Charm baryon spectroscopy from heavy quark symmetry

Phys. Rev. D91, 014031 (2015)

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Hadrons and Hadron Interaction in QCD (HHIQCD 2015)@YITP, 16 Feb. – 20 Mar. 2015

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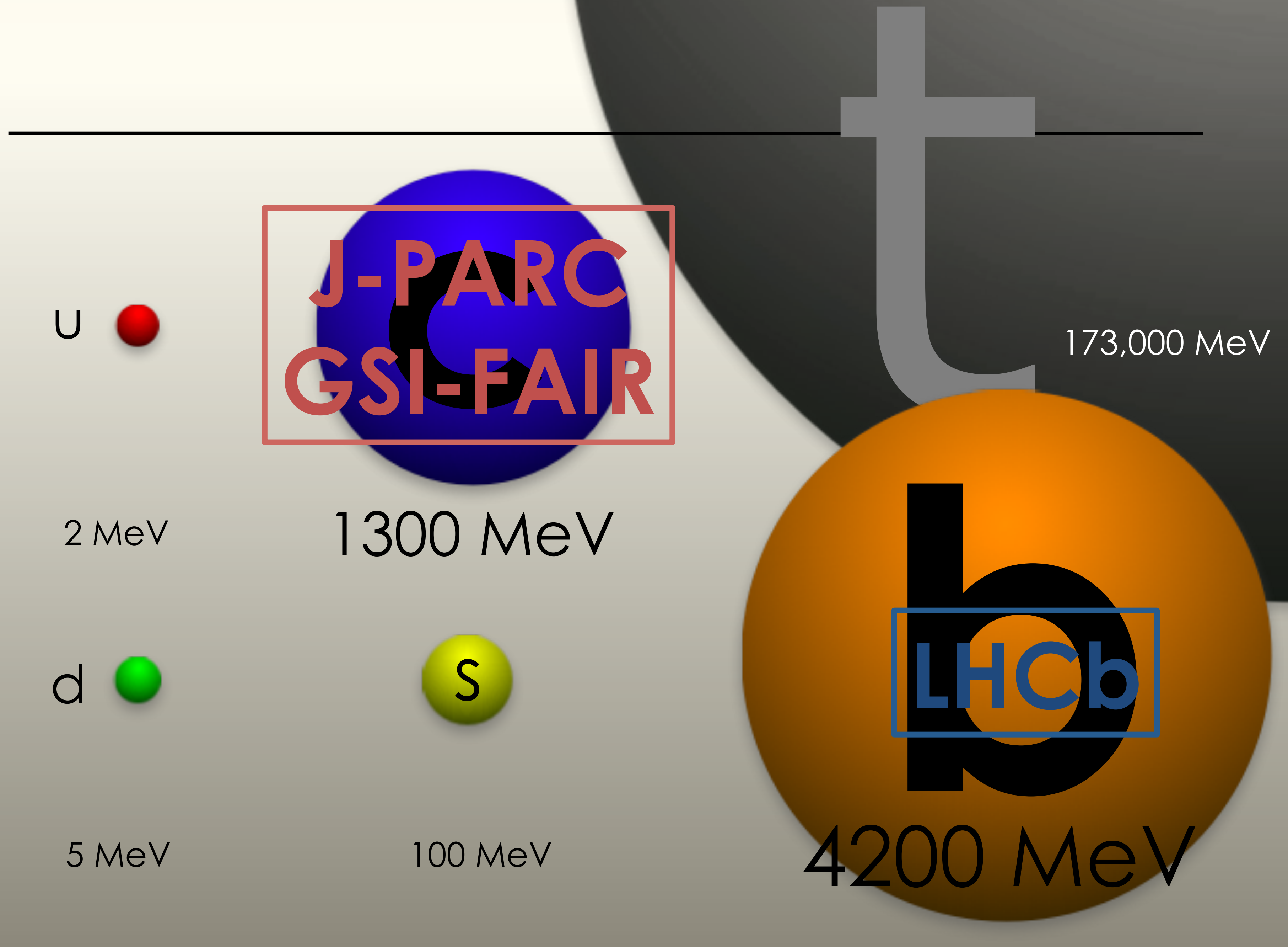
1. Heavy quark symmetry



1. Heavy quark symmetry

$$\mathcal{L}_{\text{heavy quark}} = \bar{Q}(i\not{D} - m_{\text{Q}})Q \qquad D_\mu = \partial_\mu - igA_\mu^a T^a$$

1/m_Q expansion

(positive energy state Q_v with velocity v)

Manohar, Wise, Luke, Grinstein, ...

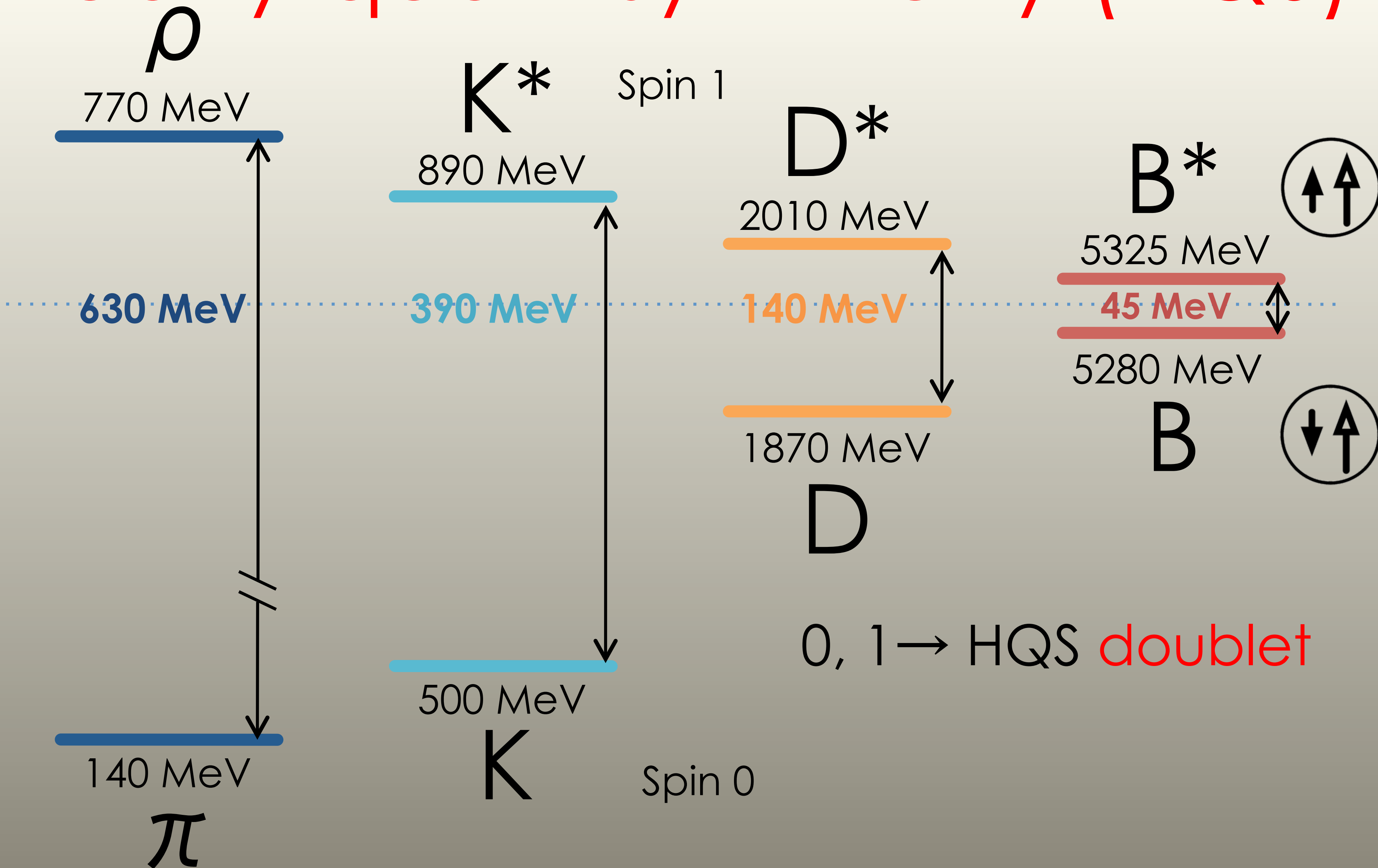
$$\mathcal{L}_{\text{HQET}} = \boxed{\bar{Q}_v v\cdot iDQ_v} + \bar{Q}_v \frac{(iD_\perp)^2}{2m_{\text{Q}}} Q_v - g_s \bar{Q}_v \frac{\sigma_{\mu\nu}G^{\mu\nu}}{4m_{\text{Q}}} Q_v + \mathcal{O}(1/m_{\text{Q}}^2)$$

