Transitions of charm/bottom baryons with pion emissions

Ref. Phys. Rev. D91, 014031 (2015)

Tokyo Institute of Technology

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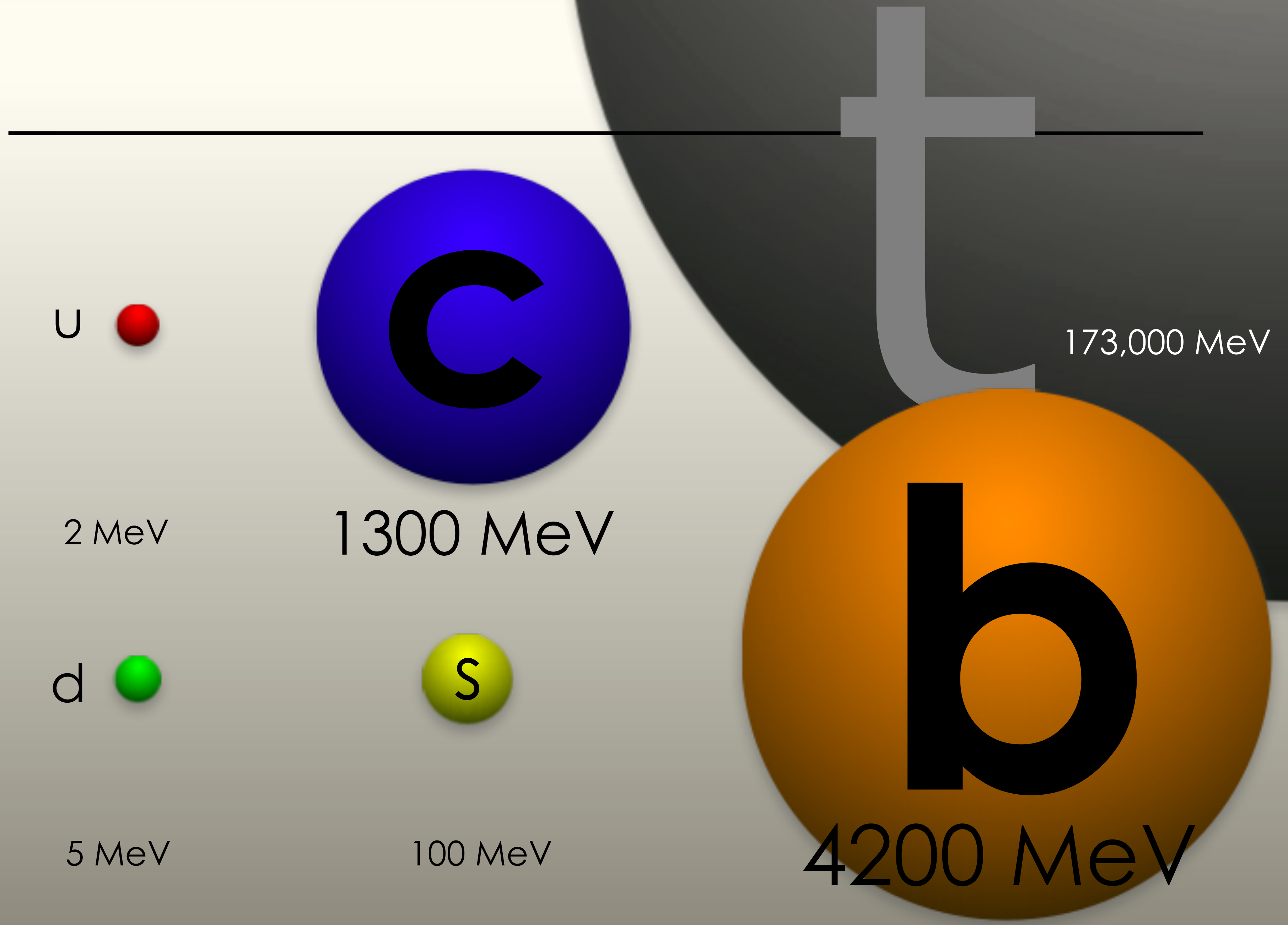
Contents

1. Heavy quark symmetry



Heavy quark symmetry (HQS)

Manohar, Wise, Luke, Grinstein, ...

Heavy baryon (Qqq)

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

Heavy quark spin 1/2

$J = j \pm 1/2$

"**Brown Muck**" : Light quarks and gluons

definite total spin j

quark # = 2 and color $\bar{\mathbf{3}}$ (**3**bar)

Mass spectrum

HQS doublet/singlet

(j≠0) (j=0)

