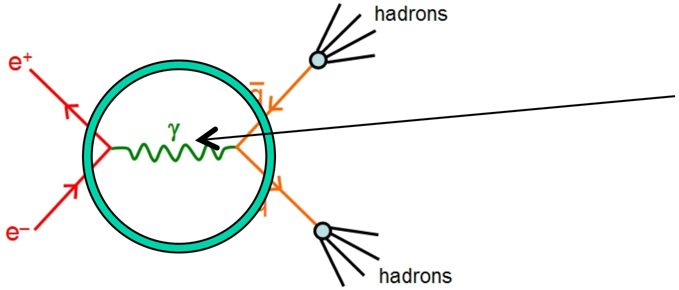
Lecture 6 − The particle ZOO

Wave description of particles → interference
All components of the wave function must be the same
amplitudes may be different
True for force carriers also: Z – γ

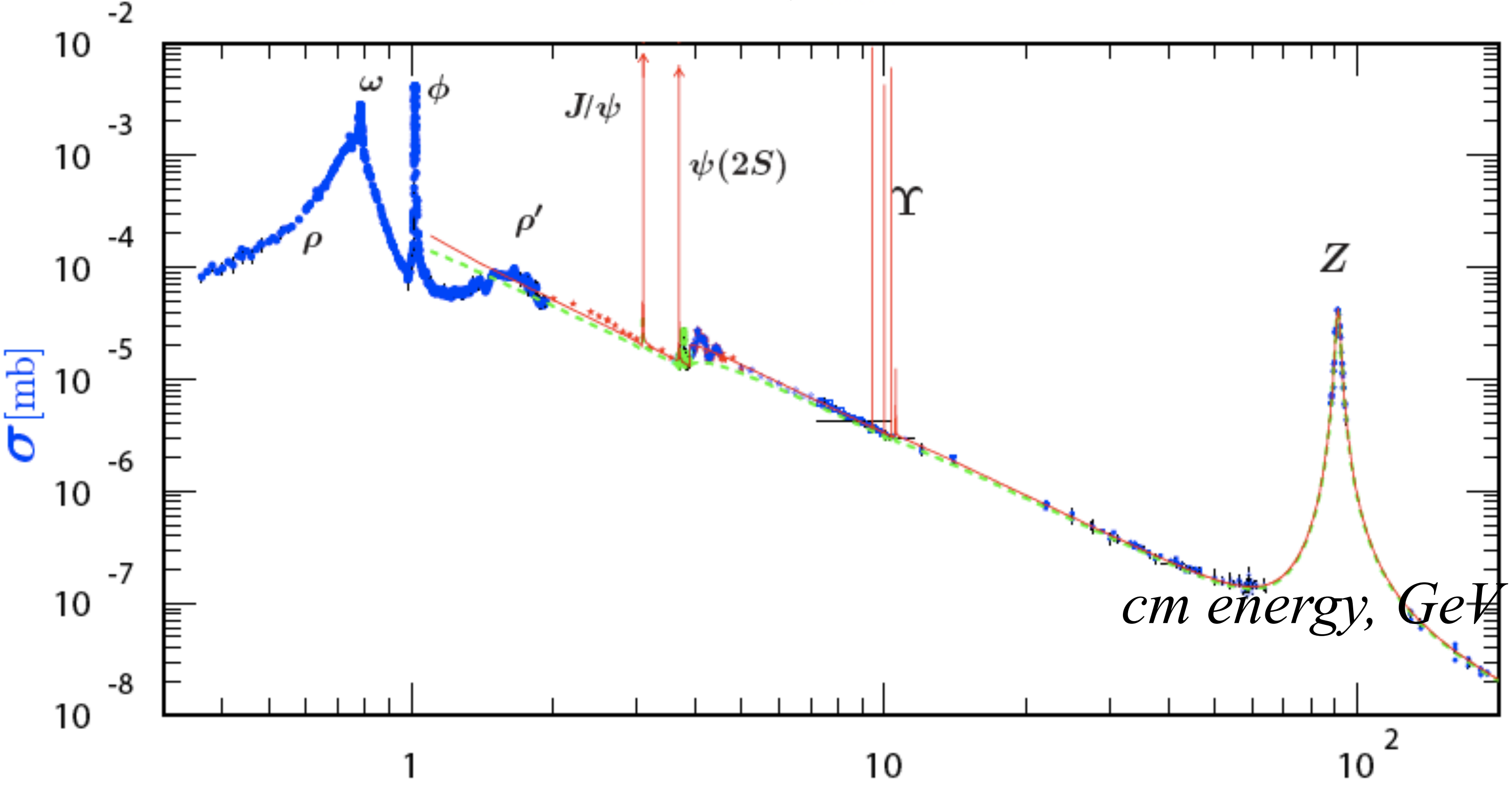
Many (several hundred) "resonance states" observed
π^+, π^-, π^0, K^+, K^-,K^0,*K*(890) , K*(1420), N**, Λ^0, Σ^+, Σ^-, *Ξ........*
-> Gell-Mann + Zweig proposed Quark Model: all elementary particles are made from smaller constituents called quarks
Until 1975 - All of the strongly interacting particles are composites of 3 quarks : up, down, strange
After 1975 − expanded to six quarks generically called flavors:
u − up, d − down, s − strange, c − charm, b − bottom, t -top

