Semileptonic *bc* to *cc* Baryon Decay and Heavy Quark Spin Symmetry

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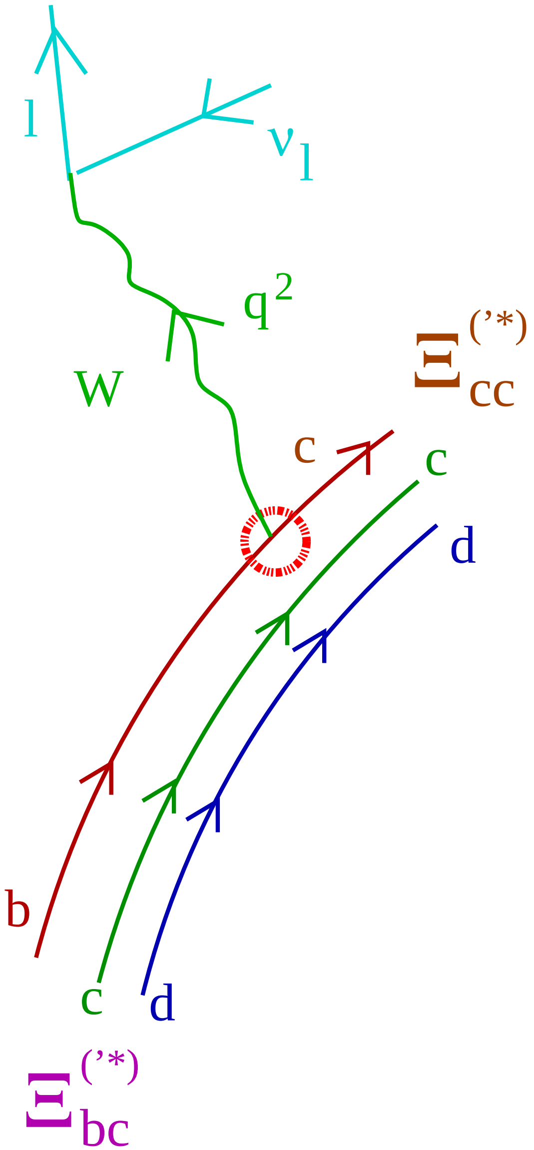
Motivation : Separate **heavy quark spin symmetries** make it possible to describe the **semileptonic decays**

$$\Xi_{bc}^{(\prime *)} \to \Xi_{cc}^{(*)}\, l\, \bar{\nu}_l, \qquad \Omega_{bc}^{(\prime *)} \to \Omega_{cc}^{(*)}\, l\, \bar{\nu}_l$$

in the limit $m_{b,c} \gg \Lambda_{QCD}$ and close to the zero recoil point

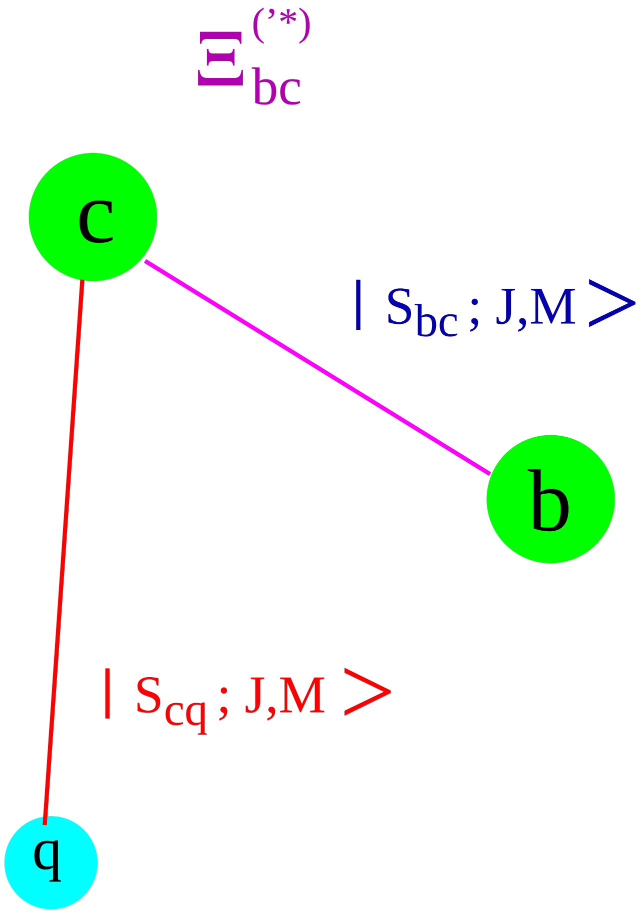


$$\mathbf{q^2} = m_{bc}^2 + m_{cc}^2 - 2 m_{bc} m_{cc} \omega, \qquad \underbrace{\boxed{1}}_{\text{zero recoil}} \le \omega \le \frac{m_{bc}^2 + m_{cc}^2 - m_l^2}{2 m_{bc} m_{cc}}$$