LO

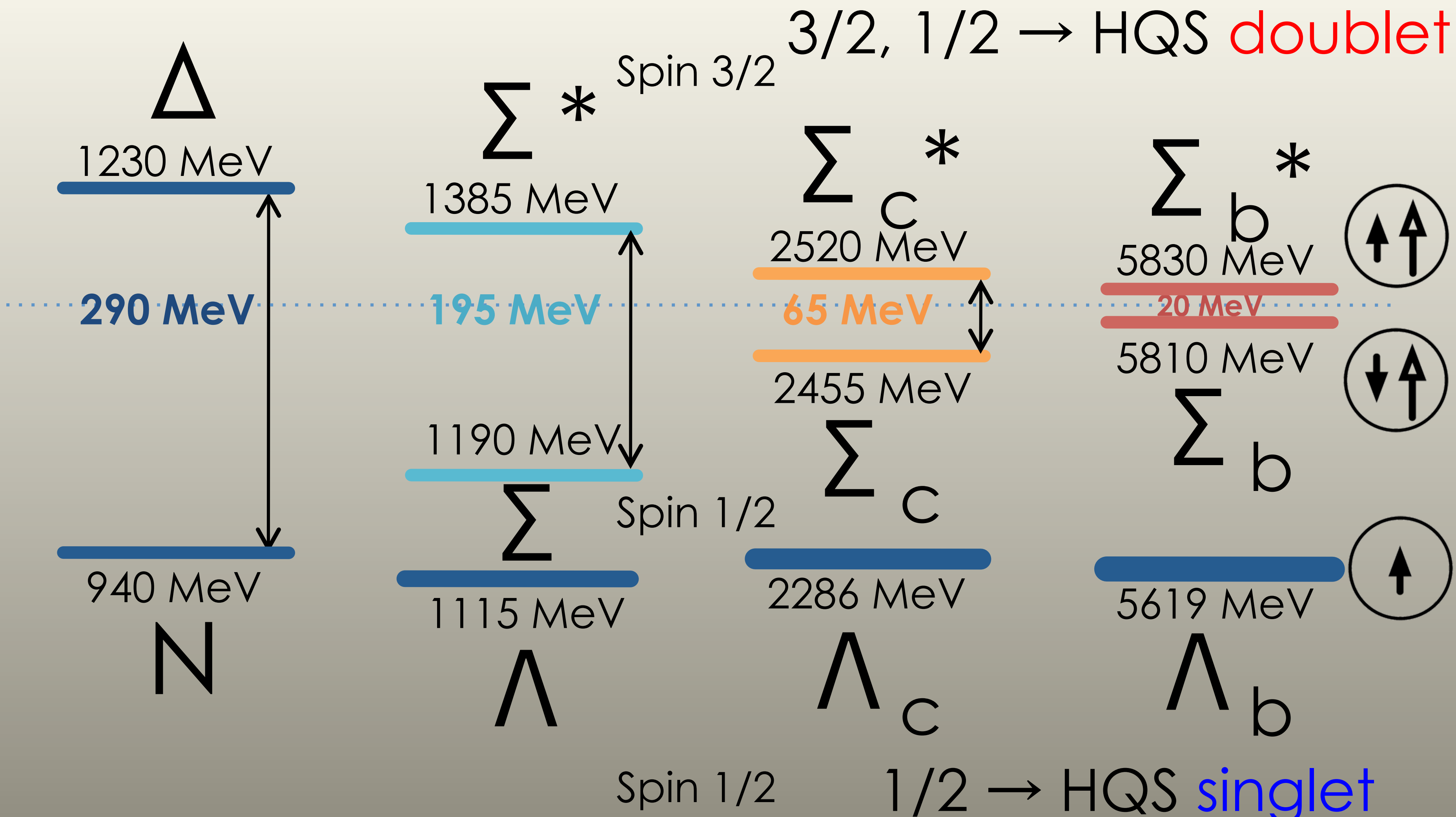
Heavy quark spin in $m_Q \to \infty$ is conserved.

Heavy quark symmetry (HQS)

Heavy quark symmetry (HQS)



Heavy quark symmetry (HQS)



Heavy quark symmetry (HQS)

Heavy baryon (Qqq)

$\Psi^{(j)}_{J}$

"**Brown Muck**" : Light quarks and gluons with definite total spin (j), quark # = 2 and color **3**bar

diquark (?)

