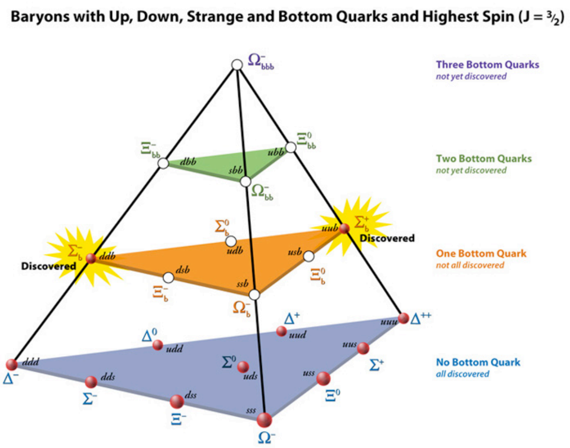
Particle Physics

Dr Victoria Martin, Spring Semester 2012

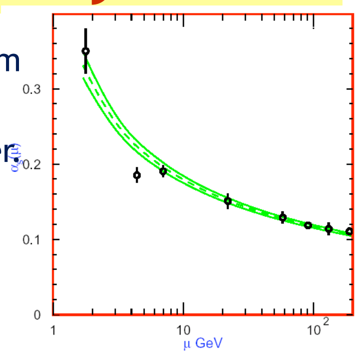
Lecture 11: Mesons and Baryons



- ★Measuring Jets
- ★Fragmentation
- ★Mesons and Baryons
- ★Isospin and hypercharge
- ★SU(3) flavour symmetry
- ★Heavy Quark states

From Tuesday: Summary

- In QCD, the coupling strength α_S decreases at high momentum transfer (q^2) increases at low momentum transfer.
- Perturbation theory is only useful at high momentum transfer.
- Non-perturbative techniques required at low momentum transfer.

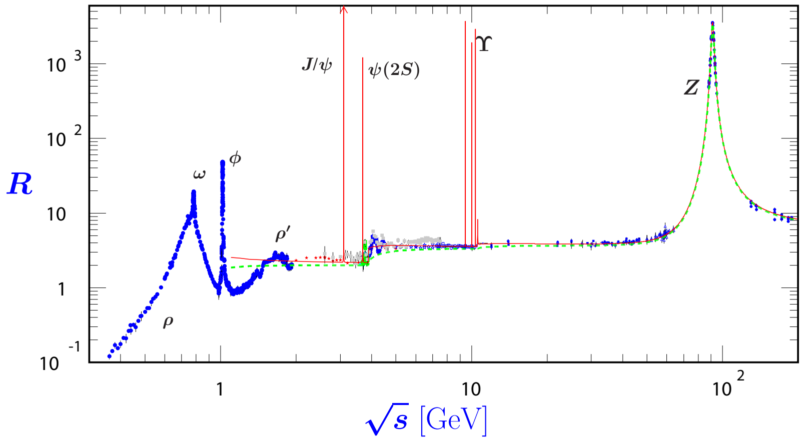


- At colliders, hard scatter produces quark, anti-quarks and gluons.
- Fragmentation (hadronisation) describes how partons produced in hard scatter become final state hadrons. Need non-perturbative techniques.
- Final state hadrons observed in experiments as jets. Measure jet p_T, η, ϕ
- Key measurement at lepton collider, evidence for N_C=3 colours of quarks.

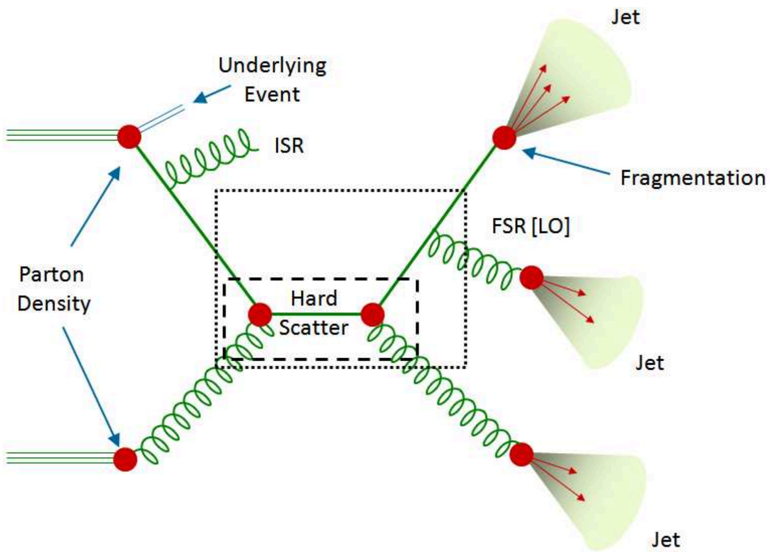
$$\mathbf{R} = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_c \frac{e_q^2}{e^2}$$

- Next lecture: mesons and baryons! Griffiths chapter 5.