1. Heavy quark symmetry

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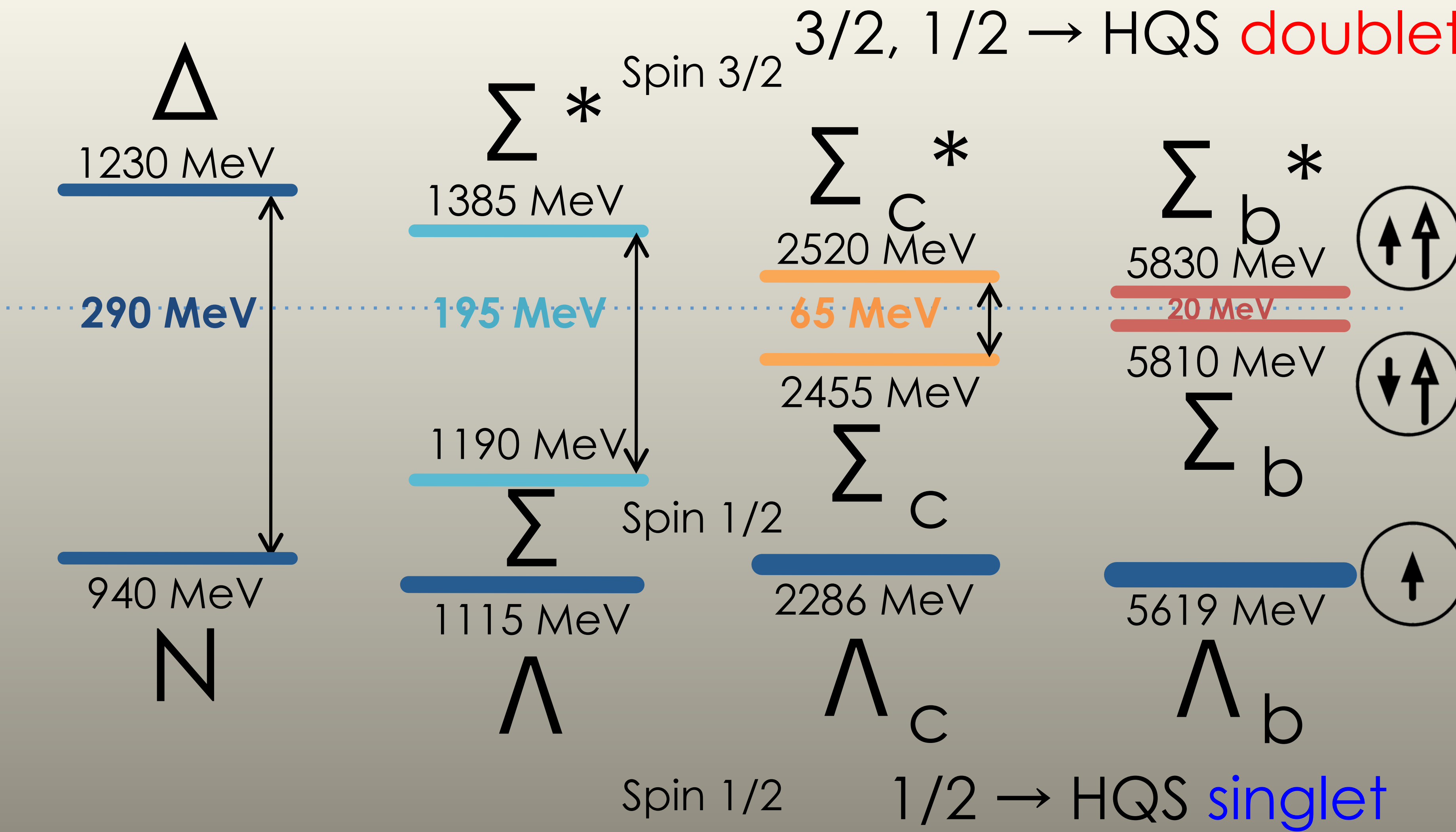
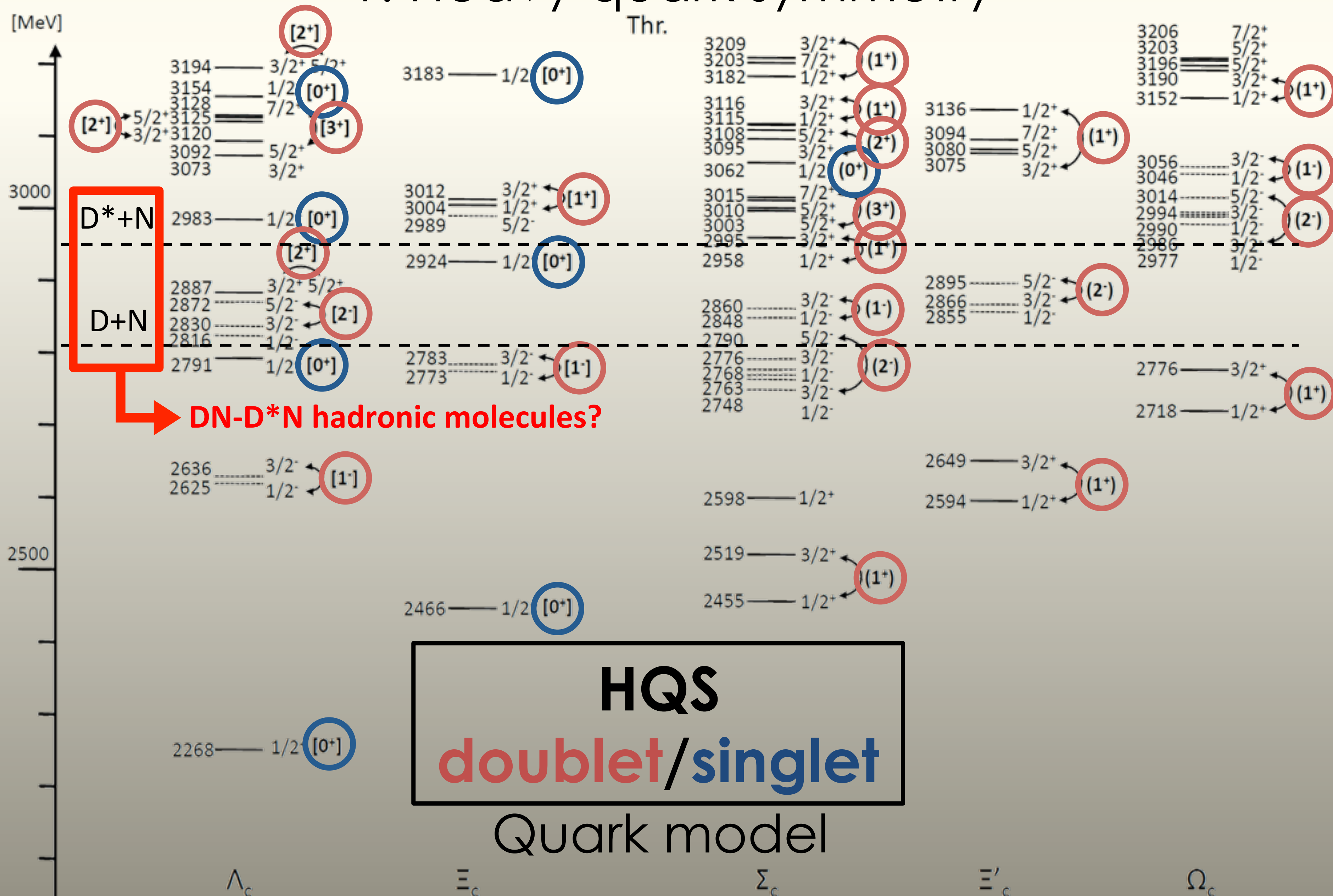
(1) Heavy Hadron Mass Spectrum



