# Nonleptonic decays of doubly charmed baryons

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Talk is based on recent paper

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# Charmed baryons

- SU(3) (u,d,s): M. Gell-Mann, G.Zweig (1964)
- SU(4) (u,d,s,c): J.D. Bjorken, S.L. Glashow (1964)
- GIM mechanism: S.L. Glashow, J. Iliopoulos, L. Maiani (1970)
- Charmed baryons in one gluon exchange model:
  A. De Rújula, H. Georgi, S.L. Glashow, 1975.
- Tremendous theoretical activities in describing doubly heavy baryons:
  - Likhoded, Kiselev et al. (nonrelativistic potential model, nonrelativistic QCD SR)
  - Faustov, Galkin et al. (relativistic quark model)
  - Dhir, Sharma at al. (effective quark mass scheme)
  - Chang, Li et al. (non-relativistic harmonic oscillator model)
  - Karliner, Rosner et al. (masses in naive quark model)
  - Hernández, Nieves et al. (nonrelativistic quark model)
  - Aliev, Azizi et al. (QCD SR)
  - Ivanov, Körner, Lyubovitskij et al. (quark confinement model)
  - ...

# Charmed baryons

- Numerous states with charm C=0 and C=1 discovered.
- There are now more precise results on the decays of single-charmed baryons

$$\Lambda_c^+ \to p\phi, \ \ \Lambda\pi^+, \ \ \Sigma^+\pi^0; \qquad \Xi_c^+ \to p\bar{K}^{*\,0}(892)$$

- Three weakly decaying baryons with C=2 expected:

$$\Xi_{cc}^{++} = ccu \quad \text{and} \quad \Xi_{cc}^{+} = ccd \qquad \text{isospin doublet}$$
$$\Omega_{cc}^{+} = ccs \qquad \text{isospin singlet}$$

- In 2005 the SELEX Coll. reported on the observation of double-charmed baryon $\Xi_{cc}^+$ with a mass of $3518 \pm 3$ MeV.
- However, other Collaborations (*BABAR*, Belle, LHCb) found no evidence for the $\Xi_{cc}^+$ nor the $\Xi_{cc}^{++}$ states in the conjectured mass region of $\sim 3500$ MeV.

# Charmed baryons

- Recently the LHCb Collaboration discovered the double charm state $\Xi_{cc}^{++}$ in the invariant mass spectrum of the final state particles $(\Lambda_c^+ K^- \pi^+ \pi^+)$.

- The extracted mass was given as $$M_{\Xi_{cc}^{++}} = (3621.40 \pm 0.78)\ \text{MeV}$$

  i.e. $\sim 100$ MeV heavier than the mass of the original SELEX double charm baryon but in agreement with the value predicted by one gluon exchange model of de Rujula, Georgi and Glashow.

- Measurement of the lifetime: $$\tau_{\Xi_{cc}^{++}} = 0.256 \pm 0.027\ \text{ps}$$

- Observation of the decay: $$\Xi_{cc}^{++} \to \Xi_c^{+} + \pi^+$$

# Charmed baryons in SU(4): $\mathbf{4 \otimes 4 \otimes 4 = 20_S \oplus 20_M \oplus 20'_M \oplus 4_A}$



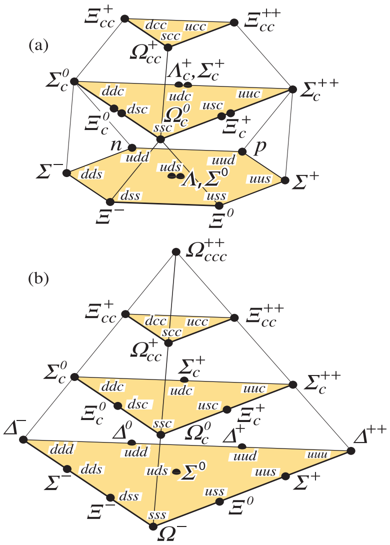
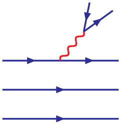


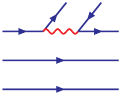

**Figure 15.4:** SU(4) multiplets of baryons made of $u$, $d$, $s$, and $c$ quarks. (a) The 20-plet with an SU(3) octet. (b) The 20-plet with an SU(3) decuplet.