	S	J^P	I	$\mathbf{S}^{\pi}_{\mathbf{hh}}$	
Ξ_{cc}	0	$\frac{1}{2}^+$	$\frac{1}{2}$	1^+	ccl
Ξ^*_{cc}	0	$\frac{3}{2}^+$	$\frac{1}{2}$	1^+	ccl
Ω_{cc}	-1	$\frac{1}{2}^+$	0	1^+	ccs
Ω^*_{cc}	-1	$\frac{3}{2}^+$	0	1^+	ccs
Ξ_{bb}	0	$\frac{1}{2}^+$	$\frac{1}{2}$	1^+	bbl
Ξ^*_{bb}	0	$\frac{3}{2}^+$	$\frac{1}{2}$	1^+	bbl
Ω_{bb}	-1	$\frac{1}{2}^+$	0	1^+	bbs
Ω^*_{bb}	-1	$\frac{3}{2}^+$	0	1^+	bbs

	S	J^P	I	$\mathbf{S}^{\pi}_{\mathbf{hh'}}$	
Ξ'_{bc}	0	$\frac{1}{2}^+$	$\frac{1}{2}$	0^+	bcl
Ξ_{bc}	0	$\frac{1}{2}^+$	$\frac{1}{2}$	1^+	bcl
Ξ^*_{bc}	0	$\frac{3}{2}^+$	$\frac{1}{2}$	1^+	bcl
Ω'_{bc}	-1	$\frac{1}{2}^+$	0	0^+	bcs
Ω_{bc}	-1	$\frac{1}{2}^+$	0	1^+	bcs
Ω^*_{bc}	-1	$\frac{3}{2}^+$	0	1^+	bcs

HQS constraints on SL FF's and Γ's of doubly heavy baryons.



For instance, let us study $\mathbf{\Xi_{bc}^{('*)}} \to \mathbf{\Xi_{cc}^{(*)}}$ SL decays,

$$p_\mu = m_{\Xi_{bc}^{('*)}} \mathbf{v}_\mu, \quad p'_\mu = m_{\Xi_{cc}^{(*)}} v'_\mu = m_{\Xi_{cc}^{(*)}} \mathbf{v}_\mu + \mathbf{k}_\mu$$

Near the zero-recoil point $\omega = 1$ ($\omega = \mathbf{v}\cdot\mathbf{v}'$) **k small residual momentum** $\Rightarrow$ $\mathbf{k}\cdot\mathbf{v} = \mathcal{O}(1/\mathbf{m}_{\mathbf{\Xi_{cc}^{(*)}}})$.

To represent the **lowest-lying S-wave bcq baryons** we use **wavefunctions comprising tensor products of Dirac matrices and spinors,** namely:

$$\mathbf{B}'_{\mathbf{bc}} = -\left[\frac{(1+\not v)}{2}\gamma_5\right]_{\alpha\beta} u_\gamma(v,r)$$

$$\mathbf{B}_{\mathbf{bc}} = \left[\frac{(1+\not v)}{2}\gamma_\mu\right]_{\alpha\beta}\left[\frac{1}{\sqrt{3}}(v^\mu+\gamma^\mu)\gamma_5 u(v,r)\right]_\gamma$$

$$\mathbf{B}^*_{\mathbf{bc}} = \mathbf{\Xi}^*_{\mathbf{bc}} = \left[\frac{(1+\not v)}{2}\gamma_\mu\right]_{\alpha\beta} u^\mu_\gamma(v,r)$$

α, β, γ Dirac indices and r baryon helicity label. These **wavefunctions** can be considered as **matrix elements of the form** $\langle 0|c_\alpha \bar{q}^c{}_\beta b_\gamma|B_{bc}^{('*)}\rangle$ where $\bar{q}^c = q^T C$ **with** C **the charge-conjugation matrix.**

