# 强子流和强子结构

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- **Interpolating Currents**
- QCD sum rule studies
- Productions of Pc states
- Decays of Pc states

# The name pentaquark was first proposed by Lipkin in 1987



WIS-87/32/May-PH

**New Possibilities for Exotic Hadrons - Anticharmed Strange Baryons***

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PLB 195 (1987) 484

Submitted to Physics Letters

May 20, 1987

**ABSTRACT**

# The name pentaquark was first proposed by Lipkin in 1987



WIS-87/32/May-PH

Volume 193, number 2,3 PHYSICS LETTERS B 16 July 1987

## POSSIBILITY OF STABLE MULTIQUARK BARYONS

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Received 8 April 1987

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## POSSIBILITY OF STABLE MULTIQUARK BARYONS

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## $Y = 2$ STATES IN SU(6) THEORY*

Freeman J. Dyson† and Nguyen-Huu Xuong

Department of Physics, University of California, San Diego, La Jolla, California

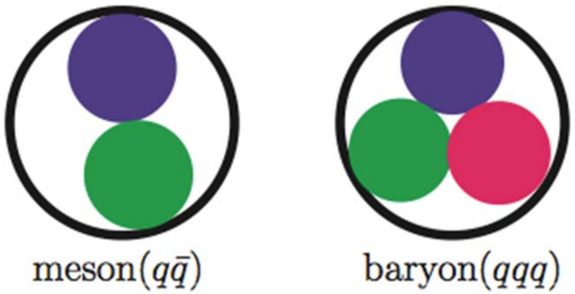
(Received 30 November 1964)

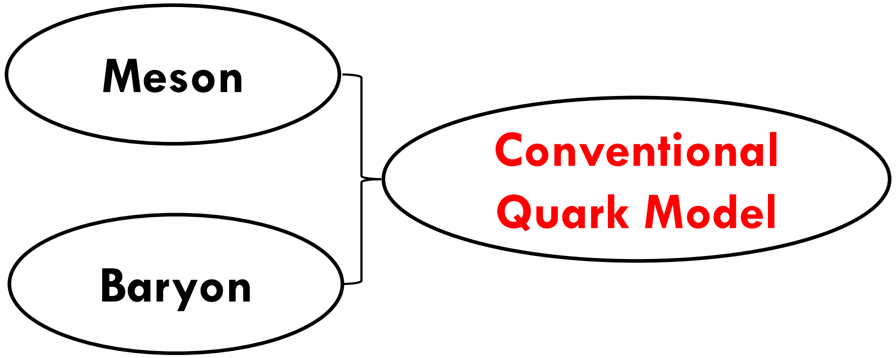
Two-baryon states. —The SU(6) theory of strongly interacting particles[1,2] predicts a classification of two-baryon states into multiplets according to the scheme

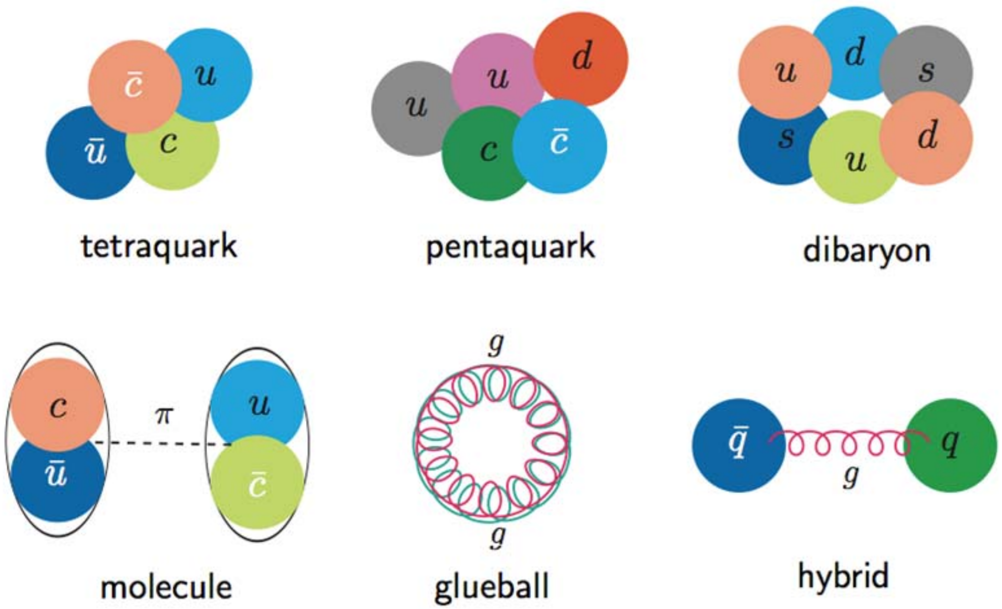
$$\underline{56} \otimes \underline{56} = \underline{462} \oplus \underline{1050} \oplus \underline{1134} \oplus \underline{490}. \qquad (1)$$

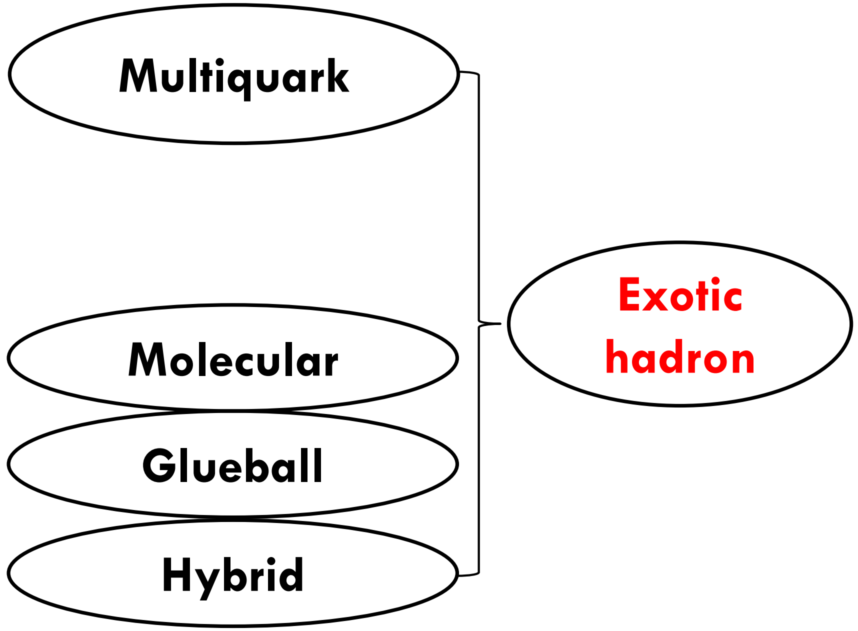
We now propose the hypothesis that all low-lying resonant states of the two-baryon system belong to the $\underline{490}$ multiplet.[3] This means that six zero-strangeness states shown in Table I should be observed. In all these states odd $T$ goes with even $J$ and vice versa.

# Categorizations




- **Identifying exotic states is one of the most important issues of particle physics**
- **Various experimental signals provide us good platform to identify exotic state**

# Theoretical explanations of experimental signals

## Resonant

- **Conventional hadrons**

- **Exotic states**
  - **Molecular states:**
    loosely bound states composed of a pair of mesons/baryons; probably bounded by the pion exchange.
  - **Multiquark states:**
    bound states of four/five/six quarks; bounded by colored-force between quarks; there are many states within the same multiplet.
  - **Hybrids:**
    bound states composed of a pair of quarks and one valance gluon.

## Non-Resonant

Many exotic states lie very close to open-charm threshold; It's quite possible that some threshold enhancements are not real resonances.

- **Kinematical effect**
- **Opening of new threshold**
- **Cusp effect**
- **Final state interaction**
- **Interference between continuum and charmonium states**
- **Triangle singularity due to the special kinematics**

## Meson Currents

| | |
|---|---|
| $\bar{q}q$ | $J^P = 0^+$ |
| $\bar{q}\gamma_5 q$ | $J^P = 0^-$ |
| $\bar{q}\gamma_\mu q$ | $J^P = 1^-$ |
| $\bar{q}\gamma_\mu\gamma_5 q$ | $J^P = 1^+$ |
| $\bar{q}\sigma_{\mu\nu} q$ | $J^P = 1^\pm$ |

# Meson Currents

| | |
|---|---|
| $\bar{q}q$ | $J^P = 0^+$ |
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**Lorentz indices only**

# Meson Currents

$\bar{q}q \qquad J^P = 0^+$

$\bar{q}\gamma_5 q \qquad J^P = 0^-$

$\bar{q}\gamma_\mu q \qquad J^P = 1^-$

$\bar{q}\gamma_\mu\gamma_5 q \qquad J^P = 1^+$

$\bar{q}\sigma_{\mu\nu} q \qquad J^P = 1^\pm$

**Lorentz indices only**

**color indices needed**

**flavor indices needed**

TABLE II: Couplings of meson operators to meson states. Color indices are omitted for simplicity.

| Operators | $J^{PC}$ | Mesons | $J^{PC}$ | Couplings | Decay Constants |
|---|---|---|---|---|---|
| $J^S = \bar{d}u$ | $0^{++}$ | – | $0^{++}$ | – | – |
| $J^P = \bar{d}i\gamma_5 u$ | $0^{-+}$ | $\pi^+$ | $0^{-+}$ | $\langle 0 \| J^P \| \pi^+ \rangle = \lambda_\pi$ | $\lambda_\pi = \frac{f_\pi m_\pi^2}{m_u + m_d}$ |
| $J^V_\mu = \bar{d}\gamma_\mu u$ | $1^{--}$ | $\rho^+$ | $1^{--}$ | $\langle 0 \| J^V_\mu \| \rho^+ \rangle = m_\rho f_{\rho^+} \epsilon_\mu$ | $f_{\rho^+} = 208$ MeV [82] |
| $J^A_\mu = \bar{d}\gamma_\mu\gamma_5 u$ | $1^{++}$ | $\pi^+$ | $0^{-+}$ | $\langle 0 \| J^A_\mu \| \pi^+ \rangle = i p_\mu f_{\pi^+}$ | $f_{\pi^+} = 130.2$ MeV [1] |
| | | $a_1(1260)$ | $1^{++}$ | $\langle 0 \| J^A_\mu \| a_1 \rangle = m_{a_1} f_{a_1} \epsilon_\mu$ | $f_{a_1} = 254$ MeV [87] |
| $J^T_{\mu\nu} = \bar{d}\sigma_{\mu\nu} u$ | $1^{\pm -}$ | $\rho^+$ | $1^{--}$ | $\langle 0 \| J^T_{\mu\nu} \| \rho^+ \rangle = i f^T_\rho (p_\mu \epsilon_\nu - p_\nu \epsilon_\mu)$ | $f^T_\rho = 159$ MeV [82] |
| | | $b_1(1235)$ | $1^{+-}$ | $\langle 0 \| J^T_{\mu\nu} \| b_1 \rangle = i f^T_{b_1} \epsilon_{\mu\nu\alpha\beta} \epsilon^\alpha p^\beta$ | $f^T_{b_1} = 180$ MeV [95] |
| $I^S = \bar{c}c$ | $0^{++}$ | $\chi_{c0}(1P)$ | $0^{++}$ | $\langle 0 \| I^S \| \chi_{c0} \rangle = m_{\chi_{c0}} f_{\chi_{c0}}$ | $f_{\chi_{c0}} = 343$ MeV [76] |
| $I^P = \bar{c}i\gamma_5 c$ | $0^{-+}$ | $\eta_c$ | $0^{-+}$ | $\langle 0 \| I^P \| \eta_c \rangle = \lambda_{\eta_c}$ | $\lambda_{\eta_c} = \frac{f_{\eta_c} m_{\eta_c}^2}{2 m_c}$ |
| $I^V_\mu = \bar{c}\gamma_\mu c$ | $1^{--}$ | $J/\psi$ | $1^{--}$ | $\langle 0 \| I^V_\mu \| J/\psi \rangle = m_{J/\psi} f_{J/\psi} \epsilon_\mu$ | $f_{J/\psi} = 418$ MeV [83] |
| $I^A_\mu = \bar{c}\gamma_\mu\gamma_5 c$ | $1^{++}$ | $\eta_c$ | $0^{-+}$ | $\langle 0 \| I^A_\mu \| \eta_c \rangle = i p_\mu f_{\eta_c}$ | $f_{\eta_c} = 387$ MeV [83] |
| | | $\chi_{c1}(1P)$ | $1^{++}$ | $\langle 0 \| I^A_\mu \| \chi_{c1} \rangle = m_{\chi_{c1}} f_{\chi_{c1}} \epsilon_\mu$ | $f_{\chi_{c1}} = 335$ MeV [77] |
| $I^T_{\mu\nu} = \bar{c}\sigma_{\mu\nu} c$ | $1^{\pm -}$ | $J/\psi$ | $1^{--}$ | $\langle 0 \| I^T_{\mu\nu} \| J/\psi \rangle = i f^T_{J/\psi} (p_\mu \epsilon_\nu - p_\nu \epsilon_\mu)$ | $f^T_{J/\psi} = 410$ MeV [83] |
| | | $h_c(1P)$ | $1^{+-}$ | $\langle 0 \| I^T_{\mu\nu} \| h_c \rangle = i f^T_{h_c} \epsilon_{\mu\nu\alpha\beta} \epsilon^\alpha p^\beta$ | $f^T_{h_c} = 235$ MeV [83] |

