Final Project suggestions

The following topics are suggested for your final project. It is important to understand that you are not expected to become an expert in these subjects, but rather get a sense for the most important questions and developments in the field. You should be able to explain the main ideas to a fellow senior undergraduate student in Physics who knows what cross sections and decay rates are and who has some idea of the particle content of the Standard Model.

You can choose one of these topics or propose your own idea. Some of these are more advanced than others (☕: undergraduates might want to start with these, 🌶: getting exciting, 🌶🌶: will definitely keep you entertained, 🌶🌶🌶: definitely a challenge, but still doable). Bear this system in mind as you make your choice, especially if you are working in a group with varying levels of expertise. If you want to propose your own idea, make sure to discuss it with me first so we can refine the scope appropriately. The project should involve a literature review and some calculations or estimates. For each topic, I provide a few suggestions of questions you should answer in your literature review and presentation.

The final project report should be between 6 to 8 pages (excluding references). You can find a template on ICON. If you use your own template, make sure to use a 11 or 12 pt font and at most a 1.5 line spacing. Make sure to include your name(s) and student number(s) on the report. I will not measure anyone's fonts or margins, but I expect your text to look professional and reasonable.

You can find a template for the report on Overleaf:

https://www.overleaf.com/read/wmbrdwbhqfwf#cc3bdc

You can work in groups of 3 to 4 people. The presentation should be from 20 to 25 minutes long. Make sure to involve everyone in your group in the presentation. I want to see ***demonstrated teamwork***, so make sure to communicate effectively with your group!

Contents

Evaluation criteria:

This is a free format project, but I expect you to include at least the following so that I can evaluate your work properly:

- A brief introduction to the topic, including the necessary theoretical background (no more than 2 pages).
- At least one feynman diagram relevant to relevant to the topic, with correct labels and particle number arrows.
- A plot that you made yourself (e.g. using Python, Mathematica, etc) that illustrates some important aspect of the topic. This could be some cross section, an oscillation probability, experimental limits as a function of time, or something similar. Avoid plotting trivial relationships, like linear scaling behaviors. Make sure to explain the plot in your report and presentation.
- Pick at least one experimental paper/measurement relevant to your topic to expand on. I expect you to be able to follow at least the main idea in the experimental measurement. For example, if you are discussing colliders, you can discuss the Higgs boson discovery, if you are covering flavor violation, you can discuss searches for $\mu \to e\gamma$ at the MEG-II experiment, or if you are talking about direct detection of dark matter, you can discuss the XENONnT limits.
- A list of references with at least 5 papers or review articles. Cite only published work with a reasonable standing in the field. This usually means the paper is not too new and has a decent number of citations (> 10, for example). No Wikipedia or similar. You can use Inspire-HEP to explore the metrics of your references.
- A conclusion section where you summarize the main points of your report and discuss open questions in the field.

0 FLS) Solar neutrinos: ☕

Review the history and current status of solar neutrino experiments, including Homestake, GALLEX/GNO, SAGE, Super-Kamiokande, and SNO. Discuss the solar neutrino problem, its resolution through neutrino oscillations, and the implications for our understanding of neutrino properties.

1. What are the main solar reactions that produce neutrinos and what are their characteristic energies?
2. What was the solar neutrino problem and how was it resolved?
3. Provide a brief overview of the Mikheyev-Smirnov-Wolfenstein (MSW) effect. Write the P_{ee} formula for solar neutrinos in the adiabatic limit neglecting θ_{13}.
4. Explore the current and future experiments aimed at measuring solar neutrinos, such as Borexino, JUNO, and Hyper-Kamiokande.
5. Why was the measurement at the SNO experiment so important and how does it help us understand that the resolution of the solar neutrino problem is neutrino oscillations?
6. Why can we infer that $m_2 > m_1$ from solar neutrino data? Why then is the sign of Δm^2_{31} not known?

1 ACZ) Neutrino masses and neutrino-less double beta decay ($0\nu\beta\beta$): 🌶🌶

Investigate the topics of direct neutrino mass measurements and neutrinoless double beta decay.

1. How can you use beta decay to measure the absolute neutrino mass scale? What is the m_β parameter that we actually measure in beta decay experiments?

2. What are the current best limits on m_β and (discuss the KATRIN experiment) and how do they compare to cosmological limits on the sum of neutrino masses?

3. Explain the significance of neutrinoless double beta decay ($0\nu\beta\beta$) in determining the Majorana nature of neutrinos and its implications for lepton number violation.

