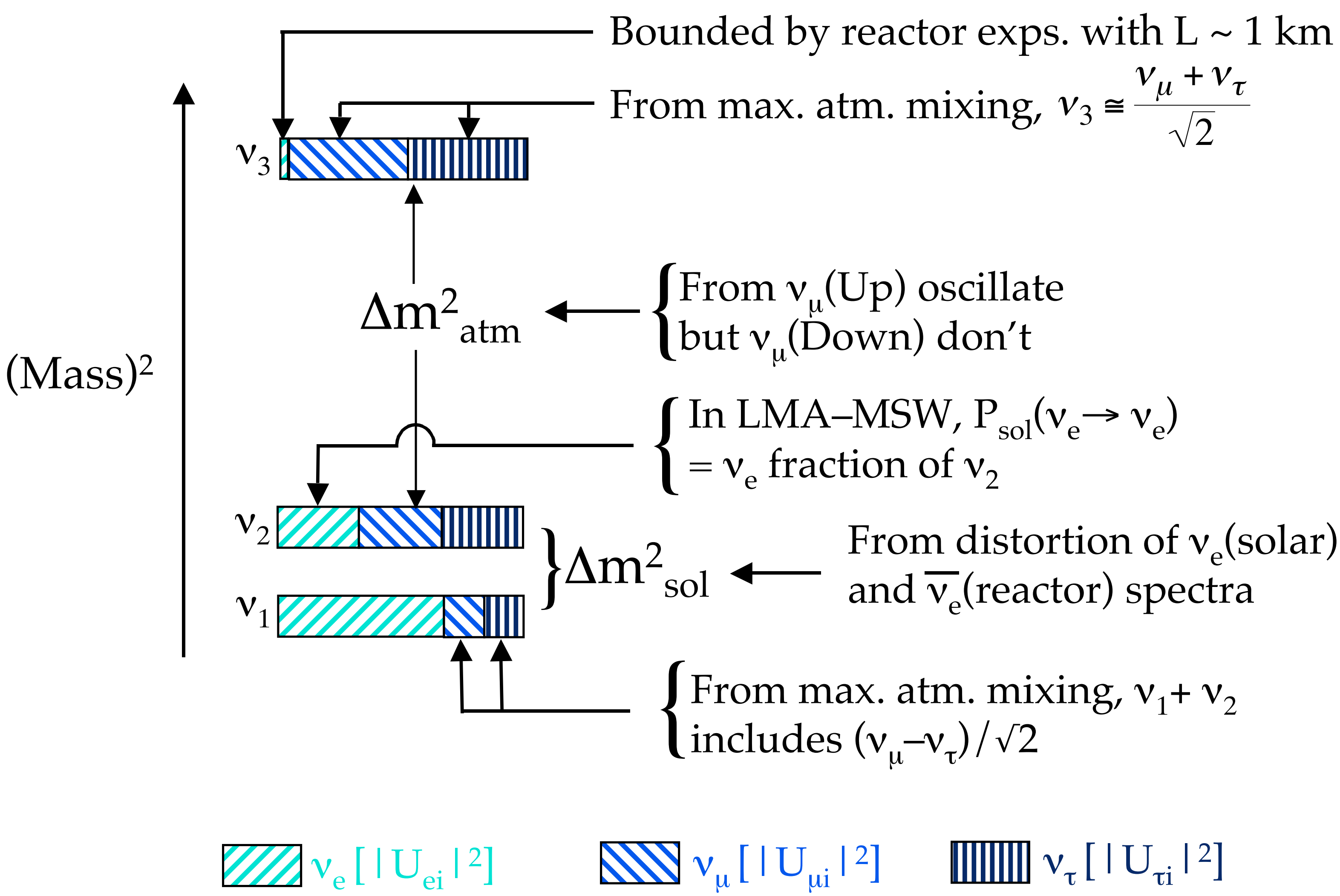
Sum of our knowledge to date…



$\Delta m^2_{sol} = \sim 8 \times 10^{-5}\ \text{eV}^2$, $\Delta m^2_{atm} = \sim 2.5 \times 10^{-3}\ \text{eV}^2$

$\nu_e\ [\,|U_{ei}|^2]$ $\nu_\mu[\,|U_{\mu i}|^2]$ $\nu_\tau\ [\,|U_{\tau i}|^2]$

Where Does This Come From?



Neutrino Oscillations:
Current Challenges: Where are we going from here?

- The dominant oscillation parameters will be known reasonably well from solar/reactor ν and from SuperK, K2K, MINOS, CNGS
  - Increase the precision on the "Solar" and "Atmospheric" parameters - is θ_{23} exactly 45°??
- The physics issues to be investigated are clearly delineated:
  - Need measurement of missing oscillation probability ($\theta_{13} = \theta_{\mu e}$)
  - Need determination of **mass hierarchy** (sign of Δm_{13})
  - Search for **CP violation** in neutrino sector
  - Measurement of **CP violation parameters - phase δ**
  - Testing **CPT** with high precision

Above can be accomplished with the $\nu_\mu \Rightarrow \nu_e$ transition.

How do we measure this sub-dominant oscillation?

- θ_{13} small (≤ 0.1) - maximize flux at the desired energy (near oscillation max)
- Minimize backgrounds - narrow energy spectrum around desired energy
- **One wants to be below τ threshold to measure subdominant oscillation**

$P(\nu_\mu \rightarrow \nu_e)$ on one slide (3 generations)

$P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$

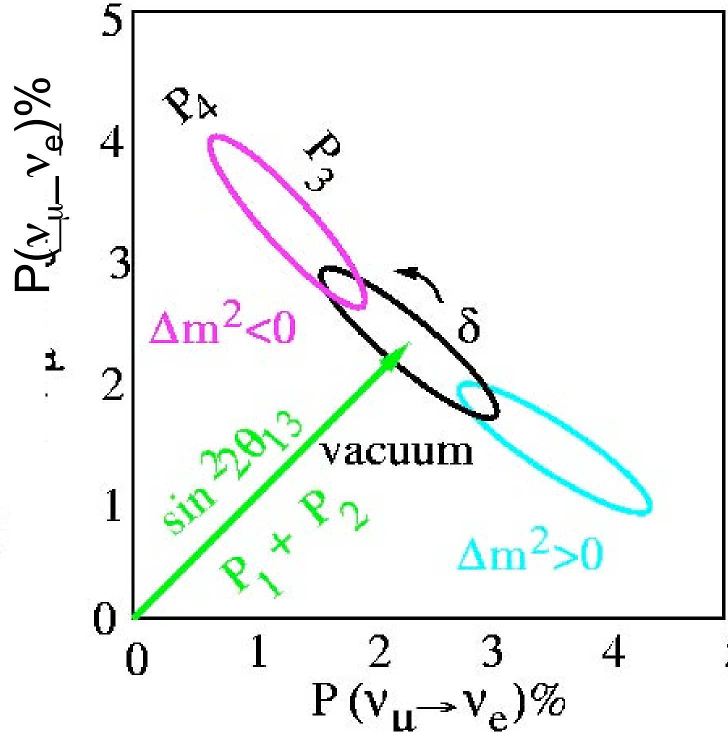
$$P_1 = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2\sin^2\frac{B_\pm L}{2}$$ Atmospheric

$$P_2 = \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\frac{AL}{2}$$ Solar

