Leptons

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What are leptons?

- Leptons are elementary particles which do not feel the strong force

- So named, to indicate a particle with a small mass

- At the time (1948) the known leptons had a mass much lighter than the the mass of the proton

Leptons as we know them today

$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix}$ electron / el. neutrino

$\begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix}$ muon / mu neutrino

$\begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$ tau / tau neutrino

and anti-leptons

$\begin{pmatrix} e^+ \\ \bar{\nu}_e \end{pmatrix}$ positron / el. anti-nu

$\begin{pmatrix} \mu^+ \\ \bar{\nu}_\mu \end{pmatrix}$ muon / mu anti-nu

$\begin{pmatrix} \tau^+ \\ \bar{\nu}_\tau \end{pmatrix}$ tau / tau anti-nu

How did we get to know them?

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Electron (e^-)

- 1896, J. J. Thomson, J. S. Townsend and H. A. Wilson: cathode rays are a bunch of particles

- Mass: ~1/1000 of the mass of the hydrogen ion (the least massive ion known)

- charge-to-mass ratio, e/m, independent of cathode material

Beta decay

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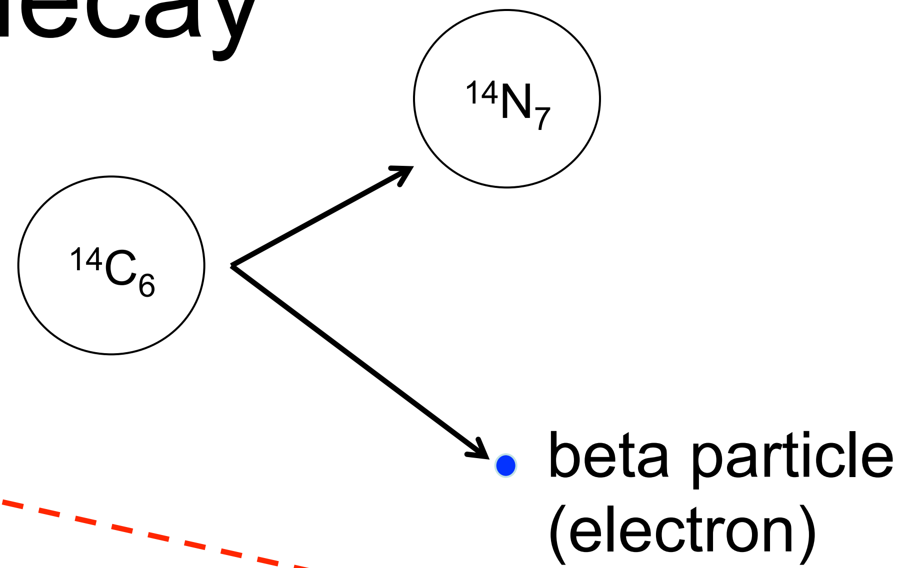
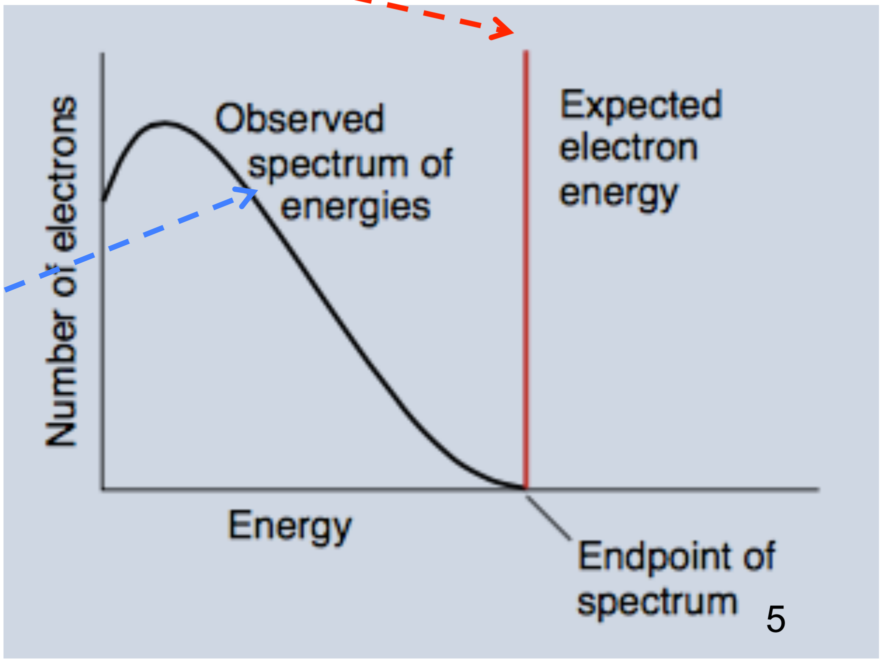
- thought to be:



- Electrons expected to have a well-defined energy
- Experiments (Chadwick, 1914) told a very different story: the spectrum spanned a continuous energy range, from zero to a maximum value



The problem of the continuous spectrum

- How could the electron have different energy in different decays?
- This led Bohr to suggest that perhaps energy was not conserved in beta decay

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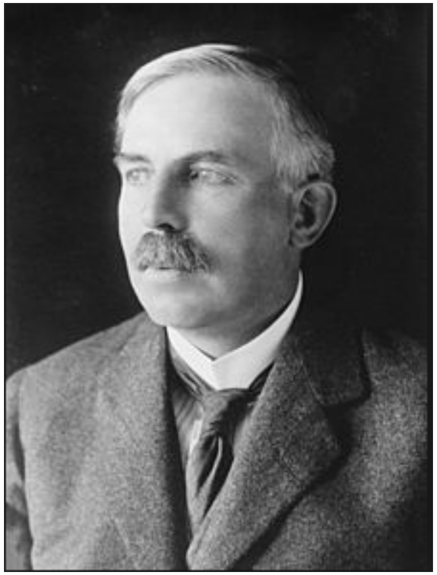
A brief detour: the neutron (*n*)

- Rutherford: the nucleus is made of protons
- To explain the nuclear masses, Rutherford also introduced particles of a mass similar to the proton, the 'neutrons'
- A neutron = a proton + an electron tightly bound together
- 1927: discovery that electron and proton have spin $\hbar/2$
- ➔ Rutherford's neutron was inconsistent with the measured spin of some nuclei



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The 'nitrogen anomaly'

- The nitrogen nuclear spin was measured and found to be 1, ➔ the N nucleus must contain an even number of particles with spin ½
- From chemistry it is known that a N atom contains 7 electrons ➔the N nucleus must have 7 protons
- With only 7 protons the N nucleus would have just half of the mass it really has
- ➔7 neutrons are necessary
- If neutrons were an *e-p* pair, the total number of particles with half-integer spin in the N nucleus would be 21, an odd number
- ➔Neutrons can not be *e-p* pairs

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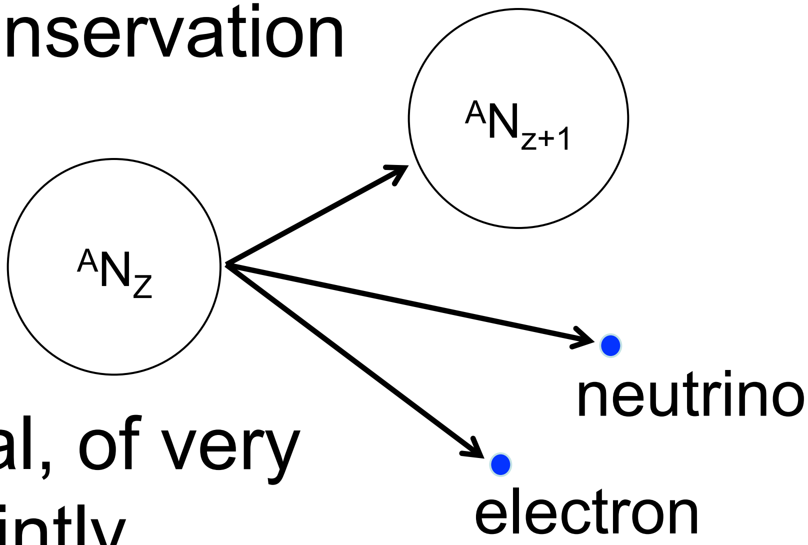
Pauli's proposal (1930)

