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)

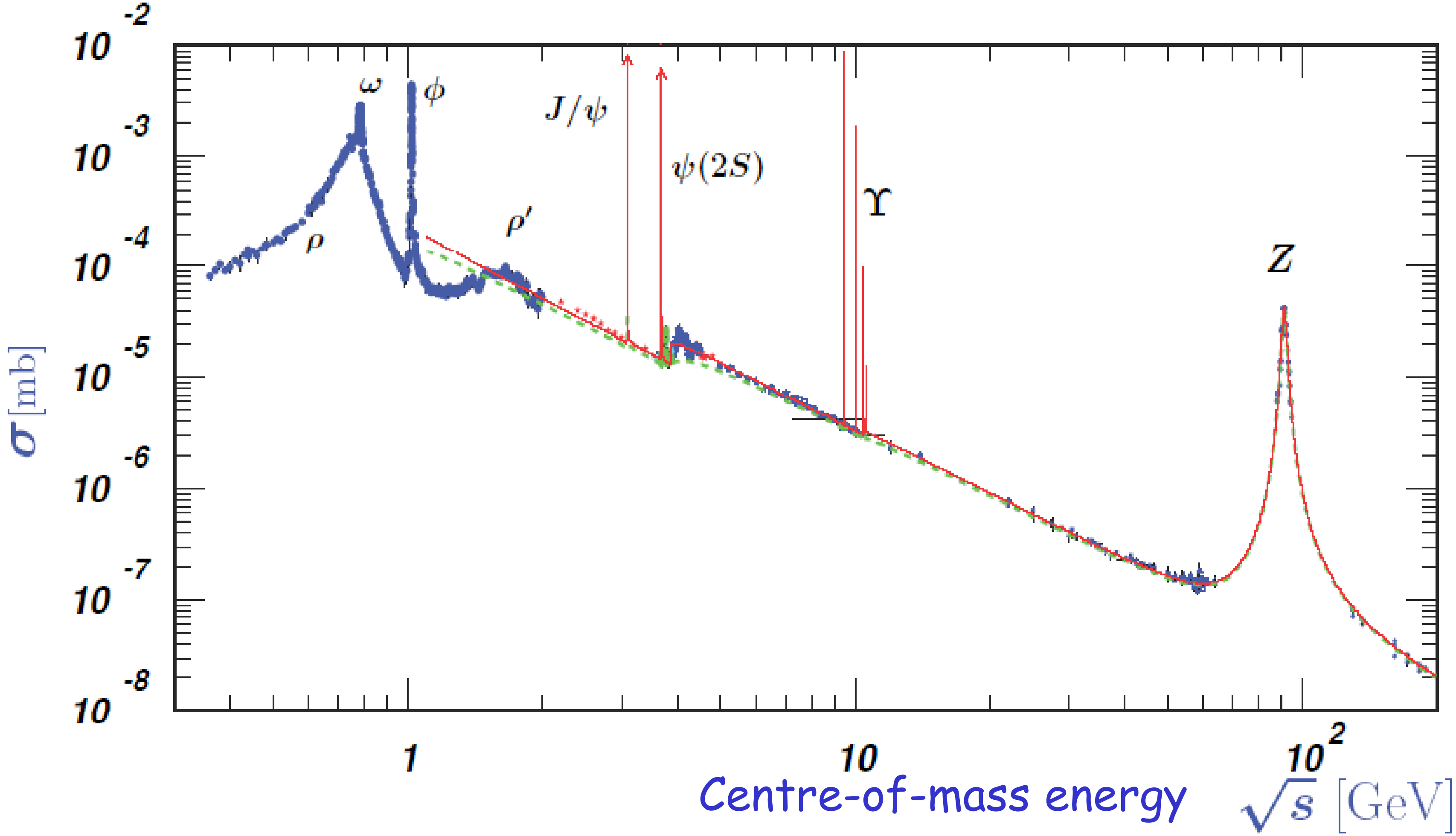
Previous lecture

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

Identifying Interaction Types

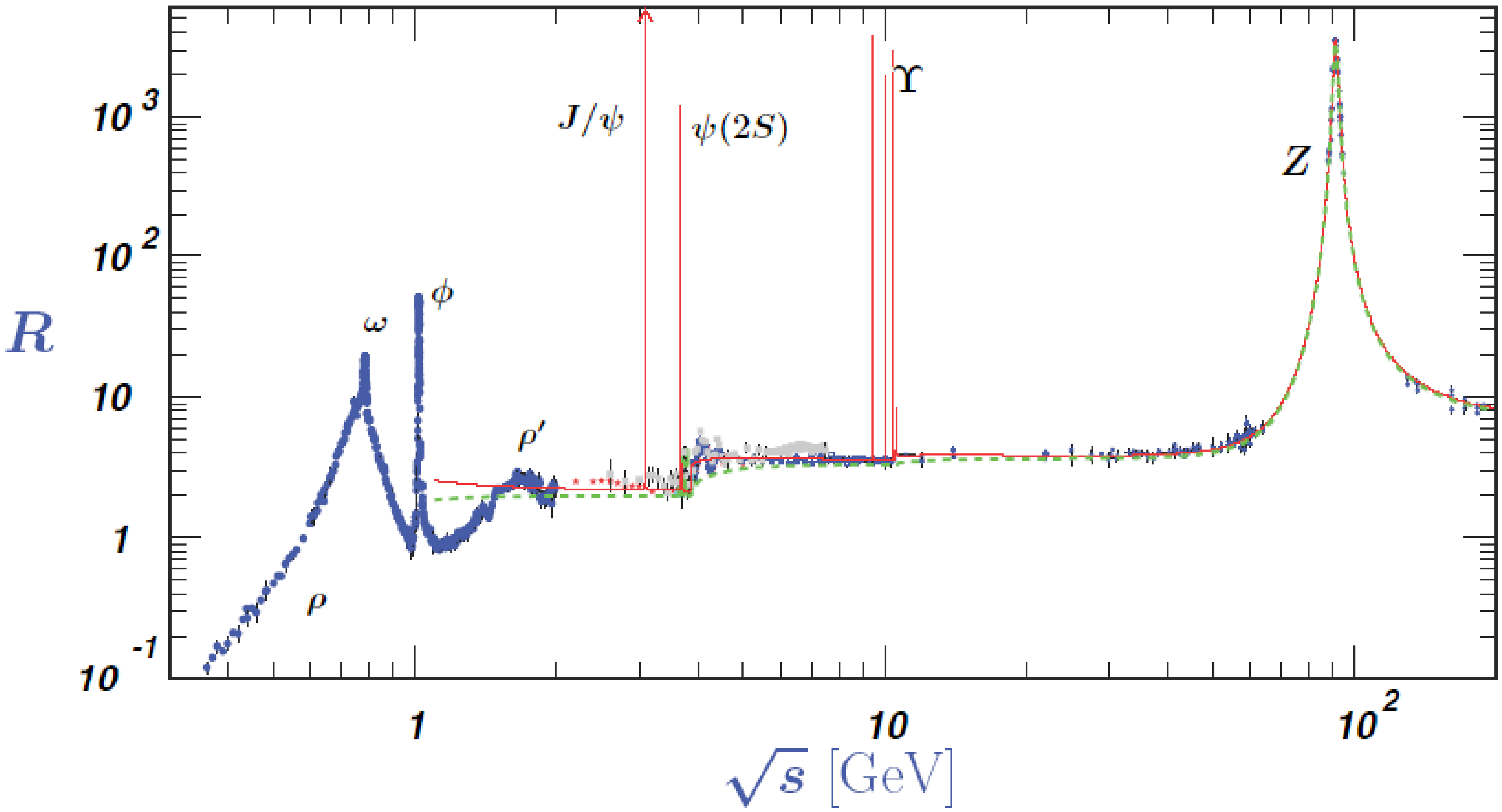
- Important to be able to identify the type of interaction based on experimental evidence.
  - May have to consider processes beyond "leading order"
  - Sometimes may be more than one interaction involved
    - ⇒ Typically interested in the most limiting one, usually the weak interaction
- Weak: characteristics 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 $\sim 10^{-22}$ 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