Under a Lorentz (Λ), and b and c quark spin (S_b and S_c) transformations, **a wavefunction** $\Gamma_{\alpha\beta}\, u_\gamma$ transforms as:

$$\begin{aligned} \Gamma\, u &\rightarrow S(\Lambda)\Gamma S^{-1}(\Lambda)\; S(\Lambda) u \\ \Gamma\, u &\rightarrow S_c \Gamma\, S_b u \end{aligned}$$

States normalised using $\mathbf{\bar{u}u}\mathrm{Tr}(\mathbf{\Gamma\overline{\Gamma}})$: **mutually orthogonal and have a common normalisation** ($\overline{\Gamma} = \gamma^0 \Gamma^\dagger \gamma^0$). States where the b and c quarks are coupled to definite spin,

$$\begin{aligned} |\mathbf{S_{bc} = 0; J = \tfrac{1}{2}}\rangle &= -\frac{1}{2}|S_{cq} = 0; J = \frac{1}{2}\rangle + \frac{\sqrt{3}}{2}|S_{cq} = 1; J = \frac{1}{2}\rangle \\ |\mathbf{S_{bc} = 1; J = \tfrac{1}{2}}\rangle &= \frac{\sqrt{3}}{2}|S_{cq} = 0; J = \frac{1}{2}\rangle + \frac{1}{2}|S_{cq} = 1; J = \frac{1}{2}\rangle \\ |\mathbf{S_{bc} = 1; J = \tfrac{3}{2}}\rangle &= |S_{cq} = 1; J = \frac{3}{2}\rangle \end{aligned}$$

Remarks:

- **We have not used definite spin combinations directly for the b and c quarks.** The reason is **to make both the spin transformations on the heavy quarks and the Lorentz transformation of the states convenient**, making it straightforward to build spin-invariant and Lorentz covariant quantities.

- **We could have combined the b quark with the light quark to a definite spin.** This would clearly interchange the spin transformations and alter the appearance of spin-invariant and Lorentz covariant quantities. **Physical results should of course be unchanged.**

For the cc baryons,

$$\mathbf{B}'_{\mathbf{cc}} = -\sqrt{\frac{\mathbf{2}}{\mathbf{3}}}\left[\frac{(1+\not{v})}{2}\gamma_5\right]_{\alpha\beta} u_\gamma(v,r)$$

$$\mathbf{B}_{\mathbf{cc}} = \sqrt{\mathbf{2}}\left[\frac{(1+\not{v})}{2}\gamma_\mu\right]_{\alpha\beta}\left[\frac{1}{\sqrt{3}}(v^\mu+\gamma^\mu)\gamma_5 u(v,r)\right]_\gamma$$

$$\mathbf{B}^*_{\mathbf{cc}} = \mathbf{\Xi}^*_{\mathbf{cc}} = \sqrt{\frac{\mathbf{1}}{\mathbf{2}}}\left[\frac{(1+\not{v})}{2}\gamma_\mu\right]_{\alpha\beta} u^\mu_\gamma(v,r)$$

- the two charm quarks can only be in a symmetric spin-1 state: B'_{cc} and B_{cc} correspond to the same baryon state Ξ_{cc}.
- normalisation: there are two ways to contract the charm quark indices, leading to $\mathbf{\bar{u}u}\mathrm{Tr}(\mathbf{\Gamma\bar{\Gamma}}) + \mathbf{\bar{u}\,\Gamma\,\bar{\Gamma}u}$. To have the same normalisation as for the bc case, we have to **include extra numerical factors**

... **construct spin-invariant and Lorentz covariant amplitudes for the weak transition matrix elements,**

SL $\Xi_{bc}^{(\prime *)} \to \Xi_{cc}^{(*)}$ decays $\leftrightarrow$ ME **weak current** $J^\mu = \bar{c}\gamma^\mu(1-\gamma_5)b$