Heavy quark with spin 1/2

$J=j\pm1/2$

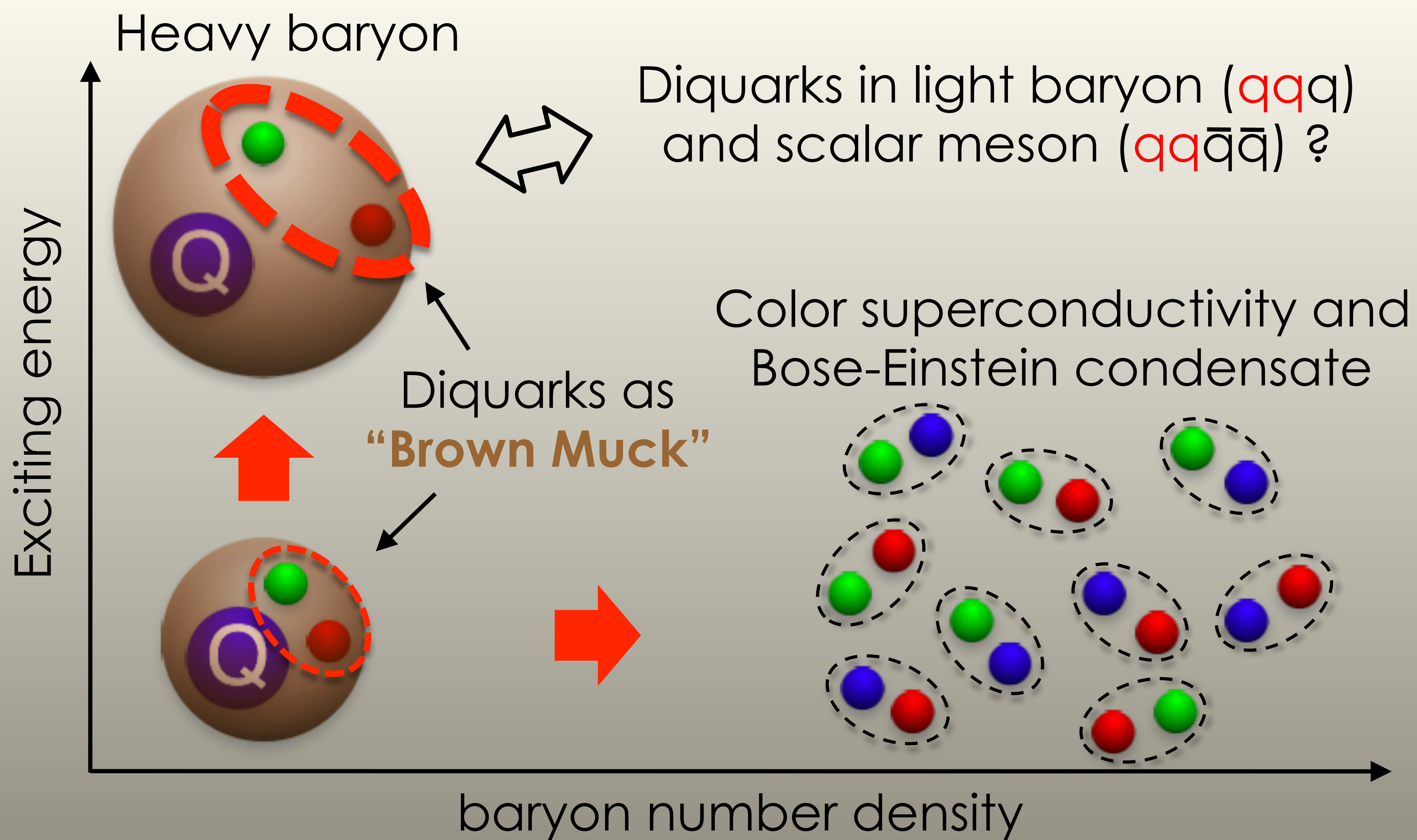
Mass spectrum

HQS doublet/singlet

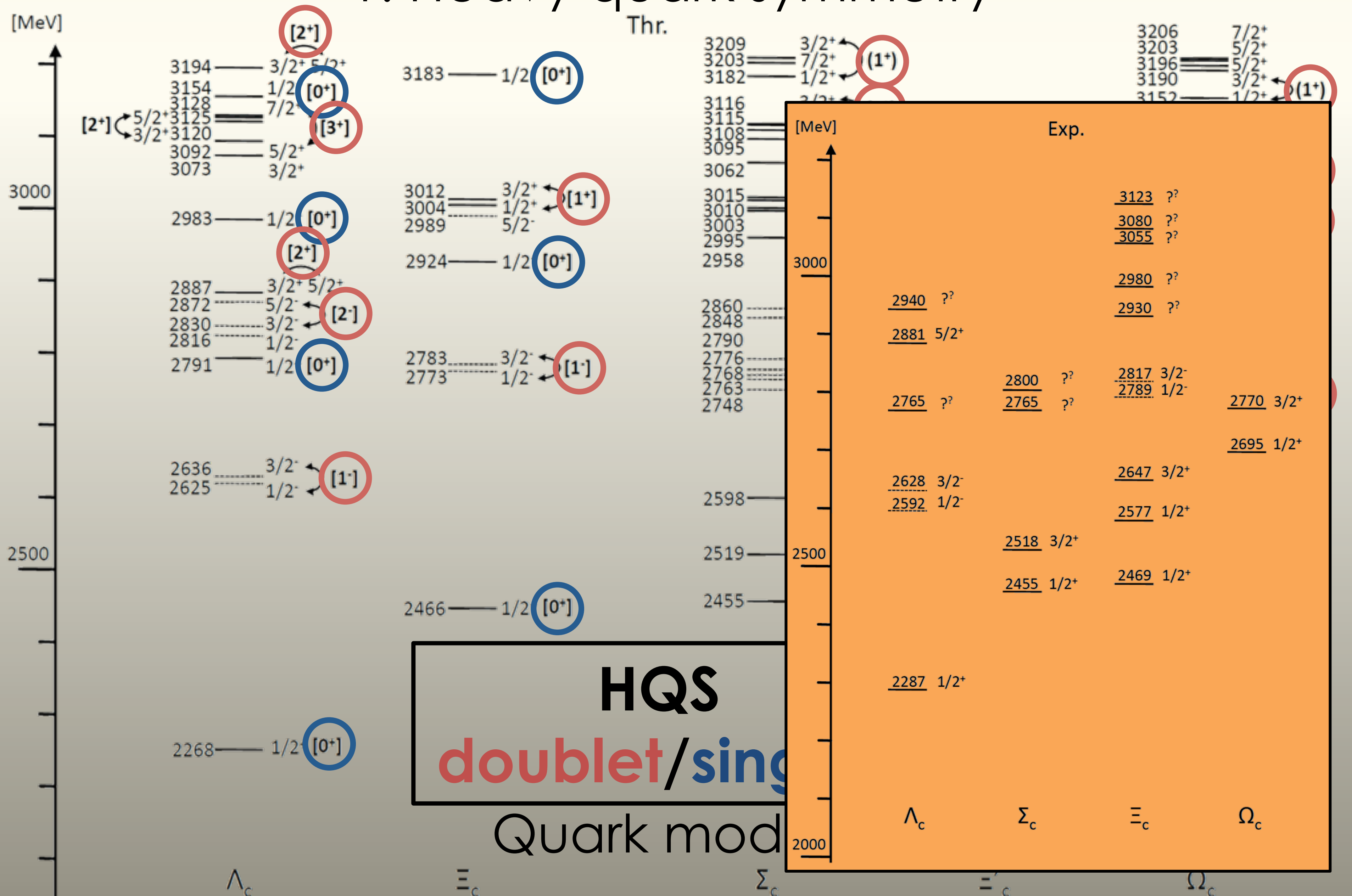
(j≠0) (j=0)

1. Heavy quark symmetry

Diquark phase diagram ?



1. Heavy quark symmetry



W.Roberts, M.Pervin, Int. J. Mod. Phys. A23, 19 (2008); Y.Yamaguchi, S.Ohkoda, T.Hyodo, A.Hosaka, S.Y., arXiv:1402.5222 [hep-ph]

Cf. Skyrme model; Y. Oh, B-Y. Park, D-P. Min Phys. Rev. D50, 3350 (1994)