# Nonleptonic two-body weak decays of baryons

- **Ground states of baryons with $J^P = \frac{1}{2}^+$ can decay only weakly.**
- **Two-body decays of baryons have five different quark topologies:**

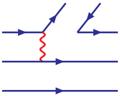


Ia

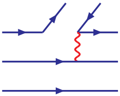


Ib

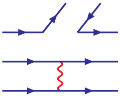
Tree diagrams



IIa



IIb



III

W-exchange diagrams

# Effective Hamiltonian

The effective Hamiltonian describing the $\bar{s}c \to \bar{u}d$ transition is given by

$$\mathcal{H}_{\rm eff} = -\frac{G_F}{\sqrt{2}} V_{cs} V_{ud}^{\dagger} \, (C_1 \, \mathcal{Q}_1 + C_2 \, \mathcal{Q}_2)$$

$$\mathcal{Q}_1 = (\bar{s}_a O_L c_b)(\bar{u}_b O_L d_a) \qquad \mathcal{Q}_2 = (\bar{s}_a O_L c_a)(\bar{u}_b O_L d_b)$$

The notation is $O^{\mu}_{L/R} = \gamma^{\mu}(1 \mp \gamma_5)$.

The matrix element can be written as

$$\langle B_2 M | \, \mathcal{H}_{\rm eff} \, | B_1 \rangle = \frac{G_F}{\sqrt{2}} \lambda_{\rm CKM} \sum_k \underbrace{C_k(\mu)}_{\rm SD} \; \underbrace{\langle B_2 M | Q_k(\mu) | B_1 \rangle}_{\rm LD}$$

- SD = Short-Distance contributions and LD = Long-Distance contributions
- The Wilson coefficients $C_i(\mu)$ are calculated perturbatively by using "matching"the full and effective theories.
- The calculation of the matrix elements $\langle B_2 M | Q_k(\mu) | B_1 \rangle$ requires the nonperturbative methods.

## Covariant Constituent Quark Model

- **The CCQM is based on a phenomenological, nonlocal relativistic Lagrangian describing the coupling of a hadron to its constituents:**

$$\mathcal{L}_{\rm int} = g_H \cdot H(x) \cdot J_H(x)$$

- **Quark currents**

$$J_M(x) = \int dx_1 \int dx_2\, F_M(x; x_1, x_2) \cdot \bar{q}^a_{f_1}(x_1)\, \Gamma_M\, q^a_{f_2}(x_2) \qquad \text{Meson}$$

$$J_B(x) = \int dx_1 \int dx_2 \int dx_3\, F_B(x; x_1, x_2, x_3) \qquad \text{Baryon}$$
$$\times\, \Gamma_1\, q^{a_1}_{f_1}(x_1) \left[\varepsilon^{a_1 a_2 a_3} q^{T\, a_2}_{f_2}(x_2)\, C\, \Gamma_2\, q^{a_3}_{f_3}(x_3)\right]$$

$$J_T(x) = \int dx_1 \ldots \int dx_4\, F_T(x; x_1, \ldots, x_4) \qquad \text{Tetraquark}$$
$$\times \left[\varepsilon^{a_1 a_2 c} q^{T\, a_1}_{f_1}(x_1)\, C \Gamma_1\, q^{a_2}_{f_2}(x_2)\right] \cdot \left[\varepsilon^{a_3 a_4 c} \bar{q}^{T\, a_3}_{f_3}(x_3)\, \Gamma_2 C\, \bar{q}^{a_4}_{f_4}(x_4)\right]$$

# The vertex functions and quark propagators

- Translational invariance for the vertex function

$$F_H(x+a, x_1+a, x_2+a) = F_H(x, x_1, x_2)\,, \qquad \forall a\,.$$

- Our choice:

$$F_B(x, x_1, \ldots, x_n) = \delta^{(4)}\Big(x - \sum_{i=1}^{n} w_i x_i\Big)\, \Phi_H\Big(\sum_{i<j}(x_i - x_j)^2\Big)$$

where $w_i = m_i / \sum_i m_i$.

