The Hunt for Leptoquarks: 1-prong τ-decay and CLFV (Charged Lepton Flavor Violation)

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What are leptoquarks and why hunt for them?

- ***Neutral* lepton flavor violation** is indeed observed with neutrino oscillations (neutrinos can change their flavors to other types of neutrinos).
- Other new theories of the universe and extensions of the standard model also naturally predict that there could be flavor violation observed in *charged* leptons, **charged lepton flavor violation**.
    - This could be possible by the existence of a mediating boson, a **leptoquark**, that carries both baryon *and* lepton numbers. It would have an associated conservation, observed by means of a fermion quantum number, F = 3B + L.
    - Example of charged lepton flavor violation: $q_a e^- \rightarrow q_b \tau^-$

Possible Leptoquark Feynman Diagrams

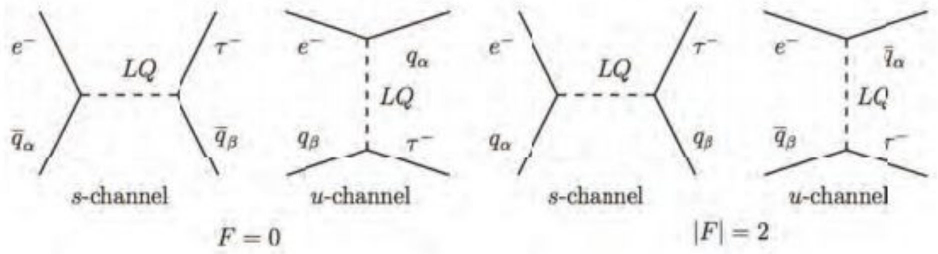


Figure 4.1: Feynman diagrams for $e \to \tau$ scattering processes via leptoquarks, which carry fermion number $F = 3B + L$ equal to 0 or ± 2 [261]

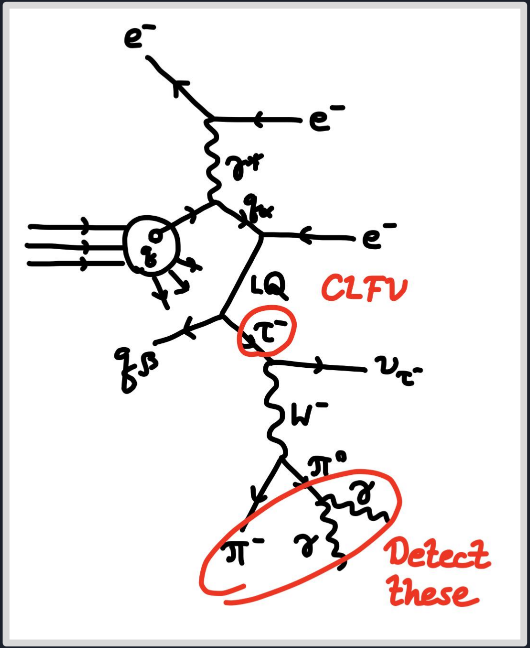
How do we infer that these processes happen?

- Speculative theories that involve CLFV predict enhanced rates of electron to tau conversions.
- So then, the diagram from the previous slide shows the exact processes we wish to observe, electron to tau conversion.
    - The tau lepton has a lifetime in its rest frame of 2.9×10^{-13} s, after this time it can undergo many possible decay modes.
- My part of this project in particular investigates what we call “1-prong” processes, decay modes of the tau lepton that results in the production of a single (1) charged particle.
    - **In particular, the decay mode:** $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$
    - This decay mode happens ~25.49% of the time.
- However, particle collisions are messy, and that mess poses a problem for detection of the decay products of the tau lepton.

When the background takes the foreground

- We are interested in the following decay mode: $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$
- So what are we looking for?
  - We see that a negatively charged pion is produced, a neutral pion, and a tau neutrino. Neutrinos are ridiculously difficult to detect, so we want to stick with the pions, a negative pion and a neutral pion.
- So we're looking for the pions, except that isn't quite it. The neutral pion undergoes a decay into two photons, giving us the following decay pathway: $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau \rightarrow \pi^- 2\gamma \nu_\tau$
  - And we can only detect the $\pi^- 2\gamma$.
  - However, we're performing our experiment by colliding a beam of electrons and protons, and that means we will have a background of **deep inelastic scattering**, which also produces negative pions and photons.
  - We'll've to look for pions and photons produced from tau leptons, in a horde of pions and photons from deep inelastic scattering, which makes it difficult to say whether or not it's evidence of a leptoquark, or just that electrons and protons are undergoing deep inelastic scattering as we expected.

