

## Physics 557 – Lecture 1

### INTRODUCTION: “High Energy and Particle Physics”

Particle physics comprises the search for understanding of the most fundamental (in some *smallest*) building blocks of the physical universe and their interactions, *i.e.*, the search for a Theory of Everything (TOE). Progress has been so rapid in the last 50 years that some scientists (at various times) have been optimistic that this goal can actually be achieved; see, e.g., *Dreams of a Final Theory* by Steven Weinberg or *The God Particle* by Leon Lederman. On the other hand history suggests that there is always another layer underneath; see also *The End of Physics* by David Lindley (which suggests that science will end if we find the theory of everything). An underlying expectation of this approach is that this “final” theory will be expressible in terms of only a *small* number of fundamental building blocks exhibiting a richness of interactions characterized by a high degree of symmetry. Theorists often use the concepts of naturalness and intrinsic elegance or beauty (is this science?) to justify new ideas or to motivate the selection of one out of a multitude of possible solutions to a question. (Such arguments are often used in favor of string theory, which, while mathematically elegant, has yet to directly confront experimental data.) Similarly to the way in which the immense variety of condensed matter physics arises from the complexity possible in the collective interactions of just electrons, nuclei, and photons, we expect the complexity of the larger universe to arise from the collective interactions of a small number of fundamental particles whose interactions are highly symmetric at a fundamental level. At the same time we anticipate that, in the realized physical states, many of the underlying symmetries are broken, allowing an enormous variety of phenomena.

Of course, physics is an experimental science. So high energy is a natural facet of particle physics because high energy is needed to

- resolve short distances in order to see the underlying fundamental structure (recall that QM tells us that  $\lambda = h/p$ ,  $f = E/h$  or  $p = \hbar k$ ,  $E = \hbar\omega$ );
- produce massive particles, which decay and so are not normally observed in the universe near equilibrium.

Thus particle physics is driven both by advances in theoretical physics, for example string theory, and by advances in accelerator and detector design (and, to be sure, by funding). The last 50 years have seen enormous advances in both theory and experiment leading us to the current “LHC era”.

Particle physics is the reductionism form of physics. Years ago it was thought that the basic building blocks were fire, earth, water and air. In more modern times the periodic table focused on atoms as the fundamental particles (of chemistry), but who wants 90+ of them? Actually this is the correct answer if your “microscope” can resolve distances of only 1 to 10 Å ( $1 \text{ \AA} = 10^{-10} \text{ m}$ ), *i.e.*, with photons of energy 1 eV to 10 eV. With improving microscopes, it became clear that atoms have internal parts, electrons and the nuclei (they could be knocked out!). Then, with resolving power of order 1 to 100 fermi ( $1 \text{ fm} = 10^{-15} \text{ m}$ ) or energies of order 10 MeV at early particle accelerators, it became clear that the nuclei also have internal structure, the neutrons and protons, and again pieces could be knocked out. At distances below approximately one fm and energies above 100 MeV even more structure was discovered, but *not* just because “internal pieces” fell out. Rather the internal structure of the proton was *excited* and resonances were observed in scattering processes (think in terms of exciting a resonant cavity, *e.g.*, an organ pipe, at its resonant frequency). Likewise new particles, the mesons, were produced. These features are all now explained in terms of strongly interacting building blocks, the quarks (and gluons), which are remarkably *never* directly observed individually. This was a major intellectual, accepting a set of fundamental degrees of freedom which are never directly observable. (However, the “footprints” of quarks and gluons, jets, are readily seen in the data.) Further there are so many types of quarks (and leptons) that further underlying structure is implied, which will, perhaps, be that suggested by string theory.

Particle physics also has much to say about and learn from cosmology and astrophysics. Together these fields of study span the range of length scales from  $10^{10}$  light years ( $\sim 10^{26} \text{ m}$ ) and energy scales from  $10^{-4} \text{ eV}$  ( $3^\circ \text{ K}$ ) all the way to the Planck length or energy determined by Newton’s gravitational constant ( $G_N = 6.67 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$ ),  $\lambda_{\text{Pl}} \sim 10^{-35} \text{ m}$  or  $E_{\text{Pl}} \sim 10^{19} \text{ GeV}$ .

Our current knowledge of the most fundamental particles and their interactions is embodied in the Standard Model: the matter fields and the gauge bosons of the electromagnetic, weak and strong interactions. This quarter we will focus on learning the vocabulary and algebraic structure (symmetries) of the Standard Model. By implication we will also cover what is not included in the Standard Model – gravity and the rest of the symmetry breaking (beyond the Higgs boson). Thus we must at least mention Grand Unification, supersymmetry and extra spatial dimensions (and Technicolor).

## BASICS

Text – See the list of suggested texts (available on the Web – <http://staff.washington.edu/sdellis/Phys5578/booklist2016.pdf>). My experience is that no single book on the list is an “obvious” first choice (although I enjoy reading several). I will attempt to make reading suggestions in the notes. I encourage you to browse the various books to see what works for you (and what you want in *your* library). Note that my approach is to “teach in circles”, learning more of the vocabulary and the mathematical structure each time around (although I admit that we will have little time for circling during a single quarter). I encourage your continuing input on both content and technique.

Quantum Field Theory – we want to be able to use this, at least as a descriptive tool, as soon as possible. We

- will use Feynman diagrams for pictorial representation and bookkeeping;
- will (eventually) perform tree level calculations of cross sections, widths *etc.*;
- will (must!) at least *mention* vacuum polarization, loop diagrams, infinities and renormalization. I encourage you to read through chapters 2, 3 and 4 in Rolnick, 6 to 8 in Griffiths and/or chapters 6 to 8 in Peskin and Schroeder.