2. Decays of excited heavy baryons

Transition decay width

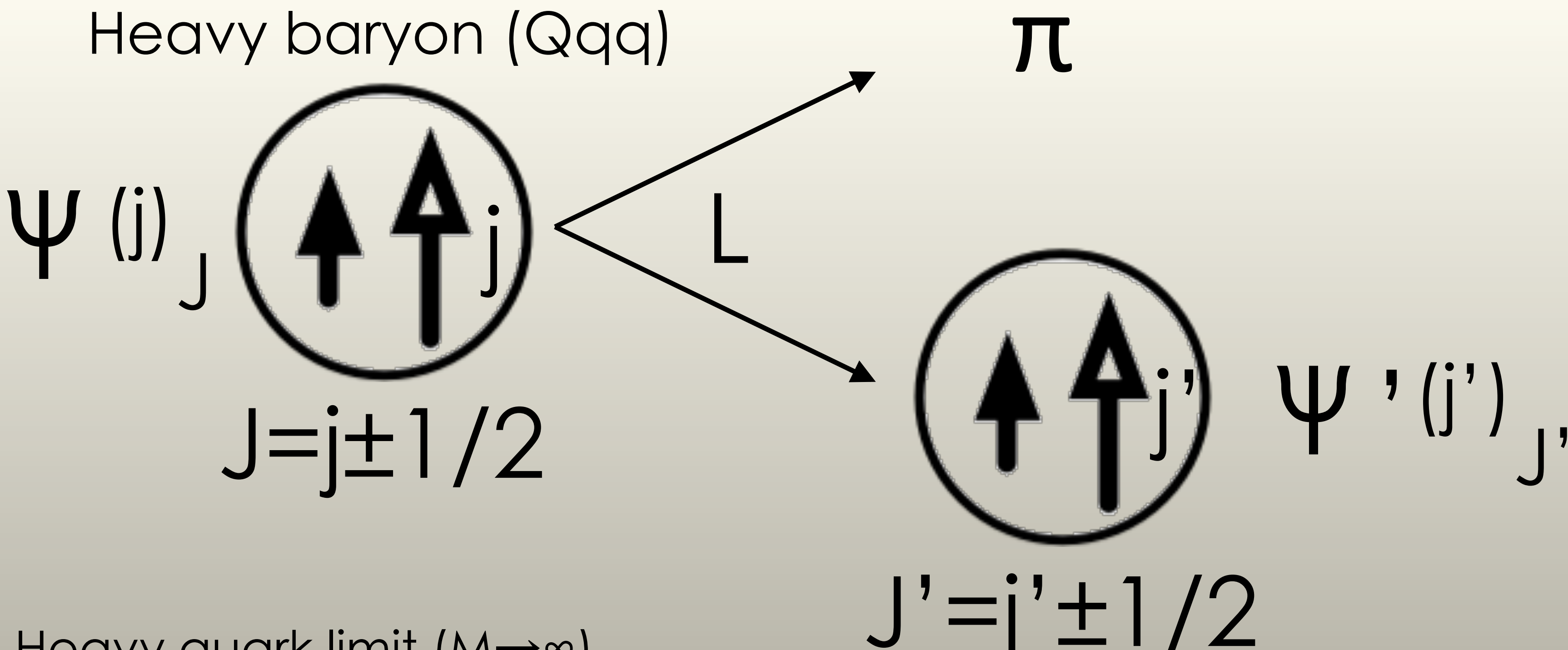
Heavy baryon (Qqq)

$\Psi^{(j)}_J$

$J=j\pm1/2$

2. Decays of excited heavy baryons

Transition decay width



Heavy quark limit (M→∞)

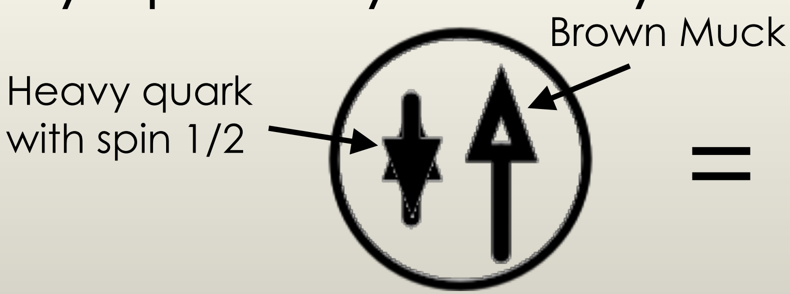
$$\Gamma[\Psi_J^{(j)} \to \Psi'^{(j')}_{J'} \pi] \propto (2j+1)(2J'+1) \left| \left\{ \begin{array}{ccc} L & j' & j \\ 1/2 & J & J' \end{array} \right\} \right|^2 + \mathcal{O}(1/M)$$

Isgur and Wise, Phys. Rev. Lett. 66, 1130 (1991)

Question: what is O(1/M)?

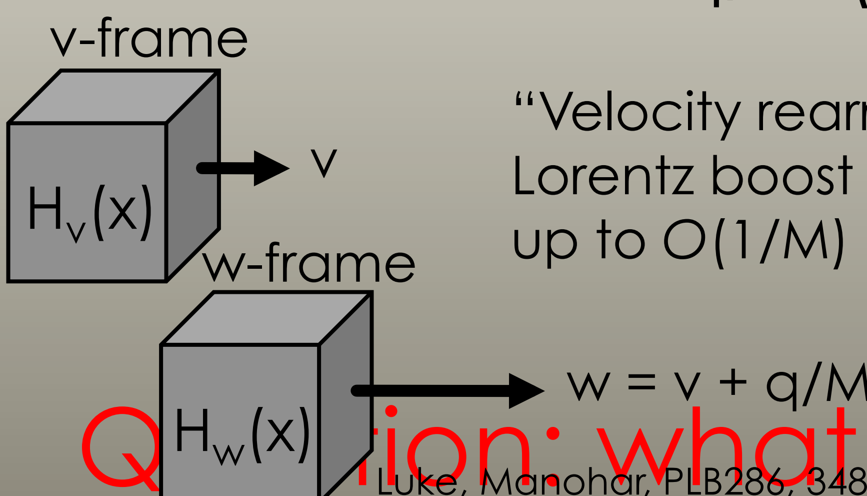
Heavy-baryon effective Lagrangian

1. Heavy quark symmetry is conserved at O(1).



2. Inv. under velocity rearrangement at O(1)+O(1/M).

$$v \rightarrow w = v + q/M \quad (q/M << 1)$$



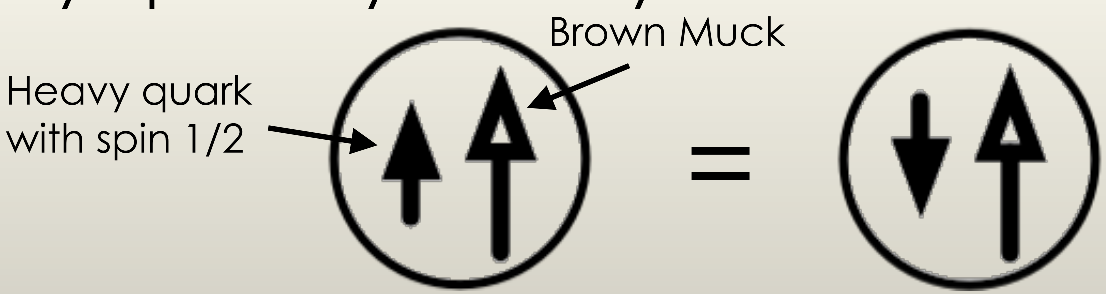
"Velocity rearrangement" :
Lorentz boost between v-frame and w-frame up to O(1/M)

Q tion: what is O(1/M)?

