TRISEP Lectures EW

Andrew: Hi, I'm Andrew and this is my twin...

Andy: ... Andy. Hi! We aren't like most of the twins you probably know.

Andrew: Nope, we are parity twins, and have the interesting feature that we are exactly identical except that Andy is the exact mirror image of me.

Andy: No, Andrew is the exact mirror image of me. Whatever the case may be, like all siblings there are things about which we do not agree.

Andrew: Yeah, for example, I am pointing to my left.

Andy: No, you are not; this direction is my right.

Andrew: Hrrmm, this really makes playing games hard. Just like Alice in Wonderland, Andy always runs the wrong way to get to the finish line.

Andy: I have no clue what you are talking about; Alice actually understood me, which is more than I can say about my own brother.

Andrew: Okay, okay, well we do agree on some things, like the direction of angular velocity of this spinning wheel.

Andy: Well, other than the fact that you are using the wrong hand for the right-hand-rule, yes, we do indeed agree.

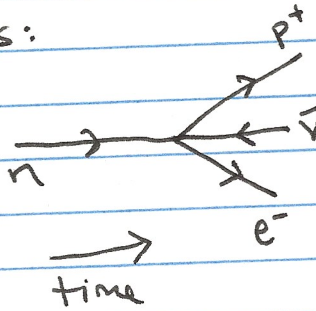
Andrew: Anyway, while we have our differences, we have always found a way to communicate, if we just have to switch "left" for "right" sometimes.

Andy: Yep, while we may disagree on directions, we agree that things <u>happen</u>; like balls rolling down hills, photons emitted from accelerating charges, or the number of jets produced in $e^+e^- \to$ hadrons collisions.

Andrew: Indeed, we have never met an interaction that was invisible to one of us...

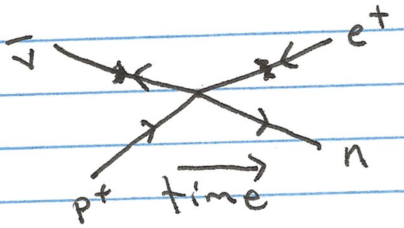
The 1930s were an exciting time for particle physics. The anti-electron, predicted by the Dirac equation in the late 1920s, was observed in 1932. Radioactivity, at least β-decay, was understood as the decay of the neutron, which was observed to decay to a proton and electron. However, if this were the only decay products, then energy conservation and angular momentum conservation are problematic. Wolfgang Pauli solved the problem by postulating the existence of an additional, unobserved, particle produced in the decay. This particle would have spin-1/2, must be electrically neutral and have an extremely small mass compared to the electron. In classy European style, Pauli introduced this particle in a letter to Lise Meitner, who was attending a conference on radioactivity in Tübingen, Germany. Pauli was unable to attend as he was required to be at a ball in Zürich, Switzerland, at the same time, hence the letter and not a talk. The letter famously opens with "Dear Radioactive Ladies and Gentlemen," and he calls this new particle the "neutron", as it must be neutral (and the atomic nucleus neutron was not named yet). Fermi later modified the name to what we now know as the <u>neutrino</u>.

It was rather quickly appreciated that whatever was responsible for mediating the decay Of the neutron could not be electromagnetism. The photon only couples to electrically charged particles, and the neutrino was neutrel so is invisible to a photon. So, the natural question to ask is what indeed are the properties of this interaction? First, so far, we have just observed neutron decay, which we can draw as:



(← technically an <u>anti</u>-neutrino)

However, this diagram can be rotated and massaged to establish observing the neutrino:



That is, we prepare a vat of a ton of protons (i.e. atomic nuclei) and observe positrons produced from some mysterious collision.