Order and focus of presentation -

- Historical – inefficient
- Experimental – often confusing if just focus on experiments
- Theoretical – logical but misleading (virgin births are rare!)
- (I choose) Phenomenological – somewhere between experiment and theory with a dose of history.

We must always remember that physics is an EXPERIMENTAL SCIENCE. I want to convey some of the flavor of how physics works in practice (my experience) – the fun, the disasters (see, *e.g.*, *Nobel Dreams* by Gary Taubes) and the beauty! In particular, we will try to pay careful attention to the situation at the LHC at CERN as it unfolds over the next 6 months.

Grading –

- There will be weekly homework assignments that will be graded.
- The course grade will be derived entirely from the homework.

- Collaboration is encouraged (just like in science) but each student must turn in individual papers.
- Homework less than 1 week late will be accepted but discounted 50%.

ASIDE: 50 years ago when I was starting graduate studies at Caltech there was no Standard Model and many physicists questioned whether quantum field theory was useful (QFT was not taught as a regular course at Caltech at the time). While QED was mostly understood at the time (without a role for renormalization theory), there was not real field theoretic description of the weak and strong interactions. The evolution of the Standard Model required a more thorough understanding of non-Abelian field theories, broken symmetries, running couplings with confinement and asymptotic freedom, and effective theories where the relevant degrees of freedom vary with the moment scale. We will try to make these points clear during the quarter.

The Web – in my efforts to be a 21<sup>st</sup> century instructor, I will try to use the course homepage and Catalyst as much as possible. Thus lecture notes (note the labeling will be for convenience and not necessarily by the day given), homework (and solutions), and supplementary materials will all be available there (I hope). There are already pointers to various web points of interest (see the bottom of our class webpage): the laboratories, the PDG and conference proceedings. I encourage you to browse the Web in “your spare time”. I will also experiment with computer-based lectures, hopefully using the materials available on the Web.

Let’s look at the [\(tentative\) syllabus](#):

## **(PROPOSED) SYLLABUS FOR PHYSICS 557**

### **Winter Quarter 2016**

PHYSICS - 557 – Some time ago (when this course was a 3 quarter sequence) the first quarter was the “historical” quarter. The general topic was particle physics with an emphasis on descriptive phenomenology, symmetries, and the general (mostly algebraic) properties of particle dynamics -- a “building block” view of the Standard Model. These topics were introduced in the context of the historical evolution of the Standard Model. A prior exposure to Feynman graph techniques was not required, as appropriate for students just beginning the field theory sequence. Given both the current one quarter structure and the exciting discoveries coming from the LHC, the plan for this year is to move more quickly to a Quantum Field Theory based understanding of the Standard Model, including the Higgs Boson, so that we can

discuss the recent results from Geneva. We will try to discuss some of the technical details (both theoretical and experimental), some of the history (i.e., my life in science), some of the connections to the rapidly evolving situation in astrophysics, and what is still missing from the Standard Model (BSM = physics Beyond the Standard Model). In any case, the expectation is that the content will be relevant to the majority (all?) of Physics Ph.D. candidates. Since we will have little time in class to cover the historical material in the first quarter lectures from previous years, I will include that content in the “lectures” for this course and you are strongly encouraged to read through all of the material. We will directly discuss only a subset of the lectures in class. You are encouraged to come to class with questions and thoughts about which topics you would most like to discuss in class. I am happy to have the course driven by largely by your preferences. Since I am necessarily proceeding differently from previous years, please bear with me as we determine how best to carry out that plan. (The outline below is clearly too much and we will likely skip some subjects the first time through.)

### Outline - 557

#### I) General (and rapid) introduction and overview (tools and words)

- Sizes, units and Standard Model vocabulary
- A Brief introduction to Cosmology
- Relativistic notation and kinematics
- Introduction to group theory and symmetries
- Collisions, cross-sections, decay widths and more kinematics
- A very brief introduction to accelerators, detectors and experiments

#### II) Introduction to the Standard Model

- Quantum numbers
- Introduction to the particles – leptons, nucleons and pions (and quarks)
- Brief summary of strangeness, resonances and flavor SU(3), of excitations and Regge Behavior, of heavier flavors and quarks
- Introduction to field theory and QED, Feynman rules and cross sections
- Local gauge symmetries: QED (U(1)), Weak Interactions (SU(2)), QCD (SU(3)) and group theory
- Introduction to the Higgs field and its quanta (the Higgs boson)
- The Standard Model of the Electro-Weak Interactions and the Higgs boson
- The Feynman rules of the E-W interactions, decay rates and cross sections
- Neutrinos, masses and mixing
- Flavor oscillations and CP violation (the neutral kaon and neutral B systems)
- Introduction to QCD and renormalized couplings

- The Quark/Parton Model
- The QCD Improved Parton Model – Asymptotic Freedom, Infrared Slavery and renormalization
- The QCD Improved Parton Model – Parton distributions, parton fragmentation and Perturbative QCD
- Nonperturbative QCD and the structure of the vacuum

### III) Beyond the Standard Model

- Grand Unification
- Super Symmetry
- Technicolor
- String theory
- Extra spatial dimensions

*(Note: Interested students are encouraged to make suggestions concerning this syllabus, which may be acted upon.)*