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Neutrino Physics
(Lecture 1)

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Neutrino Physics

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Summer School on Particle Physics

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Tentative Outline for the Next Four Lectures

1. Brief History of the Neutrino;
2. Neutrino Puzzles – The Discovery of Neutrino Masses;
3. Neutrino Oscillations;
4. What We Know We Don't Know – Next-Generation ν Oscillations;
5. What We Know We Don't Know – Majorana versus Dirac Neutrinos;
6. Neutrino Masses As Physics Beyond the Standard Model;
7. Ideas for Tiny Neutrino Masses, and Some Consequences;
8. Comments on Lepton Mixing. (see Steve King's lectures)

[**note: Questions are ALWAYS welcome**]

Short, Biased List of Recent References:

- A. Strumia and F. Vissani, hep-ph/0606054;
- R. Mohapatra and A. Yu. Smirnov, hep-ph/0603118;
- R. Mohapatra *et al.*, hep-ph/0510213;
- AdG, hep-ph/0503086;
- AdG, hep-ph/0411274.

Neutrino History:

"Are There Really Neutrinos? – An Evidential History," Allan Franklin, Perseus Books, 2001.

1 - Brief History of the Neutrino

1. 1896: Henri Becquerel discovers natural radioactivity while studying phosphorescent properties of uranium salts.
   - α rays: easy to absorb, hard to bend, positive charge, mono-energetic;
   - β rays: harder to absorb, easy to bend, negative charge, spectrum?;
   - γ rays: no charge, very hard to absorb.
2. 1897: (J.J. Thompson discovers the electron.)
3. 1914: Chadwick presents definitive evidence for a continuos β-ray spectrum. Origin unkown. Different options include several different energy loss mechanisms.

It took 15+ years to decide that the "real" β-ray spectrum was really continuos. Reason for continuos spectrum was a total mystery:

- QM: Spectra are discrete;
- Energy-momentum conservation: $N \to N' + e^-$ — electron energy and momentum well-defined.

Nuclear Physics before 1930: nucleus $= n_p p + n_e e^-$.

Example: ^{4}He $= 4p + 2e^-$, works well. However: ^{14}N $= 14p + 7e^-$ is expected to be a fermion. However, it was experimentally known that ^{14}N was a boson!

There was also a problem with the magnetic moment of nuclei: $\mu_N, \mu_p \ll \mu_e$ ($\mu = eh/4mc$). How can the nuclear magnetic moment be so much smaller than the electron one if the nucleus contains electrons?

SOLUTION: Bound, nuclear electrons are very weird!

This can also be used to solve the continuous β-ray spectrum: energy need not be conserved in nuclear processes! (N. Bohr)

"... This would mean that the idea of energy and its conservation fails in dealing with processes involving the emission and capture of nuclear electrons. This does not sound improbable if we remember all that has been said about peculiar properties of electrons in the nucleus." (G. Gamow, Nuclear Physics Textbook, 1931).

enter the neutrino...

1. 1930: Postulated by Pauli to (a) resolve the problem of continuous β-ray spectra, and (b) reconcile nuclear model with spin-statistics theorem. $\Rightarrow$
2. 1932: Chadwick discovers the neutron.

   neutron $\neq$ Pauli's neutron = neutrino (Fermi);
3. 1934: Fermi theory of Weak Interactions – current-current interaction

   $$\mathcal{H} \sim G_F\,(\bar{p}\Gamma n)\,(\bar{e}\Gamma\nu_e)\,, \qquad \text{where}\ \ \Gamma = \{1, \gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\}$$

   Way to "see" neutrinos: $\bar{\nu}_e + p \to e^+ + n$. Prediction for the cross-section - too small to ever be observed...
4. 1935: (Yukawa postulates the existence of mesons (pions) as mediators of the nuclear (strong) force: $m_\pi \sim 100$ MeV.)
5. 1936/37: ("Meson" discovered in cosmic rays. Another long, tortuous story. Turns out to be the muon...)
6. 1947: (Marshak, Bethe postulate the 2 meson hypothesis ($\pi \to \mu$). Pion observed in cosmic rays.)

Dear Radioactive Ladies and Gentlemen,

I have come upon a desperate way out regarding the wrong statistics of the ^{14}N and ^{6}Li nuclei, as well as the continuous β-spectrum, in order to save the "alternation law" statistics and the energy law. To wit, the possibility that there could exist in the nucleus electrically neutral particles, which I shall call "neutrons," and satisfy the exclusion principle... The mass of the neutrons should be of the same order of magnitude as the electron mass and in any case not larger than 0.01 times the proton mass. The continuous β-spectrum would then become understandable from the assumption that in β-decay a neutron is emitted along with the electron, in such a way that the sum of the energies of the neutron and the electron is constant...

For the time being I dare not publish anything about this idea and address myself to you, dear radioactive ones, with the question how it would be with experimental proof of such a neutron, if it were to have the penetrating power equal to about ten times larger than a γ-ray.

I admit that my way out may not seem very probable *a priori* since one would probably have seen the neutrons a long time ago if they exist. But only the one who dares wins, and the seriousness of the situation concerning the continuous β-spectrum is illuminated by my honored predecessor, Mr Debye who recently said to me in Brussels: "Oh, it is best not to think about this at all, as with new taxes."

One must therefore discuss seriously every road to salvation. Thus, dear radioactive ones, examine and judge. Unfortunately, I cannot appear personally in Tübingen since a ball... in Zürich... makes my presence here indispensible....

