# Baryon Resonances and Strong QCD

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- Introduction
- Regge trajectories
- A mass formula for baryon resonances
- A new interpretation of strong QCD
- Summary

# Experimental Status

The Particle Data Group lists:

| | | | | | | |
|---|---|---|---|---|---|---|
| Octet | N | | Σ | Λ | Ξ | |
| Decuplet | | Δ | Σ | | Ξ | Ω |
| Singlet | | | | Λ | | |
| **** | 11 | 7 | 6 | 9 | 2 | 1 |
| *** | 3 | 3 | 4 | 5 | 4 | 1 |
| ** | 6 | 6 | 8 | 1 | 2 | 2 |
| * | 2 | 6 | 8 | 3 | 3 | 0 |
| No J | - | - | 5 | - | 8 | 4 |
| Total | 22 | 22 | 26 | 18 | 11 | 4 |

- $\sim$ 100 baryon resonances
- $\sim$ 85 baryon resonances of known spin parity
- $\sim$ 50 well established baryon resonances of known spin parity

# The Baryon Wave Function

$$|\mathbf{qqq}>= |\mathbf{colour}>_{\mathbf{A}} \cdot \ |\mathbf{space}, \mathbf{spin}, \mathbf{flavour}>_{\mathbf{S}}$$

$$\mathbf{O(6)} \qquad \mathbf{SU(6)}$$

**The total wave function must be antisymmetric w.r.t. the exchange of any two quarks. The colour wave function is antisymmetric, hence the space-spin-flavour wave function must be symmetric. We now construct wave functions.**

# Spatial Symmetry

**Jacobean coordinates:**

$$\begin{aligned} \mathbf{r}_1 - \mathbf{r}_2 \\ \mathbf{r}_1 + \mathbf{r}_2 - 2\mathbf{r}_3 \\ \mathbf{r}_1 + \mathbf{r}_2 + \mathbf{r}_3 \end{aligned}$$

**Baryons (with 3 quarks): 3 flavours x 2 spins.**

$$\mathbf{6} \otimes \mathbf{6} \otimes \mathbf{6} = \mathbf{56} \oplus \mathbf{70_M} \oplus \mathbf{70_M} \oplus \mathbf{20}$$

$$\begin{aligned} \mathbf{56} &= {}^4\mathbf{10} \oplus {}^2\mathbf{8} \\ \mathbf{70} &= {}^2\mathbf{10} \oplus {}^4\mathbf{8} \oplus {}^2\mathbf{8} \oplus {}^2\mathbf{1} \\ \mathbf{20} &= {}^2\mathbf{8} \oplus {}^4\mathbf{1} \end{aligned}$$

**The 56-plet contains**

**$N^*$'s with spin 1/2**
**$\Delta^*$'s with spin 3/2**

**The 70-plet contains**

**$N^*$'s with spin 1/2 and with spin 3/2**
**$\Delta^*$'s with spin 1/2**

**($8_M$) have a mixed flavour symmetry, the 10 multiplet is symmetric, the 1 antisymmetric in flavour space.**

- **Two relevant separable motions**
- **System is bound $\Rightarrow$**
- **Two harmonic oscillators**

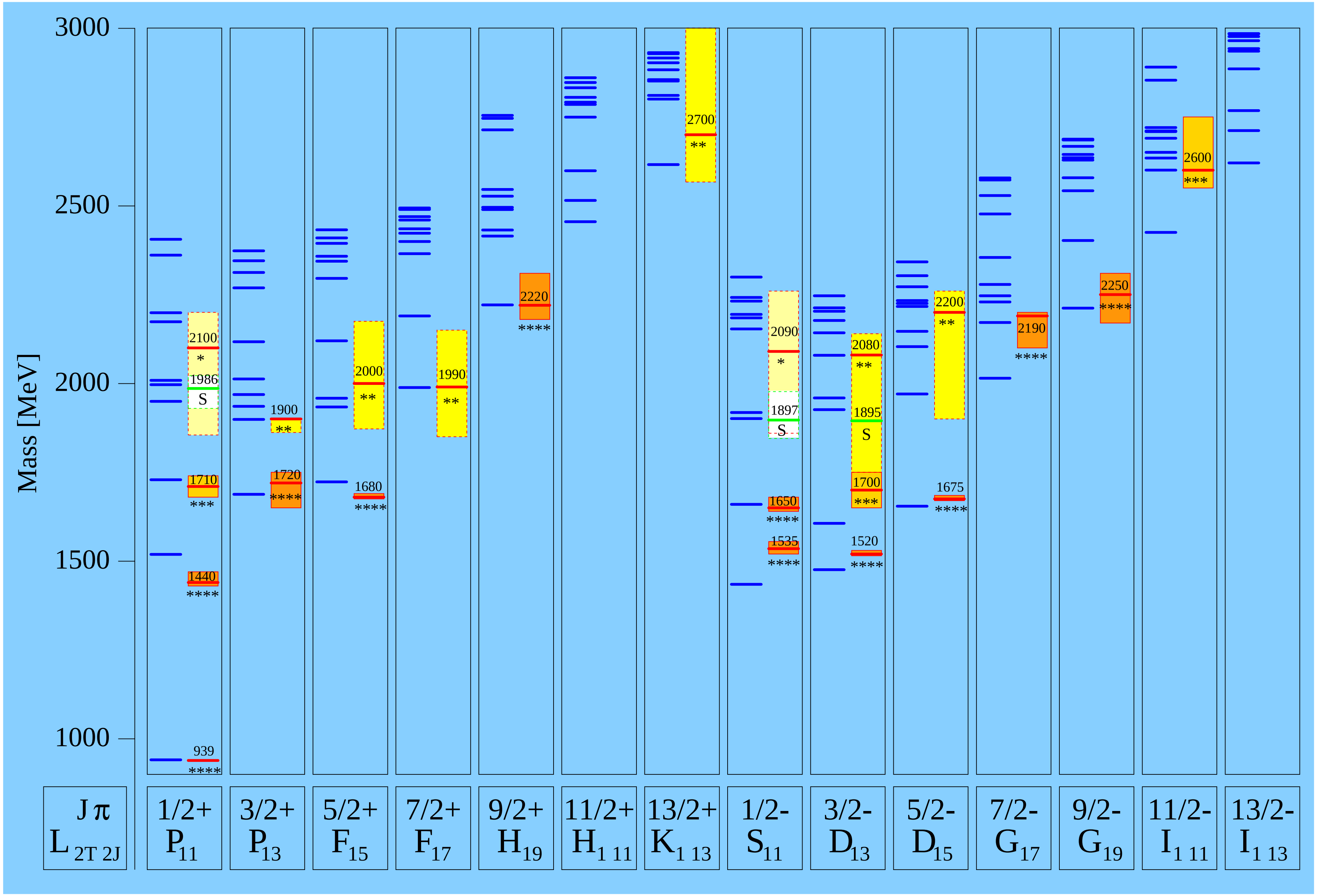
## Multiplet-structure of harmonic oscillator (Hey and Kelly, Phys. Rep. 96 (1986) 71). $\mathbf{O(6) \to O(3) \otimes O(2)}$

| N | O(6) | O(3) ⊗ O(2) | $(\mathbf{D}, \mathbf{L^P_N})$ |
|---|---|---|---|
| 0 | 1 | $1 \otimes 1$ | $(56, 0^+_0)$ |
| 1 | 6 | $3 \otimes 2_1$ | $(70, 1^-_1)$ |
| 2 | 20 | $(5+1) \otimes 2_2$ | $(70, 2^+_2)$, $(70, 0^+_2)$ |
| | | $5 \otimes 1$ | $(56, 2^+_2)$ |
| | | $3 \otimes 1$ | $(20, 1^+_2)$ |
| | 1 | $1 \otimes 1$ | $(56, 0^+_2)$ |
| 3 | 50 | $(7+3) \otimes 2_3$ | $(56, 3^-_3)$, $(20, 3^-_3)$, $(56, 1^-_3)$, $(20, 1^-_3)$ |
| | | $(7+5+3) \otimes 2_1$ | $(70, 3^-_3)$, $(70, 2^-_3)$, $(70, 1^-_3)$ |
| | 6 | $3 \otimes 2_1$ | $(70, 1^-_3)$ |
| 4 | 105 | $(9+5+1) \otimes 2_4$ | $(70, 4^+_4)$, $(70, 2^+_4)$, $(70, 0^+_4)$ |
| | | $(9+7+5+3) \otimes 2_2$ | $(70, 4^+_4)$, $(70, 3^+_4)$, $(70, 2^+_4)$, $(70, 1^+_4)$ |
| | | $(9+5+1) \otimes 1$ | $(56, 4^+_4)$, $(56, 2^+_4)$, $(56, 0^+_4)$ |
| | | $(7+5) \otimes 1$ | $(20, 3^+_4)$, $(20, 2^+_4)$ |
| | 20 | $(5+1) \otimes 1$ | $(70, 2^+_4)$, $(70, 0^+_4)$ |
| | | $3 \otimes 1$ | $(20, 1^+_4)$ |
| | | $5 \otimes 1$ | $(56, 2^+_4)$ |
| | 1 | $1 \otimes 1$ | $(56, 0^+_4)$ |