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

Atmospheric-solar interference

$$P_4 = \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$



Minakata & Nunokawa JHEP 2001

$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$$
$$A = \sqrt{2}G_F n_e$$

$$B_\pm = |A \pm \Delta_{13}|$$
$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

The $\pm$ is ν or $\overline{\nu}$

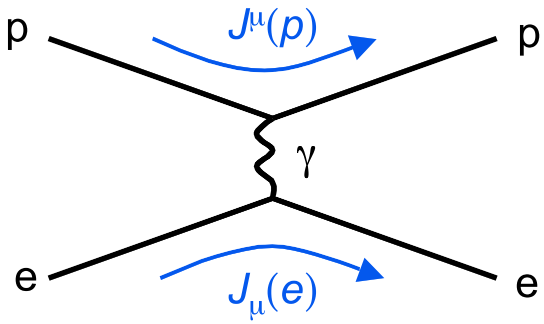
Fine, we think we know what a neutrino IS

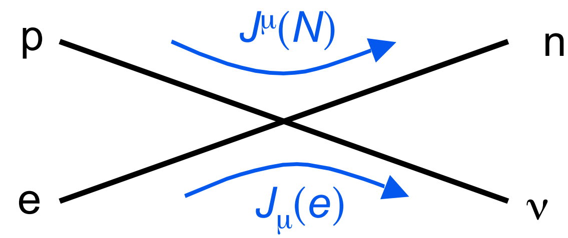
How do we use them to study QCD?

Fermi Theory - Current-Current Interaction

1934 Paper rejected by *Nature* because it contains speculations too remote from reality to be of interest to the reader!!

Developed by Fermi in 1932 to describe nuclear β-decay inspired by the success of "current-current" description of electromagnetic interactions:





$$M_{em} = \left(e\bar{u}_p\gamma^{\mu}u_p\right)\left(\frac{-1}{q^2}\right)\left(-e\bar{u}_e\gamma_{\mu}u_e\right)$$

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

$$\mathcal{H}_{weak} = \frac{G_F}{\sqrt{2}}\left[\bar{l}\gamma_{\mu}(1-\gamma_5)\nu\right]\left[\bar{f}\gamma^{\mu}(V-A\gamma_5)f\right] + h.c.$$

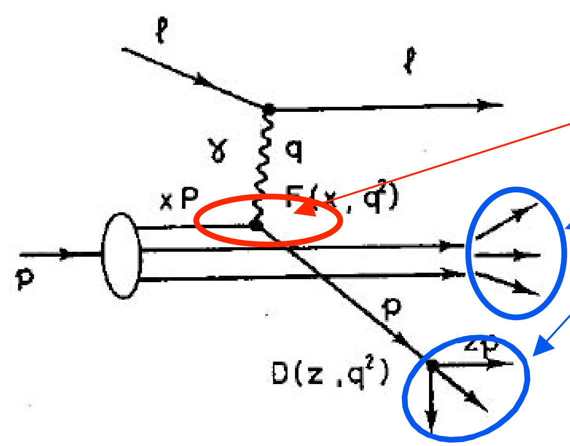
Weak interactions are maximally parity violating: $J_{\mu} \propto \left(\bar{u}_{\nu}\gamma_{\mu}(1-\gamma_5)u_e\right)$

Only left-handed fermions, and right-handed anti-fermions, participate in the CC weak interaction!

How does Neutrino Scattering Contribute to Studies of QCD?

- QCD Factorization means that we can treat the scattering and later processes separately, they occur on very different timescales:

$$A(l+h\rightarrow l+X)=\sum_q\int dx A(l+q(x)\rightarrow l+X)q_h(x)$$



hard scatter: fast

fragmentation: slow

Justification for summing probabilities rather than amplitudes for ν−q scattering.

Justification for QCD factorization and other aspects of the parton model come from formal approaches, namely the operator product expansion of the hadronic tensor.

The Cross section for DIS

- The structure functions can also be written in terms of the cross sections for absorption of different polarization states of the exchanged boson.

$$R = \frac{\sigma_L}{\sigma_T} = \left[\left(1 + \frac{4m_p^2 x^2}{Q^2}\right) F_2 - 2xF_1\right] / 2xF_1$$

$$F_1 = \frac{(2m_p\nu - Q^2)}{8\pi^2\alpha}\sigma_T$$

$$F_2 = \frac{(2m_p\nu - Q^2)}{8\pi^2\alpha}\frac{Q^2}{(Q^2+\nu^2)}\frac{\nu}{m_p}(\sigma_T + \sigma_L).$$

- Callen-Gross relation: $F_2 = 2xF_1$ (R=0)

$$\frac{d^2\sigma^{\nu,\overline{\nu}}}{dx d\nu} = \frac{G^2 M}{\pi}\left[\left(1 - \frac{\nu}{E} - \frac{Mx\nu}{2E^2} + \frac{\nu^2}{2E^2}\frac{1 + 2Mx/\nu}{1+R}\right)F_2(x) \pm \frac{\nu}{E}\left(1 - \frac{\nu}{2E}\right)xF_3(x)\right]$$

ignoring lepton mass terms which bring in 3 additional structure functions.