Your most humble servant, W. Pauli

Adapted summary of an English Translation to Pauli's letter dated December 4, 1930, from Ref. 3.

observing the unobservable:

1. 1956: "Discovery" of the neutrino (Reines and Cowan) in the Savannah River Nuclear Reactor site. ⇒

   $\bar{\nu}_e + p \to e^+ + n$. Measure positron ($e^+e^- \to \gamma$s) <u>and</u> neutron ($nN \to N^* \to N + \gamma$s) in delayed coincidence in order to get rid of backgrounds.

2. 1958: Neutrino Helicity Measured (Goldhaber et al.). Neutrinos are purely left-handed. Interact only weakly (Parity violated maximally).

   $e^- + ^{152}\text{Eu}(J=0) \to ^{152}\text{Sm}^*(J=1) + \nu \to ^{152}\text{Sm}(J=1) + \nu + \gamma$

3. 1962: The second neutrino: $\nu_\mu \neq \nu_e$ (Lederman, Steinberger, Schwarts at BNL). First neutrino beam.

$$p + Z \to \pi^+ X \to \mu^+ \nu_\mu \quad \Rightarrow \quad \begin{array}{l} \nu_\mu + Z \to \mu^- + Y \ (\text{“always”}) \\ \nu_\mu + Z \to e^- + Y \ (\text{“never”}) \end{array}$$

4. 2001: ν_τ directly observed (DONUT experiment at FNAL). Same strategy: $\nu_\tau + Z \to \tau^- + Y$. ($\tau$-leptons discovered in the 1970's). ⇒

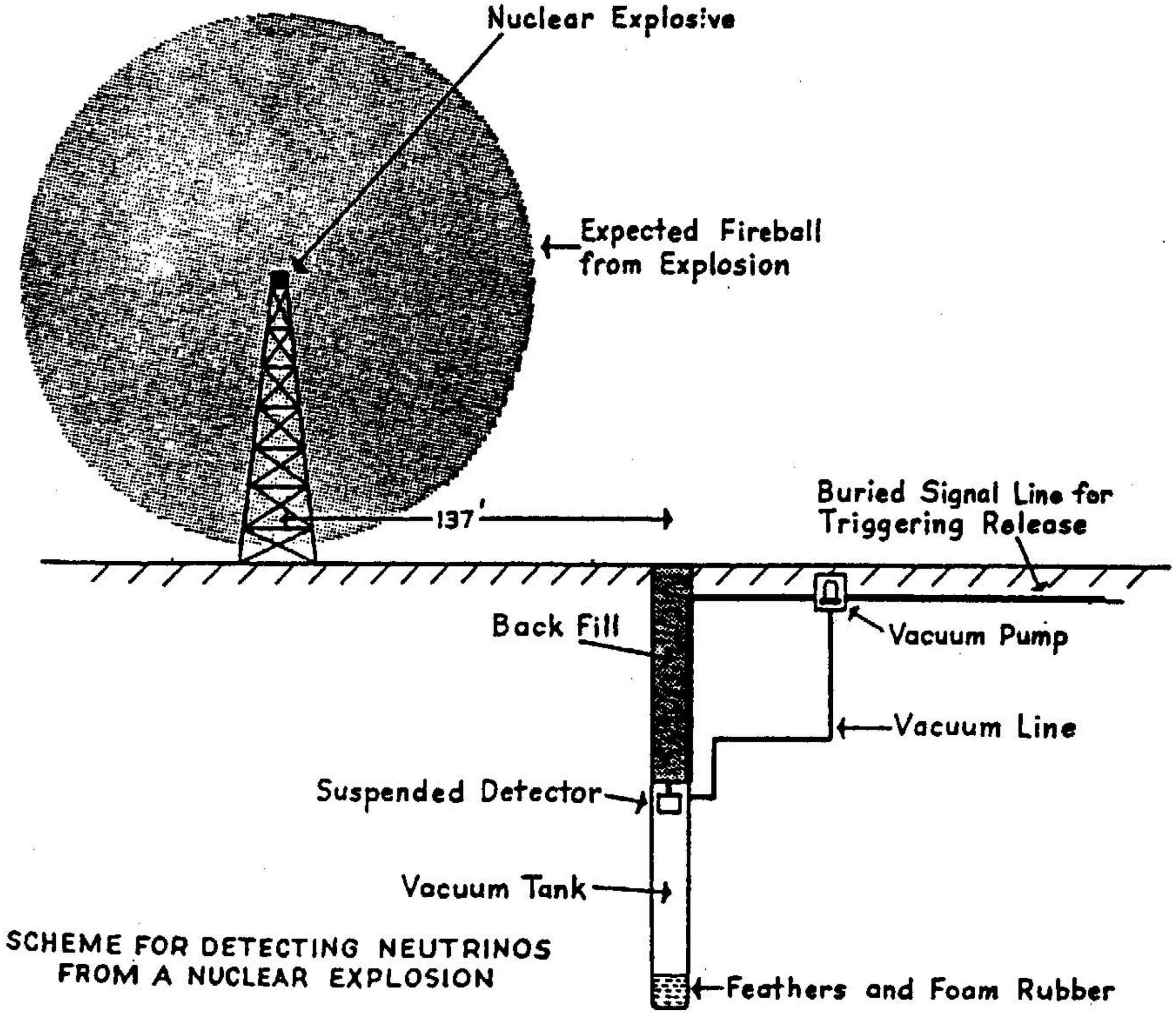


FIGURE 5.1 Scheme for detecting neutrinos from a nuclear e
(Cowan, 1964).