# Theoretical models and results

- Assume quarks move in an effective confinement potential generated by a very fast colour exchange between quarks (antisymmetrising the total wave function)
- Assume the light quarks acquire effective mass by spontanous symmetry breaking
- Assume residual interactions
  - One gluon exchange
    *relativized* quark model (Capstick and Roberts)
    OGE fixed to HFS (N-$\Delta$)
    $\tilde{L} \cdot \tilde{S}$ large, in contrast to data
    Set to zero
    (comp. by $\tilde{L} \cdot \tilde{S}$ from Thomas prec. ?)
  - Goldstone (pion) exchange
    (Gloszman and Riska)
  - Instanton interactions
    Relativistic quark model
    with instanton-induced forces
    (Kretschmer, Löring, Metsch, Petry)
- Solve equation of motion
  (using wave functions of the harmonic oscillator)

# N* RESONANCES WITH INSTANTON INDUCED FORCES



## Many problems still unsolved:

→ **Which model is right ?**

→ **Is it true that one interaction dominates ?**

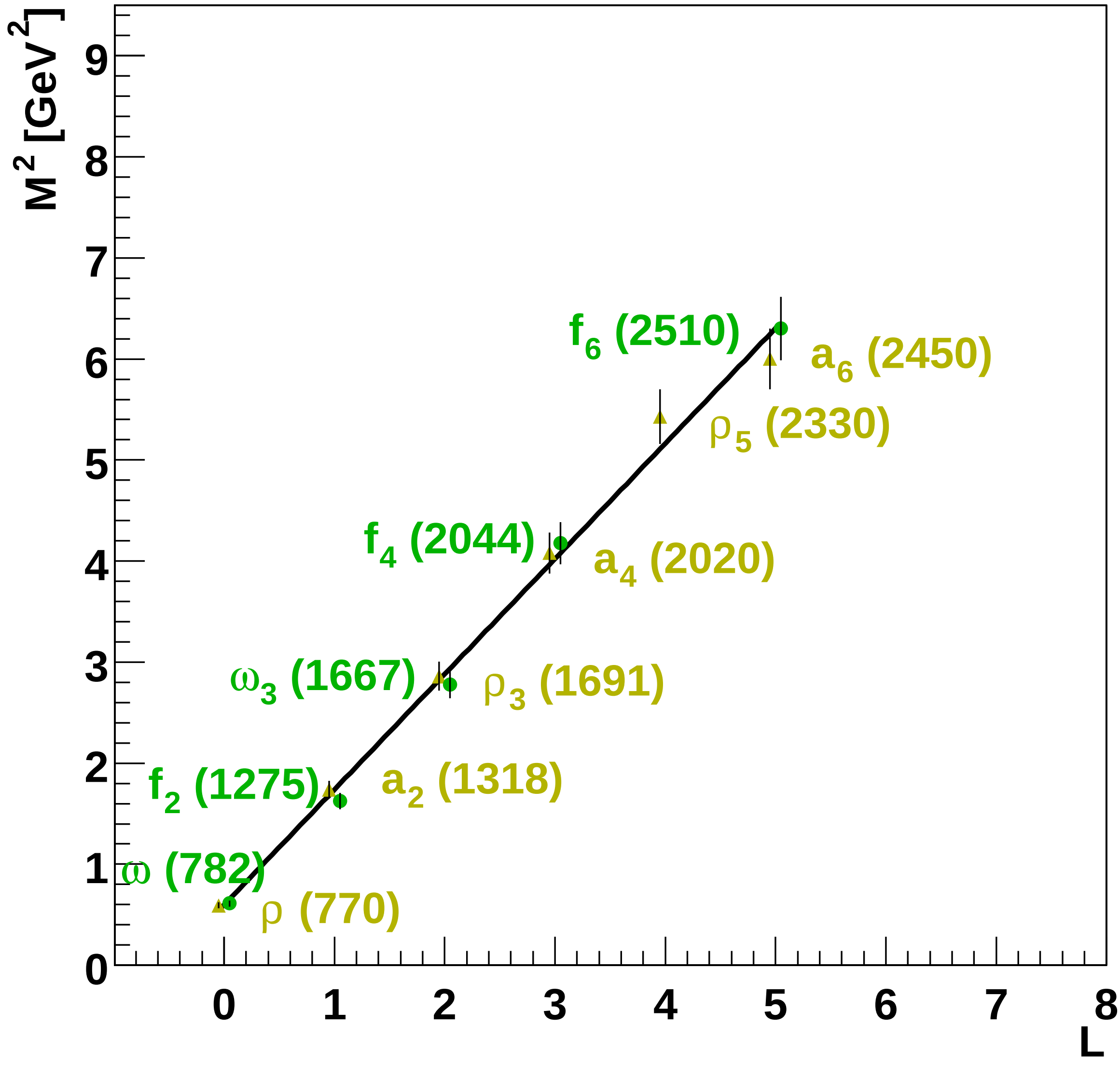
→ **Low mass of Roper, $\Delta_{3/2^+}(1600)$ ...**

