Excited Baryon Decays in 1/Nc

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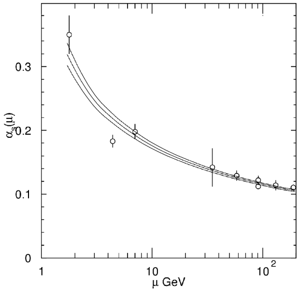
Outline

- Introduction to Large Nc QCD
- Baryon in Large Nc
- Spin-Flavor Symmetry
- Operator Analysis
- Excited Baryons
  - Masses
  - Strong Decays
- Conclusions and outlook

- Why $\frac{1}{N_c}$ Expansion?



- No perturbative expansion of QCD at low energies with respect to α_s
- Generalized QCD from 3 colors to N_c colors: Gauge group change $SU(3) \to SU(N_c)$ ('t Hooft, 1974)
- There exists a systematic expansion in powers of $1/N_c$
- Lagrangian for Large N_c

$$\mathcal{L} = -\frac{1}{2} Tr G^{\mu\nu} G_{\mu\nu} + \sum_{f=1}^{N_f} \bar{q}_f (i\not{D} - m_f) q_f$$

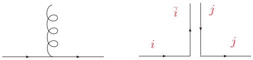
- In general two limits are used
  - 't Hooft : $N_c \to \infty, N_f$ fixed
  - Veneziano : $N_c \to \infty, \frac{N_f}{N_c}$ fixed
- $N_c \to \infty$ limit expected to be qualitatively similar to $N_c = 3$

- Feynman diagrams for large N_c

  * 't Hooft double line notation:

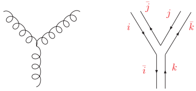
  * Interaction vertices:

quark-gluon vertex:



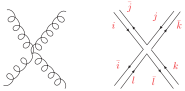
$\bar{q}_j \gamma^\mu A^{j}_{\mu\ i} q^i$

3-gluon vertex:



$A^{i}_{\mu\ j} A^{j}_{\nu\ k} \partial^\mu A^{\nu\ k}_{i}$

4-gluon vertex:



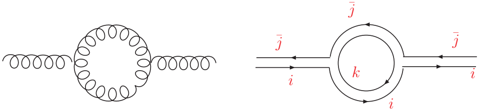
$A^{i}_{\mu\ j} A^{j}_{\nu\ k} A^{\mu\ k}_{l} A^{\nu\ l}_{i}$

- Scaling of strong coupling: $g' = \dfrac{g_0}{\sqrt{N_c}}$

  limit $N_c \to \infty$; g_0 is fixed

  $\Rightarrow$ Remove the divergence & diagrams are $\mathcal{O}(1)$

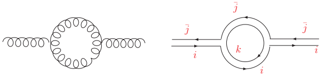
- Feynman diagrams for large N_c



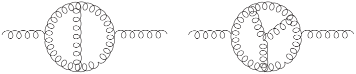
$$\underbrace{\left(\frac{1}{\sqrt{N_c}}\right)^2}_{\text{vertices}} \quad \overbrace{N_c}^{\text{Sum over k}} \quad = \quad 1$$

Introduction cont..

- Feynman diagrams for large N_c

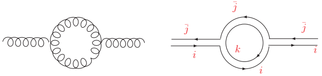


Gluon loops are $\mathcal{O}(1)$



Planar gluon insertions don't change order

- Feynman diagrams for large N_c



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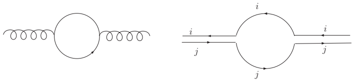
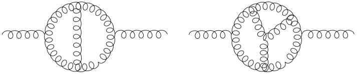


Quark loops are $\mathcal{O}(1/N_c)$



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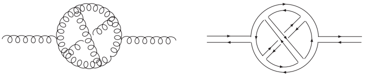
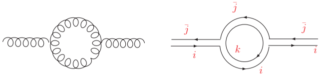


Non-planar diagrams are $\mathcal{O}(1/N_c^2)$

- Feynman diagrams for large N_c



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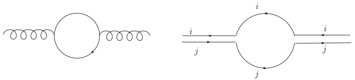