1. Heavy quark symmetry



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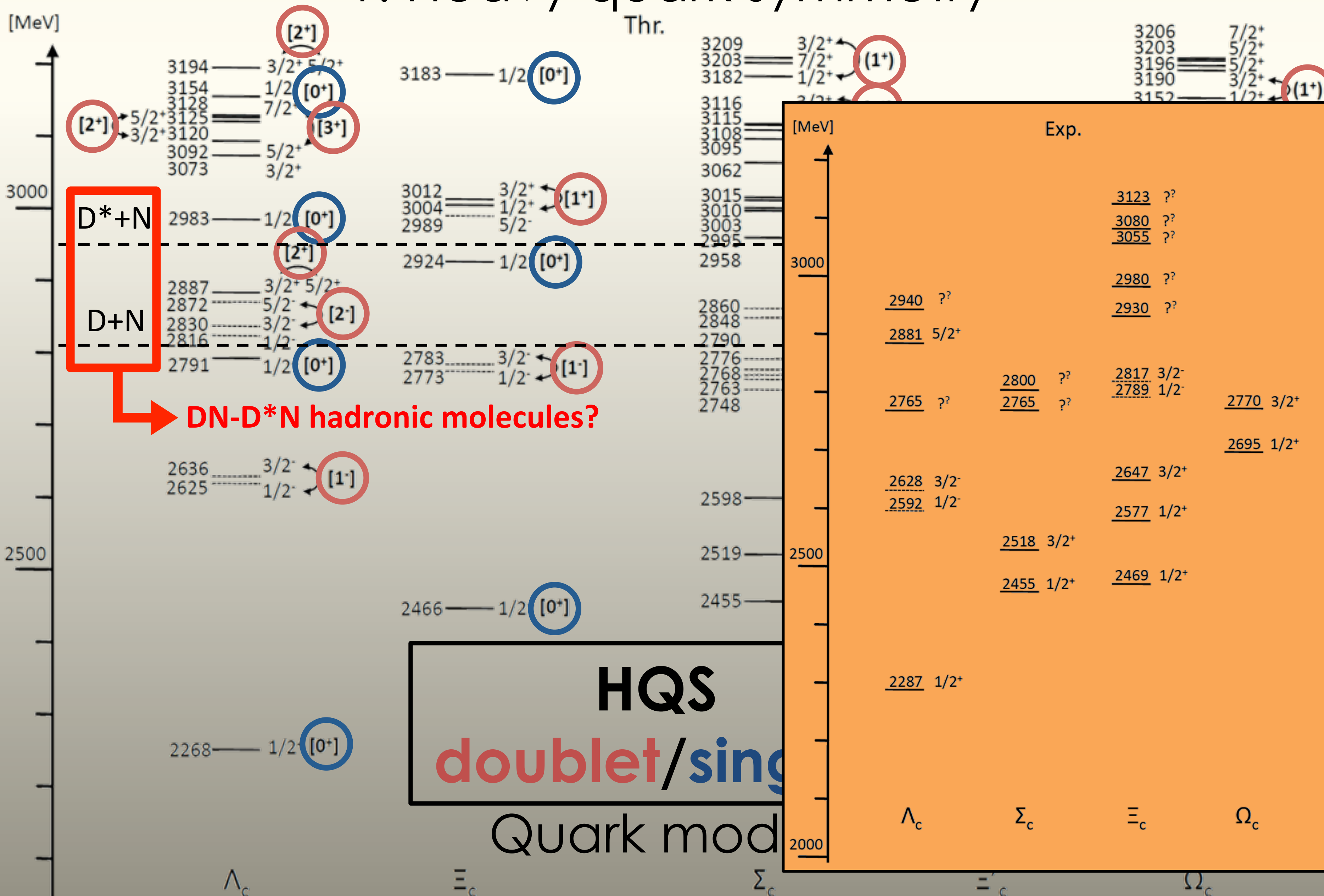
1. Heavy quark symmetry