→ **Low mass of negative-parity $\Delta^*$'s at 1950 MeV**

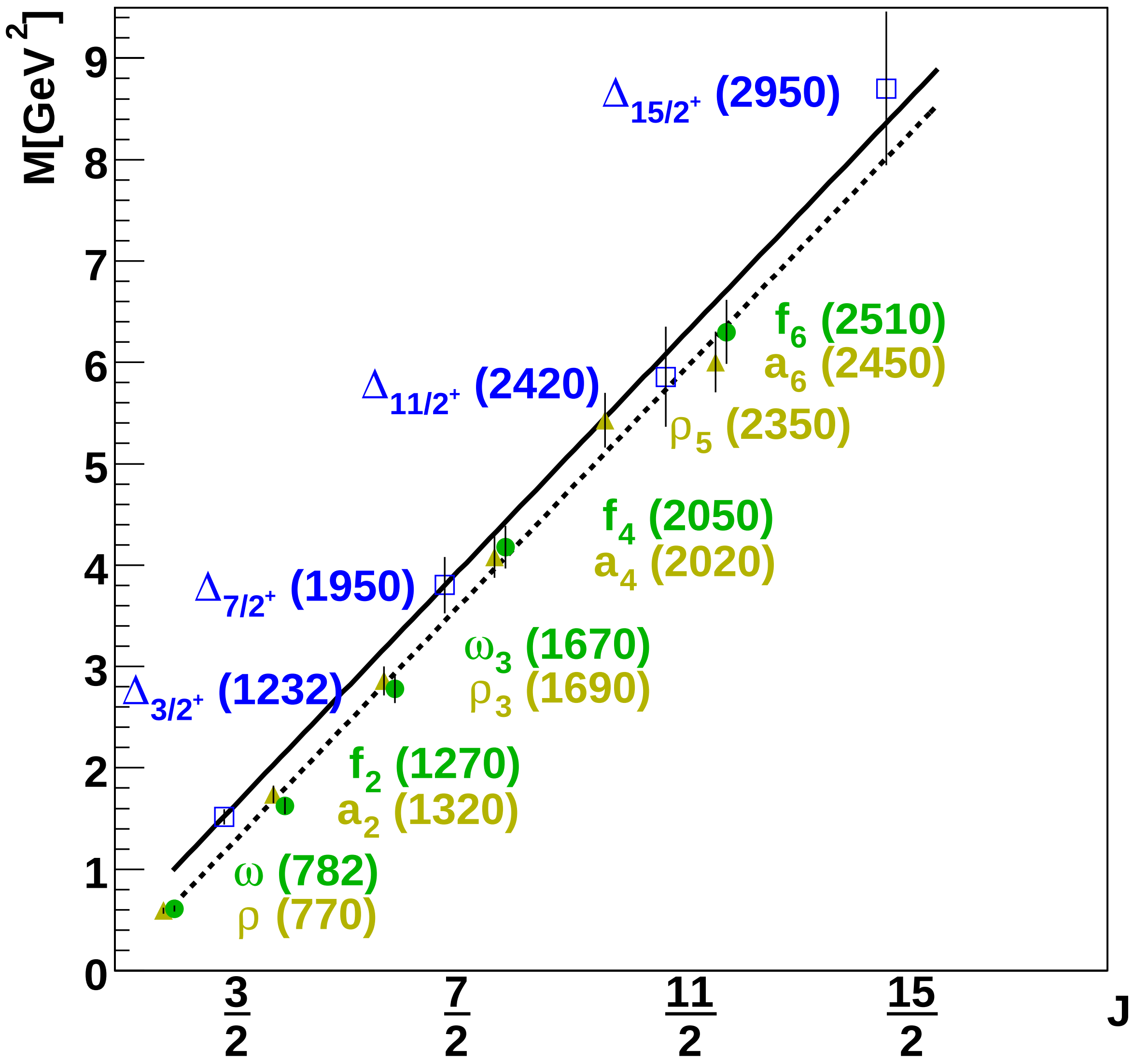
→ **Missing resonances**

→ **Decay properties of resonances**

# Phenomenological approach by Regge trajectories

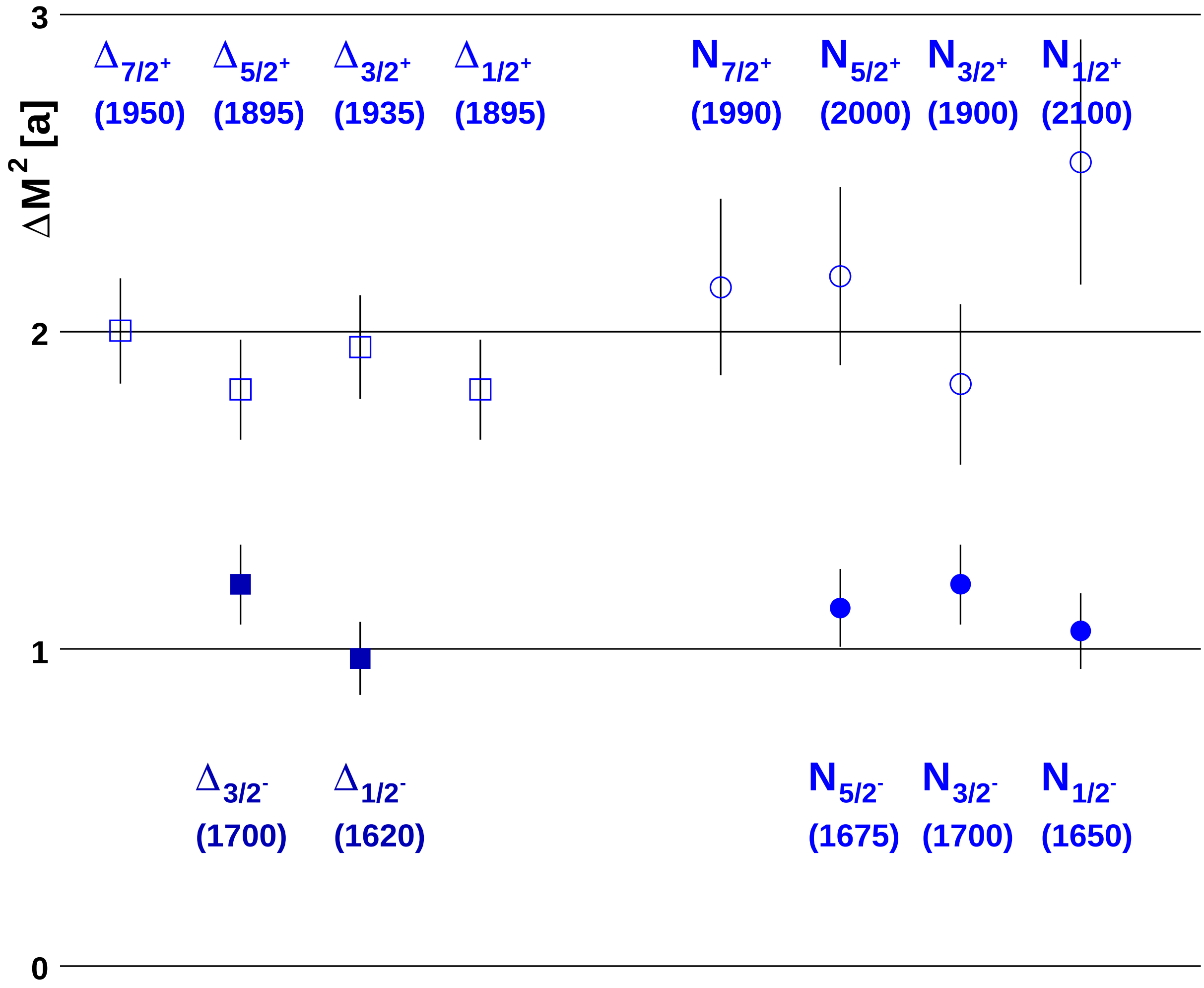



Mesons with J = L+S lie on a Regge trajectory with a slope of 1.142 $\mathrm{GeV}^2$.




