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APPLICATIONS OF THE $1/N_C$ EXPANSION TO BARYONS

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Outline

- Spin-flavor symmetry in baryons
- $1/N_c$ expansion
- Excited baryons: SU(6)xO(3) scheme
- Some general results
- Partial widths of the [70,1−]
- Configuration mixings
- Summary

SU(6)xO(3)

Multiplet	Baryon	Name, status	Exp.(MeV)
$[\mathbf{56}, 0^+]$	$N_{1/2}$	$N****$	939 ± 1
	$\Lambda_{1/2}$	$\Lambda****$	1116 ± 1
	${}^8\Sigma_{1/2}$	$\Sigma****$	1192 ± 4
	${}^8\Xi_{1/2}$	$\Xi****$	1318 ± 3
	$\Delta_{1/2}$	$\Delta****$	1232 ± 1
	${}^{10}\Sigma_{3/2}$	Σ^*****	1383 ± 3
	${}^{10}\Xi_{3/2}$	Ξ^*****	1532 ± 1
	$\Omega_{3/2}$	Ω^-****	1672 ± 2
$[\mathbf{56}, 0^+]$	$N_{1/2}$	$N(1440)****$	1440 ± 20
	$\Delta_{3/2}$	$\Delta(1600)***$	1600 ± 75
	$\Lambda_{1/2}$	$\Lambda(1600)***$	1600 ± 75
	$\Sigma_{1/2}$	$\Sigma(1660)***$	1660 ± 30
$[\mathbf{56}, 2^+]$	$N_{3/2}$	$N(1720)****$	1700 ± 50
	$\Lambda_{3/2}$	$\Lambda(1890)****$	1880 ± 30
	$N_{5/2}$	$N(1680)****$	1683 ± 8
	$\Lambda_{5/2}$	$\Lambda(1820)****$	1820 ± 5
	${}^8\Sigma_{5/2}$	$\Sigma(1915)****$	1918 ± 18
	$\Delta_{1/2}$	$\Delta(1910)****$	1895 ± 25
	$\Delta_{3/2}$	$\Delta(1920)***$	1935 ± 35
	$\Delta_{5/2}$	$\Delta(1905)****$	1895 ± 25
	$\Delta_{7/2}$	$\Delta(1950)****$	1950 ± 10
	${}^{10}\Sigma_{7/2}$	$\Sigma(2030)****$	2033 ± 8
$[\mathbf{56}, 4^+]$	$N_{9/2}$	$N(2220)****$	2245 ± 65
	$\Lambda_{9/2}$	$\Lambda(2350)***$	2355 ± 15
	$\Delta_{7/2}$	$\Delta(2390)*$	2387 ± 88
	$\Delta_{9/2}$	$\Delta(2300)*$	2318 ± 132
	$\Delta_{11/2}$	$\Delta(2420)*$	2400 ± 100
$[\mathbf{56}, 6^+]$	$N_{13/2}$	$N(2700)**$	2806 ± 207
	$\Delta_{15/2}$	$\Delta(2950)**$	2920 ± 122

Multiplet	Baryon	Name, status	Exp. (MeV)
$[\mathbf{70}, 1^-]$	$N_{1/2}$	N(1535)****	1538 ± 18
	${}^8\Lambda_{1/2}$	Λ(1670)****	1670 ± 10
	$N_{3/2}$	N(1520)****	1523 ± 8
	${}^8\Lambda_{3/2}$	Λ(1690)****	1690 ± 5
	${}^8\Sigma_{3/2}$	Σ(1670)****	1675 ± 10
	${}^8\Xi_{3/2}$	Ξ(1820)***	1823 ± 5
	$N'_{1/2}$	N(1650)****	1660 ± 20
	${}^8\Lambda'_{1/2}$	Λ(1800)***	1785 ± 65
	${}^8\Sigma'_{1/2}$	Σ(1750)***	1765 ± 35
	$N'_{3/2}$	N(1700)***	1700 ± 50
	$N'_{5/2}$	N(1675)****	1678 ± 8
	${}^8\Lambda'_{5/2}$	Λ(1830)****	1820 ± 10
	${}^8\Sigma'_{5/2}$	Σ(1775)****	1775 ± 5
	$\Delta_{1/2}$	Δ(1620)****	1645 ± 30
	$\Delta_{3/2}$	Δ(1700)****	1720 ± 50
	${}^1\Lambda_{1/2}$	Λ(1405)****	1407 ± 4
	${}^1\Lambda_{3/2}$	Λ(1520)****	1520 ± 1
$[\mathbf{70}, 2^+]$	$N'_{1/2}$	N(2100)*	1926 ± 26
	$N'_{5/2}$	N(2000)**	1981 ± 200
	$\Lambda'_{5/2}$	Λ(2110)***	2112 ± 40
	$N'_{7/2}$	N(1990)**	2016 ± 104
	$\Lambda'_{7/2}$	Λ(2020)*	2094 ± 78
	$\Delta_{5/2}$	Δ(2000)**	1976 ± 237
$[\mathbf{70}, 3^-]$	$N_{5/2}$	N(2200)**	2057 ± 180
	$N_{7/2}$	N(2190)****	2160 ± 49
	$N'_{9/2}$	N(2250)****	2239 ± 76
	$\Delta_{7/2}$	Δ(2200)*	2232 ± 87
	${}^1\Lambda_{7/2}$	Λ(2100)****	2100 ± 20
$[\mathbf{70}, 5^-]$	$N_{11/2}$	N(2600)***	2638 ± 97

Global symmetries of QCD

$U_B(1) \times SU_L(3) \times SU_L(3) \times$ Poincare

SU(6) - dynamical symmetry only for baryons

Must be non-relativistic at baryonic level

What can explain it in QCD?

