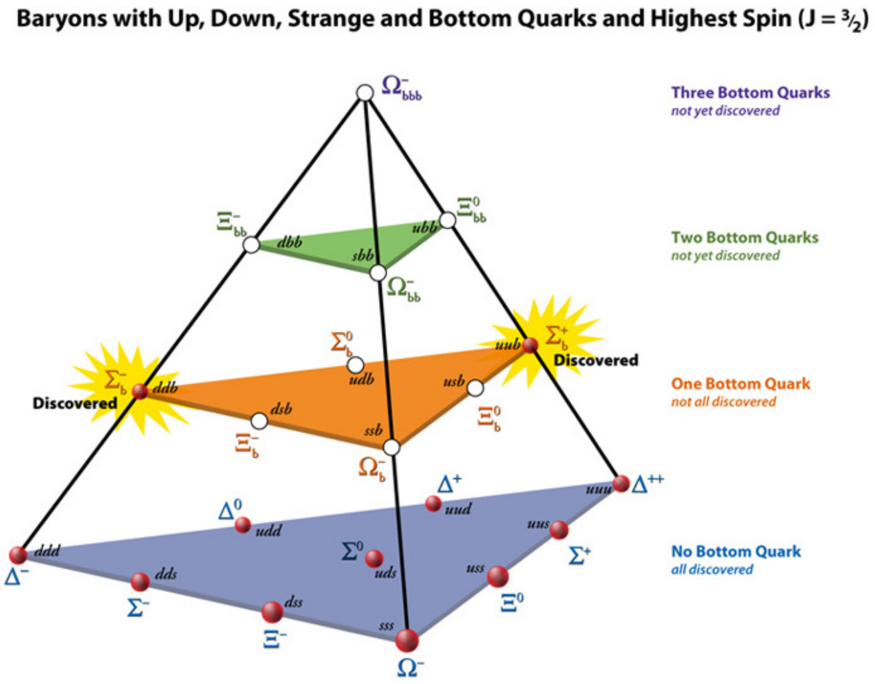
Particle Physics

Dr Victoria Martin, Prof Steve Playfer
Spring Semester 2013
Lecture 12: Mesons and Baryons


Baryons with Up, Down, Strange and Bottom Quarks and Highest Spin ($J = 3/2$)

- ★Mesons and baryons
- ★Strong isospin and strong hypercharge
- ★SU(3) flavour symmetry
- ★Heavy quark states

Review from Friday

- Using high energy deep inelastic scattering, $e^- p \rightarrow e^- X$, we find out the proton consists of partons:
  - three **valence quarks**: two up quarks, one down quark
  - **gluons** that are continuously exchanged between the quarks
  - **sea quarks:** quark-antiquark pairs produced by gluons
- In today's lecture consider the **valence quark** model of mesons and baryons

Mesons and Baryons

Mesons are quark-antiquark bound states with a **symmetric** colour wavefunction

$$\chi_c = \frac{1}{\sqrt{3}}\left[r\bar{r} + b\bar{b} + g\bar{g}\right]$$

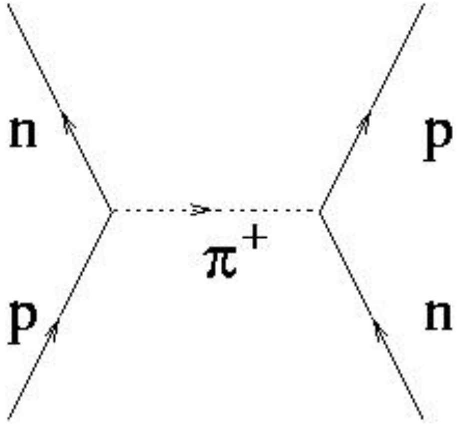
Baryons are three quark bound states with an **antisymmetric** colour wavefunction

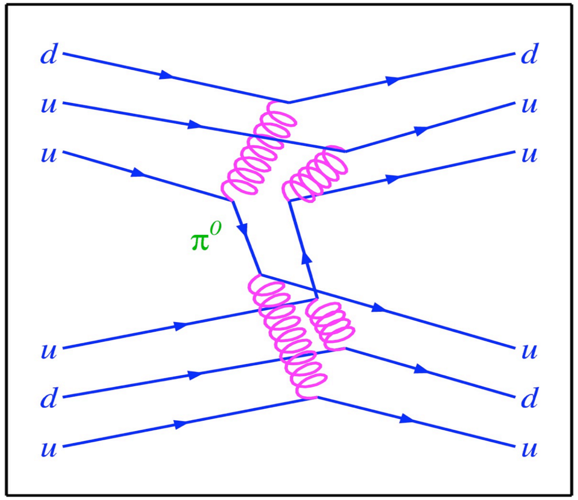
$$\chi_c = \frac{1}{\sqrt{6}}\left[rgb - rbg + gbr - grb + brg - bgr\right]$$

- All these **hadrons** are **colour neutral**
- They do not interact with each other by single gluon exchange
- They couple to each other by hadron exchange, typically through the pion (the lightest meson)
- Yukawa (1935) – the finite range of strong interactions between hadrons is due to the pion mass of **~140 MeV**

Nucleon-nucleon scattering:

a strong interaction as seen at the hadron and quark level





Constituent Quark Masses

- Because of QCD renormalisation, there is an ambiguity in how to define the quark masses. The most commonly used definition is known as the "$\overline{MS}$ scheme":

  m_u= 2.4 MeV, m_d = 4.8 MeV, m_s =104 MeV, m_c =1.27 GeV, m_b =4.20 GeV

- The light quark masses are too small to account for the hadron masses **$m(\pi^+)$ =140 MeV** is a u-dbar bound state!
- The majority of the mass of hadrons comes from QCD interactions

- The valence quark model introduces constituent quark masses

  $m_u = m_d \sim 300$ MeV, $m_s \sim 500$ MeV, $m_c \sim 1.5$ GeV, $m_b \sim 4.7$ GeV

- These are an effective model for the observed hadron masses and magnetic moments (but still don't work for the pion!)

Flavour Symmetries: Isospin

- Strong interactions are (approximately) invariant under flavour symmetry rotations.
  Known for hadrons long before quark model was invented (n-n, n-p, p-p the same).