4. What parameter is actually measured in $0\nu\beta\beta$ experiments? Explain the concept of the effective Majorana mass $m_{\beta\beta}$ and how it related to the parameter measured in direct mass measurements.

5. Discuss the current experimental limits on $0\nu\beta\beta$ from experiments like KamLAND-Zen and EXO-200. What are the future prospects for improving sensitivity?

6. You may want to produce the "Lobster" plot to illustrate the relationship between $m_{\beta\beta}$ and the lightest neutrino mass.

2 ABI) Lepton flavor violation:

Explore the theoretical and experimental aspects of lepton flavor violation, which is forbidden in the Standard Model but can occur in many extensions.

1. What is lepton flavor violation and why is it forbidden in the Standard Model?
2. What does neutrino oscillation imply for charged lepton flavor violation? How does it compare to quark flavor violation in the SM?
3. Draw a diagram in the SM and give some arguments as to why it is so suppressed (you can think of $\mu \to e\gamma$ as an example – bonus points if you can explain the GIM mechanism in a simple fashion).
4. Show the historical evolution of the experimental limits on LFV processes, such as $\mu \to e\gamma$, $\mu \to 3e$, and $\mu - e$ conversion in nuclei. What are the current best limits?
5. What are some of the current experiments that are searching for LFV? What about future ones?

3 AHM) Black hole superradiance with ultra-light fields. 🌶🌶🌶

1. What is superradiance? Give a classical analogue and a wave analogue. What does superradiance mean for the number of quanta in the wave?

2. What is *black hole* superradiance and how does it relate to ultra-light bosonic fields such as axions or other ultra-light particles? Discuss the mirror around the black hole analogy. Why does this only happen for bosons and not fermions?

3. Derive/motivate the condition for superradiant scattering of a bosonic field off a rotating black hole.

4. What does the potential look like at large distances? What do the bosonic cloud solutions look like around black holes? If a given particle carries about one $\hbar$ unit of angular momentum, what can you say about the approximate number of quanta in these clouds?

5. Why can they extract energy and angular momentum from the black hole? What happens to the cloud over time?

6. Discuss the observational signatures of black hole superradiance, such as gravitational wave emission and modifications to black hole spin distributions.

7. What are the current constraints on ultra-light bosonic fields from black hole superradiance observations? Why do we care about superradiance constraints anyway?

4 KD) The seesaw mechanisms.

In this project, you will explore one of the most popular frameworks to generate small neutrino masses in extensions of the Standard Model: the seesaw mechanism.

1. What are Majorana masses? How do they differ from Dirac masses?
2. For a single generation of neutrinos, write down the most general mass matrix of neutrinos including both ν_L and ν_R fields, including the Majorana mass for ν_R (m_R) and the Dirac mass m_D. What does the mass spectrum look like in the two limits: (i) $m_D \gg m_R$ and (ii) $m_D \ll m_R$?
3. Explain the latter limit and how it leads to the seesaw mechanism for generating small neutrino masses.
4. What are the typical values for the Dirac and Majorana masses in the seesaw mechanism to generate sub-eV neutrino masses? What does this imply for experimental searches for the heavy neutrinos?
5. Explain/motivate how the seesaw mechanism leads to the Weinberg operator and how it generates neutrino masses after electroweak symmetry breaking.
6. Is the ν_R neutrino the only particle that can trigger the seesaw mechanism? Comment on Type-II and Type-III seesaw mechanisms.
7. What are the implications of the seesaw mechanism for neutrinoless double beta decay? How about the matter-antimatter asymmetry in the universe?
8. Comment on the inverse seesaw mechanism and diagonalize the 3×3 matrix in that case to show that neutrino masses are naturally small when lepton number is approximately conserved. In terms of symmetries, why is it natural to have a small lepton number violating parameter in this case?

5 Quasi-Dirac neutrinos: ☕

Review the theoretical framework and experimental status of quasi-Dirac neutrinos.

1. What are quasi-Dirac neutrinos and how do they differ from Majorana and Dirac neutrinos?
2. What are the observational consequences of quasi-Dirac neutrinos in neutrino oscillation experiments?
3. Discuss the constraints on quasi-Dirac neutrinos from solar and astrophysical neutrino experiments.
4. What is the implication of quasi-Dirac neutrinos for the conservation of lepton number?
5. Estimate the oscillation length associated with the small mass splitting in quasi-Dirac neutrinos. How does this compare to typical baselines in neutrino experiments?
6. What is the oscillation formula for quasi-Dirac neutrinos in the two-flavor approximation? What are the neutrinos oscillating into?
7. Explore constraints from supernova neutrinos, astrophysical sources, and solar neutrinos.

