Introduction to Standard Model and Extensions (SME)

Johan Bijnens

June 20, 2007

Abstract

Introductory chapter and the five PBL cycles for the course SME 7.5 ECTS credits

Introductory Chapter

1 Introduction

This course is an introduction to some of the more theoretical aspects of the Standard Model and some common extensions. It is assumed that the students have a basic knowledge of the Standard Model, including gaugeinvariance and the Higgs mechanism at the level of the book by Kane as used in the course FYS230, theoretical particle physics.

A basic knowledge of particle physics phenomenology is required at the level of the course "FYS230: Theoretical Particle Physics" which uses the book Modern Particle Physics by G. Kane. A similar level book is "An introduction to High Energy Physics" by D. Perkins (fourth edition). Essentially a typical first proper course on particle physics should have been taken before.

The course also assumes a basic knowledge of Quantum Field Theory at the level of a typical introductory course. It assumes knowledge corresponding to the first five chapters in "Michael E. Peskin and Daniel V. Schroeder, *An Introduction to Quantum Field Theory* (1995)" as well as the basic ideas of Chapter 6. This corresponds e.g. to "F. Mandl and G. Shaw, *Quantum field theory* (1993)" or "L.H. Ryder, *Quantum field theory* (1996)." So, the students should be familiar with Feynman Diagrams and have had some rudimentary experience with divergences and renormalization.

A book which covers many of the topics we will discuss is
John F. Donoghue, Eugene Golowich and Barry R. Holstein, "Dynamics of the Standard Model" (1994), Cambridge University Press.

Otherwise, via SPIRES `http://www.slac.stanford.edu/spires/` or directly searching in the hep-ph archive in `http://arxiv.org` you can easily find lectures on all the topics treated in this course. There will also be copies of a recent relevant lecture in one of the big conferences included in every course.

There is a series of summer schools devoted to particle physics. The proceedings of those typically contain useful lecture series as well. The main series are the Les Houches and Cargese series in Europe and the TASI series in the US. The links for the schools summer 2007 are

Les Houches:	`http://w3houches.ujf-grenoble.fr/index-en.html`
Cargese:	`http://servant.web.cern.ch/servant/cargese/`
TASI:	`http://www.colorado.edu/physics/Web/TASI_info.htm`

Searching in SPIRES with the help of title search will often turn up the lectures.

2 Course Overview

2.1 The PBL cycles

This course consists of five Problem Based Learning (PBL) cycles. We will follow the seven steps as you have learned about earlier in the PBL introduction course but with a bit of a twist. After the discussion of the scenario there will be a blackboard lecture of the more traditional type giving the main line of reasoning behind the subject of the cycle if the participants wish it. The main part of each cycle is the self study in order to reach the goals discussed during the main discussion. Each cycle will also come with a set of problems to solve.

The five cycles cover different aspects of advanced particle physics.

- Parameters of the Standard Model
- Symmetries of the Standard Model
- Nonperturbative Methods
- Extensions of the Standard Model I
- Extensions of the Standard Model II

2.2 Why this order in the cycles?

The first cycle covers the parts of the Standard Model Lagrangian that are the source of most of the unknown parameters. These are also the sectors that are most easily extended both theoretically and in a way that avoids present experimental limits.

Several of these parameters turn out to be extremely hard to measure, and one therefore needs nonperturbative methods in QCD. The next two cycles cover several of these methods and some of their results. In particular, you will have learned the basic of chiral symmetry, chiral perturbation theory, heavy quark symmetry and QCD sum rules.

The last two cycles cover the most commonly discussed extensions of the Standard Model. We start by looking at some possible extensions of the Higgs sector as well as at models that do away with the Higgs altogether. It will also cover extensions of the gauge group, i.e. grand unification. The second cycle of the extensions of the Standard Model covers supersymmetry and related extensions.