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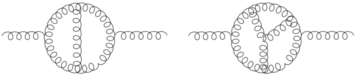

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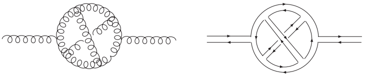
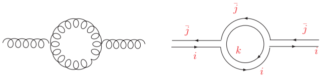


Non-planar diagrams are $\mathcal{O}(1/N_c^2)$

- The leading Feynman diagrams are planar diagrams with minimum number of quark loops

- Feynman diagrams for large N_c



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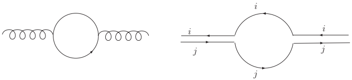

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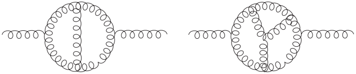

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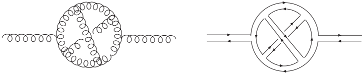


Non-planar diagrams are $\mathcal{O}(1/N_c^2)$

- The leading Feynman diagrams are planar diagrams with minimum number of quark loops
- N_c Counting: (*Witten*, 1979)
  - Mesons:

    M_{mass} $\mathcal{O}(1)$
    f_π $\mathcal{O}(\sqrt{N_c})$
    $\Gamma_{M\rightarrow MM}$ $\mathcal{O}(1/\sqrt{N_c})$

  - Baryons:

    B_{mass} $\mathcal{O}(N_c)$
    B_{size} $\mathcal{O}(1)$
    g_{BM} $\mathcal{O}(\sqrt{N_c})$

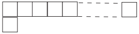
- Baryon has N_c valence quarks
- Hartee approximation is exact in $N_c \to \infty$ limit *(Witten)*
  - each quark moves in average potential generated by $(N_c - 1)$ quarks
  - total potential experienced by each quark is $\mathcal{O}(1)$
  - interaction between any pair of quarks is $\mathcal{O}(1/N_c)$
- Ground State:

$$\Psi^{GS}_{\xi_1 \ldots . \xi_{N_c}}(x_1, \ldots .. x_{N_c}) = \chi^S_{\xi_1 \ldots . \xi_{N_c}} \prod_{i=1}^{N_c} \phi(x_i)$$

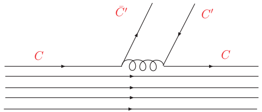
- Excited States:

$$\Psi^{S}_{\xi_1 \ldots . \xi_{N_c}}(x_1, \ldots .. x_{N_c}) = \frac{1}{\sqrt{N_c}} \chi^S_{\xi_1 \ldots . \xi_{N_c}} \sum_{i=1}^{N_c} \phi(x_1) \ldots . \phi(x_i) \ldots .. \phi(x_{N_c})$$

$$\Psi^{MS}_{\xi_1 \ldots . \xi_{N_c}}(x_1, \ldots .. x_{N_c}) = \frac{1}{\sqrt{N_c}(N_c - 1)!} \sum_{\sigma} \chi^{MS}_{\xi_{\sigma_1} \ldots . \xi_{\sigma_{N_c}}} \phi(x_{\sigma_1}) \ldots . \phi(x_{\sigma_{N_c - 1}}) \phi'(x_{\sigma_{N_c}})$$

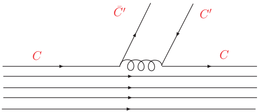


- Baryon-meson coupling



$$\overbrace{\left(\frac{1}{\sqrt{N_c}}\right)^2}^{\textbf{vertices}} \quad \underbrace{N_c}_{\textbf{sum over C}} \quad \overbrace{\frac{1}{\sqrt{N_c}}}^{\textbf{meson}} \quad \underbrace{N_c}_{\textbf{sum over C}'} \quad = \mathcal{O}(\sqrt{N_c})$$