- The neutron is a single, new, neutral particle
- In his view it would resolve both the problem of the nuclear structure and of the beta decay
- 1932: Chadwick discovers what we now call 'neutron'
- Its large mass, ~ the proton mass, and its ½ spin explained the mass and spin of the nuclei
- But the neutron could not be the beta decay particle
- A new particle was necessary with a very low mass (and a new name)

Neutrino (ν) (*)

- In beta decay there is a third, unseen particle, which shares energy with the electron and saves energy conservation (Pauli, 1930)

Now the decay looks like



- The ‘neutrino’, must be neutral, of very low mass and interact very faintly
- For this reason it was discovered only in 1956

(*) anti-neutrino, actually

Positron (e^+)

- 1931: P. A. M. Dirac predicts a new particle, same mass as the electron, positive *e* charge

- 1932: C. D. Anderson discovers the ‘positron’: first evidence of anti-matter ever

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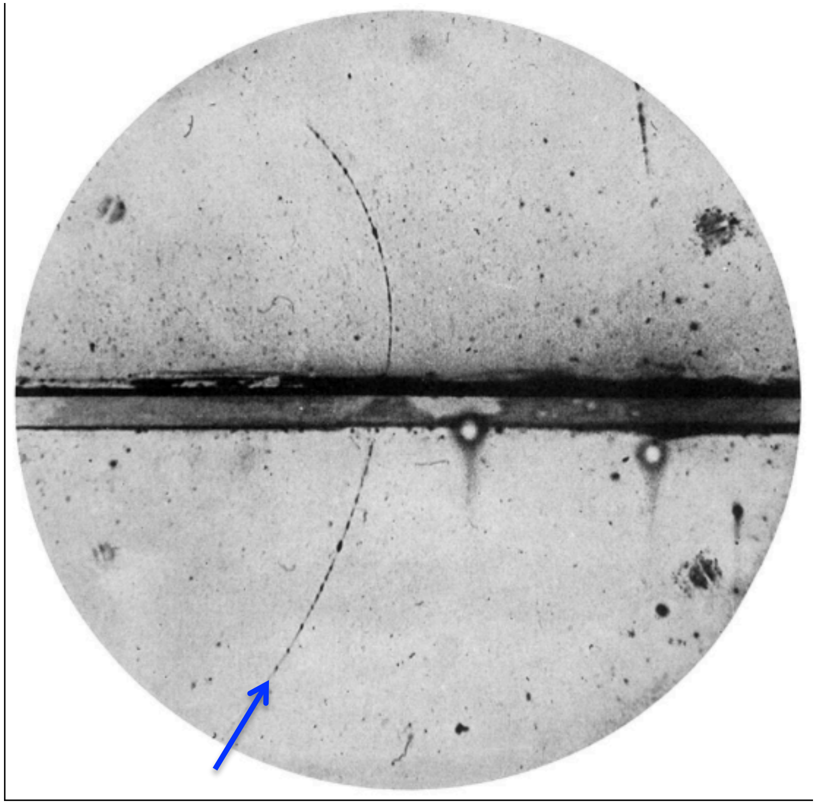
Anderson's experiment

- Cosmic rays impinged on a lead plate in a cloud chamber
- A magnet surrounded the apparatus, causing particles to bend
- A camera recorded the ion trail left by particles
- The curvature matched the mass-to-charge ratio of an electron, but in the opposite direction
- The particle's charge was positive

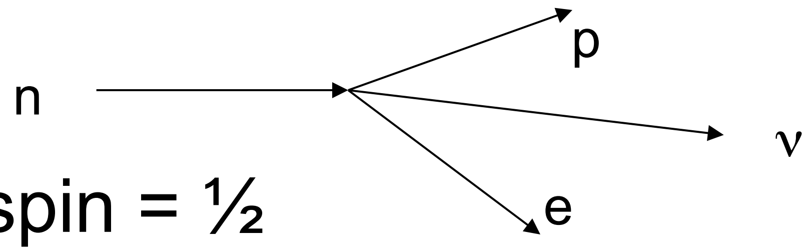


Fermi's beta decay theory (1934)

Fermi's theory based on:

1)Energy, angular momentum and spin conservation

2)A neutron in the nucleus decays producing a proton an electron and a neutrino (Pauli's hypothesis)



3)Neutrino's spin = ½

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Another detour: the pion (π)

- 1935: H. Yukawa predicts a particle as the carrier of the strong nuclear force
- With a mass of about 200 MeV
- It is what we call today a pion

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The mesotron

- 1936: C. D. Anderson and S. Neddermeyer discover a particle of about this mass
- Experiment on energy loss of cosmic rays passing through a Pt plate in a cloud chamber immersed in a magnetic field
- They found particles which curved less sharply than electrons, and more sharply than protons
- ➔ the mass was greater than an electron but smaller than a proton
- For this reason Anderson called the particle mesotron

Muon (μ)

- Was the mesotron Yukawa's particle?
- Its mass was very near to his prediction
- No, because it did not participate in the strong nuclear interaction (Conversi, Pancini, Piccioni experiment, 1947)
- The mesotron is what we now call a muon
- 1937: its existence is confirmed by J. C. Street and E. C. Stevenson's cloud chamber experiment

Pions eventually

- 1947: the charged pion was discovered by C. Powell, C. Lattes, G. Occhialini
- Photographic emulsions were placed at high altitude on mountains, where they were struck by cosmic rays
- Photographic plates were developed
- Microscopic inspection of the emulsions revealed ➔ tracks of charged subatomic particles