2.2.1 Parameters of the Standard Model

In a typical particle physics course you have gone through the Standard Model Lagrangian and learned everything about gauge theories and the Higgs mechanism. However the Higgs sector and the gauge sector together only provide five or six (with the strong CP angle) of the total number of parameters of the Standard Model. Still, people say that the standard model contains 18 or 19 or 24 or 25 parameters. What are they and how does one determine this number?

As it turns out, a fairly large numbers of these parameters are phases and even some of the masses are only known as differences of squared masses. How does one actually measure phases and similar observables in particle physics experiments.

2.2.2 Symmetries of the Standard Model

One of parts treated in the first cycle is the so-called Cabibbo-Kobayashi-Maskawa (CKM) matrix. This cycle introduces the students to the ways the absolute values of its elements are measured and in particular to the two main theoretical approximations that lie behind the measurements. These are chiral symmetry for the elements involving light quarks and heavy quark symmetry for the elements involving heavy quarks as well as for the mixed ones.

The cycle covers how these symmetries lead to relation between processes with hadrons, not only with quarks and gluons.

2.2.3 Nonperturbative Methods

In the previous cycle, chiral symmetry and heavy quark symmetries were used to find out how to measure the CKM elements. In this cycle we generalize this to higher orders in the expansion and introduce the tool of Effective Field Theory (EFT). We will also show how the general properties of field theory can be used to derive sum rules and these in turn can be used to determine precisely several parameters of the Standard Model.

2.2.4 Extensions of the Standard Model I

This is the first of two cycles treating extensions of the Standard Model. We start with the simplest extension, the two Higgs double model and the proceed with various recent and older variants of the Higgs sector, we will treat Technicolor and some of its more modern variants like topcolour and "Little Higgs." These models all suffer from some generic problems with precision data on the W and Z bosons, which will also be discussed shortly.

A second class of extensions is when the weak gauge group gets extended to larger groups and in particular when one puts together all standard model gauge groups in one single group, so-called Grand Unification.

2.2.5 Extensions of the Standard Model II

Space-time is expected to have invariance under the full Lorentzsymmetry. It turns out that extensions of space-time symmetry are rather difficult to achieve with one major exception, supersymmetry. This cycle will deal with the basics of supersymmetry and some of its consequences. The final goal will be to get a first feeling of what superstring theory might imply for experiment.

2.3 Evaluation

The problem sets together with the final discussions and evaluation of each cycle are the major part of the assessment of this course but there will also be a short oral exam to test understanding of the principles. A list of typical questions will be made available.

3 Literature

There is no single good textbook covering all of the topics that are treated in this course. There will be available copies of handwritten notes, copies of review seminars given at the large annual particle physics conferences as well as links to sources available on the web. These are given in the Sect. 1.

A book which covers many of the topics discussed in this course John F. Donoghue, Eugene Golowich and Barry R. Holstein, "Dynamics of the Standard Model" (1994), Cambridge University Press.

Cycle 1

A question on the number of parameters and their values

After having finished their basic course on particle physics several interested students get together to discuss things in more details. They have learned that the Standard Model is an elegant construction using gauge symmetries to describe interactions.

But they noticed that constructing fermion masses looked rather arbitrary, e.g. the electron mass came from a term looking like

$$-\lambda_e \overline{L} \phi e_R + h.c. \tag{1}$$

They find this a rather nice solution to giving the electron a mass, but what about all the others?

Goals and Literature List for Cycle 1 of The Standard Model and Extensions

Literature

The course is an introduction to several topics relevant in and around the Standard Model, it also includes an introduction to some of "standard" extensions of the Standard Model. There is not a course book that I know of that covers all the topics that I will present at this level. We will use several sources (with the unfortunate consequence of having sources with different conventions).

A book which covers many of the topics we will discuss is

John F. Donoghue, Eugene Golowich and Barry R. Holstein, *Dynamics of the Standard Model* (1994), Cambridge University Press

A basic knowledge of particle physics phenomenology is required at the level of the course "FYS230: Theoretical Particle Physics" which uses the book Modern Particle Physics by G. Kane. A similar level book is "An introduction to High Energy Physics" by D. Perkins (fourth edition).

