Outline

- Relativistic Kinematics
  - (4-momentum)2 invariance, invariant mass
  - Hypothesis testing, production thresholds
  - Cross-sections, flux and luminosity, accelerators
  - Particle lifetime, decay length, width
- Classification of particles
  - Fermions and bosons
  - Leptons, hadrons, quarks
  - Mesons, baryons
- 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
- Electroweak Interactions
  - Charged and neutral c
  - W, Z, LEP experiment
  - Higgs and the future
- LHC Experiments
- Future – introduction to ac

Today

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

Previous lecture

- 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 (GeV/c^2)	Width (keV)
1^3S_1	9.46	54
2^3S_1	10.02	32
3^3S_1	10.36	20
4^3S_1	10.58	20500
5^3S_1	10.87	110000
6^3S_1	11.02	79000

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

Conservation Rules

Interaction	Symbol	SI	EM	WI
Energy	E	✓	✓	✓
Momentum	P	✓	✓	✓
Angular Mom$^{n.}$	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 Conjugtion	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

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^-

- Orbital angular momentum, L
  - contributes additional factor $(-1)^L$
- Parity of meson is $P = -(-1)^L$

[For info.] Running Couplings

EM case

$$\alpha_{EM}(|q^2|) = \frac{\alpha(0)}{1 - \left(\frac{\alpha(0)}{3\pi}\right) \ln\left(|q^2| / m^2\right)} \qquad |q^2| >> m^2$$

QCD case

$$\alpha_S(|q^2|) = \frac{\alpha_S(\mu^2)}{1 + \left(\frac{\alpha_S(\mu^2)}{12\pi}\right) \left[11 N_{colours} - 2 N_{flavours}\right] \ln\left(|q^2| / m^2\right)} \qquad |q^2| >> |\mu^2|$$