- Baryon-meson coupling



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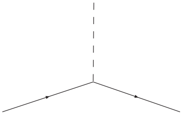
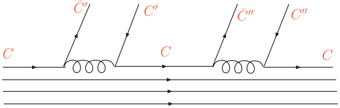
- $\pi-$ nucleon coupling:



$$\frac{\partial_\mu \pi_a}{f_\pi}(\langle B|\bar{q}\gamma^\mu\gamma_5 T^a q|B\rangle)$$
$$= g_A \frac{N_c}{f_\pi}\partial_i \pi_a \langle B|\chi^{ia}|B\rangle = \mathcal{O}(\sqrt{N_c})$$

- Baryon-meson scattering amplitude

Baryon + Meson $\longrightarrow$ Baryon + Meson



$$\overbrace{\left(\frac{1}{\sqrt{N_c}}\right)^4}^{\textbf{vertices}} \quad \underbrace{N_c}_{\textbf{sum over C}} \quad \overbrace{\left(\frac{1}{\sqrt{N_c}}\right)^2}^{\textbf{mesons}} \quad \underbrace{(N_c)^2}_{\textbf{sum over C}',\textbf{C}''} \quad = \mathcal{O}(1)$$

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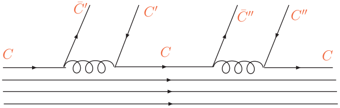

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- $\pi-$ nucleon scattering amplitude:

$$\propto \quad \frac{g_A^2}{f_\pi^2} N_c^2 (\langle B'|\chi^{jb}\chi^{ia}|B\rangle) \frac{i}{k_0} \quad \sim \mathcal{O}(N_c)$$

- $\pi-$ nucleon scattering amplitude:

$$\propto \quad \frac{g_A^2}{f_\pi^2} N_c^2 \{(\langle B'|\chi^{jb}\chi^{ia}|B\rangle)\frac{i}{k_0} - (\langle B'|\chi^{jb}\chi^{ia}|B\rangle)\frac{i}{k_0'}\}$$

$$= \frac{g_A^2}{f_\pi^2}\frac{i}{k_0} N_c^2(\langle B'|[\chi^{jb},\chi^{ia}]|B\rangle + \mathcal{O}(1/N_c^2)) \qquad \text{since } k_0' = k_0 + \mathcal{O}(1/N_c)$$

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$$= \frac{g_A^2}{f_\pi^2} \frac{i}{k_0} N_c^2 (\langle B'|[\chi^{jb},\chi^{ia}]|B\rangle + \mathcal{O}(1/N_c^2)) \qquad \text{since } k'_0 = k_0 + \mathcal{O}(1/N_c)$$

- Consistancy condition $[\chi^{jb},\chi^{ia}] = \mathcal{O}(1/N_c)$

  Gervais-Sakita-Dashen-Manohar

  $\Rightarrow$ **Contracted spin-flavor symmetry**

- Generators of contracted $SU(2N_f)$:

$$S^i, \quad T^a, \quad \chi^{ia} = \frac{G^{ia}}{N_c}$$

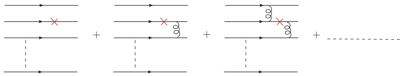
$$S^i = q^\dagger \frac{\sigma^i}{2} q$$

$$T^a = q^\dagger \frac{\lambda^a}{2} q$$

$$G^{ia} = q^\dagger \frac{\sigma^i \lambda^a}{4} q$$

- Effective operators

QCD operator $\mathcal{Q} = \bar{q}\Gamma q$



Effective operator at baryon level

$$\mathcal{Q} = \sum_n \frac{1}{N_c^{(n-1)}} C_n O^n$$

O^n is the n-body operator acting on baryon degree of freedom

- General form of effective operator

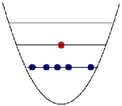
$$O = \mathcal{R} \times \mathcal{G}$$

$\mathcal{R}$ is an $O(3)$ tensor

$\mathcal{G}$ is a spin flavor tensor made of product of **n** generators of $SU(2N_f)$

- Convenient basis of states are multiplets of $SU(6) \times O(3)$
- Low excitations
  - Baryons composed of $\mathcal{O}(N_c)$ ground state quarks (**core**) and $\mathcal{O}(1)$ excited quarks
  - Core is spin flavor symmetric state as ground state baryon
- $SU(6)$ generators:

Core states (Λ_c)	Excited states (λ)
$S_c^i \;\; T_c^a \;\; G_c^{ia}$	$s^i \;\; t^a \;\; g^{ia}$



- Spin-flavor operator:

$$\mathcal{G} = \frac{1}{N_c^n} \lambda \prod_{r=1}^{n} \Lambda_c^{(r)}$$

- Excited state :

$$\left| \begin{array}{cc} J & [p,q] \\ J_z & Y, I, I_z \end{array} \right\rangle =$$

$$\sum \left(\begin{array}{cc|c} S & l & J \\ S_z & l_z & J_z \end{array} \right) \left(\begin{array}{cc|c} S^c & 1/2 & S \\ S^c_z & s_z & S_z \end{array} \right) \left(\begin{array}{cc|c} I^c & i & I \\ I^c_z & i_z & I_z \end{array} \right)$$

$$\left(\begin{array}{cc||c} [p^c, q^c] & [1,0] & [p,q] \\ Y^c, I^c & y, i & Y, I \end{array} \right) \left| \begin{array}{cc} S^c & [p^c, q^c] \\ S^c_z & Y^c, I^c, I^c_z \end{array} \right\rangle \otimes \left| \begin{array}{cc} 1/2 & [1,0] \\ s_z & y, i, i_z \end{array} \right\rangle$$

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- Wigner-Eckart theorem :

$$\left\langle \begin{array}{cc} S' & [p,q] \\ S'_z & Y',I',I'_z \end{array} \left| \mathcal{O}^{[J,8]}_{[J_z,\alpha]} \right| \begin{array}{cc} S & [p,q] \\ S_z & Y,I,I_z \end{array} \right\rangle =$$

$$\frac{1}{\sqrt{2S'+1}} \frac{1}{\sqrt{dim(p',q')}} \left(\begin{array}{cc|c} S & J & S' \\ S_z & J_z & S'_z \end{array} \right) \left(\begin{array}{cc|c} I & I^\alpha & I' \\ I_z & I^\alpha_z & I'_z \end{array} \right)$$

$$\times \sum_{r=1}^{2} \left(\begin{array}{cc||c} [p,q] & [1,1] & [p',q'] \\ Y,I & Y^\alpha, I^\alpha & Y',I' \end{array} \right)_r \left\langle \begin{array}{c} [p',q'] \\ S' \end{array} \left\| \mathcal{O}^{[J,8]} \right\| \begin{array}{c} [p,q] \\ S \end{array} \right\rangle_r$$

- Mass operator:

$$\mathcal{M} = \sum_i c_i O^i + \sum_j d_j B^j$$

O^i : Symmetric operators B^j : SU(3) breaking operators

- Ground state masses [Dashen & Manohar,etc...]

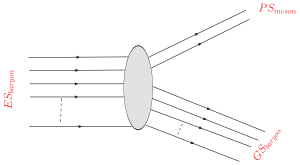
∗ Mass operator: $\mathcal{M} = C_0 N_c + C_2 \frac{S^2}{N_c} + \epsilon C_1 T^8$

parameter free mass relations

$(\Xi - \Sigma) = \frac{1}{2}(3\Lambda - \Sigma) - N$	GMO
$(\Sigma_{10} - \Delta) = (\Xi_{10} - \Sigma_{10})$	EQS
$(\Xi_{10} - \Sigma_{10}) = (\Omega - \Xi_{10})$	EQS
$(\Sigma_{10} - \Sigma) = (\Xi_{10} - \Xi)$	$8 - 10$
$(3\Lambda + \Sigma - 2(N + \Xi)) = (\Xi_{10} + \Sigma_{10} - \Omega - \Delta)$	$8 - 10$

- Excited state masses [Goity,Schat,Scoccola,etc...]
    - Symmetric states: $[56', 0^+], [56, 2^+], [56, 4^+]$
    - Mixsymmetric states: $[70, 1^-]$