| Meson Currents | | Diquark Currents | |
| --- | --- | --- | --- |
| $\bar{q}q$ | $J^P = 0^+$ | $q^T C q$ | $J^P = 0^-$ |
| $\bar{q}\gamma_5 q$ | $J^P = 0^-$ | $q^T C\gamma_5 q$ | $J^P = 0^+$ |
| $\bar{q}\gamma_\mu q$ | $J^P = 1^-$ | $q^T C\gamma_\mu q$ | $J^P = 1^+$ |
| $\bar{q}\gamma_\mu\gamma_5 q$ | $J^P = 1^+$ | $q^T C\gamma_\mu\gamma_5 q$ | $J^P = 1^-$ |
| $\bar{q}\sigma_{\mu\nu} q$ | $J^P = 1^\pm$ | $q^T C\sigma_{\mu\nu} q$ | $J^P = 1^\pm$ |

# Baryon Currents

$$\Lambda = \epsilon_{abc}\epsilon^{ABC}({q_A}^{aT} C {q_B}^{b})\gamma_5 {q_C}^{c},$$

$${N_1}^{N} = \epsilon_{abc}\epsilon^{ABD}\lambda^{N}{}_{DC}({q_A}^{aT} C {q_B}^{b})\gamma_5 {q_C}^{c},$$

$${N_2}^{N} = \epsilon_{abc}\epsilon^{ABD}\lambda^{N}{}_{DC}({q_A}^{aT} C\gamma_5 {q_B}^{b}) {q_C}^{c},$$

$${N_\mu}^{N} = \epsilon_{abc}\epsilon^{ABD}\lambda^{N}{}_{DC}({q_A}^{aT} C\gamma_\mu\gamma_5 {q_B}^{b})\gamma_5 {q_C}^{c},$$

$${\Delta_\mu}^{P} = \epsilon_{abc}{S_P}^{ABC}({q_A}^{aT} C\gamma_\mu {q_B}^{b}) {q_C}^{c},$$

$${\Delta_{\mu\nu}}^{P} = \epsilon_{abc}{S_P}^{ABC}({q_A}^{aT} C\sigma_{\mu\nu} {q_B}^{b})\gamma_5 {q_C}^{c}.$$

Color: $3\otimes3\otimes3 = 1$

Flavor: $3\otimes3\otimes3 = 1\oplus8 \oplus 8\oplus10$

a,b,c are color indices

A,B,C are flavor indices (q=u,d,s)

$\epsilon^{ABC}$ denotes totally antisymmetric

${S_P}^{ABD}$ denotes totally symmetric

# The current well coupling to $[\bar{D}^0\Sigma_c^+]$

flavor contents

$$[\bar{c}_d(x)\gamma_5 u_d(x)][\varepsilon^{abc}(u_a^T(x)C\gamma_5 d_b(x))c_c(x)]$$

color indices

$$\langle 0|J|X_{1/2}\rangle = f_X u(p)$$

## 存在多种构型：

- 分子态构型一：$[\bar{c}_d c_d][\epsilon^{abc} q_a q_b q_c]$
- 分子态构型二：$[\bar{c}_d q_d][\epsilon^{abc} c_a q_b q_c]$
- 紧束缚五夸克态构型一：$\epsilon^{abc} \bar{c}_a [\epsilon^{bde} c_d q_e][\epsilon^{cfg} q_f q_g]$

……

## 以上构型满足**local条件**时会存在一定的关联：

- The Fierz transformation
- The color rearrangement

$$\delta^{de}\epsilon^{abc} = \delta^{da}\epsilon^{ebc} + \delta^{db}\epsilon^{aec} + \delta^{dc}\epsilon^{abe}$$

$[\bar{c}_d c_d][\epsilon^{abc} u_a u_b d_c]$ → $[\bar{c}_d u_d][\epsilon^{abc} c_a u_b d_c]$ & $[\bar{c}_d d_d][\epsilon^{abc} c_a u_b u_c]$

$\eta$ → $\xi$ & $\psi$

$$\eta_1 = [\epsilon_{abc}(u_a^T C d_b)\gamma_5 u_c][\bar{c}_d c_d]$$

$$\begin{aligned}
&= -\frac{5}{16}\xi_1 - \frac{5}{16}\xi_2 - \frac{1}{16}\xi_3 - \frac{1}{16}\xi_4 - \frac{5}{16}\xi_5 \\
&+ \frac{5}{16}\xi_6 + \frac{1}{16}\xi_7 - \frac{1}{16}\xi_8 - \frac{5}{32}\xi_{10} \\
&- \frac{1}{32}\xi_{11} - \frac{1}{16}\xi_{13} - \frac{1}{16}\xi_{14} - \frac{1}{16}\xi_{15} \\
&- \frac{1}{16}\xi_{16} - \frac{1}{16}\xi_{17} + \frac{1}{16}\xi_{18} - \frac{1}{16}\xi_{19} + \frac{1}{16}\xi_{20} \\
&+ \frac{i}{16}\xi_{21} - \frac{i}{16}\xi_{22} + \frac{i}{16}\xi_{23} - \frac{i}{16}\xi_{24} - \frac{i}{16}\xi_{25} \\
&- \frac{i}{16}\xi_{26} - \frac{i}{16}\xi_{27} - \frac{i}{16}\xi_{28} + \frac{1}{32}\xi_{29} + \frac{1}{32}\xi_{30} \\
&- \frac{i}{16}\xi_{33} + \frac{i}{16}\xi_{34} + \frac{i}{16}\xi_{35} - \frac{i}{16}\xi_{36} + \frac{1}{32}\xi_{37} \\
&+ \frac{1}{32}\xi_{38} - \frac{i}{16}\xi_{43} \\
&+ \frac{1}{16}\psi_1 + \frac{1}{16}\psi_2 + \frac{1}{16}\psi_3 - \frac{1}{16}\psi_4 - \frac{i}{16}\psi_5 \\
&+ \frac{i}{16}\psi_6 + \frac{i}{16}\psi_7 + \frac{i}{16}\psi_8 - \frac{1}{32}\psi_9 - \frac{1}{32}\psi_{10} \\
&+ \frac{i}{16}\psi_{13} - \frac{i}{16}\psi_{14} - \frac{i}{16}\psi_{15} \\
&+ \frac{i}{16}\psi_{16} - \frac{1}{32}\psi_{18} - \frac{1}{32}\psi_{19} + \frac{i}{16}\psi_{23} \,.
\end{aligned}$$

# 7个$\bar{D}^{(*)}\Sigma_c^{(*)}$分子态和对应的试探流：

$$|\bar{D}\Sigma_c; 1/2^-; \theta\rangle = \cos\theta\, |\bar{D}^0\Sigma_c^+; 1/2^-\rangle + \sin\theta\, |D^-\Sigma_c^{++}; 1/2^-\rangle\,, \tag{18}$$

$$|\bar{D}^*\Sigma_c; 1/2^-; \theta\rangle = \cos\theta\, |\bar{D}^{*0}\Sigma_c^+; 1/2^-\rangle + \sin\theta\, |D^{*-}\Sigma_c^{++}; 1/2^-\rangle\,, \tag{19}$$

$$|\bar{D}^*\Sigma_c; 3/2^-; \theta\rangle = \cos\theta\, |\bar{D}^{*0}\Sigma_c^+; 3/2^-\rangle + \sin\theta\, |D^{*-}\Sigma_c^{++}; 3/2^-\rangle\,, \tag{20}$$

$$|\bar{D}\Sigma_c^*; 3/2^-; \theta\rangle = \cos\theta\, |\bar{D}^0\Sigma_c^{*+}; 3/2^-\rangle + \sin\theta\, |D^-\Sigma_c^{*++}; 3/2^-\rangle\,, \tag{21}$$

$$|\bar{D}^*\Sigma_c^*; 1/2^-; \theta\rangle = \cos\theta\, |\bar{D}^{*0}\Sigma_c^{*+}; 1/2^-\rangle + \sin\theta\, |D^{*-}\Sigma_c^{*++}; 1/2^-\rangle\,, \tag{22}$$

$$|\bar{D}^*\Sigma_c^*; 3/2^-; \theta\rangle = \cos\theta\, |\bar{D}^{*0}\Sigma_c^{*+}; 3/2^-\rangle + \sin\theta\, |D^{*-}\Sigma_c^{*++}; 3/2^-\rangle\,, \tag{23}$$

$$|\bar{D}^*\Sigma_c^*; 5/2^-; \theta\rangle = \cos\theta\, |\bar{D}^{*0}\Sigma_c^{*+}; 5/2^-\rangle + \sin\theta\, |D^{*-}\Sigma_c^{*++}; 5/2^-\rangle\,, \tag{24}$$

$$\eta_1 = [\delta^{ab}\bar{c}_a\gamma_5 u_b]\,[\epsilon^{cde}u_c^T\mathbb{C}\gamma_\mu d_d\gamma^\mu\gamma_5 c_e] = \bar{D}^0\,\Sigma_c^+\,, \tag{27}$$

$$\eta_2 = [\delta^{ab}\bar{c}_a\gamma_\nu u_b]\,\gamma^\nu\gamma_5\,[\epsilon^{cde}u_c^T\mathbb{C}\gamma_\mu d_d\gamma^\mu\gamma_5 c_e] = \bar{D}^{*0}_\nu\,\gamma^\nu\gamma_5\,\Sigma_c^+\,, \tag{28}$$

$$\eta_3^\alpha = P_{3/2}^{\alpha\nu}\,[\delta^{ab}\bar{c}_a\gamma_\nu u_b]\,[\epsilon^{cde}u_c^T\mathbb{C}\gamma_\mu d_d\gamma^\mu\gamma_5 c_e] = P_{3/2}^{\alpha\nu}\,\bar{D}^{*0}_\nu\,\Sigma_c^+\,, \tag{29}$$

