Heavy-Quark Spin Symmetry Violation effects in Charmed Baryon Production
- A Concise Clarification -

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in collaboration with
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Heavy Quark Symmetry

- QCD Lagrangian: $\mathcal{L}_Q = \bar{Q}(i\not{D} - m_Q)Q, \quad D_\mu = \partial_\mu - igA^a_\mu T^a,$

- $1/m_Q$ expansion of positive energy state Q_v with velocity v: (Manohar, Wise, Luke, Grinstein, ...)
  $\mathcal{L}_{\text{HQET}} = \underbrace{\bar{Q}_v v \cdot iDQ_v}_{\textbf{LO}} + \bar{Q}_v \frac{(iD_\perp)^2}{2m_Q} Q_v - g_s \bar{Q}_v \frac{\sigma_{\mu\nu}G^{\mu\nu}}{4m_Q} Q_v + \mathcal{O}(1/m_Q^2)$

- In LO, heavy quark spin in $m_Q \to \infty$ is conserved

- At NLO: $1/m_Q$ expansion

$$\mathcal{L}_{\text{HQET}} = \bar{Q}_v v \cdot iDQ_v + \underbrace{\bar{Q}_v \frac{(iD_\perp)^2}{2m_Q} Q_v - \overbrace{g_s \bar{Q}_v \frac{\sigma_{\mu\nu}G^{\mu\nu}}{4m_Q} Q_v}^{\text{magnetic gluon}}}_{\text{NLO in } 1/m_Q \text{ expansion}} + \mathcal{O}(1/m_Q^2)$$

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Heavy Hadron Effective Theory

- At LO: $1/m_Q$ expansion in *quark* $\Longleftrightarrow$ $1/M$ expansion in *hadron*
  HQS gives doublet/singlet in mass spectrum in exotic heavy hadrons and nuclei

- LO + NLO:
  - HQS doublet:
    - Baryon: $\Sigma_c \left(J^P = \frac{1}{2}^+\right) \Longleftrightarrow \Sigma_c^* \left(J^P = \frac{3}{2}^+\right)$
    - Meson: $\bar{D} \left(J^P = 0^-\right) \Longleftrightarrow \bar{D}^* \left(J^P = 1^-\right)$
  - HQS singlet: $\Lambda_c \left(J^P = \frac{1}{2}^+\right)$

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- **Universal Predictions:** ensures consistency in predictions across different heavy quark systems, due to the similar behavior under HQSS
- **Study of Multiquark Systems:** of exotic states, such as tetraquarks and pentaquarks

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- For $p\bar{p} \to Y_c \bar{Y}_c$, the charmed quark production is *highly off-shell*, which not satisfy with HQSS assumption
- **We assert that the charmed baryon production process can be explained by HQSS framework, but to what extent?**
- **Thus, we would like to know whether how much of HQSS is *conserved* or *violated*, for the $p\bar{p} \to Y_c \bar{Y}_c$ processes?**

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Research Objectives

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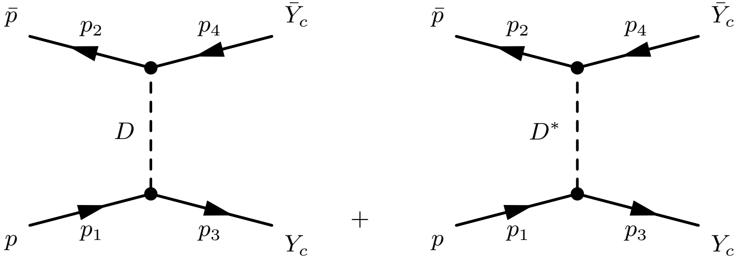

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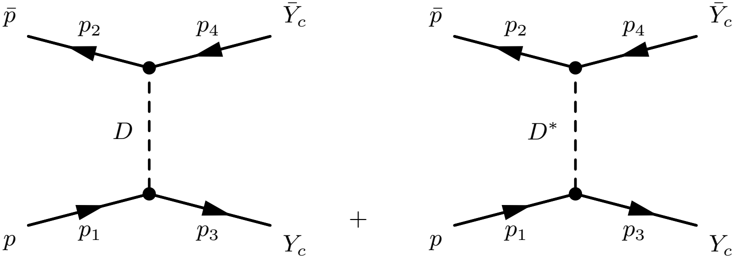