R



QCD production at Hadron Colliders



- Much more complicated due initial state hadrons not being fundamental particles
- Every object is colour charged: all object can interact with each other.
- QCD is very strong
- Not able to use perturbation theory to describe the interactions with low four momentum transfer q.

Hadron Collider Dictionary

- The **hard scatter** is an initial scattering at high q^2 between partons (gluons, quarks, antiquarks).
- The **underlying event** is the interactions of what is left of the protons after parton scattering.
- **Initial and final state radiation** (ISR and FSR) are high energy gluon emissions from the scattering partons.
- **Fragmentation** is the process of producing final state particles from the parton produced in the hard scatter.
- A hadronic **jet** is a collimated cone of particles associated with a final state parton, produced through fragmentation.
- Transverse quantities are measured transverse to the beam direction.
- An event with high **transverse momentum** (p_T) jets or isolated leptons, is a signature for the production of high mass particles (W,Z,H,t).
- An event with **missing transverse energy** ($\not{E}_T$) is a signature for neutrinos, or other missing neutral particles.
- A **minimum bias** event has no missing energy, and no high mass final states particles (W,Z,H,b,t). At the LHC these are treated as background.

Measuring Jets

- A jet has a four-momentum $E = \sum_i E_i \quad \vec{p} = \sum_i \vec{p}_i$
  - ➡ Where the constituents (i) are hadrons detected as charged tracks and neutral energy deposits.

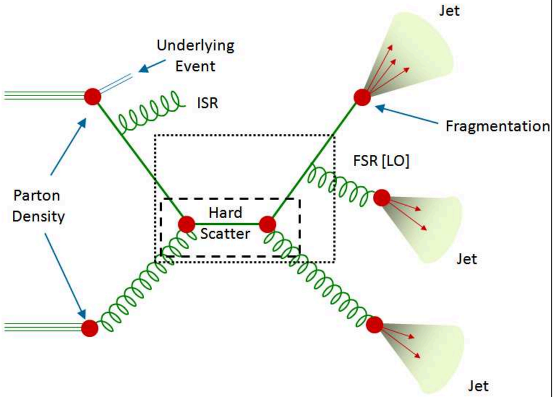
- Transverse momentum of jet:
$$p_T^{\mathrm{JET}} = \sqrt{p_x^2 + p_y^2}$$
- Position in the detector in two coordinates:
  - ➡ ***Pseudorapidity*** of jet (η) $\quad \eta^{\mathrm{JET}} = -\ln\left(\tan\frac{\theta}{2}\right)$

    with polar angle, θ $\quad \cos\theta = \frac{\sqrt{p_x^2+p_y^2}}{p_z}$
  - ➡ **Azimuthal angle** of jet (ϕ) $\quad \phi^{\mathrm{JET}} = \tan^{-1}\left(\frac{p_y}{p_x}\right)$

- To assign individual constituents to the jet, simplest algorithm is to define a **cone** around a central value: η^{JET}, ϕ^{JET}.
$$R^2 = (\eta_i - \eta^{\mathrm{JET}})^2 + (\phi_i - \phi^{\mathrm{JET}})^2$$
- All objects with R less than a given value (typically 0.4 or 0.7) are assigned to the jet
- Many sophisticated jet clustering algorithms exist which take into account QCD effects.