What other properties might we like to establish? Well, as written, this diagram is strange: there is "nothing" mediating the interaction. Particle types change literally due to some "magic" at the point of intersection. Why is this problematic? Well, we can estimate the cross-section for neutrino-proton scattering, $\sigma(\bar{\nu}p^+ \to e^+ n)$. Recall that there were two components of the cross section: the de Broglie wavelength factors of the initial particles, p^+ and $\bar{\nu}$, and the quantum mechanical wavefunction overlap of the initial and final states, $\langle e^+ n | \bar{\nu} p^+ \rangle$. That is, the cross section is

$$\sigma(\bar{\nu} p^+ \to e^+ n) \sim \frac{1}{E_{cm}^2} |\langle e^+ n | \bar{\nu} p^+ \rangle|^2$$

Now, so far, we have provided no mediating or intermediate particle to connect the initial and final states. All particles interact at a single, space-time point, as illustrated in the diagram. For a fixed center of mass energy, we can only resolve distances or times of the order of $1/E_{cm}$, the de Broglie wavelength of any of the particles. A point-like interaction means that regardless of E_{cm}, the interaction occurs at a single point. Thus everything must happen in a space time volume on the order of $\lambda_{dB}^4 \sim E_{cm}^{-4}$: spins must be projected, particle types changed, etc. The only way that this can always happen is if the probability scales like the inverse of the overlap volume:

$$|\langle e^+ n | \bar{\nu} p^+ \rangle|^2 \propto E_{cm}^4$$

Now, with this scaling, the units don't work out for the cross section, so we introduce a constant, but dimensionful, quantity G_F to take care of that. We then establish

$$\sigma(\bar{\nu} p^+ \to e^+ n) \sim \frac{1}{E_{cm}^2} G_F^2 E_{cm}^4 \sim G_F^2 E_{cm}^2,$$

and G_F is called the Fermi Constant and obviously has units of squared inverse energy.

Now you see the problem. This interaction predicts that $\sigma \to \infty$ as $E_{cm} \to \infty$, which makes no sense. We often say that this "violates unitarity" or conservation of probability of quantum mechanics. So, there are two outs: give up on an axiom of probability, or modify our theory. Which seems more reasonable? :)

Another aspect of this interaction that is very odd takes quite a leap to consider it. If all you care about are scattering rates or total energy production or the like, you don't care about the individual particles' spin configurations, for example, in neutron decay. And until the late 1950s, no experiment was concerned about the spins of the particles in neutron decay. (Actually, this isn't true as there was an experiment from 1928 that probed this. However, it was not well understood and apparently mostly lost to history until nearly 1960.) CN Yang and TD Lee, two theorists at Columbia noted this gaping hole in analyses and further noted that no* experiment had been performed to establish the parity properties of neutron decay, to firmly establish if Andrew's or Andy's view of the universe was more complete.

They communicated this to another Columbia colleague, CS Wu, who, in the days between Christmas and New Years 1956, performed the measurement that conclusively demonstrated parity *violation* in neutron decays. The set up was extremely simple and exploited the observations of Andrew and Andy for what they agree and disagree on. First, recall that Andrew and

Andy agree when they use the right-hand-rule for determining direction of vectors formed from a cross product. The most familiar vectors formed from a cross product are angular momentum ($\vec{L} = \vec{r} \times \vec{p}$) and magnetic field ($\vec{B} \propto \vec{J} \times \vec{r}$ by Biot-Savart Law). So, what Wu, et al., did was polarize the spins of the nucleus of ^{60}Co in a magnetic field, at very low temperature so thermal fluctuations were minimal. So, Andy and Andrew are in harmony so far.

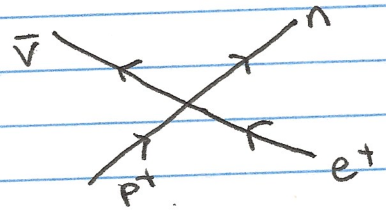
Then, ^{60}Co decays to $^{60}Ni + e^- + \bar{\nu} + 2\gamma$ (i.e., neutron decay plus energy in photons), but on the final state we just measure the velocity of the electron. Velocity or momentum is not formed from a cross product and so Andy and Andrew disagree as to the direction that the electron travels after decay. However, if it is observed that the electron travels parallel and anti-parallel to the magnetic field just as often, then Andy and Andrew live to argue another day.