- Excited baryon decays into ground state baryon & pseudoscalar meson



- The most general form of the invariant amplitude

$$\mathcal{M} = (-1)^{l_\pi} \sqrt{2M_B^*}\, Y^*_{l_\pi,\mu}(\hat{\mathrm{k}}_\pi) \sum_{\mu,\alpha} \underbrace{\left\langle \begin{array}{cc} l_\pi & [1,1] \\ l_{\pi_3} & \alpha \end{array} \middle| \mathcal{P}^{[l_\pi,8]}_{[\mu,\alpha]} \middle| \begin{array}{c} [0,0] \\ 0 \end{array} \right\rangle}_{\textbf{mesonic operator}}$$

$$\times \underbrace{\left\langle \begin{array}{cc} S' & [p',q'] \\ S'_3 & \alpha_f \end{array} \middle| \mathcal{B}^{[l_\pi,8]}_{[-\mu,-\alpha]} \middle| \begin{array}{cc} J & [p,q] \\ J_3 & \alpha_i \end{array} \right\rangle}_{\textbf{baryonic operator}}$$

- The general form of the baryonic operator

$$\mathcal{B}^{[l_\pi,8]}_{[\mu,\alpha]} = (\frac{k_\pi}{\Lambda})^{l_\pi} \sum_n c_n(k_\pi)(\mathcal{O}^{[l_\pi,8]}_{[\mu,\alpha]})_n$$

- Effective operator

$$(\mathcal{O}^{[l_\pi,8]}_{[\mu,\alpha]})_n = \sum \langle lm, j' j'_3 | l_\pi \mu \rangle \overbrace{\xi^l_m}^{\text{O(3) operator}} \underbrace{(\mathcal{G}^{[j',8]}_{[j'_3,\alpha]})_n}_{\text{SU(2N}_f\text{) operators}}$$

- Decay width

$$\Gamma = f_{phs} \frac{(2I'+1)}{(2J+1)(2I+1)} \underbrace{\left| \sum_n c_n \mathcal{B}([p',q'],S',[p,q],J)_n \right|^2}_{\mathcal{A}^2}$$

$$f_{phs} = \frac{k_\pi^{(2l_\pi+1)}}{8\pi^2\Lambda^{2l_\pi}} \frac{M_B}{M^*_B}$$

- $[56, 0^+]$ P-wave decays
  - * All independent operators up to $\mathcal{O}(1/N_c)$:

$$O_1 = \frac{1}{N_c}(\xi^0 G)^{[1,8]}_{[i,\alpha]}$$

$$O_2 = \frac{1}{N_c^2}(\xi^0 \{S, G\}^{[1,8]})^{[1,8]}_{[i,\alpha]}$$

$$B_1 = \frac{1}{N_c}(d^{8ab}\xi^0 G)^{[1,8]}_{[i,\alpha]}$$

$$B_2 = \frac{i}{N_c}(f^{8ab}\xi^0 G)^{[1,8]}_{[i,\alpha]}$$

  - * Matrix elements :

Channel	O_1	O_2	B_1
π	$\mathcal{O}(1)$	$\mathcal{O}(1/N_c)$	$\mathcal{O}(1)$
$K(\bar{K})$	$\mathcal{O}(\frac{1}{\sqrt{N_c}})$	$\mathcal{O}(\frac{1}{N_c^{3/2}})$	$\mathcal{O}(\frac{1}{\sqrt{N_c}})$
η	$\mathcal{O}(1/N_c)$	$\mathcal{O}(1/N_c^2)$	$\mathcal{O}(1/N_c)$

- $[56, 0^+]$ P-wave decays: $\mathcal{A} = \sum_{i=1}^{2} c_i O_i + \sum_{j=1}^{2} d_j B_j$

		LO (Mev)
	χ^2_{dof}	2.23
	dof	6
	c_1	10.43 ± 1.5
	c_2	....
	d_1	....
$N^* \to N\pi$	211.25 ± 87.5	89.9
$N^* \to \Delta\pi$	81.25 ± 35.2	12.2
$\Lambda^* \to N\bar{K}$	33.75 ± 25.2	0
$\Lambda^* \to \Sigma\pi$	52.5 ± 51.3	72.4
$\Sigma^* \to N\bar{K}$	24 ± 20	0
$\Delta^* \to N\pi$	61.25 ± 31.5	92.1
$\Delta^* \to \Delta\pi$	192.5 ± 76	54.8