The course also assumes a basic knowledge of Quantum Field Theory at the level of a typical introductory course. It assumes knowledge corresponding to the first five chapters in "Michael E. Peskin and Daniel V. Schroeder, *An Introduction to Quantum Field Theory* (1995)" as well as the basic ideas of Chapter 6. This corresponds e.g. to "F. Mandl and G. Shaw, *Quantum field theory* (1993)" or "L.H. Ryder, *Quantum field theory* (1996)."

A useful starting point for other references is the 2006 Rochester conference (`http://ichep06.jinr.ru/`) and the Particle Data Book reviews (`http://pdg.lbl.gov`).

In particular the talks on neutrino physics and CP violation are relevant for this cycle. Included are: handwritten notes which might be useful, a part of the baBar handbook on oscilations and a copy of the theory talks on neutrinos and CP violation at the 2006 Rochester conference.

Goals

- Parameters of the Standard Model
- Neutrino oscillations
- Oscillations and Decays: how to measure phases
- Unitarity triangle(s)

Cycle 2

Determining mixing angles

The PDG 2006 lists the following numbers:

$$|V_{ud}| = 0.97377 \pm 0.00027 \quad (2)$$
$$|V_{us}| = 0.2257 \pm 0.0021 \quad (3)$$
$$|V_{cb}| = (41.6 \pm 0.6) \times 10^{-3} \quad (4)$$
$$|V_{ub}| = (4.31 \pm 0.30) \times 10^{-3} \quad (5)$$

The PDG talks about superallowed beta decays, K_{e3} decays, heavy quark to heavy quark transitions and inclusive semileptonic decays. Digging a little deeper words like chiral and heavy quark symmetry appear.

Goals and Literature List for Cycle 2 of The Standard Model and Extensions

Literature

John F. Donoghue, Eugene Golowich and Barry R. Holstein, *Dynamics of the Standard Model* (1994), Cambridge University Press, sections IV.1, VI.1 and parts of VII.1,VIII.1,XIII.3, XIV.2.

For the chiral symmetry part, many references are accessible via `http://www.thep.lu.se/~bijnens/chpt.hml`. In particular, S. Scherer, hep-ph/0210398 is a very extensive introduction to chiral perturbation theory. Chapter 2 of J. Bijnens, hep-ph/0604043 also contains useful information. The semileptonic decay chapter of J. Bijnens, hep-ph/0204068, covers some other important aspects. The heavy quark part is covered in many lectures, some useful ones are M. Neubert, hep-ph/9610266, M. Wise, hep-ph/9805468.

The lectures by Pich, hep-ph/9806303, contain parts useful for this and for the next cycle.

Goals

- Global exact and approximate symmetries of the Standard Model.
- Chiral and Heavy Quark Symmetries.
- Consequences: Linear versus nonlinear sigma model and pi-pi scattering.
- Determining the weak mixing angles using the chiral and heavy quark symmetries.

Exercises

- When we looked at the heavy quark limit in semileptonic decays, we derived the relations at a fixed velocity. Explain why.
- Derive $\pi^1\pi^1 \to \pi^2\pi^2$ scattering in the low energy limit from both the linear and the nonlinear sigma model and show that they are equal in the low-energy limit.
- Derive the GMO relation from the lowest order Chiral Perturbation Theory Lagrangian
- Derive the amplitude for the decay $K^+ \to \pi^0 e^+ \nu$ from the lowest order Chiral Perturbation Theory Lagrangian and the connection to QCD.

- Try to look up a bit how the other elements from the CKM matrix are determined experimentally.