- **Our aim is to investigate the violation in HQSS in terms of the heavy quarks spin quantum number i.e. spin-$\frac{1}{2}$ from Σ_c and spin-$\frac{3}{2}$ from Σ_c^***

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HQSS properties and its transformation

In the heavy-quark limit $m_Q \to \infty$, the spin interaction between light and heavy quarks is decoupled. As a consequent, the pseudoscalar and vector D mesons as well as spin- $\frac{1}{2}$ and spin- $\frac{3}{2}$ baryons form degenerate states. We find

$$
\begin{aligned}
H_a &= P_+(v)\left(D_a^\mu \gamma_\mu + i\gamma_5 D_a\right) && , \bar{H}_a = \gamma_0 H_a^\dagger \gamma_0 \\
T_{ab}^\mu &= P_+(v)\left(\Sigma_{ab}^\mu + \frac{i}{\sqrt{3}}(\gamma^\mu + v^\mu)\gamma_5 \Sigma_{ab}\right) && , \bar{T}_{ab}^\mu = \left(T_{ab}^\mu\right)^\dagger \gamma_0 \\
T &= P_+(v)\Lambda && , \bar{T} = T^\dagger \gamma_0
\end{aligned}
$$

where $P_+(v) = \frac{1}{2}(1 + \not{v})$ is the positive covariant velocity projection operator and obey the following the HQSS $SU(2)_v$ transformations:

$$
\begin{aligned}
H_a &\to e^{-i\theta_\alpha S^\alpha} H_a, & \bar{H}_a &\to \bar{H}_a e^{i\theta_\alpha S^\alpha} \\
T_{ab}^\mu &\to e^{-iS_\alpha \theta^\alpha} T_{ab}^\mu, & \bar{T}_{ab}^\mu &\to \bar{T}_{ab}^\mu e^{i\theta_\alpha S^\alpha} \\
T &\to e^{-iS_\alpha \theta^\alpha} T, & \bar{T} &\to \bar{T} e^{iS_\alpha \theta^\alpha}
\end{aligned}
$$

where S^α is the heavy-quark spin operator with the properties:

$$
S^\alpha = \frac{1}{2}\gamma_5\left[\not{v}, \gamma^\alpha\right], \quad S_\alpha^\dagger \gamma_0 = \gamma_0 S_\alpha, \quad [\not{v}, S_\alpha] = 0, \quad [S_\alpha, \gamma_5] = 0
$$

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Conserving Heavy Quark Spin Symmetry (CHQSS) and Violating Heavy Quark Spin Symmetry (VHQSS) Lagrangians

- Respect CPT, Lorent Symmetry and Flavor symmetry

- With the super field effective Lagrangians

$$\mathcal{L}^{\text{CHQSS}} = \frac{1}{2}c_1 \left\langle \bar{T}^{\mu}_{ab}\gamma_5 N_b H_a \gamma_\mu + \text{h.c.} \right\rangle + \frac{1}{2}c_2 \left\langle \bar{T}\gamma_5 N_a H_a \gamma_5 + \text{h.c.} \right\rangle$$

$$\mathcal{L}^{\text{VHQSS}} = -\frac{1}{4}b_1 \left\langle \bar{T}^{\mu}_{ab}\gamma^\nu N_b H_a \gamma_\mu \gamma_\nu \gamma_5 + \text{h.c.} \right\rangle + \frac{1}{2}b_2 \left\langle \bar{T}\gamma^\mu N_a H_a \gamma_\mu + \text{h.c.} \right\rangle + \frac{1}{4}b_3 \left\langle \bar{T}\sigma^{\mu\nu} N_a H_a \sigma_{\mu\nu} + \text{h.c.} \right\rangle$$