- Assign quantum numbers to characterise these symmetries.
  ➡Strong Isospin (I, I_3): a flavour symmetry between u and d quarks
  $I = 1/2$ doublet with $I_3(\mathbf{u}) = +1/2$ and $I_3(\mathbf{d}) = -1/2$
  (by analogy to S=1/2 with spin states ↑ and ↓)

- Strong interactions are invariant under isospin rotations $\mathbf{u} \leftrightarrow \mathbf{d}$ **or** $p \leftrightarrow n$

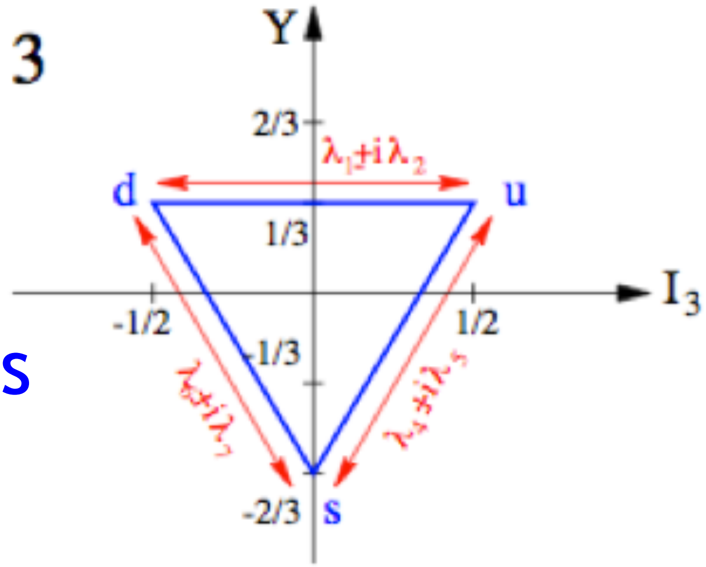
- For heavy quarks introduce quantum numbers for each flavour:
  ➡Strangeness (S), Charm (C), Beauty (B), Truth (T)
  S(s) = -1, S(sbar) = +1, B(b) = -1 , B(bbar) = +1
  C(c) = +1, C(cbar) = -1, T(t) = +1 , T(tbar) = -1

- Strong interactions are (almost) flavour independent, and conserve quark flavour

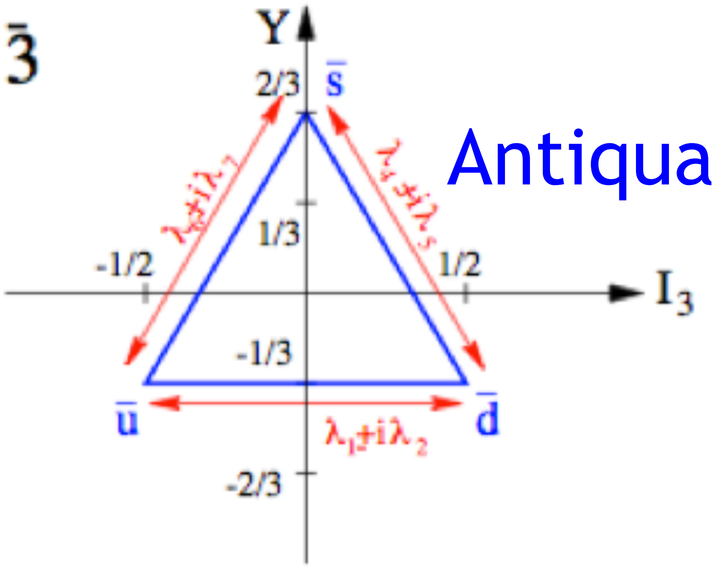
SU(3) Flavour Symmetry

- An SU(3) flavour symmetry is exhibited between **u, d** and **s** quarks
- The symmetry is broken by the **s** quark mass $m_s \sim 100\ \mathrm{MeV} \gg m_u, m_d$

- Classify hadrons in SU(3) multiplets using convenient quantum numbers:
  - Strong Hypercharge $Y = S + \mathcal{B}$ (where $\mathcal{B} = \frac{1}{3}[N(q) - N(\bar{q})]$ is baryon number)
  - Strong Isospin I_3 (note that electric charge $Q = I_3 + Y/2$)