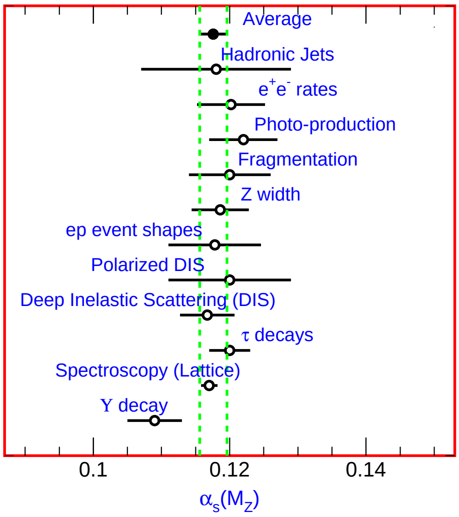
Cycle 3

Effective field theory

John and Jane have finished their obligatory quantum field theory course and have started talking with the various people in the department about what they should do next. One of the instructors tells them that the fact that the sky is blue, proton decay and theoretical predictions for $\pi\pi$ scattering all can be dealt with using the same method.

Measuring α_S

The students have been to a conference on strong interactions and have just finished listening to the review talk on strong interactions. There was a plot shown from the review of particle properties



with the various determinations of α_S. They are surprised at the accuracy shown for the measurement from τ decays. During dinner they continue discussing this and finally remember that the speaker mentioned something about OPE and sum rules.

Goals and Literature List for Cycle 3 of The Standard Model and Extensions

Literature

John F. Donoghue, Eugene Golowich and Barry R. Holstein, *Dynamics of the Standard Model* (1994), Cambridge University Press, Chapters VI and VII for the effective field theory/chiral perturbation theory part as well as section XI.5 for the sum rules.

Effective Field Theory and the Operator Product Expansion have many uses in the high energy physics phenomenology (and many other areas of physics). A useful introduction to effective field theory are the lectures by Kaplan, nucl-th/0510023, Chapters 1, 2 and 3. The parts about baryons are not relevant for this course. There are many uses of effective field theory which we will not touch upon. For the chiral perturbation theory part, many references are accessible via `http://www.thep.lu.se/~bijnens/chpt.hml`. In particular, S. Scherer, hep-ph/0210398 is a very extensive introduction to chiral perturbation theory. Chapter 2 of J. Bijnens, hep-ph/0604043 also contains useful information. The lectures by Pich, hep-ph/9806303, contain parts useful for this and for the previous cycle.

Sum rules are an immediate consequence of the basic properties of field theories. The main underlying aspect is that amplitudes can be consistently continued to kinematical variables that are complex, not just real. Singularities are known to exists only as poles and for real intermediate states. This combined with Cauchy's theorem allows for amany different relations. When QCD came by, combining these sum rules with the operator product expansion became a very useful tool. Section XI.5 in DGH gives a good first introduction to the subject, E. de Rafael's lectures, hep-ph/9802448, and the review by Colangelo and Khodjamirian, hep-ph/0010175, contain good introductions to the subject. There will also be hand-written notes available about the complex analysis, Weinberg sum rules and the use of sum-rules in τ-decays available. The original papers are useful to read (especially the older ones), but might be bit difficult.

- "Precise relations between the spectra of vector and axial vector mesons,". S. Weinberg, Phys.Rev.Lett. 18 (1967) 507-509.
- "QCD and Resonance Physics: Sum Rules," M. Shifman, A. Vainshtein, V. Zakharov, Nucl.Phys.B147 (1979) 385-447.
- "QCD and Resonance Physics: Applications," M. Shifman, A. Vainshtein, V. Zakharov, Nucl.Phys.B147 (1979) 448-518.

Goals

- The general ideas behind effective field theory: how a mass gap or a separation of scales leads to a possibility of doing this.
- Think about how you would deal with the standard model as an effective field theory only. How would you extend it?
- The principles behind renormalization and powercounting in effective field theories.
- The principle behind sum rules and dispersion relations
- The operator product expansion (principle only, no details) and how this puts many of the old sum rules on a firm footing.
- Sum rules and determination of α_S and quark masses.