QCD expansion parameters $m_{u,d,s}$ $1/N_c$

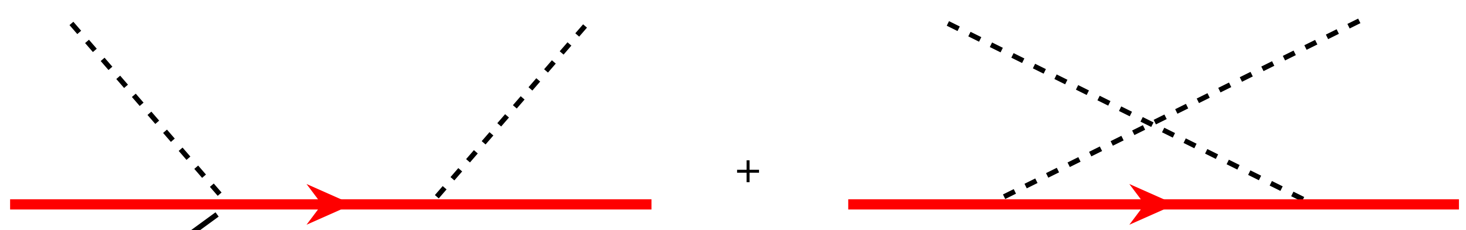
$1/N_c$ expansion $SU_c(3) \longrightarrow SU_c(N_c)$

Provides additional way of ordering non-perturbative QCD

Scalings in N_c

	Mesons	Baryons
Mass	N_c^0	N_c
Γ	$1/N_c$	N_c^0
coupling to pions	$N_c^{-n_\pi/2}$	$N_c^{(1-n_\pi)/2}$

SU(6) from consistency: Gervais & Sakita; Dashen & Manohar



$$g_A \frac{N_c}{F_\pi} \partial_i \pi^a X^{ia} = \mathcal{O}(\sqrt{N_c})$$

$$\propto \frac{N_c^2}{F_\pi^2} \left\{ \langle B' \mid X^{jb} X^{ia} \mid B \rangle \frac{i}{k_0} - \langle B' \mid X^{ia} X^{jb} \mid B \rangle \frac{i}{k_0'} \right\}$$

$$(\text{since } \; k_0 = k_0' + \mathcal{O}(1/N_c) :)$$

$$= \frac{N_c^2}{F_\pi^2} \frac{i}{k_0} \left(\langle B' \mid [X^{jb}, X^{ia}] \mid B \rangle + \mathcal{O}(1/N_c^2) \right)$$

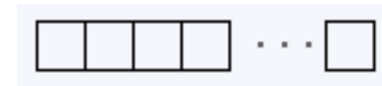
$$\{T^a, S^i, G^{ia} = N_c X^{ia}\}$$

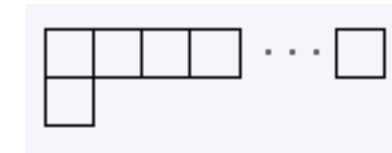
SU(6)

$$\langle B' \mid [X^{jb}, X^{ia}] \mid B \rangle = \mathcal{O}(1/N_c)$$

Implementing the 1/N$_c$ expansion

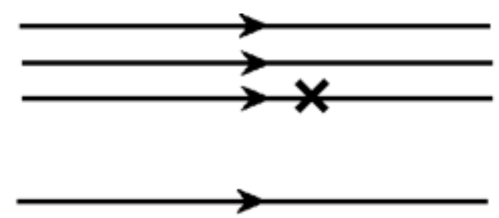
Baryons in multiplets of SU(6)





Effective operators:

$$\hat{Q} = \bar{q}\,\Gamma\, q$$



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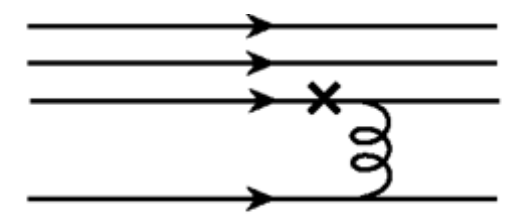


$$\hat{Q} = \sum_{n,i} C_{ni}\, \mathcal{Q}_{ni}$$

$\mathcal{Q}_{ni}$ n − body operators

1/N$_c$ power counting $\left(\frac{1}{N_c}\right)^{n-1-\kappa}$

1-body

	1	S^i	T^a	G^{ia}
κ :	1	0	0	1

2-body

	$\frac{1}{N_c}S^iS^j$	$\frac{1}{N_c}S^iG^{ja}$	$\frac{1}{N_c}T^aT^b$	$\frac{1}{N_c}G^{ia}T^b$	$\frac{1}{N_c}G^{ia}G^{jb}$
κ :	0	1	0	1	2

Effective operators built with tensor products of generators

Effective coefficients

$C_{n,i}(\overline{m}_q, q)$ contain the unknown QCD dynamics

$$C_{n,i} = \sum_{\nu=0} C_{n,i}(\nu) \left(\frac{1}{N_c}\right)^{\nu}$$

Masses of GS baryons

$$M_{GS} = c_1\, N_c + \frac{c_{HF}}{N_c}\, (S^2 - \frac{3}{4} N_c) - c_{\mathcal{S}} \frac{m_s - m_{u,d}}{\Lambda}\, \mathcal{S} + \mathcal{O}(1/N_c^2; m_s/N_c)$$

Gursey-Radicati

Mass relation among 8 and 10

	$\Sigma - \Lambda = \mathcal{O}(m_s/N_c)$	74 MeV
GMO	$\Xi_8 - \Sigma_8 = \frac{1}{2}(3\Lambda - \Sigma_8) - N$	128 vs 141 MeV
ES	$\Sigma_{10} - \Delta = \Xi_{10} - \Sigma_{10}$	153 vs 145
”	$\Omega^- - \Xi_{10} = \Xi_{10} - \Sigma_{10}$	142 vs 145
8-10	$\Sigma_{10} - \Sigma_8 = \Xi_{10} - \Xi_8$	212 vs 195