baryons: proton, neutron,…. are made out of 3 quarks
mesons: π, K, ρ, ψ ..... are made out of quark – antiquark pairs

cross-section for e+e- annihilation into hadrons



virtual photon



cm energy, GeV

σ and R in e^+e^- Collisions

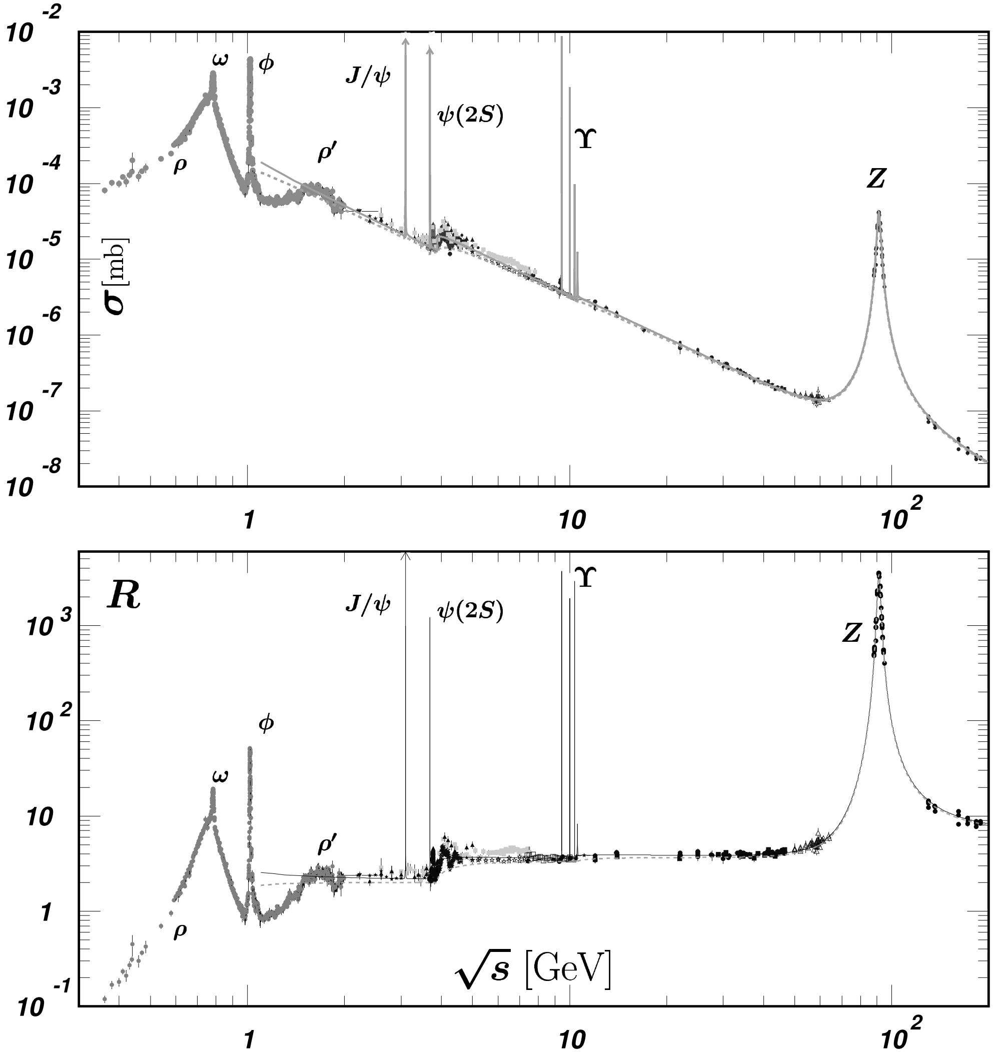
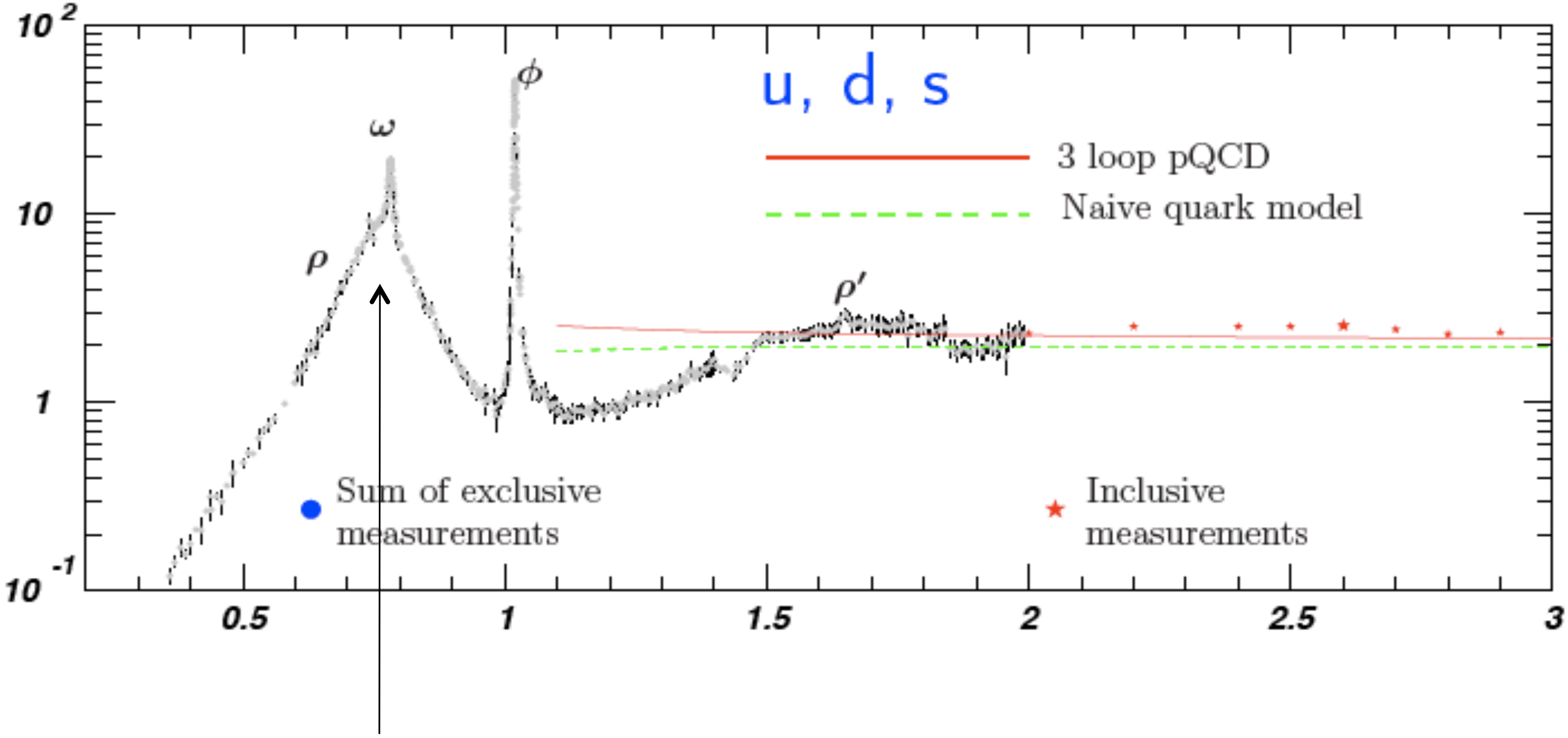