ν-quark Scattering

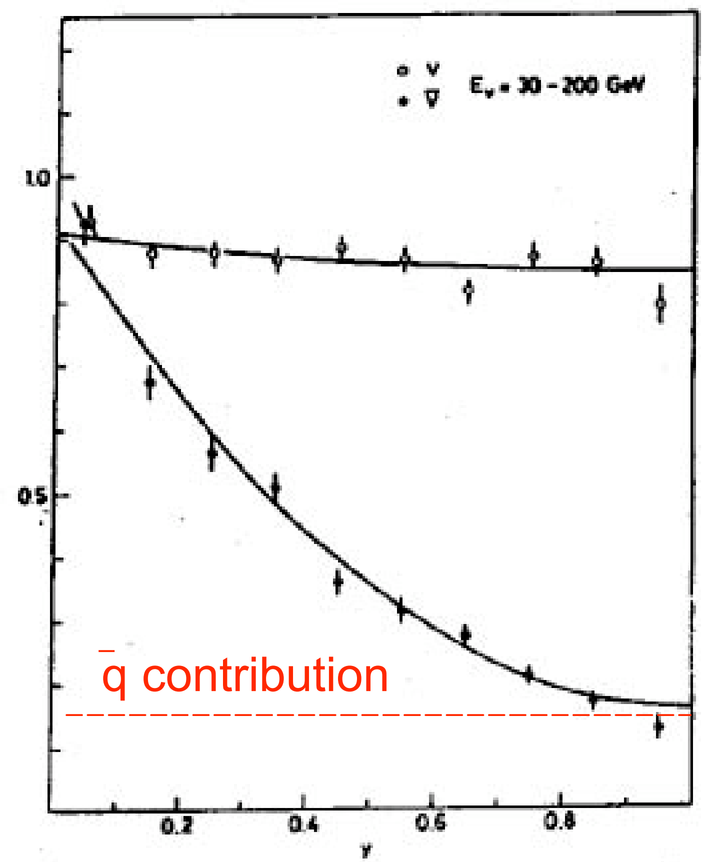
- From our discussion of neutrino-electron scattering we found that the helicity combinations (LL,RR = νq, $\bar{\nu}\bar{q}$) are J=0 combinations with flat-y dependence, and LR,RL combinations ($\bar{\nu}$q, ν$\bar{q}$) are J=1 combinations with $(1\text{-}y)^2$ dependence.

- From weak-isospin we see that neutrinos scatter from T_3=-1/2, anti-nu from T_3=+1/2

$$\frac{d\sigma^{\nu p}}{dxdy} = \frac{G^2 s}{\pi}\left(xd(x) + xs(x) + x\bar{u}(x)(1-y)^2\right)$$

$$\frac{d\sigma^{\bar{\nu} p}}{dxdy} = \frac{G^2 s}{\pi}\left(x\bar{d}(x) + x\bar{s}(x) + xu(x)(1-y)^2\right)$$

(ignoring c, b,t quarks., c quark mass)



Structure Functions and PDFs

$$F_2^{\nu,\bar{\nu}} = 2\sum_i x(Q_i(x) + \bar{Q}_i(x))$$

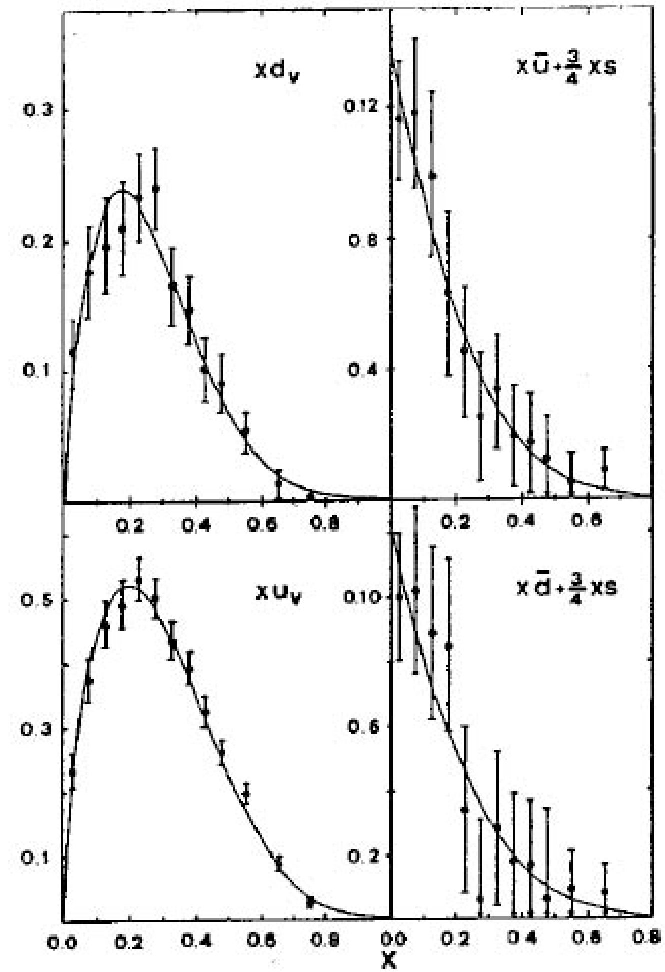
$$xF_3^{\nu,\bar{\nu}} = 2\sum_i x(Q_i(x) - \bar{Q}_i(x))$$

- Parton distributions are usually written for the proton, neutron PDFs are given by isospin symmetry: $u_n(x) = d_p(x)$ etc.

- Since we are usually scattering from targets with roughly equal numbers of neutrons and protons it is often convenient to talk about scattering from an "isoscalar" target.

$\sigma_N = (\sigma_p + \sigma_n)/2$

- For targets like iron with a neutron excess a small correction is applied to achieve this.



WA25 - CERN

Neutrino Structure Functions Wonderfully Efficient in Isolating Quark Flavors

Recall 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 $\bar{s}$.

Using Leading order expressions:

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

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

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

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

Taking combinations of the Structure functions

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

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

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

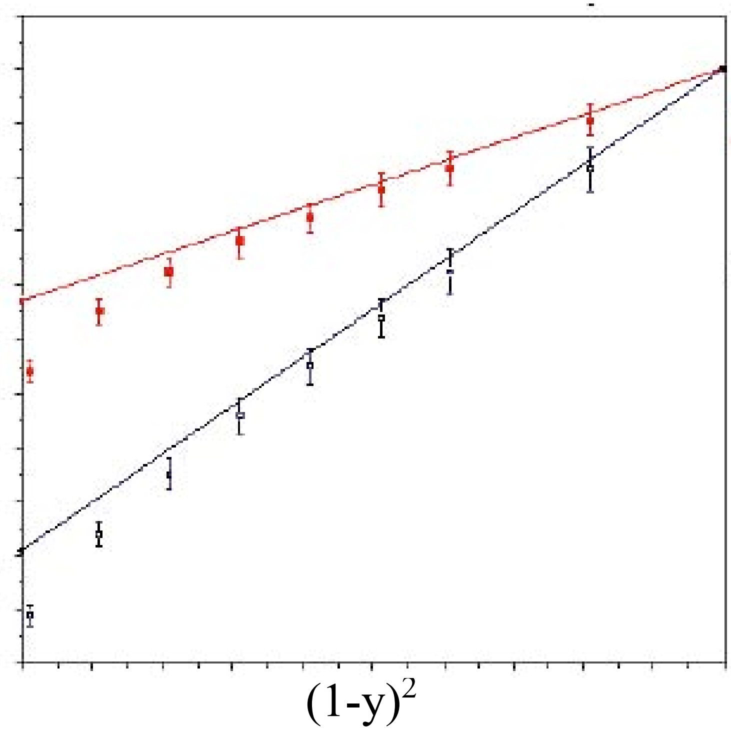
Structure Function Extraction

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

$+ y^2 F_L$

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

$$\frac{\sigma\left(x,Q^2,(1-y)^2\right)}{G^2/2\pi x}$$



Neutrino
Statistical + 5% systematic

Anti-Neutrino
Statistical only

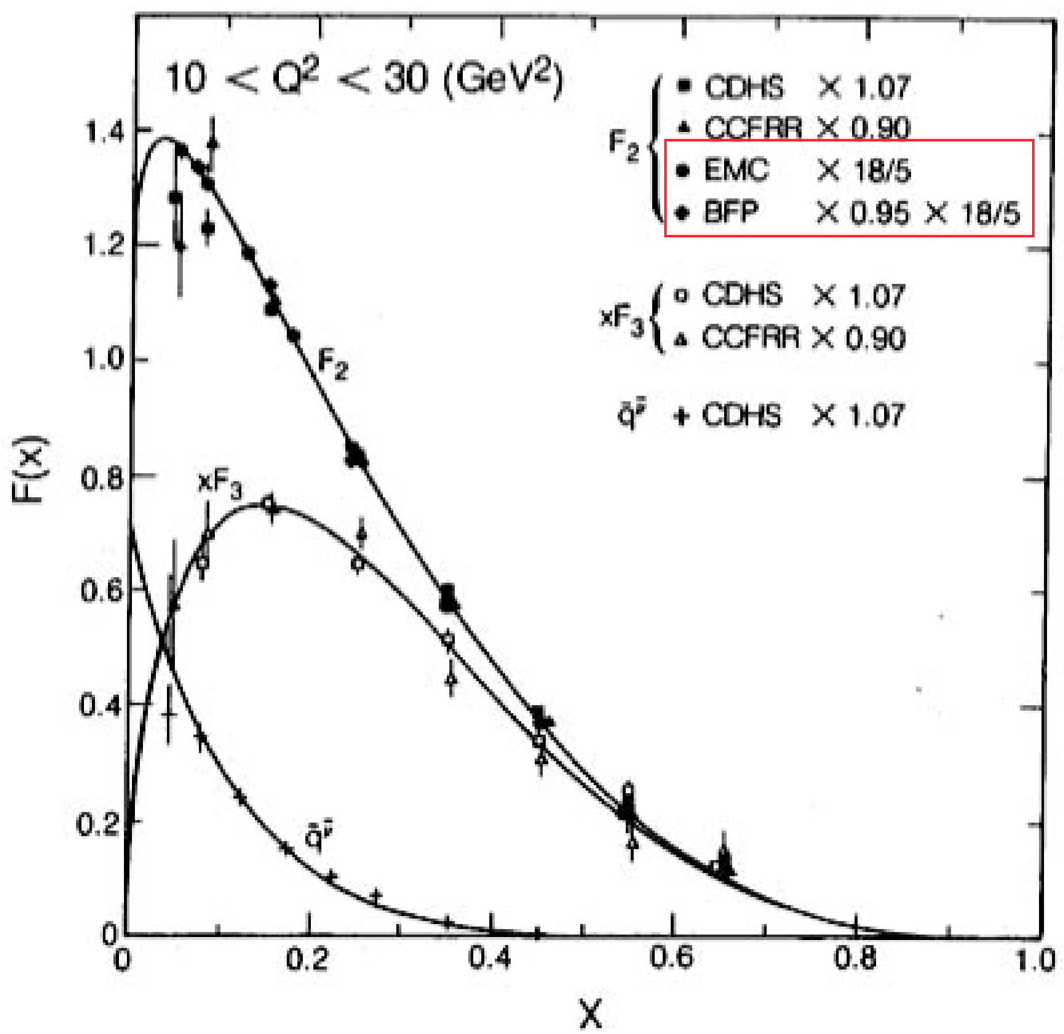
$R = R_{whitlow}$

$X = 0.1 - 0.125$
$Q^2 = 2 - 4\ GeV^2$

Meant to give an impression only!
Kinematic cuts in (1-y) not shown.

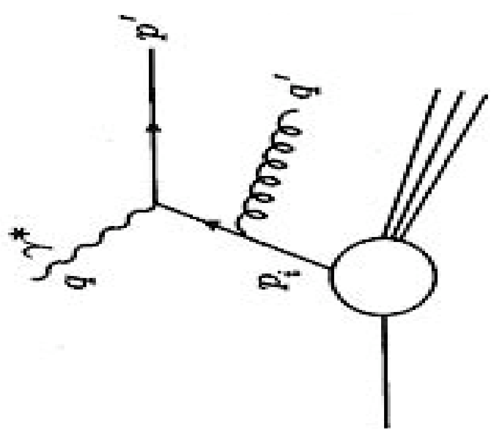
Momentum Distributions and Parton Universality

- It is straightforward to relate the structure functions from charged lepton and neutrino scattering.
- The fact that they are in good agreement justifies earlier claims of parton universality!