Luke, Manohar, PLB286, 348 (1992), Kitazawa, Kurimoto, PLB323, 65 (1994)

Heavy-baryon effective Lagrangian

1. Heavy quark symmetry is conserved at O(1).



2. Inv. under velocity rearrangement at O(1)+O(1/M).

$$v \to w = v + q/M \quad (q/M << 1)$$

3. Heavy quark symmetry breaking terms at O(1/M).

2. Decays of excited heavy baryons

(A part of) brief history of “Qqq baryon” effective theory

Brown Muck spin and parity	Heavy Mass Expansion LO: O(1)	NLO: O(1/M)
$j^P=0^+, 1^+$	T-M. Yan, H-Y Cheng, C-Y. Cheung, G-L Lin, Y-C. Lin,, H-L. Yu PRD46, 1148 (1992) (P-wave decay)	H-Y Cheng, C-Y. Cheung, G-L Lin, Y-C. Lin, T-M. Yan, H-L. Yu PRD49, 2490 (1994) (P-wave decay)
$j^P=0^\pm, 1^\pm$ $(j^P,j^{P'})$ and $(j^P,j+1^{P'})$	H-Y Cheng, C-K Chua PRD75, 014006 (2007) (S-, P-, D-wave decay)	
Arbitrary j^P $(j,j)^P$ and $(j,j+1)^P$	SY. PRD91, 014031 (2015) (P-wave decay)	

2. Decays of excited heavy baryons

Falk, Nucl. Phys. B378, 79 (1992)

Effective baryon field with brown muck spin j

$$\psi^{\mu_1\cdots\mu_j} = A^{\mu_1\cdots\mu_j} u_h$$

Brown muck with spin j — Heavy quark spin 1/2 → Total spin j±1/2

- Constraint conditions

$$\not{v}\psi^{\mu_1\cdots\mu_j} = \psi^{\mu_1\cdots\mu_j}$$

$$\psi^{\mu_1\cdots\mu_k\cdots\mu_\ell\cdots\mu_j} = \psi^{\mu_1\cdots\mu_\ell\cdots\mu_k\cdots\mu_j}$$

$$v_{\mu_1}\psi^{\mu_1\cdots\mu_j} = 0$$

$$g_{\mu_1\mu_2}\psi^{\mu_1\mu_2\cdots\mu_j} = 0$$

Cf. Rarita-Schwinger field for spin 3/2

- Projection to j-1/2 and j+1/2 states

$$\psi_{j-1/2}^{\mu_1\cdots\mu_{j-1}} = \sqrt{\frac{j}{2j+1}}\gamma_5\gamma_{\mu_j}\psi^{\mu_1\cdots\mu_j}$$

$$\psi_{j+1/2}^{\mu_1\cdots\mu_j} = \psi^{\mu_1\cdots\mu_j} - \frac{1}{2j+1}\left\{\left(\gamma^{\mu_1}+v^{\mu_1}\right)\gamma_{\nu_1}g_{\nu_2}^{\mu_2}\cdots g_{\nu_j}^{\mu_j} + \cdots \right.$$

$$\left. + g_{\nu_1}^{\mu_1}\cdots g_{\nu_{j-1}}^{\mu_{j-1}}\left(\gamma^{\mu_j}+v^{\mu_j}\right)\gamma_{\nu_j}\right\}\psi^{\nu_1\cdots\nu_j}$$

2. Decays of excited heavy baryons

SY. PRD91, 014031 (2015)

Interaction Lagrangian at LO+NLO

(j,j+1) transitions -- different brown-muck spin j, j+1 in initial and final states --

LO (HQS conserving)

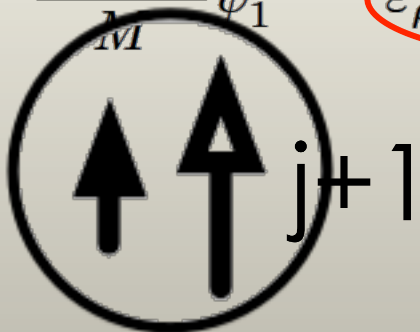
Cf. For j=0,1; Cheng, et al., PRD49, 2490 (1994)

$$\mathcal{L}^{(j,j+1)}_{\rm int} = g^{(j,j+1)} \bar{\psi}_1^{\mu_1\cdots\mu_j} \mathcal{A}_{\rho_{j+1}} \psi_2^{\rho_1\cdots\rho_j\rho_{j+1}} g_{\mu_1\rho_1}\cdots g_{\mu_j\rho_j} + \frac{g_1^{(j,j+1)}}{M}\bar{\psi}_1^{\mu_1\cdots\mu_j}\varepsilon_{\rho_{j+1}\rho\sigma\tau}v^{\rho} \mathcal{A}^{\sigma} S_v^{\tau} \psi_2^{\rho_1\cdots\rho_j\rho_{j+1}} g_{\mu_1\rho_1}\cdots g_{\mu_j\rho_j} + \text{h.c.}$$

NLO (HQS breaking)

$$\Psi(j+1)_J \xrightarrow{\text{p-wave}} \Psi(j)_{J'} + \pi$$

Pauli-Lubanski vector (spin operator) $S_v^{\mu} = -\frac{1}{2}\gamma_5\left(\gamma^{\mu}\not{v} - v^{\mu}\right)$



J=j+3/2, j+1/2   J'=j±1/2

2. Decays of excited heavy baryons

SY. PRD91, 014031 (2015)

Constraint among decay widths

(j,j+1) transitions -- different brown-muck spin j, j+1 in initial and final states --

$$2\,\check{\Gamma}[\Psi^{(2)}_{3/2}\to\Psi^{(1)}_{1/2}\pi] - 4\,\check{\Gamma}[\Psi^{(2)}_{3/2}\to\Psi^{(1)}_{3/2}\pi] = \check{\Gamma}[\Psi^{(2)}_{5/2}\to\Psi^{(1)}_{3/2}\pi] + \mathcal{O}(1/M^2)$$

$$\frac{3}{2}\,\check{\Gamma}[\Psi^{(3)}_{5/2}\to\Psi^{(2)}_{3/2}\pi] - 6\,\check{\Gamma}[\Psi^{(3)}_{5/2}\to\Psi^{(2)}_{5/2}\pi] = \check{\Gamma}[\Psi^{(3)}_{7/2}\to\Psi^{(2)}_{5/2}\pi] + \mathcal{O}(1/M^2)$$

$$\frac{4}{3}\,\check{\Gamma}[\Psi^{(4)}_{7/2}\to\Psi^{(3)}_{5/2}\pi] - 8\,\check{\Gamma}[\Psi^{(4)}_{7/2}\to\Psi^{(3)}_{7/2}] = \check{\Gamma}[\Psi^{(4)}_{9/2}\to\Psi^{(3)}_{7/2}\pi] + \mathcal{O}(1/M^2)$$

For any j≥1 ...

$$\frac{j+1}{j}\,\check{\Gamma}[\Psi^{(j+1)}_{j+1/2}\to\Psi^{(j)}_{j-1/2}\pi] - (2j+2)\,\check{\Gamma}[\Psi^{(j+1)}_{j+1/2}\to\Psi^{(j)}_{j+1/2}\pi] = \check{\Gamma}[\Psi^{(j+1)}_{j+3/2}\to\Psi^{(j)}_{j+1/2}\pi] + \mathcal{O}(1/M^2)$$

A constraint on different decay channels at O(1/M).

This is a “weaker” constraint to Isgur-Wise’s constraint.