- The quark propagators

$$S_q(x_1 - x_2) = \int \frac{d^4k}{(2\pi)^4 i}\, \frac{e^{-ik(x_1-x_2)}}{m_q - \not k}$$

- Infrared confinement (cutting an analog of the proper time on the upper limit)

## Some applications

- Semileptonic, nonleptonic and rare $B\,(B_c, B_s)$–decays
- Exclusive semileptonic $D\,(D_s)$–decays
- Analyzing new physics in the decays $\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau$
- Semileptonic decay $\Lambda_b \to \Lambda_c + \tau^- + \bar{\nu_\tau}$
- Heavy-to-light semileptonic decays of $\Lambda_b$ and $\Lambda_c$
- Rare decays $\Lambda_b \to \Lambda + \ell^+\ell^-$
- Polarization effects in the cascade decay
  $\Lambda_b \to \Lambda(\to p\pi^-) + J/\psi(\to \ell^+\ell^-)$
- Strong and radiative decays of the tetraquark state $X(3872)$.
  Four-quark structure of $Z_c(3900)$, $Z_b(10610)$, $Z_b'(10650)$ exotic states

## Some double charmed baryon decays

**We will consider the decays that belong to the same topological class:**

$$\Xi_{cc}^{++} \quad \rightarrow \quad \Xi_c^{+}\,(\Xi_c'^{+}) + \pi^{+}(\rho^{+}) \qquad \text{T-Ia and W-IIb}$$

$$\Omega_{cc}^{+} \quad \rightarrow \quad \Xi_c^{+}\,(\Xi_c'^{+}) + \bar{K}^{0}(K^{*\,0}) \qquad \text{T-Ib and W-IIb}$$

**Quantum numbers and interpolating currents:**

| Baryon | $J^P$ | Interpolating current | Mass (MeV) |
|---|---|---|---|
| $\Xi_{cc}^{++}$ | $\frac{1}{2}^{+}$ | $\varepsilon_{abc}\,\gamma^{\mu}\gamma_5\,u^a(c^b C\gamma_{\mu}c^c)$ | $3621.2 \pm 0.7$ * |
| $\Omega_{cc}^{+}$ | $\frac{1}{2}^{+}$ | $\varepsilon_{abc}\,\gamma^{\mu}\gamma_5\,s^a(c^b C\gamma_{\mu}c^c)$ | 3710.0 ** |
| $\Xi_c'^{+}$ | $\frac{1}{2}^{+}$ | $\varepsilon_{abc}\,\gamma^{\mu}\gamma_5\,c^a(u^b C\gamma_{\mu}s^c)$ | $2578.4 \pm 0.5$ * |
| $\Xi_c^{+}$ | $\frac{1}{2}^{+}$ | $\varepsilon_{abc}\,c^a(u^b C\gamma_5 s^c)$ | $2467.93 \pm 0.18$ * |

* PDG: Review of Particle Physics, Phys. Rev. D , 2018

** One-gluon exchange model: A. De Rujula, H. Georgi and S.L. Glashow, Phys. Rev. D, 1975;
J.G. Korner, M. Kramer and D. Pirjol, Prog. Part. Nucl. Phys., 1994.

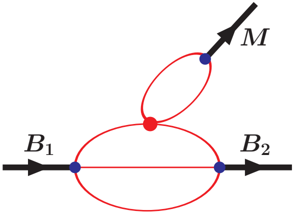
# Körner-Pati-Woo (KPW) theorem

J.G. Körner, Nucl. Phys. B25, 282 (1971); J.C. Pati and C.H. Woo, Phys. Rev. D3, 2920 (1971)

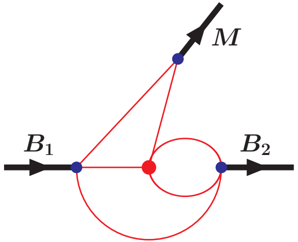
The $W$–exchange contributions to the above decays fall into two classes:

- The decays with a $\Xi_c'^{+}$-baryon containing a symmetric $\{us\}$ diquark described by the interpolating current $\varepsilon_{abc}\,(u^b C\gamma_\mu s^c)$.
- The $W$–exchange contribution is strongly suppressed due to the KPW theorem which states that the contraction of the flavor antisymmetric current-current operator with a flavor symmetric final state configuration is zero in the $SU(3)$ limit.
- The decays with a $\Xi_c^{+}$-baryon containing a antisymmetric $[us]$ diquark described by the interpolating current $\varepsilon_{abc}\,(u^b C\gamma_5 s^c)$.
- In this case the $W$–exchange contribution is not a priori suppressed.

# Matrix elements




tree diagrams Ia, Ib




W-exchange diagram IIb

$$< B_2\, M|\mathcal{H}_{\rm eff}|B_1 >= \frac{G_F}{\sqrt{2}} V_{cs} V_{ud}^{\dagger}\, \bar{u}(p_2)\Big(12\, C_T\, M_T + 12\,(C_1 - C_2)\, M_W\Big) u(p_1).$$

$$C_T = \begin{cases} C_T = +(C_2 + \xi C_1) & \text{charged meson} \\ C_T = -(C_1 + \xi C_2) & \text{neutral meson} \end{cases}$$

The factor of $\xi = 1/N_c$ is set to zero in the numerical calculations.

# Tree-diagram contribution: factorization

The contribution from the tree diagram factorizes into two pieces:

$$M_T = M_T^{(1)} \cdot M_T^{(2)}$$

$$M_T^{(1)} = N_c\, g_M \int \frac{d^4k}{(2\pi)^4 i} \widetilde{\Phi}_M(-k^2)\, \mathrm{tr}\left[O_L S_d(k - w_d q)\Gamma_M S_{s(u)}(k + w_{s(u)} q)\right]$$

$$M_T^{(2)} = g_{B_1} g_{B_2} \int \frac{d^4k_1}{(2\pi)^4 i} \int \frac{d^4k_2}{(2\pi)^4 i} \widetilde{\Phi}_{B_1}\left(-\vec{\Omega}_1^{\,2}\right) \widetilde{\Phi}_{B_2}\left(-\vec{\Omega}_2^{\,2}\right)$$
$$\times\ \Gamma_1 S_c(k_2)\gamma^\mu S_c(k_1 - p_1) O_R S_{u(s)}(k_1 - p_2)\widetilde{\Gamma}_2 S_{s(u)}(k_1 - k_2)\gamma_\mu\gamma_5$$

The $M_T^{(1)}$ is related to the leptonic decay constants:

$$M_T^{(1)} = \begin{cases} -f_P \cdot q & \text{pseudoscalar meson} \\ +f_V m_V \cdot \epsilon_V & \text{vector meson} \end{cases}$$

# W-exchange diagram contribution: no factorization

$$\begin{aligned} M_W &= g_{B_1} g_{B_2} g_M \int \frac{d^4k_1}{(2\pi)^4 i} \int \frac{d^4k_2}{(2\pi)^4 i} \int \frac{d^4k_3}{(2\pi)^4 i} \widetilde{\Phi}_{B_1}\Big(-\vec{\Omega}_1^{\,2}\Big) \widetilde{\Phi}_{B_2}\Big(-\vec{\Omega}_2^{\,2}\Big) \widetilde{\Phi}_M(-P^2) \\ &\times \; 2\Gamma_1 S_c(k_1)\gamma^\mu S_c(k_2)(1-\gamma_5) S_d(k_2-k_1+p_2)\Gamma_M S_{s(u)}(k_2-k_1+p_1)\gamma_\mu\gamma_5 \\ &\times \; \mathrm{tr}\Big[S_{u(s)}(k_3)\widetilde{\Gamma}_2 S_{s(u)}(k_3-k_1+p_2)(1+\gamma_5)\Big] \end{aligned}$$

Here $\Gamma_1 \otimes \widetilde{\Gamma}_2 = I \otimes \gamma_5$ for $B_2 = \Xi_c^+$ and $-\gamma_\nu\gamma_5 \otimes \gamma^\nu$ for $B_2 = \Xi_c'^{\,+}$.

