835 Syllabus (Fall, 2007): Collider Physics

1 Introduction to High-Energy Physics (wks 1-4)

1.1 Elementary Particles and Fundamental Forces

a. Elementary particles and fundamental forces

b. Theoretical frame work: Quantum field theory

1.2 The Standard Model

a. Gauge interactions: QED, SU(2), SU(3)

b. The Standard Model

c. Spontaneous gauge symmetry breaking

d. Quark masses and mixing

e. Lepton masses and mixing

f. Neutrino masses

1.3 The Symmetries of the SM

a. Global symmetries

b. The Custodial symmetry

1.4 The Need for going beyond the Standard Model

a. One beautiful model, many open questions:
Triviality and unitarity; Naturalness or gauge hierarchy; Dark Matter.

b. Supersymmetry? Grand unification?

c. Technicolor?

d. Quantum gravity; Superstring?

1.5 Collider Physics: HEP in the next two decades

a. The need for high energy colliders

b. Progress of collider programs

c. Collider detectors: What can be "seen"?

2 Calculational Techniques in HEP (wks 5-6)

2.1 Scattering Cross Section and Decay Width

2.2 Phase Space and Kinematics

a. General phase space element

b. Two-body phase space and Mandelstam variables

c. Three-body phase space and the Dalitz plot

d. n-body phase space and the reduction formula

e. Breit-Wigner resonance and narrow-width approximation

2.3 Calculations of Transition Matrix Elements

a. Traditional Method: Trace technique

b. Helicity amplitudes, color factors

c. Madgraph package etc.

d. Algebraic manipulations (optional)

We learn different calculational techniques of the matrix elements through examples. The basic, yet very important processes include

$$\pi^+ \to \ell^+\nu, \quad \mu^- \to \nu_\mu \bar{\nu}_e e^-, \tag{1}$$

$$e^+e^- \to \ell^+\bar{\ell}^-, \quad e^+e^- \to q\bar{q}, \tag{2}$$

$$\nu e \to \nu e, \quad \nu q \to \nu q, \quad \ell q \to \ell q, \tag{3}$$

$$q\bar{q}' \to W^\pm \to \ell^\pm \nu, \quad q\bar{q} \to \gamma g. \tag{4}$$

2.4 Monte Carlo Techniques

a. Monte Carlo simulations

b. Phase space optimization

2.5 Radiative Corrections (optional)

a. Regularization and Renormalization

b. Loop integrals: Veltman-Passarino reduction

We learn radiative correction calculations through examples, such as $e^+e^- \to q\bar{q}$, and electroweak corrections to M_Z and M_W or m_h.

3 Weak Decays of Heavy Fermions (wk 7)

3.1 $V - A$ and General $V \pm A$ Decays

3.2 Heavy Quark Decays and Distributions

a. Spectator approximation

b. Lepton kinematics and missing p_T

c. Heavy quark effective theory (optional)

3.3 Top-quark Decay

a. SM Decay $t \to Wb$ and $t \to Wb \to \ell\nu b$ (two two-body)

b. Rare decays as a window to new physics (optional)

4 Parton Model and Fragmentation (wk 8)

4.1 The Parton Model

a. Example: Deeply inelastic scattering (DIS)

b. From structure functions to parton distribution functions

4.2 Fragmentation Functions

a. Example: $e^+e^- \to pX$

b. Independent fragmentation model

c. String fragmentation model

4.3 Heavy Quark Fragmentation (optional)

5 Quantum Chromo-Dynamics (wks 9-10)

5.1 Renormalization Group Equations, Running Coupling

5.2 QCD Corrections to DIS

a. QCD improved structure functions: DGLAP evolutuions

b. Minimal subtraction scheme

5.3 QCD Corrections to Fragmentation (optional)

5.4 QCD Corrections to Drell-Yan Process

a. Real emission and virtual correction

b. DIS vs $\overline{MS}$ (optional)

5.5 Jets

a. Two-jet physics in e^+e^- collisions

b. Three-jet physics in e^+e^- collisions

a. Jet inclusive in hadron-hadron collisions

d. Jet-finding algorithms (optional)

5.6 Monte Carlo Shower (optional)

6 SM phenomenology at Colliders (wks 11-12)

6.1 Heavy Flavor Production

a. Quarkonia production and decay in e^+e^- Collisions

b. Open flavor production and $B-\overline{B}$ oscillation in e^+e^- Collisions (optional)

c. Quarkonia production in hadronic collisions:
Color singlet, octet mechanisms (optional)

d. Open flavor production: Top-quark pair production

e. Single Top-quark production

f. Top-quark as a window to new physics (optional)

6.2 Weak Boson Physics

a. $W,\ Z$ decays

b. W or Z production and the QCD K-factor

c. $p_T(\ell)$ and transverse mass distribution for W

d. Transverse motion of W/Z (optional)

f. $e^+e^- \to W^+W^-$ and testing the gauge-boson coupling

g. $p\bar{p} \to W\gamma$, radiation amplitude zero (optional)

h. $p\bar{p} \to W^+W^-, W^\pm Z$ (optional)

6.3 Higgs Boson Physics

a. $h \to f\bar{f}$, b. $h \to gg, \gamma\gamma$, c. $h \to W^+W^-, ZZ$

d. $e^+e^- \to Zh$, e. $e^+e^- \to \nu\bar{\nu}WW(ZZ) \to \nu\bar{\nu}h$

f. $pp \to W(Z)h$, g. $pp \to gg \to h$, h. $pp \to q\bar{q}WW\ (ZZ) \to q\bar{q}h$

6.4 SEWS: $W_LW_L \to W_LW_L, t\bar{t}$ (optional)

7 Theories Beyond the SM (wks 13-14)

7.1 Extended Higgs Sectors

a. Two-Higgs doublets

b. plus singlets, or plus triplets

7.2 Extended gauge sectors (optional)

a. Left-Right symmetric model

b. SU(5) GUTs

c. SO(10) GUTs

7.3 Supersymmetric SM Model

a. Supersymmetry

b. SUSY partners and their interactions

c. R-parity and R-parity violation

d. SUSY breaking: The mass spectrum

e. SUSY flavor problem (optional)

7.4 SUSY GUTs (optional)

a. Gauge coupling unification

b. Yukawa unification

c. SUGRA

d. Gauge-mediated SUSY breaking

e. Phenomenological implications (optional)

7.5 Low Scale Quantum Gravity (optional)

a. Large extra dimensions

b. Randall-Sundrum models

7.6 Dynamical Models (optional)

a. Technicolor (TC) and ETC

b. Little Higgs theories

8 Collider searches for new physics (wk 15, if time permitting)

8.1 New gauge bosons

8.2 New heavy fermions

8.3 SUSY Phenomenology at e^+e^- Colliders

a. $e^+e^- \to \chi^+\chi^-, \chi_1^0\chi_2^0$

b. $e^+e^- \to \tilde{f}\tilde{f}^*$

c. Measuring SUSY parameters: $\tan\beta$ and μ

8.4 SUSY Phenomenology at Hadron Colliders

a. $pp \to \tilde{q}\tilde{q}^*$

a. $pp \to \tilde{g}\tilde{g}^*$

a. $pp \to \chi^\pm\chi_i^0$