QCD and Scaling Violations

- At higher order in QCD the nucleon looks somewhat different



$$\alpha_s(Q^2) = 12\pi/[(33 - 2N_f)ln(Q^2/\Lambda^2)]$$

Calculations of the structure functions in terms of parton distributions now are somewhat more complicated and involve the "splitting functions"

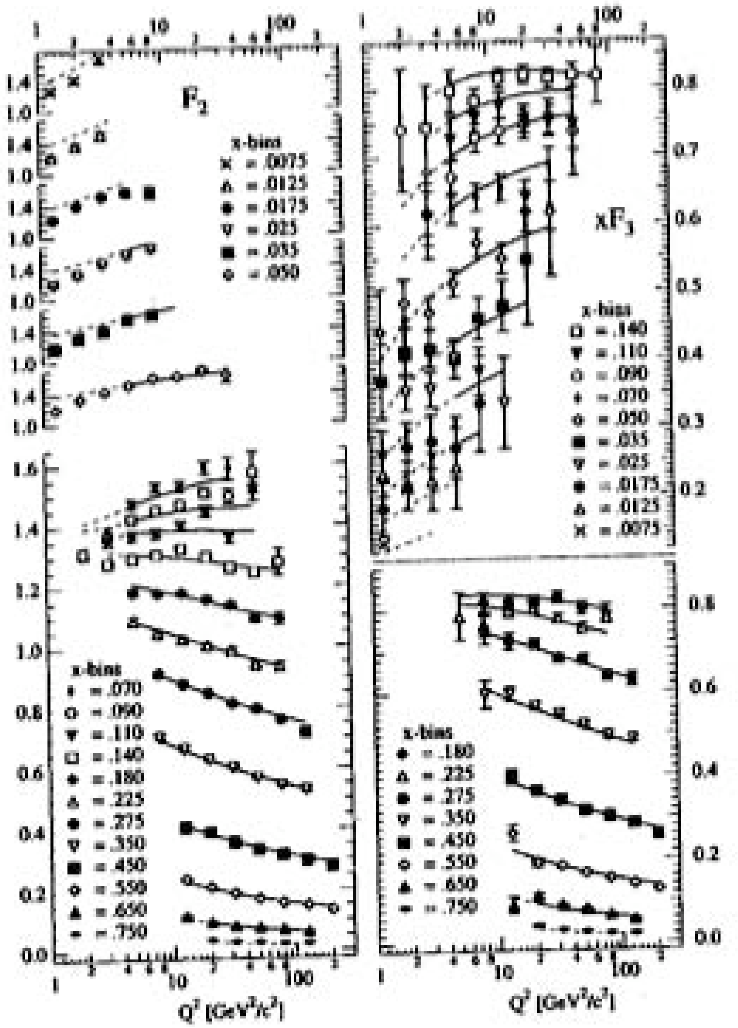
Pqq(x/y) = probability of finding a quark with momentum x within a quark with momentum y

Pgq(x/y) = probability of finding a quark with momentum x within a gluon with momentum y.

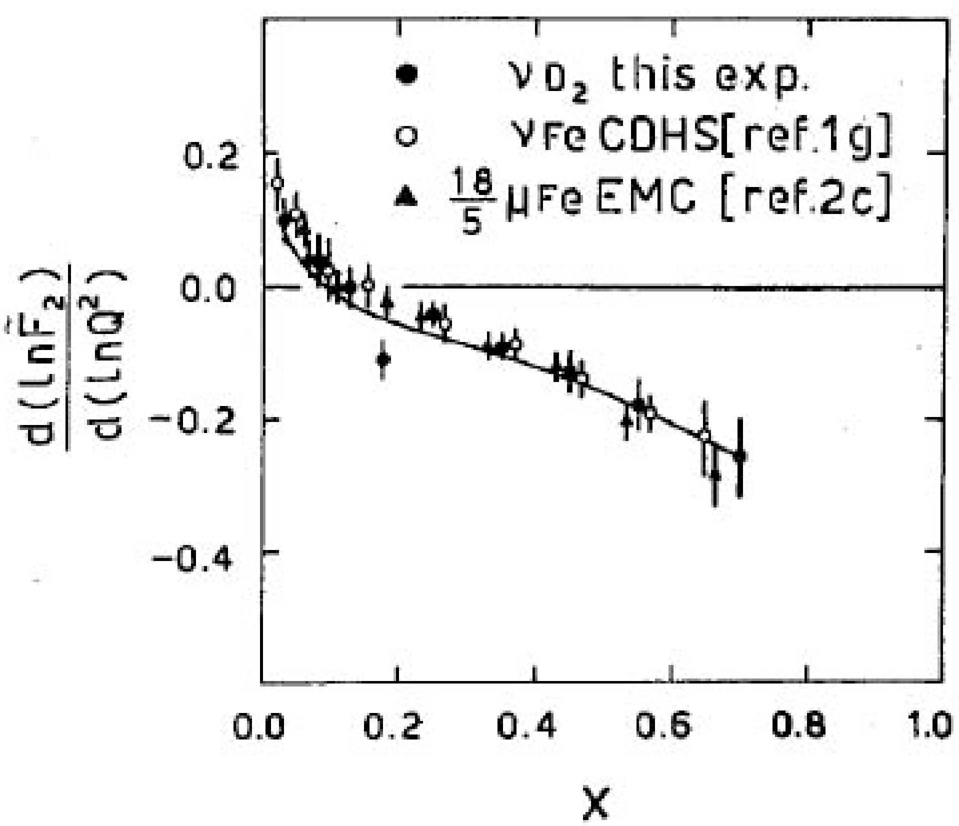
$$P_{qq}(z) = \frac{4}{3}\frac{1+z^2}{(1-z)} + 2\delta(1-z) \qquad P_{gq}(z) = \frac{1}{2}\left[z^2 + (1-z)^2\right]$$

QCD and ν scattering

- QCD therefore predicts the Q^2 evolution of the structure functions in terms of



$$\frac{\partial x F_3(x, Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_0^1 P_{qq}(x/y) x F_3(y, Q^2) dy/y$$

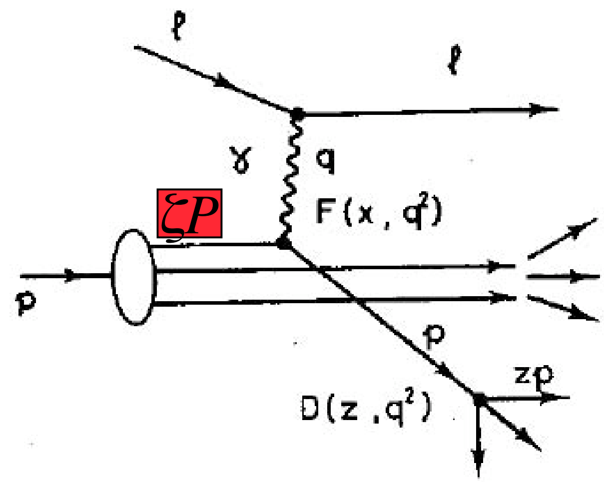


Heavy Quark Production

- Production of heavy quarks like charm requires a re-examination of the parton kinematics:

$$(q + \zeta p)^2 = m_c^2$$

$$q^2 + 2\zeta p \bullet q + \zeta^2 M^2 = m_c^2$$



$$\zeta \cong \frac{Q^2 + m_c^2}{2M\nu} = \frac{Q^2 + m_c^2}{Q^2 / x}$$

$$\zeta \cong x\left(1 + \frac{m_c^2}{Q^2}\right)$$

"slow rescaling" - The effects of the ~ 1 GeV charm mass are not negligible even at 100 GeV neutrino energy.