Quarks



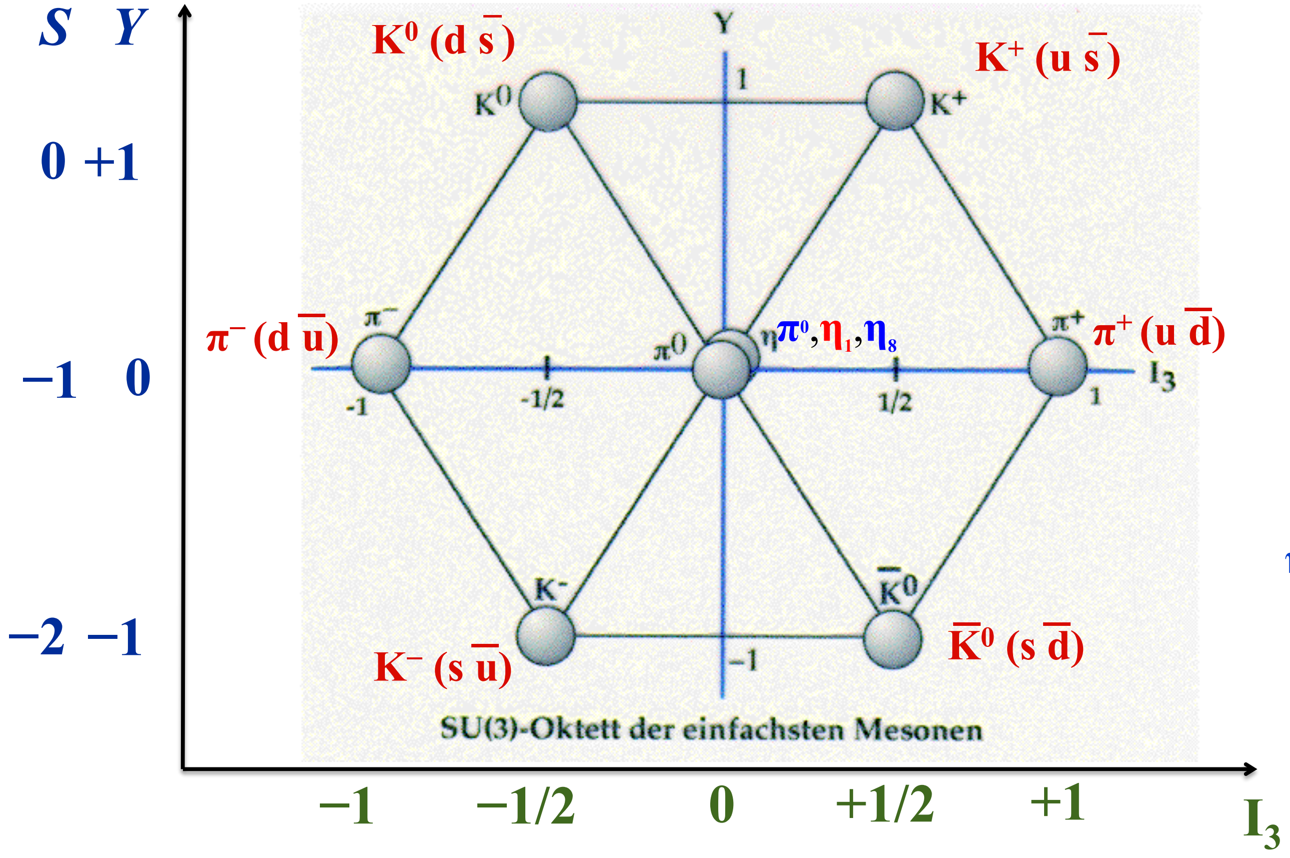
Antiquarks

These are the basic building blocks for constructing mesons ($q\bar{q}$) and baryons (qqq)

The *J*=0 Pseudoscalar Mesons

- Total angular momentum, ***J*=0**: orbital angular momentum, ***L=0;*** one spin-up and one spin-down ↑ ↓ quark
- The allowed flavour combinations are given by the Gell Mann λ matrices,

  ➡same matrices that describe the allowed colour combinations of gluons.



SU(3)-Oktett der einfachsten Mesonen

M(K^0, $\bar{K}^0$) = 498 MeV

M(K^+,K^-) = 494 MeV

M(π^+,π^-) = 140 MeV

M(π^0)=135 MeV

M(η)=550 MeV

M(η’)=960 MeV

$$\pi^0 = 1/\sqrt{2}\ [\, d\,\bar{d} - u\,\bar{u}\,]$$

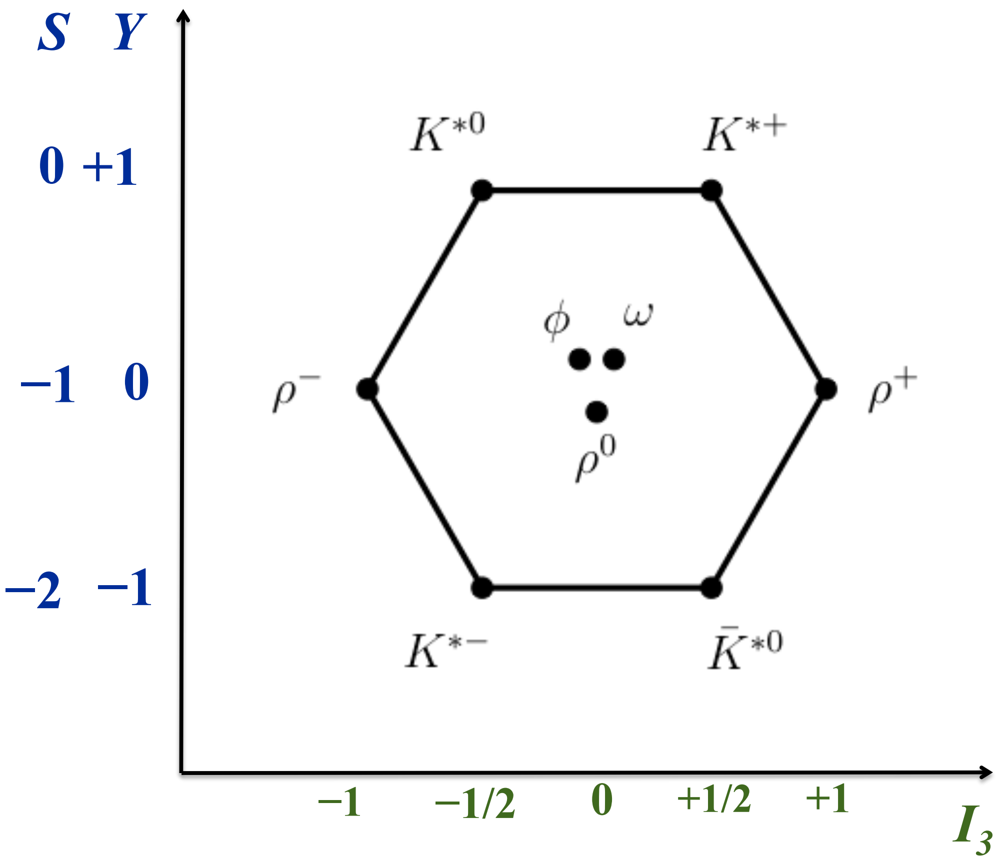
$$\eta_8 = 1/\sqrt{6}\ [\, d\,\bar{d} + u\,\bar{u} - 2\, s\,\bar{s}\,]$$