To verify the KPW theorem in the case of $B_2 = \Xi_c'^{\,+}$ we use the identity

$$\mathrm{tr}\Big[S_u(k_3)\gamma_\nu S_s(k_3-k_1+p_2)\Big] = -\,\mathrm{tr}\Big[S_s(-k_3+k_1-p_2)\gamma_\nu S_u(-k_3)\Big]$$

Then by shifting $k_3 \to -k_3+k_1-p_2$ one gets the same expression with opposite sign and $u \leftrightarrow s$ interchange. Thus, if $m_u = m_s$ then $M_W \equiv 0$.

**It directly confirms the KPW–theorem.**

# Invariant and helicity amplitudes

**The transition amplitudes in terms of invariant amplitudes:**

$$< B_2\, P|\mathcal{H}_{\rm eff}|B_1 > \;=\; \frac{G_F}{\sqrt{2}} V^*_{cs} V_{ud}\, \bar{u}(p_2)\,(A + \gamma_5\, B)\, u(p_1)$$

$$< B_2\, V|\mathcal{H}_{\rm eff}|B_1 > \;=\; \frac{G_F}{\sqrt{2}} V^*_{cs} V_{ud}$$

$$\times\; \bar{u}(p_2)\, \epsilon^*_{V\delta} \left(\gamma^\delta V_\gamma + p_1^\delta V_p + \gamma_5 \gamma^\delta V_{5\gamma} + \gamma_5 p_1^\delta\, V_{5p}\right) u(p_1)$$

**The invariant amplitudes in terms of helicity amplitudes:**

$$H^V_{\frac{1}{2}\,t} = \sqrt{Q_+}\, A \qquad H^A_{\frac{1}{2}\,t} = \sqrt{Q_-}\, B$$

$$H^V_{\frac{1}{2}\,0} = +\sqrt{Q_-/q^2}\left(m_+\, V_\gamma + \tfrac{1}{2} Q_+\, V_p\right) \qquad H^V_{\frac{1}{2}\,1} = -\sqrt{2Q_-}\, V_\gamma$$

$$H^A_{\frac{1}{2}\,0} = +\sqrt{Q_+/q^2}\left(m_-\, V_{5\gamma} + \tfrac{1}{2} Q_-\, V_{5p}\right) \qquad H^A_{\frac{1}{2}\,1} = -\sqrt{2Q_+}\, V_{5\gamma}$$

**Here** $m_\pm = m_1 \pm m_2$, $Q_\pm = m_\pm^2 - q^2$ **and** $|\mathbf{p}_2| = \lambda^{1/2}(m_1^2, m_2^2, q^2)/(2m_1)$.

**The parity relations:** $H^V_{-\lambda_2,-\lambda_M} = +H^V_{\lambda_2,\lambda_M}\,,\; H^A_{-\lambda_2,-\lambda_M} = -H^A_{\lambda_2,\lambda_M}$

# Decay widths

**The two-body decay widths read**

$$\Gamma\Big(B_1 \to B_2 + P(V)\Big) = \frac{G_F^2}{32\pi}\left|V_{cs}^* V_{ud}\right|^2 \frac{|\mathbf{p}_2|}{m_1^2}\mathcal{H}_{P(V)}$$

$$\mathcal{H}_P = \left|H_{\frac{1}{2}\,t}\right|^2 + \left|H_{-\frac{1}{2}\,t}\right|^2,$$

$$\mathcal{H}_V = \left|H_{\frac{1}{2}\,0}\right|^2 + \left|H_{-\frac{1}{2}\,0}\right|^2 + \left|H_{\frac{1}{2}\,1}\right|^2 + \left|H_{-\frac{1}{2}\,-1}\right|^2,$$