Charm identified through decays to μ+, di-muon events allow measurement of:

- CKM matrix elements
- m_c - from threshold behavior
- s and sbar quark distributions

Latest ν Scattering Results - NuTeV

Martin Tzanov

The NuTeV Experiment at Fermilab the most recent neutrino experiment to investigate QCD:

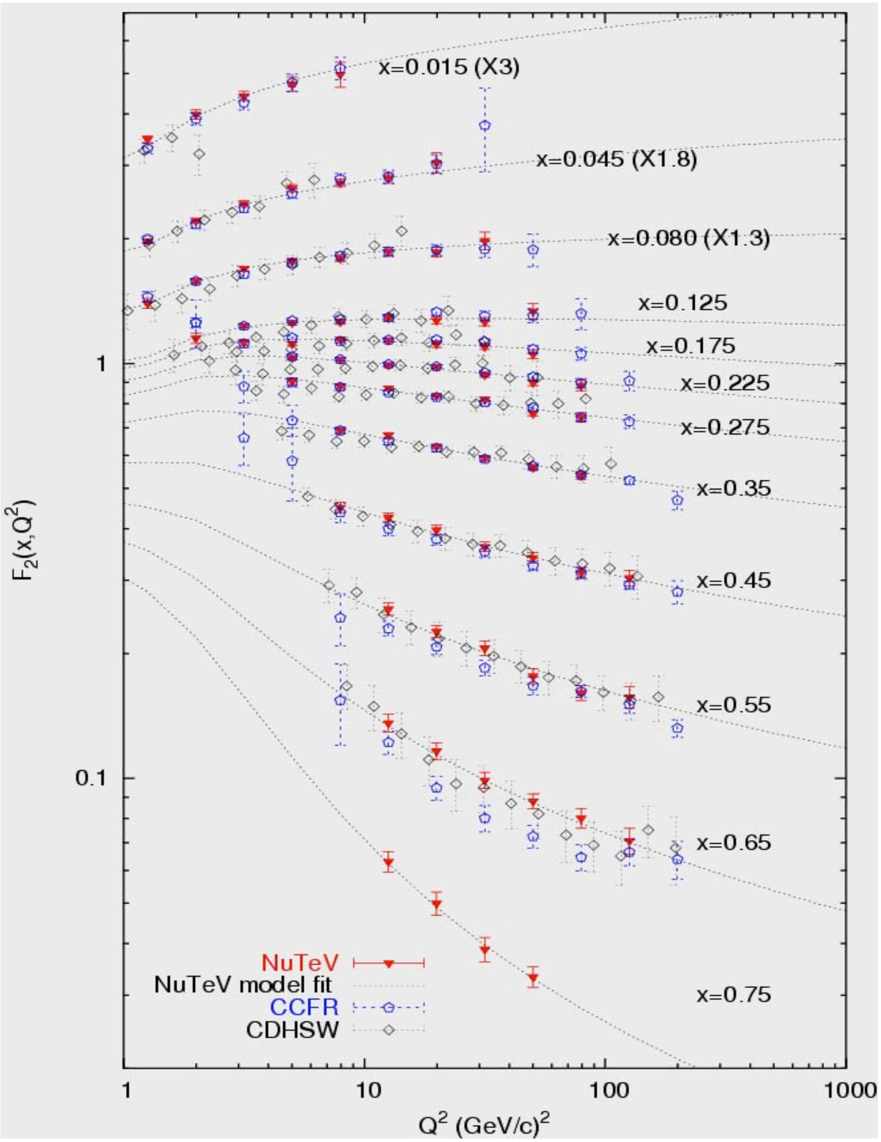
NuTeV accumulated over 3 million ν/ ν events with $20 \le E_\nu \le 400$ GeV.

NuTeV considered 23 systematic uncertainties.

NuTeV agrees with **charge lepton** data for $x < 0.5$.
Perhaps smaller nuclear correction at high-x for neutrino scattering.

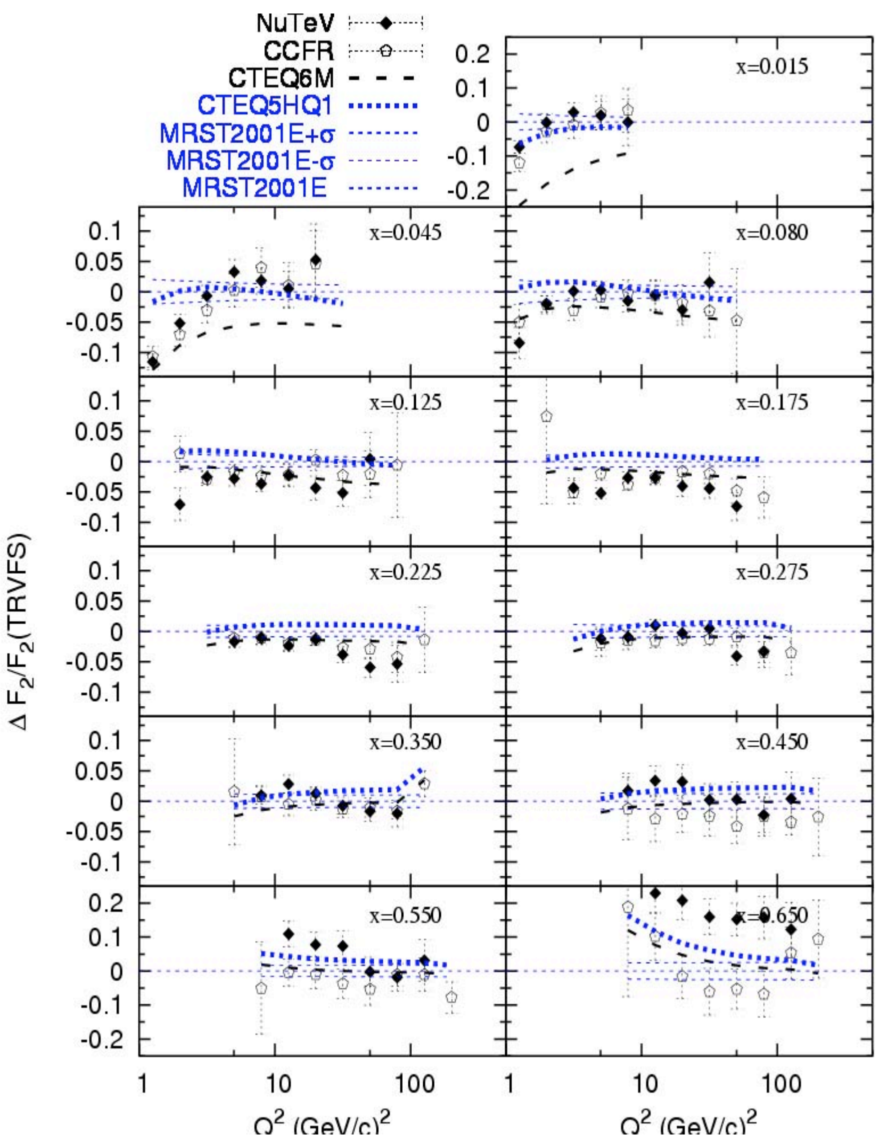
NuTeV F_2 and xF_3 agrees with **theory** for medium x.
At low x different Q^2 dependence.
At high x ($x>0.6$) NuTeV is systematically higher.