$$\eta_1 = 1/\sqrt{3}\ [\, d\,\bar{d} + u\,\bar{u} + s\,\bar{s}\,]$$

Observed **η,η’** mesons are mixtures of η_1 and η_8

The *J=1* Vector Mesons

- Total angular momentum, ***J=1***: ***L=0***, both quarks with same spin ↑ ↑



$M(K^{*+},K^{*-}) = 892$ MeV

$M(K^{*0}, K^{*0}) = 896$ MeV

$M(\rho^+,\rho^-) = 776$ MeV

$M(\rho^0)=767$ MeV

$M(\omega)=783$ MeV

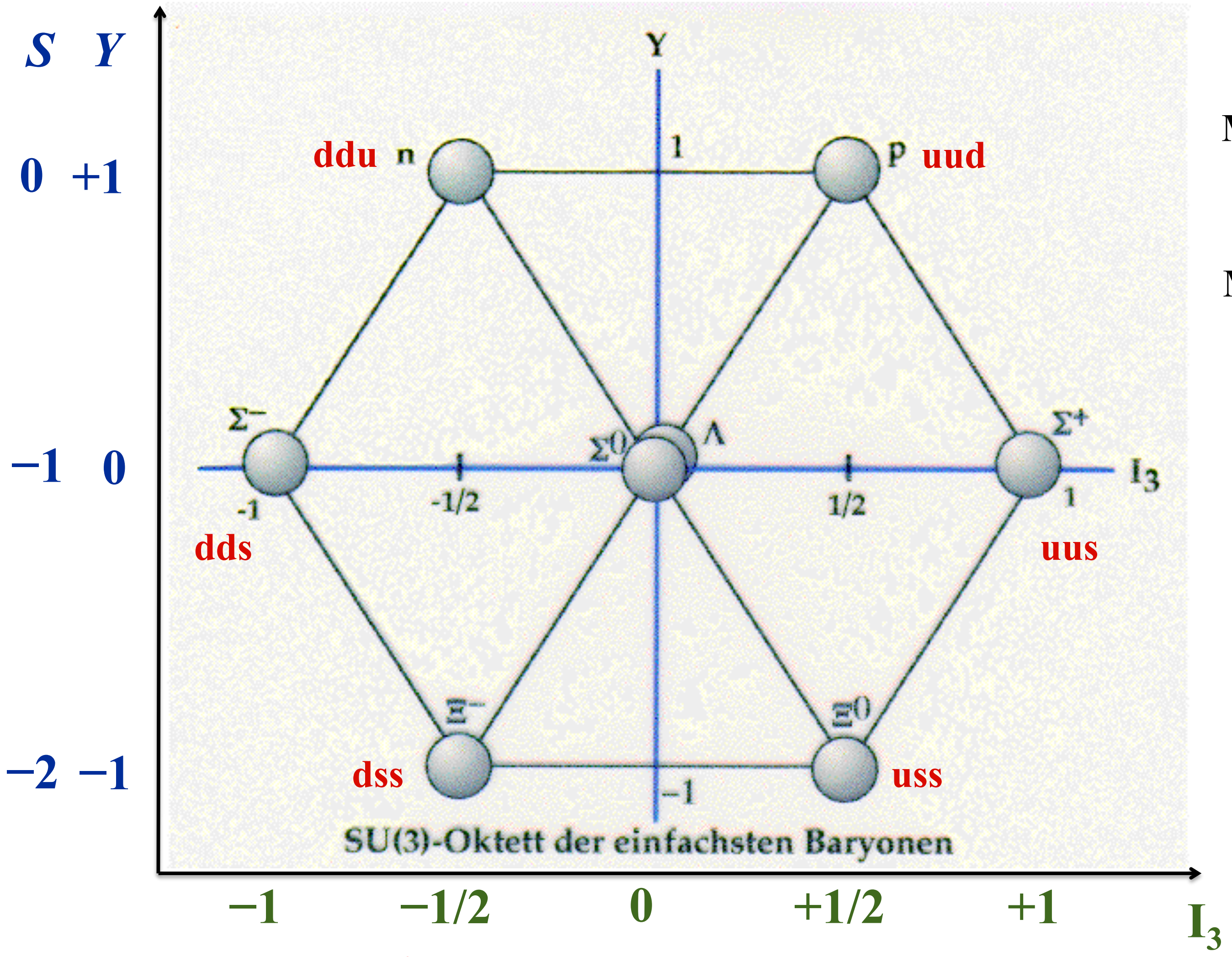
$M(\phi)=1019$ MeV

$\omega = 1/\sqrt{2}\ [\, d\,\bar{d} + u\,\bar{u}\,]$ $\qquad \phi = s\,\bar{s}$

$\rho^0 = 1/\sqrt{2}\ [\, d\,\bar{d} - u\,\bar{u}\,]$

The $J=1/2$ Baryon Octet

- $L=0$, Quark spin composition is ↑↑↓



M(n) = 940 MeV

M(p) = 938 MeV

M(Λ) = 1116 MeV

M(Σ) = 1193 MeV

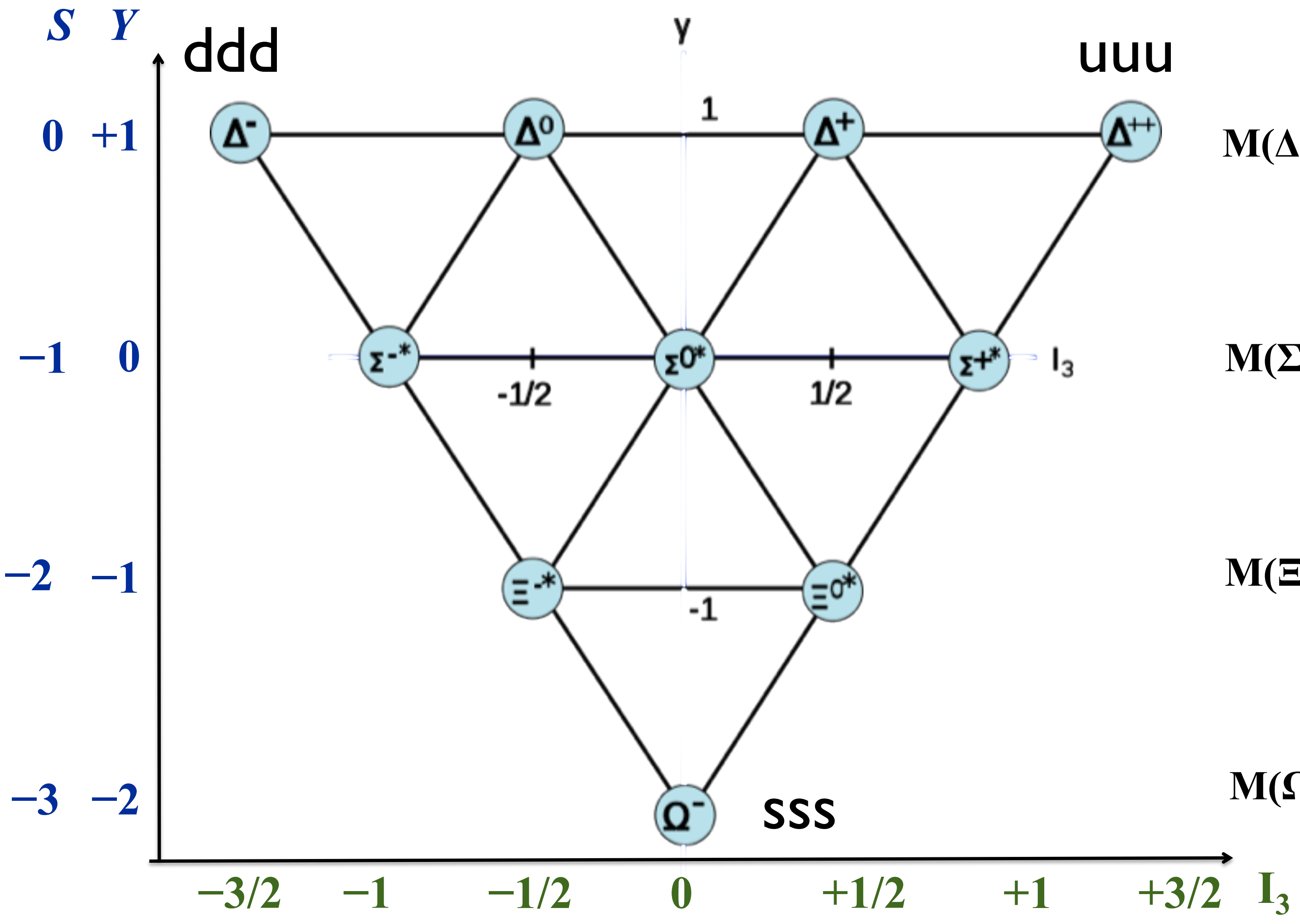
M(Ξ) = 1318 MeV

Λ^0 = [uds] isospin singlet state $I=0$

Σ^0 = [uds] isospin triplet state $I=1$

The $J=3/2$ Baryon Decuplet

- Total angular momentum $J=3/2$: all spins aligned ↑↑↑, $L=0$



M(Δ) = 1232 MeV

M(Σ*)=1383 MeV

M(Ξ*)=1532 MeV

M(Ω)=1672 MeV

Δ^{++} and Baryon Wavefunctions

- The overall wavefunction of a system of identical fermions must be antisymmetric under exchange of any two fermions

$$\psi\,(\Delta^{++}) = u_{\uparrow}u_{\uparrow}u_{\uparrow} = \chi_c\,\chi_f\,\chi_S\,\chi_L$$