$$\eta_4^\alpha = [\delta^{ab}\bar{c}_a\gamma_5 u_b]\,P_{3/2}^{\alpha\mu}[\epsilon^{cde}u_c^T\mathbb{C}\gamma_\mu d_d c_e] = \bar{D}^0\,\Sigma_c^{*+;\alpha}\,, \tag{30}$$

$$\eta_5 = [\delta^{ab}\bar{c}_a\gamma_\nu u_b]\,P_{3/2}^{\nu\mu}[\epsilon^{cde}u_c^T\mathbb{C}\gamma_\mu d_d c_e] = \bar{D}^{*0}_\nu\,\Sigma_c^{*+;\nu}\,, \tag{31}$$

$$\eta_6^\alpha = [\delta^{ab}\bar{c}_a\gamma_\nu u_b]\,P_{3/2}^{\alpha\rho}\,\gamma^\nu\gamma_5\,P_{\rho\mu}^{3/2}[\epsilon^{cde}u_c^T\mathbb{C}\gamma^\mu d_d c_e] = \bar{D}^{*0}_\nu\,P_{3/2}^{\alpha\rho}\,\gamma^\nu\gamma_5\,\Sigma_{c;\rho}^{*+}\,, \tag{32}$$

$$\eta_7^{\alpha\beta} = P_{5/2}^{\alpha\beta,\nu\rho}\,[\delta^{ab}\bar{c}_a\gamma_\nu u_b]\,P_{\rho\mu}^{3/2}[\epsilon^{cde}u_c^T\mathbb{C}\gamma^\mu d_d c_e] = P_{5/2}^{\alpha\beta,\nu\rho}\,\bar{D}^{*0}_\nu\,\Sigma_{c;\rho}^{*+}\,, \tag{33}$$

# Discussions on interpolating currents

- The current well describes the internal color, flavor, spin and orbital quantum numbers.

- The current well describes **hadron's internal symmetries**, e.g, Pauli principle is automatically satisfied.

- A current can couple to different states, and different currents can couple to the same state.

- What happens if we diagonalize all the currents, given that the number of currents is more the number of states?

# CONTENTS

- Interpolating Currents
- **QCD sum rule studies**
- Productions of Pc states
- Decays of Pc states

# QCD Sum Rules

- In sum rule analyses, we consider two-point correlation functions:

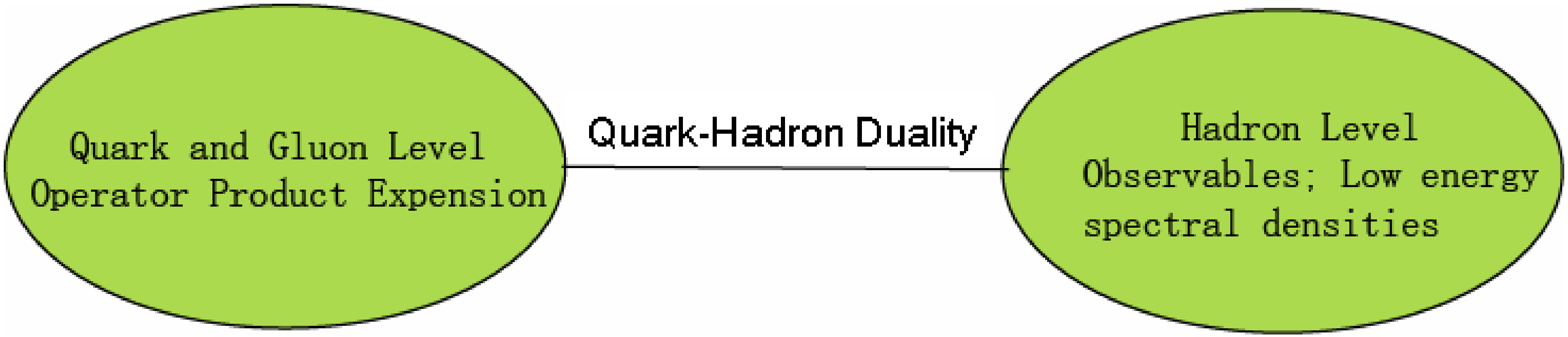
$$\Pi\left(q^2\right) \stackrel{\text{def}}{=} i \int d^4x e^{iqx} \langle 0|T\eta(x)\eta^+(0)\,|0\rangle$$
$$\approx \sum_n \langle 0|\eta|n\rangle\langle n|\eta^+|0\rangle$$

where η is the current which can couple to hadronic states.

- By using the dispersion relation, we can obtain the spectral density

$$\Pi\left(q^2\right) = \int_{s_<}^{\infty} \frac{\rho(s)}{s - q^2 - i\varepsilon} ds$$

- In QCD sum rule, we can calculate these matrix elements from QCD (OPE) and relate them to observables by using dispersion relation.



SVZ sum rule (Shifman 1979)

## Quark and Gluon Level

(Convergence of OPE)

$$\Pi_{\mathrm{OPE}}(q^2) \xrightarrow[s\,=\,-q^2]{\text{dispersion relation}} \rho_{OPE}(s) = a_n\, s^n + a_{n-1}\, s^{n-1}$$

Quark-Hadron Duality

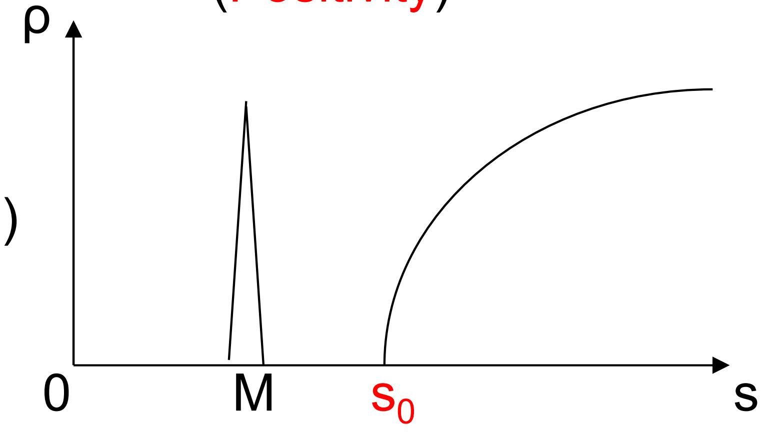
## Hadron Level

$$\Pi_{phys}(q^2) = f_P^2 \frac{\not{q} + M}{q^2 - M^2} \longleftrightarrow \rho_{phys}(s) = \lambda_x^2 \delta(s - M_x^2) + \cdots$$

(for baryon case)

(Positivity)

(Sufficient amount of Pole contribution)



# QCD Sum Rules

- Borel transformation to suppress the higher order terms:

$$\Pi(M_B^2) \equiv f^2 e^{-M^2/M_B^2} = \int_{s_<}^{s_0} e^{-s/M_B^2} \rho(s) ds$$

- Two parameters

$M_B$ ,   $s_0$

We need to choose certain region of ($M_B$, $s_0$).

- **Criteria**

1. Stability
2. Convergence of OPE
3. Positivity of spectral density
4. Sufficient amount of pole contribution

# Parity of Pentaquark


Y. Chung, H. G. Dosch, M. Kremer and D. Schall, Nucl. Phys. B 197, 55 (1982)

D. Jido, N. Kodama and M. Oka, Phys. Rev. D 54, 4532 (1996)

Y. Kondo, O. Morimatsu and T. Nishikawa, Nucl. Phys. A 764, 303 (2006)

K. Ohtani, P. Gubler and M. Oka, Phys. Rev. D 87, no. 3, 034027 (2013)


- Assuming $J$ is a pentaquark current, $\gamma_5 J$ is its partner having the opposite parity.
- They can couple to the same physical state through

$$< 0|\, J\, |P(q)> = f_P u(q)\,, \qquad < 0|\, \gamma_5 J\, |P(q)> = f_P \gamma_5 u(q).$$

- The same pentaquark current $J$ can couple to states of both positive and negative parities through

$$< 0|\, J\, |P(q)> = f_P u(q)\,, \qquad < 0|\, J\, |P'(q)> = f_{P'} \gamma_5 u'(q).$$

where $|P(q)>$ has the same parity as $J$, while $|P'(q)>$ has the opposite parity.

$$f_P^2 \frac{\not{q} + M}{q^2 - M^2} \qquad\qquad f_P^2 \frac{-\not{q} + M}{q^2 - M^2}$$

The sum rule results obtained using $J_\mu^{\bar{D}^*\Sigma_c}$ are:

$$M_{[\bar{D}^*\Sigma_c],3/2^-} = 4.37^{+0.18}_{-0.12}\ \mathrm{GeV}\,.$$

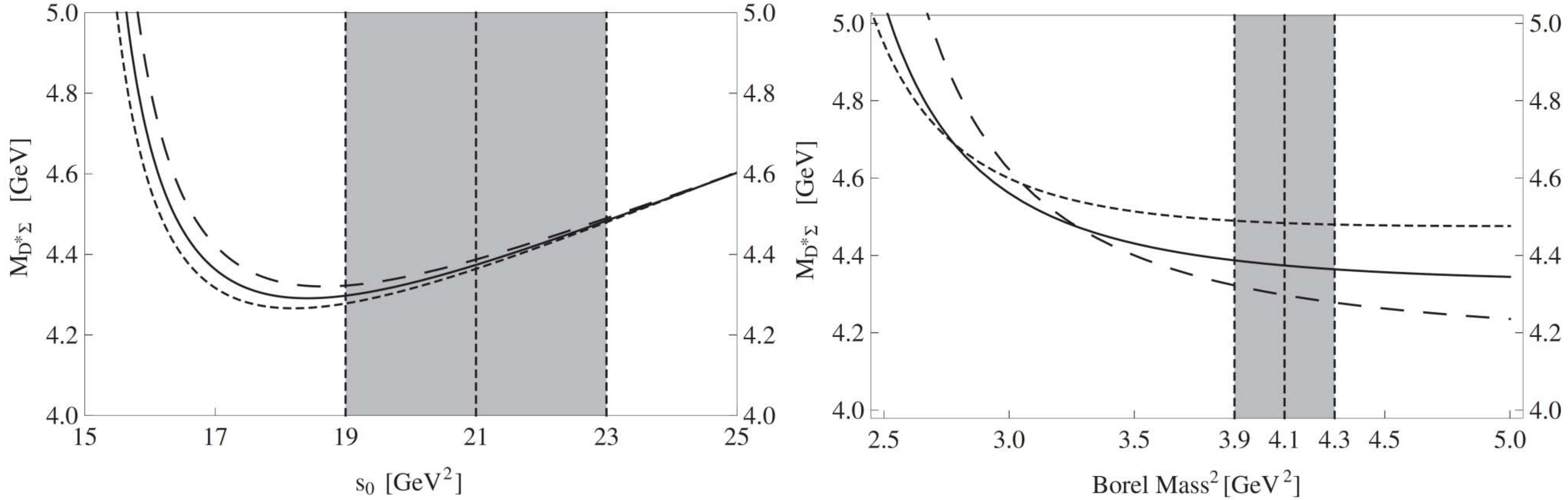



FIG. 1: The variation of $M_{[\bar{D}^*\Sigma_c],3/2^-}$ with respect to the threshold value $s_0$ (left) and the Borel mass $M_B$ (right). In the left figure, the