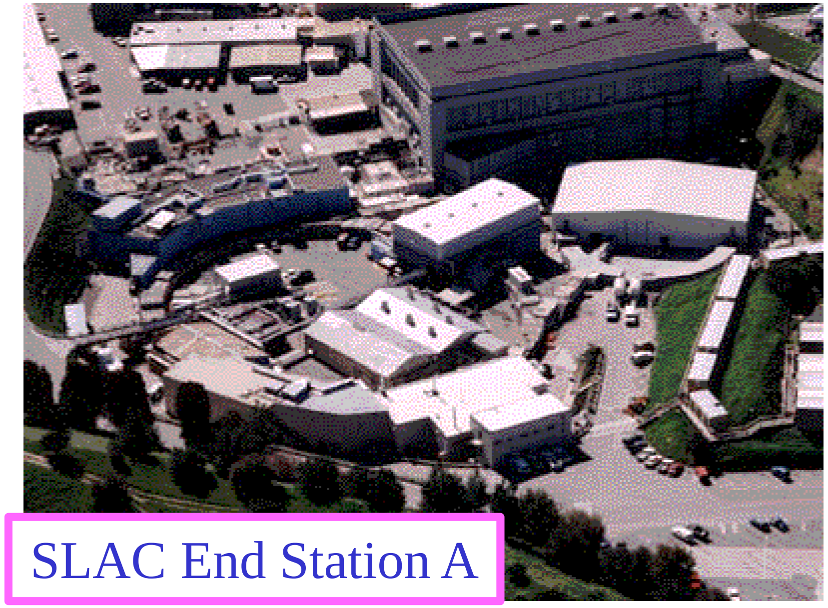
cross-section ratio: ($e^+e^- \rightarrow$ hadrons)/ ($e^+e^- \rightarrow \mu^+\mu^-$)



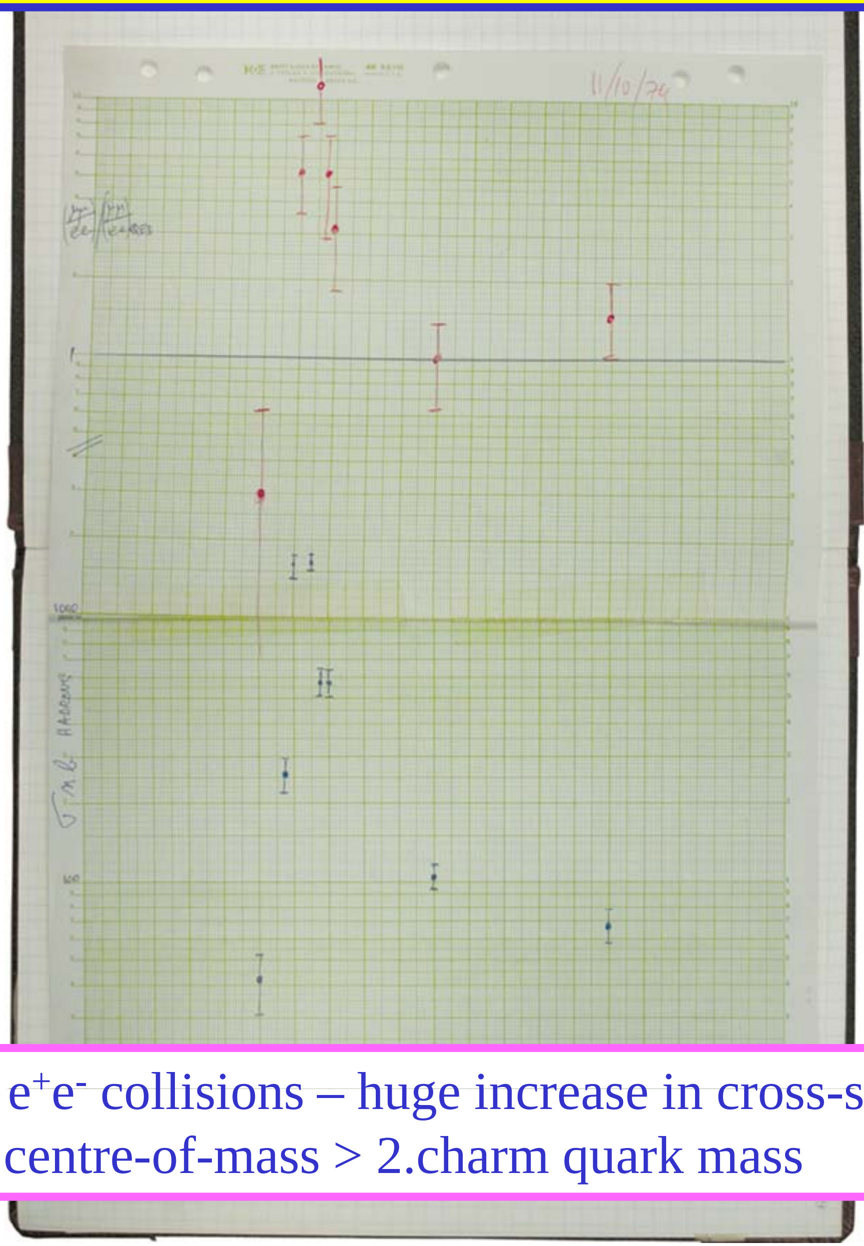
http://pdg.lbl.gov/2008/reviews/hadronicrpp.pdf