Excited baryons

Need to extend to SU(6)xO(3)

Not a consequence of large N_c but of phenomenology

$$[56, 0^+], [56, 2^+], [70, 1^-], etc$$

Masses

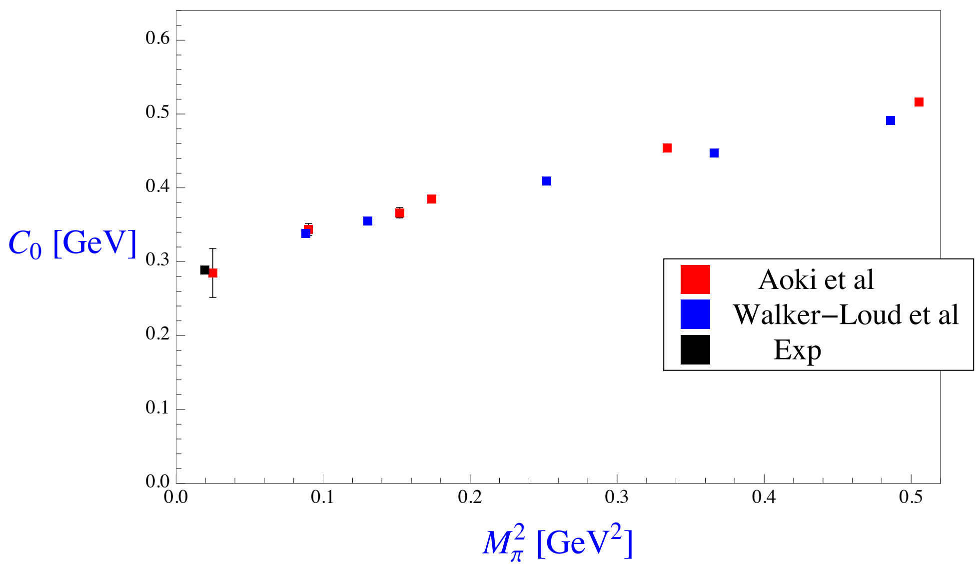
$$M = N_c\, M_0 + M_1 + \frac{1}{N_c}\, M_2 + \frac{m_s - m_{u,d}}{\Lambda}\, M_{SB} + \cdots$$

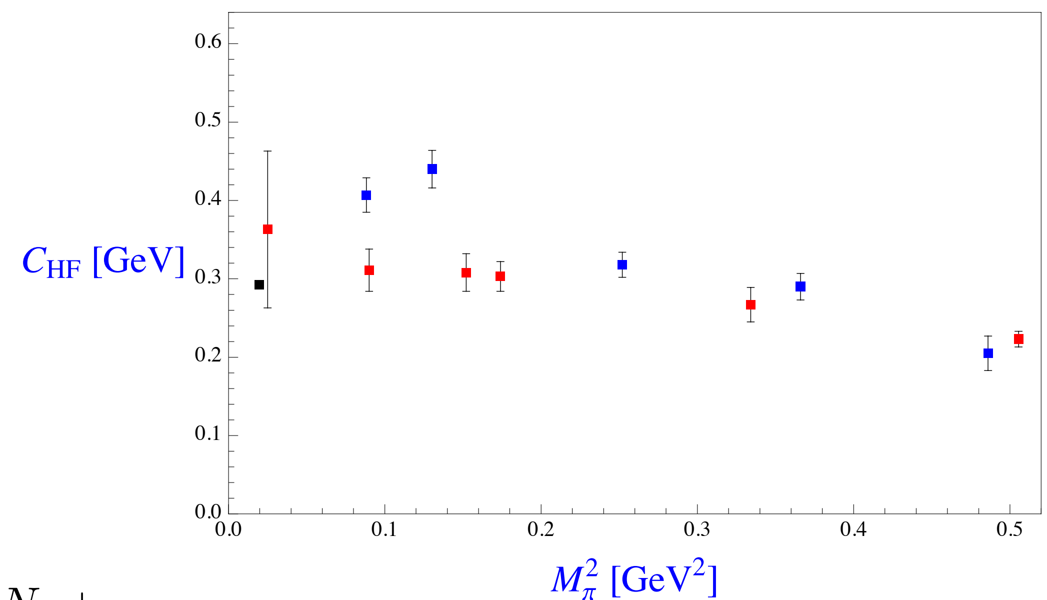
From mass analyses: BW masses from PDG

- Subleading order of natural size (or smaller)
- Hyperfine effects most important for SU(6) breaking
- Numerous mass relations well satisfied in [56,2+]