Figure 40.6: World data on the total cross section of $e^+e^- \to hadrons$ and the ratio $R(s) = \sigma(e^+e^- \to hadrons, s)/\sigma(e^+e^- \to \mu^+\mu^-, s)$. $\sigma(e^+e^- \to hadrons, s)$ is the experimental cross section corrected for initial state radiation and electron-positron vertex loops, $\sigma(e^+e^- \to \mu^+\mu^-, s) = 4\pi\alpha^2(s)/3s$. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are an educative guide: the broken one is a naive quark-parton model prediction and the solid one is 3-loop pQCD prediction (see "Quantum chromodynamics" section of this *Review*, Eq. (9.12) or, for more details, K. G. Chetyrkin *et al.*, Nucl. Phys. B **586** (2000) 56 (Erratum *ibid.* B **634** (2002) 413). Breit-Wigner parameterizations of J/ψ, $\psi(2S)$, and $\Upsilon(nS), n = 1, 2, 3, 4$ are also shown. The full list of references to the original data and the details of the R ratio extraction from them can be found in `hep-ph/0312114`. Corresponding computer-readable data files are available at http://pdg.ihep.su/xsect/contents.html. (Courtesy of the COMPAS(Protvino) and HEPDATA(Durham) Groups, August 2005. Corrections by P. Janot (CERN) and M. Schmitt (Northwestern U.))



$\rho - \omega$ interference

Antiparticle *– a particle with the same mass but opposite charge or magnetic property*

Observations:

- *gamma conversion – creation of electron + positron pair*
- *antiproton observed as secondary negative particle with mass equal to that of a proton, can be produced in p-p collisions*
- *π mesons of opposite charges produced in collisions*
- *resonance states of opposite charge observed in scattering and collisions resulting in multi-particle production*

Problem with neutral particles:

No opposite charge - eg, π^o, η

Explanation given by the Quark Model:

-> These particles are also their own antiparticles

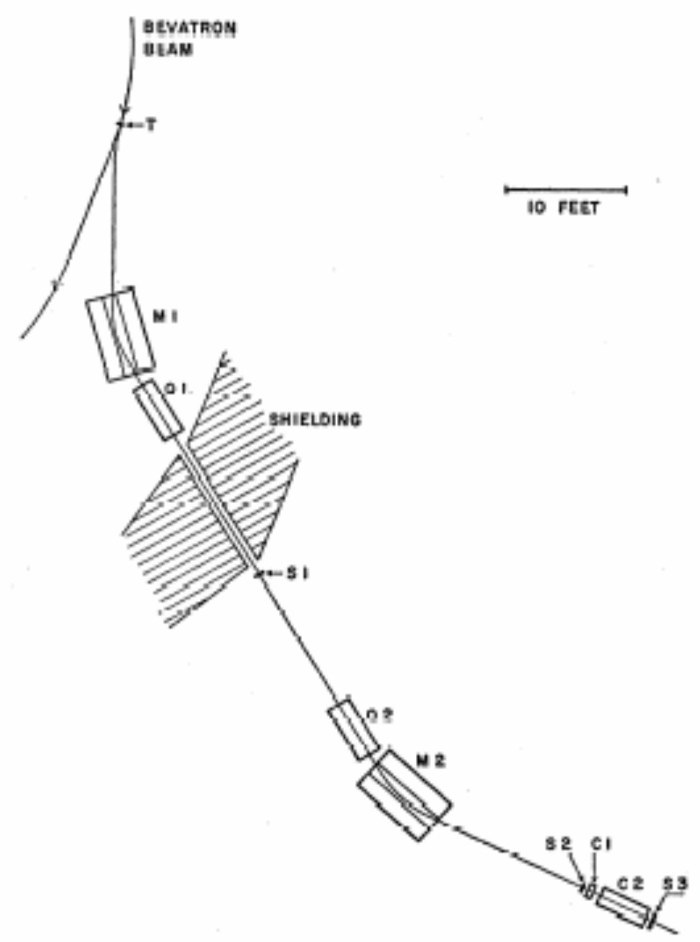
Antiproton discovery (1955)

Threshold energy for antiproton ($\bar{p}$) production in proton – proton collisions