**$\Delta^*$'s with L even and J = L+3/2 have the same slope as mesons.**

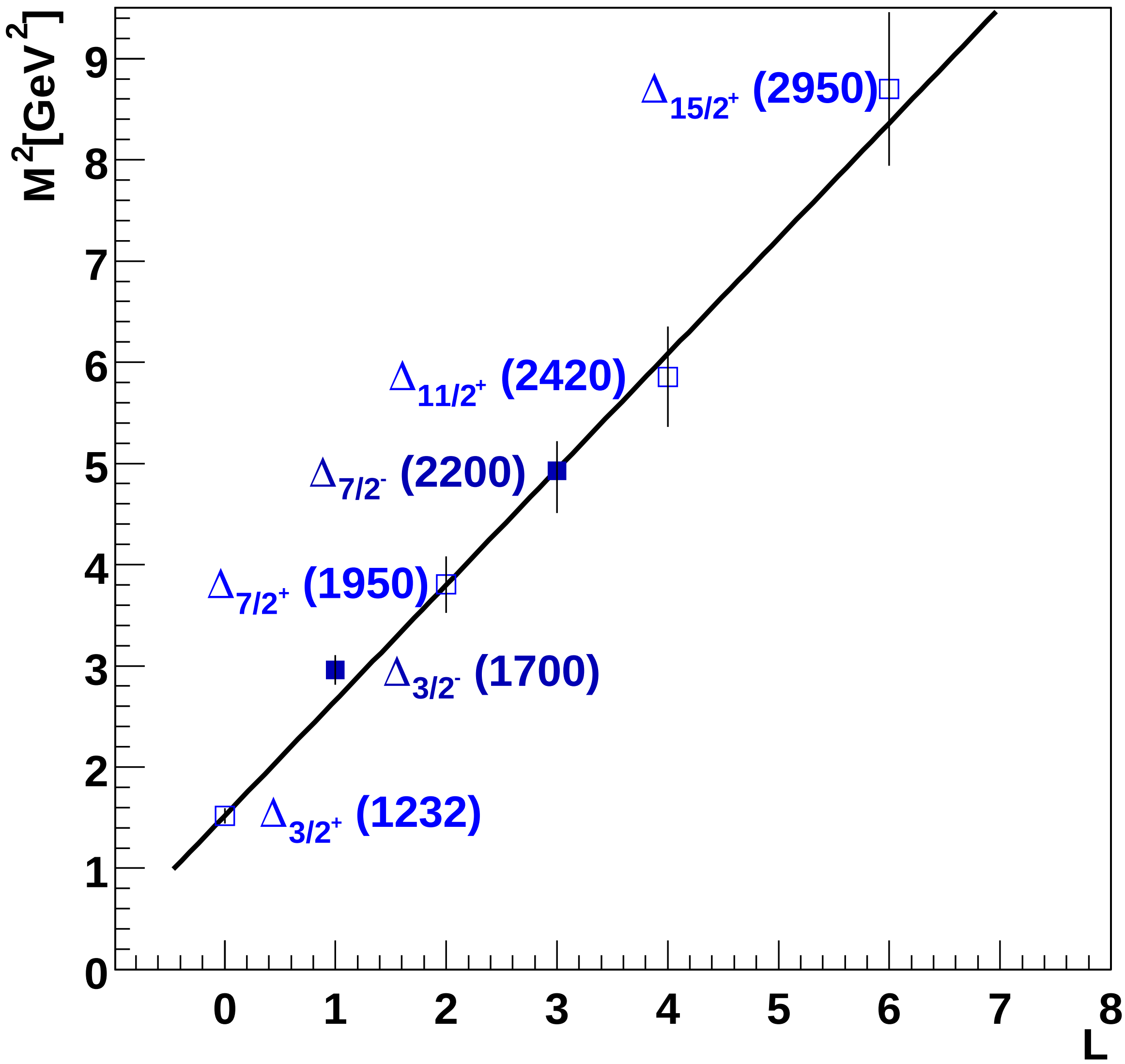
# Spin-orbit couplings



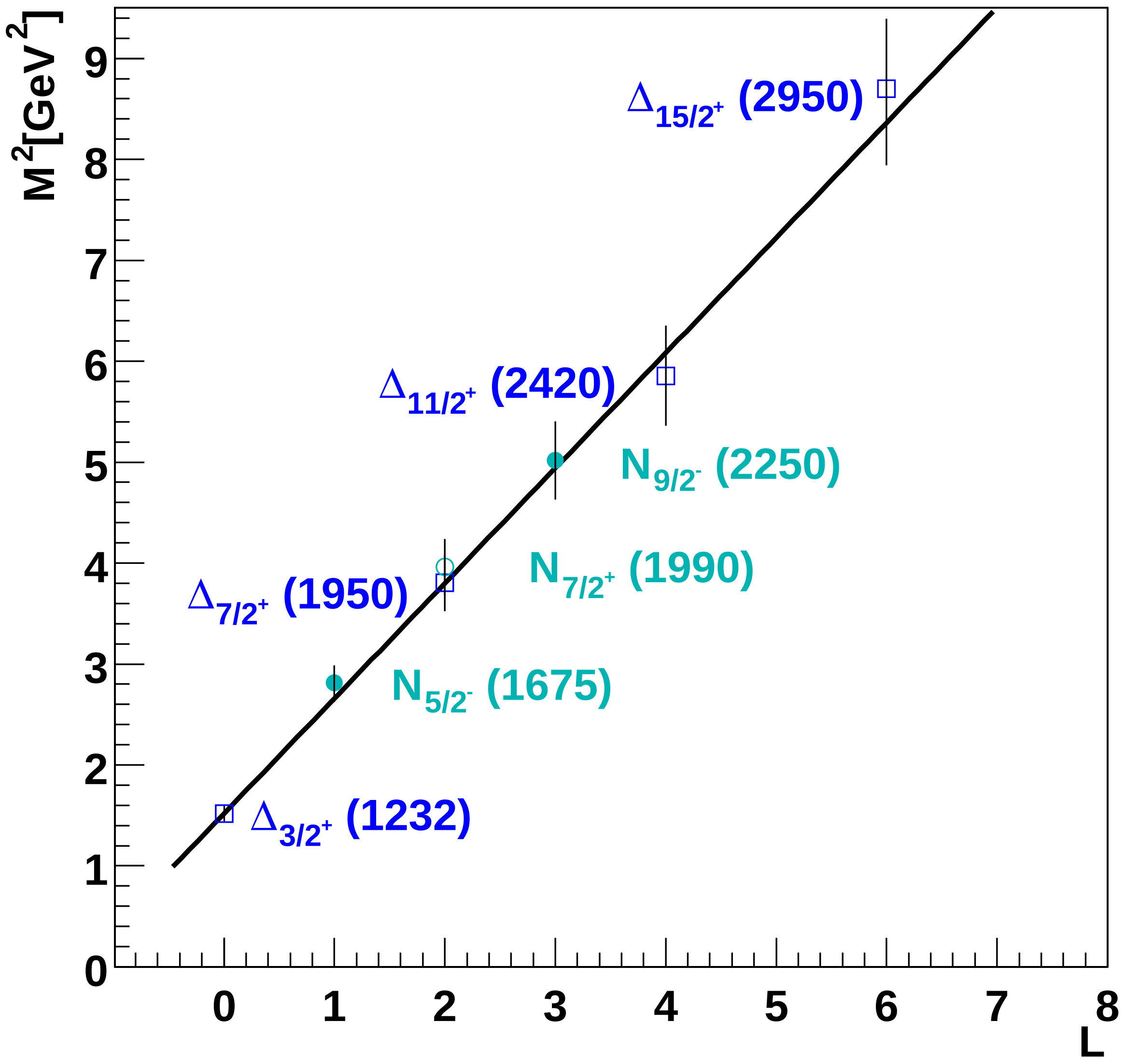

**$\Delta$ and N resonances assigned to supermultiplets with defined orbital angular momentum.**

**At 2a:**
$\tilde{L}(\mathbf{2}) + \tilde{S}(\mathbf{3/2}) = \tilde{J}(\mathbf{7/2}^+, \mathbf{5/2}^+, \mathbf{3/2}^+, \mathbf{1/2}^+)$.

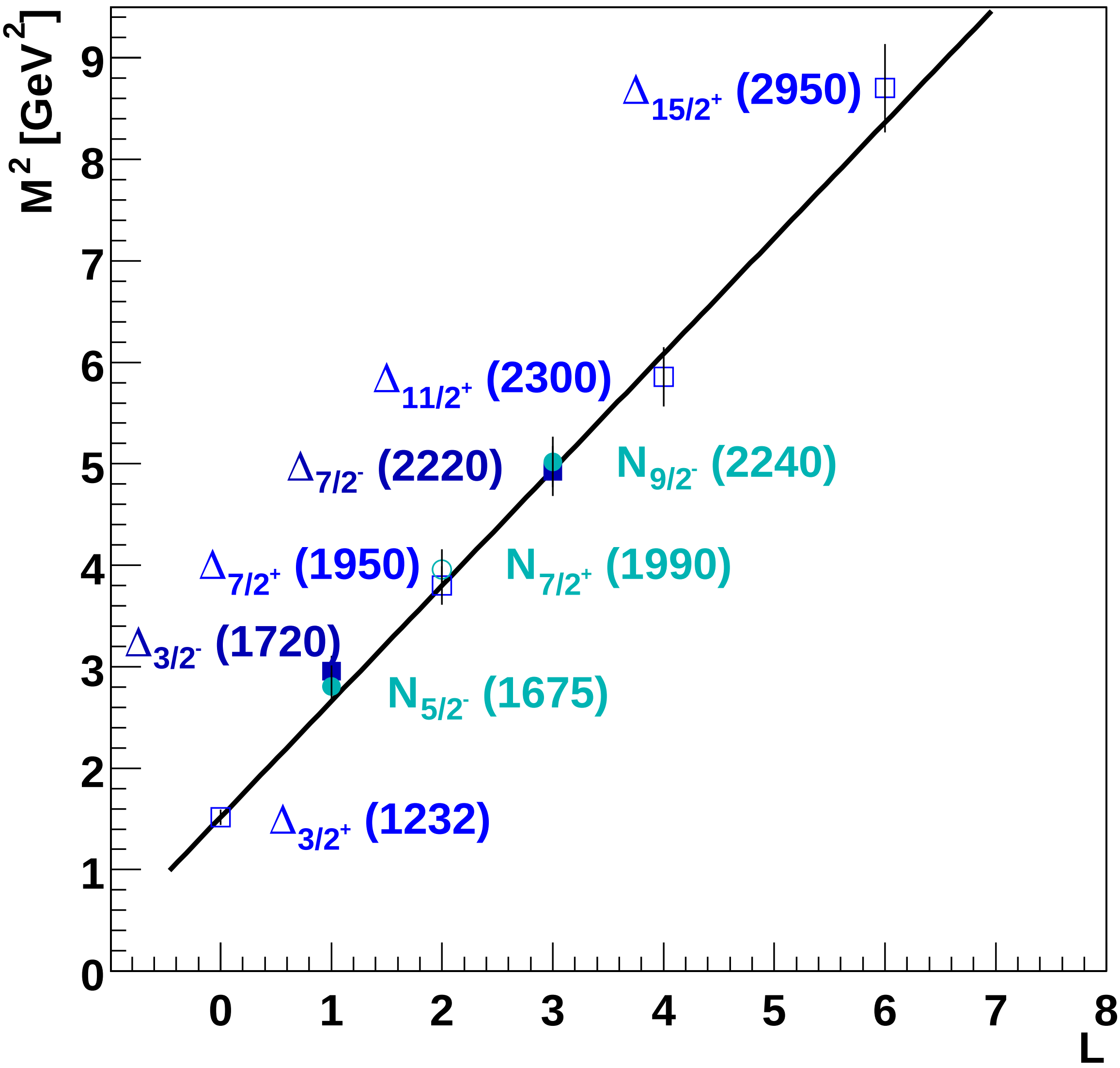
**At 1a:**
**$\Delta$ with** $\tilde{L}(\mathbf{1}) + \tilde{S}(\mathbf{1/2}) = \tilde{J}(\mathbf{3/2}^+, \mathbf{1/2}^+)$
**N with** $\tilde{\mathbf{L}}(\mathbf{1}) + \tilde{S}(\mathbf{3/2}) = \tilde{J}(\mathbf{5/2}^+, \mathbf{3/2}^+, \mathbf{1/2}^+)$