We first build transition amplitudes between the $B_{bc}^{(\prime *)}$ and $\Xi_{cc}^{(*)}$ states and subsequently take linear combinations to obtain transitions from $\Xi_{bc}^{(\prime *)}$ states. **The most general form for the ME respecting the HQSS is ($j^\mu = \gamma^\mu(1-\gamma_5)$):**

$$
\begin{aligned}
\langle \Xi_{cc}^{(*)}, v, k, M' | J^\mu(0) | B_{bc}^{(\prime *)}, v, M \rangle &= \bar{u}_{cc}(v,k,M') j^\mu u_{bc}(v,M) \mathrm{Tr}[\Gamma_{bc} \boldsymbol{\Omega} \overline{\Gamma}_{cc}] \\
&+ \bar{u}_{cc}(v,k,M') \Gamma_{bc} \boldsymbol{\Omega} \overline{\Gamma}_{cc} j^\mu u_{bc}(v,M)
\end{aligned}
$$

$$
\begin{aligned}
\Gamma_{bc} &\to S_c \Gamma_{bc}, \quad u_{bc} \to S_b u_{bc} \\
\overline{\Gamma}_{cc} &\to \overline{\Gamma}_{cc} S_c^\dagger, \quad \bar{u}_{cc} \to \bar{u}_{cc} S_c^\dagger \\
\bar{c} j^\mu b : j^\mu &\to S_c j^\mu S_b^\dagger
\end{aligned}
$$

... **construct spin-invariant and Lorentz covariant amplitudes for the weak transition matrix elements,**
SL $\Xi_{bc}^{(\prime *)} \to \Xi_{cc}^{(*)}$ decays $\leftrightarrow$ ME **weak current** $J^\mu = \bar{c}\gamma^\mu(1-\gamma_5)b$
We first build transition amplitudes between the $B_{bc}^{(\prime *)}$ and $\Xi_{cc}^{(*)}$ states and subsequently take linear combinations to obtain transitions from $\Xi_{bc}^{(\prime *)}$ states. **The most general form for the ME respecting the HQSS is ($j^\mu = \gamma^\mu(1-\gamma_5)$):**

$$\langle \Xi_{cc}^{(*)}, v, k, M' | J^\mu(0) | B_{bc}^{(\prime *)}, v, M\rangle = \bar{u}_{cc}(v,k,M') S_c^\dagger S_c j^\mu S_b^\dagger S_b u_{bc}(v,M) \mathrm{Tr}[S_c \Gamma_{bc} \boldsymbol{\Omega} \overline{\Gamma}_{cc} S_c^\dagger] + \bar{u}_{cc}(v,k,M') S_c^\dagger S_c \Gamma_{bc} \boldsymbol{\Omega} \overline{\Gamma}_{cc} S_c^\dagger S_c j^\mu S_b^\dagger S_b u_{bc}(v,M)$$

$$\begin{aligned} \Gamma_{bc} &\to S_c\Gamma_{bc}, \quad u_{bc} \to S_b u_{bc} \\ \overline{\Gamma}_{cc} &\to \overline{\Gamma}_{cc} S_c^\dagger, \quad \bar{u}_{cc} \to \bar{u}_{cc} S_c^\dagger \\ \bar{c} j^\mu b : j^\mu &\to S_c j^\mu S_b^\dagger \end{aligned}$$

where M and M' are the helicities of the initial and final states

$$\boldsymbol{\Omega} = -\frac{1}{\sqrt{2}}\eta(\mathbf{v}\cdot\mathbf{v}')$$

is the most general Dirac matrix that can be written in terms of the vectors k and v.

- terms with a factor of $\not{v}$ can be omitted because of the equations of motion ($\not{v}u = u$, $\not{v}\Gamma = \Gamma$, $\gamma_\mu u^\mu = 0$, $v_\mu u^\mu = 0$),
- terms with $\not{k}$ will always lead to contributions proportional to $v \cdot k = \mathcal{O}(1/m_{\Xi_{cc}^{(*)}})$.

$\Xi_{bc} \to \Xi_{cc}$	$\eta\, \bar{u}_{cc} \left(2\gamma^\mu - \frac{4}{3}\gamma^\mu\gamma_5\right) u_{bc}$
$\Xi'_{bc} \to \Xi_{cc}$	$\frac{-2}{\sqrt{3}}\eta\, \bar{u}_{cc} \left(-\gamma^\mu\gamma_5\right) u_{bc}$
$\Xi_{bc} \to \Xi^*_{cc}$	$\frac{-2}{\sqrt{3}}\eta\, \bar{u}^\mu_{cc} u_{bc}$
$\Xi'_{bc} \to \Xi^*_{cc}$	$-2\eta\, \bar{u}^\mu_{cc} u_{bc}$
$\Xi^*_{bc} \to \Xi_{cc}$	$\frac{-2}{\sqrt{3}}\eta\, \bar{u}_{cc} u^\mu_{bc}$
$\Xi^*_{bc} \to \Xi^*_{cc}$	$-2\eta\, \bar{u}^\lambda_{cc} \left(\gamma^\mu - \gamma^\mu\gamma_5\right) u_{bc\,\lambda}$