- After tracing all fields in heavy quark spin space

$$\mathcal{L}^{\text{CHQSS}} = \frac{c_1}{\sqrt{3}}\bar{\Sigma}_{ab}\gamma^\mu N_b D^a_\mu + c_1 \bar{\Sigma}^{\mu}_{ab}\gamma_5 N_b D^a_\mu + ic_2 \bar{\Lambda}\gamma_5 N_a D^a + \text{h.c.},$$

$$\mathcal{L}^{\text{VHQSS}} = \frac{i\sqrt{3}}{2}b_1 \bar{\Sigma}_{ab}\gamma_5 N_b D_a + \frac{i}{\sqrt{3}}b_1 \bar{\Sigma}_{ab}\sigma^{\mu\nu} N_b D^a_\mu v_\nu - ib_1 \epsilon_{\mu\nu\alpha\beta}\bar{\Sigma}^{\mu}_{ab}\gamma^\nu N_b D^\alpha_a v^\beta + b_2 \bar{\Lambda}\gamma^\mu N_a D^a_\mu + ib_3 \bar{\Lambda}\sigma^{\mu\nu} N_a D^a_\mu v_\nu + \text{h.c.}.$$

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$$\mathcal{L}^{\text{VHQSS}} = \frac{i\sqrt{3}}{2}b_1\bar{\Sigma}_{ab}\gamma_5 N_b D_a + \frac{i}{\sqrt{3}}b_1\bar{\Sigma}_{ab}\sigma^{\mu\nu}N_b D^a_{\mu}v_{\nu} - ib_1\epsilon_{\mu\nu\alpha\beta}\bar{\Sigma}^{\mu}_{ab}\gamma^{\nu}N_b D^{\alpha}_a v^{\beta} + b_2\bar{\Lambda}\gamma^{\mu}N_a D^a_{\mu} + ib_3\bar{\Lambda}\sigma^{\mu\nu}N_a D^a_{\mu}v_{\nu} + \text{h.c.}.$$

- We note that the CHQSS terms contain vector couplings between Σ_c, (Σ_c^*) and D^*, whereas the Λ_c couples to pseudoscalar D mesons.
- VHQSS terms contain tensor couplings between Σ_c, (Σ_c^*) and D^* as well as pseudoscalar cloupled to D, whereas the Λ_c couples to D^* with the vector and tensor terms.
- However, the coupling constants, c_1, c_2, b_1, b_2 and b_3 are free parameters. We can obtain the coupling constants from the well-know couplings from the effective Lagrangian in the literature by matching the structures in the heavy quark mass expansion.

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Heavy Quark Mass Expansion

In the large heavy-quark mass limit, single heavy-quark hadrons can be considered as slowly varying fields, $D_v^{\pm}(x)$, $D_v^{\mu\,\pm}(x)$, $\Sigma_v^{\pm}(x)$, $\Sigma_v^{\pm\,\mu}(x)$ and $\Lambda_{\pm}$

$$\Phi = \{D^{\pm}, D^{*\pm}, \Sigma^{\pm}, \Sigma^{*\pm}, \Lambda^{\pm}\}$$

Φ	$D = \begin{pmatrix} D^0 & D^+ \end{pmatrix}$	$D^* = \begin{pmatrix} D^{*0} & D^{*+} \end{pmatrix}$	$N = \binom{p}{n}$	$\Lambda_c = \Lambda_c^+$	$\Sigma_c = \begin{pmatrix} \Sigma_c^{++} \\ \Sigma_c^{+} \\ \Sigma_c^{0} \end{pmatrix}$	$\Sigma_c^* = \begin{pmatrix} \Sigma_c^{*++} \\ \Sigma_c^{*+} \\ \Sigma_c^{*0} \end{pmatrix}$
J^P:	0^+	1^+	$\frac{1}{2}^+$	$\frac{1}{2}^+$	$\frac{1}{2}^+$	$\frac{3}{2}^+$
m (GeV^2)	1.867	2.008	0.938	2.286	2.455	2.520