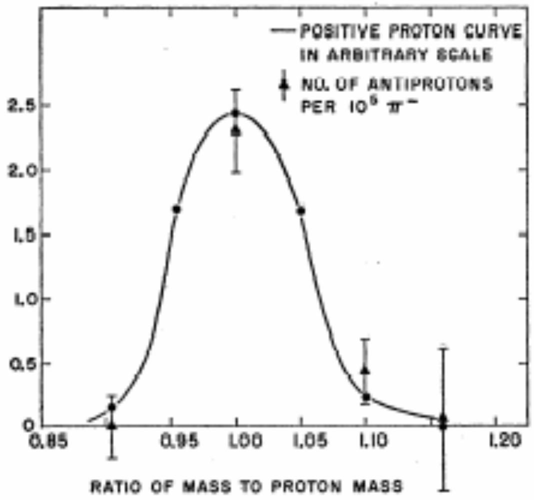
Baryon number conservation -> simultaneous production of $\bar{p}$ and p (or $\bar{p}$ and n)

Example: $p+p \rightarrow p+p+\bar{p}+p$ **Threshold energy ~ 6 GeV**

"Bevatron": 6 GeV
proton synchrotron in Berkeley



- **build a beam line for 1.19 GeV/c momentum**
- **select negatively charged particles (mostly π^-)**
- **reject fast π^- by Čerenkov effect: light emission in transparent medium if particle velocity v > *c* / *n* (*n*: refraction index) – antiprotons have v < *c* / *n* -> no Čerenkov light**
- **measure time of flight between counters S_1 and S_2 (12 m path): 40 ns for π^-, 51 ns for antiprotons**



For fixed momentum, time of flight gives particle velocity, hence particle mass

p = mv

Comments:

Momentum measurement in magnetic field

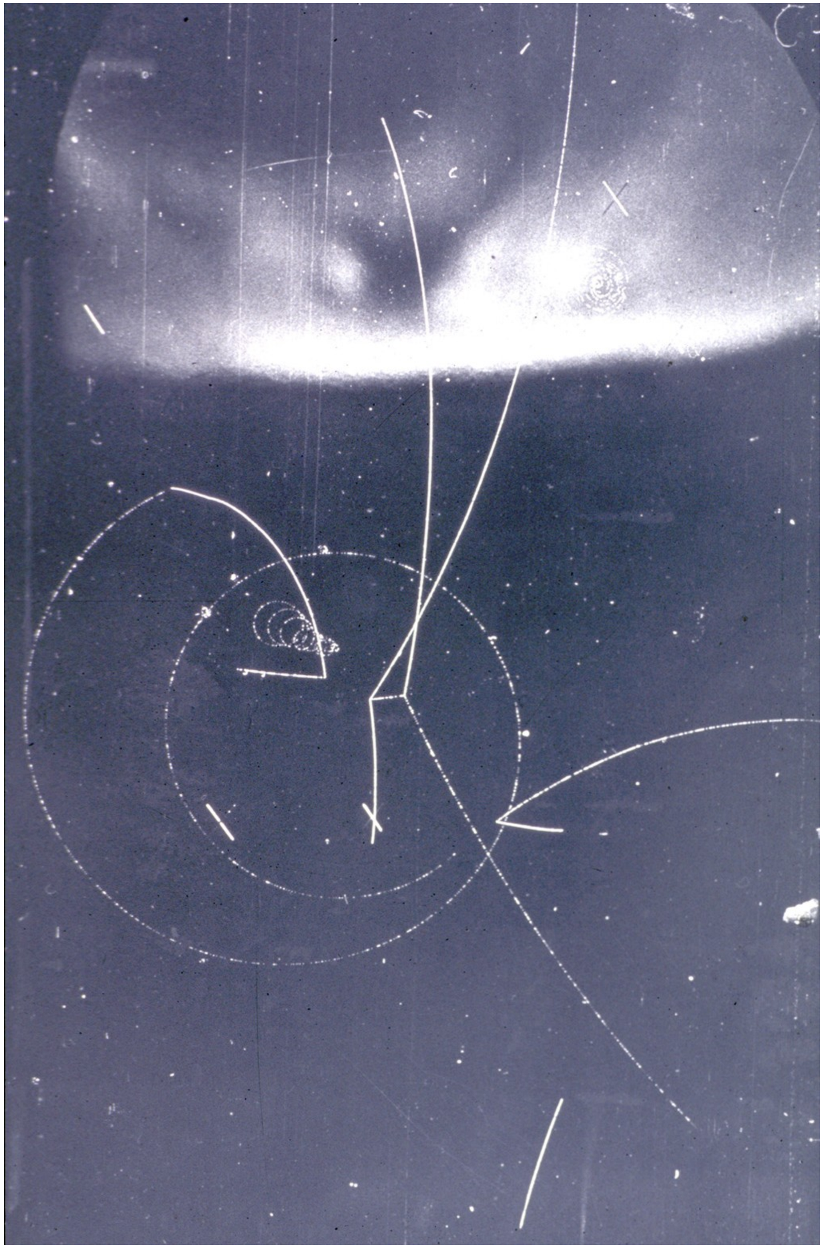
p (GeV/c) = 0.3 B (Tesla) × ρ (curvature, m^{-1})