# QCD sum rule results

| State | $M$ [MeV] |
|---|---|
| $P_c(4312)^+$ | $4311.9 \pm 0.7^{+6.8}_{-0.6}$ |
| $P_c(4440)^+$ | $4440.3 \pm 1.3^{+4.1}_{-4.7}$ |
| $P_c(4457)^+$ | $4457.3 \pm 0.6^{+4.1}_{-1.7}$ |

TABLE I: Masses and decay constants of the $X_{1\cdots7}$, extracted from the currents $J_{1\cdots7}$.

| Currents | Configuration | $s_0^{min}$ [GeV$^2$] | Working Regions | | Pole [%] | Mass [GeV] | $f_X$ [GeV$^6$] | Candidate |
|---|---|---|---|---|---|---|---|---|
| | | | $s_0$ [GeV$^2$] | $M_B^2$ [GeV$^2$] | | | | |
| $J_1$ | $\lvert\bar{D}\Sigma_c; 1/2^-\rangle$ | 22.4 | $24.0 \pm 1.0$ | 3.27–3.52 | 40–48 | $4.30^{+0.10}_{-0.10}$ | $(1.19^{+0.18}_{-0.19}) \times 10^{-3}$ | $P_c(4312)^+$ |
| $J_2$ | $\lvert\bar{D}^*\Sigma_c; 1/2^-\rangle$ | 25.5 | $27.0 \pm 1.0$ | 3.78–3.99 | 40–46 | $4.48^{+0.10}_{-0.10}$ | $(2.24^{+0.30}_{-0.34}) \times 10^{-3}$ | $P_c(4457)^+$ (?) |
| $J_3$ | $\lvert\bar{D}^*\Sigma_c; 3/2^-\rangle$ | 24.6 | $26.0 \pm 1.0$ | 3.51–3.72 | 40–46 | $4.46^{+0.10}_{-0.11}$ | $(1.15^{+0.16}_{-0.18}) \times 10^{-3}$ | $P_c(4440)^+$ (?) |
| $J_4$ | $\lvert\bar{D}\Sigma_c^*; 3/2^-\rangle$ | 24.2 | $25.0 \pm 1.0$ | 3.33–3.45 | 40–44 | $4.43^{+0.10}_{-0.10}$ | $(0.65^{+0.10}_{-0.11}) \times 10^{-3}$ | |
| $J_5$ | $\lvert\bar{D}^*\Sigma_c^*; 1/2^-\rangle$ | 26.0 | $27.0 \pm 1.0$ | 3.43–3.56 | 40–44 | $4.51^{+0.11}_{-0.10}$ | $(1.12^{+0.17}_{-0.19}) \times 10^{-3}$ | |
| $J_6$ | $\lvert\bar{D}^*\Sigma_c^*; 3/2^-\rangle$ | 25.3 | $27.0 \pm 1.0$ | 3.69–3.98 | 40–48 | $4.52^{+0.11}_{-0.11}$ | $(0.85^{+0.13}_{-0.14}) \times 10^{-3}$ | |
| $J_7$ | $\lvert\bar{D}^*\Sigma_c^*; 5/2^-\rangle$ | 24.7 | $26.0 \pm 1.0$ | 3.22–3.42 | 40–46 | $4.55^{+0.13}_{-0.15}$ | $(0.65^{+0.10}_{-0.11}) \times 10^{-3}$ | |

Uncertainties not enough to extract binding energies

# QCD sum rule results

TABLE I: Masses and decay constants of the $X_{1\cdots7}$, extracted from the currents $J_{1\cdots7}$.

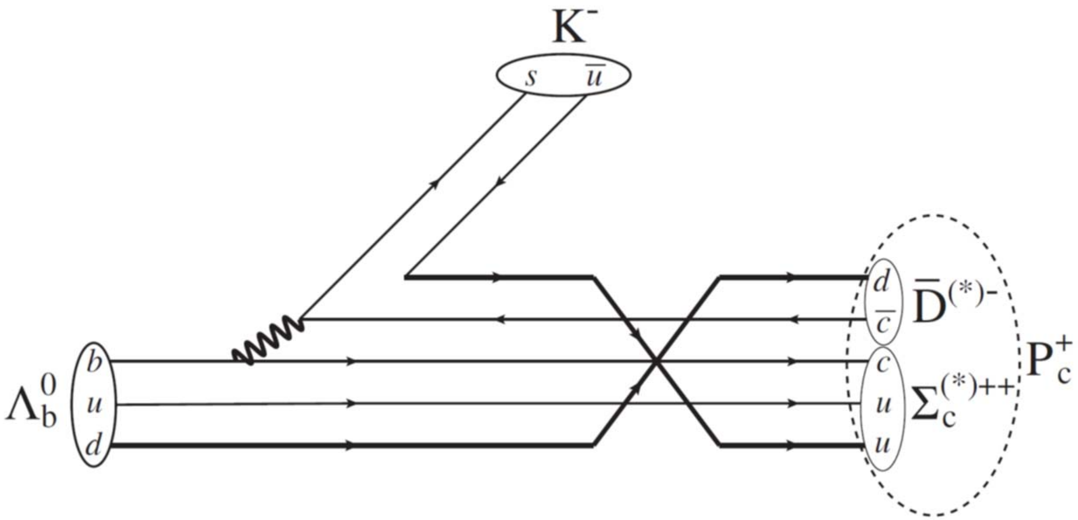
| Currents | Configuration | $s_0^{min}$ [GeV$^2$] | Working Regions | | Pole [%] | Mass [GeV] | $f_X$ [GeV$^6$] | Candidate |
|---|---|---|---|---|---|---|---|---|
| | | | $s_0$ [GeV$^2$] | $M_B^2$ [GeV$^2$] | | | | |
| $J_1$ | $\|\bar{D}\Sigma_c; 1/2^-\rangle$ | 22.4 | $24.0 \pm 1.0$ | 3.27–3.52 | 40–48 | $4.30^{+0.10}_{-0.10}$ | $(1.19^{+0.18}_{-0.19}) \times 10^{-3}$ | $P_c(4312)^+$ |
| $J_2$ | $\|\bar{D}^*\Sigma_c; 1/2^-\rangle$ | 25.5 | $27.0 \pm 1.0$ | 3.78–3.99 | 40–46 | $4.48^{+0.10}_{-0.10}$ | $(2.24^{+0.30}_{-0.34}) \times 10^{-3}$ | $P_c(4457)^+$ (?) |
| $J_3$ | $\|\bar{D}^*\Sigma_c; 3/2^-\rangle$ | 24.6 | $26.0 \pm 1.0$ | 3.51–3.72 | 40–46 | $4.46^{+0.10}_{-0.11}$ | $(1.15^{+0.16}_{-0.18}) \times 10^{-3}$ | $P_c(4440)^+$ (?) |
| $J_4$ | $\|\bar{D}\Sigma_c^*; 3/2^-\rangle$ | 24.2 | $25.0 \pm 1.0$ | 3.33–3.45 | 40–44 | $4.43^{+0.10}_{-0.10}$ | $(0.65^{+0.10}_{-0.11}) \times 10^{-3}$ | |
| $J_5$ | $\|\bar{D}^*\Sigma_c^*; 1/2^-\rangle$ | 26.0 | $27.0 \pm 1.0$ | 3.43–3.56 | 40–44 | $4.51^{+0.11}_{-0.10}$ | $(1.12^{+0.17}_{-0.19}) \times 10^{-3}$ | |
| $J_6$ | $\|\bar{D}^*\Sigma_c^*; 3/2^-\rangle$ | 25.3 | $27.0 \pm 1.0$ | 3.69–3.98 | 40–48 | $4.52^{+0.11}_{-0.11}$ | $(0.85^{+0.13}_{-0.14}) \times 10^{-3}$ | |
| $J_7$ | $\|\bar{D}^*\Sigma_c^*; 5/2^-\rangle$ | 24.7 | $26.0 \pm 1.0$ | 3.22–3.42 | 40–46 | $4.55^{+0.13}_{-0.15}$ | $(0.65^{+0.10}_{-0.11}) \times 10^{-3}$ | |

$$\langle 0|J|X_{1/2}\rangle = f_X u(p)$$

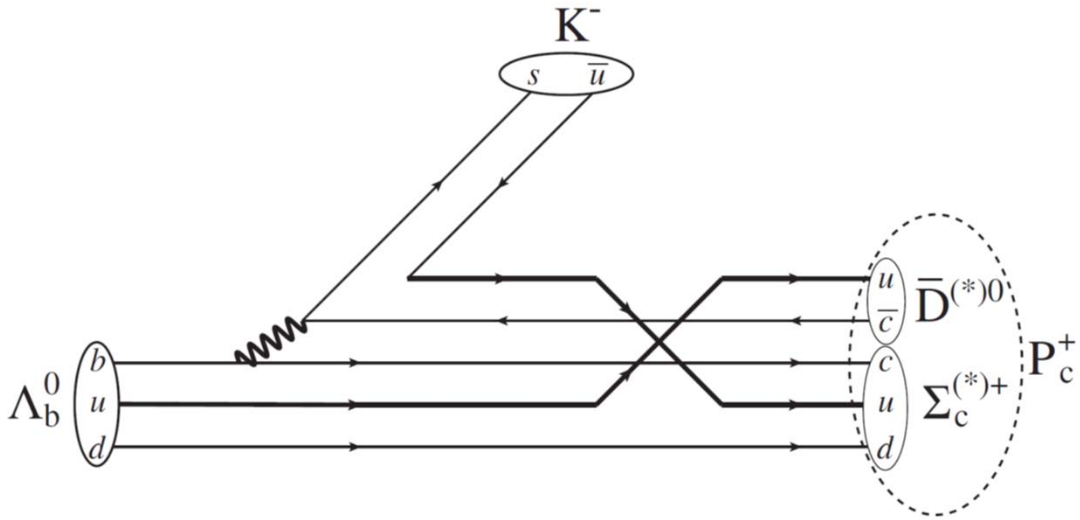
# CONTENTS

- Interpolating Currents
- QCD sum rule studies
- **Productions of Pc states**
- Decays of Pc states

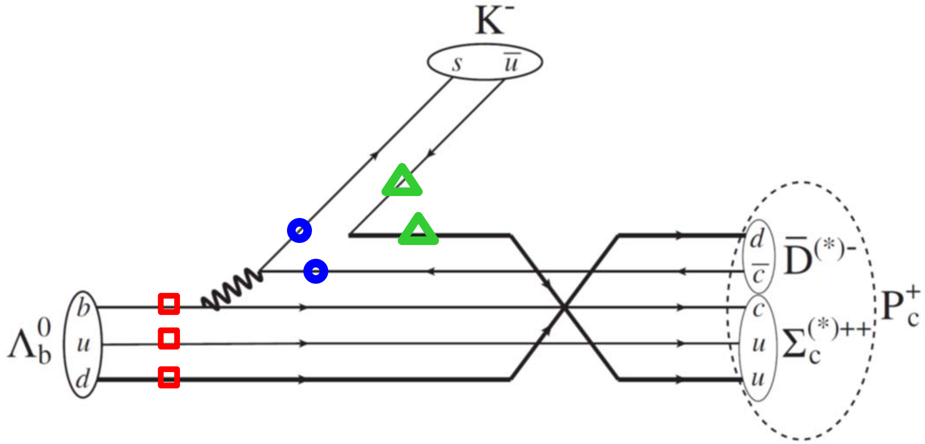
# $P_c^+$ in $\Lambda_b^0 \longrightarrow J/\psi K^- p$ decays