- For the slowly varying heavy quark mass expansion, one can decompose the hadronic fields as

$$\Phi(x) = \exp(-im_\Phi v\cdot x)\Phi_v^+(x) + \exp(+im_\Phi v\cdot x)\Phi_v^-(x)$$

$$\not{v}\Phi_v = \Phi_v$$

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Effective Lagrangians with heavy quark mass expansion

- $SU(2)_f$ effective Lagrangians

$$\mathcal{L} = \mathcal{L}^P + \mathcal{L}^A + \mathcal{L}^V + \mathcal{L}^T + \text{h.c.}$$

$$\mathcal{L}^P = g_1 \bar{\Sigma} i\gamma_5 N D + g_2 \bar{\Lambda} i\gamma_5 N D$$

$$\mathcal{L}^A = -\frac{g_3}{m_D}\bar{\Sigma}\gamma^\mu\gamma_5\partial_\mu D N - \frac{g_4}{m_D}\bar{\Lambda}\gamma^\mu\gamma_5\partial_\mu D N - \frac{g_5}{m_D}\bar{\Sigma}^\mu\partial_\mu D N$$

$$\mathcal{L}^V = f_1\bar{\Sigma}\gamma^\mu N D_\mu + f_2\bar{\Lambda}\gamma^\mu N D_\mu + f_3\bar{\Sigma}^\mu i\gamma_5 N D_\mu$$

$$\mathcal{L}^T = \frac{ih_1}{2m_D}\bar{\Sigma}\sigma^{\mu\nu} N D_{\mu\nu} + \frac{ih_2}{2m_D}\bar{\Lambda}\sigma^{\mu\nu} N D_{\mu\nu} + \frac{ih_3}{2m_D}\bar{\Sigma}^\mu\gamma^\nu\gamma_5 N D_{\mu\nu} + \frac{ih_4}{4m_D}\epsilon_{\mu\nu\alpha\beta}\bar{\Sigma}^\mu\gamma^\nu N D^{\alpha\beta}$$

- With the heavy quark mass expansion

$$\mathcal{L}_v = \mathcal{L}_v^P + \mathcal{L}_v^A + \mathcal{L}_v^V + \mathcal{L}_v^T + \text{h.c.}$$

$$\mathcal{L}^P = g_1\bar{\Sigma}_v i\gamma_5 N D_v + g_2\bar{\Lambda} i\gamma_5 N D$$

$$\mathcal{L}^A = \frac{g_3}{m_D}\bar{\Sigma}_v i\gamma_5 D_v N + \frac{g_4}{m_D}\bar{\Lambda}_v i\gamma_5 D_v N$$

$$\mathcal{L}^V = f_1\bar{\Sigma}_v\gamma^\mu N D_{v\mu} + f_2\bar{\Lambda}_v\gamma^\mu N D_{v\mu} + f_3\bar{\Sigma}_v^\mu i\gamma_5 N D_{v\mu}$$

$$\mathcal{L}^T = h_1\bar{\Sigma}_v\sigma^{\mu\nu} N v_\mu D_{v\nu} + h_2\bar{\Lambda}_v\sigma^{\mu\nu} N v_\mu D_{v\nu} + h_3\bar{\Sigma}_v^\mu\gamma^\nu\gamma_5 N v_\mu D_{v\nu} + h_4\epsilon_{\mu\nu\alpha\beta}\bar{\Sigma}_v^\mu\gamma^\nu N v^\alpha D_v^\beta$$

where $\Sigma_v^\mu v_\mu = 0 = D_v^\mu v_\mu$ and $\bar{\Sigma}_v \not{v} = \bar{\Sigma}_v$ have been used.

