

# Physics 3102, Fall 2025

## Course Title: Collider Physics Phenomenology

Room 105 Allen Hall, MF 12:00–1:15 PM

First meeting on Aug. 25, last class on Dec. 5.

**Prerequisites:** Physics 3717 (Particle Physics) and 3765 (QFT-I), or equivalent.

### References:

- arXiv:hep-ph/0508097, TASI Lecture notes by Tao Han
- V.D. Barger and R.J.N. Phillips: *Collider Physics*, Updated ed.
- André Rubbia: *Phenomenology of Particle Physics*, Cambridge University press, 1<sup>st</sup> edition 2022.
- Review of Particle Physics, PDG, Phys. Rev. D 110 (2024) 3, 030001.

**Course description:** With the outstanding performance of the LHC in searching for fundamental laws of nature and the planning of its luminosity upgrade, as well as the recent excitement in future colliders for the coming decades, it is timely to offer such a course for those who have genuine interests in theoretical and experimental high energy physics. The course is open to graduate students in the field of particle physics and cosmology, in both theoretical and experimental research directions.

I intend to present the rather basic knowledge and methodology for collider phenomenology. The theoretical framework is Quantum Field Theory and the Standard Model of particle physics, fully utilizing the relativistic kinematics. I will try to present the materials in a self-contained manner without relying on too much technicality from other advanced courses. Given the wide range of topics and anticipate a broad spectrum of registrants, the course is designed to have significant flexibility in breadth and depth.

**Grade:** The grade will be based on:

- a. 60% homework performance (bi-weekly)
- b. 20% oral presentation (about 20–30 min.) on a topic related to the course materials or your research interests, during the semester whenever you are ready
- c. 20% participation of discussions during the lectures and after class

### Tips for the course:

I list a few items that hopefully would help the students at any level to optimize their learning in the due course.

- Throughout this semester, any physics topic will be discussed at a *qualitative* level and a *quantitative* level. For a technically poorly prepared student (no Phys 3717 yet), it is of most importance to understand the topics at a qualitative level, namely to learn the basic concepts and the general approaches. It would be viewed as a success if this can even be achieved.

- For a technically well prepared student (with Field Theory Phys 3717, 3718 and particle Physics Phys 3765, 3766), you should go beyond the basic concepts and emphasize collider physics techniques, both analytical and numerical.
- For advanced students who already start research, you may try to make connections between your research and the course materials, as well as your random thoughts.
- The course offers tremendous flexibility and capacity. Everyone should be encouraged to go as far as you can, and no one should be discouraged by not learning certain topics as well as you wished.
- Group study is strongly encouraged, although you should try out (or struggle) with the homework first on your own.
- Do ask a lot of questions to me, to yourself and to each other.

Hope this course serves well for your future research.

The tentative table of contents follows.

# Collider Phenomenology

## Basic Knowledge and Techniques

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### 1 Introduction

- 1.1 Elementary Particle Physics . . . . .
- 1.2 Particles Physics Phenomenology . . . . .
- 1.3 High-energy Colliders . . . . .
  - 1.3.1 Colliding beam parameters . . . . .
  - 1.3.2 Historical perspectives of colliders . . . . .
- 1.4 About This Book . . . . .
- 1.5 Convention . . . . .

### 2 Preclude

- 2.1 Special Relativity . . . . .
  - 2.1.1 Space-time transformation . . . . .
  - 2.1.2 Irreducible representations of Poincaré group . . . . .
- 2.2 Quantum-Mechanical Description for a One-particle State . . . . .
  - 2.2.1 Equations of Motion . . . . .
- 2.3 Quantum Field Description . . . . .
  - 2.3.1 Scalar fields . . . . .
  - 2.3.2 Fermion fields and spinors . . . . .
  - 2.3.3 Vector fields . . . . .
- 2.4 Lagrangian Formalism of Interacting Field Theory . . . . .
  - 2.4.1 Perturbation method . . . . .
  - 2.4.2 Standard Model of electroweak and strong interactions . . . . .
  - 2.4.3 General formulation . . . . .

### 3 Description of Transition Processes

- 3.1 Transition Rate . . . . .
  - 3.1.1 Non-relativistic scattering . . . . .
  - 3.1.2 Partial wave properties . . . . .
  - 3.1.3 Resonance, bound-state, pair-production . . . . .
  - 3.1.4 Lorentz invariant formulation . . . . .
  - 3.1.5 Event rate . . . . .
- 3.2 General Properties of S-Matrix . . . . .
  - 3.2.1 Analyticity . . . . .
  - 3.2.2 Crossing symmetry . . . . .
  - 3.2.3 Unitarity . . . . .
  - 3.2.4 Threshold Behaviors . . . . .

### 4 Relativistic Kinematics and Phase Space

- 4.1 Relativistic Kinematics . . . . .
- 4.2 One-particle Final State . . . . .
- 4.3 Two-body Kinematics . . . . .
- 4.4 Three-body Kinematics . . . . .
- 4.5 Recursion Relation for the Phase Space Element . . . . .
- 4.6 Monte Carlo Method . . . . .
- 4.7 Geometrical Perspectives of Kinematics . . . . .

### 5 Particle Detection at Colliders

- 5.1 What Particles Look Like in a Detector . . . . .
- 5.2 Particle Detector at Colliders . . . . .
- 5.3 Event Selection and Triggering . . . . .
- 5.4 Objects and Observables . . . . .

6

Lepton Colliders

6.1

Resonant production . . . . .

6.2

Effective photon approximation . . . . .

6.3

Beam polarization . . . . .

6.4

Production cross sections . . . . .

6.5

Photon Colliders . . . . .

6.5.1

Back-scattered laser spectrum . . . . .

6.5.2

Production cross sections . . . . .

7

Lepton-Hadron Colliders

7.1

DIS and the parton model . . . . .

7.2

QCD and DGLAP evolution equations . . . . .

7.3

Parton luminosities . . . . .

7.4

Production cross sections . . . . .

8

Hadron-Hadron Colliders

8.1

Total cross section . . . . .

8.2

Hadron collider kinematics . . . . .

8.3

Parton luminosities . . . . .

8.4

Production cross sections . . . . .

8.5

The invariant mass variable . . . . .

8.6

The narrow width approximation . . . . .

8.7

The transverse mass variable . . . . .

8.8

The cluster transverse mass variable . . . . .

9

From Kinematics to Dynamics

9.1

*t*-channel Enhancement . . . . .

9.1.1

Splitting functions . . . . .

9.2

Asymmetries . . . . .

9.2.1

Forward-backward asymmetry . . . . .

9.2.2

Triple product . . . . .

9.3

More Involved Observables . . . . .

9.3.1

Kinematical End-points . . . . .

9.3.2

MT2 . . . . .

9.3.3

Kinematical boundaries . . . . .

10

Methodology of Particle Physics Phenomenology

10.1

From Lagrangian to Observables . . . . .

10.1.1

Construction of the Lagrangian . . . . .

10.1.2

Particle spectrum and their interactions . . . . .

10.1.3

Identify and invent observables . . . . .

10.1.4

Examples . . . . .

10.2

Uncover a Theory . . . . .