SLAC

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^-

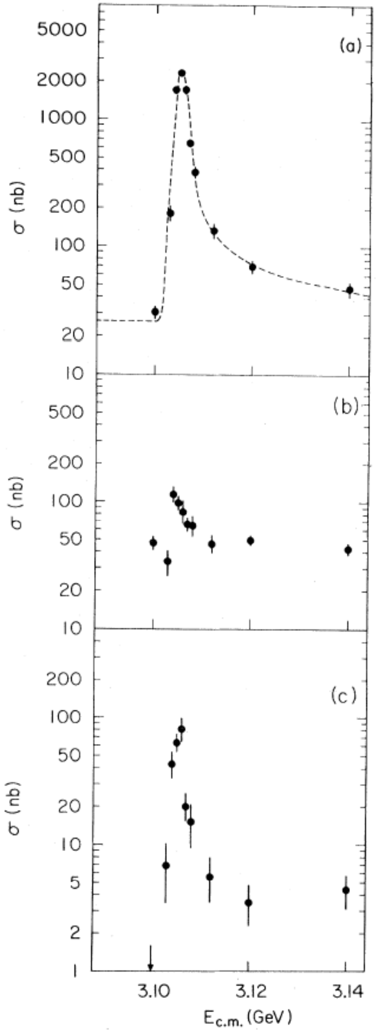


FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes.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

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

p+Be→J+X

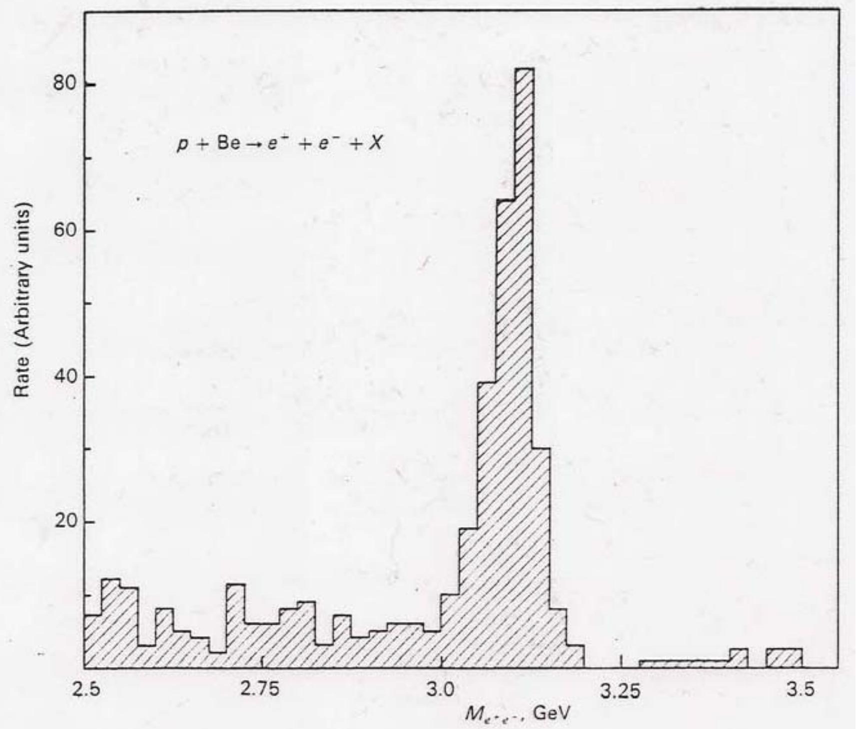


Figure 5.10 Results of Aubert *et al.* (1974) indicating the narrow resonance ψ/J in the invariant-mass distribution of e^+e^- pairs produced in inclusive reactions of protons with a beryllium target. The experiment was carried out with the 28-GeV AGS at Brookhaven National Laboratory.