Observations on masses

Quark mass dependencies of GS mass coefficients

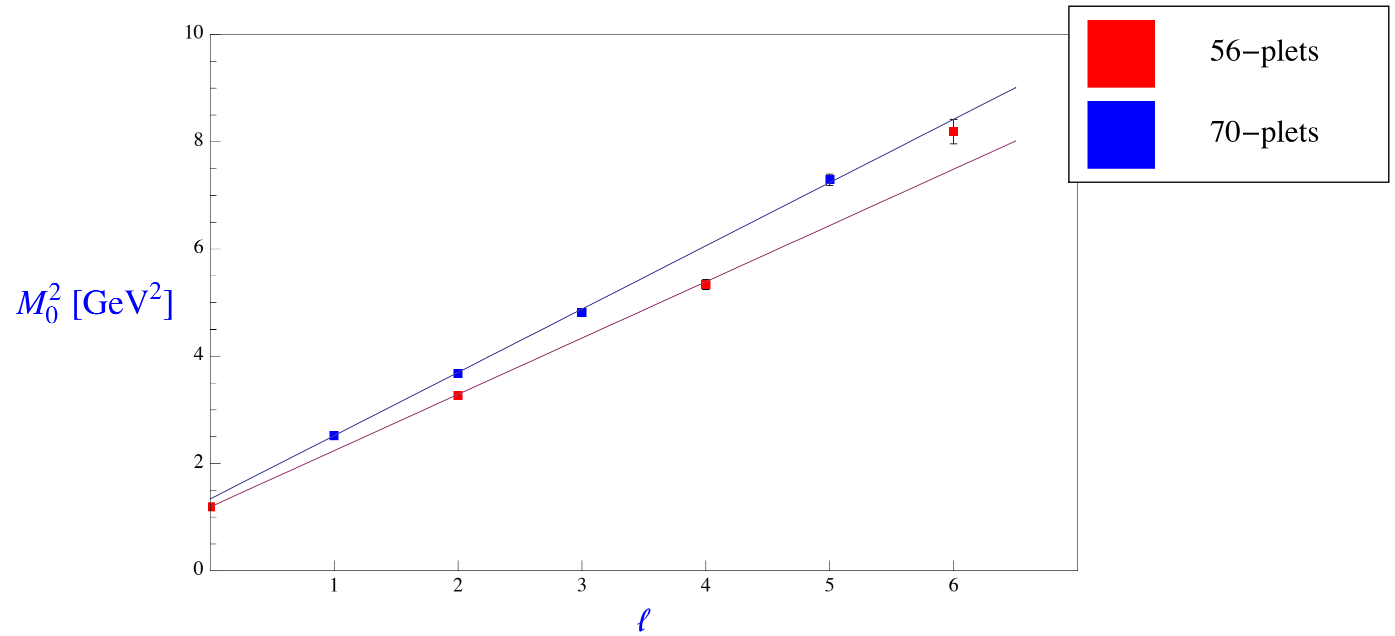




$$\sigma = \frac{\partial m_N}{\partial m_q} = \sigma_0 + \sigma_1/N_c + \cdots$$
$$\sigma_0 = 43 \pm 0.2\ MeV \quad \text{(Aoki et al)}$$
$$55 \pm 0.25\ MeV \quad \text{(Walker − Loud et al)}$$

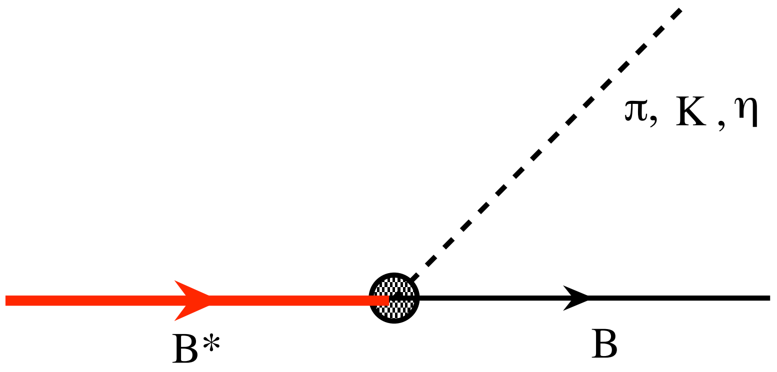
Linear trajectories for LO mass term

JLG & Matagne



Strong decays of 70-plet

JLG, Schat, Scoccola; JLG, Jayalath, Gonzalez, Scoccola



$$\mathcal{M}(\ell_\pi(Y_\pi, I_\pi), B, B^*) = (-1)^{\ell_\pi} \sqrt{2M_{B^*}} \, \frac{\sqrt{N_c}}{F_\pi} \langle B_{GS} \mid \mathbf{B}^{\ell_\pi(Y_\pi, I_\pi)} \mid B^* \rangle$$

$$\mathbf{B}^{\ell_\pi,(Y_\pi,I_\pi)} = \left(\frac{k_\pi}{\Lambda}\right)^{\ell_\pi} \sum_n C_n \, O_n^{\ell_\pi(Y_\pi,I_\pi)}$$

$$O_n^{\ell_\pi(Y_\pi,I_\pi)} = \left[\xi^\ell \, \mathcal{G}_n^{j_n(Y_\pi,I_\pi)}\right]^{(\ell_\pi(Y_\pi,I_\pi))}$$

PDG Name	State	Mass [MeV]	Γ_T [MeV]	BR % S − wave	BR % D − wave
$N(1535)$	$N_{1/2}$	1535(10)	150(25)	$N\pi : 45(10)$ $N\eta : 52.5(7.5)$	$\Delta\pi < 1$
$N(1520)$	$N_{3/2}$	1520(5)	113(12.5)	$\Delta\pi : 8.5(3.5)$	$N\pi : 60(5)$ $\Delta\pi : 12(2)$
$N(1650)$	$N'_{1/2}$	1657(13)	165(20)	$N\pi : 77.5(17.5)$ $N\eta : 6.5(3.5)$ $\Lambda K : 7(4)$	$\Delta\pi : 4(3)$
$N(1700)$	$N'_{3/2}$	1700(50)	100(50)		$N\pi : 10(5)$ $\Lambda K < 3$
$N(1675)$	$N_{5/2}$	1675(5)	148(18)		$N\pi : 40(5)$ $\Lambda K < 1$
$\Lambda(1670)$	$\Lambda_{1/2}$	1670(10)	37.5(12.5)	$N\bar{K} : 25(5)$ $\Lambda\eta : 17.5(7.5)$ $\Sigma\pi : 40(15)$	
$\Lambda(1690)$	$\Lambda_{3/2}$	1690(5)	60(10)		$N\bar{K} : 25(5)$ $\Sigma\pi : 30(10)$
$\Lambda(1800)$	$\Lambda'_{1/2}$	1785(65)	300(100)	$N\bar{K} : 32.5(7.5)$	
$\Lambda(1830)$	$\Lambda_{5/2}$	1820(10)	85(25)		$N\bar{K} : 6.5(3.5)$ $\Sigma\pi : 55(20)$ $\Sigma^*\pi > 15$
$\Lambda(1405)$	$\Lambda''_{1/2}$	1406(4)	50(2)	$\Sigma\pi : 100$	
$\Lambda(1520)$	$\Lambda''_{3/2}$	1519(1)	15.6(1)		$N\bar{K} : 45(1)$ $\Sigma\pi : 42(1)$