SY. PRD91, 014031 (2015)

Analogy

Gell-Mann, Okubo relation

$$4m_K^2 = 3m_\eta^2 + m_\pi^2$$

Flavor $SU(3)$ symmetry breaking
(Gell-Mann, Oaks, Renner relation)

$$\begin{aligned} m_\pi^2 &= 2B_0\hat{m}, \\ m_K^2 &= B_0(\hat{m} + m_s), \\ m_\eta^2 &= \frac{2}{3}B_0(\hat{m} + 2m_s), \end{aligned}$$

2. Decays of excited heavy baryons

SY. PRD91, 014031 (2015)

Interaction Lagrangian at LO+NLO

(j,j) transitions -- same brown-muck spin j in initial and final states --

j ≥ 1

NLO (velocity-rearrangement)

$$\begin{aligned}\mathcal{L}_{\rm int}^{(j,j)} &= g^{(j,j)}\bar\psi_1^{\mu_1\cdots\mu_j} i\varepsilon_{\mu_1\rho_1\alpha\beta}v^\alpha \mathcal{A}^\beta \psi_2{}^{\rho_1}{}_{\mu_2\cdots\mu_j} \\ &+ \frac{g^{(j,j)}}{2M}\bar\psi_1^{\mu_1\cdots\mu_j} i\varepsilon_{\mu_1\rho_1\alpha\beta} iD_\perp^\alpha(\psi_2)\mathcal{A}^\beta\psi_2{}^{\rho_1}{}_{\mu_2\cdots\mu_j} \\ &- \frac{g^{(j,j)}}{2M}\bar\psi_1^{\mu_1\cdots\mu_j} i\varepsilon_{\mu_1\rho_1\alpha\beta} i\overleftarrow{D}_\perp^\alpha(\psi_1)\mathcal{A}^\beta\psi_2{}^{\rho_1}{}_{\mu_2\cdots\mu_j} \\ &+ \frac{g_1^{(j,j)}}{2M}\bar\psi_1^{\mu_1\cdots\mu_j} S_v\cdot\mathcal{A}\,\psi_{2\mu_1\cdots\mu_j} \\ &+ \frac{g_2^{(j,j)}}{2M}\bar\psi_1^{\mu_1\cdots\mu_j}(S_{v\mu_1}\mathcal{A}_{\rho_1} + S_{v\rho_1}\mathcal{A}_{\mu_1})\psi_2{}^{\rho_1}{}_{\mu_2\cdots\mu_j} \\ &+ \text{h.c.} + \mathcal{O}(1/M^2)\end{aligned}$$

NLO (HQS breaking)

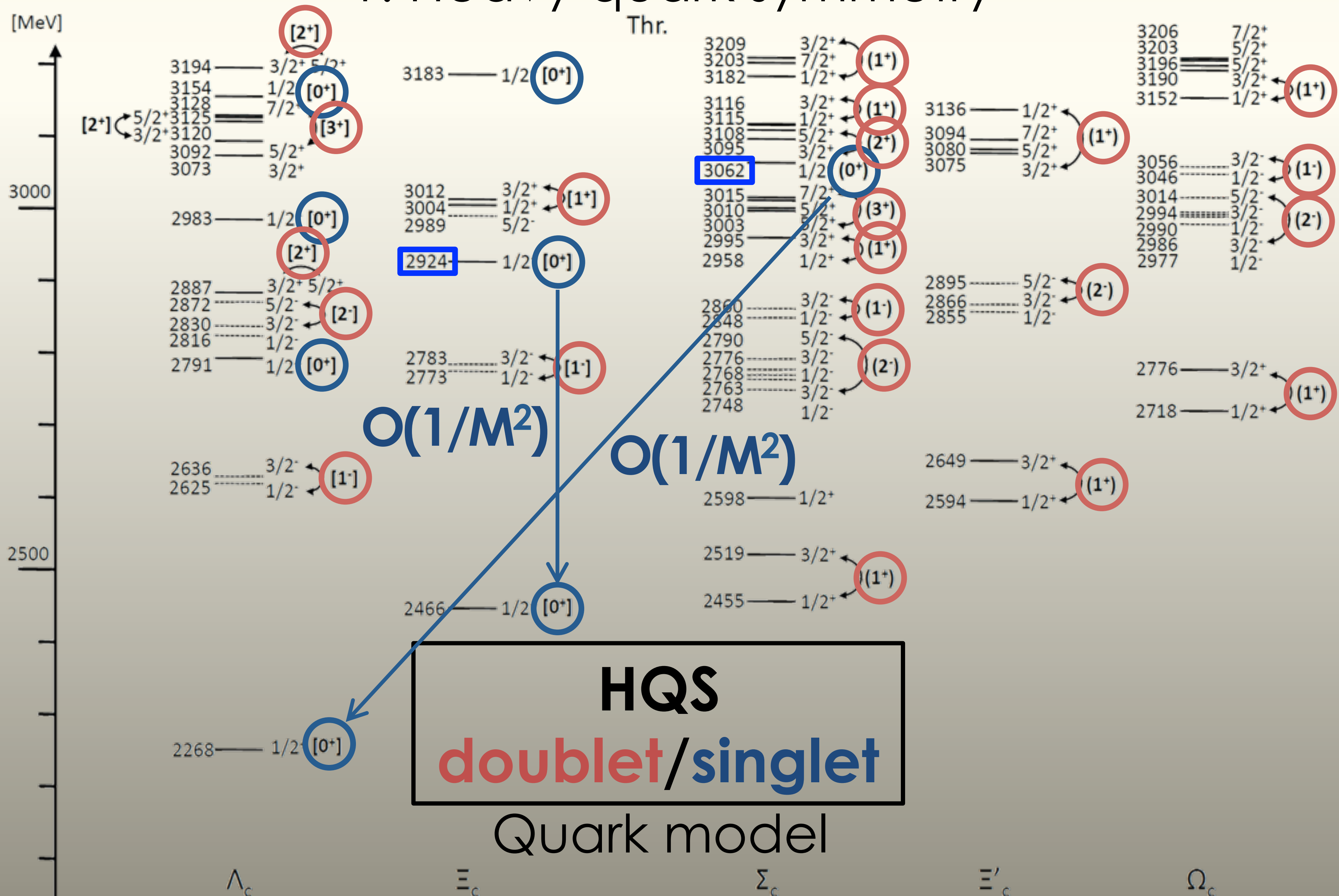
$\Sigma_c(3062)$(QM) → $\Lambda_c\pi$
$\Xi_c(2924)$(QM) → $\Xi_c\pi$

j = 0

$$\mathcal{L}_{\rm int}^{(0,0)} = \frac{g_1^{(0,0)}}{M}\bar\psi_1 S_v\cdot\mathcal{A}\,\psi_2 + \text{h.c.} + \mathcal{O}(1/M^2)$$

$1/2^\pm \to 1/2^\pm$ transition (HQS singlet) is very small; $O(1/M^2)$.

1. Heavy quark symmetry



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2. Decays of excited heavy baryons

SY. PRD91, 014031 (2015)

Interaction Lagrangian at LO+NLO

(j,j) transitions -- same brown-muck spin j in initial and final states --

j ≥ 1

NLO (velocity-rearrangement)

$$
\begin{aligned}
\mathcal{L}_{\rm int}^{(j,j)} &= g^{(j,j)} \bar{\psi}_1^{\mu_1\cdots\mu_j} i\varepsilon_{\mu_1\rho_1\alpha\beta} v^\alpha \mathcal{A}^\beta {\psi_2^{\rho_1}}_{\mu_2\cdots\mu_j} \\
&+ \frac{g^{(j,j)}}{2M} \bar{\psi}_1^{\mu_1\cdots\mu_j} i\varepsilon_{\mu_1\rho_1\alpha\beta} i D_\perp^\alpha(\psi_2) \mathcal{A}^\beta {\psi_2^{\rho_1}}_{\mu_2\cdots\mu_j} \\
&- \frac{g^{(j,j)}}{2M} \bar{\psi}_1^{\mu_1\cdots\mu_j} i\varepsilon_{\mu_1\rho_1\alpha\beta} i \overleftarrow{D}_\perp^\alpha(\psi_1) \mathcal{A}^\beta {\psi_2^{\rho_1}}_{\mu_2\cdots\mu_j} \\
&+ \frac{g_1^{(j,j)}}{2M} \bar{\psi}_1^{\mu_1\cdots\mu_j} S_v \cdot \mathcal{A} \psi_{2\mu_1\cdots\mu_j} \\
&+ \frac{g_2^{(j,j)}}{2M} \bar{\psi}_1^{\mu_1\cdots\mu_j} \left(S_{v\mu_1} \mathcal{A}_{\rho_1} + S_{v\rho_1} \mathcal{A}_{\mu_1} \right) {\psi_2^{\rho_1}}_{\mu_2\cdots\mu_j} \\
&+ \text{h.c.} + \mathcal{O}(1/M^2)
\end{aligned}
$$