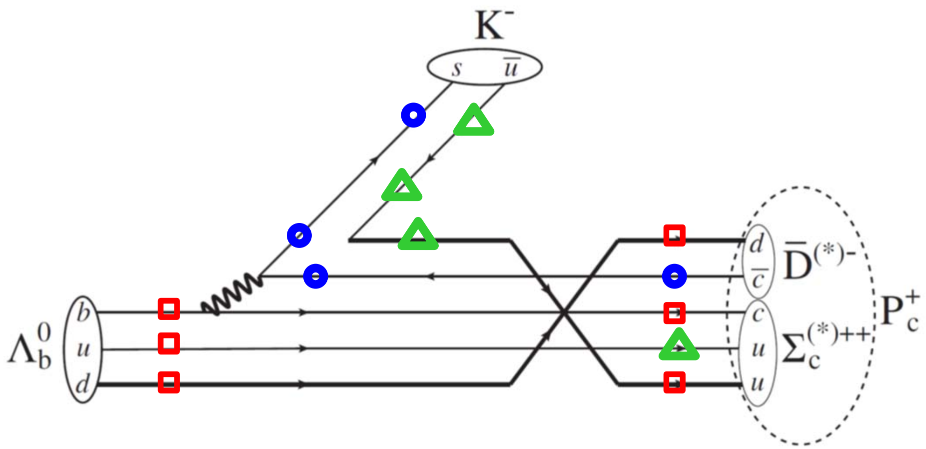

(a) $\Lambda_b^0 \to D^{(*)-}\Sigma_c^{(*)++}K^-$




(b) $\Lambda_b^0 \to \bar{D}^{(*)0}\Sigma_c^{(*)+}K^-$

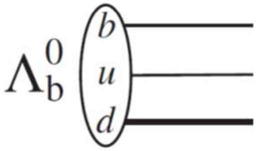



$P_c^+$ in $\Lambda_b^0 \longrightarrow J/\psi K^- p$ decays

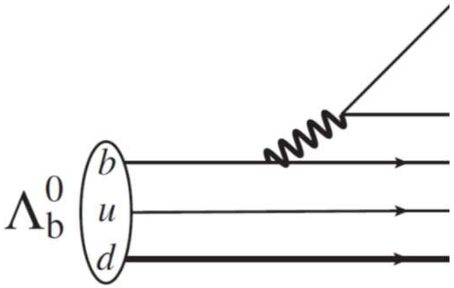



$P_c^+$ in $\Lambda_b^0 \longrightarrow J/\psi K^- p$ decays

$$
\begin{aligned}
\epsilon^{abc}\delta^{de}\delta^{fg} &= \left(\epsilon^{ebc}\delta^{da} + \epsilon^{aec}\delta^{db} + \epsilon^{abe}\delta^{dc}\right) \times \delta^{fg} \\
&= \epsilon^{gbc}\delta^{da}\delta^{fe} + \epsilon^{egc}\delta^{da}\delta^{fb} + \epsilon^{ebg}\delta^{da}\delta^{fc} \\
&+ \epsilon^{gec}\delta^{db}\delta^{fa} + \epsilon^{agc}\delta^{db}\delta^{fe} + \epsilon^{aeg}\delta^{db}\delta^{fc} \\
&+ \epsilon^{gbe}\delta^{dc}\delta^{fa} + \epsilon^{age}\delta^{dc}\delta^{fb} + \epsilon^{abg}\delta^{dc}\delta^{fe} \,.
\end{aligned}
$$

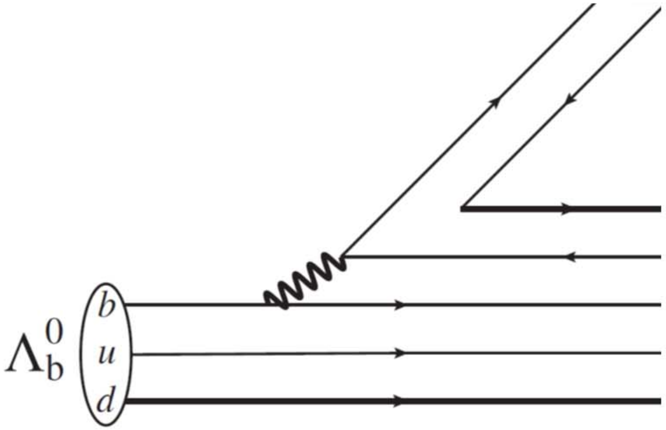



$$\Lambda_b^0 \quad \longrightarrow \quad J_{\Lambda_b^0}(x) = [\epsilon^{abc} u_a^T \mathbb{C} \gamma_5 d_b b_c](x)$$




$$\Lambda_b^0 \longrightarrow J_{\Lambda_b^0}(x) = [\epsilon^{abc} u_a^T \mathbb{C}\gamma_5 d_b b_c](x)$$

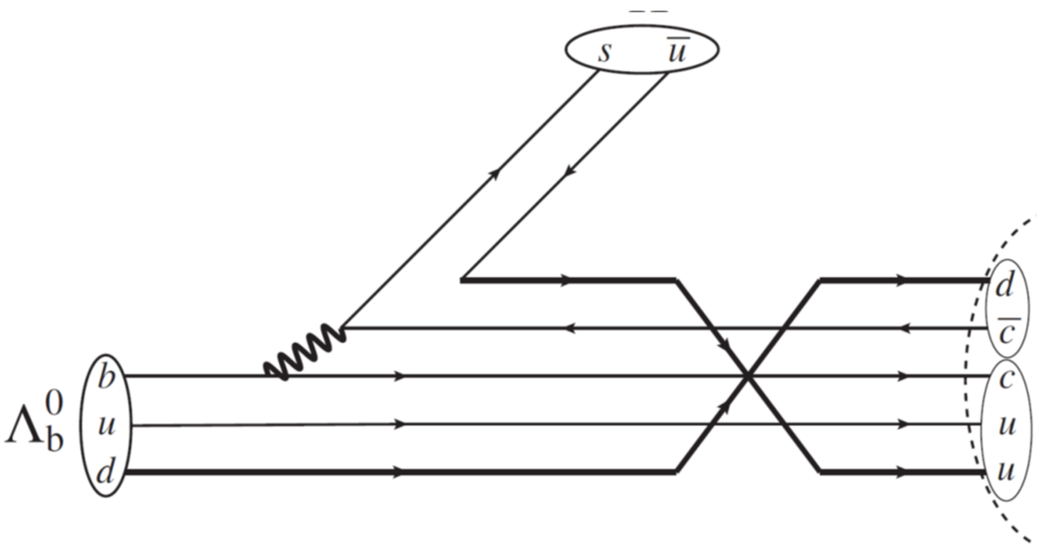
$$\xrightarrow{\text{weak}} [\epsilon^{abc} u_a^T \mathbb{C}\gamma_5 d_b \gamma_\rho (1-\gamma_5) c_c](x) \;\times\; [\delta^{de} \bar{c}_d \gamma^\rho (1-\gamma_5) s_e](y)$$




$$\Lambda_b^0 \xrightarrow{\qquad\qquad} J_{\Lambda_b^0}(x) = [\epsilon^{abc} u_a^T \mathbb{C}\gamma_5 d_b b_c](x)$$

$$\xrightarrow{\text{weak}} [\epsilon^{abc} u_a^T \mathbb{C}\gamma_5 d_b \gamma_\rho (1-\gamma_5) c_c](x) \;\times\; [\delta^{de} \bar{c}_d \gamma^\rho (1-\gamma_5) s_e](y)$$

$$\xrightarrow{\text{QPC}} [\epsilon^{abc} u_a^T \mathbb{C}\gamma_5 d_b \gamma_\rho (1-\gamma_5) c_c](x) \;\times\; [\delta^{de} \bar{c}_d \gamma^\rho (1-\gamma_5) s_e](y) \;\times\; [\delta^{fg} \bar{u}_f u_g](z)$$




$$\Lambda_b^0 \xrightarrow{\qquad\qquad} J_{\Lambda_b^0}(x) = [\epsilon^{abc} u_a^T \mathbb{C}\gamma_5 d_b b_c](x)$$

$$\xrightarrow{\text{weak}} [\epsilon^{abc} u_a^T \mathbb{C}\gamma_5 d_b \gamma_\rho (1-\gamma_5) c_c](x) \times [\delta^{de} \bar{c}_d \gamma^\rho (1-\gamma_5) s_e](y)$$

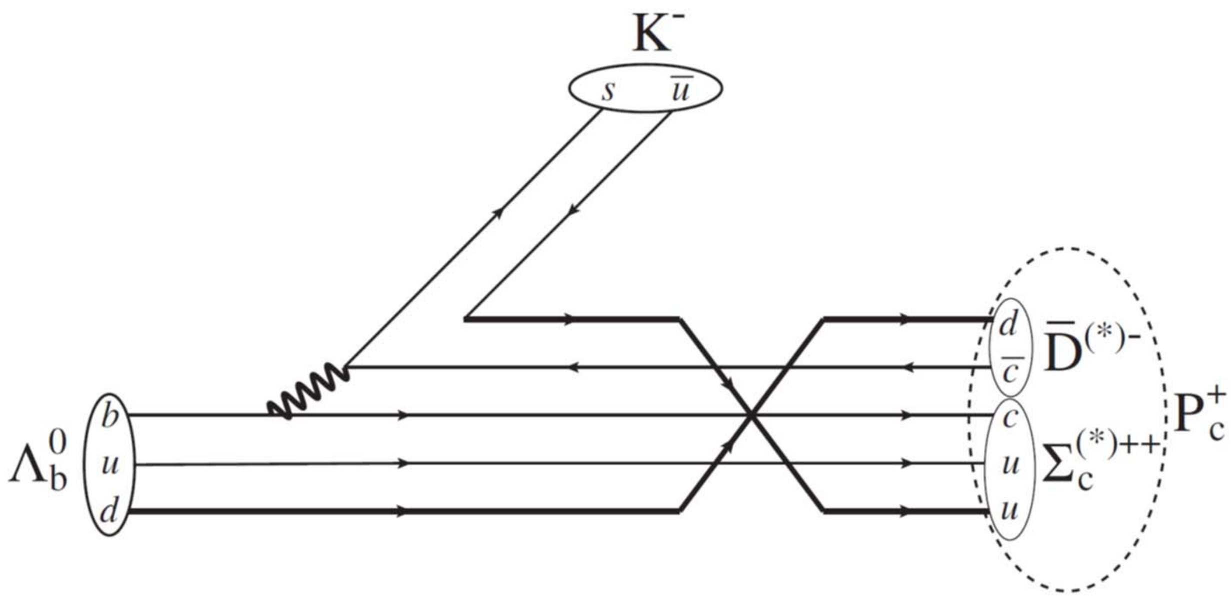
$$\xrightarrow{\text{QPC}} [\epsilon^{abc} u_a^T \mathbb{C}\gamma_5 d_b \gamma_\rho (1-\gamma_5) c_c](x) \times [\delta^{de} \bar{c}_d \gamma^\rho (1-\gamma_5) s_e](y) \times [\delta^{fg} \bar{u}_f u_g](z)$$

$$\overset{\text{color}}{=\!=\!=} \epsilon^{agc} \delta^{db} \delta^{fe} \times u_a^T(x) \mathbb{C}\gamma_5 d_b(x) \gamma_\rho (1-\gamma_5) c_c(x) \times \bar{c}_d(y) \gamma^\rho (1-\gamma_5) s_e(y) \times \bar{u}_f(z) u_g(z) + \cdots$$