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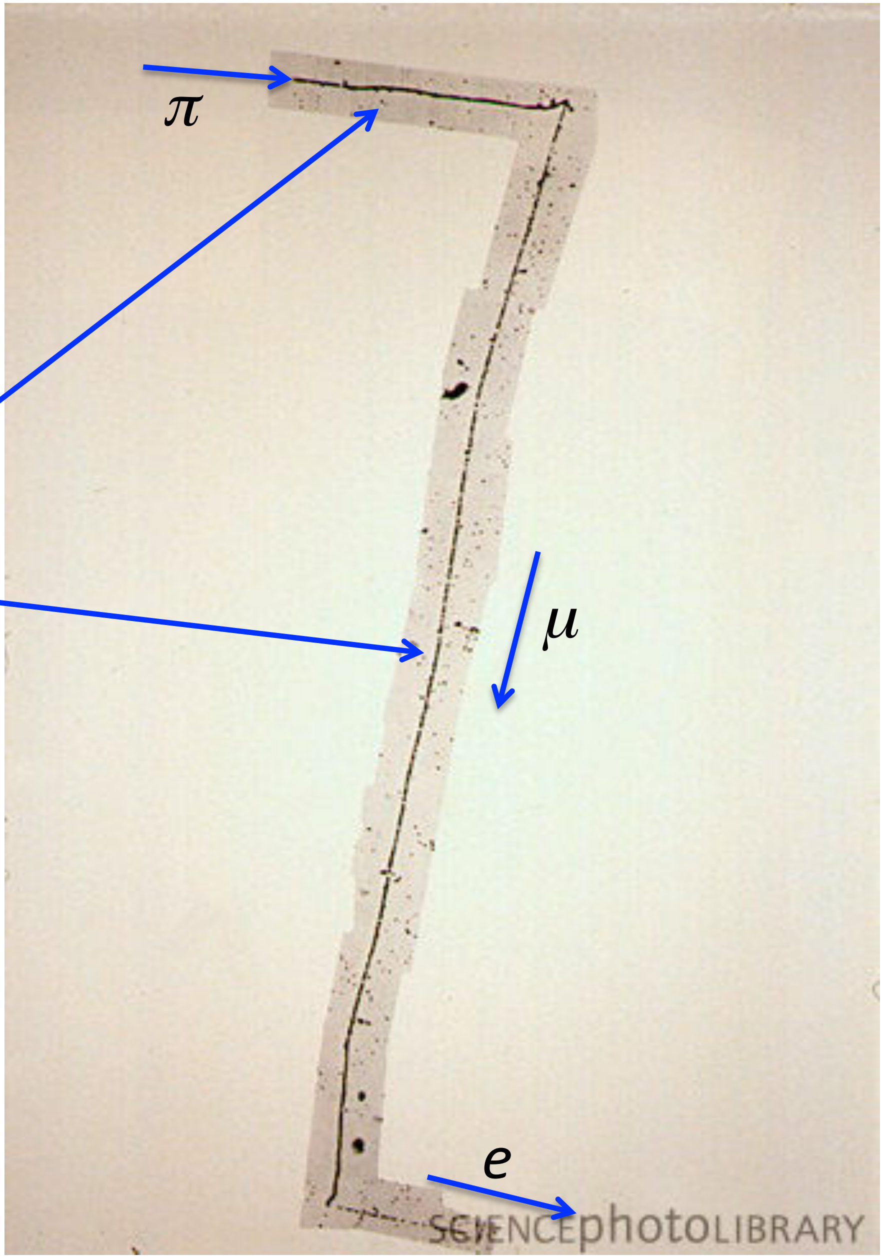
Emulsion with a π-μ-e decay

- Pions identified by their "double meson" tracks
- due to decay into a muon
- Apparent non-conservation of momentum at the two decay vertices
- ➔ neutral radiation must be present at the vertices



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Pions and muons

- So pions decay as $\pi \rightarrow \mu$ + *neutrals*
- Lab studies found that the spin of the pion is 0 and that of the muon is ½
- Consistent with the fact that the neutral radiation be a neutrino

- The muon decays as $\mu \rightarrow e$ + *neutrals*
- One would expect the decay $\mu \rightarrow e + \gamma$ and the electron energy to be fixed

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Steinberger

- Studying the stopping of muons in matter, he found a number of decay electrons five times less then expected
- Fermi’s suggestion: If the muon decayed in an electron and two particles,
  - the electron energy would fall in a range of values,
  - the electrons with an energy lower than the experiment threshold would not be detected

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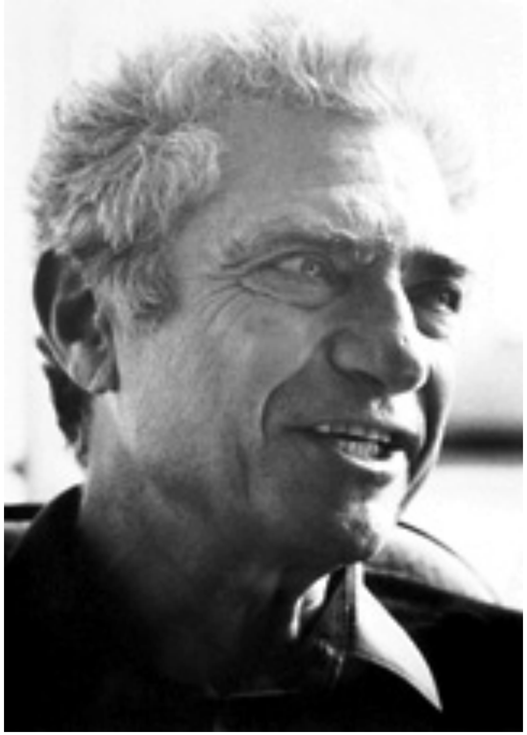
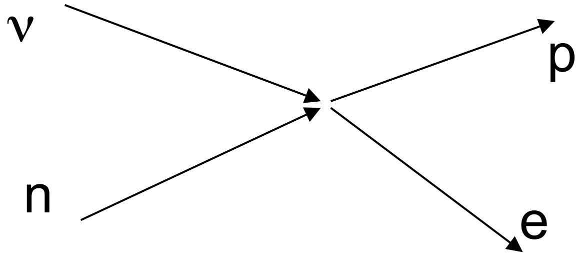
Steinberger (1948)

- Steinberger's experiment confirmed that the muon decays in an electron and two particles
- These particles must be neutral and their spin must be globally 0
- All was consistent with the idea that they were two neutrinos
- This was eight years before the (anti)neutrino was discovered



Bethe and Peierls

- Many physicist did not believe in the real existence of the neutrino, yet, since a direct proof of its existence still lacked
- Extending Fermi's theory, Bethe and Peierls computed the probability of the production reaction



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Bruno Pontecorvo

- The computed probability was so minute that they concluded: “there is no practical way to detect a neutrino”
- 1946: Pontecorvo reads their work and concludes:
- if you have a source of neutrinos of very high intensity
- occasionally a few of them would interact with the nuclei of the detector

- A uranium nuclear reactor produces ~10^{16} neutrinos/s$^{(*)}$
- With patience and the right detector, it could be possible to detect neutrinos

(*) antineutrinos, actually

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Radiochemical detection

- Pontecorvo proposed the reaction

$$\nu + Cl^{17} \rightarrow Ar^{18} + e^{-} \qquad \left(\nu + n \rightarrow p + e^{-}\right)$$

- with a threshold energy is 0.81 MeV

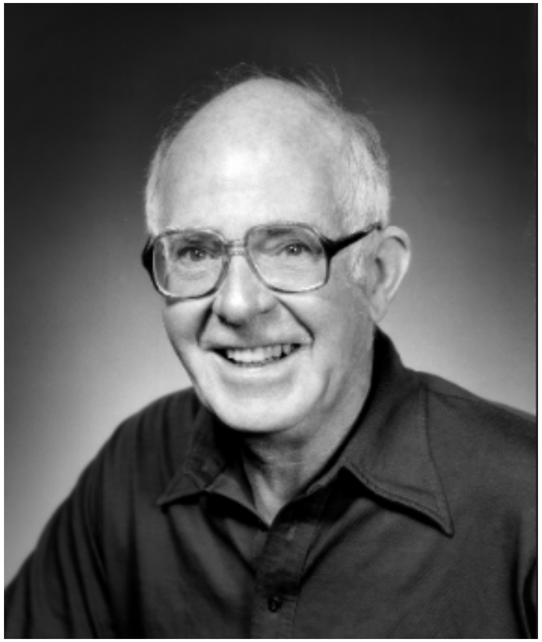
- The argon isotope decays via electron capture with a half life of 35 days

$$^{18}Ar + e^{-} \rightarrow \nu + {}^{17}Cl^{*}$$

- The de-excitation of the resulting Cl atom ejects Auger electrons

Ray Davis

- 1948: based on Pontecorvo’s reaction, Davis builds a detector with 3900 liters of CCl_4 at the research reactor in Brookhaven*
- The radioactive argon is removed by bubbling helium through the tank of CCl_4
- Argon is then separated from helium by absorbtion in a charcoal trap...
- and passed into a proportional counter where the Auger electrons from Ar decay are detected
- The result was null: the signals were the same either the reactor was on or off



* The 2002 Nobel Prize in Physics - Advanced Information". Nobelprize.org. Nobel Media AB 2014. Web. 10 Jul 2018. <http://www.nobelprize.org/nobel_prizes/physics/laureates/2002/advanced.html>