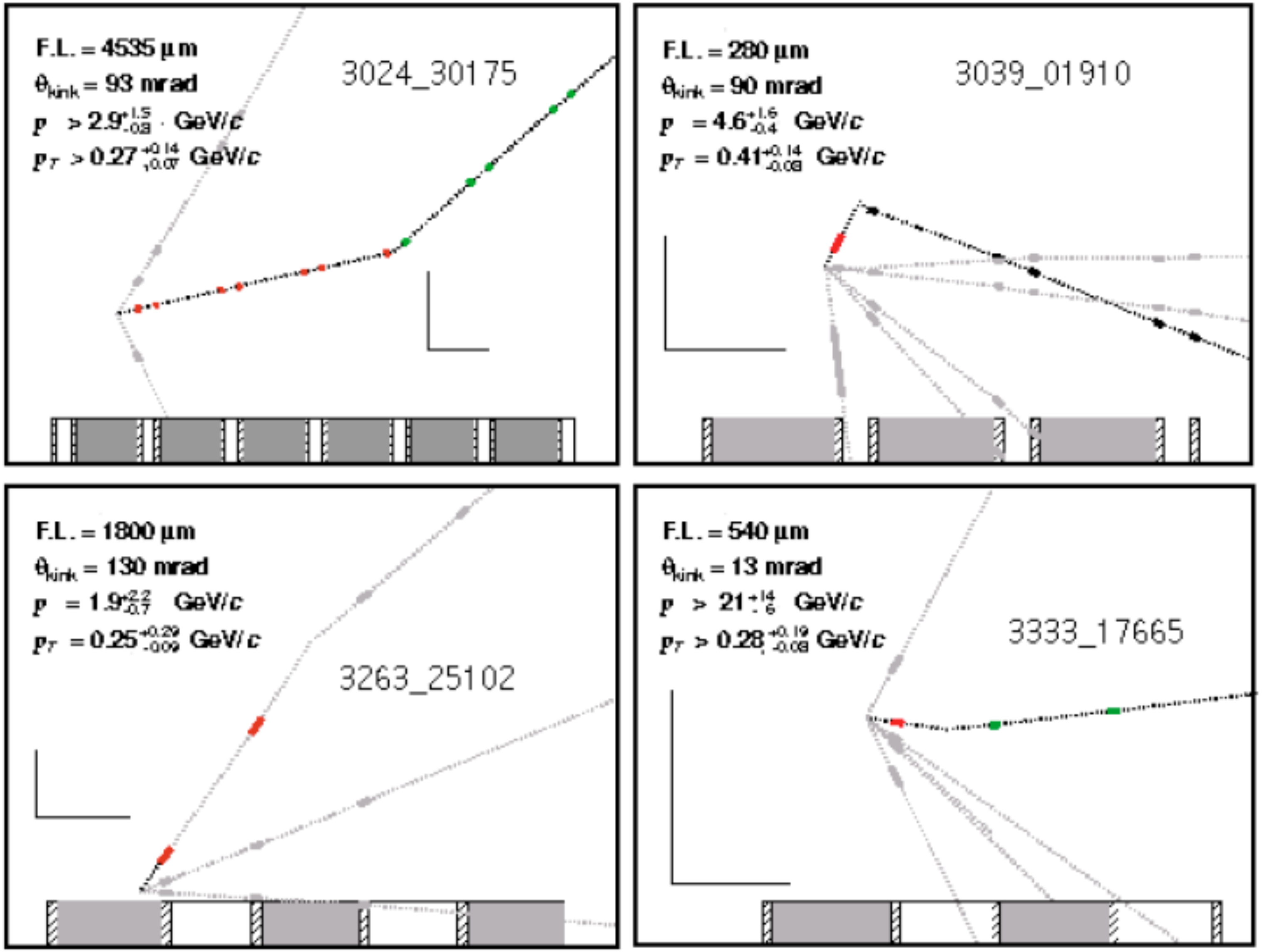


Figure 4-6: The four tau neutrino charged current events. The scale is given by the perpendicular lines (vertical: 0.1 mm, horizontal: 1 mm). The bar on the bottom shows the target material (solid: steel, hatched: emulsion, clear: plastic base).