$$\xrightarrow{\text{move}} \epsilon^{agc} \delta^{db} \delta^{fe} \times u_a^T(x) \mathbb{C}\gamma_5 d_b(y) \gamma_\rho (1-\gamma_5) c_c(x) \times \bar{c}_d(y) \gamma^\rho (1-\gamma_5) s_e(z) \times \bar{u}_f(z) u_g(x) + \cdots$$

$$\overset{\text{Fierz:}d_b \leftrightarrow u_g}{=\!=\!=} -\frac{\delta^{db}\delta^{fe}}{4} \times [\epsilon^{agc} u_a^T \mathbb{C}\gamma_\mu u_g \gamma_\rho (1-\gamma_5) c_c](x) \times \bar{c}_d(y) \gamma^\rho (1-\gamma_5) s_e(z) \times \bar{u}_f(z) \gamma^\mu \gamma_5 d_b(y) + \cdots$$

$$\overset{\text{Fierz:}d_b \leftrightarrow s_e}{=\!=\!=} +\frac{1+\gamma_5}{16} \times [\epsilon^{agc} u_a^T \mathbb{C}\gamma_\mu u_g \gamma^\mu \gamma_5 c_c](x) \times [\delta^{db} \bar{c}_d \gamma_5 d_b](y) \times [\delta^{fe} \bar{u}_f \gamma_5 s_e](z) + \cdots$$




$$
\begin{aligned}
\Lambda_b^0 &\xrightarrow{\qquad\qquad} J_{\Lambda_b^0}(x) = [\epsilon^{abc} u_a^T \mathbb{C}\gamma_5 d_b b_c](x) \\
&\xrightarrow{\text{weak}} [\epsilon^{abc} u_a^T \mathbb{C}\gamma_5 d_b \gamma_\rho (1-\gamma_5) c_c](x) \;\times\; [\delta^{de} \bar{c}_d \gamma^\rho (1-\gamma_5) s_e](y) \\
&\xrightarrow{\text{QPC}} [\epsilon^{abc} u_a^T \mathbb{C}\gamma_5 d_b \gamma_\rho (1-\gamma_5) c_c](x) \;\times\; [\delta^{de} \bar{c}_d \gamma^\rho (1-\gamma_5) s_e](y) \;\times\; [\delta^{fg} \bar{u}_f u_g](z) \\
&\overset{\text{color}}{=\!=\!=} \epsilon^{agc} \delta^{db} \delta^{fe} \times u_a^T(x) \mathbb{C}\gamma_5 d_b(x) \gamma_\rho (1-\gamma_5) c_c(x) \times \bar{c}_d(y) \gamma^\rho (1-\gamma_5) s_e(y) \times \bar{u}_f(z) u_g(z) + \cdots \\
&\xrightarrow{\text{move}} \epsilon^{agc} \delta^{db} \delta^{fe} \times u_a^T(x) \mathbb{C}\gamma_5 d_b(y) \gamma_\rho (1-\gamma_5) c_c(x) \times \bar{c}_d(y) \gamma^\rho (1-\gamma_5) s_e(z) \times \bar{u}_f(z) u_g(x) + \cdots \\
&\overset{\text{Fierz:}d_b \leftrightarrow u_g}{=\!=\!=} -\frac{\delta^{db}\delta^{fe}}{4} \times [\epsilon^{agc} u_a^T \mathbb{C}\gamma_\mu u_g \gamma_\rho (1-\gamma_5) c_c](x) \times \bar{c}_d(y) \gamma^\rho (1-\gamma_5) s_e(z) \times \bar{u}_f(z) \gamma^\mu \gamma_5 d_b(y) + \cdots \\
&\overset{\text{Fierz:}d_b \leftrightarrow s_e}{=\!=\!=} +\frac{1+\gamma_5}{16} \times [\epsilon^{agc} u_a^T \mathbb{C}\gamma_\mu u_g \gamma^\mu \gamma_5 c_c](x) \times [\delta^{db} \bar{c}_d \gamma_5 d_b](y) \times [\delta^{fe} \bar{u}_f \gamma_5 s_e](z) + \cdots \\
&\xrightarrow{\text{move:}y\to x} +\frac{1+\gamma_5}{8\sqrt{2}} \times \xi_1(x) \times [\bar{u}_a \gamma_5 s_a](z) + \cdots
\end{aligned}
$$

# Current algebra results

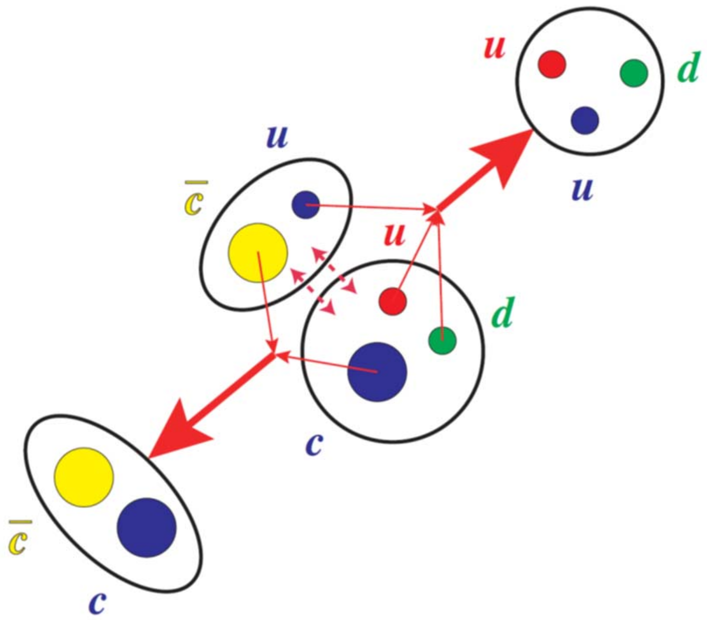
$$\Lambda_b^0 \longrightarrow +\frac{1+\gamma_5}{8\sqrt{2}} \times \xi_1(x) \times [\bar{u}_a\gamma_5 s_a](z)$$
$$+\frac{(1+\gamma_5)(g_{\nu\rho}-i\sigma_{\nu\rho})}{16\sqrt{2}}\left(\xi_3^\nu(x) - \frac{1}{4}\gamma^\nu\gamma_5\xi_2(x)\right)[\bar{u}_a\gamma^\rho\gamma_5 s_a](z)$$
$$+\frac{(1+\gamma_5)(g_{\alpha\nu}\gamma_\rho+g_{\alpha\rho}\gamma_\nu)}{8\sqrt{2}}\left(\xi_7^{\alpha\nu}(x) - \frac{1}{9}\gamma^\alpha\gamma_5\xi_6^\nu(x) - \frac{1}{9}\gamma^\nu\gamma_5\xi_6^\alpha(x) + \frac{2}{9}g^{\alpha\nu}\xi_5(x)\right)[\bar{u}_a\gamma^\rho\gamma_5 s_a](z)$$
$$+\cdots.$$

$$\frac{\mathcal{B}\left(\Lambda_b^0 \to K^-\left(|\bar{D}\Sigma_c\rangle_{1/2^-} : |\bar{D}^*\Sigma_c\rangle_{1/2^-} : |\bar{D}^*\Sigma_c\rangle_{3/2^-} : |\bar{D}\Sigma_c^*\rangle_{3/2^-} : |\bar{D}^*\Sigma_c^*\rangle_{1/2^-} : |\bar{D}^*\Sigma_c^*\rangle_{3/2^-} : |\bar{D}^*\Sigma_c^*\rangle_{5/2^-}\right)\right)}{\mathcal{B}\left(\Lambda_b^0 \to |\bar{D}^*\Sigma_c\rangle_{3/2^-}K^-\right)}$$
$$\approx \quad 8.2 : 1.2 : \mathbf{1} : 0 : 4.8 : 0.18 : 0\,.$$

# CONTENTS

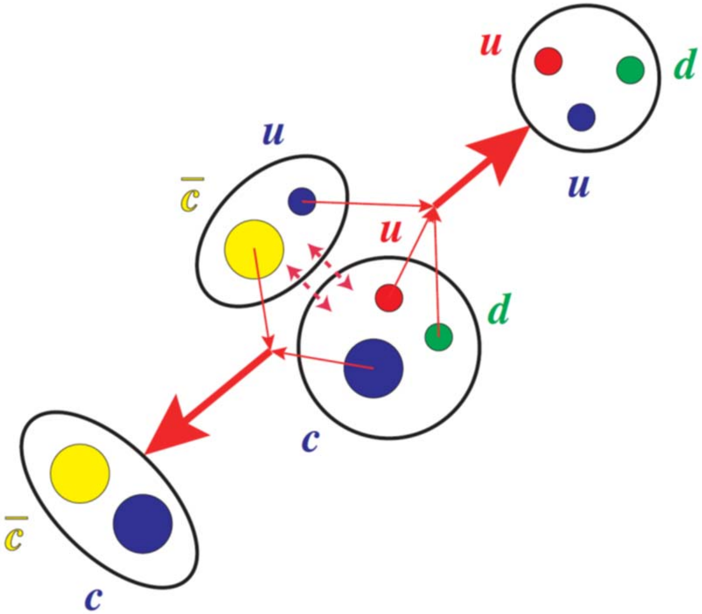
- Interpolating Currents
- QCD sum rule studies
- Productions of Pc states
- **Decays of Pc states**

# $P_c^+ \longrightarrow J/\psi p$ decays



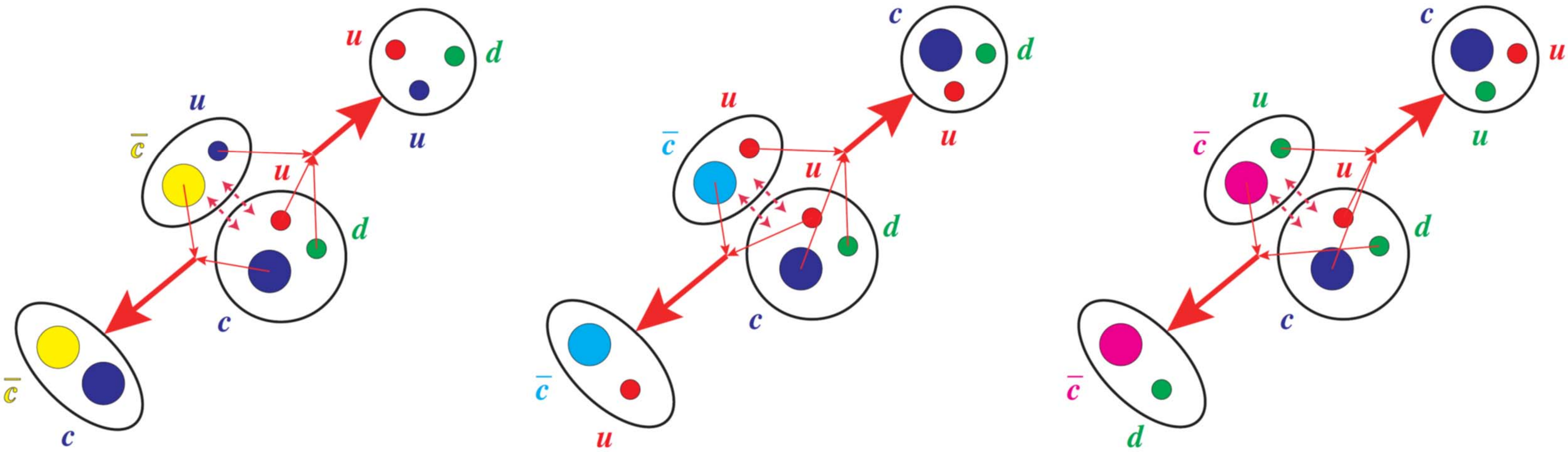

$$
\begin{aligned}
&\left[\delta^{ab}\bar{c}_a(x)u_b(x)\right]\ \left[\epsilon^{cde}u_c(y)d_d(y)c_e(y)\right] \\
\xlongequal{\text{color}}\ &\frac{1}{3}\delta^{ae}\epsilon^{bcd}\ \bar{c}_a(x)u_b(x)\ u_c(y)d_d(y)c_e(y)+\cdots \\
\xrightarrow{\text{move}}\ &\frac{1}{3}\delta^{ae}\epsilon^{bcd}\ \bar{c}_a(x)u_b(y)\ u_c(y)d_d(y)c_e(x)+\cdots \\
\xlongequal{\text{Fierz}}\ &\frac{1}{3}\ \left[\delta^{ae}\bar{c}_a(x)c_e(x)\right]\ \left[\epsilon^{bcd}u_c(y)d_d(y)u_b(y)\right]+\cdots\ .
\end{aligned}
$$