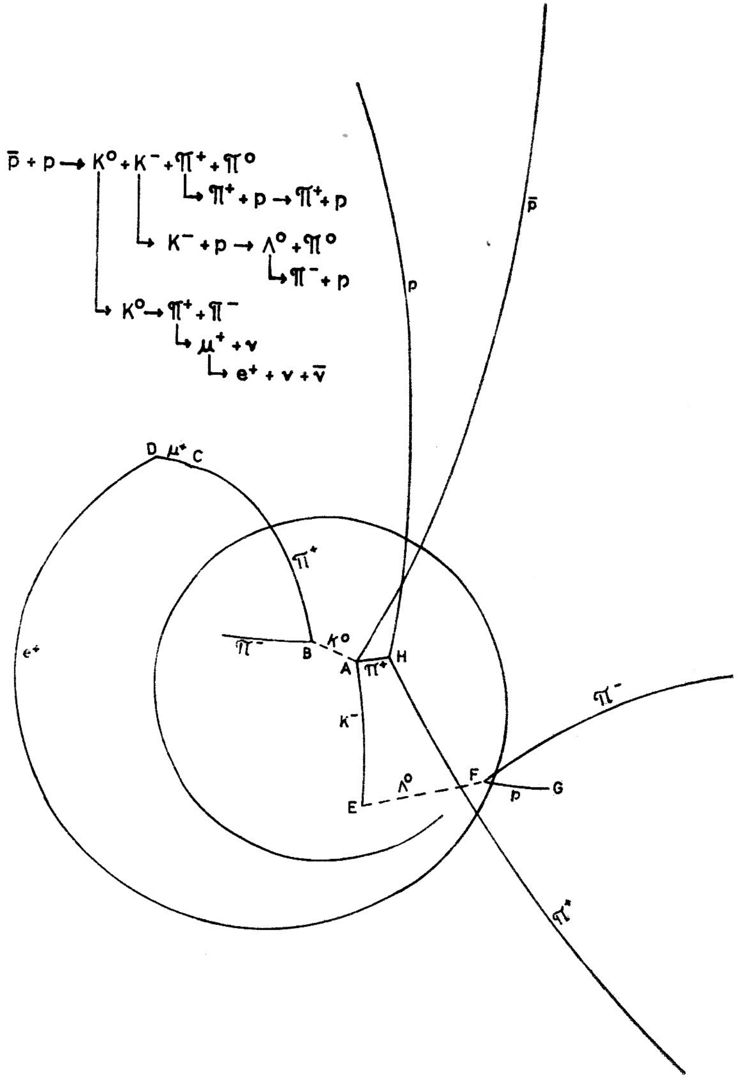
$\rho = 1/R$

Only one particle observed – second proton production implied by conservation law

Distance + timing -> velocity -> mass = p/v

Example of antiproton annihilation at rest in a liquid hydrogen bubble chamber





Conservation laws

- *All massive particle, unless prevented by some rule, decay into lighter particles.*
- *Massless particles (photons) or very light particles (electrons, neutrinos) do not decay because all other particles are heavier.*
- *There are several general rules that come from mechanics and electromagnetic interactions:*
- *These conservation laws are:*
    - *conservation of energy*
    - *conservation of momentum*
    - *conservation of angular momentum*
    - *conservation of charge*
- *If a particle decay is allowed by the above, but is not observed, we inve new conservation laws. Baryon (3 quark states) number conservation is an example of such law.*

CONSERVED QUANTUM NUMBERS

Why is the free proton stable?