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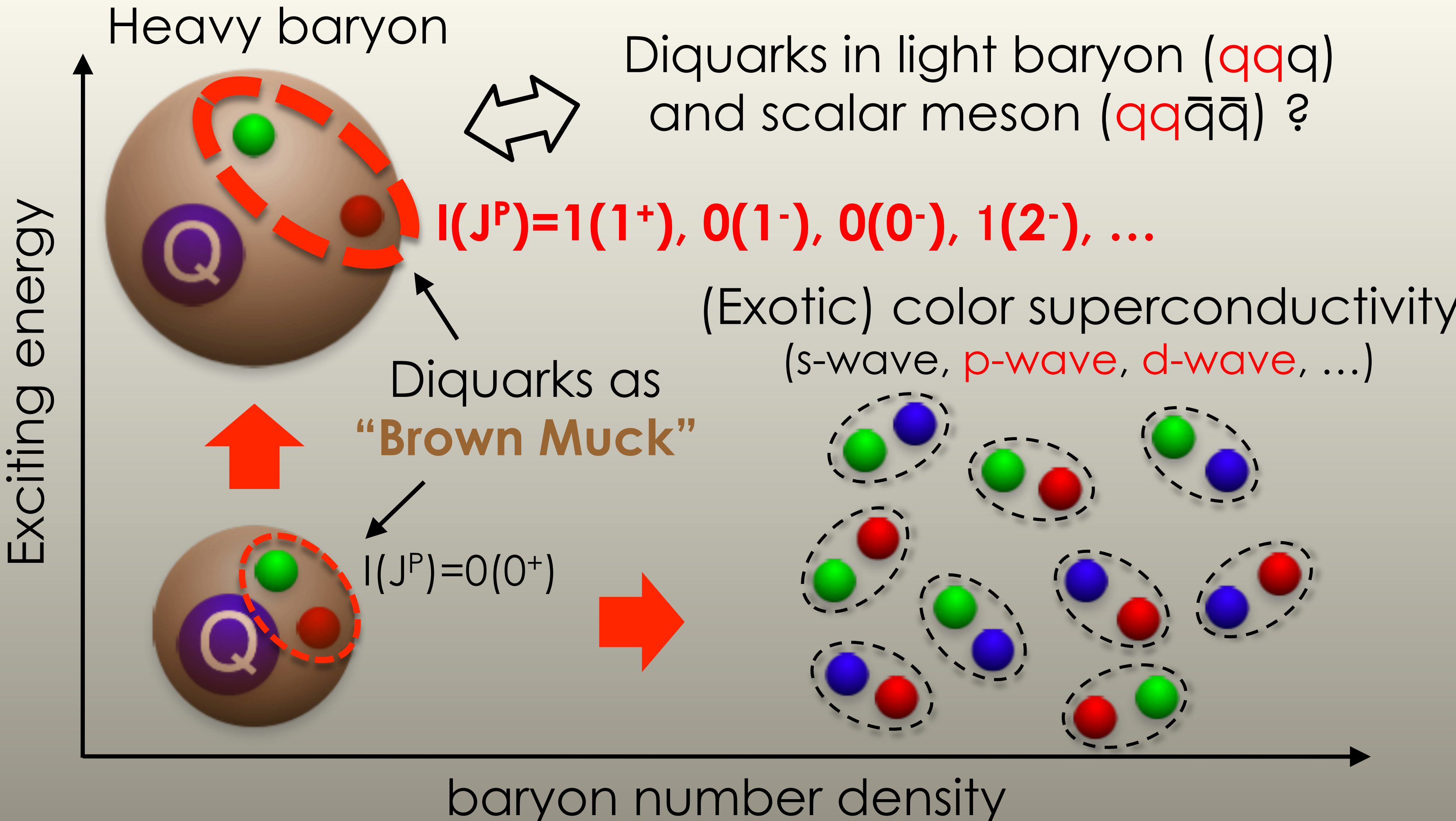
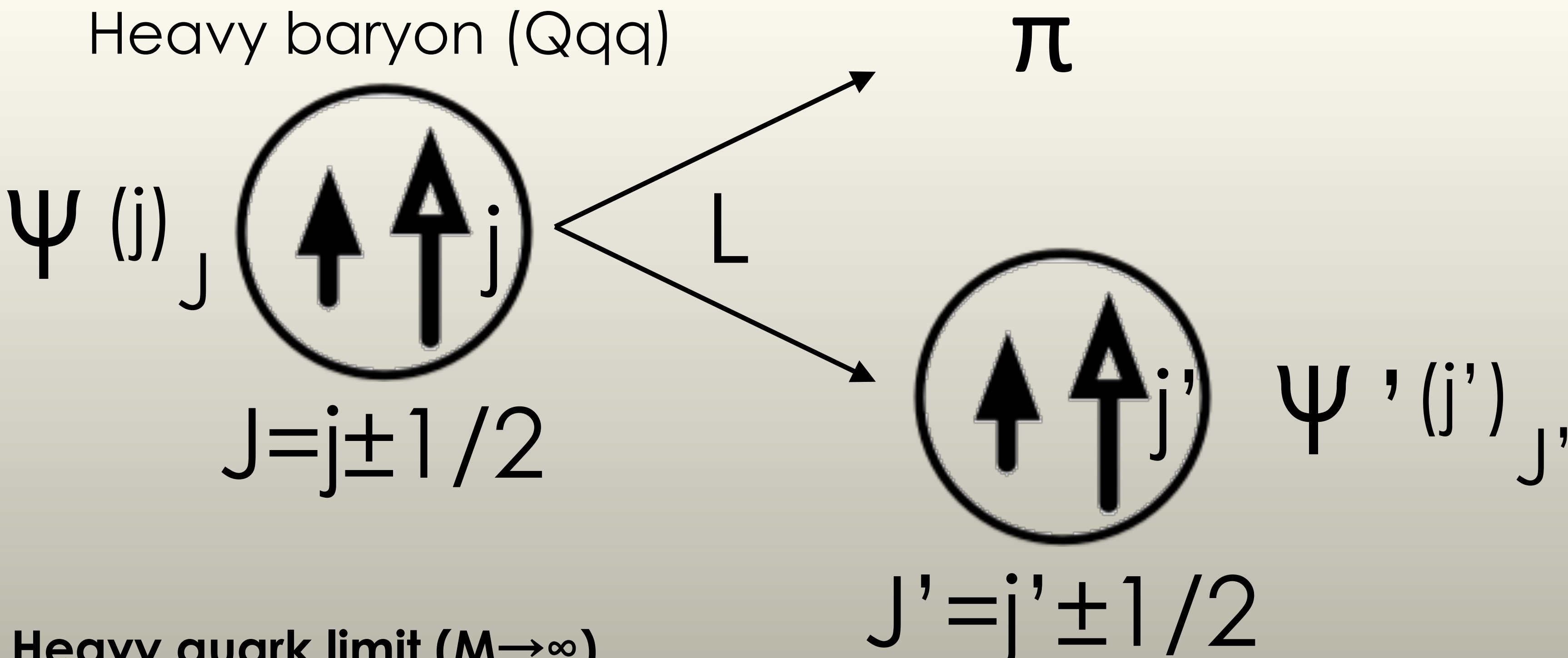
(2) Diquark Phase Diagram