Exercises

- Write down a dimension 6 operator in the standard model that mediates proton decay. How big does Λ have to be when you take into account that the proton lifetime is larger than 10^{34} years. Try to write down all dimension six operators that violate baryon number in the standard model and show that they conserve $B-L$ (baryon minus lepton number)
- In the previous cycle you derived the Gell-Mann Okubo relation and got at a first estimate of the light quark mass ratios. How big corrections can you expect to these from simple chiral perturbation theory power counting. How big are the actual corrections when the full calculation is done?
- Derive the mass and coupling to the photon of the ρ-meson using QCD sum rules.

Cycle 4

An event with a τ^+-τ^- pair

The control room of the CMS experiment at the LHC is suddenly a low noisier than usual. Djelilah was lookin online at some events to pass the time and saw now two extremely narrow jets opposite to each other. Each of them consists out of three charged particles only. On closer look, these turn out to be taus and the total energy for the event is about 800 GeV.

Funny regularities

The charges in the standard model, especially the $U(1)_Y$ charges of the fermions look rather arbitrary, $1, 1/3, 4/3, -2/3, \ldots$.

Goals and Literature List for Cycle 4 of The Standard Model and Extensions

Literature

John F. Donoghue, Eugene Golowich and Barry R. Holstein, *Dynamics of the Standard Model* (1994), Cambridge University Press, sections XV.1, XV.3 and pages 465-466 for the Higgs part, and pages 438-439 for Grand Unification.

A general introduction to the probles associated with the Higgs sector is C. Quigg, arXiv:0704.2232 [hep-ph] which is required reading for this cycle.

Models with more than one Higgs doublet are almost as old as the Standard Model itself and models that produce neutrino masses typically also include more complicated Higgs sectors. These typically lead to possible new sources of CP-violation and produce more charged scalars as well. There is an enormous literature on this subject, also with supersymmetric theories that require the presence of at least two Higgs doublets. A reasonable good overview of motivations for and signals of an extended Higgs sector is J.Gunion, hep-ph/0212150. Another recent review is F. Ginzburg and M. Krawczyk, hep-ph/0408011.

Technicolor was introduced early on by Weinberg and Susskind. It is the prototype strongly interacting Higgs sector or Higgsless models. A fairly recent review covering the main parts is C. Hill and E. Simmons, hep-ph/0203079. A more recent attempt to write the collider phenomenology in a consistent fashion is R. Foadi et al., arXiv:0706.1696 [hep-ph]. An earlier, but quite readable review is R. Kaul, Rev.Mod.Phys. 55 (1983) 449.

A more recent variant, albeit also with a longer history, are the Little Higgs models as reviewed recently by M. Perelstein, hep-ph/0512128 and M. Schmaltz and D. Tucker-Smith, hep-ph/0502182.

Grand Unified Theories were dreamed of by Salam, Georgi, Glashow and others. It became a very poular subject after Georgi and Glashow, Phys. Rev. Lett. 32 (1974) 438-441, found a nice model. A (very long) overview of the phenomenology is the review by P. Langacker, Phys. Rept. 72 (1981) 185. These models have gone somewhat out of favour since no proton decay has been seen and the unification of forces is not working quite so well. Within supersymmetric versions things work better. See the recent review by S. Raby, hep-ph/0608183 for more references.

Goals

- Getting an understanding of the general phenomenology of extended Higgs sector models and constraints from flavour physics.
- Understand the principles behind a strongly interacting Higgs sector and the main experimental constraints on it.
- Understand the basics of using a (pseudo) Goldstone boson as the Higgs field of the Standard Model.
- Grand Unification: ideas and principles
- Limits from proton decay

Exercises

- Weinberg found a very strong constraint on the way the different Higgs doublets couple to fermions (i.e. the possible Yukawa couplings). Explain how this constraint comes about.
- Show that by using the nonlinear sigma model instead of the linear sigma model, no Higgs particle appears in the standard model. Show that the L_9 and L_{10} terms in the equivalent chiral Lagrangian lead to changes in the W and Z masses and the triple-gauge couplings. (called α_i in DGH). It is this type of scaling up that has lead to the statement that LEP precision experiments have ruled out technicolor.
- Predict $sin\theta_W$ from the minimal SU(5) model. Why is the supersymmetric version different?
- Relate the bottom and the tau mass in the minimal grand unified model.
- A 600 GeV particle decaying into $\tau^+\tau^-$ is discovered at the LHC. Give at least three possible explanations for it within various extensions of the standard model. How would you distinguish the various options?