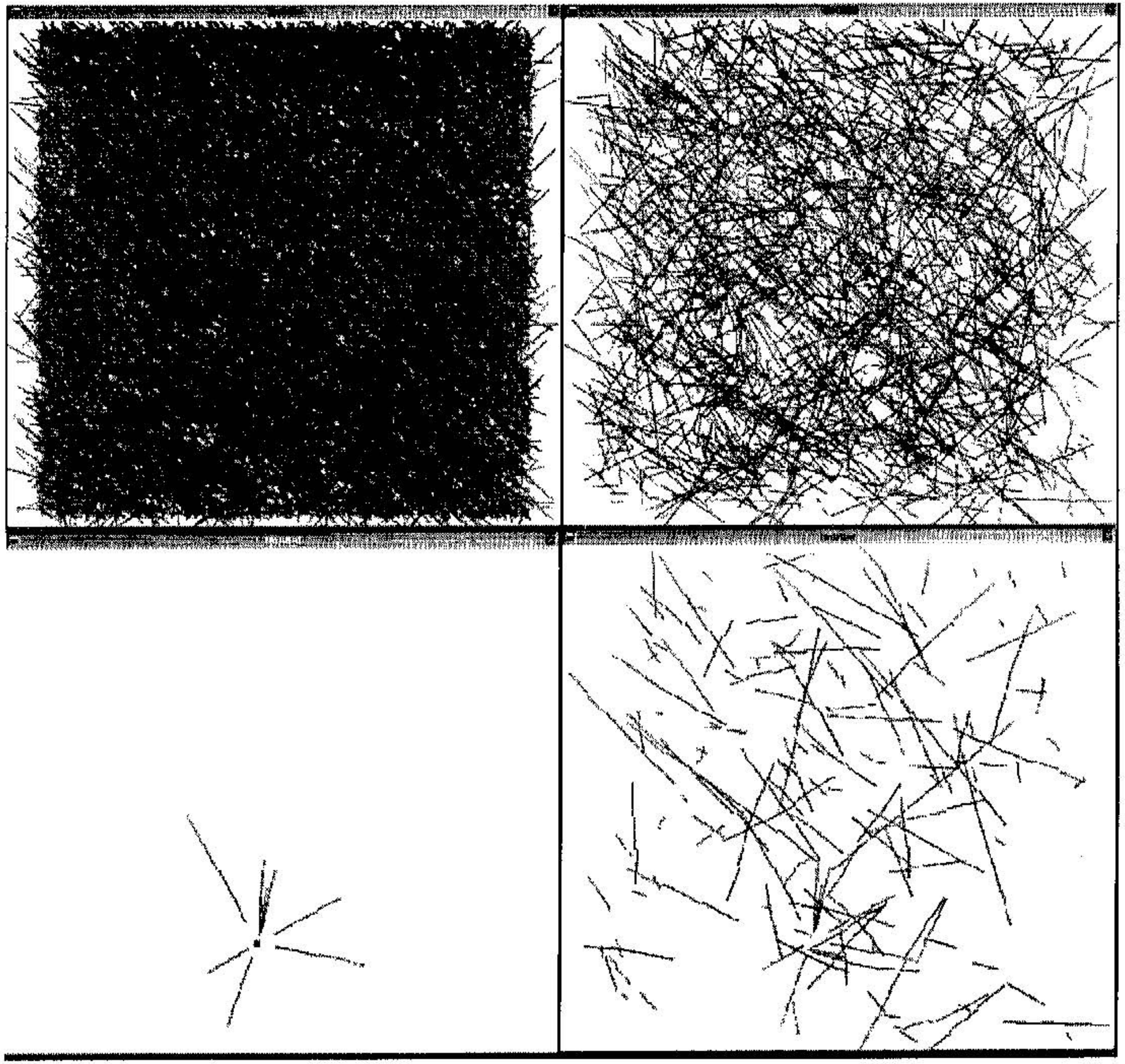
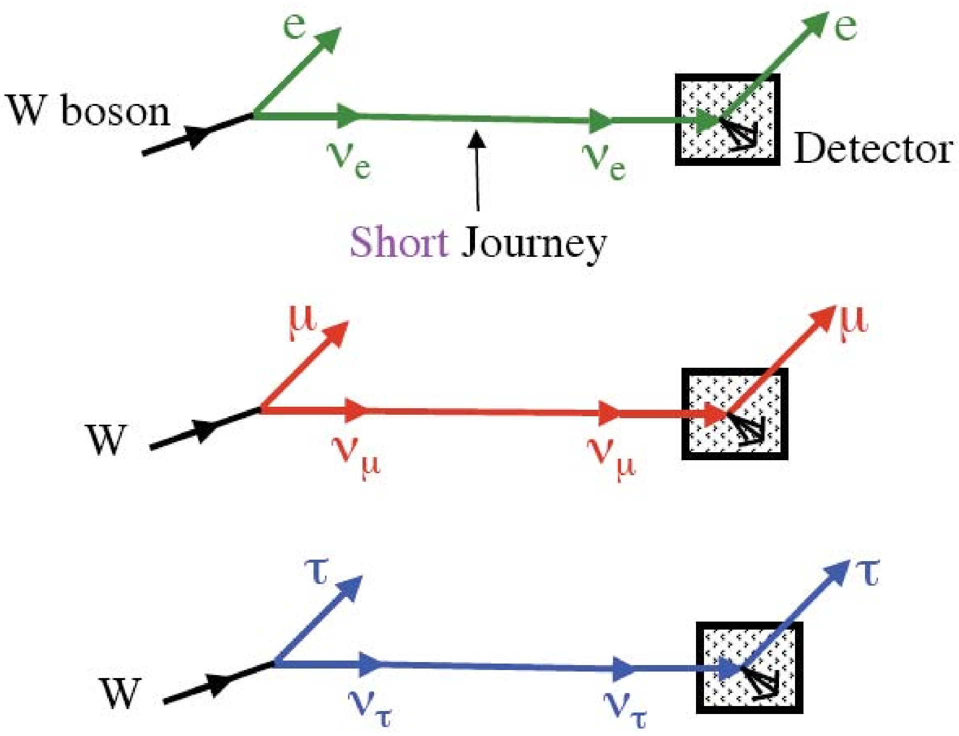


図 5.12: net scan 反応点探索の各段階 (左上から時計回り)。1) 読み込んだ全ての飛跡 ($5 \times 5 \mathrm{mm}^2$)、2) 測定領域を突き抜けている飛跡の排除、3) 低運動量の飛跡の排除、4) 一点 ($4 \mu\mathrm{m}$ 以内) 収束している飛跡

HUNTING FOR

Until recently, this is how we pictured neutrinos:



- come in three flavors (see figure);
- interact only via weak interactions ($W^{\pm}, Z^0$);
- have ZERO mass – helicity good quantum number;
- ν_L field describes 2 degrees of freedom:
  - left-handed state ν,
  - right-handed state $\bar{\nu}$ (CPT conjugate);
- neutrinos carry lepton number:
  - $L(\nu) = +1$,
  - $L(\bar{\nu}) = -1$.