## $P_c^+ \longrightarrow J/\psi p$ decays




$$\begin{aligned}\eta_4^\alpha \;\rightarrow\;& [\bar{c}_a \gamma_\mu c_a]\left(-\frac{1}{32} g^{\alpha\mu} - \frac{i}{96}\sigma^{\alpha\mu}\right) N \\ &+ [\bar{c}_a \gamma_\mu \gamma_5 c_a]\left(-\frac{1}{32} g^{\alpha\mu}\gamma_5 - \frac{i}{96}\sigma^{\alpha\mu}\gamma_5\right) N \\ &+ [\bar{c}_a \sigma_{\mu\nu} c_a]\left(\frac{i}{48} g^{\alpha\mu}\gamma^\nu + \frac{1}{96}\epsilon^{\alpha\mu\nu\rho}\gamma_\rho\gamma_5\right) N \\ &+ \cdots ,\end{aligned}$$

# $P_c^+$ decays




(a) $\eta \to \theta$ (b) $\eta \to \eta$ (c) $\eta \to \xi$

# Fierz transform results

| Configuration | Decay Channels | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $J/\psi p$ | $\eta_c p$ | $\chi_{c0} p$ | $\chi_{c1} p$ | $h_c p$ | $\bar{D}^0 \Lambda_c^+$ | $\bar{D}^{*0} \Lambda_c^+$ | $\bar{D}^0 \Sigma_c^+$ | $D^- \Sigma_c^{++}$ | $\bar{D}^{*0} \Sigma_c^+$ | $D^{*-} \Sigma_c^{++}$ |
| $\lvert \bar{D}\Sigma_c; 1/2^- \rangle$ | 1 | 3.8 | – | – | – | – | $0.69t$ | – | – | – | – |
| $\lvert \bar{D}^*\Sigma_c; 1/2^- \rangle$ | 1 | 0.35 | 0.016 | $10^{-4}$ | – | $3.4t$ | $1.2t$ | $0.12t$ | $0.23t$ | – | – |
| $\lvert \bar{D}^*\Sigma_c; 3/2^- \rangle$ | 1 | 0.005 | – | – | – | – | $0.34t$ | $10^{-5}t$ | $10^{-5}t$ | – | – |
| $\lvert \bar{D}\Sigma_c^*; 3/2^- \rangle$ | 1 | 0.70 | – | – | – | – | $250t$ | – | – | – | – |
| $\lvert \bar{D}^*\Sigma_c^*; 1/2^- \rangle$ | 1 | 31 | 0.30 | 0.10 | 0.02 | $34t$ | $1.5t$ | $0.15t$ | $0.30t$ | $0.35t$ | $0.70t$ |
| $\lvert \bar{D}^*\Sigma_c^*; 3/2^- \rangle$ | 1 | 0.006 | – | 0.008 | – | – | $0.39t$ | $10^{-5}t$ | $10^{-4}t$ | $0.04t$ | $0.08t$ |
| $\lvert \bar{D}^*\Sigma_c^*; 5/2^- \rangle$ | – | | | | | – | | | | | |

# Our results

$$\mathcal{R}_1(P_c) \equiv \frac{\mathcal{B}\left(\Lambda_b^0 \to P_c K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to |\bar{D}^* \Sigma_c\rangle_{3/2^-} K^-\right)} \quad \Longrightarrow \quad \mathcal{R}_2(P_c) \equiv \frac{\mathcal{B}(\Lambda_b^0 \to P_c K^- \to J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \to |\bar{D}^* \Sigma_c\rangle_{3/2^-} K^- \to J/\psi p K^-)}$$

| Configuration | Decay Channels | | | | | | | | | | | Productions | | Candidate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $J/\psi p$ | $\eta_c p$ | $\chi_{c0} p$ | $\chi_{c1} p$ | $h_c p$ | $\bar{D}^0 \Lambda_c^+$ | $\bar{D}^{*0} \Lambda_c^+$ | $\bar{D}^0 \Sigma_c^+$ | $D^- \Sigma_c^{++}$ | $\bar{D}^{*0} \Sigma_c^+$ | $D^{*-} \Sigma_c^{++}$ | $\mathcal{R}_1$ | $\mathcal{R}_2$ | |
| $\vert\bar{D}\Sigma_c; 1/2^-\rangle$ | 1 | 3.8 | – | – | – | – | $0.69t$ | – | – | – | – | 8.2 | 2.0 | $P_c(4312)^+$ |
| $\vert\bar{D}^*\Sigma_c; 1/2^-\rangle$ | 1 | 0.35 | 0.016 | $10^{-4}$ | – | $3.4t$ | $1.2t$ | $0.12t$ | $0.23t$ | – | – | 1.2 | 0.25 | $P_c(4457)^+$ (?) |
| $\vert\bar{D}^*\Sigma_c; 3/2^-\rangle$ | 1 | 0.005 | – | – | – | – | $0.34t$ | $10^{-5}t$ | $10^{-5}t$ | – | – | **1** | **1** | $P_c(4440)^+$ (?) |
| $\vert\bar{D}\Sigma_c^*; 3/2^-\rangle$ | 1 | 0.70 | – | – | – | – | $250t$ | – | – | – | – | – | – | |
| $\vert\bar{D}^*\Sigma_c^*; 1/2^-\rangle$ | 1 | 31 | 0.30 | 0.10 | 0.02 | $34t$ | $1.5t$ | $0.15t$ | $0.30t$ | $0.35t$ | $0.70t$ | 4.8 | 0.09 | |
| $\vert\bar{D}^*\Sigma_c^*; 3/2^-\rangle$ | 1 | 0.006 | – | 0.008 | – | – | $0.39t$ | $10^{-5}t$ | $10^{-4}t$ | $0.04t$ | $0.08t$ | 0.18 | 0.16 | |
| $\vert\bar{D}^*\Sigma_c^*; 5/2^-\rangle$ | – | | | | | – | | | | | | – | – | |

LHCb, PRL 122, 222001 (2019)

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}$$

| State | $\mathcal{R}$ [%] |
|---|---|
| $P_c(4312)^+$ | $0.30 \pm 0.07^{+0.34}_{-0.09}$ |
| $P_c(4440)^+$ | $1.11 \pm 0.33^{+0.22}_{-0.10}$ |
| $P_c(4457)^+$ | $0.53 \pm 0.16^{+0.15}_{-0.13}$ |

$$\frac{\mathcal{R}(P_c(4312)^+)}{\mathcal{R}(P_c(4440)^+)} = 0.27^{+0.32}_{-0.14},$$

$$\frac{\mathcal{R}(P_c(4457)^+)}{\mathcal{R}(P_c(4440)^+)} = 0.48^{+0.25}_{-0.25}.$$

LHCb, PRL 122, 222001 (2019)

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}$$

| State | $\mathcal{R}$ [%] |
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| $P_c(4457)^+$ | $0.53 \pm 0.16^{+0.15}_{-0.13}$ |

$$\frac{\mathcal{R}(P_c(4312)^+)}{\mathcal{R}(P_c(4440)^+)} = 0.27^{+0.32}_{-0.14}\,,$$

$$\frac{\mathcal{R}(P_c(4457)^+)}{\mathcal{R}(P_c(4440)^+)} = 0.48^{+0.25}_{-0.25}\,.$$

***t* ≈ 1:**

$$\mathcal{R}_2(|\bar{D}\Sigma_c;1/2^-\rangle) = \frac{\mathcal{R}_2(|\bar{D}\Sigma_c;1/2^-\rangle)}{\mathcal{R}_2(|\bar{D}^*\Sigma_c;3/2^-\rangle)} \approx 2.0\,,$$

$$\mathcal{R}_2(|\bar{D}^*\Sigma_c;1/2^-\rangle) = \frac{\mathcal{R}_2(|\bar{D}^*\Sigma_c;1/2^-\rangle)}{\mathcal{R}_2(|\bar{D}^*\Sigma_c;3/2^-\rangle)} \approx 0.25\,,$$

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$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}$$

| State | $\mathcal{R}$ [%] |
|---|---|
| $P_c(4312)^+$ | $0.30 \pm 0.07^{+0.34}_{-0.09}$ |
| $P_c(4440)^+$ | $1.11 \pm 0.33^{+0.22}_{-0.10}$ |
| $P_c(4457)^+$ | $0.53 \pm 0.16^{+0.15}_{-0.13}$ |

$$\frac{\mathcal{R}(P_c(4312)^+)}{\mathcal{R}(P_c(4440)^+)} = 0.27^{+0.32}_{-0.14},$$

$$\frac{\mathcal{R}(P_c(4457)^+)}{\mathcal{R}(P_c(4440)^+)} = 0.48^{+0.25}_{-0.25}.$$

Uncertainties:

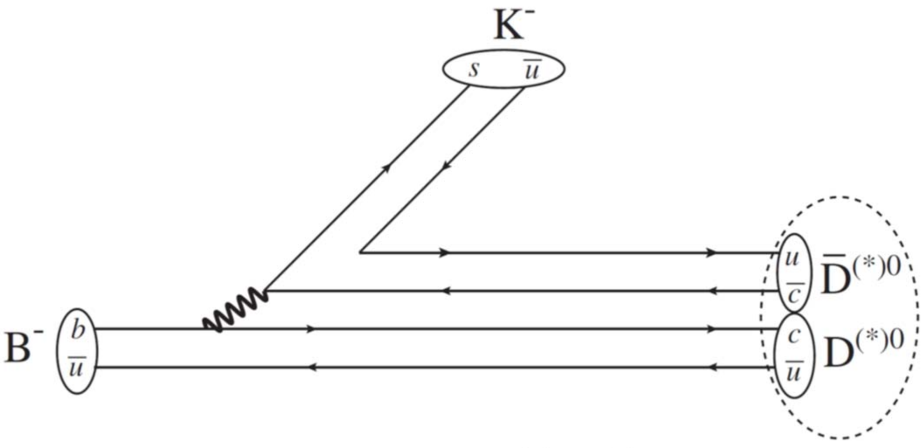
| | |
|---|---|
| Masses from QCD sum rules | $X \pm 5\%$ |
| Decays | $X^{+100\%}_{-50\%}$ |
| Productions | $X^{+200\%}_{-66\%}$ |
| $R_2$ | $X^{+300\%}_{-75\%}$ |

$t \approx 1$:

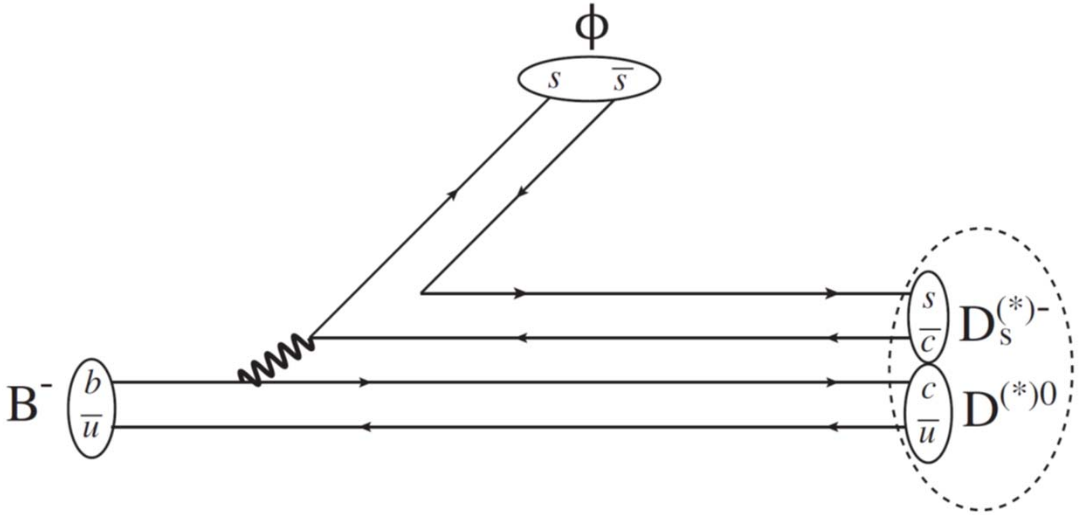
$$\mathcal{R}_2(|\bar{D}\Sigma_c; 1/2^-\rangle) = \frac{\mathcal{R}_2(|\bar{D}\Sigma_c; 1/2^-\rangle)}{\mathcal{R}_2(|\bar{D}^*\Sigma_c; 3/2^-\rangle)} \approx 2.0,$$

$$\mathcal{R}_2(|\bar{D}^*\Sigma_c; 1/2^-\rangle) = \frac{\mathcal{R}_2(|\bar{D}^*\Sigma_c; 1/2^-\rangle)}{\mathcal{R}_2(|\bar{D}^*\Sigma_c; 3/2^-\rangle)} \approx 0.25,$$

# Hadronic molecules in B decays

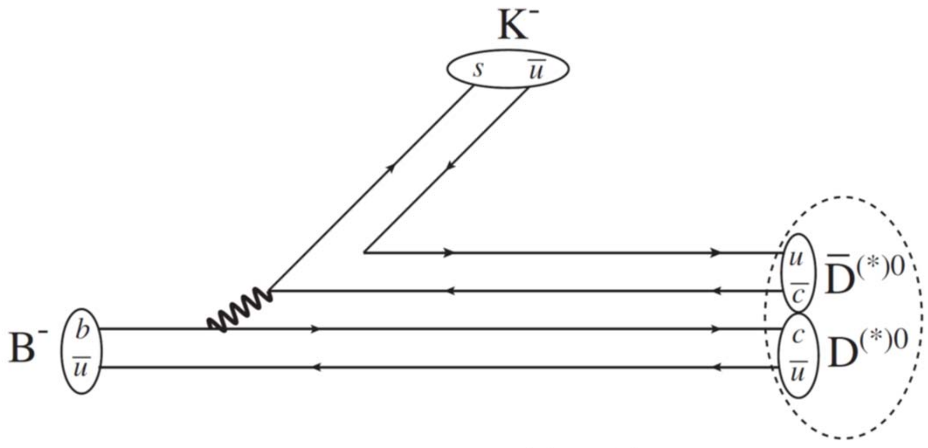



$D^{(*)}\overline{D}^{(*)}$ molecules




$D^{(*)}D_s^{(*)-}$ molecules

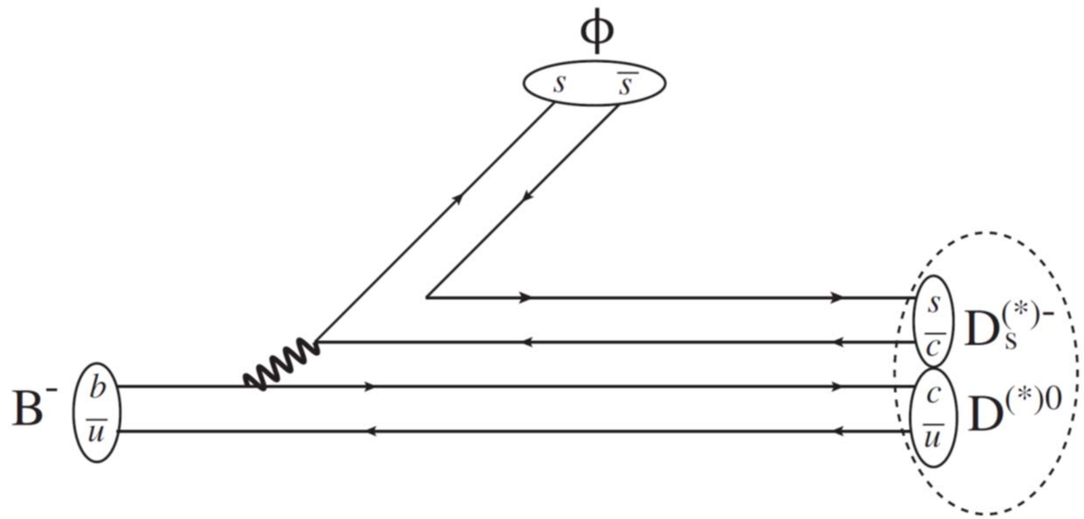
# Hadronic molecules in B decays




$D^{(*)}\bar{D}^{(*)}$ molecules

| | |
|---|---|
| $\|D\bar{D};0^{++}\rangle$ | – |
| $\|D\bar{D}^*;1^{++}\rangle$ | $X(3872)$ |
| $\|D\bar{D}^*;1^{+-}\rangle$ | $Z_c(3900)$ |
| $\|D^*\bar{D}^*;0^{++}\rangle$ | – |
| $\|D^*\bar{D}^*;1^{+-}\rangle$ | $Z_c(4020)$ |
| $\|D^*\bar{D}^*;2^{++}\rangle$ | – |

$J/\psi\pi$




$D^{(*)}D_s^{(*)-}$ molecules

| | |
|---|---|
| $\|D\bar{D}_s;0^{+}\rangle$ | – |
| $\|D\bar{D}_s^*;1^{++}\rangle$ | $Z_{cs}(3985)$ |
| $\|D\bar{D}_s^*;1^{+-}\rangle$ | $Z_{cs}(4000)$ |
| $\|D^*\bar{D}_s^*;0^{+}\rangle$ | – |
| $\|D^*\bar{D}_s^*;1^{+}\rangle$ | $Z_{cs}(4220)$ |
| $\|D^*\bar{D}_s^*;2^{+}\rangle$ | – |

$J/\psi K$

$$\sqrt{2}|D\bar{D}_s^*;1^{++}\rangle = |DD_s^{*-}\rangle_{J=1} + |D^*D_s^-\rangle_{J=1} \,,$$
$$\sqrt{2}|D\bar{D}_s^*;1^{+-}\rangle = |DD_s^{*-}\rangle_{J=1} - |D^*D_s^-\rangle_{J=1} \,,$$

| Configuration | $\mathcal{R}_1$ | $\mathcal{R}_2$ | $\eta_c\bar{K}$ | $J/\psi\bar{K}$ | $\chi_{c0}\bar{K}$ | $h_c\bar{K}$ | $\eta_c\bar{K}^*$ | $J/\psi\bar{K}^*$ | $\chi_{c1}\bar{K}^*$ | $D\bar{D}_s^*$ | $D^*\bar{D}_s$ | $D^*\bar{D}_s^*$ | Candidate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\|D\bar{D}_s;0^+\rangle$ | – | $11d_6$ | 1 | – | – | – | – | 0.001 | – | – | – | – | – |
| $\|D\bar{D}_s^*;1^{++}\rangle$ | $0.79d_3$ | $6.6d_6$ | – | – | 0.012 | – | – | 1 | – | 25 | 68 | – | $Z_{cs}(3985)$ |
| $\|D\bar{D}_s^*;1^{+-}\rangle$ | $0.75d_3$ | $6.2d_6$ | – | 1 | – | – | 0.093 | – | – | 41 | 87 | – | $Z_{cs}(4000)$ |
| $\|D^*\bar{D}_s^*;0^+\rangle$ | – | – | 1 | – | – | – | – | 0.088 | – | – | – | 0.001 | – |
| $\|D^*\bar{D}_s^*;1^+\rangle$ | $1.8d_3$ | – | – | 1 | – | 0.002 | 0.36 | – | $10^{-7}$ | – | – | 31 | $Z_{cs}(4220)$ |
| $\|D^*\bar{D}_s^*;2^+\rangle$ | – | – | 1 | – | – | – | – | 27 | – | – | – | 0.055 | – |

$$\mathcal{B}(B^- \to K^- X(3872) \xrightarrow{\omega} K^- J/\psi\pi\pi\pi) = (6.0 \pm 2.2) \times 10^{-6} \,,$$

$$\mathcal{B}(B^- \to \phi J/\psi K^-) = (5.0 \pm 0.4) \times 10^{-5} \,,$$

$$\frac{\mathcal{B}(B^- \to \phi Z_{cs}(4000) \to \phi J/\psi K^-)}{\mathcal{B}(B^- \to \phi J/\psi K^-)} = (9.4 \pm 2.1 \pm 3.4) \times 10^{-2} \,,$$

$$\frac{\mathcal{B}(B^- \to \phi Z_{cs}(4220) \to \phi J/\psi K^-)}{\mathcal{B}(B^- \to \phi J/\psi K^-)} = (10 \pm 4^{+10}_{-\ 7}) \times 10^{-2} \,.$$

$$\frac{\mathcal{B}(B^- \to \phi Z_{cs}(4000) \to \phi J/\psi K^-)}{\mathcal{B}(B^- \to K^- X(3872) \xrightarrow{\omega} K^- J/\psi\pi\pi\pi)} = 0.78 \pm 0.44 \,,$$

$$\frac{\mathcal{B}(B^- \to \phi Z_{cs}(4220) \to \phi J/\psi K^-)}{\mathcal{B}(B^- \to K^- X(3872) \xrightarrow{\omega} K^- J/\psi\pi\pi\pi)} = 0.83^{+0.95}_{-0.74} \,.$$

$$\frac{\mathcal{B}(B^- \to \phi |D\bar{D}_s^*\rangle_{1^{+-}} \to \phi J/\psi K^-)}{\mathcal{B}(B^- \to K^- |D\bar{D}^*\rangle_{1^{++}} \xrightarrow{\omega} K^- J/\psi\pi\pi\pi)} \approx 0.28 \,,$$

$$\frac{\mathcal{B}(B^- \to \phi |D^*\bar{D}_s^*\rangle_{1^{+-}} \to \phi J/\psi K^-)}{\mathcal{B}(B^- \to K^- |D\bar{D}^*\rangle_{1^{++}} \xrightarrow{\omega} K^- J/\psi\pi\pi\pi)} \approx 2.7 \,,$$

# Summary

- We studied mass spectra of Pc states through QCD sum rules.

- We studied their productions in $\Lambda_b$ decays through current algebra.

- We studied their decays through Fierz transformation.

**Thank you very much!**