**where** $H = H^V - H^A$.

## $\Omega_{cc}^{+} \rightarrow \Xi_c'^{+} + \bar{K}^0 (\bar{K}^{*0})$

| Helicity | Tree diagram | $W$ diagram | total |
|---|---|---|---|
| $H^V_{\frac{1}{2}\,t}$ | 0.20 | $-0.01$ | 0.19 |
| $H^A_{\frac{1}{2}\,t}$ | 0.25 | $-0.01$ | 0.24 |
| $\Gamma(\Omega_{cc}^{+} \rightarrow \Xi_c'^{+} + \bar{K}^0) = 0.15 \cdot 10^{-13}$ GeV | | | |
| $H^V_{\frac{1}{2}\,0}$ | $-0.25$ | $0.04 \times 10^{-1}$ | $-0.25$ |
| $H^A_{\frac{1}{2}\,0}$ | $-0.50$ | 0.01 | $-0.49$ |
| $H^V_{\frac{1}{2}\,1}$ | 0.27 | $-0.01$ | 0.26 |
| $H^A_{\frac{1}{2}\,1}$ | 0.56 | $0.04 \times 10^{-2}$ | 0.56 |
| $\Gamma(\Omega_{cc}^{+} \rightarrow \Xi_c'^{+} + \bar{K}^{*0}) = 0.74 \cdot 10^{-13}$ GeV | | | |

## $\Omega_{cc}^{+} \to \Xi_c^{+} + \bar{K}^0(\bar{K}^{*\,0})$

| Helicity | Tree diagram | $W$ diagram | total |
|---|---|---|---|
| $H^V_{\frac{1}{2}\,t}$ | $-0.35$ | $1.06$ | $0.71$ |
| $H^A_{\frac{1}{2}\,t}$ | $-0.10$ | $0.31$ | $0.21$ |
| $\Gamma(\Omega_{cc}^{+} \to \Xi_c^{+} + \bar{K}^0) = 0.95 \cdot 10^{-13}$ GeV | | | |
| $H^V_{\frac{1}{2}\,0}$ | $0.50$ | $-0.69$ | $-0.19$ |
| $H^A_{\frac{1}{2}\,0}$ | $0.18$ | $-0.45$ | $-0.27$ |
| $H^V_{\frac{1}{2}\,1}$ | $-0.11$ | $-0.24$ | $-0.35$ |
| $H^A_{\frac{1}{2}\,1}$ | $-0.18$ | $0.66$ | $0.48$ |
| $\Gamma(\Omega_{cc}^{+} \to \Xi_c^{+} + \bar{K}^{*\,0}) = 0.62 \cdot 10^{-13}$ GeV | | | |

## $\Xi_{cc}^{++} \to \Xi_c'^{+} + \pi^+(\rho^+)$

| Helicity | Tree diagram | $W$ diagram | total |
|---|---|---|---|
| $H^V_{\frac{1}{2}\,t}$ | $-0.38$ | $-0.01$ | $-0.39$ |
| $H^A_{\frac{1}{2}\,t}$ | $-0.55$ | $-0.02$ | $-0.57$ |
| $\Gamma(\Xi_{cc}^{++} \to \Xi_c'^{+} + \pi^+) = 0.82 \cdot 10^{-13}$ GeV | | | |
| $H^V_{\frac{1}{2}\,0}$ | $0.60$ | $0.04 \times 10^{-1}$ | $0.61$ |
| $H^A_{\frac{1}{2}\,0}$ | $1.20$ | $0.01$ | $1.21$ |
| $H^V_{\frac{1}{2}\,1}$ | $-0.49$ | $-0.01$ | $-0.50$ |
| $H^A_{\frac{1}{2}\,1}$ | $-1.27$ | $0.01 \times 10^{-1}$ | $-1.27$ |
| $\Gamma(\Xi_{cc}^{++} \to \Xi_c'^{+} + \rho^+) = 4.27 \cdot 10^{-13}$ GeV | | | |