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

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

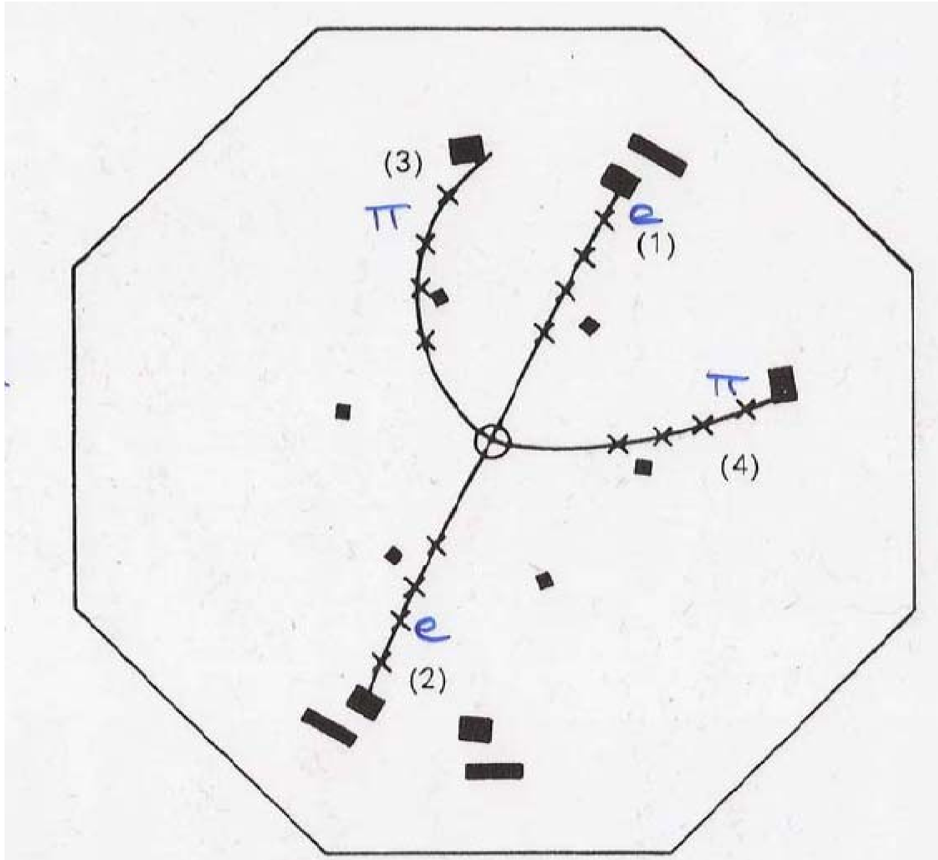
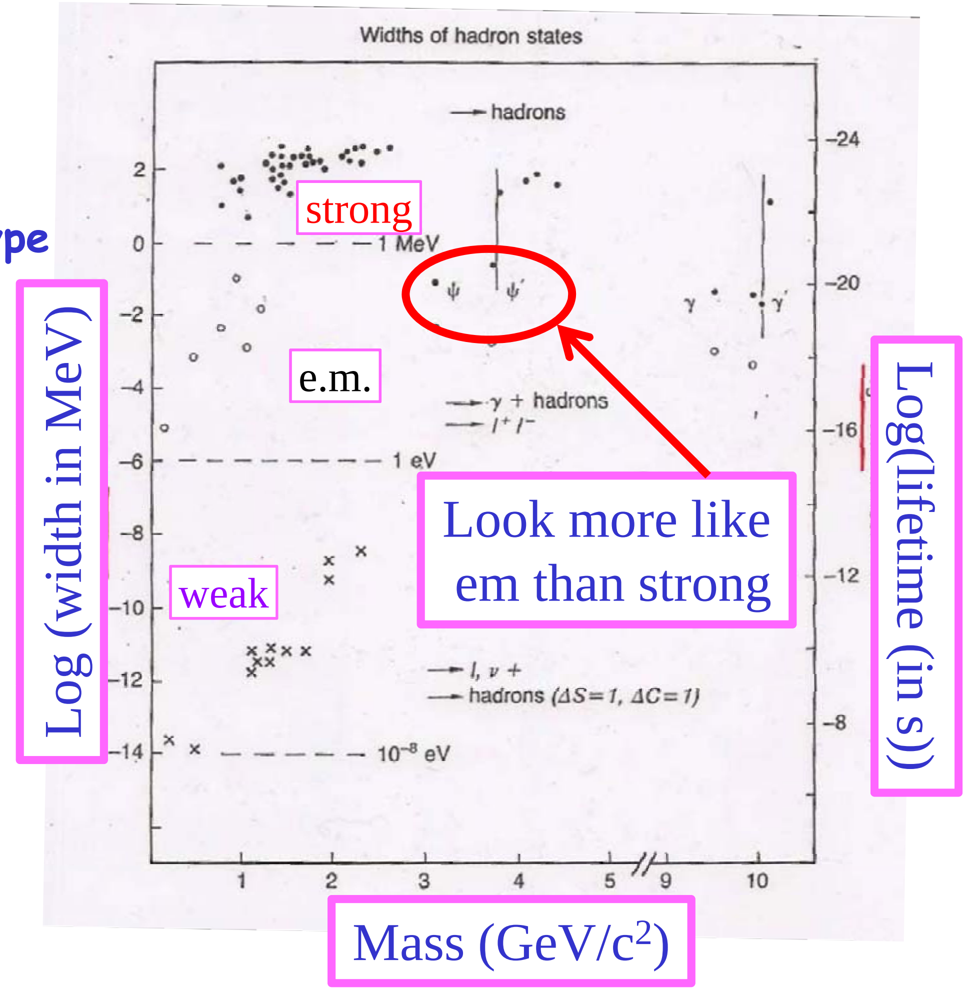