**$\Delta^*$'s with odd L and $J = L + 1/2$ fall on the same trajectory.**

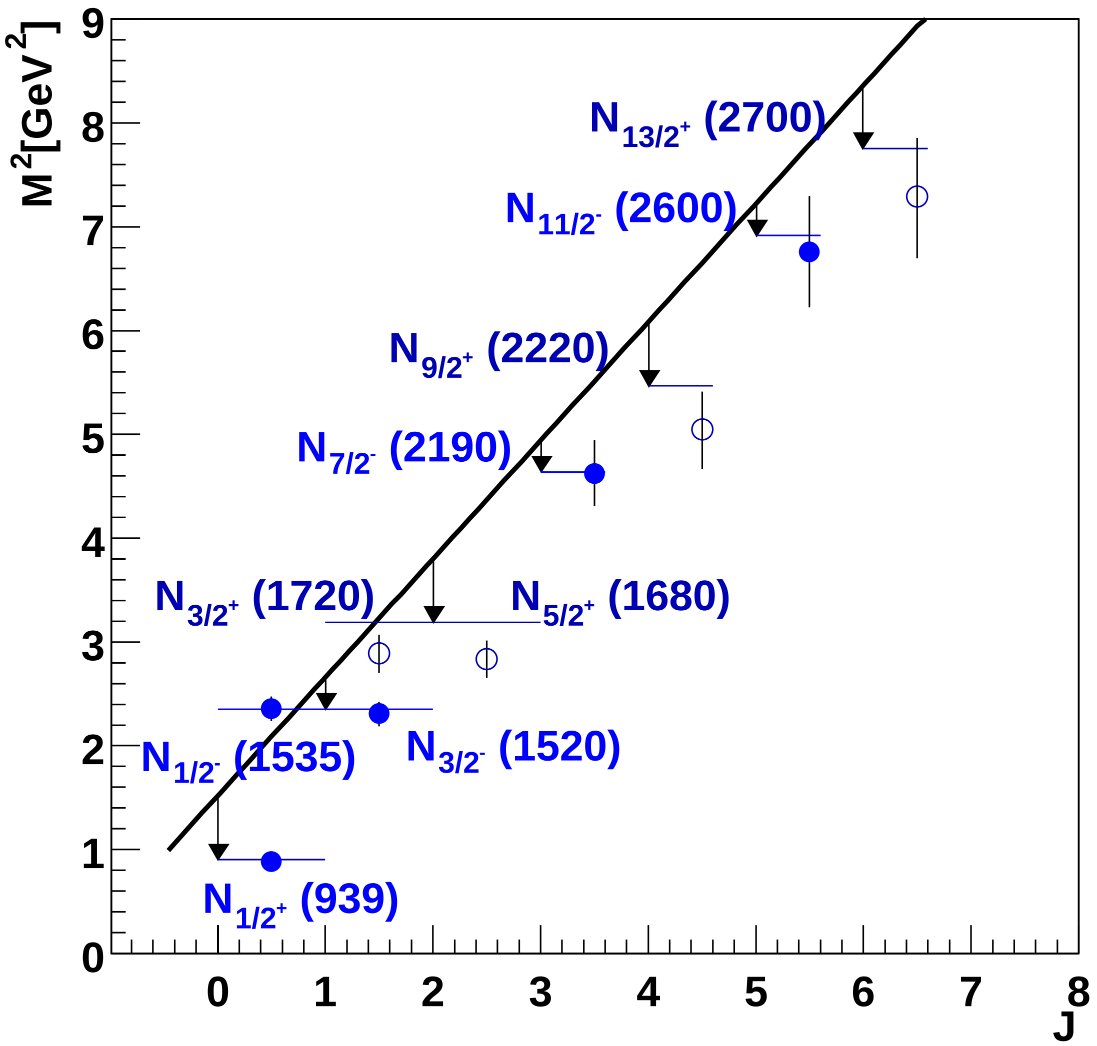



N*'s with intrinsic spin 3/2 fall on the same trajectory.



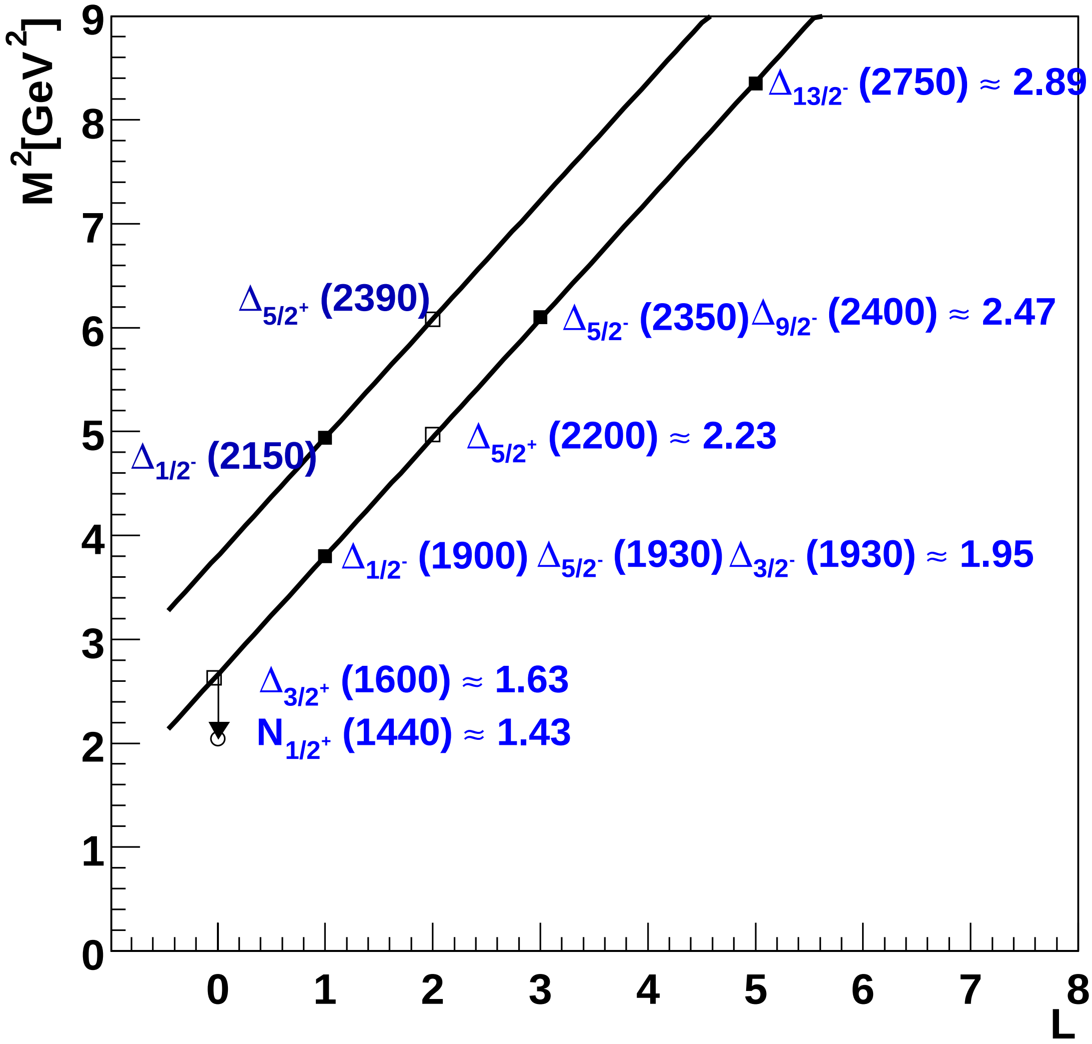

**The lowest $\Delta^*$ (with spin 1/2 and 3/2) and the $N^*$'s with intrinsic spin 3/2 and $J = L + 3/2$ fall on the same Regge trajectory.**

# What is about $N^*$ with intrinsic spin $S = 1/2$ ?




The $N^*$ masses (with intrinsic spin $S = 1/2$) lie below the standard Regge trajectory. They are smaller by about 0.6 GeV$^2$ for $N^*$ in the 56-plet, and by 0.3 GeV$^2$ for $N^*$ in the 70-plet.

# Radial excitations




Radial excitations have masses larger than the lower mass state by one $\hbar\omega$ (not 2 $\hbar\omega$).

# OBSERVATIONS AND CONCLUSIONS

1. The slope of the Regge trajectory for mesons is the same as for $\Delta^*$, $a = 1.142\,\mathrm{GeV}^2$
   $\Rightarrow$ Effective quark - diquark interaction !

2. N and $\Delta$ resonances with spin $S = 3/2$ lie on a common Regge trajectory.
   $\Rightarrow$ No significant octet-decuplet splitting.

3. $\Delta^*$ resonances with S=1/2 and S=3/2 are on the same Regge trajectory.
   $\Rightarrow$ No significant spin-spin interaction.

4. $N^*$'s and $\Delta^*$'s can be grouped into supermultiplets with defined L and S but different J.
   $\Rightarrow$ No significant $\tilde{L} \cdot \tilde{S}$ splitting.

5. There is a mass shift $\propto$ to $(q_1q_2 - q_2q_1)(\uparrow\downarrow - \downarrow\uparrow)$ in baryonic wave functions. $\Rightarrow$ Instanton interactions are important.