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The importance of being null

- 1955: Davis tries again with a bigger detector at Savannah River (more powerful reactor)
- Again no neutrino signal
- Why?
- Unknown at the time: nuclear reactors do not produce neutrinos, but antineutrinos
- the transformation of Cl in Ar is possible with neutrinos, but not with antineutrinos
- With hindsight, this failure was in fact a success:
- Davis had proved that neutrinos and antineutrinos are different particles

Reines & Cowan

- They planned to use a nuclear reactor as a source

- The (anti)neutrinos from a reactor can induce an ‘inverse’ beta decay

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

- if the ‘neutrino’ existed, electric charge conservation would have produced a positron (and a neutron)

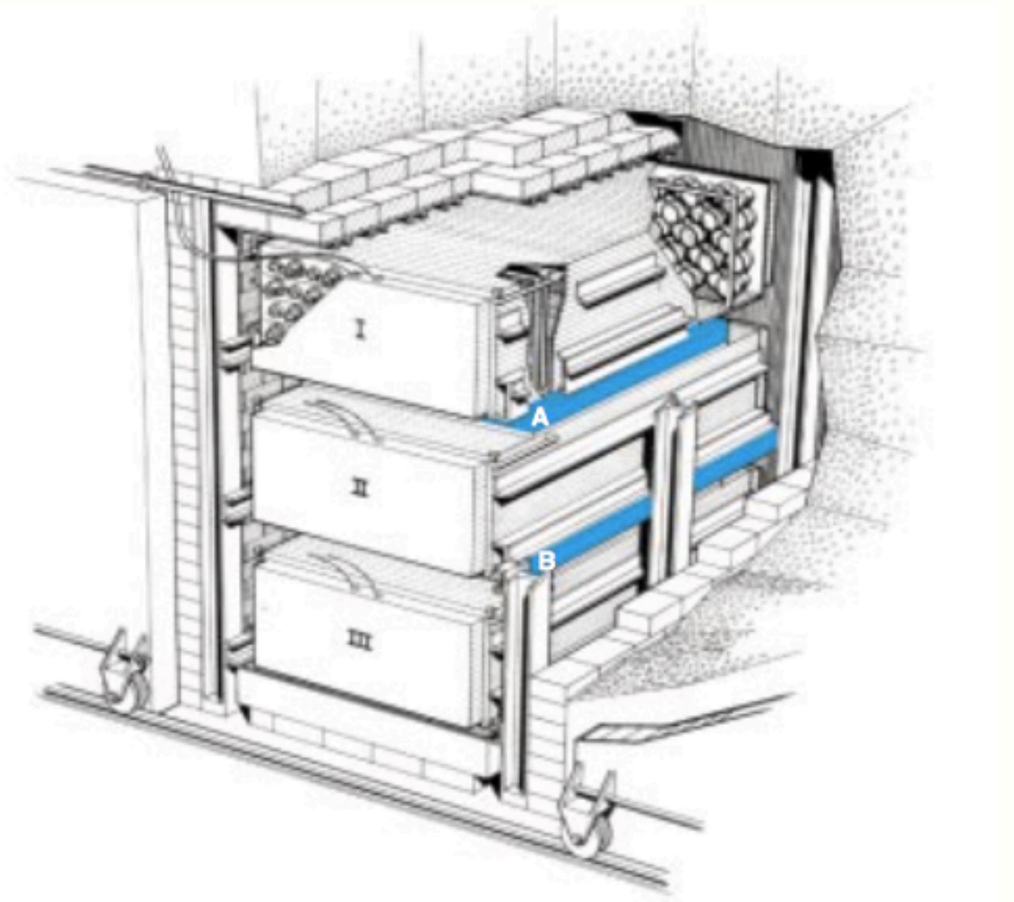
- 1955: they bring a detector to Savannah River, bury it 12 meters underground to screen off cosmic rays, at a distance of 11 meters from the core

Experiment setup (*)

- The detector targets (A and B containers) are filled with water with dissolved cadmium chloride (to enhance neutron capture probability), sandwiched with three scintillation detectors (I, II, III) + PMTs
- The (anti)neutrino interaction is

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

- Both e^{+} and n interact in the target and produce gamma rays which are detected in the scintillators



The Savannah River Neutrino Detector

The neutrino detector is illustrated here inside its lead shield. Each of two large, flat plastic tanks (pictured in light blue and labeled A and B) was filled with 200 liters of water. The protons in the water provided the target for inverse beta decay; cadmium chloride dissolved in the water provided the cadmium nuclei that would capture the neutrons. The target tanks were sandwiched between three scintillation detectors (I, II, and III). Each detector contained 1,400 liters of liquid scintillator that was viewed by 110 photomultiplier tubes. Without its shield, the assembled detector weighed about 10 tons.

(*) http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-97-2534-02

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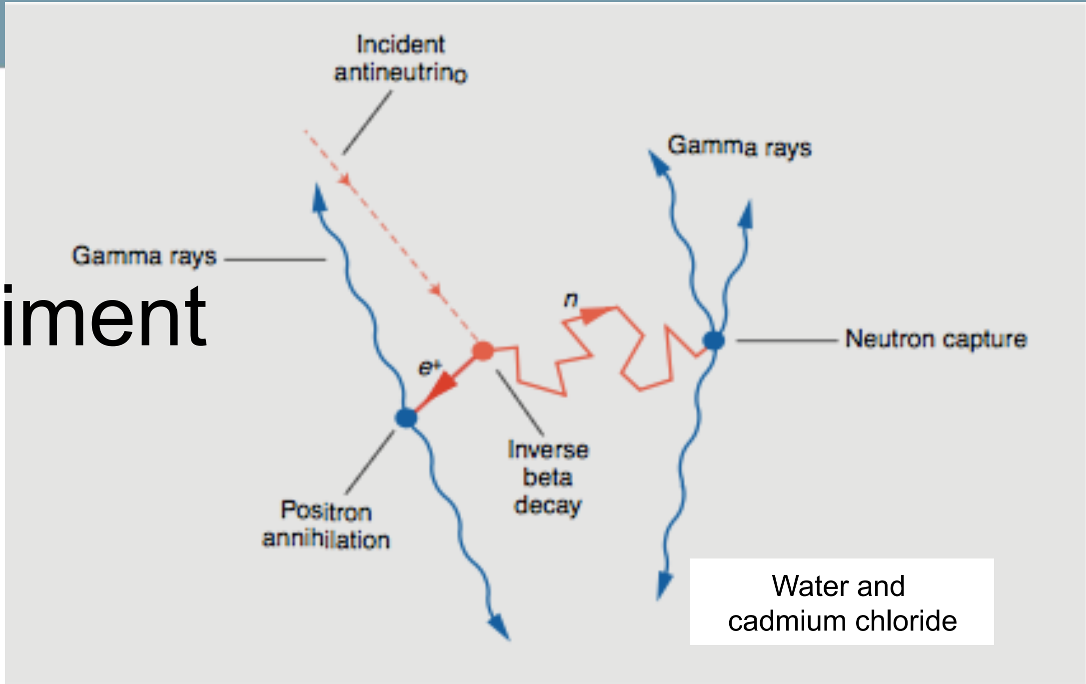
Reines-Cowan experiment



- The e^+ interacts promptly with an electron in the water

$$e^+ + e^- \rightarrow 2\gamma$$

- γ rays energy: 2 x 0.511 MeV

- The *n* wanders in the water losing energy by scattering
- After a few μs, the *n* is captured by a Cd nucleus
- The excited Cd nucleus de-excites emitting a few gamma rays (energy ~9 MeV)
- The gammas enter the scintillators and start electron cascades which eventually produce UV photons, detected by the PMTs
- Signature of the neutrino capture:
- two prompt gamma rays from the positron in different scintillators
- followed by retarded (~5 μs) gamma rays from Cd de-excitation