Figure 5.12 Example of the decay $\psi'(3.7) \rightarrow \psi(3.1) + \pi^+ + \pi^-$ observed in a spark chamber detector. The $\psi(3.1)$ decays to $e^+ + e^-$. Tracks (3) and (4) are due to the relatively low-energy (150-MeV) pions, and (1) and (2) to the 1.5-GeV electrons. The magnetic field and the 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).]

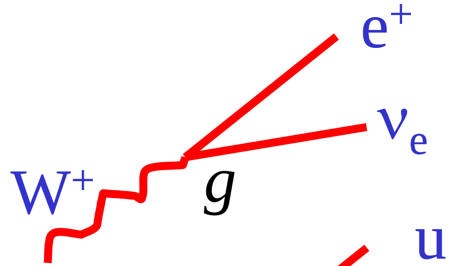
Strong, e.m., weak interactions (W.I.)

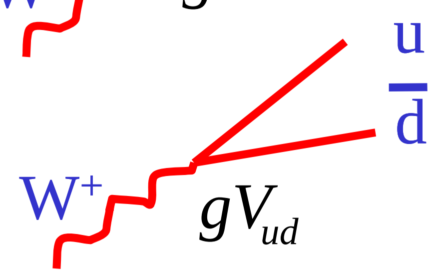
- So far, have discussed strong interaction in terms of binding quarks into hadrons
- Particle decays also determined by type of interactions allowed
- Strength of interaction reflected in lifetime of decaying particle
- Many hadronic resonances, lifetimes
  - $\tau \sim 10^{-23}$s
  - Deduced from width, $\Gamma \sim 10\text{-}100$ 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.)



W coupling to quarks

- Cabibbo theory
  - W boson couples to lepton/neutrinos with <u>universal</u> coupling, g
  - W boson couples to **u** quark and a **d** quark with coupling g.V_{ud}





- W does not couple directly to physical/mass states of u and d quarks
  - Actually couples to a u-type and a linear combination of d-type quarks in all 3 generations
  - Without this, would be no decay of lightest strange mesons, etc.!
- Effectively, a "rotation" of mass eigenstates to the weak eigenstates

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{vmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{vmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$$= \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