Remarks:

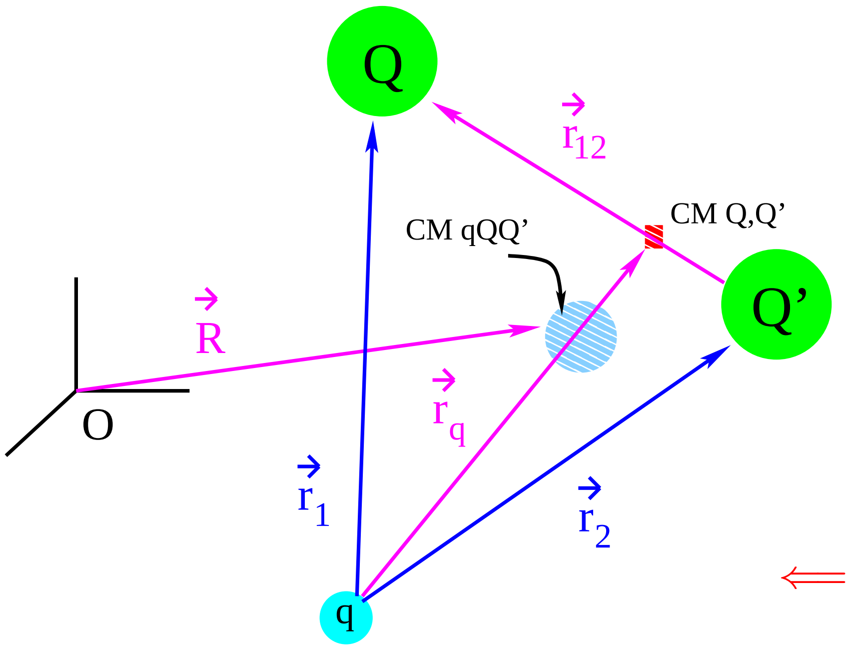
- If the b and c quarks become degenerate, then vector current conservation ensures that $\eta(\mathbf{1}) = \mathbf{1}$.
- **Savage and White (PLB 271 (1991) 410)** found similar results: approach where the two heavy quarks bind into a colour antitriplet which appears as a pointlike colour source to the light degrees of freedom + **"superflavor"** formalism of Georgi and Wise. We find two differences to their results (one of these was already pointed out by Sanchis-Lozano PLB 321 (1994) 407).
- Our approach, where we consider the spin transformations of each heavy quark explicitly, is **straightforward and similar** to that used to describe B_c **meson decays:** Jenk-

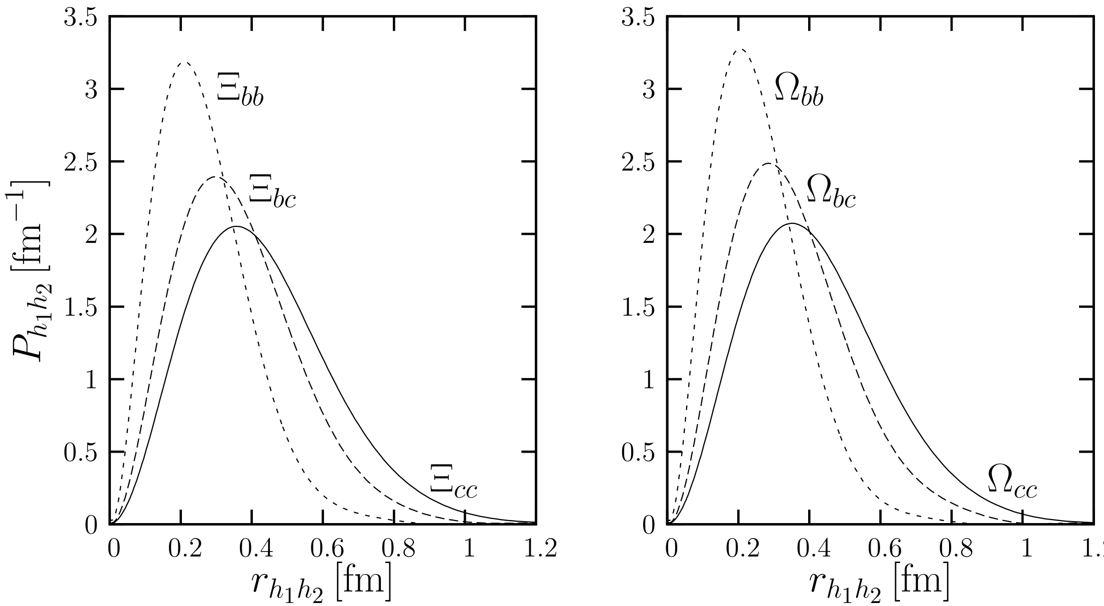
ins, Luke, Manohar and Savage, NPB 390 (1993) 463.