➡ The Δ^{++} wavefunction is symmetric in flavour χ_f and spin χ_S ($J=3/2$)

➡ There is no orbital angular momentum $L=0$, spatially symmetric χ_L

➡ Hence it must have an antisymmetric colour wavefunction χ_c

- Why are there no $J=1/2$ **uuu, ddd, sss** baryons?

Baryon	Colour	Flavour	Spin	Spatial	Total
Δ^{++}	A	S	S	S	A
p	A	A or S	A or S	S	A

- Full proton wave function is:

$$\psi(p) = \frac{1}{\sqrt{18}}[u_{\downarrow}u_{\uparrow}d_{\uparrow} + u_{\uparrow}u_{\downarrow}d_{\uparrow} - 2\,u_{\uparrow}u_{\uparrow}d_{\downarrow} + u_{\downarrow}d_{\uparrow}u_{\uparrow} + u_{\uparrow}d_{\downarrow}u_{\uparrow} - 2\,u_{\uparrow}d_{\uparrow}u_{\downarrow} + d_{\downarrow}u_{\uparrow}u_{\uparrow} + d_{\uparrow}u_{\downarrow}u_{\uparrow} - 2\,d_{\uparrow}u_{\uparrow}u_{\downarrow}]$$

Heavy Quark Mesons and Baryons

- Heavy mesons and baryons are obtained by replacing one (or more) of the light **u,d,s** quarks by a heavy **c** or **b** quark
- There are no bound state hadrons containing **t** quarks

Lowest lying charm meson states with **M(D) ~ 1.9 GeV:**

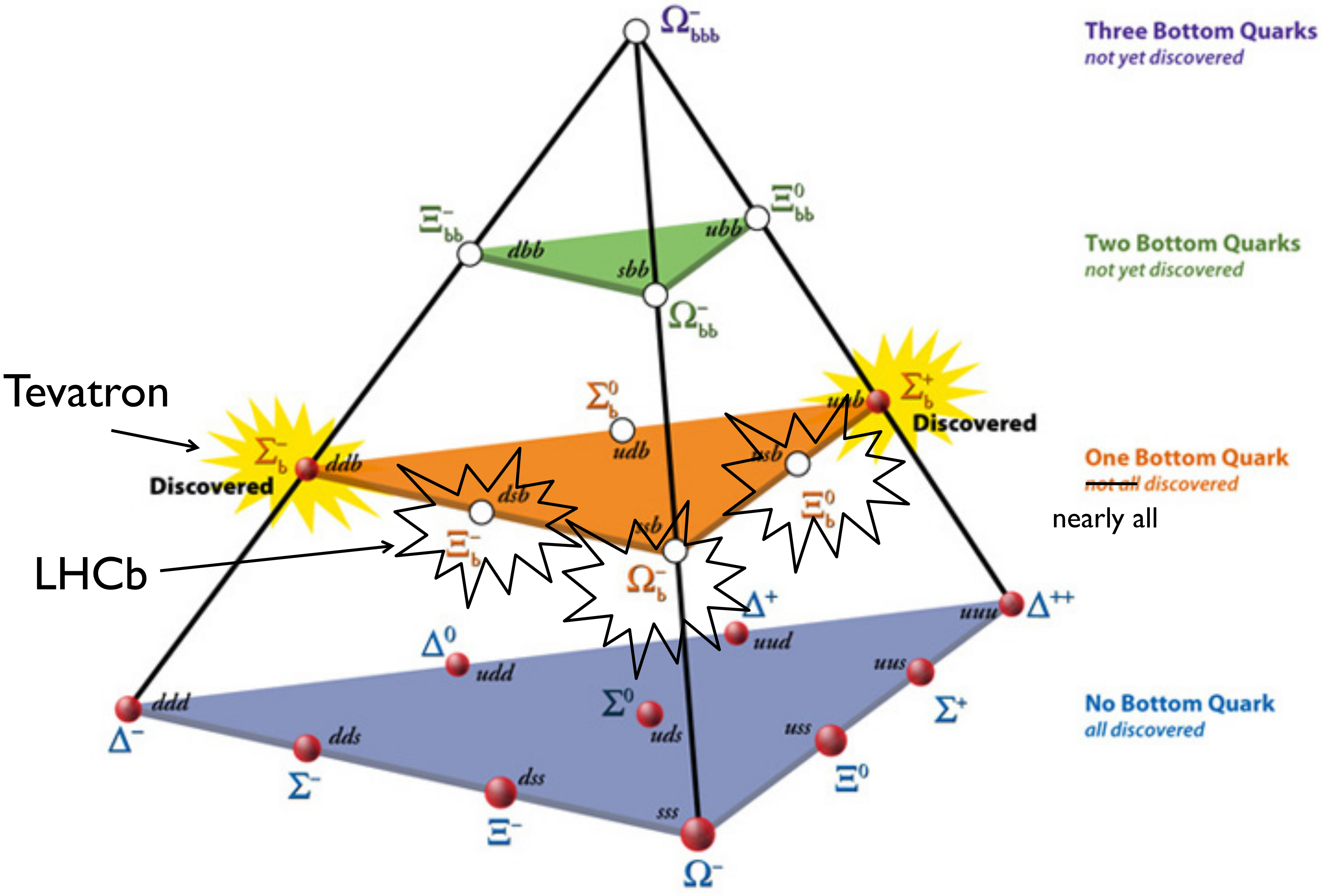
$\mathbf{D^+ (c\,\bar{d}),\ D^- (\bar{c}\,d),\ D^0 (c\,\bar{u}),\ \bar{D}^0 (\bar{c}\,u),\ D_s^+ (c\,s),\ D_s^- (c\,\bar{s})}$