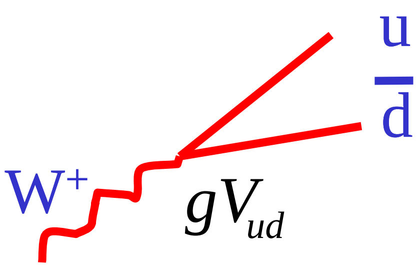
$$i.e. \quad d' = d\cos\theta_C + s\sin\theta_C$$

$$s' = -d\sin\theta_C + s\cos\theta_C$$

$$\theta_C \approx 13.1^0$$

Cabibbo Theory and Golden Rule

- Convention to "rotate" d type quarks, but could equally well rotate u type quarks



- Cabibbo theory is historical name when dealing with 1st and 2nd generations only

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{vmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{vmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$$= \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$$= \begin{pmatrix} 0.974 & 0.225 \\ 0.225 & 0.974 \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

- "Fermi Golden Rule" for decay/scattering rates – see QM text
- Rate is product of two terms

$$Rate = \tfrac{2\pi}{\hbar} \left| M_{fi} \right|^2 \rho(E)$$

$$\rho(E) \; is \;\; phase \;\; space \;\; factor \, , dN \,/\, dE$$

- A dynamical term, derived from Feynman diagrams.
  - Enters as the |QM amplitude|², (sometimes called "matrix element"²)
  - For our case, amplitude is proportional to the product of couplings present in diagram
- A kinematical term, purely depending on energy/momenta/masses
  - Independent of particle types
  - Variously called "phase space factor" or "density of states"
  - More energy available in final state (apart from masses) increases this statistical counting factor: number of states possible with energy *E* available

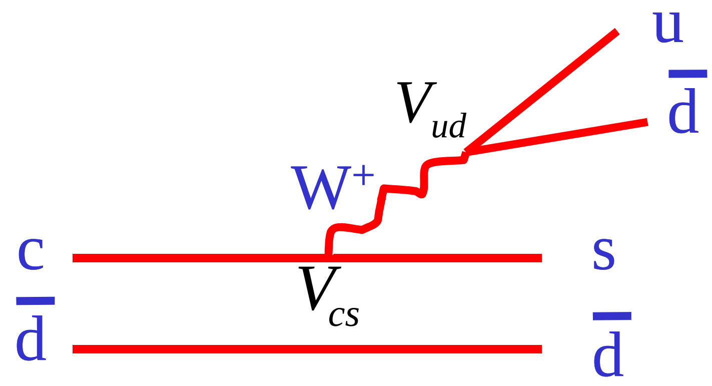
Example: Cabibbo Suppression

$$D^+ \to \bar{K}^0 \;\; \pi^+$$

$$(c\bar{d}) \to (s\bar{d})(u\bar{d})$$

Amplitude

$$\propto V_{ud} V_{cs}$$



"Cabibbo favoured" decay

Rate $\propto \left| V_{ud} V_{cs} \right|^2 = \left| \cos\theta_C \; \cos\theta_C \right|^2$

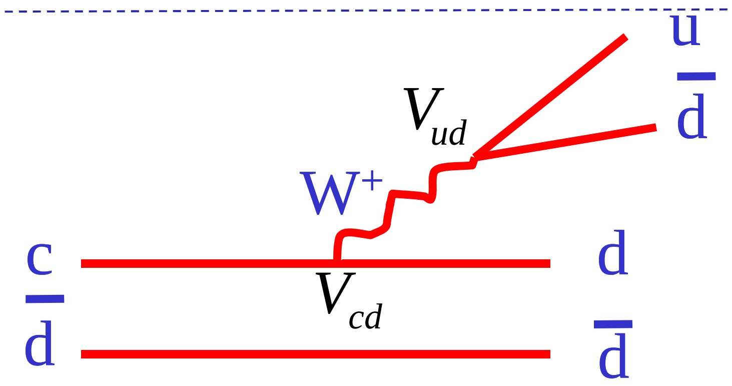
$\propto V_{ud} V_{cd}$

$$D^+ \to \pi^0 \;\; \pi^+$$

$$(c\bar{d}) \to (d\bar{d})(u\bar{d})$$

Amplitude

$$\propto V_{ud} V_{cd}$$



"Cabibbo suppressed" decay

Rate $\propto \left| V_{ud} V_{cd} \right|^2 = \left| \cos\theta_C \; \sin\theta_C \right|^2$