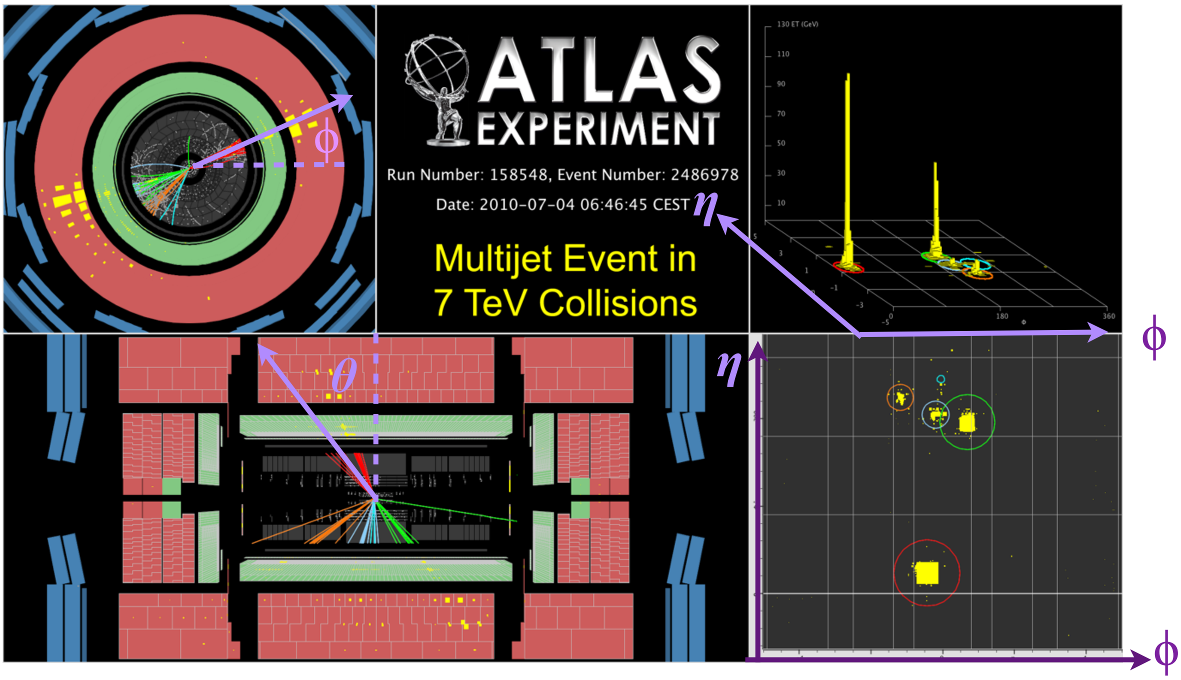
Jet Fragmentation

- **Fragmentation** or **hadronisation** is the process of producing final state particles from the parton produced in the hard scatter.
- Gluon momentum transfer, q, varies
  - ➡ both perturbative and non-perturbative methods are needed to describe/model fragmentation



- Initial parton radiates gluon, which can form quark anti-quark pairs, modeled using perturbative QCD
- Hadrons are formed using non-perturbative models of colour confinement. Several stochastic models exist, with many parameters:
  - PYTHIA, HERWIG, SHERPA
- The jet fragmentation algorithms are tuned to match data

ATLAS Multijet Event



- η and ϕ act as map of activity in the detector

Mesons and Baryons

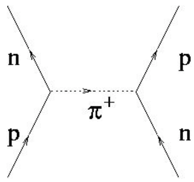
- Mesons are quark-antiquark bound states with symmetric colour wavefunction which is colour neutral:

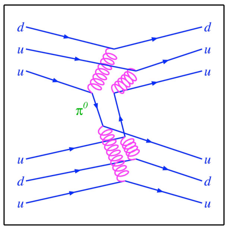
$$\chi_c = \frac{1}{\sqrt{3}}\left[r\bar{r} + b\bar{b} + g\bar{g}\right]$$

- Baryons are three quark bound states. They have an antisymmetric colour wavefunction which is colour neutral:

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

- As hadrons are colour neutral, they do not interact with each other by single gluon exchange.
- Instead they couple to each other by hadron exchange, typically through the lightest $q\bar{q}$ meson, pion (π^+, π^0, π^-)





- Yukawa (1935) - the finite range of strong interactions between hadrons is due to the pion mass of ~**140 MeV**

Constituent Quark Masses

- Because of QCD renormalisation, there is an ambiguity as how to define an absolute mass, most commonly used is the $\overline{\text{MS}}$ scheme.
  ➡ $m_u = 2.4$ **MeV**, $m_d = 4.8$ **MeV**, $m_s = 104$ **MeV**

- These are too small to account for the hadron masses!

- The majority of the mass of hadrons comes from QCD interactions.