However, what Wu observed was shocking. More electrons were emitted in the direction opposite to the nuclear spin, demonstrating that this neutron decay indeed had a preferred direction or parity. When told of this result, Pauli said that it was "total nonsense" and that it "must be repeated." Well, Wu was right, as experiment after experiment after experiment demonstrated parity violation in nuclear decays. Actually, this violation turns out to be maximal: in neutron decays, the electron is always left-handed: its spin is opposite to its momentum.

By angular momentum conservation, the anti-neutrino is therefore always right-handed, or a neutrino is always left-handed. If we assume (as we will in these lectures) that neutrinos are massless, *all* neutrinos are left-handed: their spin is *always* opposite to their momentum, independent of frame. Indeed, every experiment that has been performed has only observed (the effect of) left-handed neutrinos.

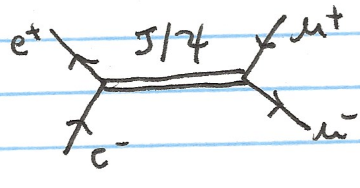
So, we have two mysteries: how are these interactions consistent with probability or "unitarized" and how can they only couple left-handed particles. We will establish the first in these lectures and comment on the second where we can.

First, let's give a name to the interaction that mediates neutron decay. The neutron lives for about 15 minutes, so the rate of decay is very slow; or, that the coupling of this interaction is "weak", compared to decay rates of other particles. So, we will refer to this interaction as *the* weak nuclear force. Second, let's revisit the diagram for $\bar{\nu}p^+ \to e^+ n$ scattering:



Werner Heisenberg noted (again in the 1930s) that protons and neutrons were extremely similar, except for pesky electromagnetism, and established an (approximate) symmetry between isotopes of elements with the same atomic weight (or between protons and neutrons) referred to as isotopic spin, or, isospin. It is called isospin because it is the unitary combination of two objects (protons and neutrons), forming the group SU(2), which is identical to the familiar rotation group in quantum mechanics. However, isospin does not change any spacetime properties of the particles; it is thus "internal" and just changes their label. Isospin motivates a relationship between protons and neutrons and therefore a relationship between electrons and neutrinos. So, this suggests that this interaction couples the pairs ($e^+\bar{\nu}$) to (p^+n). In both pairs, an initial charged particle (e^+ or p^+) transforms into a neutral particle ($\bar{\nu}$ or n). Thus, whatever mediates this interaction must itself be electrically charged. Hence, we refer to it as the "charged current", until we get a better name.

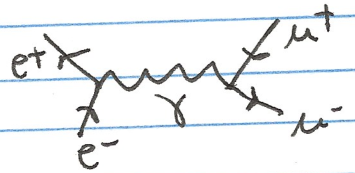
Next, let's revisit $e^+e^-\to\mu^+\mu^-$ scattering, our old friend, but plot the cross-section over many decades of center-of-mass energy $E_{cm}\equiv\sqrt{s}$. This is such a plot, from the PDG, which incorporates a huge number of experimental results. At low $E_{cm}\sim 1$ GeV, the cross section has bumps all over due to hadronic resonances; or, new intermediate particles that could mediate this process. For example, one of the strongest resonances is that of the J/ψ particle, a bound state of a charm and anti-charm quark:



Near $E_{cm}\sim m_{J/\psi}$, the J/ψ (nearly) becomes a real particle which could/would live forever. As such the scattering rate goes through the roof.

Further, because we know that photons or electromagnetism could mediate $e^+e^- \to \mu^+\mu^-$, and we do not measure directly the mediating particle, the photon and the J/ψ must interfere quantum mechanically, just like the two-slit experiment. For the photon to interfere with J/ψ, they must also share some quantum numbers, otherwise we could distinguish them in this experiment. Both the photon and J/ψ are electrically neutral, for example, but clearly the J/ψ has a non-zero mass, unlike the photon.