Lowest lying bottom meson states with **M(B) ~ 5.3 GeV**

$\mathbf{B^0 (\bar{b}\,d),\ \bar{B}^0 (b\,\bar{d}),\ B^- (b\,\bar{u}),\ B^+ (\bar{b}\,u),\ \bar{B}_S^0 (\bar{b}\,s),\ B_s^0 (b\,\bar{s})}$

- Heavy baryons Λ_c **(cud)** , Λ_b **(bud)** …
- Charmonium $\Psi(c\,\bar{c})$ and Bottomonium $\Upsilon(b\,\bar{b})$

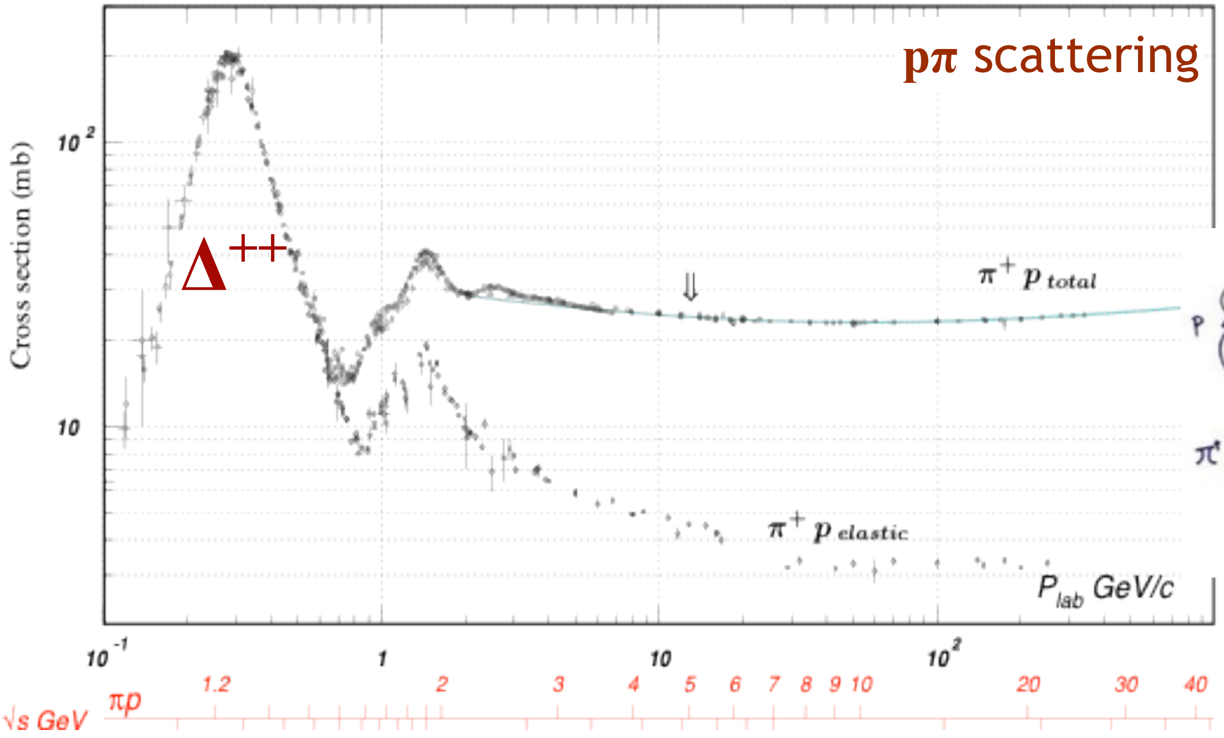
Baryons with Up, Down, Strange and Bottom Quarks and Highest Spin (J = ³⁄₂)