# $\Xi_{cc}^{++} \to \Xi_c^+ + \pi^+(\rho^+)$

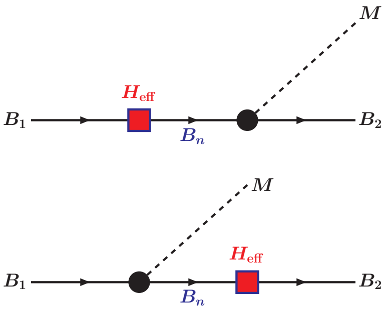
| Helicity | Tree diagram | $W$ diagram | total |
|---|---|---|---|
| $H^V_{\frac{1}{2}\,t}$ | $-0.70$ | 0.99 | 0.29 |
| $H^A_{\frac{1}{2}\,t}$ | $-0.21$ | 0.30 | 0.09 |
| $\Gamma(\Xi_{cc}^{++} \to \Xi_c^+ + \pi^+) = 0.18 \cdot 10^{-13}$ GeV | | | |
| $H^V_{\frac{1}{2}\,0}$ | 1.17 | $-0.70$ | 0.47 |
| $H^A_{\frac{1}{2}\,0}$ | 0.45 | $-0.44$ | 0.003 |
| $H^V_{\frac{1}{2}\,1}$ | $-0.20$ | $-0.23$ | $-0.43$ |
| $H^A_{\frac{1}{2}\,1}$ | $-0.41$ | 0.62 | 0.21 |
| $\Gamma(\Xi_{cc}^{++} \to \Xi_c^+ + \rho^+) = 0.63 \cdot 10^{-13}$ GeV | | | |

# Estimating uncertainties in the decay widths

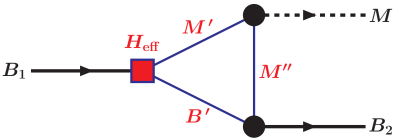
- The only free parameter in our approach is the size parameter $\Lambda_{cc}$.
- We have chosen $\Lambda_{cc} = \Lambda_c = 0.8675$ GeV.
- To estimate the uncertaintity caused by the choice of the size parameter we allow the size parameter to vary from 0.6 to 1.135 GeV.
- We evaluate the mean $\bar{\Gamma} = \sum \Gamma_i / N$ and the mean square deviation $\sigma^2 = \sum (\Gamma_i - \bar{\Gamma})^2 / N$.
- The rate errors amount to $6 - 15\%$.

| Mode | Width (in $10^{-13}$ GeV) |
|---|---|
| $\Omega_{cc}^+ \to \Xi_c^{\prime\,+} + \bar{K}^0$ | $0.14 \pm 0.01$ |
| $\Omega_{cc}^+ \to \Xi_c^{\prime\,+} + \bar{K}^{*\,0}$ | $0.72 \pm 0.06$ |
| $\Omega_{cc}^+ \to \Xi_c^+ + \bar{K}^0$ | $0.87 \pm 0.13$ |
| $\Omega_{cc}^+ \to \Xi_c^+ + \bar{K}^{*\,0}$ | $0.58 \pm 0.07$ |
| $\Xi_{cc}^{++} \to \Xi_c^{\prime\,+} + \pi^+$ | $0.77 \pm 0.05$ |
| $\Xi_{cc}^{++} \to \Xi_c^{\prime\,+} + \rho^+$ | $4.08 \pm 0.29$ |
| $\Xi_{cc}^{++} \to \Xi_c^+ + \pi^+$ | $0.16 \pm 0.02$ |
| $\Xi_{cc}^{++} \to \Xi_c^+ + \rho^+$ | $0.59 \pm 0.04$ |