Flavour Symmetries: Isospin

- Flavour symmetries are symmetries between interchange of quark flavour.
- Flavour symmetries were proposed before quarks were hypothesised to explain observed phenomena.
- Strong interactions are (approximately) invariant under flavour symmetry rotations.

- Assign quantum numbers to characterise these symmetries.
  - ➡ Isospin (I, I_3);
  - ➡ Strangeness (S);
  - ➡ hypercharge (Y)

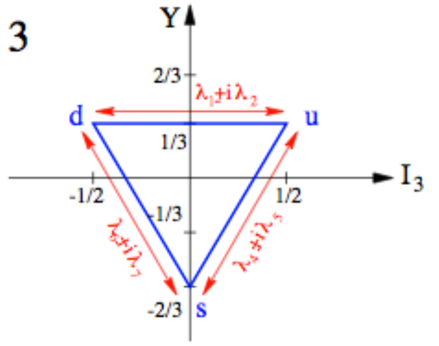
- **Isospin** symmetry between **u** and **d** quarks
- Strong interactions are invariant under isospin rotation $\mathbf{u} \leftrightarrow \mathbf{d}$, or equivalently, $p \leftrightarrow n$
- Observed as **u** and **d** have same strong interactions and similar mass
- The **u** and **d** quarks form an ***isospin doublet***:
  - Use quantum number total isospin (I) and third-component of isospin (I_3)

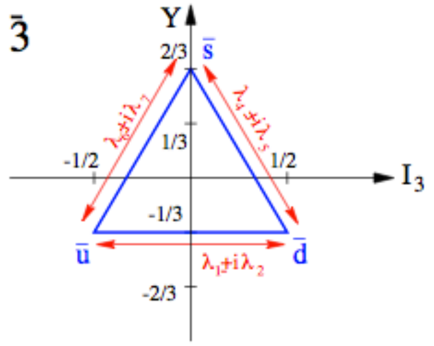
    $I = 1/2$ with $I_3(\mathrm{u}) = +1/2$ and $I_3(\mathrm{u}) = -1/2$

    (by analogy to S=1/2 with spin states ↑ and ↓)

SU(3) Flavour Symmetry

- SU(3) flavour symmetry between **u, d** and **s** quarks
  - Symmetry is broken by the **s** quark mass $\mathrm{m_s} \sim 100$ MeV
- Strong interactions are almost invariant under SU(3) flavour symmetry
- The **s** quark is assigned a strangeness **S=−1** ($\overline{\mathrm{s}}$ has **S=+1**)
- Two useful combinations:
  - hypercharge $Y = S + B$ (where $B = ⅓\ [N(\mathrm{q}) - N(\overline{\mathrm{q}})]$ is baryon number)
  - Electric charge: $Q = I_3 + Y/2$



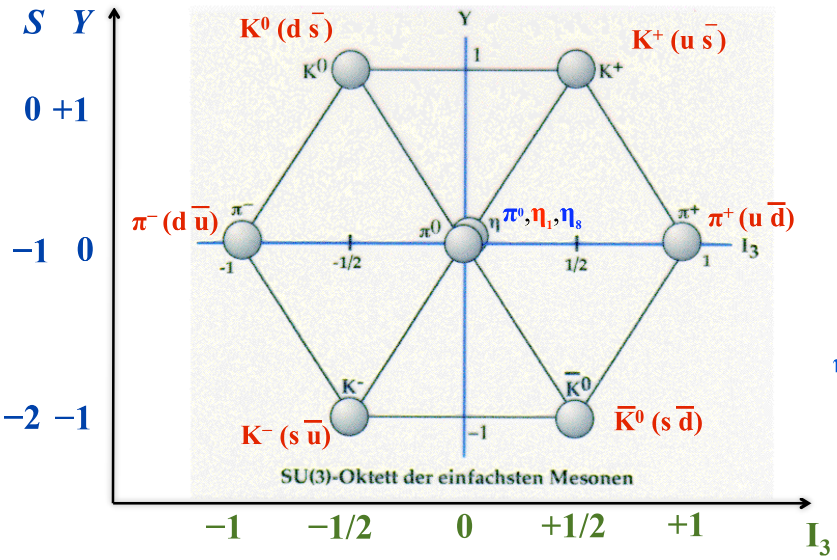


These are the basic building blocks for constructing meson ($\mathrm{q}\,\overline{\mathrm{q}}$) and baryon (qqq) multiplets

- Mainly states with no orbital angular momentum (L) between the quarks.