With this in mind, let's travel along the cross section to higher E_{cm}. Note that after about $E_{cm} \sim 10$ GeV, the cross section falls off like $1/E_{cm}^2$, exactly as expected from the de Broglie wavelength argument with a photon mediator:



However, something magical happens at about $E_{cm} \sim 91$ GeV. The cross section increases by nearly three orders of magnitude! Within E+M, 91 GeV is not special, so this cannot be a manifestation of an electromagnetic phenomena. However, it cannot be unrelated to the photon as again, whatever this is must share some quantum numbers with the photon. It must, for example be electrically neutral, but apparently have a mass around 91 GeV. We will correspondingly refer to it as the "neutral current."

Okay, what else can we see in e^+e^- collisions? From isospin + neutron decay, we expect that the charged current relates $(e^+\bar{\nu})$ or $(e^-\nu)$ to one another. So... perhaps the charged current could mediate the interaction

$$e^+e^- \to \nu\bar{\nu}?$$

If it does, we could look for this, but there is a problem. Neutrinos are electrically neutral, nearly massless, and apparently don't interact much otherwise. So, there's basically no hope to observe two neutrinos in our experiment. Instead in collider physics, the presence of neutrinos is typically manifest through their absence, and violation of conservation laws if they did not exist. In particular, if you did not observe neutrinos in $e^+e^- \to \nu\bar{\nu}$, you would observe electron-positron collision to *nothing*. All that energy would apparently be *missing*. Thus, the effect of neutrinos at colliders is referred to as missing energy, missing transverse momentum, MET or $\not{E}_T$. So, our experimental signature would be

$$e^+e^- \to \nu\bar{\nu} \rightsquigarrow e^+e^- \to \not{E}_T \text{ or nothing.}$$

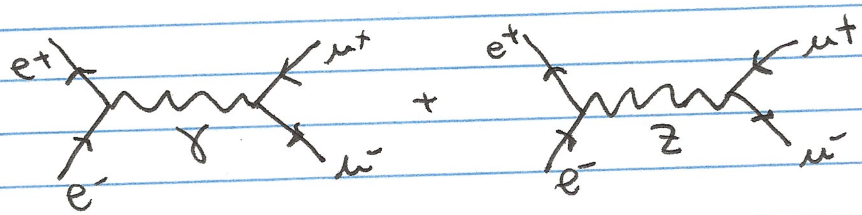
As you might guess, measuring "nothing" is challenging, and so this is *not* what experiments do. Instead, they require the presence of another, relatively benign, particle as a probe of $\not{E}_T$ events. It is easy to produce photons in e^+e^- collisions, so let's add one:

$$e^+e^- \to \nu\bar{\nu}\gamma \rightsquigarrow e^+e^- \to \gamma + \not{E}_T$$

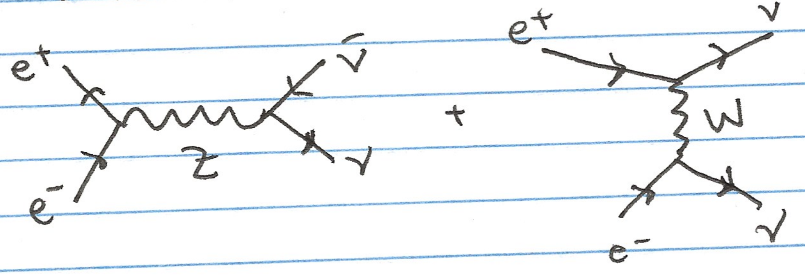
So, we look for a photon and an imbalance of conservation of momentum of the final state particles. Note that the photon just is emitted off of the e^- or e^+ and not the neutrinos, and so is relatively benign, as it shouldn't effect how the neutrinos are produced.

