

# Outline

## ■ Relativistic Kinematics

- ▶ (4-momentum)<sup>2</sup> invariance, invariant mass
- ▶ Hypothesis testing, production thresholds
- ▶ Cross-sections, flux and luminosity, accelerators
- ▶ Particle lifetime, decay length, width

Today

## ■ Classification of particles

- ▶ Fermions and bosons
- ▶ Leptons, hadrons, quarks
- ▶ Mesons, baryons

- [Lecture 16 \(4 slides/page\)](#) Charmonium, upsilon systems and parity
  - Griffiths Sect. 5.4
  - Williams Sect. 10.8

## ■ Quark Model

- ▶ Meson and baryon multiplets
- ▶ Isospin, strangeness, c, b, t quarks

## ■ Particle Interactions

- ▶ Colour charge, QCD, gluons, fragmentation, running couplings
- ▶ Strong and weak decays, conservation rules
- ▶ Virtual particles and range of forces
- ▶ **Parity**, charge conjugation, CP
- ▶ Weak decays of quarks
- ▶ **Charmonium and upsilon systems**

Previous  
lecture

## ■ Electroweak Interactions

- ▶ Charged and neutral currents
- ▶ W, Z, LEP experiment
- ▶ Higgs and the future

## ■ LHC Experiments

## ■ Future - introduction to ac

- [Lecture 15 \(4 slides/page\)](#) Identifying interactions and charmonium
  - Griffiths, p 83 and pp. 171-176
  - [Photo history of SLAC, 1962-2002](#) - recommended easy viewing
  - [Historical accounts of discovery of charm quark](#)
  - *Discovery of a Narrow Resonance in e+e- Annihilation*, [Phys. Rev. Lett. 33, 1406-1408 \(1974\)](#)
  - [An informal history of SLAC](#), 1984 article by Richter (1976 Nobel Prize (with Ting) for J/psi discovery)
  - Nobel Prize lists: [SLAC's](#), [BNL](#)
  - [End Station A](#) as used for ILC R&D facility (up to 2008)

# Upsilon system

| Upsilon  | Mass ( $\text{GeV}/c^2$ ) | Width (keV) |
|----------|---------------------------|-------------|
| $1^3S_1$ | 9.46                      | 54          |
| $2^3S_1$ | 10.02                     | 32          |
| $3^3S_1$ | 10.36                     | 20          |
| $1^3S_1$ | 10.58                     | 20500       |
| $1^3S_1$ | 10.87                     | 110000      |
| $1^3S_1$ | 11.02                     | 79000       |

BB production threshold  
( $m_B=5.279 \text{ GeV}/c^2$ )

# Conservation Rules

| Interaction                | Symbol | SI | EM | WI |
|----------------------------|--------|----|----|----|
| Energy                     | E      | ✓  | ✓  | ✓  |
| Momentum                   | P      | ✓  | ✓  | ✓  |
| Angular Mom <sup>n</sup> . | J      | ✓  | ✓  | ✓  |
| Charge (e.m, colour)       | Q      | ✓  | ✓  | ✓  |
| Fermion number             |        | ✓  | ✓  | ✓  |
| Quark number               |        | ✓  | ✓  | ✓  |
| Baryon number              | B      | ✓  | ✓  | ✓  |
| Lepton number              | L      | ✓  | ✓  | ✓  |
| Electron number            | $L_e$  | ✓  | ✓  | ✓  |
| Muon number                | $L_m$  | ✓  | ✓  | ✓  |
| Tau number                 | $L_t$  | ✓  | ✓  | ✓  |
| Quark flavour              |        | ✓  | ✓  | ✗  |
| Isospin                    | I      | ✓  | ✗  | ✗  |
| Parity                     | P      | ✓  | ✓  | ✗  |
| Charge Conjugation         | C      | ✓  | ✓  | ✗  |
| Time reversal              | T      | ✓  | ✓  | ✗  |
| Matter-Antimatter          | CP     | ✓  | ✓  | ✗  |
| Quantum Field Theory       | CPT    | ✓  | ✓  | ✓  |

|   |             |
|---|-------------|
| ✓ | conserved   |
|   | Not         |
| ✗ | necessarily |
|   | conserved   |

# Intrinsic Parity

- All particles have intrinsic parity quantum number
- By convention, fundamental fermions (quarks, leptons) have  $P=+1$  (even)
- Fundamental anti-fermions have  $P=-1$  (odd)
- Parity is multiplicative
  - ▶ Examples
- Orbital angular momentum,  $L$ 
  - ▶ contributes additional factor  $(-1)^L$
- Parity of meson is  $P = -(-1)^L$

| Particle   |                               | Parity | $J^P$           |
|------------|-------------------------------|--------|-----------------|
| Quark      | $q$                           | +1     | $\frac{1}{2}^+$ |
| Anti-quark | $\bar{q}$                     | -1     | $\frac{1}{2}^-$ |
| Pion       | $q\bar{q}$                    | -1     | $0^-$           |
| Rho        | $q\bar{q}$                    | -1     | $1^-$           |
| Proton     | $qqq$                         | +1     | $\frac{1}{2}^+$ |
| antiproton | $\bar{q}\bar{q}\bar{q}$       | -1     | $\frac{1}{2}^-$ |
| Photon     | $(\gamma \rightarrow e^+e^-)$ | -1     | $1^-$           |