2. Decays of excited heavy baryons

Transitions by strong decay



Heavy quark limit (M→∞)

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

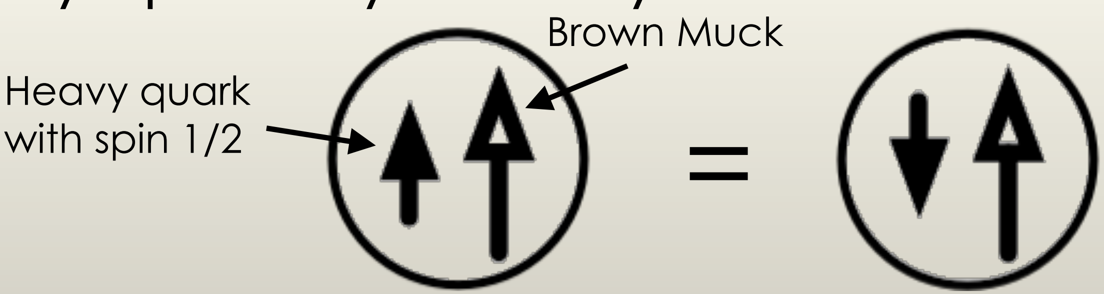
***Conservation of "spin" of brown muck: j=j'+L**

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

Question: what is O(1/M)?