6 eV sterile neutrinos: ☕

Survey the status of sterile neutrinos with $\Delta m^2_{41} \sim \mathcal{O}(1\text{ eV})$, including the experimental results that have hinted at (LSND, MiniBooNE, and gallium anomalies) or excluded (IceCube, MINOS+, solar neutrinos, cosmology) their existence. Discuss the theoretical implications and possible models that can accommodate eV sterile neutrinos.

1. What are sterile neutrinos and how do they differ from active neutrinos?
2. What are the appearance and disappearance oscillation probability formulae in the 3+1 model and how do they reduce to the two-flavor formula in the short-baseline limit?
3. Discuss the interplay between appearance and disappearance channels. What does the observation of $\nu_\mu \to \nu_e$ appearance imply for ν_μ disappearance channels?
4. Summarize the key experimental results that suggest the existence of eV sterile neutrinos, including LSND, MiniBooNE, and the gallium anomaly. What reaction is used to produce and detect neutrinos in each one of these experiments?
5. What are the main experimental constraints on eV sterile neutrinos from disappearance searches. Take, for example, the MINOS/MINOS+ and reactors experiments.
6. How can existing experiments like MicroBooNE and SBN help to clarify the status of eV sterile neutrinos?

7 Colliders and future prospects: 🌶

Discuss the main proposals for future colliders.

1. Why would we want to build a new collider with higher energy than the LHC?
2. Explain the concept of luminosity and center of mass energy in colliders. How do they differ from fixed-target experiments?
3. Describe the Large Hadron Collider, its main achievements, and principle of operation. What are its main limitations?
4. Describe the principle of operation of each future collider proposal: the Future Circular Collider (FCC, both in e^+e^- and p^+p^+ modes), the International Linear Collider (ILC), and the muon collider.
5. Discuss the unique challenges and advantages/disadvantages of a muon collider given that the muon is unstable.
6. Discuss synchrotron radiation and how it scales with mass.
7. What is the neutrino radiation hazard in a muon collider?

8 The neutrino fog in DM direct detection: 🌶

Discuss the neutrino fog (a.k.a. the neutrino floor) for dark matter direct detection.

1. Describe the detection process used by direct detection experiments to search for WIMP dark matter.
2. What are the main backgrounds for direct detection experiments? Why are dark matter detectors underground?
3. Why are neutrinos an irreducible background for direct detection experiments?
4. Estimate the typical nuclear recoil energies expected from WIMP-nucleus scattering.
5. What are the limits on the dark matter nucleon cross section from current experiments like XENONnT, LZ, and PandaX-4T? What are the future prospects for improving sensitivity? Explain the standard plot used to present these limits.
6. In the main plot of direct detection (σ vs $m_{\rm DM}$), where is the neutrino fog? How far are we from it?
7. What are some of the proposed methods to distinguish between a dark matter signal and the neutrino background?

9 Light dark matter and dark sectors: 🌶🌶

Discuss what happens for dark matter direct detection if the dark matter mass is below the GeV scale in mass. You may want to still have it above the MeV scale. Provide a broad overview of the shift in experimental techniques required if compared to WIMP searches.

1. What kinds of cross sections are required to produce the correct relic abundance of light (MeV) dark matter in the early universe? What does this imply for force carriers? Discuss the Lee-Weinberg bound and how it can be avoided.
2. Give one example of a mediator particle that can mediate interactions between light dark matter and the Standard Model.
3. What are the kinds of experimental constraints on this mediator?
4. Why are nuclear recoils not enough to detect sub-GeV dark matter? What are the alternatives?

10 The QCD axion: 🌶🌶🌶

(For the one looking for a challenge — QFT strongly recommended — for this one, you will have to aim at a more advanced audience.) Study the QCD axion as a solution to the strong CP problem.

1. What is the strong CP problem and how does the axion solve it?
2. Why is the axion so light and why is it so weakly coupled to ordinary matter?
3. What are the main experimental and observational constraints on the QCD axion? You can discuss laboratory or astrophysical bounds. Talk about Maxwell's equations in the presence of an axion field.
4. Discuss the axion as a dark matter candidate.

11 Other ideas:

11.1 Long-baseline experiments. ☕

11.2 The two-neutrino exchange long-range force. 🌶

11.3 Supernova neutrinos. 🌶

11.4 Indirect dark matter detection. 🌶

11.5 keV sterile neutrino dark matter. 🌶

11.6 The anomalous magnetic moment of leptons. 🌶

11.7 Neutrino spin-flavor precession in the Sun. 🌶🌶