# Other approaches to the W-exchange diagrams




**Pole model**




**Final State Interaction (FSI) approach**

# Comparison with other approaches. Abbr.: M=NRQM, T=HQET

| Mode | Width (in $10^{-13}$ GeV) | | | | | |
|---|---|---|---|---|---|---|
| | our | Dhir | Jiang | Wang | Yu | Likhoded |
| $\Omega_{cc}^{+} \to \Xi_c'^{+} + \bar{K}^0$ | 0.15 | 0.31 (M)<br>0.59 (T) | | | | |
| $\Omega_{cc}^{+} \to \Xi_c^{+} + \bar{K}^0$ | 0.95 | 0.68 (M)<br>1.08 (T) | | | | |
| $\Omega_{cc}^{+} \to \Xi_c'^{+} + \bar{K}^{*0}$ | 0.74 | | $2.64^{+2.72}_{-1.79}$ | | | |
| $\Omega_{cc}^{+} \to \Xi_c^{+} + \bar{K}^{*0}$ | 0.62 | | $1.38^{+1.49}_{-0.95}$ | | | |
| $\Xi_{cc}^{++} \to \Xi_c'^{+} + \pi^+$ | 0.82 | 1.40 (M)<br>1.93 (T) | | 1.10 | | |
| $\Xi_{cc}^{++} \to \Xi_c^{+} + \pi^+$ | 0.18 | 1.71 (M)<br>2.39 (T) | | 1.57 | 1.58 | 2.25 |
| $\Xi_{cc}^{++} \to \Xi_c'^{+} + \rho^+$ | 4.27 | | $4.25^{+0.32}_{-0.19}$ | 4.12 | 3.82 | |
| $\Xi_{cc}^{++} \to \Xi_c^{+} + \rho^+$ | 0.63 | | $4.11^{+1.37}_{-0.86}$ | 3.03 | 2.76 | 6.70 |

# References


- N. Sharma and R. Dhir, Phys. Rev. D 96, 113006 (2017).
- R. Dhir and N. Sharma, Eur. Phys. J. C 78, 743 (2018).
- L. J. Jiang, B. He and R. H. Li, Eur. Phys. J. C 78, 961 (2018).
- W. Wang, F. S. Yu and Z. X. Zhao, Eur. Phys. J. C 77, 781 (2017).
- F. S. Yu, H. Y. Jiang, R. H. Li, C. D. Lü, W. Wang and Z. X. Zhao, Chin. Phys. C 42, 051001 (2018).
- V. V. Kiselev and A. K. Likhoded, Phys. Usp. 45, 455 (2002) [Usp. Fiz. Nauk 172, 497 (2002)].
- A. V. Berezhnoy, A. K. Likhoded and A. V. Luchinsky, Phys. Rev. D 98, 113004 (2018).

# Summary and outlook

- We have calculated the branchings of the nonleptonic two-body decays of the doubly charmed baryons $\Xi_{cc}^{++}$ and $\Omega_{cc}^{+}$ including the tree diagrams as well as $W$-exchange contribution.
- We made use of the covariant confined quark model to calculate the factorizable graph as well as the $W$-exchange contribution which is described by the genuine tree-loop diagram.
- We have checked the Körner-Pati–Woo (KPW) theorem which states that the $W$–exchange contribution to the decays with a $\Xi_c^{\prime +}$-baryon in the final state is strongly suppressed.
- We have found that the $W$–exchange contribution in the case of a $\Xi_c^{+}$-baryon in the final state is of the same order as the factorizable graph contribution.

# Summary and outlook

- We now have the tools at hand to calculate all Cabibbo favored and Cabibbo suppressed nonleptonic two-body decays of the double charm ground state baryons $\Xi_{cc}^{++}$, $\Xi_{cc}^{+}$ and $\Omega_{cc}^{+}$. These would also include the $1/2^+ \to 3/2^+ + P(V)$ nonleptonic decays not treated in this paper.
- Of particular interest are the modes

$$\begin{aligned} \Xi_{cc}^{+} &\to \Sigma^{(*)+} + D^{(*)0} \\ \Xi_{cc}^{+} &\to \Xi^{(*)0} + D_s^{(*)+} \\ \Omega_{cc}^{+} &\to \Xi^{(*)0} + D^{(*)+} \end{aligned}$$

They proceed only due to a single $W$-exchange contribution.
- Three modes involving the final state $3/2^+$ baryons ($\Sigma^{*+}$ and $\Xi^{*0}$) are forbidden due to the KPW theorem. It would be interesting to check on this prediction of the quark model.