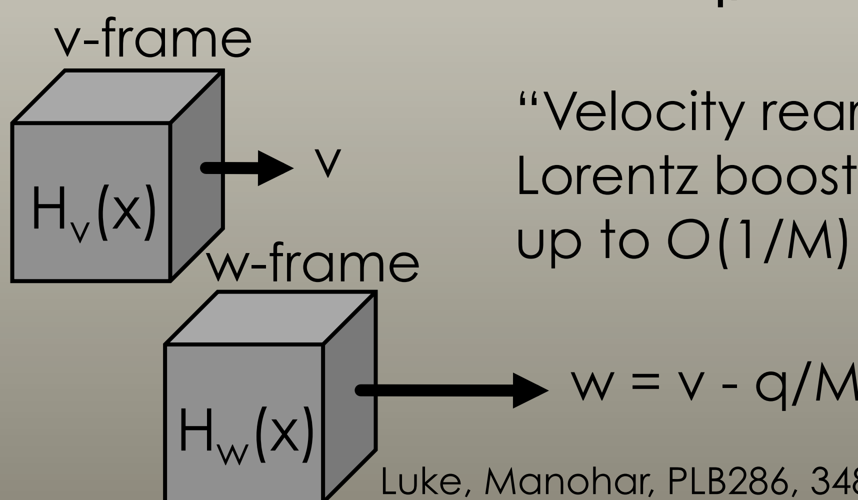
Heavy-baryon effective Lagrangian

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



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

$$v \to w = v + q/M \;(\, q/M \ll 1 \,)$$



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

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

2. Decays of excited heavy baryons

Heavy-baryon effective Lagrangian

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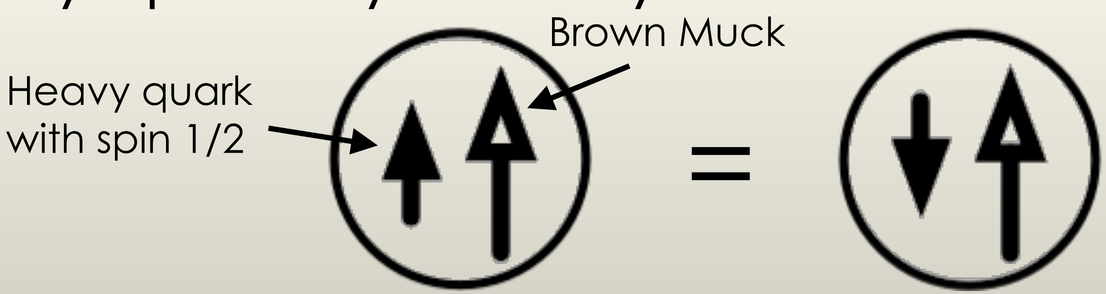
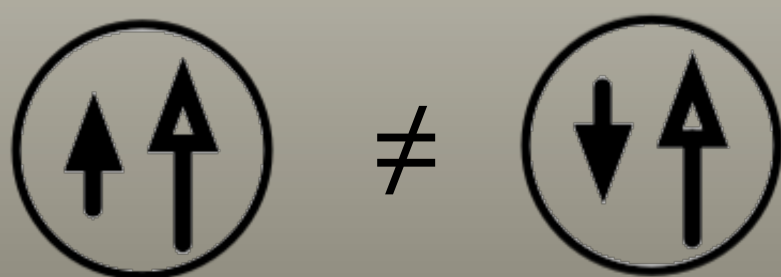


2. Inv. under velocity rearrangement at O(1)+O(1/M).

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

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

$$\not{v}\psi^{\mu_1\cdots\mu_j} = \psi^{\mu_1\cdots\mu_j}$$ Positive-energy heavy quark

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

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

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

Cf. Rarita-Schwinger field for spin 3/2

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

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

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

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

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)

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

NLO (HQS breaking)

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

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

J=j±1/2 J'=j+3/2, 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.

2. Decays of excited heavy baryons

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)

Some numerical studies ...

(1,0) transitions

$$\underset{j=1}{\Sigma_Q^{(*)}} \rightarrow \underset{j=0}{\Lambda_Q}\,\pi$$

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 ...

(1,0) transitions

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

j=1 j=0

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

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

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

~6% (?)

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

2. Decays of excited heavy baryons

SY. PRD91, 014031 (2015)

Some numerical studies ...

(1,0) transitions

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

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** (present 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** (present theory)