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Matching Relation

- The expanded $SU(2)_f$ effective Lagrangians

$$\mathcal{L}_v = \mathcal{L}_v^P + \mathcal{L}_v^A + \mathcal{L}_v^V + \mathcal{L}_v^T + \text{h.c.}$$
$$\mathcal{L}^P = g_1 \bar{\Sigma}_v i\gamma_5 N D_v + g_2 \bar{\Lambda} i\gamma_5 N D$$
$$\mathcal{L}^A = \frac{g_3}{m_D} \bar{\Sigma}_v i\gamma_5 D_v N + \frac{g_4}{m_D} \bar{\Lambda}_v i\gamma_5 D_v N$$
$$\mathcal{L}^V = f_1 \bar{\Sigma}_v \gamma^\mu N D_{v\mu} + f_2 \bar{\Lambda}_v \gamma^\mu N D_{v\mu} + f_3 \bar{\Sigma}_v^\mu i\gamma_5 N D_{v\mu}$$
$$\mathcal{L}^T = h_1 \bar{\Sigma}_v \sigma^{\mu\nu} N v_\mu D_{v\nu} + h_2 \bar{\Lambda}_v \sigma^{\mu\nu} N v_\mu D_{v\nu} + h_3 \bar{\Sigma}_v^\mu \gamma^\nu \gamma_5 N v_\mu D_{v\nu} + h_4 \epsilon_{\mu\nu\alpha\beta} \bar{\Sigma}_v^\mu \gamma^\nu N v^\alpha D_v^\beta$$

- The super-multiplet HQSS Lagrangians

$$\mathcal{L}^{\text{CHQSS}} = \frac{c_1}{\sqrt{3}} \bar{\Sigma}_{ab} \gamma^\mu N_b D_\mu^a + c_1 \bar{\Sigma}_{ab}^\mu \gamma_5 N_b D_\mu^a + ic_2 \bar{\Lambda} \gamma_5 N_a D^a + \text{h.c.},$$
$$\mathcal{L}^{\text{VHQSS}} = \frac{i\sqrt{3}}{2} b_1 \bar{\Sigma}_{ab} \gamma_5 N_b D_a + \frac{i}{\sqrt{3}} b_1 \bar{\Sigma}_{ab} \sigma^{\mu\nu} N_b D_\mu^a v_\nu - ib_1 \epsilon_{\mu\nu\alpha\beta} \bar{\Sigma}_{ab}^\mu \gamma^\nu N_b D_a^\alpha v^\beta + b_2 \bar{\Lambda} \gamma^\mu N_a D_\mu^a + ib_3 \bar{\Lambda} \sigma^{\mu\nu} N_a D_\mu^a v_\nu + \text{h.c.}.$$

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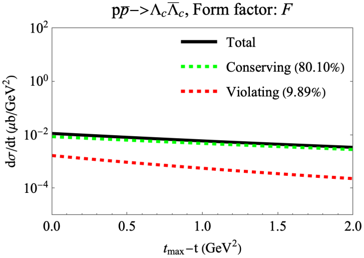
Matching Relation 2

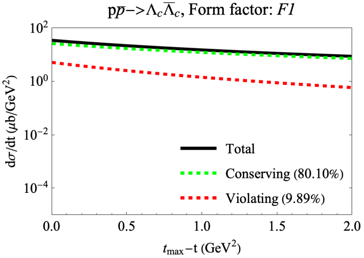
- For CHQSS Lagrangians: $c_1 = \sqrt{3} f_1 = \frac{1}{2} f_3 = h_3,\ c_2 = g_2 + g_4$
- For VHQSS Lagrangians: $b_1 = \frac{2}{\sqrt{3}}(g_1 + g_3),\ b_1 = \sqrt{3} h_1,\ b_1 = -2 f_4,\ b_2 = f_2,\ b_3 = h_2$
- Input parameters (Coupling constants): $SU(3)$ symmetry relations from $g_{\pi NN}$, replacing strange hadrons by the charmed ones.(Thanat2022):
  - $g_1 = 3.2,\ g_2 = 16.65,\ g_3 = 10.63,\ g_4 = 14.33$
  - $f_1 = 12.7,\ f_2 = -5.11$
  - $h_1 = 5.8,\ h_2 = -10.4$
- The form factors