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 SU(3) λ matrices,
  - ➡ same matrices that describe the allowed colour combinations of gluons.



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

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

$M(\pi^+, \pi^-) = 140$ MeV

$M(\pi^0) = 135$ MeV

$M(\eta) = 550$ MeV

$M(\eta') = 960$ MeV

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

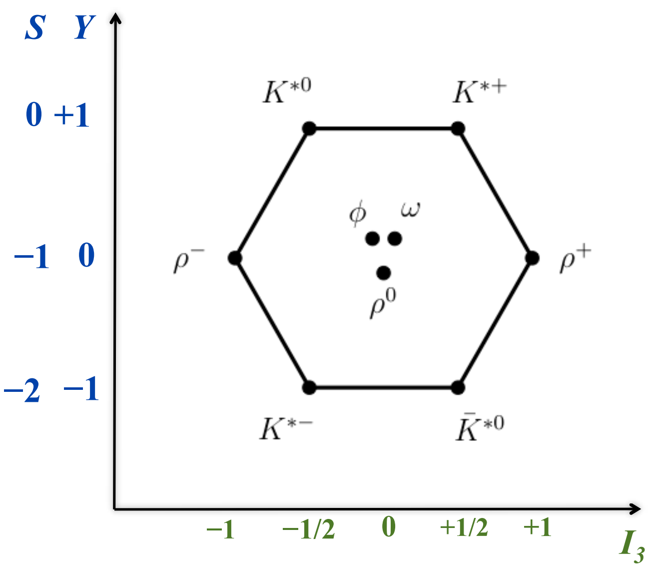
$\eta_8 = 1/\sqrt{6}\ [\, d\bar{d} + u\bar{u} - 2\, s\bar{s}\,]$