So, let's look for $e^+e^- \to \gamma + \not{E}_T$ in experiment and plot the cross section as a function of E_{cm}. Fascinatingly, the cross section exhibits a feature at around 91 GeV, which we had already established as interesting. The neutral current is not the photon, so it could interact with neutrinos through some other mechanism. Thus, the neutral and charged currents must be related some how if they both could mediate $e^+e^- \to \nu\bar{\nu}$.

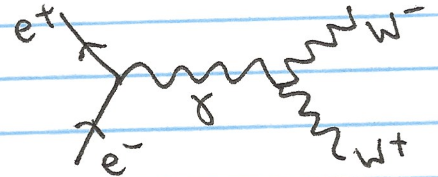
Let's now draw some diagrams and give some names to things. We will call the neutral current the Z boson and it or the photon can mediate $e^+e^- \to \mu^+\mu^-$:



Further, let's call the charged current the W^+ or W^- bosons (according to their charge) and they, or the Z boson can mediate $e^+e^- \to \nu\bar{\nu}$:



By the transitive property of relationships, we therefore have four spin-1 bosons that are intimately related: γ, Z, W^+, W^-. There is no intrinsic energy scale with E&M, and so the photon is massless. We observed that 91 GeV was special, and ascribe this to the mass of the Z boson: $m_Z \sim 91$ GeV. We have not, however, established the mass of the W boson. However, it is electrically charged and so couples to the photon. Thus, we can look for $e^+e^- \to W^+W^-$ corresponding to the diagram:



Can we estimate the cross section for this process? As usual, let's separate out the de Broglie bit from the wavefunction overlap:

$$\sigma(e^+e^- \to W^+W^-) \sim \frac{1}{E_{cm}^2} |\langle W^+W^- | e^+e^- \rangle|^2 .$$

As anti-particles, the W^+ and W^- have identical masses, call it m_W. Therefore, this cross section depends on two energies, E_{cm} and m_W. Equivalently, we can express these two energies as E_{cm} and the W boson momentum

$$|\vec{p}| = \sqrt{\frac{E_{cm}^2}{4} - m_W^2}\,,$$ which only exists if $E_{cm} > 2m_W$.

Thus, we can write

$$\sigma(e^+e^- \to W^+W^-) \sim \frac{1}{E_{cm}^2} \left(\frac{|\vec{p}|}{E_{cm}} \right)^{\alpha} ,$$ for some exponent α.

This parametrization is nice because $|\vec{p}|/E_{cm} \to$ const.

as $E_{cm} \to \infty$. Further, if $E_{cm} \to 2m_W$ from above, the cross section had better vanish because the energy is not large enough to produce the W bosons. Then $\alpha > 0$. Thus, we can look for a threshold energy at which the cross section for this process turns on and use it to establish the mass of the W boson. Doing this, we find that $m_W \sim 80.38$ GeV.

Apparently, we find four related spin-1 bosons. If there is a symmetry that relates them and mixes them, the simplest such Lie group is $U(2)$ or $SU(2) \otimes U(1)$. Recall that $SU(2)$ has three generators (three axis for rotation in 3D) and $U(1)$ has 1, so there are a total of four objects that can be mixed by the action of $SU(2) \otimes U(1)$. We refer to this theory as the unified electroweak force.

Finally, the high mass of the W boson / charged current explains the lack of mediating particle in neutron decays. If the W boson is essentially at rest, its relevant wavelength is its Compton wavelength, proportional to $1/m_W$. The mass of the neutron is about 1 GeV, and so there is no way that its Compton wavelength can resolve the W boson: $\lambda_c^n \gg \lambda_c^W \Rightarrow m_W \gg m_n$. Hence, the particles in neutron decay might as well effectively interact at a point. Thus we say that this interaction of four fermions (a "four-Fermi interaction") is a low energy effective theory of the weak force.