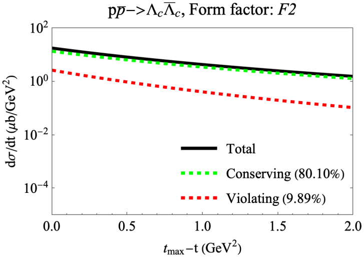
$$F(t) = k^2 \frac{\Lambda^4}{\Lambda^4 + \left(t - m_\phi^2\right)^2},$$

$$F_n(t) = k \left(\frac{\Lambda^2}{\Lambda^2 - t}\right)^n, \quad (n = 1, 2),$$

Preliminary Results: $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$







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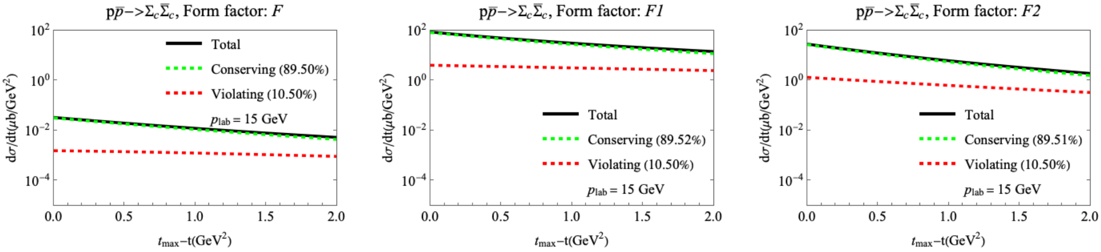
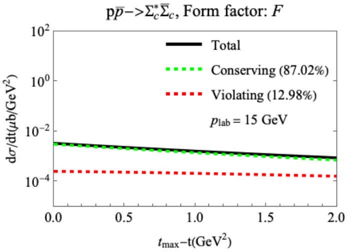
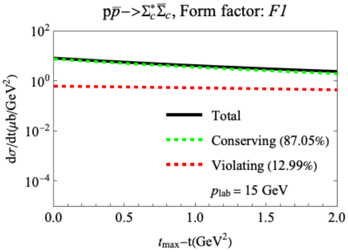
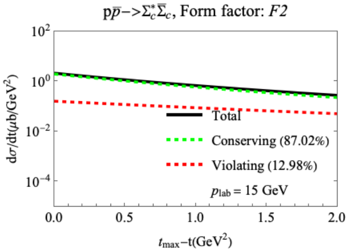


Preliminary Results: $p\bar{p} \to \Sigma_c^* \bar{\Sigma}_c$







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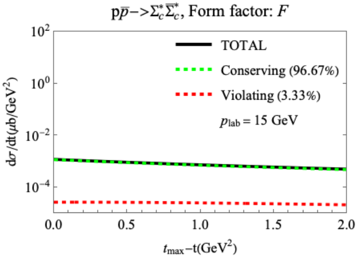
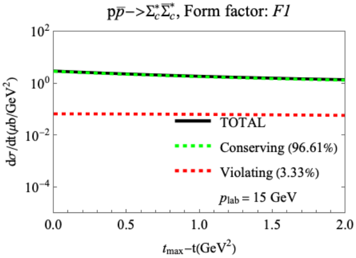
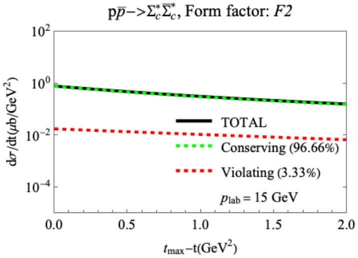
Preliminary Results: $p\bar{p} \to \Sigma_c^* \bar{\Sigma}_c^*$







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Summary and Outlook

- We constructed the conserving and violating HQSS Lagragians to study $p\bar{p} \to Y_c \bar{Y}_c$ reactions.
- The conserving terms are vector couplings for Σ_c and D^* and pseudoscalar couplings for Λ_c and D.
- The violating terms are pseudoscalar couplings for Σ_c and D, tensor coupling for Σ_c and D^* and vector and tensor couplings for Λ_c and D^*.
- We calculated the differential cross-section for $p\bar{p} \to Y_c \bar{Y}_c$ processes and estimated the contributions of the CHQSS and VHQSS.
- We plan to put coupling constants from other theoretical calculations, for instances, Light-Cone QCD sum rules, and etc.