Feynman Diagram

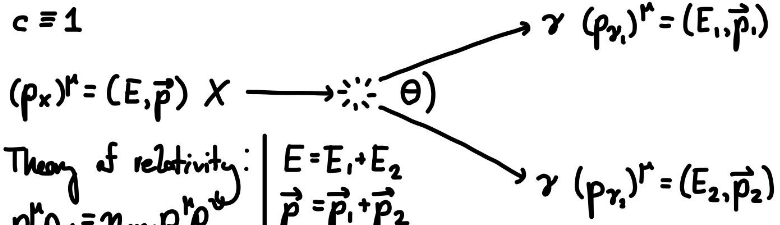


My goal this semester

- Essentially, I have to make an algorithm so that we can identify the pions and photons from tau decays out of all the pions and photons our detector detects.
    - Essentially performing cuts in the kinematic variables of our experiment that isolates our pions and photons, after finding out what the cuts should be.
- Potential strategies:
    - With a simulation of an electron beam colliding with a proton beam with leptoquark physics turned on, could investigate the ROOT files to find ranges of energy, angle, momentum, etc., that have a correlation to tau-produced pions and photons, and not with pions and photons from the DIS background.
    - Could also use known four-momentum of the photons and pions and the structure of the detector to find the source of detected particles. We could take every possible pair of photons and see if they could have originated from a particle with an invariant mass that coincides with the neutral pion.
        - Reconstruction is done by calculating the **invariant mass** from the decayed particle's energy and three-momentum, and seeing if it coincides with the invariant mass of a **neutral pion**.
        - $(m_X)^2 = 2E_1E_2(1 - \cos(\theta))$

Calculating invariant mass (in case anyone asks?)

$c \equiv 1$



Theory of relativity:

$$p^\mu p_\mu = \eta_{\mu\nu} p^\mu p^\nu = E^2 - \vec{p}\cdot\vec{p} = \underline{m^2}$$

$$\therefore m_\gamma^2 = E_\gamma^2 - p_\gamma^2 = 0$$

$$\downarrow$$

$$(E_\gamma = p_\gamma)$$

$$E = E_1 + E_2$$

$$\vec{p} = \vec{p}_1 + \vec{p}_2$$

$$m_X^2 = E_1^2 + 2E_1E_2 + E_2^2 - \vec{p}_1\cdot\vec{p}_1 - 2\vec{p}_1\cdot\vec{p}_2 - \vec{p}_2\cdot\vec{p}_2$$

$$= \underbrace{2m_\gamma^2}_{=0} + 2(E_1E_2 - \vec{p}_1\cdot\vec{p}_2)$$

$$= 2(E_1E_2 - p_1p_2\cos(\theta))$$

$$\underline{m_X^2 = 2E_1E_2(1-\cos(\theta))}$$

My goal this semester

- After reconstructing the invariant mass of the parent particle of the two photons, we can check if the invariant mass coincides with the invariant mass of the neutral pion.
- Possible issue with assuming that the photons did not interact with other particles in such a manner that they followed trajectories we could not predict.
- Note on photon path reconstruction (interesting aside):
  - We detect photons through electromagnetic calorimeters, where they deposit energy.
  - It might be possible to, given an energy deposition E_0 by some photon at a detector at location x_0, to use theoretical calculations of $dE/dx|_{x0}$ to estimate the energy deposition E by the same photon at a detector that is dx away from x_0, at location x_0 + dx. We could then see which detectors have that energy deposition.
  - The most glaring issue is that due to low resolution of the calorimeters, we'd have a lot of particles depositing energy into the same spot, giving us ridiculous background, in addition to the issue of identifying a detector through which only one photon travelled in the first place for our theoretical calculations.

Questions?