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No Nukes*

- Initially they thought of using an atomic bomb as a neutrino source
- This looks like a very silly idea, but there were reasons for that
- The bomb is not only an intense source, but also very short lived, so that the background events are minimized
- 1952: they realized how to reduce the background for a reactor experiment
- New idea: detect not only the positron, but also the neutron
- The delayed coincidence between the positron signal and the neutron capture signal is a powerful signature to discriminate neutrino events from background
- This issue was so critical that their first experiment at Hanford (1953) was inconclusive, due to cosmic-ray background

* The Reines-Cowan Experiments, Los Alamos Science 25 (1997). http://library.lanl.gov/cgi-bin/getfile?00326606.pdf

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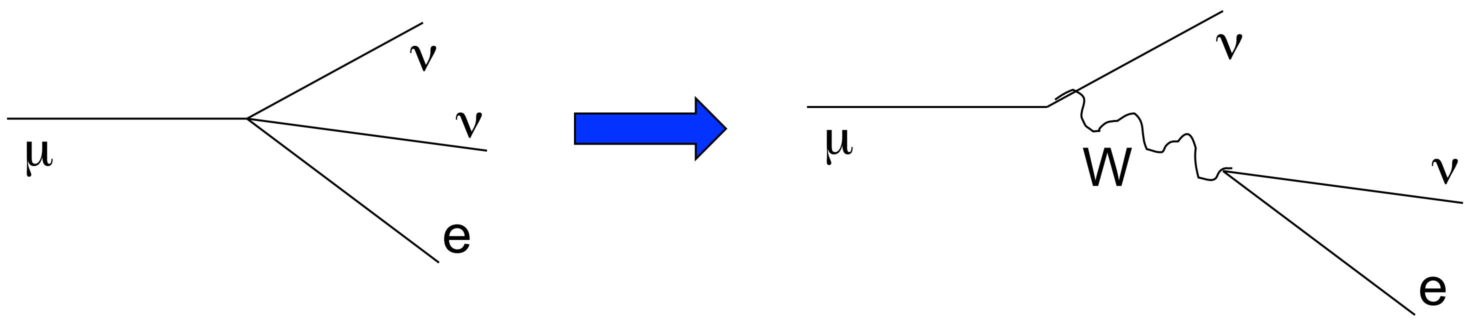
The neutrino discovery

(electron antineutrino, actually)

- In 1956 the experiment reported the detection of free neutrinos
- For this discovery the Nobel Prize in Physics was awarded to Reines in 1995, but not to Cowan, who had died in 1974

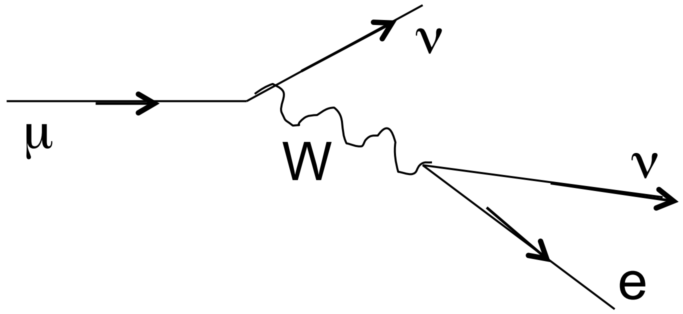
Enter the W boson (1949)

- Fermi's theory had a problem
- As energy grows, the probability of a neutrino interaction grows beyond 100%
- The way out was to give up the idea that the four particles interact at a single point
- In analogy with electromagnetism Lee, Rosenbluth and Yang proposed that also the weak force is mediated by a boson, called *W*

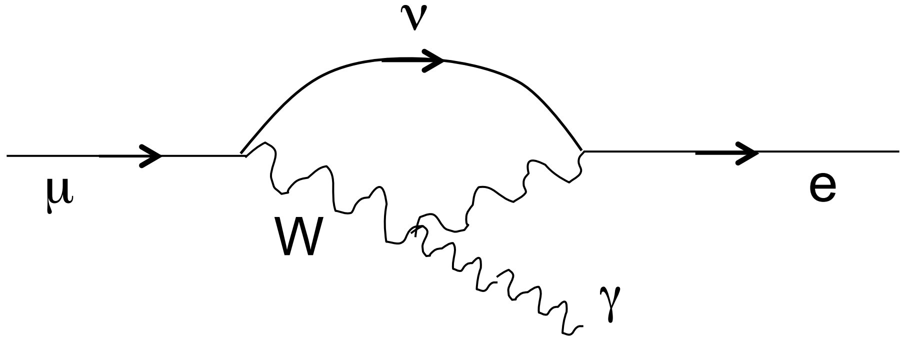


More neutrinos

- Consider the new diagram



- G. Feinberg: if the two neutrinos are of the same kind, a diagram like the following is possible



- and the muon should convert into an electron and a photon (~1 in 10^4 times), contrary to evidence

$$\mu \not\rightarrow e + \gamma$$

- Pontecorvo theorized as to why this conversion does not happen
- If it did not happen, something had to be forbidding it
- Proposal: the muon has a special property, ‘muon-ness’, what we today call flavor
- The electron also has its own flavor and both are conserved in interactions
- Because of this conservation the decay $\mu \rightarrow e + \gamma$ is forbidden
- He extended this idea to neutrinos: they come in two flavors, electron neutrino ν_e and muon neutrino ν_μ

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e- and mu-neutrino (ν_e ν_μ)

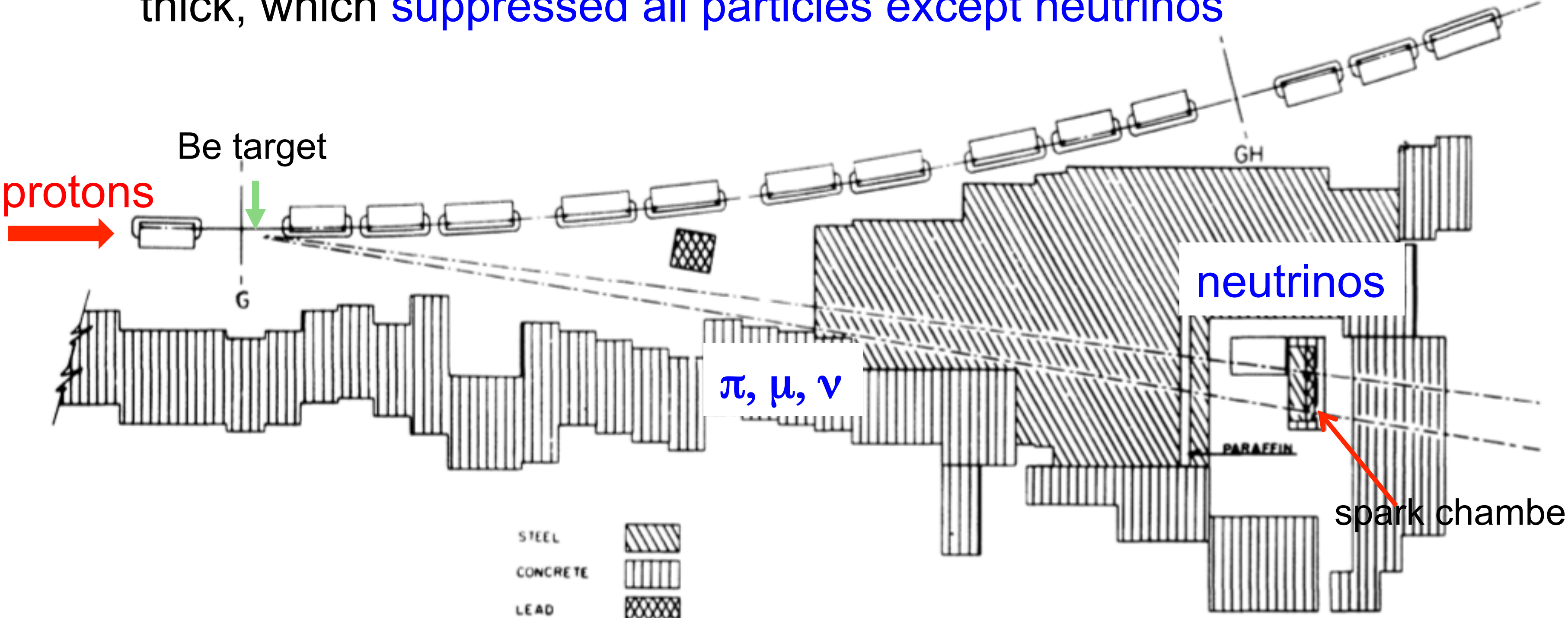
To test the 2-neutrino hypothesis he proposed to scatter neutrinos on matter: e-nu's should produce electrons, while μ-nu's should produce muons