2– Neutrino Puzzles

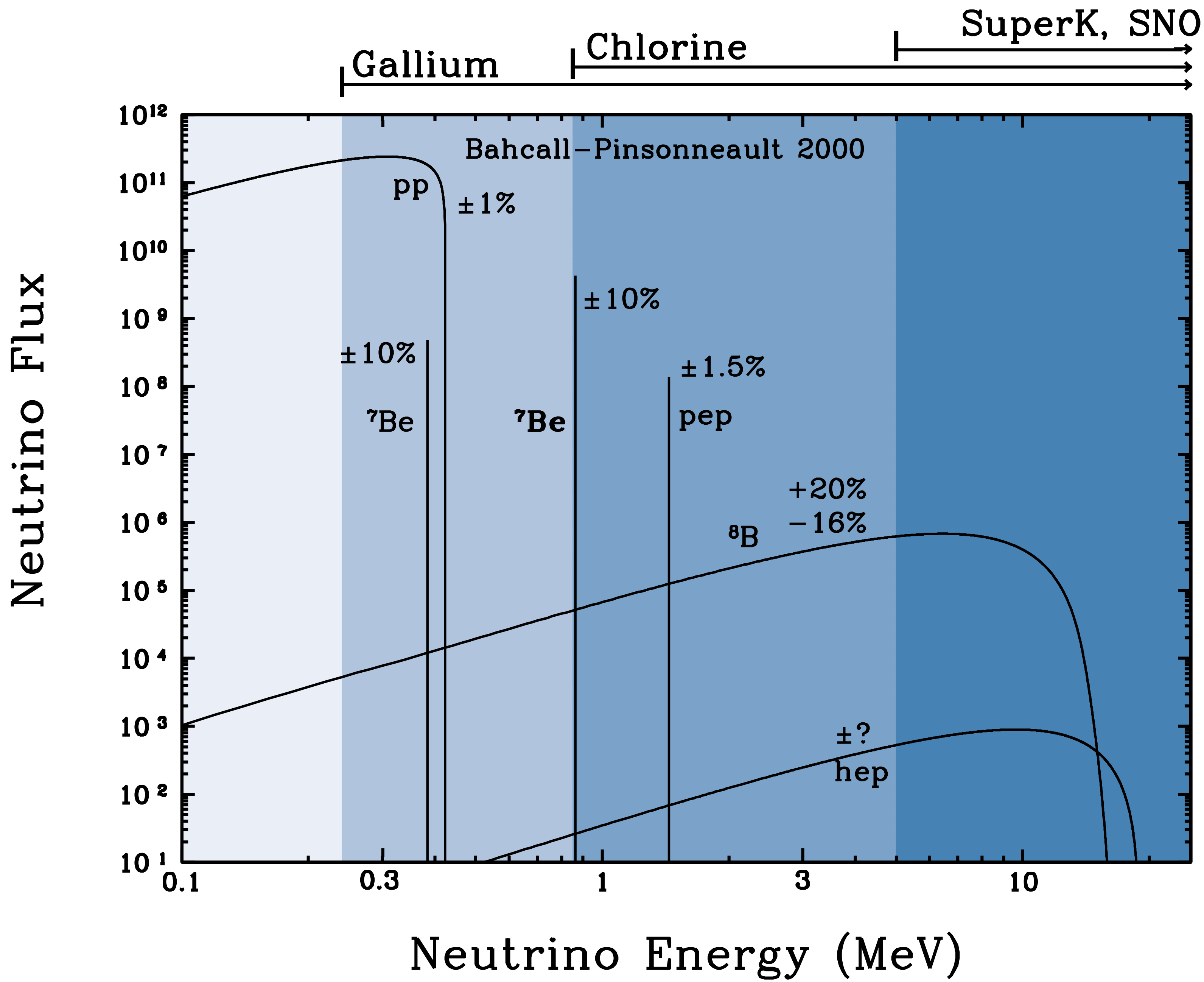
Long baseline neutrino experiments have revealed that neutrinos change flavor after propagating a finite distance, violating the definitions in the previous slide. The rate of change depends on the neutrino energy E_ν and the baseline L.

- $\nu_\mu \to \nu_\tau$ and $\bar{\nu}_\mu \to \bar{\nu}_\tau$ — atmospheric experiments [“indisputable”];
- $\nu_e \to \nu_{\mu,\tau}$ — solar experiments [“indisputable”];
- $\bar{\nu}_e \to \bar{\nu}_{\rm other}$ — reactor neutrinos [“indisputable”];
- $\nu_\mu \to \nu_{\rm other}$ from accelerator experiments [“really strong”].

Table 1. Nuclear reactions responsible for producing almost all of the Sun's energy and the different "types" of solar neutrinos (nomenclature): *pp*-neutrinos, *pep*-neutrinos, *hep*-neutrinos, ^{7}Be-neutrinos, and ^{8}B-neutrinos. 'Termination' refers to the fraction of interacting protons that participate in the process.

Reaction	Termination (%)	Neutrino Energy (MeV)	Nomenclature
$p+p\rightarrow{}^2\mathrm{H}+e^++\nu_e$	99.96	<0.423	*pp*-neutrinos
$p+e^-+p\rightarrow{}^2\mathrm{H}+\nu_e$	0.044	1.445	*pep*-neutrinos
$^2\mathrm{H}+p\rightarrow{}^3\mathrm{He}+\gamma$	100	–	–
$^3\mathrm{He}+{}^3\mathrm{He}\rightarrow{}^4\mathrm{He}+p+p$	85	–	–
$^3\mathrm{He}+{}^4\mathrm{He}\rightarrow{}^7\mathrm{Be}+\gamma$	15	–	–
$^7\mathrm{Be}+e^-\rightarrow{}^7\mathrm{Li}+\nu_e$	15	0.863(90%) 0.386(10%)	^{7}Be-neutrinos
$^7\mathrm{Li}+p\rightarrow{}^4\mathrm{He}+{}^4\mathrm{He}$		–	–
$^7\mathrm{Be}+p\rightarrow{}^8\mathrm{B}+\gamma$	0.02	–	–
$^8\mathrm{B}\rightarrow{}^8\mathrm{Be}^*+e^++\nu_e$		<15	^{8}B-neutrinos
$^8\mathrm{Be}\rightarrow{}^4\mathrm{He}+{}^4\mathrm{He}$		–	–
$^3\mathrm{He}+p\rightarrow{}^4\mathrm{He}+e^++\nu_e$	0.00003	<18.8	*hep*-neutrinos