Possible proton decay modes (allowed by all known conservation laws: energy – momentum, electric charge, angular momentum):

$$p \rightarrow \pi^\circ + e^+$$

$$p \rightarrow \pi^\circ + \mu^+$$

$$p \rightarrow \pi^+ + \nu$$

. . . . .

No proton decay ever observed – the proton is STABLE

Limit on the proton mean life depends on the assumed decay mode and date:

$t_p > 1.6$ x 10^{33} **years for decays to μ^+ and $\tau > 1.3$ x 10^{34} years for decays to e^+**

Invent a new quantum number : “Baryonic Number” B

B = 1 for proton, neutron

B = -1 for antiproton, antineutron

B = 0 for $e^\pm$, $\mu^\pm$, neutrinos, mesons, photons

Require conservation of baryonic number in all particle processes:

$$\sum_i B_i = \sum_f B_f$$

(***i*** **:** initial state particle ; ***f*** **:** final state particle)

Strangeness

Late 1940's: discovery of a variety of heavier mesons (K – mesons) and baryons ("hyperons") – studied in detail in the 1950's at the new high-energy proton synchrotrons (the 3 GeV "cosmotron" at the Brookhaven National Lab and the 6 GeV Bevatron at Berkeley)

Examples of mass values

Mesons (spin = 0): $m(K^{\pm}) = 493.68\ \mathrm{MeV}/c^2$; $m(K^{\circ}) = 497.67\ \mathrm{MeV}/c^2$

Hyperons (spin = ½): $m(\Lambda) = 1115.7\ \mathrm{MeV}/c^2$; $m(\Sigma^{\pm}) = 1189.4\ \mathrm{MeV}/c^2$

$m(\Xi^{\circ}) = 1314.8\ \mathrm{MeV}/c^2$; $m(X^{-}) = 1321.3\ \mathrm{MeV}/c^2$

Properties

- Abundant production in proton – nucleus , p – nucleus collisions
- Production cross-section typical of strong interactions ($\sigma > 10^{-27}\ \mathrm{cm}^2$)
- Production in pairs (example: $p^{-} + p \rightarrow K^{\circ} + \Lambda$; $K^{-} + p \rightarrow \Xi^{-} + K^{+}$)
- Decaying to lighter particles with mean life values $10^{-8} – 10^{-10}$ s (as expected for a weak decay)

Examples of decay modes

$K^{\pm} \rightarrow \pi^{\pm}\pi^{\circ}$; $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$; $K^{\pm} \rightarrow \pi^{\pm}\pi^{\circ}\pi^{\circ}$; $K^{\circ} \rightarrow \pi^{+}\pi^{-}$; $K^{\circ} \rightarrow \pi^{\circ}\pi^{\circ}$; . . .

$\Lambda \rightarrow p\,\pi^{-}$; $\Lambda \rightarrow n\,\pi^{\circ}$; $\Sigma^{+} \rightarrow p\,\pi^{\circ}$; $\Sigma^{+} \rightarrow n\,\pi^{+}$; $\Sigma^{+} \rightarrow n\,\pi^{-}$; . . .

$\Xi^{-} \rightarrow \Lambda\pi^{-}$; $\Xi^{\circ} \rightarrow \Lambda\pi^{\circ}$