Thank you.

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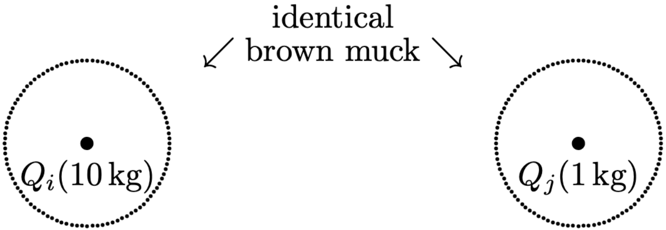
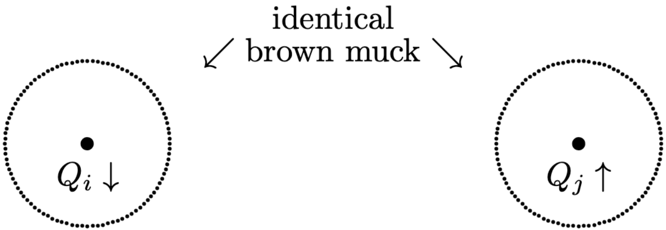
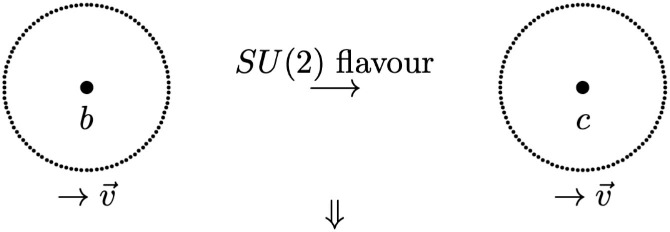
Scaling of the Interaction



Heavy Quark Spin Symmetry



Heavy Quark Flavor Symmetry



$$p_b^\mu \neq p_c^\mu$$

Summary of Chiral Quark Symmetry

- infinite quark mass limit: $m_Q \to \infty$ $(m_Q \gg \Lambda_{\rm QCD})$
- relevant quantum numbers: flavor (f) and spin (s)
- provided relations: $B \Leftrightarrow B^*$, $D \Leftrightarrow D^*$, $\Lambda_c \Leftrightarrow \Lambda_b$ or $\Sigma_c \Leftrightarrow \Sigma_c^*$
- complementary to Chiral Symmetry $(m_q \ll \Lambda_{\rm QCD})$
- NOT a symmetry of the Lagrangians (whole S-Matrix), BUT an Effective Theory (certain matrix elements)
- good approximation to QCD in a certain kinematic region
- Q interacts predominantly by the exchange of soft g

<table>
<tr><th colspan="2" rowspan="2">intermediate particle</th><th colspan="3">$SU(2)_f$</th><th colspan="3">CHQSS</th><th colspan="3">VHQSS</th></tr>
<tr><th>Λ</th><th>Σ_{ab}</th><th>Σ^{μ}_{ab}</th><th>Λ</th><th>Σ_{ab}</th><th>Σ^{μ}_{ab}</th><th>Λ</th><th>Σ_{ab}</th><th>Σ^{μ}_{ab}</th></tr>
<tr><td>D_a</td><td>pseudo-scalar (P)</td><td>g_2</td><td>g_1</td><td></td><td rowspan="2">c_2</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">b_1</td><td rowspan="2"></td></tr>
<tr><td>$\partial^{\mu} D_a$</td><td>axial-vector (A)</td><td>g_4</td><td>g_3</td><td></td></tr>
<tr><td>D^{μ}_a</td><td>vector (V)</td><td>f_2</td><td>f_1</td><td>f_3</td><td></td><td rowspan="2">c_1</td><td rowspan="2">c_1</td><td>b_2</td><td rowspan="2">b_1</td><td rowspan="2">b_1</td></tr>
<tr><td>$\partial^{\mu} D^{\nu}_a$</td><td>tensor (T)</td><td>h_2</td><td>h_1</td><td>h_3, h_4</td><td></td><td>b_3</td></tr>
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