Cycle 5

The mysterious missing momentum and a symmetry question

The LHC has started up and an event is seen with 5 jets, one of which is a b-quark jet and the jets are rather spread out in all directions. In addition, there is a lot of missing transverse momentum. This creates great excitement in the control room and the discussion about it immediately starts.

During the discussion of what this event could be, one of the more theoretically inclined students remembers all the funny words from their latest summer school starting with the Coleman-Mandula theorem. It seems that it is not easy to have a symmetry larger than Poincaré invariance.

Goals and Literature List for Cycle 5 of The Standard Model and Extensions

Literature

The literature is awash with lectures and reviews on supersymmetry and strings at all levels.

Supersymmetry and supergravity were developed in the 1970's and phenomenology started in earnest in the early 1980's. Those developments were reviewed in three standard references:

A book that gives the formal development is J. Bagger and J. Wess, Supersymmetry and Supergravity, Princeton University Press, second edition, 1992 (the first edition was in 1982) and two (heavily cited) reviews of early supersymmetric phenomenology are H. Nilles, Phys. Rep. 110 (1984) 1 and H. Haber and G. Kane, Phys. Rep. 117 (1985) 75.

A large part of the early phenomenology is still valid even if most of the then considered parameter space has been ruled out since then with a few fairly famous false alarms.

The main literature is the review "A Supersymmetry primer," S. Martin, hep-ph/9709356, but more recent lectures on various aspects are

- M. Luty, hep-th/0509029, "2004 TASI lectures on supersymmetry breaking"
- C. Csaki, hep-ph/0404096, "TASI lectures on extra dimensions and branes."
- G. Kane, hep-ph/0202185, "TASI lectures on weak scale supersymmetry: A Top motivated bottom up approach."
- R. Ratazzi, hep-ph/0607055, "Cargese lectures on extra-dimensions."
- I. Aitchison, hep-ph/0505105, "Supersymmetry and the MSSM: An Elementary introduction."
- J. Ellis, hep-ph/0203114, "Supersymmetry for Alp hikers."
- The talks and proceedings of the SUSY 06 conference: http://susy06.physics.uci.edu/

We will also use some parts of the book "An Introduction to Quantum Field Theory," by M. Peskin and D. Schroeder, (1995).

For the string theory part one should look at

- L. Susskind, "Superstrings," Phys.World 16N11 (2003) 29-35, http://physicsweb.org/article/world/16/11/8
- http://superstringtheory.com/

- G. Kane, P. Kumar, J. Shao, hep-ph/0610038 "LHC String Phenomenology."
- J. Schwarz, popular lecture on superstrings, http://strings04.lpthe.jussieu.fr/talks/Schwarz.pdf

There will be notes available for the extra dimension/superstring part.

Goals

- Global Supersymmetry: what is it?
- Supersymmetry breaking and especially soft supersymmetry breaking
- The MSSM: basic phenomenology.
- Extra dimensions: generic features
- Kaluza-Klein versus large extra dimensions
- What are (super)strings and some generic properties

Exercises

- Exercise 3.5 in the book by Peskin and Schroeder. Note that
- Determine the total number of parameters in the MSSM
- Explain why we need two Higgs fields in the MSSM and prove the (tree level) bound that there is always a Higgs with mass less than the Z-boson.
- Explain why phenomenology with and without R-parity is so qualitatively different.
- Find a possible explanation for the event described in the scenario. Can you think of a standard model possibility too?