Positive Parity Excited Baryon Decays

- $[56, 0^+]$ P-wave decays: $\mathcal{A} = \sum_{i=1}^{2} c_i O_i + \sum_{j=1}^{2} d_j B_j$

		LO (Mev)	NLO Sym (Mev)
	χ^2_{dof}	2.23	0.70
	dof	6	5
	c_1	10.43 ± 1.5	9.34 ± 1.02
	c_2	....	-10.66 ± 3.74
	d_1	....	....
$N^* \to N\pi$	211.25 ± 87.5	89.9	200.6
$N^* \to \Delta\pi$	81.25 ± 35.2	12.2	60
$\Lambda^* \to N\bar{K}$	33.75 ± 25.2	0	51.6
$\Lambda^* \to \Sigma\pi$	52.5 ± 51.3	72.4	103.5
$\Sigma^* \to N\bar{K}$	24 ± 20	0	7.1
$\Delta^* \to N\pi$	61.25 ± 31.5	92.1	54.8
$\Delta^* \to \Delta\pi$	192.5 ± 76	54.8	122.4

- NLO corrections are considerable ($> 20\%$)

Positive Parity Excited Baryon Decays

- $[56, 0^+]$ P-wave decays: $\mathcal{A} = \sum_{i=1}^{2} c_i O_i + \sum_{j=1}^{2} d_j B_j$

		LO (Mev)	NLO Sym (Mev)	NLO Sym.Bk(Mev)
	χ^2_{dof}	2.23	0.70	0.77
	dof	6	5	4
	c_1	10.43 ± 1.5	9.34 ± 1.02	9.66 ± 1.11
	c_2	....	-10.66 ± 3.74	-11.26 ± 3.73
	d_1	....	....	20.4 ± 3.29
$N^* \to N\pi$	211.25 ± 87.5	89.9	200.6	214.5
$N^* \to \Delta\pi$	81.25 ± 35.2	12.2	60	65
$\Lambda^* \to N\bar{K}$	33.75 ± 25.2	0	51.6	37.9
$\Lambda^* \to \Sigma\pi$	52.5 ± 51.3	72.4	103.5	110.6
$\Sigma^* \to N\bar{K}$	24 ± 20	0	7.1	5.2
$\Delta^* \to N\pi$	61.25 ± 31.5	92.1	54.8	56.2
$\Delta^* \to \Delta\pi$	192.5 ± 76	54.8	122.4	130.8

- $SU(3)$ breaking is considerable

- $[56, 2^+]$ P-wave decays:

$$O_1 = \frac{1}{N_c}(\xi^2 G)^{[1,8]}_{[i,\alpha]}$$

$$O_2 = \frac{1}{N_c^2}(\xi^2 \{S, G\}^{[1,8]})^{[1,8]}_{[i,\alpha]}$$

$$O_3 = \frac{1}{N_c^2}(\xi^2 \{S, G\}^{[2,8]})^{[1,8]}_{[i,\alpha]}$$

$$B_1 = \frac{1}{N_c}(d^{8ab}\xi^2 G)^{[1,8]}_{[i,\alpha]}$$

$$B_2 = \frac{i}{N_c}(f^{8ab}\xi^2 G)^{[1,8]}_{[i,\alpha]}$$

$$\mathcal{A} = \sum_{i=1}^{3} c_i O_i + \sum_{j=1}^{2} d_j B_j$$

- $[56, 2^+]$ P-wave decays:

		LO (Mev)
	χ^2_{dof}	1.6
	dof	6
	c_1	4.20 ± 0.51
	c_2	....
	c_2	....
	d_1	....
$N^*_{3/2} \to N\pi$	34 ± 16	20.2
$N^*_{3/2} \to \Lambda K$	18 ± 17	0
$N^*_{5/2} \to \Delta\pi$	13 ± 5	7.9
$\Lambda^*_{3/2} \to N\bar{K}$	36 ± 22	0
$\Lambda^*_{3/2} \to \Sigma\pi$	8.5 ± 6	18.4
$\Delta^*_{1/2} \to N\pi$	52 ± 19	30.5
$\Delta^*_{3/2} \to N\pi$	28 ± 19	16.6