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

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

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

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

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

$M(\omega) = 783$ MeV

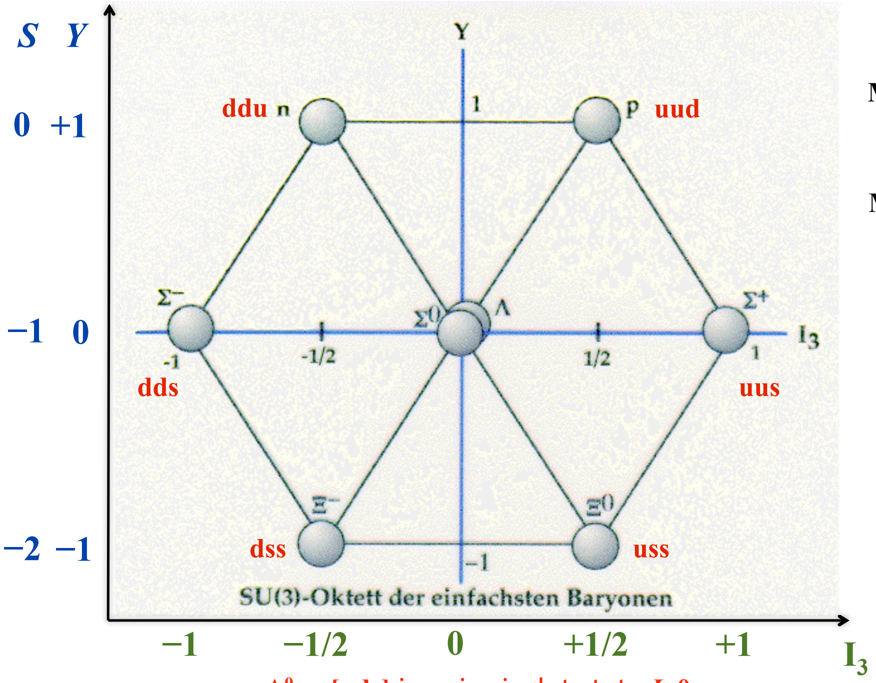
$M(\phi) = 1019$ MeV

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

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

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

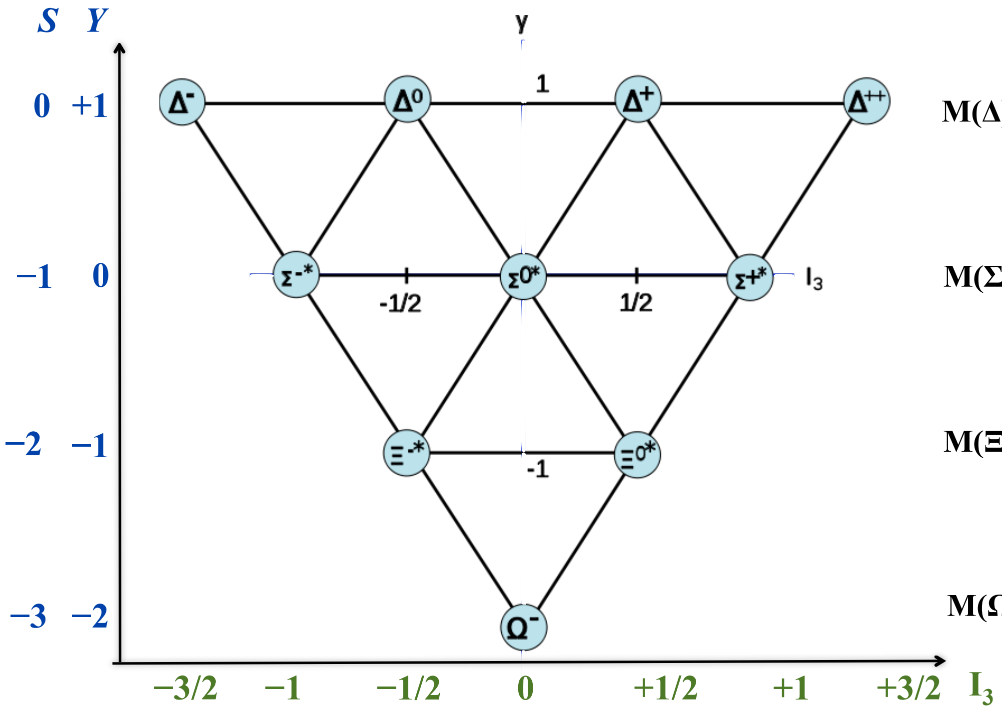
M(Ξ) = 1318 MeV

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

- Further evidence for quark colour

- 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:

$$\psi(p) = \frac{1}{\sqrt{18}}[\mathrm{u}_\downarrow \mathrm{u}_\uparrow \mathrm{d}_\uparrow + \mathrm{u}_\uparrow \mathrm{u}_\downarrow \mathrm{d}_\uparrow - 2\,\mathrm{u}_\uparrow \mathrm{u}_\uparrow \mathrm{d}_\downarrow + \mathrm{u}_\downarrow \mathrm{d}_\uparrow \mathrm{u}_\uparrow + \mathrm{u}_\uparrow \mathrm{d}_\downarrow \mathrm{u}_\uparrow - 2\,\mathrm{u}_\uparrow \mathrm{d}_\uparrow \mathrm{u}_\downarrow + \mathrm{d}_\downarrow \mathrm{u}_\uparrow \mathrm{u}_\uparrow + \mathrm{d}_\uparrow \mathrm{u}_\downarrow \mathrm{u}_\uparrow - 2\,\mathrm{d}_\uparrow \mathrm{u}_\uparrow \mathrm{u}_\downarrow]$$

Summary

- Quarks are confined to **colourless** bound states, collectively known as **hadrons**:
  - ➡ **mesons:** quark and anti-quark. Bosons (s=0, 1) with a symmetric colour wavefunction.
  - ➡ **baryons**: three quarks. Fermions (s=1/2, 3/2) with antisymmetric colour wavefunction.
  - ➡ **anti-baryons**: three anti-quarks.
- Lightest mesons & baryons described by isospin (I, I_3), strangeness (S) and hypercharge Y
  - ➡ isospin I=½ for **u** and **d** quarks; (isospin combined as for spin)
  - ➡ I_3=+½ (isospin up) for up quarks; I_3=–½ (isospin down) for down quarks
  - ➡ S=+1 for strange quarks (additive quantum number)
  - ➡ hypercharge $Y = S + B$
- Hadrons display SU(3) flavour symmetry between **u d** and **s** quarks. Used to predict the allowed meson and baryon states.
- As baryons are fermions, the overall wavefunction must be **anti-symmetric.** The wavefunction is product of colour, flavour, spin and spatial parts: $\psi = \chi_c\, \chi_f\, \chi_S\, \chi_L$ an odd number of these must be anti-symmetric.
  - consequences: no **uuu**, **ddd** or **sss** baryons with total spin J=½ (S=½, L=0)
- Residual strong force interactions between colourless hadrons propagated by mesons.