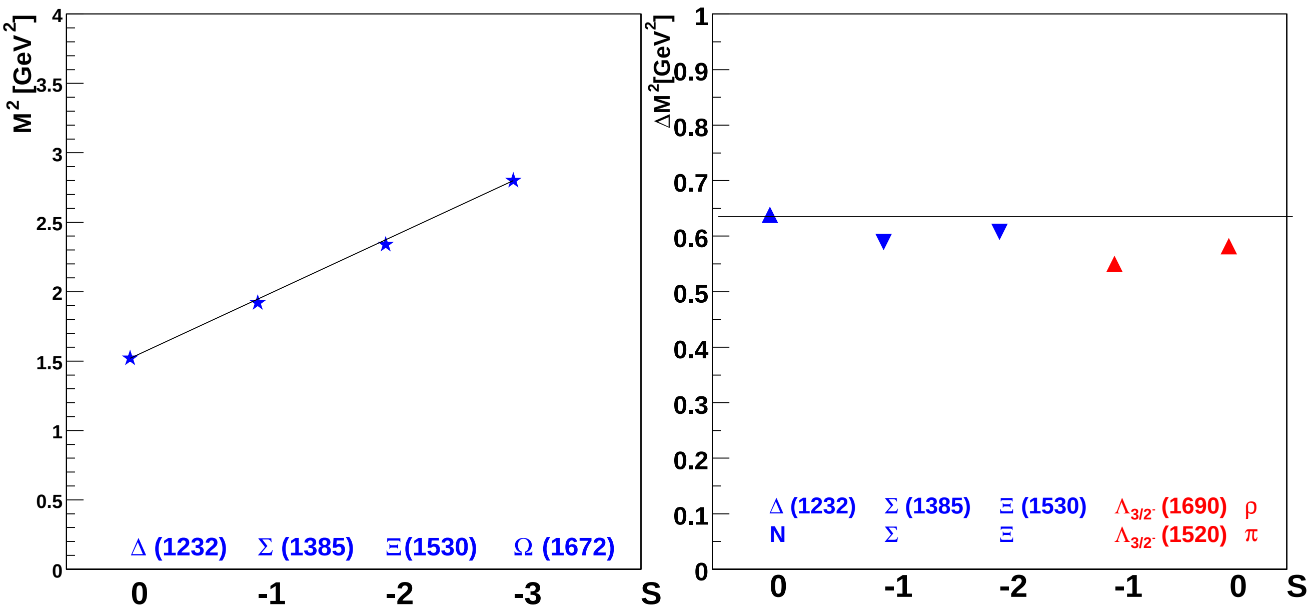
6. Daughter trajectories have the same slope and an intercept which is higher by $a = 1.142\,\mathrm{GeV}^2$ per n, both for mesons and baryons.
   $\Rightarrow$ Effective quark - diquark interaction !

7. With increasing mass, $N^*$'s have $J = L + 1/2$ ;
   $\Delta^*$'s with even J prefer $J = L + 3/2$
   $\Delta^*$'s with odd J prefer $J = L + 1/2$
   $\Rightarrow$ Rotational symmetry dynamically broken !

# A new mass formula:

$$M^2 = M_\Delta^2 + \frac{n_s}{3} \cdot M_s^2 + a \cdot (L + N) - s_i \cdot I_{sym}$$

$$M_s^2 = \left(M_\Omega^2 - M_\Delta^2\right), \qquad s_i = \left(M_\Delta^2 - M_N^2\right)$$




$M_N$, $M_\Delta$, $M_\Omega$ from PDG

$a = 1.142/\mathrm{GeV}^2$ from mesonic Regge slope

$n_s$ number of strange quarks in baryon

L intrinsic orbital angular momentum

$N + 1$ principal quantum number

$I_{sym}$ fraction of wf antisymmetric in spin and flavour:

$$\begin{aligned}
I_{sym} &= 1.0 \quad \text{for } S = 1/2 \text{ and } N = 56; \\
I_{sym} &= 0.5 \quad \text{for } S = 1/2 \text{ and } N = 70; \\
I_{sym} &= 1.5 \quad \text{for } S = 1/2 \text{ and } N = 1; \\
I_{sym} &= 0 \quad \text{otherwise.}
\end{aligned}$$

# $N^*$'s

| Baryon | Status | $D_L$ | N | $M_e$ | $M_m$ | $\Gamma_e$ | $\Gamma_m$ | $\sigma$ | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|---|
| $N_{1/2^+}(939)$ | **** | $(56,^2 8)_0$ | 0 | 939 | - | - | - | - | - |
| $N_{1/2^+}(1440)$ | **** | $(56,^2 8)_0$ | 1 | 1450 | 1423 | 250-450 | 87 | 37 | 0.53 |
| $N_{1/2^+}(1710)$ | *** | $(56,^2 8)_0$ | 2 | 1710 | 1779 | 50-250 | 176 | 53 | 1.69 |
| $^1N_{1/2^+}(2100)$ | * | $(56,^2 8)_0$ | 2 | 2100 | 2076 | - | 251 | 70 | 0.12 |
| $N_{1/2^-}(1535)$ | **** | $(70,^2 8)_1$ | 0 | 1538 | 1530 | 100-250 | 114 | 41 | 0.04 |
| $N_{3/2^-}(1520)$ | **** | $(70,^2 8)_1$ | 0 | 1523 | 1530 | 110-135 | 114 | 41 | 0.03 |
| $N_{1/2^-}(1650)$ | **** | $(70,^4 8)_1$ | 0 | 1660 | 1631 | 145-190 | 139 | 46 | 0.4 |
| $N_{3/2^-}(1700)$ | *** | $(70,^4 8)_1$ | 0 | 1700 | 1631 | 50-150 | 139 | 46 | 2.25 |
| $N_{5/2^-}(1675)$ | **** | $(70,^4 8)_1$ | 0 | 1678 | 1631 | 140-180 | 139 | 46 | 1.04 |
| $N_{3/2^+}(1720)$ | **** | $(56,^2 8)_2$ | 0 | 1700 | 1779 | 100-200 | 176 | 53 | 2.22 |
| $N_{5/2^+}(1680)$ | **** | $(56,^2 8)_2$ | 0 | 1683 | 1779 | 120-140 | 176 | 53 | 3.28 |
| $N_{3/2^+}(1900)$ | ** | $(70,^4 8)_2$ | 0 | 1900 | 1950 | - | 219 | 62 | 0.65 |
| $N_{5/2^+}(2000)$ | ** | $(70,^4 8)_2$ | 0 | 2000 | 1950 | - | 219 | 62 | 0.65 |
| $N_{7/2^+}(1990)$ | ** | $(70,^4 8)_2$ | 0 | 1990 | 1950 | - | 219 | 62 | 0.42 |
| $N_{1/2^-}(2090)$ | * | $(70,^2 8)_1$ | 2 | 2090 | 2151 | - | 269 | 74 | 0.68 |
| $N_{3/2^-}(2080)$ | ** | $(70,^2 8)_1$ | 2 | 2080 | 2151 | - | 269 | 74 | 0.92 |
| $N_{5/2^-}(2200)$ | ** | $(70,^2 8)_3$ | 0 | 2220 | 2151 | - | 269 | 74 | 0.87 |
| $N_{7/2^-}(2190)$ | **** | $(70,^2 8)_3$ | 0 | 2150 | 2151 | 350-550 | 269 | 74 | 0 |
| $N_{9/2^-}(2250)$ | **** | $(70,^4 8)_3$ | 0 | 2240 | 2223 | 290-470 | 287 | 78 | 0.05 |
| $N_{9/2^+}(2220)$ | **** | $(56,^2 8)_4$ | 0 | 2245 | 2334 | 320-550 | 315 | 84 | 1.12 |
| $N_{11/2^-}(2600)$ | *** | $(70,^2 8)_5$ | 0 | 2650 | 2629 | 500-800 | 389 | 102 | 0.04 |
| $N_{13/2^+}(2700)$ | ** | $(56,^2 8)_6$ | 0 | 2700 | 2781 | - | 427 | 111 | 0.53 |
| | | | | | | dof: | 21 | $\sum\chi^2$: | 17.53 |