NuTeV F_2 Measurement on Iron



- **Isoscalar ν-Fe F_2**
- **NuTeV F_2 is compared with CCFR and CDHSW results the line is a fit to NuTeV data**
- **All systematic uncertainties are included**
- **All data sets agree for *x<0.4*.**
- **At *x>0.4* NuTeV agrees with CDHSW**
- **At *x>0.4* NuTeV is systematically above CCFR**

Comparison with Theory for F_2

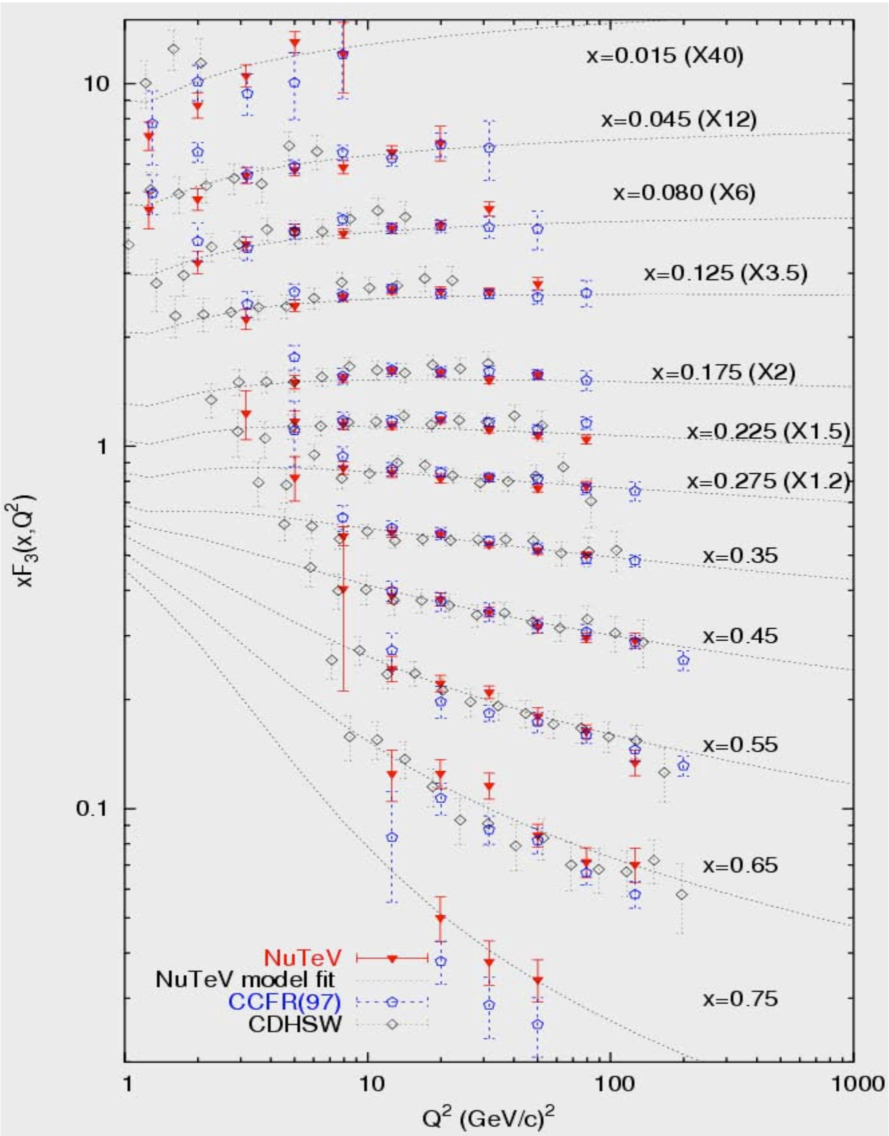


- **Baseline is TRVFS(MRST2001E)**
- **NuTeV and CCFR F_2 are compared to TRVFS(MRST2001E)**