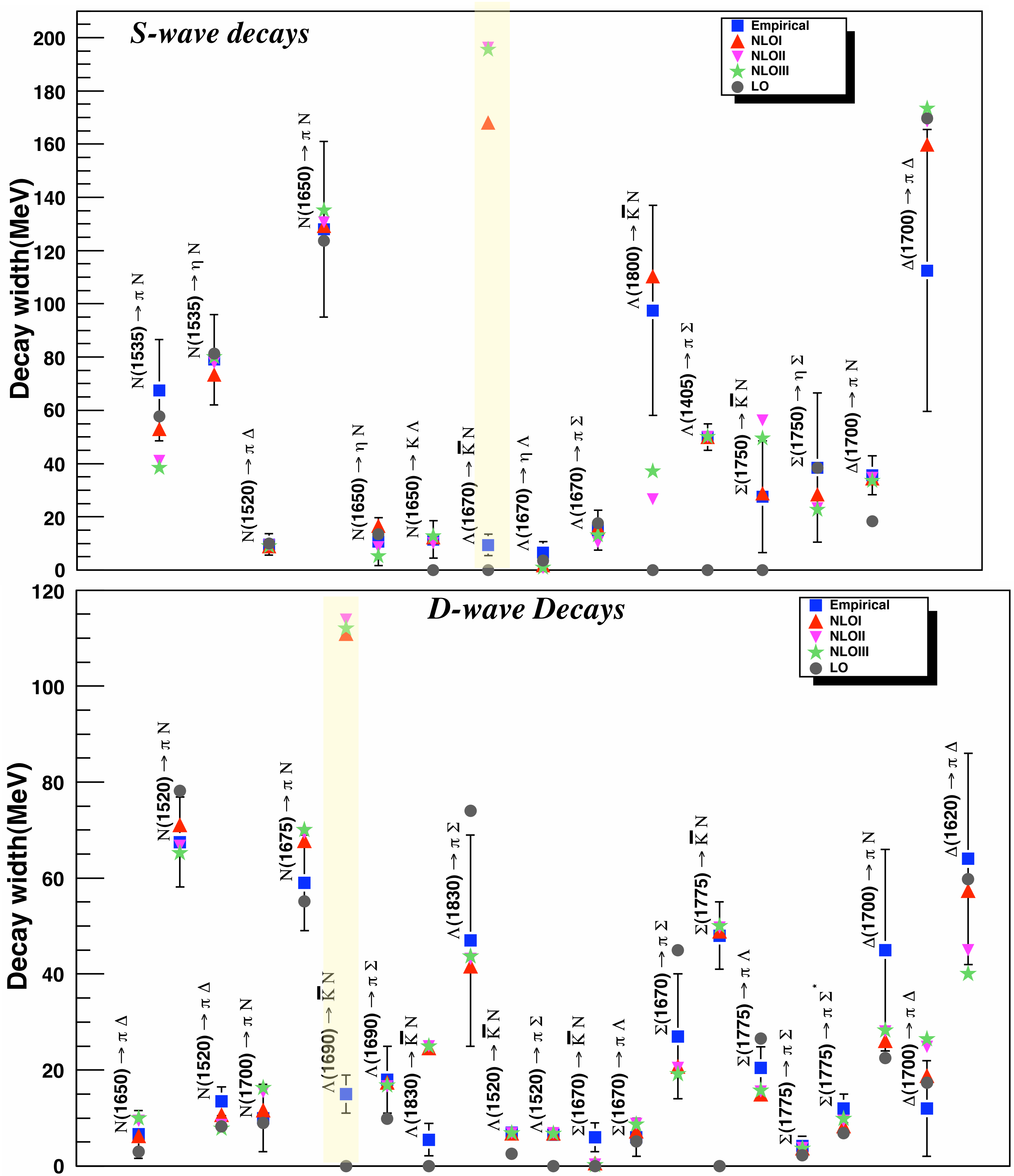
PDG Name	State	Mass [MeV]	Γ_T [MeV]	BR % S − wave	BR % D − wave
$\Sigma(1670)$	$\Sigma_{3/2}$	1675(10)	60(20)		$N\bar{K} : 10(3)$ $\Lambda\pi : 10(5)$ $\Sigma\pi : 45(15)$
$\Sigma(1750)$	$\Sigma'_{1/2}$	1765(35)	110(50)	$N\bar{K} : 25(15)$ $\Sigma\pi < 8$ $\Sigma\eta : 35(20)$	
$\Sigma(1775)$	$\Sigma_{5/2}$	1775(5)	120(15)		$N\bar{K} : 40(3)$ $\Lambda\pi : 17(3)$ $\Sigma\pi : 3.5(1.5)$ $\Sigma^*\pi : 10(2)$
$\Delta(1620)$	$\Delta_{1/2}$	1630(30)	143(7.5)	$N\pi : 25(5)$	$\Delta\pi : 45(15)$
$\Delta(1700)$	$\Delta_{3/2}$	1710(40)	300(100)	$\Delta\pi : 37.5(12.5)$	$N\pi : 15(5)$ $\Delta\pi : 4(3)$