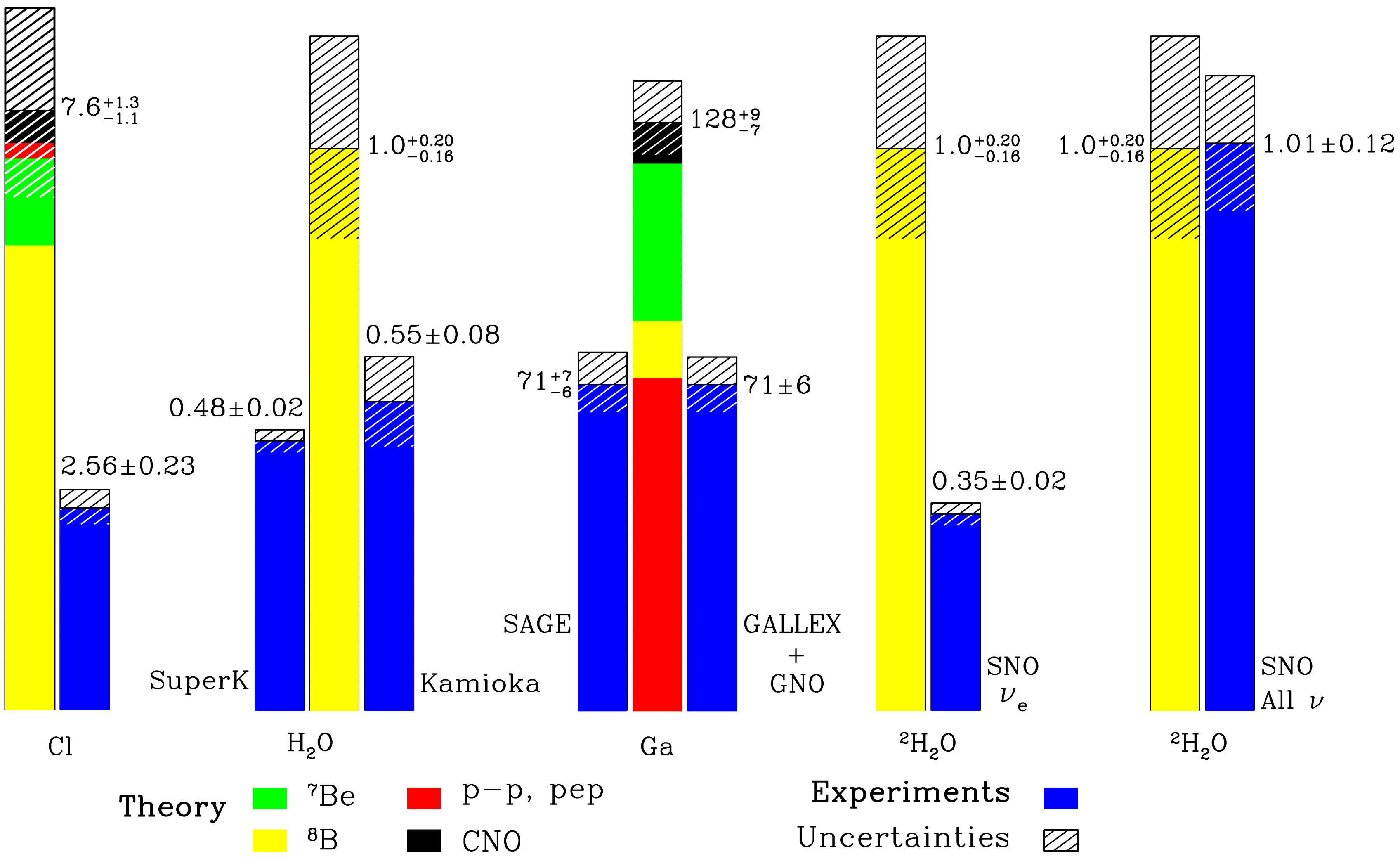
Note: Adapted from Ref. 12. Please refer to Ref. 12 for a more detailed explanation.