the problem of the minute cross section would be overcome by producing beams of neutrinos at new high-energy accelerators (1959)

At that time in USSR there were not suitable accelerators. Nearly at the same time in USA, M. Schwartz, Lee and Yang moved along the same path

Schwartz-Steinberger-Ledermann experiment* (1962) - beam production

- The 15-GeV proton beam of BNL's Alternating Gradient Synchrotron was slammed into a 3" Be target, producing pions
- Pions decayed into muons and neutrinos
- The extracted beam was passed through a wall of steel 13.5 meters thick, which suppressed all particles except neutrinos



* G. Danby *et al.*,Phys. Rev. Lett. **9**, 36 (1962)

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Schwartz-Steinberger-Ledermann experiment – detector

- spark chamber: 90 Al plates (1” thick), kept at high potential, separated by gas-filled gaps (3/8” thick)
- Neutrinos would occasionally interact with a nucleon in an Al nucleus, transforming the nucleon and producing either an electron or a muon

$$\nu + N \rightarrow N' + l$$

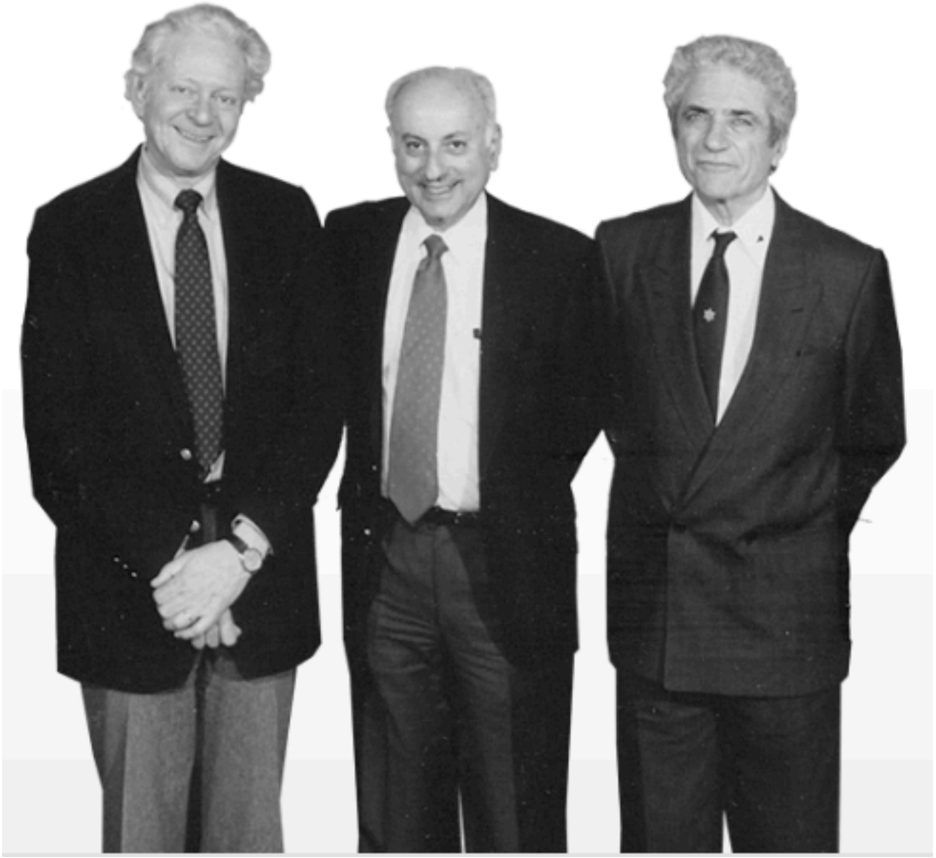
- This lepton would ionize the gas, creating a visible spark track between the plates of the chamber
- The kind of this track would tell if it was produced by an electron or a muon

Schwartz-Steinberger-Ledermann experiment − results

- The experiment sent ~3.48 x 10^{17} protons on the target
- 51 events were identified as high-energy neutrinos that had passed through the steel wall
- The tracks left by the charged particles through the Al plates showed no further interaction: consistent with muons but not with electrons
- Only muons were produced, suggesting that the neutrinos in the beam were different from beta-decay neutrinos

Ledermann
Schwartz Steinberger

- The experiment won the 1988 Nobel Prize in Physics



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Lepton numbers

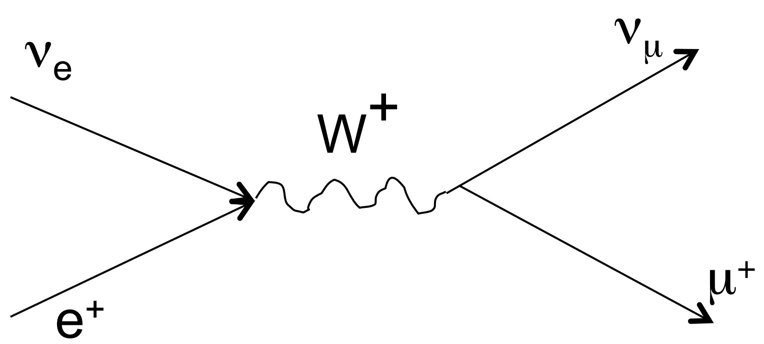
- Formally lepton flavor is indicated with a lepton number
- We associate a lepton number of +1 to particles
- and of -1 to anti-particles,
- separately for the electron and the muon sectors

particle	e lepton number	μ lepton number
electron	1	0
e neutrino	1	0
positron	-1	0
e antineutrino	-1	0
negative muon	0	1
μ neutrino	0	1
positive muon	0	-1
μ antineutrino	0	-1

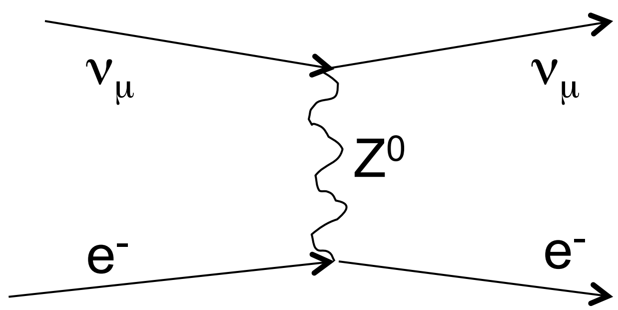
- Lepton numbers are conserved in interactions (oscillations excepted)

