# Outline

- Relativistic Kinematics
  - (4-momentum)2 invariance, invariant mass
  - Hypothesis testing, production thresholds
  - Cross-sections, flux and luminosity, accelerators
  - Particle lifetime, decay length, width
- Class
  - Griffiths, pp. 136-144, 149-151, 161.
  - Perkins, pp. 71-76, 83-86,
  - Some experimental studies of T/CPT invariance
    - CERN Press Release, 7 Mar 2012 NEW 1st resonant transitions measured in antihydrogen
    - Phys. Rep. 374 (2003) pp.165-270, *Physics at CPLEAR*, A. Angelopoulos et al. (CPLEAR Collaboration), pg ~171.
    - preprint CERN-EP-2001-060, *T-violation and CPT-invariance measurements in the CPLEAR experiment: a detailed description of the analysis of neutral-kaon decays to e pi nu* , Angelopoulos et al.
    - Phys. Rev. D 83, 092001 (2011), *Precise Measurements of Direct CP Violation, CPT Symmetry, and Other Parameters in the Neutral Kaon System*
- Quar
- Parti
  - 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 currents
  - W, Z, LEP experiments
  - Higgs and the future
- LHC Experiments
- Future – introduction to accelerator physics

Today

Lecture 17 (4 slides/page) - Parity, Charge conjugation, Time reversal symmetries

Previous lecture

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

# 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), follows from above
- Parity is multiplicative
  - E.g. pion has P=-1 as $P(q)P(\overline{q})=1x-1$
  - Further examples (table)
- 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 | $\overline{q}$ | -1 | $\frac{1}{2}^-$ |
| Pion | $q\overline{q}$ | -1 | $0^-$ |
| Rho | $q\overline{q}$ | -1 | $1^-$ |
| Proton | $qqq$ | +1 | $\frac{1}{2}^+$ |
| antiproton | $\overline{q}\overline{q}\overline{q}$ | -1 | $\frac{1}{2}^-$ |
| Photon | $(\gamma \rightarrow e^+e^-)$ | -1 | $1^-$ |

# P and T transformations

| Observable | Parity transform | Time, T, transform |
|---|---|---|
| Position, **r** | -**r** (polar vector) | **r** |
| Momentum, **p** | -**p** | -**p** |
| Spin, **σ** | **σ** | –**σ** |
| Longitudinal polarisation, **σ.p** | -**σ**.**p** | **σ**.**p** |
| Electric field, **E** | -**E** | **E** |
| Magnetic field, **B** | **B** | -**B** |
| Magnetic dipole moment, **σ.B** | **σ**.**B** | **σ**.**B** |
| Electric dipole moment, **σ.E** | -**σ**.**E** | -**σ**.**E** |