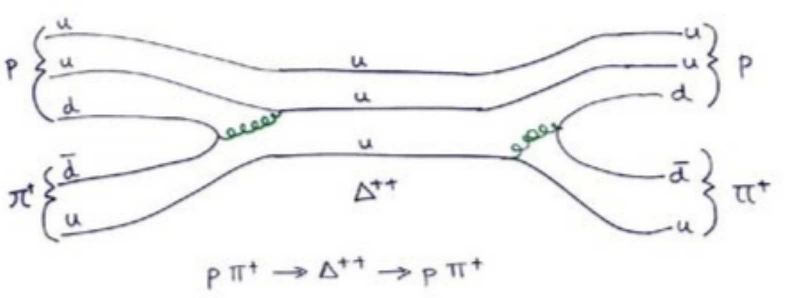
Resonances

- Most hadrons decay due to the strong force, and have very short lifetime $\tau \sim 10^{-24}$ s
- Evidence for the existence of these states are **resonances** in cross-sections
- Shape is Breit-Wigner distribution with width Γ from Fermi's Golden rule, $\Gamma \sim |\mathcal{M}|^2 \rho$

$$\sigma = \sigma_{\max} \frac{\Gamma^2/4}{(E-M)^2 + \Gamma^2/4}$$

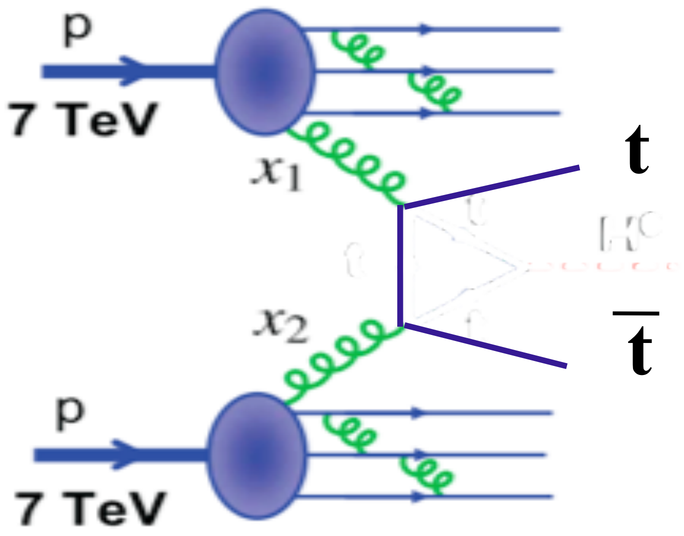


M(Δ^{++}) = 1230 MeV
Γ(Δ^{++}) = 120 MeV



Discovery of the Heavy Quarks

- Collider experiments discovered the charm (1974), bottom (1977) and top quarks (1995)
- $e^+e^-\rightarrow \mathbf{c\bar{c}}$ and $e^+e^-\rightarrow \mathbf{b\bar{b}}$ give narrow charmonium and bottomonium resonances near threshold (electromagnetic interaction)
- At higher energies produced in pairs at hadron colliders through gluons (strong interaction)

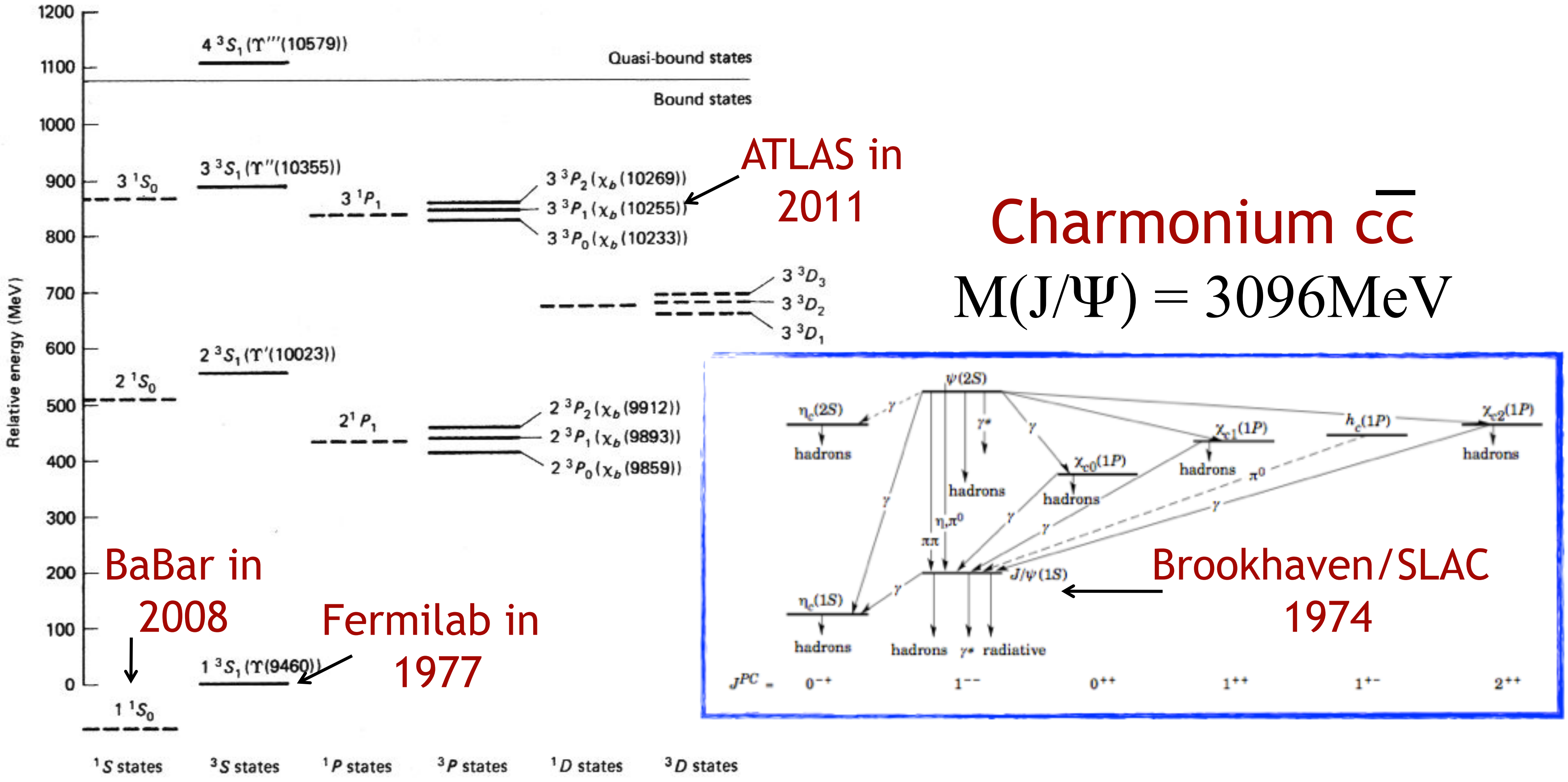


Can identify heavy quark jets by tagging decays of **c** and **b** quarks with lifetimes $\tau_c \sim 0.4\text{ps}, \tau_b \sim 1.5\text{ps}$