NLO (HQS breaking)

2. Decays of excited heavy baryons

SY. PRD91, 014031 (2015)

Interaction Lagrangian at LO+NLO

(j,j) transitions -- same brown-muck spin j in initial and final states --

$$\check{\Gamma}(\Psi^{(1)}_{1/2} \to \Psi'^{(1)}_{3/2}\pi) = 2\,\check{\Gamma}(\Psi^{(1)}_{3/2} \to \Psi'^{(1)}_{1/2}\pi) + \mathcal{O}(1/M^2)$$

$$\check{\Gamma}(\Psi^{(2)}_{3/2} \to \Psi'^{(2)}_{5/2}\pi) = \frac{3}{2}\,\check{\Gamma}(\Psi^{(2)}_{5/2} \to \Psi'^{(2)}_{3/2}\pi) + \mathcal{O}(1/M^2)$$

$$\check{\Gamma}(\Psi^{(3)}_{5/2} \to \Psi'^{(3)}_{7/2}\pi) = \frac{4}{3}\,\check{\Gamma}(\Psi^{(3)}_{7/2} \to \Psi'^{(3)}_{5/2}\pi) + \mathcal{O}(1/M^2)$$

For any j≥1 ...

$$\check{\Gamma}[\Psi^{(j)}_{j-1/2} \to \Psi'^{(j)}_{j+1/2}\pi] = \frac{j+1}{j}\,\check{\Gamma}[\Psi^{(j)}_{j+1/2} \to \Psi'^{(j)}_{j-1/2}\pi] + \mathcal{O}(1/M^2)$$

This holds not only at O(1/M) but also at O(1).

2. Decays of excited heavy baryons

SY. PRD91, 014031 (2015)

Some numerical studies ...

How small is NLO to LO?

2. Decays of excited heavy baryons

SY. PRD91, 014031 (2015)

Some numerical studies ...

(0,1) transitions

$$\Sigma_{Q}^{(*)} \to \Lambda_{Q}\,\pi$$

j=1 j=0

Charm

Belle, arXiv:1404.5389

$$\Gamma[\Sigma_c^{++} \to \Lambda_c^+ \pi^+] \simeq 1.84 \pm 0.04^{+0.07}_{-0.20}\ \mathrm{MeV}$$
$$\Gamma[\Sigma_c^{0} \to \Lambda_c^+ \pi^-] \simeq 1.76 \pm 0.04^{+0.09}_{-0.21}\ \mathrm{MeV}$$

$$\Gamma[\Sigma_c^{*\,++} \to \Lambda_c^+ \pi^+] \simeq 14.77 \pm 0.25^{+0.18}_{-0.30}\ \mathrm{MeV}$$
$$\Gamma[\Sigma_c^{*\,0} \to \Lambda_c^+ \pi^-] \simeq 15.41 \pm 0.41^{+0.20}_{-0.32}\ \mathrm{MeV}$$

$\simeq$: p-wave π transition assumed

2. Decays of excited heavy baryons

SY. PRD91, 014031 (2015)

Some numerical studies ...

(0,1) transitions

$$\Sigma_Q^{(*)} \to \Lambda_Q \pi$$

j=1 j=0

$$\Gamma[\Psi^{(1)}_{1/2} \to \Psi^{(0)}_{1/2}\pi] = \frac{1}{3}\left(g^{(1,0)\,2} - \frac{2g^{(1,0)}g_1^{(1,0)}}{M} \right) K^{(1,0)}_{1/2,1/2}$$

$$\Gamma[\Psi^{(1)}_{3/2} \to \Psi^{(0)}_{1/2}\pi] = \frac{1}{3}\left(g^{(1,0)\,2} + \frac{g^{(1,0)}g_1^{(1,0)}}{M} \right) K^{(1,0)}_{3/2,1/2}$$

$$g^{(0,1)} = 0.83 \quad g_1^{(0,1)}/M = 0.048$$

~6% (?)

$$M = (M^{(1)}_{1/2} + 2M^{(1)}_{3/2})/3$$

2. Decays of excited heavy baryons

SY. PRD91, 014031 (2015)

Some numerical studies ...

(0,1) transitions

$$\Sigma_Q^{(*)} \rightarrow \Lambda_Q \pi$$

j=1 j=0

Bottom PDG2014

$$\Gamma[\Sigma_b^+ \to \Lambda_b^0 \pi^+] \simeq 9.7^{+4.0}_{-3.0}\,\mathrm{MeV}$$
$$\Gamma[\Sigma_b^- \to \Lambda_b^0 \pi^-] \simeq 4.9^{+3.3}_{-2.4}\,\mathrm{MeV}$$

← 5.1 MeV (theory)

$$\Gamma[\Sigma_b^{*+} \to \Lambda_b^0 \pi^+] \simeq 11.5 \pm 2.8\,\mathrm{MeV}$$
$$\Gamma[\Sigma_b^{*-} \to \Lambda_b^0 \pi^-] \simeq 7.5 \pm 2.3\,\mathrm{MeV}$$

← 9.6 MeV (theory)