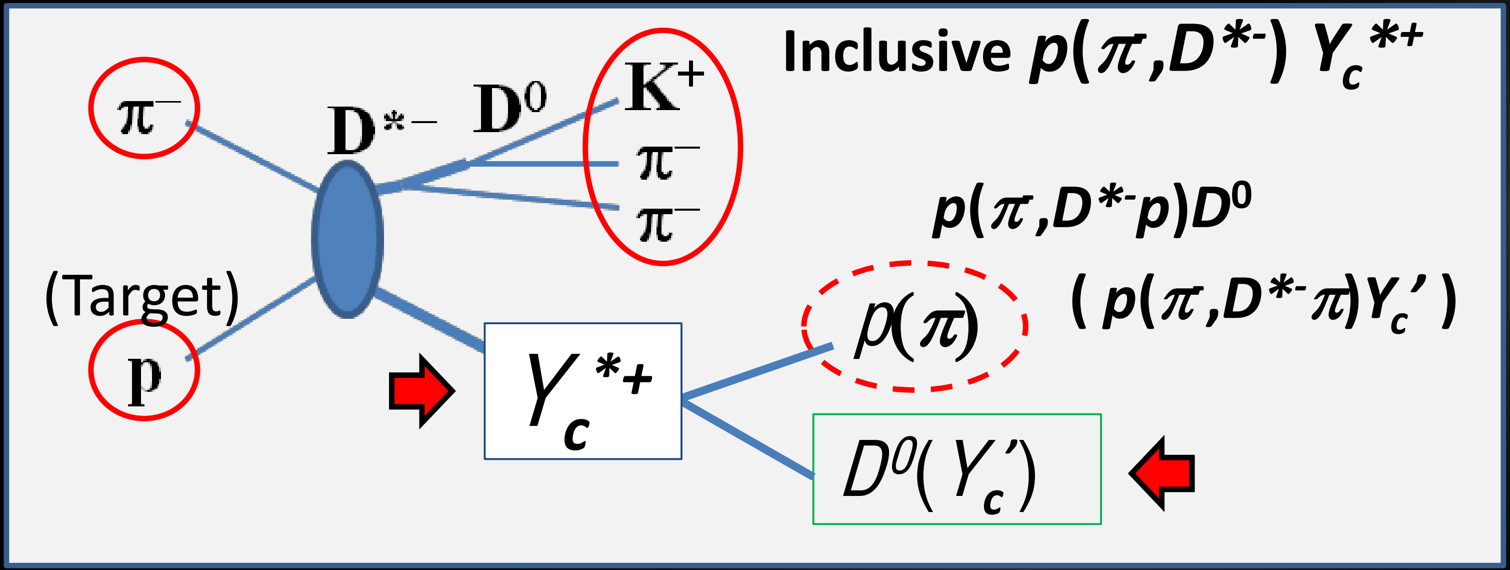
$\simeq$: p-wave transition supposed

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 is considered.
3. Relations for decay widths in several channels are obtained model-independently.
4. They will be useful for identifications of HQS doublet/singlet in experimental analysis.
5. Other contributions except for $1/m_Q$? (isospin breaking, chiral expansion, etc.)

Charmed Baryon Spectroscopy

Using Missing Mass Techniques

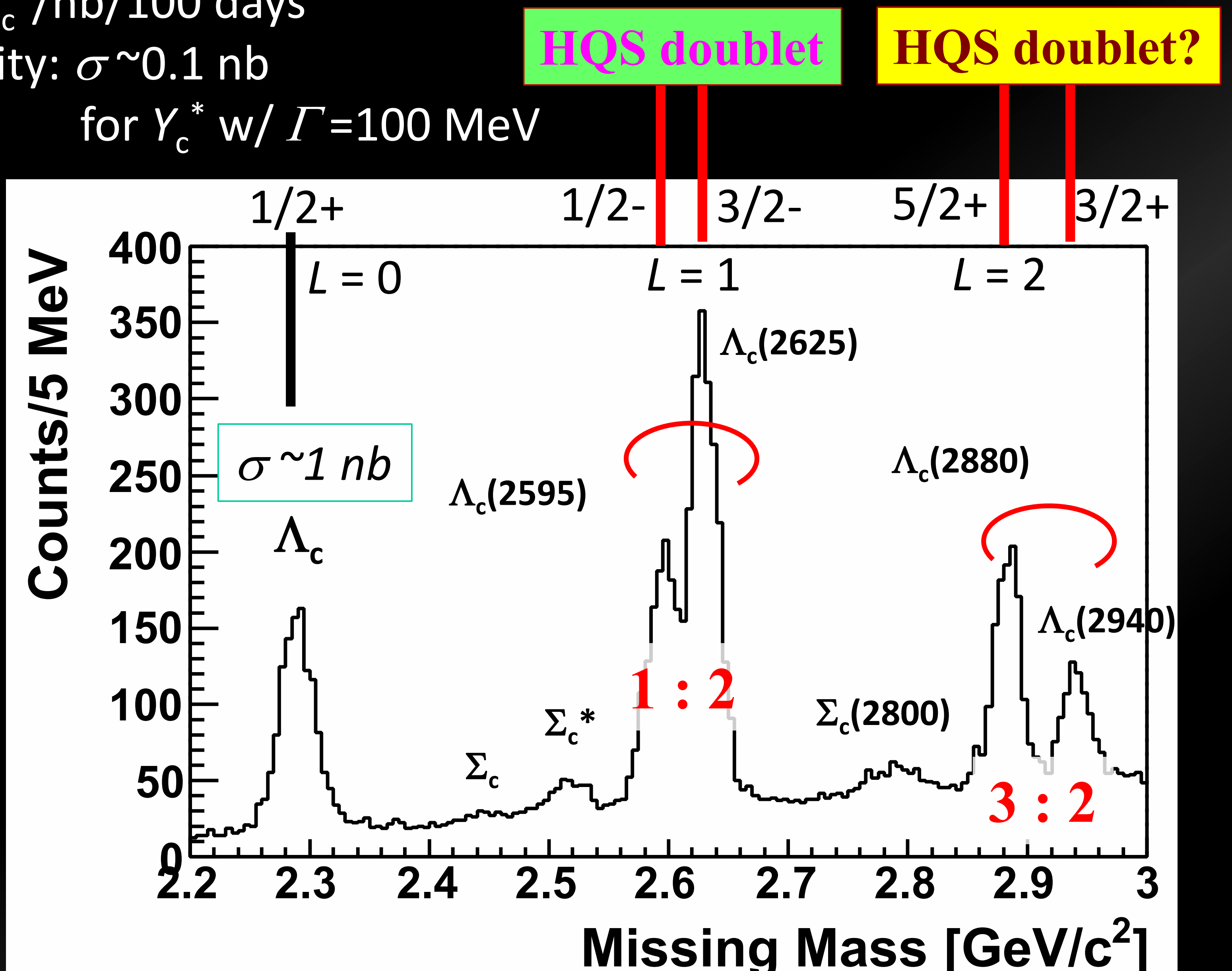


Conducted by the E50 experiment at J-PARC

Missing Mass Spectrum (Sim.)