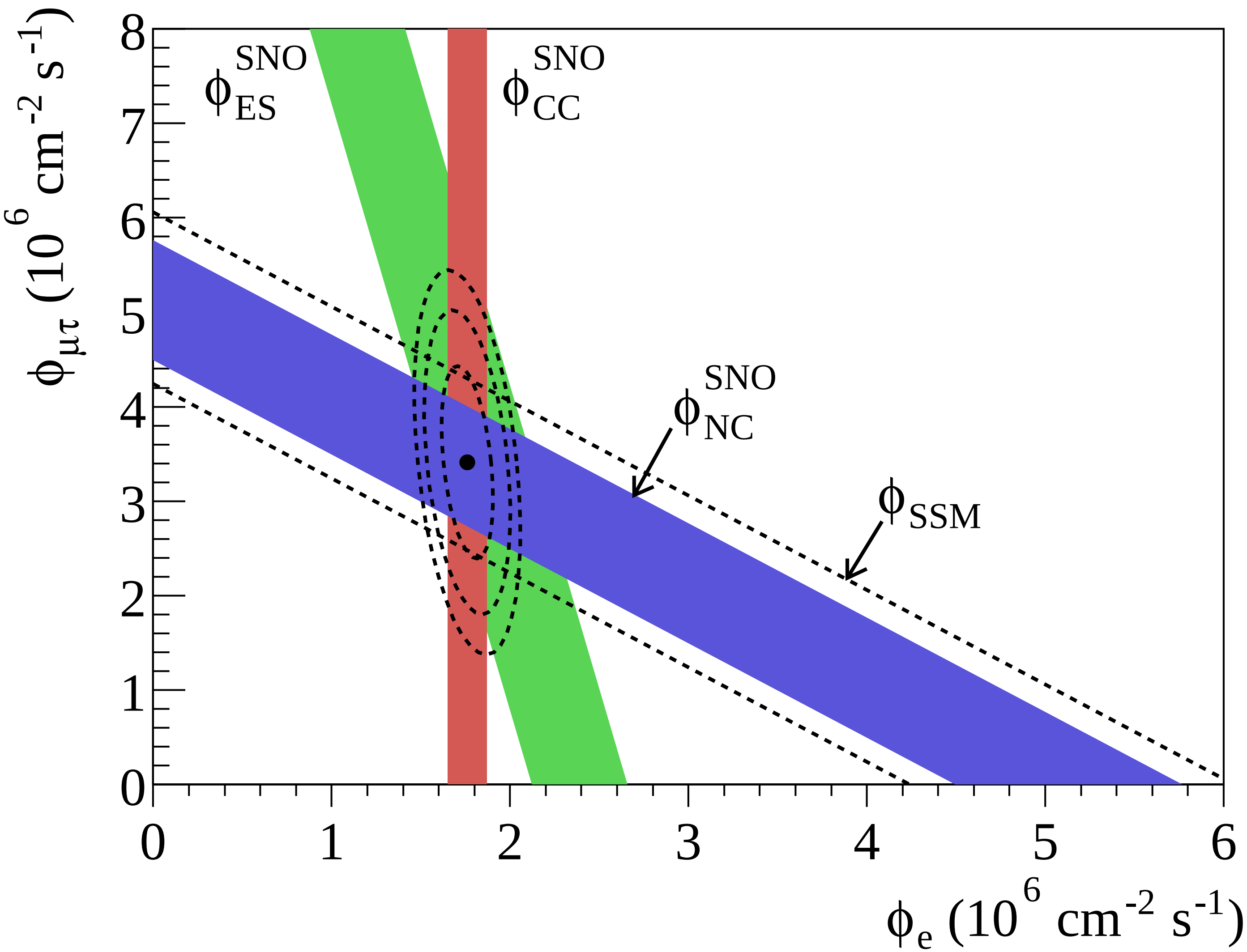
Gallium
Chlorine
SuperK, SNO
Bahcall−Pinsonneault 2000
pp
±1%
±10%
±10%
±1.5%
7Be
7Be
pep
+20%
−16%
8B
±?
hep
Neutrino Flux
Neutrino Energy (MeV)
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
0.1
0.3
1
3
10

Total Rates: Standard Model vs. Experiment

Bahcall–Pinsonneault 2000



The SNO Experiment: conclusive evidence for flavor change



SNO Measures:

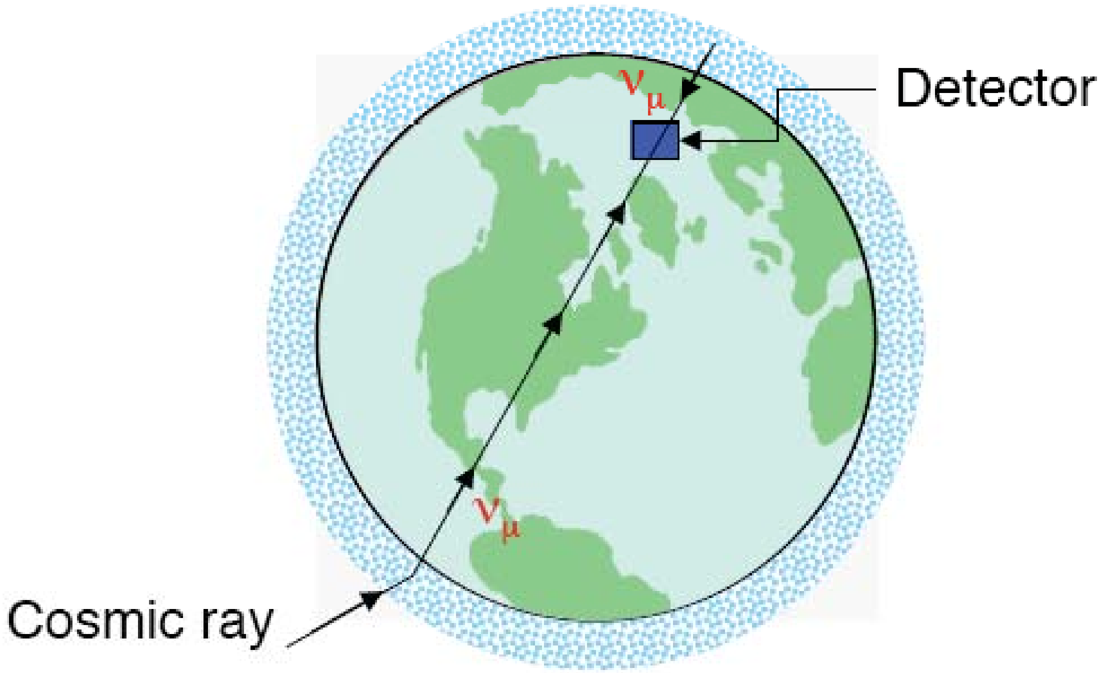
$[CC]\ \nu_e + {}^2H \rightarrow p + p + e^-$

$[ES]\ \nu + e^- \rightarrow \nu + e^-$

$[NC]\ \nu + {}^2H \rightarrow p + n + \nu$

different reactions sensitive to different neutrino flavors.