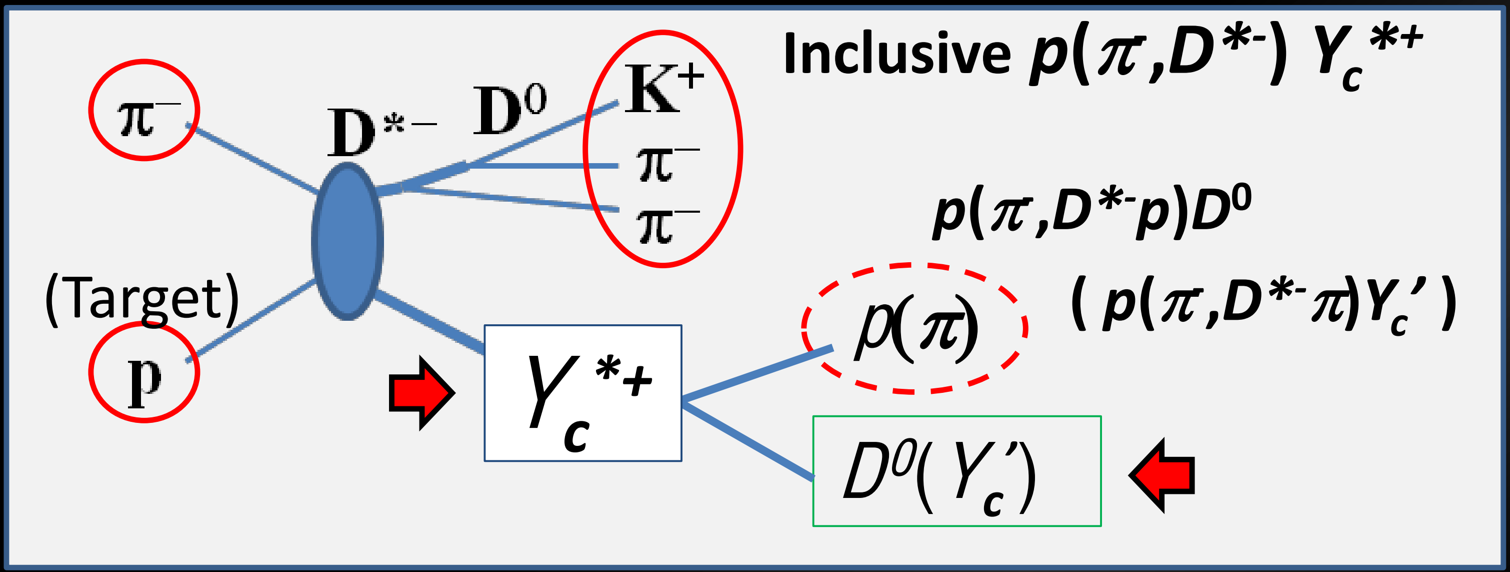
$\simeq$: p-wave transition supposed

3. Conclusion

1. Strong decays of one-pion emission from excited heavy baryons are discussed.
2. Heavy quark symmetry (HQS) at LO+NLO in $1/m_Q$ expansion was considered.
3. Relations for decay widths in several channels were obtained *model-independently*.
4. They will be useful for identifications of the HQS doublet/singlet in experimental analysis.
5. Other higher order contributions?
   (isospin breaking, chiral expansion, etc.)

Charmed Baryon Spectroscopy

Using Missing Mass Techniques

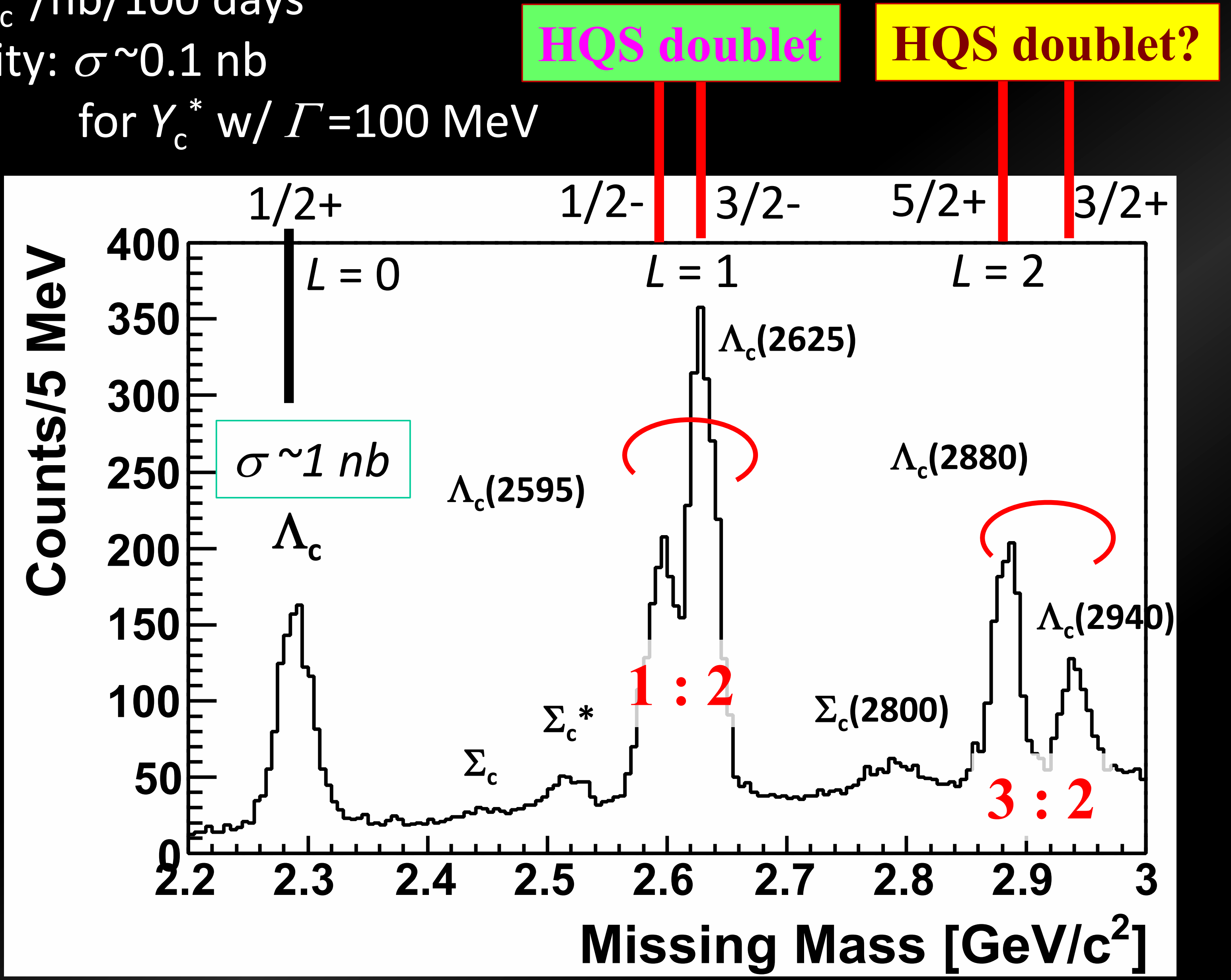


Conducted by the E50 experiment at J-PARC

Missing Mass Spectrum (Sim.)

Noumi 2014

- ~1000 Y_c^*/nb/100 days
- Sensitivity: σ ~0.1 nb for Y_c^* w/ Γ=100 MeV



2. Decays of excited heavy baryons

SY. PRD91, 014031 (2015)

Constraint among decay widths

(j,j+1) transitions

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$$\frac{3}{2}\,\check{\Gamma}[\Psi^{(3)}_{5/\ldots} \ldots \mathcal{O}(1/M^2)$$

$$\frac{4}{3}\,\check{\Gamma}[\Psi \ldots \mathcal{O}(1/M^2)$$

$$\frac{j+1}{j}\,\check{\Gamma}[\Psi^{(\ldots}_{j\ldots} \ldots \pi]+\mathcal{O}(1/M^2)$$

A cons… O(1/M).

Example: j=1

$$\Gamma[\Psi^{(2)}_{3/2}\to\Psi^{(1)}_{1/2}\pi] = \frac{5}{18}\left(g^{(1,2)^2} - \frac{g^{(1,2)}g_1^{(1,2)}}{M}\right)K^{(2,1)}_{3/2,1/2}$$

$$\Gamma[\Psi^{(2)}_{3/2}\to\Psi^{(1)}_{3/2}\pi] = \frac{1}{18}\left(g^{(1,2)^2} - \frac{4g^{(1,2)}g_1^{(1,2)}}{M}\right)K^{(2,1)}_{3/2,3/2}$$

$$\Gamma[\Psi^{(2)}_{5/2}\to\Psi^{(1)}_{3/2}\pi] = \frac{1}{3}\left(g^{(1,2)^2} + \frac{g^{(1,2)}g_1^{(1,2)}}{M}\right)K^{(2,1)}_{5/2,3/2}$$

$$K^{(j+1,j)}_{J_2,J_1} = \frac{1}{2\pi f_\pi^2}\left(\Delta^{(j+1,j)^2}_{J_2,J_1} - m_\pi^2\right)^{3/2}$$

$$\Delta^{(j+1,j)}_{J_2,J_1} = m_\pi^2/2M^{(j+1)}_{J_2} + M^{(j+1)}_{J_2} - M^{(j)}_{J_1}$$