- $[56, 2^+]$ P-wave decays:

		LO (Mev)	NLO Sym(Mev)
	χ^2_{dof}	1.6	1.2
	dof	6	4
	c_1	4.20 ± 0.51	2.96 ± 0.32
	c_2	....	0.10 ± 1.09
	c_2	....	0.38 ± 2.34
	d_1	....	....
$N^*_{3/2} \to N\pi$	34 ± 16	20.2	27.8
$N^*_{3/2} \to \Lambda K$	18 ± 17	0	0.67
$N^*_{5/2} \to \Delta\pi$	13 ± 5	7.9	10.4
$\Lambda^*_{3/2} \to N\bar{K}$	36 ± 22	0	8.9
$\Lambda^*_{3/2} \to \Sigma\pi$	8.5 ± 6	18.4	16.2
$\Delta^*_{1/2} \to N\pi$	52 ± 19	30.5	45.9
$\Delta^*_{3/2} \to N\pi$	28 ± 19	16.6	22

- NLO corrections are negligible ($< 1\%$)

- $[56, 2^+]$ P-wave decays:

		LO (Mev)	NLO Sym(Mev)	NLO Sym.Bk(Mev)
	χ^2_{dof}	1.6	1.2	1.0
	dof	6	4	3
	c_1	4.20 ± 0.51	2.96 ± 0.32	2.92 ± 0.32
	c_2	....	0.10 ± 1.09	0.10 ± 1.12
	c_2	....	0.38 ± 2.34	0.44 ± 2.38
	d_1	....	....	3.68 ± 2.03
$N^*_{3/2} \to N\pi$	34 ± 16	20.2	27.8	27
$N^*_{3/2} \to \Lambda K$	18 ± 17	0	0.67	2.9
$N^*_{5/2} \to \Delta\pi$	13 ± 5	7.9	10.4	10.1
$\Lambda^*_{3/2} \to N\bar{K}$	36 ± 22	0	8.9	37.9
$\Lambda^*_{3/2} \to \Sigma\pi$	8.5 ± 6	18.4	16.2	15.7
$\Delta^*_{1/2} \to N\pi$	52 ± 19	30.5	45.9	45.2
$\Delta^*_{3/2} \to N\pi$	28 ± 19	16.6	22	21.3

- Considerably large $SU(3)$ breaking

- $[56, 2^+]$ F-wave decays:

$$O_1 = \frac{1}{N_c}(\xi^2 G)^{[3,8]}_{[i,\alpha]}$$

$$O_2 = \frac{1}{N_c^2}(\xi^2 \{S, G\}^{[1,8]})^{[3,8]}_{[i,\alpha]}$$

$$O_3 = \frac{1}{N_c^2}(\xi^2 \{S, G\}^{[2,8]})^{[3,8]}_{[i,\alpha]}$$

$$B_1 = \frac{1}{N_c}(d^{8ab}(\xi^2 G)^{[3,8]}_{[i,\alpha]}$$

$$B_2 = \frac{i}{N_c}(f^{8ab}\xi^2 G)^{[3,8]}_{[i,\alpha]}$$

$$\mathcal{A} = \sum_{i=1}^{3} c_i O_i + \sum_{j=1}^{2} d_j B_j$$

- $[56, 2^+]$ F-wave decays:

		LO (Mev)
	χ^2_{dof}	3.4
	dof	8
	c_1	0.5 ± 0.04
	c_2	....
	c_3	....
	d_1	....
$N^*_{1/2} \to N\pi$	88 ± 8	26.3
$\Delta^*_{5/2} \to N\pi$	40 ± 13	14.6
$\Delta^*_{7/2} \to N\pi$	114 ± 25	83.5
$\Sigma^*_{7/2} \to N\bar{K}$	35 ± 7	0
$\Sigma^*_{7/2} \to \Lambda\pi$	35 ± 7	47.6
$\Sigma^*_{7/2} \to \Sigma\pi$	13.1 ± 4.8	16
$\Sigma^*_{7/2} \to \Sigma_{10}\pi$	17.5 ± 9.1	12.7
$\Sigma^*_{5/2} \to N\bar{K}$	12 ± 7	0
$\Sigma^*_{7/2} \to \Xi K$	1.75 ± 1.75	0