Charged and neutral currents

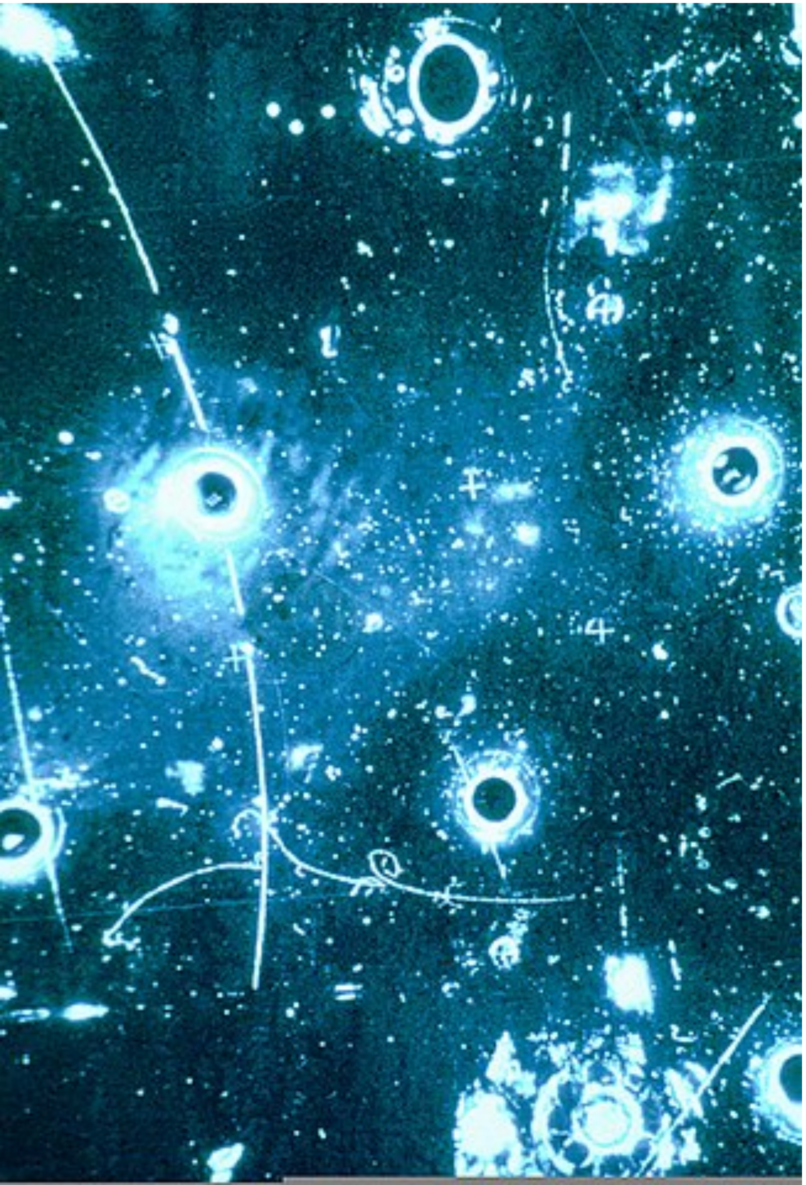
- There are two types of weak interactions
- A charged current interaction involves the exchange of a charged weak boson ($W^{\pm}$)



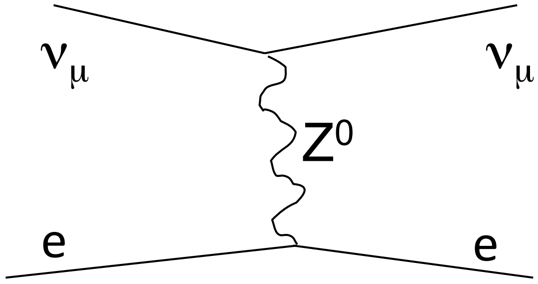
- A neutral current interaction involves the exchange of the neutral weak boson (Z^0)



Neutral currents



- Neutral currents were discovered in 1973 at Cern with the bubble chamber Gargamelle
- This discovery confirmed the unification theories of the electromagnetic and weak forces



Martin Perl

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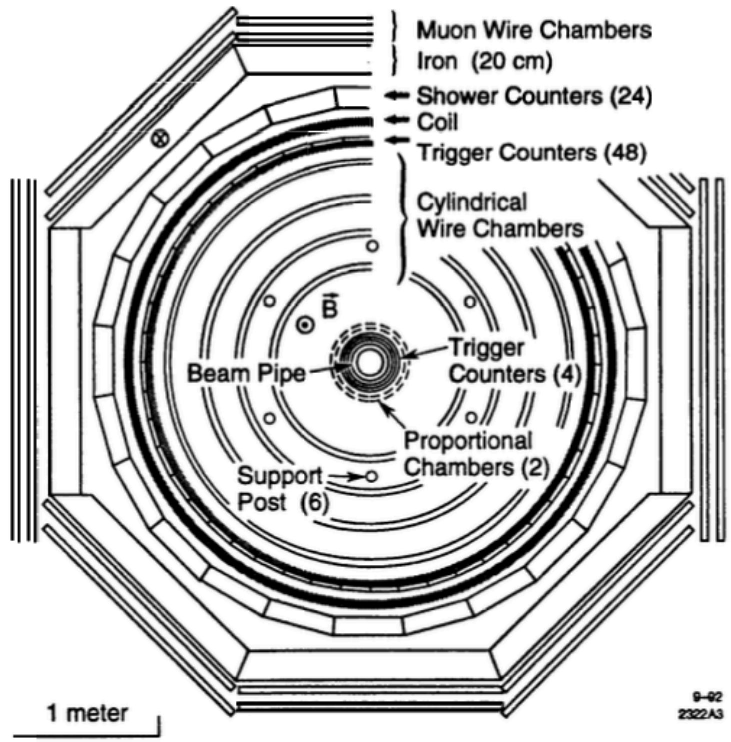
- He proposed to produce new leptons *l* via the reaction

$$e^+ + e^- \rightarrow l^+ + l^-$$

- at the SPEAR e$^+$e$^-$ collider and detect the subsequent decay

$$l^+ \rightarrow \bar{\nu}_l + e^+ + \nu_e \qquad l^- \rightarrow \nu_l + \mu^- + \bar{\nu}_\mu$$

$$l^- \rightarrow \nu_l + e^- + \bar{\nu}_e \qquad l^+ \rightarrow \bar{\nu}_l + \mu^+ + \nu_\mu$$



The Mark I detector

- with the SLAC-LBL detector (aka Mark I)
- The SPEAR e$^+$e$^-$ collider began operation in 1973
- The Mark I was one of the first large-solid-angle, general purpose detectors built for colliding beams

Martin Perl

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$$e^+ + e^- \rightarrow \begin{matrix} l^+ \rightarrow \bar{\nu}_l + e^+ + \nu_e \\ l^- \rightarrow \nu_l + \mu^- + \bar{\nu}_\mu \end{matrix}$$

$$e^+ + e^- \rightarrow \begin{matrix} l^+ \rightarrow \bar{\nu}_l + \mu^+ + \nu_\mu \\ l^- \rightarrow \nu_l + e^- + \bar{\nu}_e \end{matrix}$$

new sought-for events

$$e^+ + e^- \rightarrow \begin{matrix} l^+ \rightarrow \bar{\nu}_l + e^+ + \nu_e \\ l^- \rightarrow \nu_l + e^- + \bar{\nu}_e \end{matrix}$$

$$e^+ + e^- \rightarrow \begin{matrix} l^+ \rightarrow \bar{\nu}_l + \mu^+ + \nu_\mu \\ l^- \rightarrow \nu_l + \mu^- + \bar{\nu}_\mu \end{matrix}$$

background

$$e^+ + e^- \rightarrow \begin{matrix} e^+ \\ e^- \end{matrix}$$

$$e^+ + e^- \rightarrow \begin{matrix} \mu^+ \\ \mu^- \end{matrix}$$

Third generation: τ

- 1976: the Mark I detector finds events of the type

$e^+e^- \to e^\pm\mu^\mp + \geq 2$ undetected particles

- for which there was no 'conventional' explanation
- This was the discovery of another lepton particle, still heavier than the muon, the tau*
- For this discovery Perl won the Nobel Prize in Physics in 1995

* M. L. Perl *et al.*, Phys. Rev. Lett. **35**, 1489 (1975)

Is there also a ν_τ?