# $\Delta$

| Baryon | Status | $D_L$ | N | $M_e$ | $M_m$ | $\Gamma_e$ | $\Gamma_m$ | $\sigma$ | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|---|
| $\Delta_{3/2^+}(1232)$ | **** | $(56,^4 10)_0$ | 0 | 1232 | 1232 | - | - | - | - |
| $\Delta_{3/2^+}(1600)$ | *** | $(56,^4 10)_0$ | 1 | 1625 | 1631 | 250-450 | 139 | 46 | 0.02 |
| $\Delta_{1/2^+}(1750)$ | * | $(70,^2 10)_0$ | 1 | 1750 | 1631 | - | 139 | 46 | 6.69 |
| $\Delta_{1/2^-}(1620)$ | **** | $(70,^2 10)_1$ | 0 | 1645 | 1631 | 120-180 | 139 | 46 | 0.09 |
| $\Delta_{3/2^-}(1700)$ | **** | $(70,^2 10)_1$ | 0 | 1720 | 1631 | 200-400 | 139 | 46 | 3.74 |
| $\Delta_{1/2^-}(1900)$ | ** | $(56,^4 10)_1$ | 1 | 1900 | 1950 | 140-240 | 219 | 62 | 0.65 |
| $\Delta_{3/2^-}(1940)$ | * | $(56,^4 10)_1$ | 1 | 1940 | 1950 | - | 219 | 62 | 0.03 |
| $\Delta_{5/2^-}(1930)$ | *** | $(56,^4 10)_1$ | 1 | 1945 | 1950 | 250-450 | 219 | 62 | 0.01 |
| $\Delta_{1/2^+}(1910)$ | **** | $(56,^4 10)_2$ | 0 | 1895 | 1950 | 190-270 | 219 | 62 | 0.79 |
| $\Delta_{3/2^+}(1920)$ | *** | $(56,^4 10)_2$ | 0 | 1935 | 1950 | 150-300 | 219 | 62 | 0.06 |
| $\Delta_{5/2^+}(1905)$ | **** | $(56,^4 10)_2$ | 0 | 1895 | 1950 | 280-440 | 219 | 62 | 0.79 |
| $\Delta_{7/2^+}(1950)$ | **** | $(56,^4 10)_2$ | 0 | 1950 | 1950 | 290-350 | 219 | 62 | 0 |
| $\Delta_{1/2^-}(2150)$ | * | $(70,^2 10)_1$ | 2 | 2150 | 2223 | - | 287 | 78 | 0.88 |
| $\Delta_{7/2^-}(2200)$ | * | $(70,^2 10)_3$ | 0 | 2200 | 2223 | - | 287 | 78 | 0.09 |
| $^1\Delta_{5/2^+}(2000)$ | ** | $(70,^2 10)_2$ | 1 | 2200 | 2223 | - | 287 | 78 | 0.09 |
| $\Delta_{5/2^-}(2350)$ | * | $(56,^4 10)_1$ | 0 | 2350 | 2467 | - | 348 | 92 | 1.62 |
| $\Delta_{9/2^-}(2400)$ | ** | $(56,^4 10)_3$ | 1 | 2400 | 2467 | - | 348 | 92 | 0.53 |
| $\Delta_{7/2^+}(2390)$ | * | $(56,^4 10)_4$ | 0 | 2390 | 2467 | - | 348 | 92 | 0.7 |
| $\Delta_{9/2^+}(2300)$ | ** | $(56,^4 10)_4$ | 0 | 2300 | 2467 | - | 348 | 92 | 3.3 |
| $\Delta_{11/2^+}(2420)$ | **** | $(56,^4 10)_4$ | 0 | 2400 | 2467 | 300-500 | 348 | 92 | 0.53 |
| $\Delta_{13/2^-}(2750)$ | ** | $(56,^4 10)_5$ | 1 | 2750 | 2893 | - | 455 | 118 | 1.47 |
| $\Delta_{15/2^+}(2950)$ | ** | $(56,^4 10)_6$ | 0 | 2950 | 2893 | - | 455 | 118 | 0.23 |
| | | | | | | dof: | 21 | $\sum\chi^2$: | 22.31 |

# $\Sigma$

| Baryon | Status | $D_L$ | N | $M_e$ | $M_m$ | $\Gamma_e$ | $\Gamma_m$ | $\sigma$ | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|---|
| $\Sigma_{1/2^+}(1193)$ | **** | $(56,^2 8)_0$ | 0 | 1193 | 1144 | - | - | 30 | 2.67 |
| $\Sigma_{3/2^+}(1385)$ | **** | $(56,^4 10)_0$ | 0 | 1384 | 1394 | - | - | 30 | 0.11 |
| $\Sigma(1480)$ | * | | | | | | | | |
| $\Sigma(1560)$ | ** | $(56,^2 8)_0$ | 1 | 1560 | 1565 | - | 32 | 31 | 0.03 |
| $\Sigma_{1/2^+}(1660)$ | *** | $(70,^2 8)_0$ | 1 | 1660 | 1664 | 40-200 | 57 | 33 | 0.01 |
| $\Sigma_{1/2^+}(1770)$ | * | $(70,^2 10)_0$ | 1 | 1770 | 1757 | - | 80 | 36 | 0.13 |
| $\Sigma_{1/2^+}(1880)$ | ** | $(56,^2 8)_0$ | 2 | 1880 | 1895 | - | 115 | 42 | 0.13 |
| $\Sigma_{1/2^-}(1620)$ | ** | $(70,^2 8)_1$ | 0 | 1620 | 1664 | - | 57 | 33 | 1.78 |
| $\Sigma_{3/2^-}(1580)$ | ** | $(70,^2 8)_1$ | 0 | 1580 | 1664 | - | 57 | 33 | 6.48 |
| $\Sigma(1690)$ | ** | $(70,^2 10)_1$ | 0 | 1690 | 1757 | - | 80 | 36 | 3.46 |
| $\Sigma_{1/2^-}(1750)$ | *** | $(70,^4 8)_1$ | 0 | 1765 | 1757 | 60-160 | 80 | 36 | 0.05 |
| $\Sigma_{3/2^-}(1670)$ | **** | $(70,^4 8)_1$ | 0 | 1675 | 1757 | 40-80 | 80 | 36 | 5.19 |
| $\Sigma_{5/2^-}(1775)$ | **** | $(70,^4 8)_1$ | 0 | 1775 | 1757 | 105-135 | 80 | 36 | 0.25 |
| $\Sigma_{1/2^-}(2000)$ | * | $(70,^2 8)_1$ | 1 | 2000 | 1977 | - | 135 | 45 | 0.26 |
| $\Sigma_{3/2^-}(1940)$ | *** | $(70,^2 8)_1$ | 1 | 1925 | 1977 | 150-300 | 135 | 45 | 1.34 |
| $\Sigma_{3/2^+}(1840)$ | * | $(56,^2 8)_0$ | 2 | 1840 | 1895 | - | 115 | 42 | 1.71 |
| $\Sigma_{5/2^+}(1915)$ | **** | $(56,^2 8)_0$ | 2 | 1918 | 1895 | 80-160 | 115 | 42 | 0.3 |
| $^1\Sigma_{3/2^+}(2080)$ | ** | $(56,^4 10)_0$ | 2 | 2080 | 2056 | - | 155 | 49 | 0.24 |
| $^1\Sigma_{5/2^+}(2070)$ | * | $(56,^4 10)_0$ | 2 | 2070 | 2058 | - | 155 | 49 | 0.06 |
| $^1\Sigma_{7/2^+}(2030)$ | **** | $(56,^4 10)_0$ | 2 | 2033 | 2056 | 150-200 | 155 | 49 | 0.22 |
| $\Sigma(2250)$ | *** | $(70,^2 8)_3$ | 0 | 2245 | 2248 | 60-150 | 203 | 59 | 0 |
| $\Sigma_{7/2^-}(2100)$ | * | $(70,^2 8)_3$ | 0 | 2100 | 2248 | - | 203 | 59 | 6.29 |
| $\Sigma(2455)$ | ** | $(56,^2 8)_4$ | 0 | 2455 | 2424 | - | 247 | 69 | 0.2 |
| $\Sigma(2620)$ | ** | $(70,^2 8)_5$ | 0 | 2620 | 2708 | - | 318 | 85 | 1.07 |
| $\Sigma(3000)$ | * | $(56,^2 8)_6$ | 0 | 3000 | 2857 | - | 355 | 94 | 2.31 |
| $\Sigma(3170)$ | * | $(70,^2 8)_7$ | 0 | 3170 | 3102 | - | 416 | 108 | 0.4 |
| | | | | | | dof: | 25 | $\sum\chi^2$: | 34.69 |

# Λ

| Baryon | Status | $D_L$ | N | $M_e$ | $M_m$ | $\Gamma_e$ | $\Gamma_m$ | $\sigma$ | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|---|
| $\Lambda_{1/2^+}(1115)$ | **** | $(56,^2 8)_0$ | 0 | 1116 | 1144 | - | - | 30 | 0.87 |
| $\Lambda_{1/2^+}(1600)$ | *** | $(56,^2 8)_0$ | 1 | 1630 | 1565 | 50-250 | 32 | 31 | 4.4 |
| $\Lambda_{1/2^+}(1810)$ | *** | $(56,^2 8)_0$ | 2 | 1800 | 1895 | 50-250 | 115 | 42 | 5.12 |
| $\Lambda_{1/2^-}(1405)$ | **** | $(70,^2 1)_1$ | 0 | 1407 | 1460 | 50 | 6 | 30 | 3.12 |
| $\Lambda_{3/2^-}(1520)$ | **** | $(70,^2 1)_1$ | 0 | 1520 | 1460 | 16 | 6 | 30 | 4 |
| $\Lambda_{1/2^-}(1670)$ | **** | $(70,^2 8)_1$ | 0 | 1670 | 1664 | 25-50 | 57 | 33 | 0.03 |
| $\Lambda_{3/2^-}(1690)$ | **** | $(70,^2 8)_1$ | 0 | 1690 | 1664 | 50-70 | 57 | 33 | 0.62 |
| $\Lambda_{1/2^-}(1800)$ | *** | $(70,^4 8)_1$ | 0 | 1785 | 1757 | 200-400 | 80 | 36 | 0.6 |
| $\Lambda_{5/2^-}(1830)$ | **** | $(70,^4 8)_1$ | 0 | 1820 | 1757 | 60-110 | 80 | 36 | 3.06 |
| $\Lambda_{3/2^+}(1890)$ | **** | $(56,^2 8)_2$ | 0 | 1880 | 1895 | 60-200 | 115 | 42 | 0.13 |
| $\Lambda_{5/2^+}(1820)$ | **** | $(56,^2 8)_2$ | 0 | 1820 | 1895 | 70-90 | 115 | 42 | 3.19 |
| $\Lambda(2000)$ | * | $(70,^4 8)_2$ | 0 | 2000 | 2056 | - | 155 | 49 | 1.31 |
| $\Lambda_{5/2^+}(2110)$ | *** | $(70,^4 8)_2$ | 0 | 2115 | 2056 | 150-250 | 155 | 49 | 1.45 |
| $\Lambda_{7/2^+}(2020)$ | * | $(70,^4 8)_2$ | 0 | 2020 | 2056 | - | 155 | 49 | 0.54 |
| $\Lambda_{7/2^-}(2100)$ | **** | $(70,^2 1)_3$ | 0 | 2100 | 2101 | 100-250 | 166 | 51 | 0 |
| $\Lambda_{3/2^-}(2325)$ | * | $(70,^2 8)_1$ | 2 | 2325 | 2248 | - | 203 | 59 | 1.7 |
| $\Lambda_{9/2^+}(2350)$ | *** | $(56,^2 8)_4$ | 0 | 2355 | 2424 | 100-250 | 247 | 69 | 1 |
| $\Lambda(2585)$ | ** | $(70,^4 8)_2$ | 0 | 2585 | 2551 | - | 279 | 76 | 0.2 |
| | | | | | | dof: | 18 | $\sum\chi^2$: | 31.34 |