Relative rates

$$\frac{D^+ \to \bar{K}^0 \;\; \pi^+}{D^+ \to \pi^0 \;\; \pi^+} \propto \left| V_{ud} V_{cs} \right|^2 / \left| V_{ud} V_{cd} \right|^2 = \left| 1/\tan\theta_C \right|^2 \sim 1/20$$

3 Flavour case: CKM Matrix

- Generalisation to 3 generations: CKM (Cabibbo-Kobayashi-Maskawa) Matrix
- Rotation of mass to weak eigenstates
- 2x2 Cabibbo matrix is merely the upper left part of the full 3x3 CKM matrix
- $\lambda = \sin\theta_C$

Cabibbo

$$\begin{vmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{vmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix}$$

CKM (magnitudes only)

$$\begin{vmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{vmatrix} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\begin{vmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{vmatrix} \approx \begin{pmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.008 & 0.040 & 0.999 \end{pmatrix}$$

- Note: small size of
  - V_{ub}, V_{cb}, V_{td}
  - Observations?? Impact on lifetimes of b, c decays?

Strange Particle Production

- Properties of SI, WI important in production/decay of strange and heavier quarks
- Production requires strong (or EM) to give large cross-section. Requires $s\bar{s}$ production to conserve strangeness
  - Strange hadrons created in pairs - so-called "associated production"
  - Examples of production (on board): p (π^+, π^-, K^-)
- SI decays 13 orders magnitude faster than WI, so WI decays only observed when SI/EM forbidden by (e.g.) flavour conservation rules.
- Heavy strange hadrons (i.e. excited states) decay to lighter strange hadrons by SI
  - Examples of SI decays (on board): p (π^+, π^-, K^-)
  - Conserves flavour and other quantum numbers
  - Typical lifetime of strong decays ~10^{-22}-10^{-23}s, called resonances
- Process continues until arrive at lightest strange hadrons (kaons), which are stable under SI because of strangeness conservation
- WI decays only observed when SI and EM forbidden by, e.g. flavour conservation.

Light Strange Particle Decays

- Lightest strange particles
- Mesons
  - $K^+ = u\bar{s}$, $K^0 = d\bar{s}$, $\bar{K}^0 = \bar{d}s$, $K^- = \bar{u}s$
    - $\Rightarrow S = \pm 1$
- Baryons
  - $\Lambda^0 = u\,d\,s$
    - $\Rightarrow S = -1$
  - $\Sigma^+ = u\,u\,s$, $\Sigma^- = d\,d\,s$,
    - $\Rightarrow S = -1$
    - $\Rightarrow$ [not $\Sigma^0 = u\,d\,s$ – not lightest uds: $m_{\Sigma^0} - m_{\Lambda}$ = (76.959 ± 0.023) MeV
  - $\Xi^0 = u\,s\,s$, $\Xi^- = d\,s\,s$
    - $\Rightarrow S=-2$
  - $\Omega^- = s\,s\,s$
    - $\Rightarrow S=-3$
  - Feynman diagrams on board
- These can only decay with change in strangeness, so must be weak decays.
- Typical lifetimes ~ 10^{-8} – 10^{-11} s

Heavy Quark (c, b, t) Decays

- Same pattern as in strange hadrons
- SI, EM and weak neutral current (Z^0) also conserve flavour for C, B, T
  - Each flavour number can change by 1 unit in a single W mediated reaction
- Heavy particles decay to lighter by SI, conserving flavours
  - e.g. $\tau \sim 10^{-23}$s, Feynman diagram on board

$$D^{*+} \rightarrow D^0 \pi^0$$
$$(c\bar{d}) \rightarrow (c\bar{u})(u\bar{d})$$

- Lightest particle of each flavour decays by WI, changing flavour
  - e.g $D^0 \rightarrow K^- \pi^+$ $\tau \sim 4.1\times10^{-13}$s, diagram on board

$$(c\bar{u}) \rightarrow (s\bar{u})(u\bar{d})$$

  - e.g. $B^+ \rightarrow \bar{D}^0 \pi^+$ $\tau \sim 1.6\times10^{-12}$s, diagram on board

$$(u\bar{b}) \rightarrow (u\bar{c})(u\bar{d})$$

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

[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

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