Analysis to $1/N_c$ and 1-body SU(3) breaking

Operator bases

S-wave: 3 LO, 2 NLO, 2 SU(3) breakers

D-wave: 4 LO, 3 NLO, 1 SU(3) breaker


S-wave decays
Decay width(MeV)
0
20
40
60
80
100
120
140
160
180
200
Empirical
NLOI
NLOII
NLOIII
LO
N(1535) → π N
N(1535) → η N
N(1520) → π Δ
N(1650) → π N
N(1650) → η N
N(1650) → K Λ
Λ(1670) → K̄ N
Λ(1670) → η Λ
Λ(1670) → π Σ
Λ(1800) → K̄ N
Λ(1405) → π Σ
Σ(1750) → K̄ N
Σ(1750) → η Σ
Δ(1700) → π N
Δ(1700) → π Δ
D-wave Decays
Decay width(MeV)
0
20
40
60
80
100
120
Empirical
NLOI
NLOII
NLOIII
LO
N(1650) → π Δ
N(1520) → π N
N(1520) → π Δ
N(1700) → π N
N(1675) → π N
Λ(1690) → K̄ N
Λ(1690) → π Σ
Λ(1830) → K̄ N
Λ(1830) → π Σ
Λ(1520) → K̄ N
Λ(1520) → π Σ
Σ(1670) → K̄ N
Σ(1670) → π Λ
Σ(1670) → π Σ
Σ(1775) → K̄ N
Σ(1775) → π Λ
Σ(1775) → π Σ
Σ(1775) → π Σ*
Δ(1700) → π N
Δ(1700) → π Δ
Δ(1620) → π Δ

Mixing angle	θ_{N_1}	θ_{N_3}	θ_{Λ_1}	θ_{Λ_3}	θ_{Σ_1}	θ_{Σ_3}
Decays	0.39	2.75	0.21	2.51	1.14	2.19
Decays + Masses	0.48	2.81	0.81	2.57	0.95	3.0
Decays + Masses + Photo − couplings	0.40	2.81	Gonzalez & Scoccola			

S-wave relations at LO

$$\frac{\tilde\Gamma(N(1535)\to N\pi)-\tilde\Gamma(N(1650)\to N\pi)}{\tilde\Gamma(N(1535)\to N\pi)+\tilde\Gamma(N(1650)\to N\pi)}=\frac{1}{5}(3\cos 2\theta_{N_1}-4\sin 2\theta_{N_1})\to\theta_{N_1}=0.46(10)\ or\ 1.76(10)$$

$$\frac{\tilde\Gamma(N(1535)\to N\eta)-\tilde\Gamma(N(1650)\to N\eta)}{\tilde\Gamma(N(1535)\to N\eta)+\tilde\Gamma(N(1650)\to N\eta)}=\sin 2\theta_{N_1}\to\theta_{N_1}=0.51(27)$$

$$\tilde\Gamma(N(1535)\to N\pi)+\tilde\Gamma(N(1650)\to N\pi)=\tilde\Gamma(\Delta(1535)\to\Delta\pi)\quad 51(10)\ (th)\ vs\ 31(15)\ (exp)$$

$$\frac{\tilde\Gamma(\Delta(1620)\to N\pi)}{\tilde\Gamma(\Delta(1700)\to\Delta\pi)}=\quad 0.1\ (th)\quad vs\quad 0.29(15)\ (exp)$$

D-wave relations at LO

$$2\tilde\Gamma(\Delta(1620)\to\Delta\pi)+\tilde\Gamma(\Delta(1700)\to\Delta\pi)=15\tilde\Gamma(\Delta(1620)\to N\pi)+32\tilde\Gamma(\Delta(1700)\to N\pi)$$

$$5.9(1.9)\quad vs\quad 8.3(2.3)$$

$$\tilde\Gamma(N(1535)\to\Delta\pi)+\tilde\Gamma(N(1650)\to\Delta\pi)+11\tilde\Gamma(\Delta(1620)\to\Delta\pi)=132\tilde\Gamma(\Delta(1700)\to N\pi)+90\tilde\Gamma(N(1675)\to N\pi)$$

$$32(11)\quad vs\quad 41(10)$$

$S - wave\ Relation$	$Exp\ \ Test$
$\frac{N(1650)\to\pi N}{N(1535)\to\eta N} = \frac{N(1535)\to\pi N}{N(1650)\to\eta N}$	$0.6 \pm 0.2\ vs\ 4.4 \pm 4.0$
$\frac{N(1650)\to\eta N}{\Sigma(1750)\to\eta\Sigma} = 1$	0.12 ± 0.14
$\frac{N(1535)\to\eta N}{\Lambda(1670)\to\eta\Lambda} = 1$	5.4 ± 3.2
$\frac{\Delta(1620)\to\pi N}{\Delta(1700)\to\pi\Delta} = 2/5$	0.29 ± 0.15
$\frac{N(1535)\to\pi N}{\Lambda(1670)\to\pi\Sigma} = 1$	4.4 ± 2.5
$\frac{N(1650)\to\pi N}{\Lambda(1670)\to\eta\Lambda} = \frac{\Lambda(1670)\to\pi\Sigma}{N(1650)\to\eta N}$	$2.1 \pm 0.9\ vs\ 0.8 \pm 0.6$
$\frac{N(1650)\to\pi N}{N(1535)\to\eta N} = \frac{N(1535)\to\pi N}{N(1650)\to\eta N}$	$0.6 \pm 0.2\ vs\ 4.4 \pm 4.0$
$\frac{N(1535)\to\pi N}{N(1650)\to\pi N}$	$\theta_1 = 0.30 \pm 0.08 \quad 1.6 \pm 0.08$
$\frac{N(1535)\to\pi N}{\Delta(1620)\to\pi N}$	$\theta_1 = 0.33 \pm 0.08 \quad 1.57 \pm 0.08$
$\frac{N(1535)\to\eta N}{N(1650)\to\eta N}$	$\theta_1 = 0.68 \pm 0.14 \quad 1.22 \pm 0.14$
$\frac{N(1520)\to\pi\Delta}{\Delta(1700)\to\pi\Delta}$	$\theta_3 = 2.48 \pm 0.08 \quad 2.96 \pm 0.09$