# $\Xi$ AND $\Omega$

| Baryon | Status | $D_L$ | N | $M_e$ | $M_m$ | $\Gamma_e$ | $\Gamma_m$ | $\sigma$ | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|---|
| $\Xi_{1/2^+}(1320)$ | **** | $(56,^2 8)_0$ | 0 | 1315 | 1317 | - | - | 30 | 0 |
| $\Xi_{3/2^+}(1530)$ | **** | $(56,^4 10)_0$ | 0 | 1532 | 1540 | 9 | - | 30 | 0.07 |
| $\Xi(1620)$ | * | | | 1620 | | | | | |
| $\Xi(1690)$ | *** | $(56,^2 8)_0$ | 1 | 1690 | 1696 | $<30$ | 21 | 30 | 0.04 |
| $\Xi_{3/2^-}(1820)$ | *** | $(70,^2 8)_1$ | 0 | 1823 | 1787 | 14-39 | 43 | 32 | 1.27 |
| $\Xi(1950)$ | *** | $(56,^2 8)_2$ | 0 | 1950 | 2004 | 40-80 | 98 | 39 | 1.92 |
| $\Xi(2030)$ | *** | $(56,^2 8)_2$ | 0 | 2025 | 2004 | 15-35 | 98 | 39 | 0.29 |
| $\Xi(2120)$ | * | $(56,^4 10)_2$ | 0 | 2120 | 2157 | - | 136 | 45 | 0.68 |
| $\Xi(2250)$ | ** | $(56,^4 10)_2$ | 0 | 2250 | 2157 | - | 136 | 45 | 4.27 |
| $\Xi(2370)$ | ** | $(70,^2 8)_3$ | 0 | 2370 | 2340 | - | 182 | 55 | 0.3 |
| $\Xi(2500)$ | * | $(56,^2 8)_4$ | 0 | 2500 | 2510 | - | 224 | 64 | 0.02 |
| | | | | | | dof: | 10 | $\sum\chi^2$: | 8.86 |

| Baryon | Status | $D_L$ | N | $M_e$ | $M_m$ | $\Gamma_e$ | $\Gamma_m$ | $\sigma$ | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|---|
| $\Omega_{3/2^+}(1672)$ | **** | $(56,^4 10)_0$ | 0 | 1672 | - | - | - | - | - |
| $\Omega(2250)$ | **** | $(56,^4 10)_2$ | 0 | 2252 | 2254 | 37-73 | 77 | 36 | 0 |
| $\Omega(2380)$ | ** | - | - | 2380 | - | - | - | - | - |
| $\Omega(2470)$ | ** | $(70,^2 10)_0$ | 1 | 2474 | 2495 | 39-105 | 137 | 46 | 0.21 |
| | | | | | | dof: | 2 | $\sum\chi^2$: | 0.21 |

- $\chi^2 = 117$ **for 97 data points.**
- **All but 3 observed states are predicted:**

**$\Rightarrow$ There are no (baryonic) hybrids!**
**$\Rightarrow$ There are no pentaquarks!**

# A NEW MASS FORMULA: INTERPRETATION

**Contradiction:**

1. Baryon resonances are quark-diquark excitations
2. Baryon resonances need the full multiplet structure

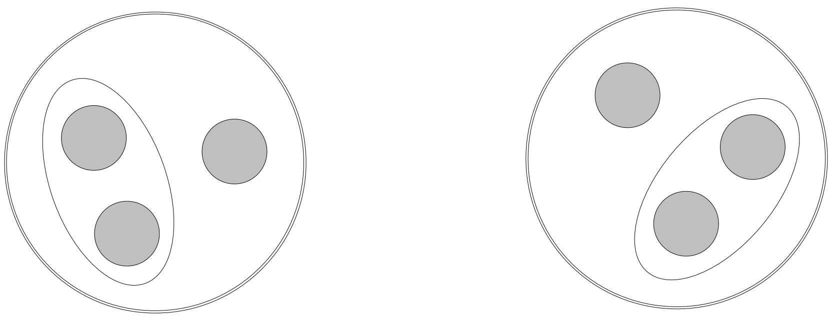
**Solution:**

1. refers to the colour interaction
2. refers to the flavour decomposition

**Example:**

$N_{3/2^-}(1520)$ $\quad L = 1 \quad S = 1/2 \rightarrow \; J = 3/2$

Both harmonic oscillators are coherently excited (in flavour space). Dynamics is given by colour !



**Flavour diquark** $\neq$ **Colour diquark**

# Interactions

1. Confinement

Colour-neutral (Pomeron-like)
Quarks polarise vacuum
Vacuum transmits interaction

When two quarks are separated, the space between them is filled with polarised vacuum. The net colour charge remains unchanged, the energy density is constant. This gives a linear confinement potential.

2. Flavour exchange

Meson exchange with long range and/or instanton interactions

$$\Lambda = 1\,\mathrm{GeV} = \Lambda_\chi$$

3. Colour exchange

Gluon exchange short range
Screened by polarised vacuum

$$\Lambda = 200\,\mathrm{MeV} = \Lambda_{\mathrm{QCD}}$$

# Answers to the questions:

1. **What are the effective degrees of freedom ?**

   **Quarks polarise the quark and gluon condensates; quark plus polarisation cloud form a constituent quark which carries defined colour. Colour exchange is screened by the polarisation cloud. Flavour exchange is fast: flavour is not a property of constituent quarks.**

2. **Why are quarks confined ?**

   **The net colour-charge of a quark plus polarisation cloud is the colour of the current quark before 'dressing'. When quarks are separated, constituent-quark masses increase with distance. The colour 'source' needs a 'colour' sink. The energy density along the string due to the polarised condensates is constant.**

3. **What are the effective forces ?**

   **Confinement originates from Pomeron-exchange-like forces transmitted by the polarisation of the vacuum condensates. Flavour-exchange between constituent quarks is important and occurs with a frequency of $1/\tau \sim \Lambda_\chi$. It could be realised by meson exchange or by instantons at the surface between two constituent quarks. Instanton interactions play an important role.**

## Related topics:

1. Spin crisis
   Quark spin induces polarisation into condensates;

   the polarised gluon-condensate provides the gluonic contribution to the proton spin

   quark condensate provides the quark and orbital ($^3P_0$) contributions

2. $^3P_0$ model for decays
   A $\bar{q}q$ pair from condensate shifted to mass shell

3. New interpretation of glueballs and hybrids

   Do hybrids exist ? Does the flux tube filled with polarised condensates support transverse oscillations/rotations ? Or only longitudinal 'acustical' shock waves ?

   Can a state of localised polarised-condensate propagate in space (in a soliton-like solution) ?

# Summary

- The excitation spectrum of baryons is very similar to that of mesons.

  Meson and baryon Regge trajectories have the same slope

  Mesons and baryons have the same spacing in radial excitations.

  The octet-decuplet splitting is the same as the $\rho - \pi$ splitting.

- The excitation spectrum of baryons is much richer than that of mesons.

  From meson physics we expect 56-plets for L even, 70-plet for L odd.

  We have 70-plets for L=0 and L=2. Best evidence is from
  $\mathbf{N_{1/2^+}(2100)}$, $\mathbf{N_{3/2^+}(1900)}$, $\mathbf{N_{5/2^+}(2000)}$, $\mathbf{N_{7/2^+}(1990)}$
  and from $\Lambda_{5/2^+}(2110)$, $\Lambda_{7/2^+}(2020)$

  We have 56-plets for L odd. Best evidence is from
  $\mathbf{\Delta_{1/2^-}(1900)}$, $\mathbf{\Delta_{3/2^-}(1940)}$, $\mathbf{\Delta_{5/2^-}(1930)}$

- Flavour symmetry exploits full $O(6) \otimes SU(6)$
  Interaction is due to a quark-diquark.

- Flavour is not a property of constituent quarks.
  Vacuum condensates play a decisice role !