Atmospheric Neutrinos



Isotropy of the $\gtrsim 2$ GeV cosmic rays + Gauss' Law + No ν_μ disappearance

$$\Rightarrow \frac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} = 1 .$$

But Super-Kamiokande finds for $E_\nu > 1.3$ GeV

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

UP $\neq$ DOWN – neutrinos can tell time! $\rightarrow$ neutrinos have mass.

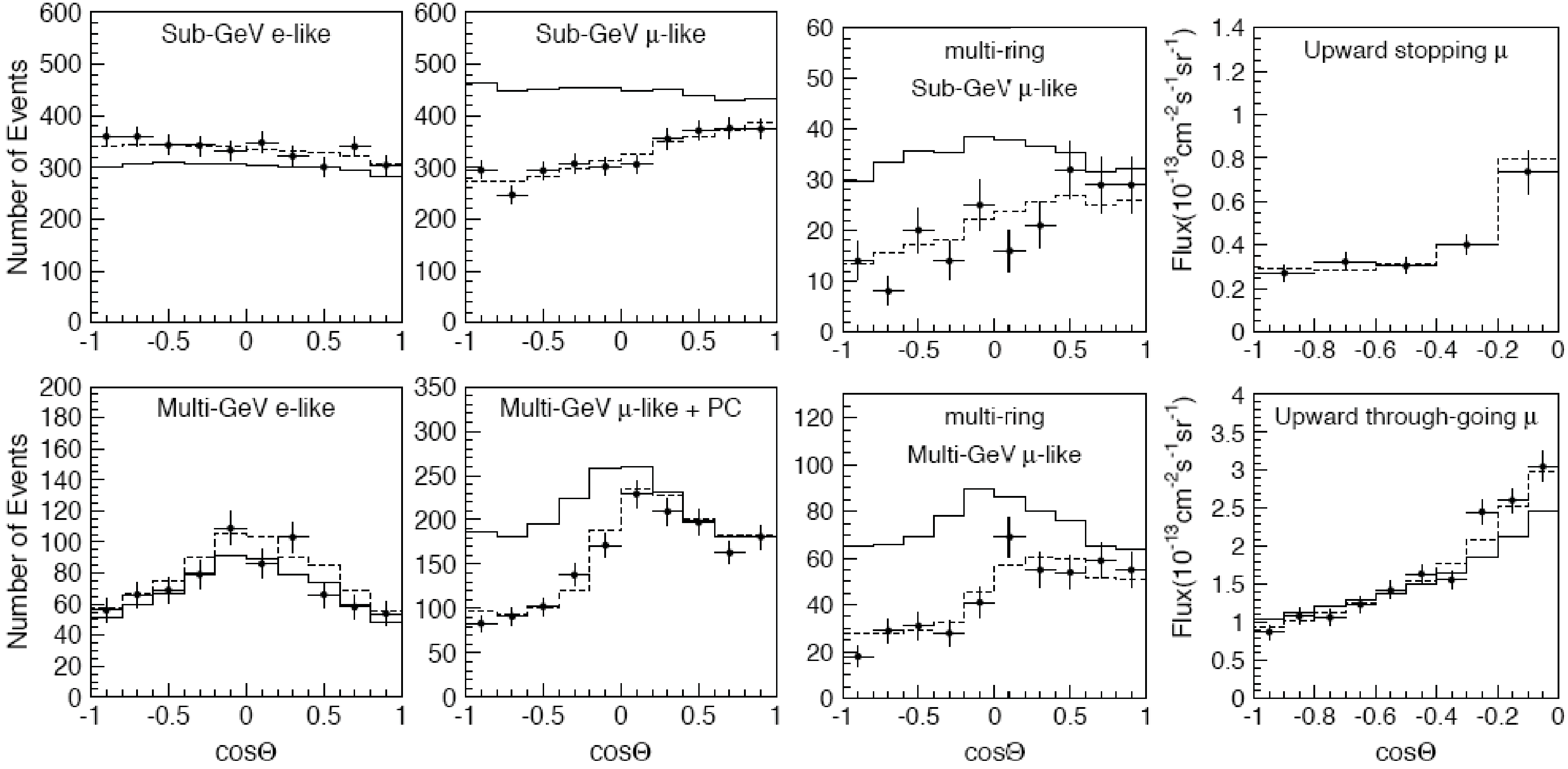


Figure 4. Zenith angle distribution for fully-contained single-ring e-like and μ-like events, multi-ring μ-like events, partially contained events and upward-going muons. The points show the data and the solid lines show the Monte Carlo events without neutrino oscillation. The dashed lines show the best-fit expectations for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. From M. Ishitsuka [Super-Kamiokande Collaboration], hep-ex/0406076.

3 - Mass-Induced Neutrino Flavor Oscillations

Neutrino Flavor change can arise out of several different mechanisms. The simplest one is to postulate that **neutrinos have mass**. It also turns out to be the correct mechanism, and **only** explanation that successfully explains **all** long-baseline data consistently.

Neutrinos with a well defined mass:

$$\nu_1, \nu_2, \nu_3, \ldots \qquad \text{with masses} \;\; m_1, m_2, m_3, \ldots$$

How do these states (neutrino mass eigenstates) relate to the neutrino flavor eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$?

$$\nu_\alpha = U_{\alpha i}\nu_i \qquad \alpha = e, \mu, \tau, \quad i = 1, 2, 3$$

U is a unitary mixing matrix. I'll talk more about it later.