$D - wave\ Relation$	$Exp\ \ Test$
$\frac{N(1675)\to\pi N}{\Lambda(1830)\to\pi\Sigma} = 1$	0.92 ± 0.46
$\frac{\Sigma(1670)\to\pi\Lambda}{\Sigma(1670)\to\pi\Sigma} = 1/2$	0.12 ± 0.10
$\frac{\Sigma(1775)\to\pi\Lambda}{\Sigma(1775)\to\pi\Sigma} = 1/2$	3.1 ± 1.6
$\frac{\Sigma(1775)\to\pi\Sigma}{\Sigma(1775)\to\pi\Sigma_{10}} = 8/7$	1.3 ± 0.6
$\frac{2\Delta(1620)\to\pi\Delta+\Delta(1700)\to\pi\Delta}{8\Delta(1700)\to\pi N+N(1675)\to\pi N} = 1$	2.9 ± 1.2
$\frac{\frac{2}{9}\ N(1535)\to\pi\Delta+\frac{2}{9}\ N(1650)\to\pi\Delta+\frac{20}{3}\ \Delta(1620)\to\pi\Delta}{16\Delta(1700)\to\pi N+15N(1675)\to\pi N} = 1$	2.6 ± 1.2
$\frac{\frac{1}{36}\ N(1520)\to\pi N+\frac{1}{36}\ N(1700)\to\pi N+\frac{5}{12}\ \Delta(1620)\to\pi\Delta}{\Delta(1700)\to\pi N+N(1675)\to\pi N} = 1$	2.5 ± 1.2

