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, qua
  - Mesons, baryons
- Quark Model
  - Meson and baryon mu
  - Isospin, strangeness,
- 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 currents
  - W, Z, LEP experiments
  - Higgs and the future
- LHC Experiments
- Future – introduction to accelerator physics

Today

- 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)

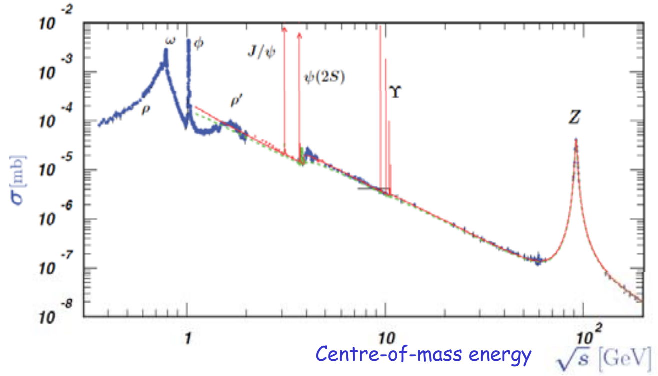
Previous lecture

- Lecture 14 (4 slides/page) CKM matrix, heavy flavour production and decay
  - Griffiths, pp. 74-77, 324-329

Identifying Interaction Types

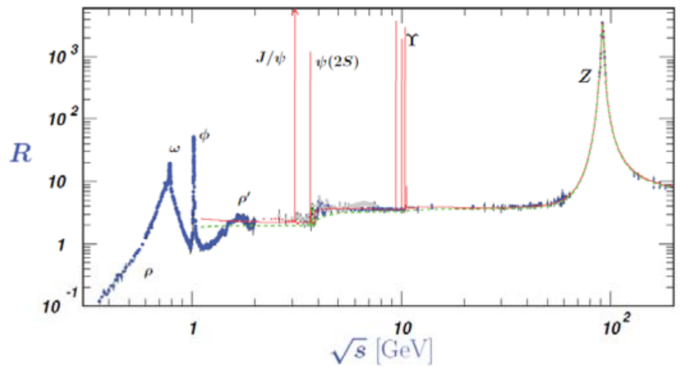
- Important to be able to identify the type of interaction based on experimental evidence.
  - May have to consider processes beyond "leading order"
  - Sometimes may be more than one interaction involved
    - ⇒ Typically interested in the most limiting one, usually the weak interaction
- Weak: characteristics are (most obvious first)
  - Neutrinos involved
  - Changes flavour
  - Long lifetime (>10^{-14}s)
  - W and Z bosons involved
  - Parity violated
- Electromagnetic:
  - Photons involved (real, or virtual)
  - e.g. $\pi^0 \rightarrow e^+e^-, \gamma e^+e^-, e^+e^- e^+e^-$,
- Strong:
  - All quantum numbers conserved
  - Short lifetime (<10^{-19}s, more commonly ~10^{-22} 10^{-23}s
  - High cross-section (for production in collisions)
- Examples

cross-section ($e^+e^- \rightarrow$ hadrons)



http://pdg.lbl.gov/2008/reviews/hadronicrpp.pdf

cross-section ratio: ($e^+e^- \rightarrow$ hadrons)/ ($e^+e^- \rightarrow \mu^+\mu^-$)



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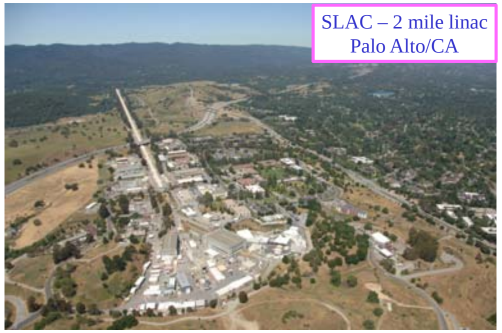
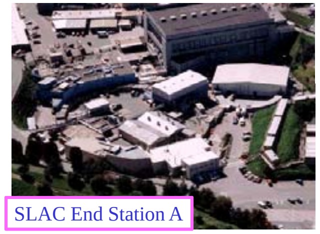
SLAC