Noumi 2014

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



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)

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

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

NLO (velocity-rearrangement)

NLO (HQS breaking)

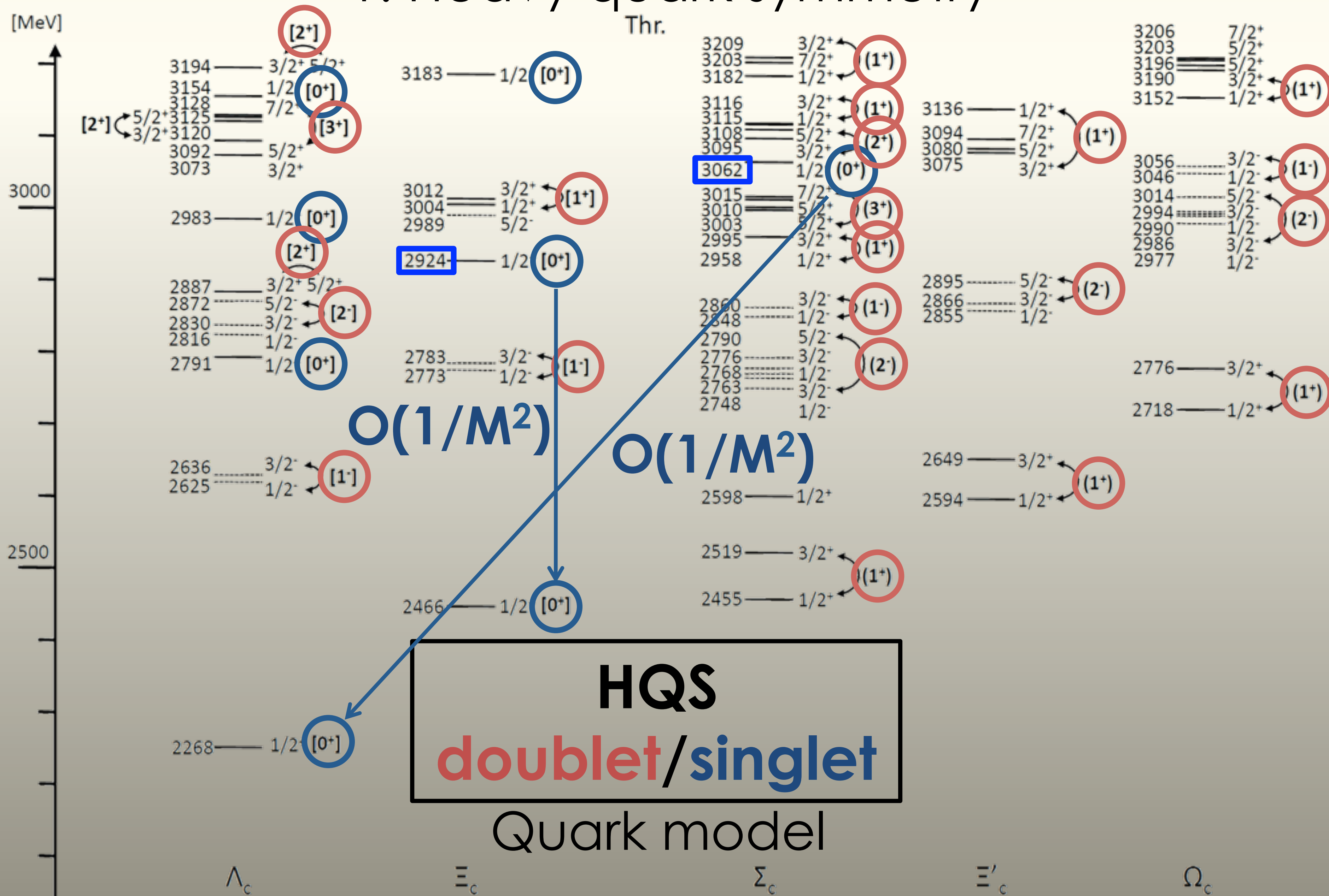
j = 0

$$\mathcal{L}_{\rm int}^{(0,0)} = \frac{g_1^{(0,0)}}{M}\bar{\psi}_1 S_v\cdot\mathcal{A}\,\psi_2 + \text{h.c.} + \mathcal{O}(1/M^2)$$

Σ_c(3062)(QM) → $\Lambda_c\pi$
Ξ_c(2924)(QM) → $\Xi_c\pi$

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

1. Heavy quark symmetry



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Interaction Lagrangian at LO+NLO

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

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

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. arXiv:1408.3703

Constraint among decay widths

(j,j+1) transisions

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↓ 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).

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

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

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

A cons… O(1/M).

Example: j=1

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

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

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

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

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

Heavy quark symmetry (HQS)