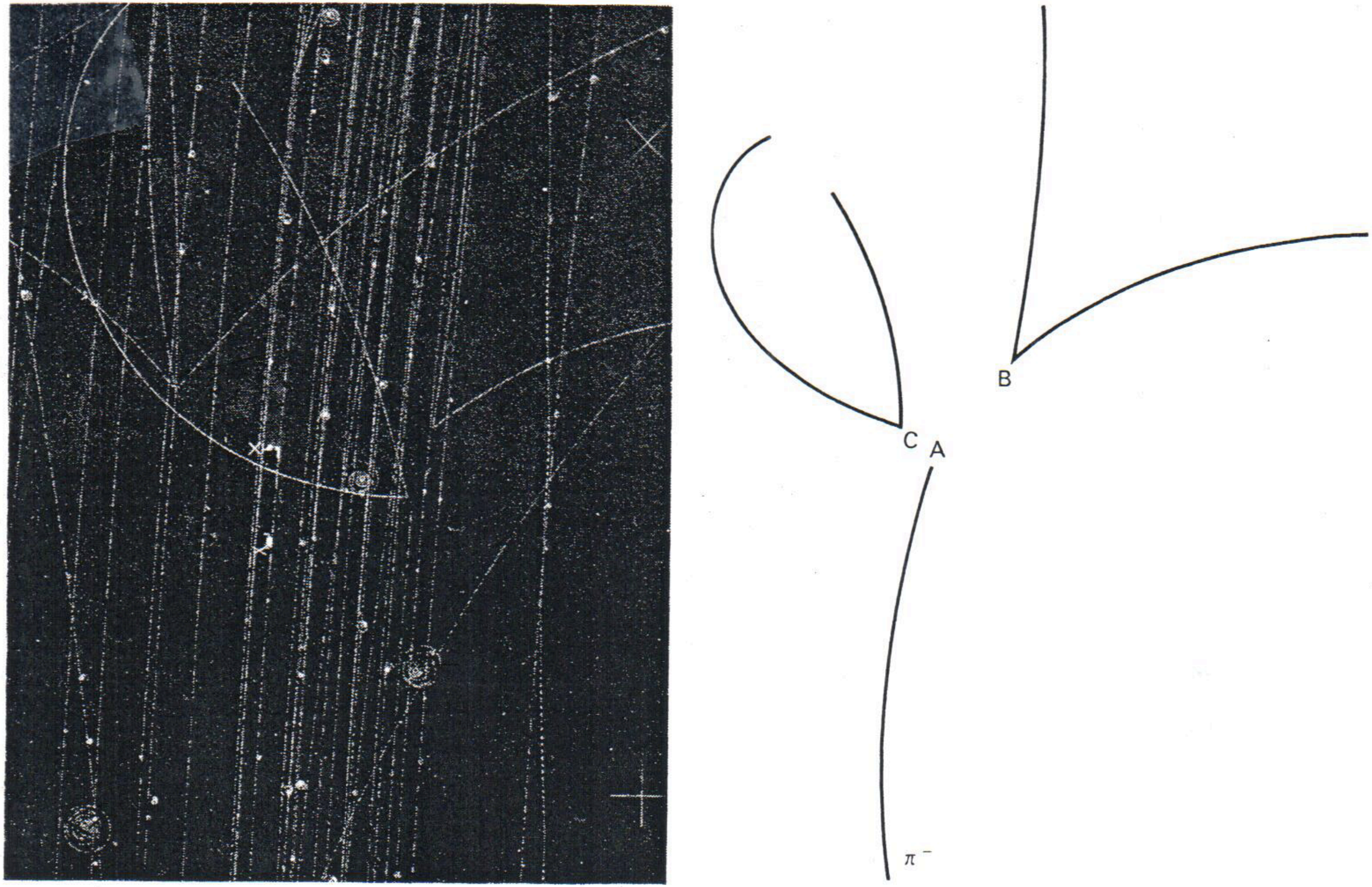


Figure 1.3 An example of associated production, due to the interaction at A of a 4-GeV/c negative pion in a hydrogen bubble chamber: $\pi^- + p \rightarrow \Lambda + K^0$. The Λ-hyperon decays at B according to $\Lambda \rightarrow p + \pi^-$, and the K^0-meson at C according to $K^0 \rightarrow \pi^+ + \pi^-$. (Courtesy CERN.)

Comment on frequency of production and lifetime

Recall relative strength of strong, electromagnetic and weak interactions. In e.g., proton-proton collisions there is an abundant production of mesons and both baryonic and mesonic resonances. The resonances decay at a time scale of 10^{-23} *s that we consider a typical time scale of strong interactions.*
The electromagnetic decays e.g., π^0 *decay to two photons has a typical lifetime of* $\sim 10^{-17}$ *s*
The characteristic lifetime of particles decaying due to weak interactions is $\sim 10^{-6} \div 10^{-8}$ *s. These are called "long-lived" particles.*
A particle may have e.g., both strong and weak decays. The corresponding decay branching fractions will be inversely proportional to the ratio of the relative strength of strong and weak interactions.