- Single heavy quark production needs a W boson (weak interaction)

Heavy Quark bound states

Bottomonium $b\bar{b}$ $M(\Upsilon(1S)) = 9460\text{MeV}$



ATLAS in 2011

BaBar in 2008

Fermilab in 1977

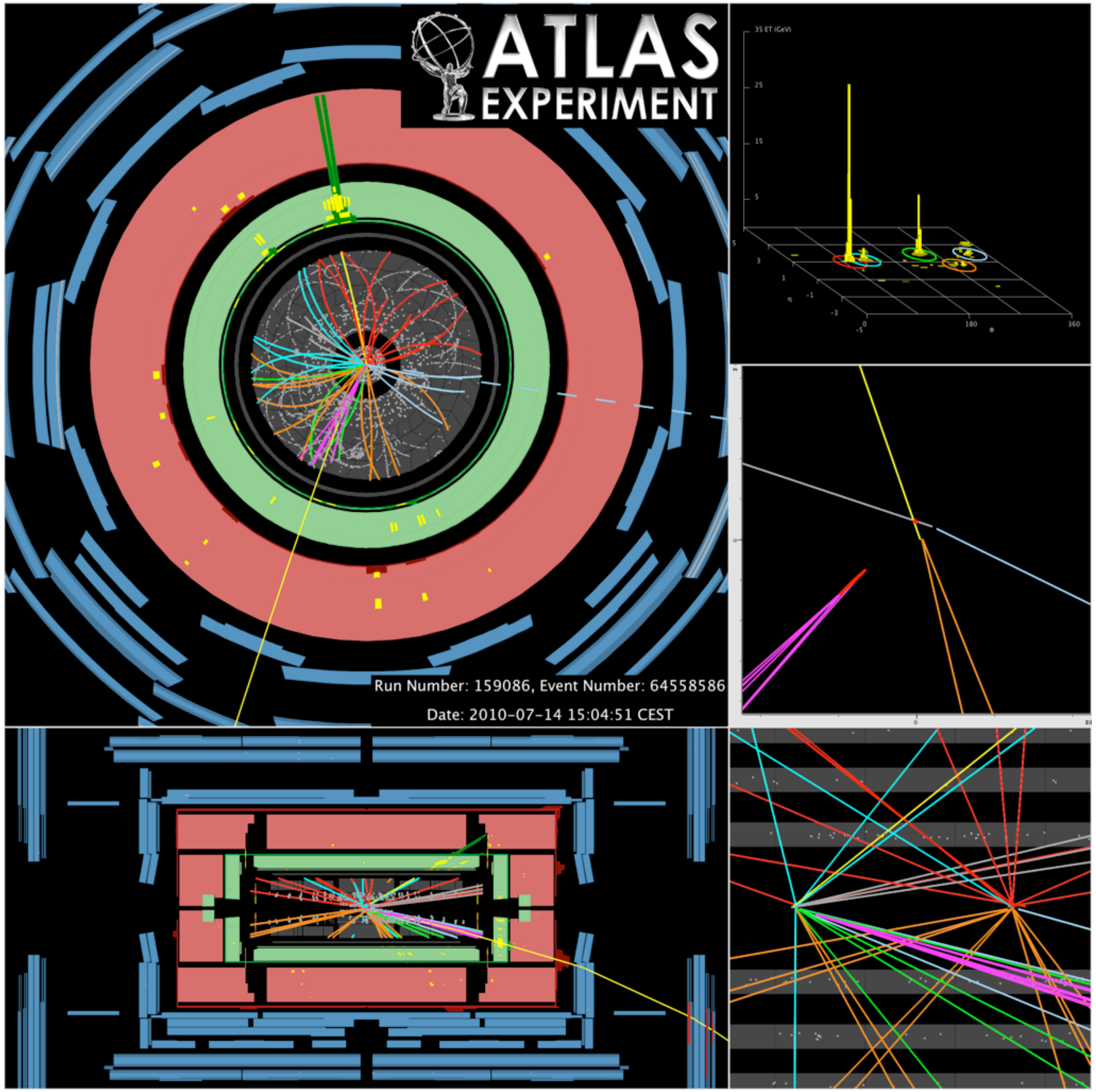
Charmonium $c\bar{c}$

$M(J/\Psi) = 3096\text{MeV}$

Brookhaven/SLAC 1974

- Analogous to hydrogen spectroscopy with quark-quark potential $V_{q\bar{q}}(r) = -4/3\,\alpha_S/r + kr$ (see lecture 9)

$t\bar{t} \rightarrow W^+ b\, W^- \bar{b}$ candidate event



- Lines are project paths of charged particles through the detector.
- Not all particles originate from collision point.
- Particle produced and travelled short distance before decaying, indicates production of a b-quark!

Summary

- Quarks are confined in **colourless** bound states, collectively known as **hadrons**:
  - ➡ **mesons:** quark and anti-quark. Bosons ($J=0, 1$) with symmetric colour wavefunction.
  - ➡ **baryons**: three quarks. Fermions ($J=1/2, 3/2$) with antisymmetric colour wavefunction.
- The strong force between colourless hadrons is propagated by mesons.
- The lightest mesons & baryons are characterised by strong isospin (I, I_3), strangeness (S) and strong hypercharge Y
  - ➡ strong isospin $I = ½$ for $\mathbf{u}$ and $\mathbf{d}$ quarks with $I_3 = +½$ and $I_3 = -½$
  - ➡ $S = -1$ for strange quarks (and similarly for heavy flavours C,B,T)
  - ➡ strong hypercharge $Y = S + B$ *(Baryon Number)*
  - ➡ charge $Q = I_3 + Y/2$
- Hadrons display SU(3) flavour symmetry between $\mathbf{u}$ $\mathbf{d}$ and $\mathbf{s}$ quarks. The symmetry predicts the allowed meson and baryon states.
- Strong decays of most hadrons cause **resonances** due to very short lifetimes.
- Heavy b and c quarks also form bound states with each other and with the light quarks.
- The t quark does not form bound states, but has been observed at hadron colliders.