SU(3) breaking very important

Two observations on decays

56-plets

$$\Gamma(N^*,\ \Delta^* \to N\eta,\ \Delta\eta) = \mathcal{O}(1/N_c^2)$$

70-plets

Strict large N_c

$$\theta_1 = \cos^{-1}(1/\sqrt{3}) = 54.7^o \qquad Phen: 23^o$$

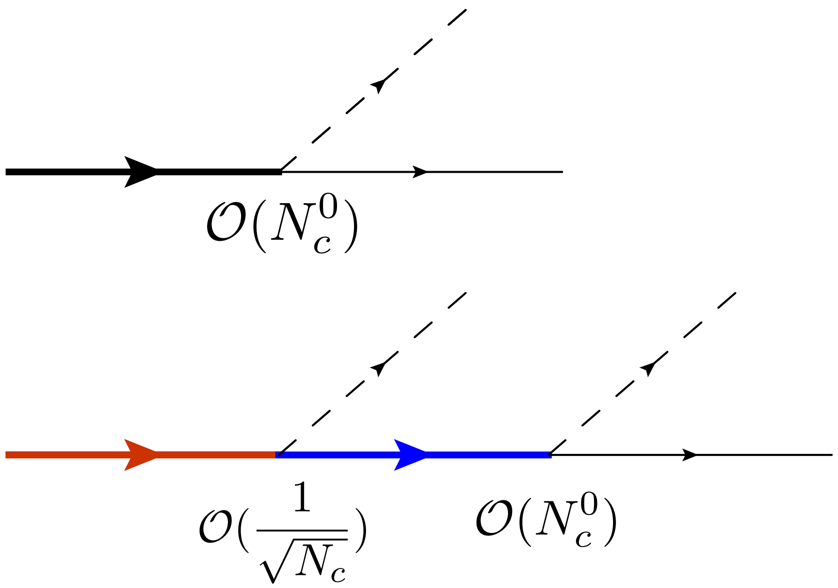
$$N(1535) \nrightarrow N\pi$$

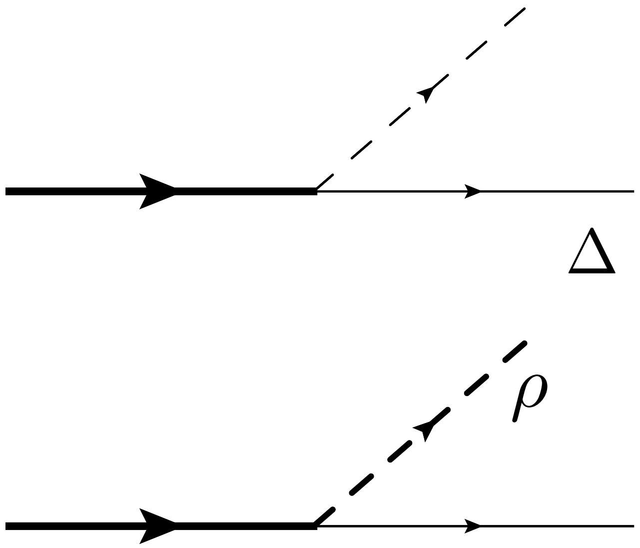
$$N(1535) \to N\eta$$

$$N(1650) \to N\pi$$

$$N(1650) \nrightarrow N\eta$$

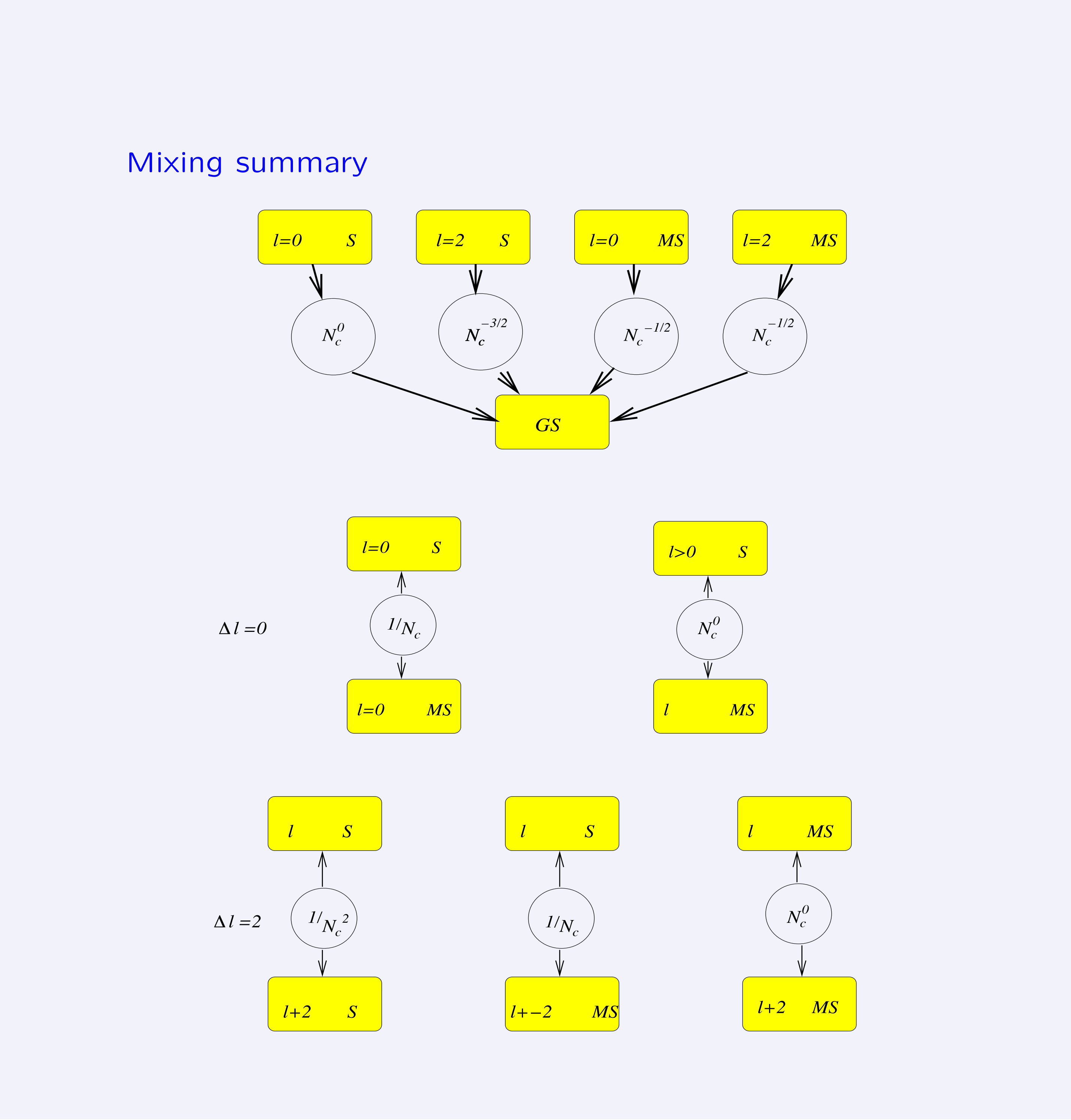
2 pion channels





State	$N\pi\pi(\%)$	
$D_{13}(1520)$	$40-50$	
		$\Delta\pi \sim 15-20$
		$N\rho \sim 15-25$
$S_{11}(1650)$	$12-20$	
		$\Delta\pi \sim 1-7$
		$N\rho \sim 4-12$
		$N(1440)\pi < 5$
$D_{13}(1700)$	$85-95$	
		$\Delta\pi > 30$
		$N\rho \sim 7$
$D_{15}(1675)$	$50-60$	
		$\Delta\pi \sim 50-60$
		$N\rho < 1-3$
$S_{31}(1620)$	$40-70$	
		$\Delta\pi \sim 30-60$
		$N(1440)\pi \sim 11$
$D_{33}(1700)$	$80-90$	
		$\Delta\pi \sim 30-60$
		$N\rho \sim 30-55$
		$N(1535)\pi \sim 4$
$\cdots$	$\cdots$	$\cdots$
$P_{31}(1910)$	$80-95$	
		$\Delta\pi \sim 6$
		$N\rho \sim 30$
		$N(1440)\pi \sim 56$
$P_{33}(1920)$	~ 100	
		$\Delta\pi \sim 41$
		$N(1535)\pi \sim 6$
		$N(1440)\pi \sim 53$

Configuration mixings



Summary on $1/N_c$ in baryons

- In principle, $1/N_c$ gives rigorous connection to QCD
- An expansion for sorting out effects by magnitude
- In baryons it basically organizes how SU(6) symmetry is broken
- Gives relationships which are beyond dynamics at a given order in $1/N_c$ - parameter independent relations, which serve as tests
- Important dynamical insight associated with small coefficients: small spin-orbit; small 3-body forces; dominance of 1-body operators in strong decays and photo-couplings
- Relevant dynamics is hidden in effective coefficients: both long and short distance effects
- It can be applied to lattice results (mass spectrum) which is very promising
- It should be no problem to implement $1/N_c$ in phenomenological models used in PWA