- In 1976 the Standard Model was born already and so physicists expected that there existed a neutrino associated to the tau

- It was only in 2000 that the tau neutrino was directly produced

DONUT experiment, setup

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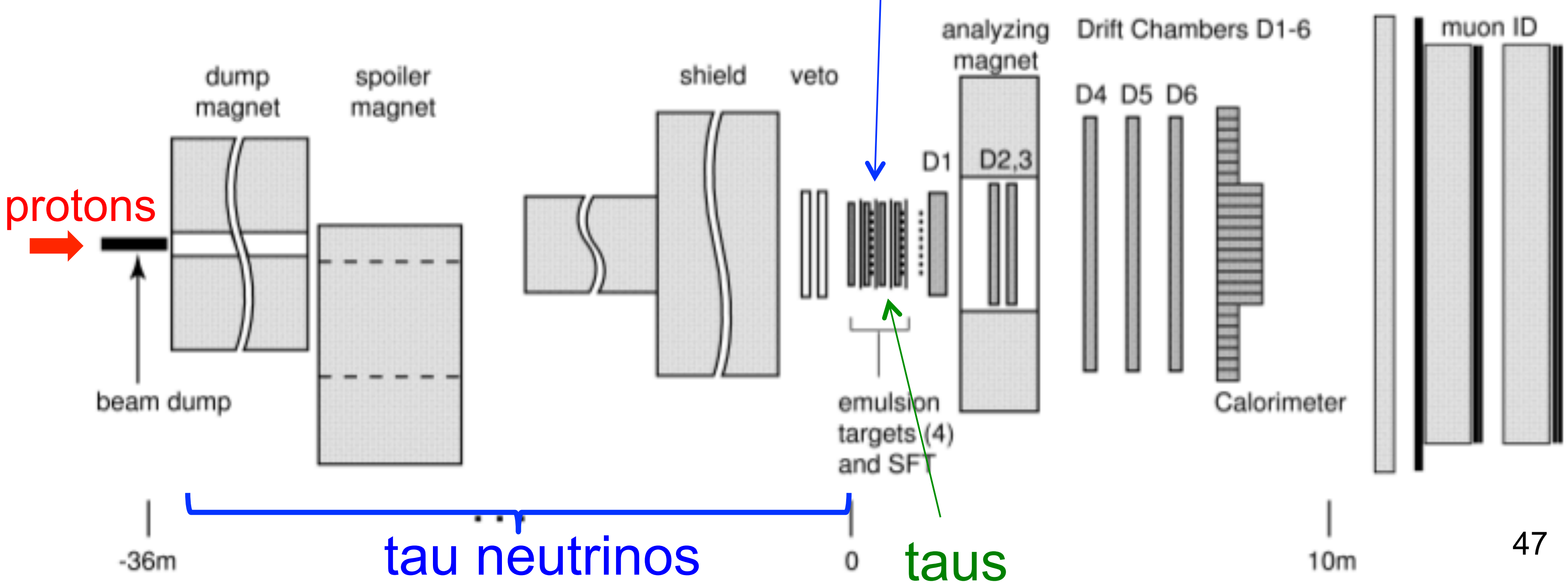
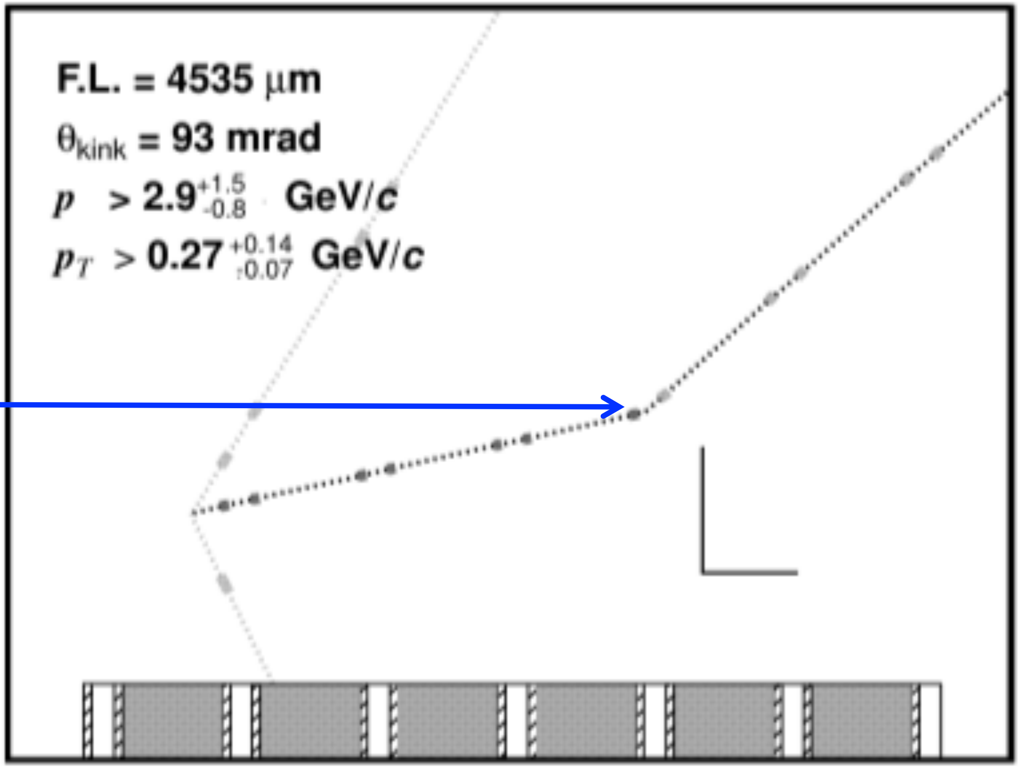
- 1997: at Fermilab's Tevatron, scientists produced an intense neutrino beam, expected to contain tau neutrinos
- 3'-long target: iron plates + layers of emulsion, which recorded the particle interactions
- One in 10^6 τ-neutrinos interacted with an iron nucleus and produced a τ lepton

$$\nu_\tau + n \to \tau^- + p \qquad \bar{\nu}_\tau + p \to \tau^+ + n$$



DONUT, results*

- The tau lepton leaves a 1-mm long track in the emulsion
- Main signature: track with a kink
- Indicating the decay of the tau lepton shortly after its creation



- Recorded: six million potential interactions
- Candidate events: 1000
- of these, 4 events provided evidence for the tau neutrino
- In 2000 the experiment reported the direct production of the ν_τ

* K. Kodama *et al.*, Phys. Lett B 504 (2001)

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Leptons

This completes the lepton family, as we know it today

$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix}$	electron el. neutrino	$\begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix}$	muon mu neutrino	$\begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$	tau tau neutrino
$\begin{pmatrix} e^+ \\ \bar{\nu}_e \end{pmatrix}$	positron el. anti-nu	$\begin{pmatrix} \mu^+ \\ \bar{\nu}_\mu \end{pmatrix}$	muon mu anti-nu	$\begin{pmatrix} \tau^+ \\ \bar{\nu}_\tau \end{pmatrix}$	tau tau anti-nu

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References

- Most of the material in the presentation was found in the beautiful book ‘Neutrino’ by Frank Close, Oxford University Press

- Physicist portraits were downloaded from the web

- Much useful information was found on Wikipedia pages − support Wikipedia!