$$\frac{F_2^{NuTeV} - F_2^{TRVFS}}{F_2^{TRVFS}}$$

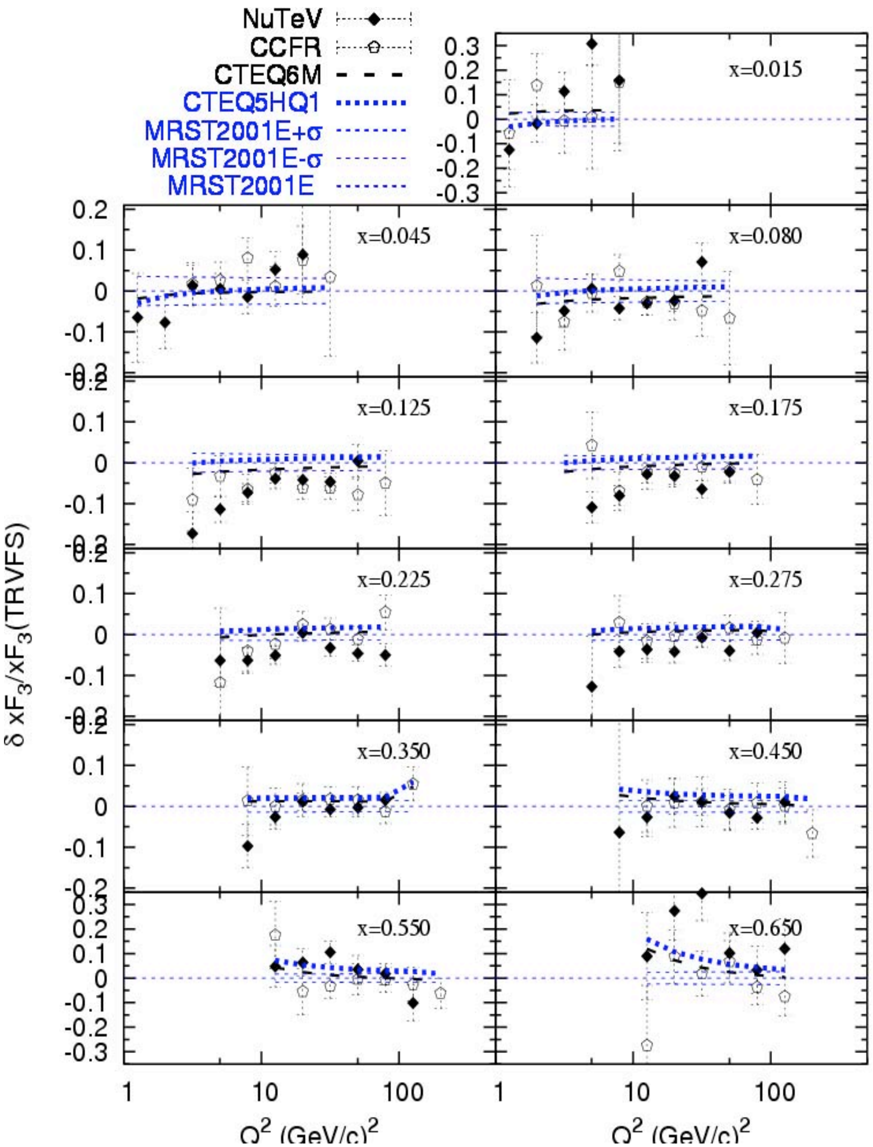
- **Theoretical models shown are:**
  - **ACOT(CTEQ6M)**
  - **ACOT(CTEQ5HQ1)**
  - **TRVFS (MRST2001E)**
- **Theory curves are corrected for:**
  - **target mass** *(H. Georgi and H. D. Politzer,*
- **NuTeV F_2 agrees with theory for medium x.**
- **At low x different Q^2 dependence.**
- **At high x >0.6) NuTeV is systematically higher.**
- **nuclear effects – parameterization from charge lepton data, assumed to be the same for neutrino scattering ---- WRONG!**

NuTeV xF_3 Measurement on Fe



- **Isoscalar ν-Fe xF_3**
- **NuTeV xF_3 is compared with CCFR and CDHSW results**
  - **the line is a fit to NuTeV data**
- **All systematic uncertainties are included**
- **All data sets agree for *x<0.4*.**
- **At *x>0.4* NuTeV agrees with CDHSW**
- **At *x>0.4* NuTeV is systematically above CCFR**

Comparison with Theory for xF_3



- **Baseline is TRVFS(MRST2001E).**
- **NuTeV and CCFR xF_3 are compared to TRVFS(MRST2001E)**

$$\frac{xF_3^{NuTeV} - xF_3^{TRVFS}}{xF_3^{TRVFS}}$$

- **Theoretical models shown are:**
  - **- ACOT(CTEQ6M)**
  - **- ACOT(CTEQ5HQ1)**
  - **- TRVFS (MRST2001E)**
- **theory curves are corrected for:**
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- **At low x different Q^2 dependence.**
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- **nuclear effects – parameterization from charge lepton data, assumed to be the same for neutrino scattering ---- WRONG!**

Summary

- **Very exciting times in Neutrino Physics**
- Neutrinos not only have surprised us with a small but significant mass but they are demonstrating mixing in a very different manner than quarks… why?
- Still many open questions in the neutrino sector? Very crucial but experimentally very difficult questions to answer:
  - The **NOνA Experiment** has the potential to measure the missing strength $\sin^2\theta_{13}$ and determine the order of neutrino mass states (sign of Δm_{13}). Will start taking data in 2011.
- Neutrinos, with their ability to taste particular quarks can add significantly to our QCD studies if we can only determine how nuclear effects mask their quark level interactions.

Milestones in the History of Neutrino Physics

- 1930 - Pauli postulates the existence of the neutrino
- 1934 - Enrico Fermi develops a comprehensive theory of radioactive decays, including Pauli's hypothetical particle, which Fermi coins the neutrino (Italian: "little neutral one").
- 1959 - Discovery of a particle fitting the expected characteristics of the neutrino is announced by Clyde Cowan and Fred Reines.
- 1962 - Experiment at Brookhaven National Laboratory discovered a second type of neutrino (ν_μ).
- 1968 - The first experiment to detect ν_e produced by the Sun's burning (using a liquid Chlorine target deep underground) reports that less than half the expected neutrinos are observed.
- 1985 - The IMB experiment observes fewer atmospheric ν_μ interactions than expected.
- 1989 - Kamiokande becomes the second experiment to detect ν_e from the Sun finding only about 1/3 the expected rate.
- 1994 - Kamiokande finds that ν_μ traveling the greatest distances from the point of production to the detector exhibit the greatest depletion.
- 1997 - Super-Kamiokande reports a deficit of cosmic-ray ν_μ and solar ν_e, at rates agreeing with earlier experiments.
- 1998 - The Super-Kamiokande collaboration announces evidence of non-zero neutrino mass at the Neutrino '98 conference.
- 2000 - First direct evidence for the ν_τ announced at Fermilab by DONUT collaboration.
- 2004 - K2K Experiment confirms (with limited statistics) Super -Kamiokande discovery .
- 2005 - MINOS starts data-taking to **STUDY** Neutrino Oscillation Phenomena

Probability for ν_e Apperance

$P(\nu_\mu \to \nu_e$ in vacumn$) = P_1 + P_2 + P_3 + P_4$

- $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$ "Atmospheric"
- $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$ "Solar"
- $P_3 = J \sin(\delta) \sin(1.27\ \Delta m_{13}^2\ L/E)$
- $P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{13}^2\ L/E)$

} Atmospheric-solar interference

where $J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \sin(1.27\ \Delta m_{13}^2\ L/E) \sin(1.27\ \Delta m_{12}^2\ L/E)$

In matter at oscillation maximum, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$ ($E_R \approx 11$ GeV for the earth's Crust), where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.

This is about ±30% effect for NuMI, about ±11% effect for T2K