- $[56, 2^+]$ F-wave decays:

		LO (Mev)	NLO Sym(Mev)
	χ^2_{dof}	3.4	2.1
	dof	8	6
	c_1	0.5 ± 0.04	0.5 ± 0.02
	c_2	....	-0.28 ± 0.05
	c_3	....	0.18 ± 0.1
	d_1	....	....
$N^*_{1/2} \to N\pi$	88 ± 8	26.3	71.5
$\Delta^*_{5/2} \to N\pi$	40 ± 13	14.6	38.1
$\Delta^*_{7/2} \to N\pi$	114 ± 25	83.5	118.6
$\Sigma^*_{7/2} \to N\bar{K}$	35 ± 7	0	53.1
$\Sigma^*_{7/2} \to \Lambda\pi$	35 ± 7	47.6	35.3
$\Sigma^*_{7/2} \to \Sigma\pi$	13.1 ± 4.8	16	11.9
$\Sigma^*_{7/2} \to \Sigma_{10}\pi$	17.5 ± 9.1	12.7	14.7
$\Sigma^*_{5/2} \to N\bar{K}$	12 ± 7	0	4.5
$\Sigma^*_{7/2} \to \Xi K$	1.75 ± 1.75	0	0.7

- C2 effects are $< 10\%$ and C3 effects are $< 5\%$

- $[56, 2^+]$ F-wave decays:

		LO (Mev)	NLO Sym(Mev)	NLO Sym.Bk(Mev)
	χ^2_{dof}	3.4	2.1	0.5
	dof	8	6	5
	c_1	0.5 ± 0.04	0.5 ± 0.02	0.55 ± 0.02
	c_2	....	-0.28 ± 0.05	-0.39 ± 0.05
	c_3	....	0.18 ± 0.1	0.2 ± 0.1
	d_1	....	....	0.16 ± 0.05
$N^*_{1/2} \to N\pi$	88 ± 8	26.3	71.5	87.4
$\Delta^*_{5/2} \to N\pi$	40 ± 13	14.6	38.1	40.6
$\Delta^*_{7/2} \to N\pi$	114 ± 25	83.5	118.6	123
$\Sigma^*_{7/2} \to N\bar{K}$	35 ± 7	0	53.1	36
$\Sigma^*_{7/2} \to \Lambda\pi$	35 ± 7	47.6	35.3	34.3
$\Sigma^*_{7/2} \to \Sigma\pi$	13.1 ± 4.8	16	11.9	11.5
$\Sigma^*_{7/2} \to \Sigma_{10}\pi$	17.5 ± 9.1	12.7	14.7	18.3
$\Sigma^*_{5/2} \to N\bar{K}$	12 ± 7	0	4.5	3
$\Sigma^*_{7/2} \to \Xi K$	1.75 ± 1.75	0	0.7	0.5

- $SU(3)$ breaking effects are $< 10\%$

- $1/N_c$ is successfully applied to excited baryon decays
- Clear dominance of one-body LO operator G^{ia} as in chiral quark model
- $1/N_c$ order of decay channels:

Channel	**Amplitude**	**Width**
π	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$K(\bar{K})$	$\mathcal{O}(1/\sqrt{N_c})$	$\mathcal{O}(1/N_c)$
η	$\mathcal{O}(1/N_c)$	$\mathcal{O}(1/N_c^2)$

- NLO coefficients poorly determined due to the large errors in input widths
- More precise inputs needed to determine significance of NLO corrections

Outlook

- Negative parity excited baryon decays: $[70, 1^-]$
  - There are 7 symmetric operators
  - There are more than 20 $SU(3)$ breaking operators at the LO
  - There are two mixing angles
- Same method can be applied to excited baryon EM decays