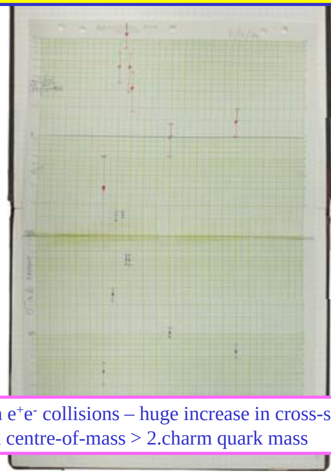


SLAC – 2 mile linac
Palo Alto/CA

Charmonium at SLAC



SLAC End Station A



J/psi mass from 2xbeam energy in e^+e^- collisions – huge increase in cross-section when energy available in centre-of-mass > 2.charm quark mass

e^+e^- experimental data

hadrons

$\mu^+\mu^-$

e^+e^-

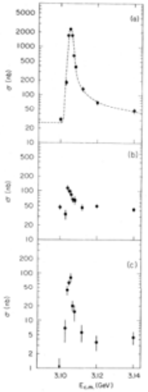


FIG. 1. Cross section versus energy for (a) multihadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes. The cross sections shown in (b) and (c) are integrated over the detector acceptance. The total hadron cross section, (a), has been corrected

- *Discovery of a Narrow Resonance in e+e- Annihilation*, Phys. Rev. Lett. 33, 1406-1408 (1974)

p+Be→J+X

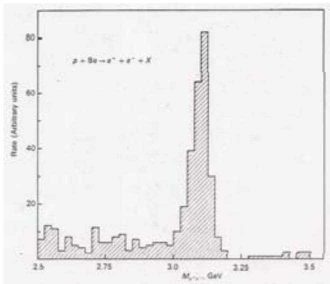


Figure 5.10 Results of Aubert et al. (1974) indicating the narrow resonance ψ/J in the invariant-mass distribution of e^+e^- pairs produced in inclusive reactions of protons with a beryllium target. The experiment was carried out with the 28-GeV AGS at Brookhaven National Laboratory.

J/psi mass from "reconstruction" of decay products in final state
i.e. calculation of the invariant mass from measured energy and momenta

$e^+e^- \rightarrow \psi$

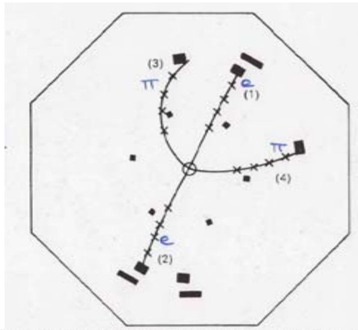


Figure 5.12 Example of the decay $\psi'(3.7) \rightarrow \psi(3.1) + \pi^+ + \pi^-$ observed in a spark chamber detector. The $\psi(3.1)$ decays to $e^+ + e^-$. Tracks (3) and (4) are due to the relatively low-energy (150-MeV) pions, and (1) and (2) to the 1.5-GeV electrons. The magnetic field and the SPEAR beam pipe are normal to the plane of the figure. The trajectory shown for each particle is the best fit through the sparks, indicated by crosses. [From G. S. Abrams *et al.*, *Phys. Rev. Letters* 34, 1181 (1975).]

Strong, e.m., weak interactions (W.I.)

- So far, have discussed strong interaction in terms of binding quarks into hadrons
- Particle decays also determined by type of interactions allowed
- Strength of interaction reflected in lifetime of decaying particle
- Many hadronic resonances, lifetimes
  - $\tau \sim 10^{-23}$s
  - Deduced from width, $\Gamma \sim 10\text{-}100$ MeV
  - These are Strong Interaction decays
- Some much longer lived hadrons
  - $\tau \sim 10^{-10}$s
  - Can be measured directly
  - These are Weak Interaction decays
- Some with intermediate lifetimes (e.m.)