- **Spin symmetry** for both the b and c quarks **enormously simplifies** the description of all $\boldsymbol{\Xi_{bc}^{(\prime *)} \to \Xi_{cc}^{(*)}\, l\, \bar{\nu}_l}$ decays in the heavy quark limit and near the zero recoil point. **All the weak transition matrix elements are given in terms of a single universal function.** Lorentz covariance alone allows a large number of form factors (six form factors to describe $\Xi_{bc} \to \Xi_{cc}$, another six for $\Xi'_{bc} \to \Xi_{cc}$, eight each for $\Xi_{bc} \to \Xi^*_{cc}$, $\Xi'_{bc} \to \Xi^*_{cc}$ and $\Xi^*_{bc} \to \Xi_{cc}$, and even more for $\Xi^*_{bc} \to \Xi^*_{cc}$).

Test: QM [EPJA 32 (2007) 183]

$$\eta(\mathbf{v}\cdot\mathbf{v}') = \int d^3r_1 d^3r_2 \exp[-i\vec{k}\cdot\vec{r}_{12}/2][\mathbf{\Psi^{\Xi}_{cc}}(\mathbf{r_1},\mathbf{r_2},\mathbf{r_{12}})]^* \, \mathbf{\Psi^{\Xi}_{bc}}(\mathbf{r_1},\mathbf{r_2},\mathbf{r_{12}})$$

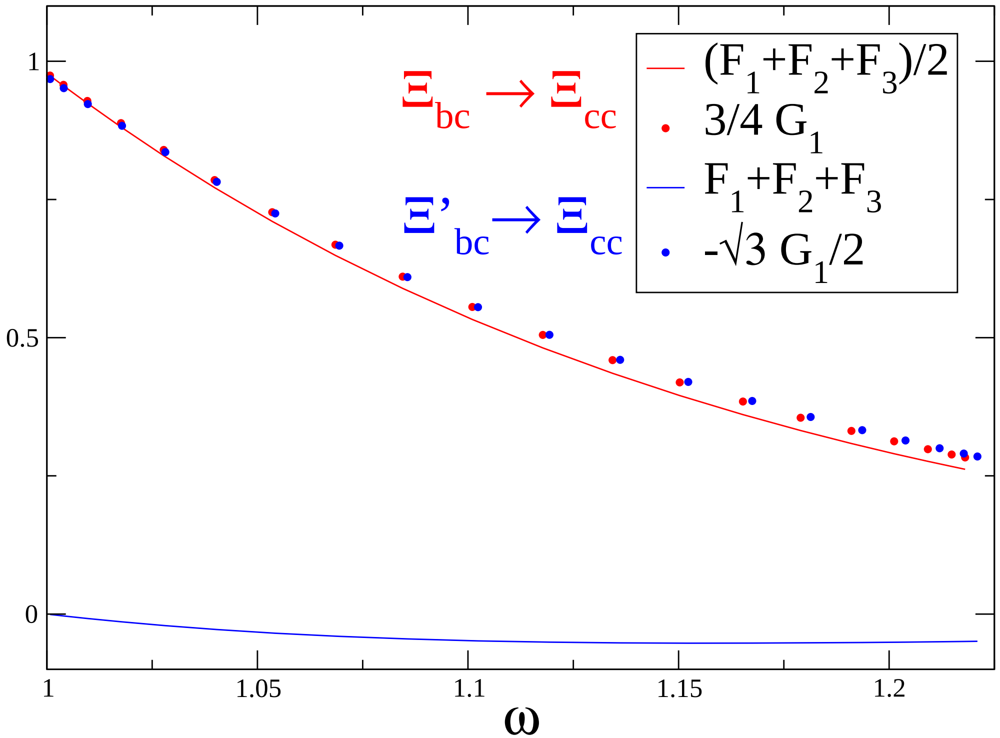


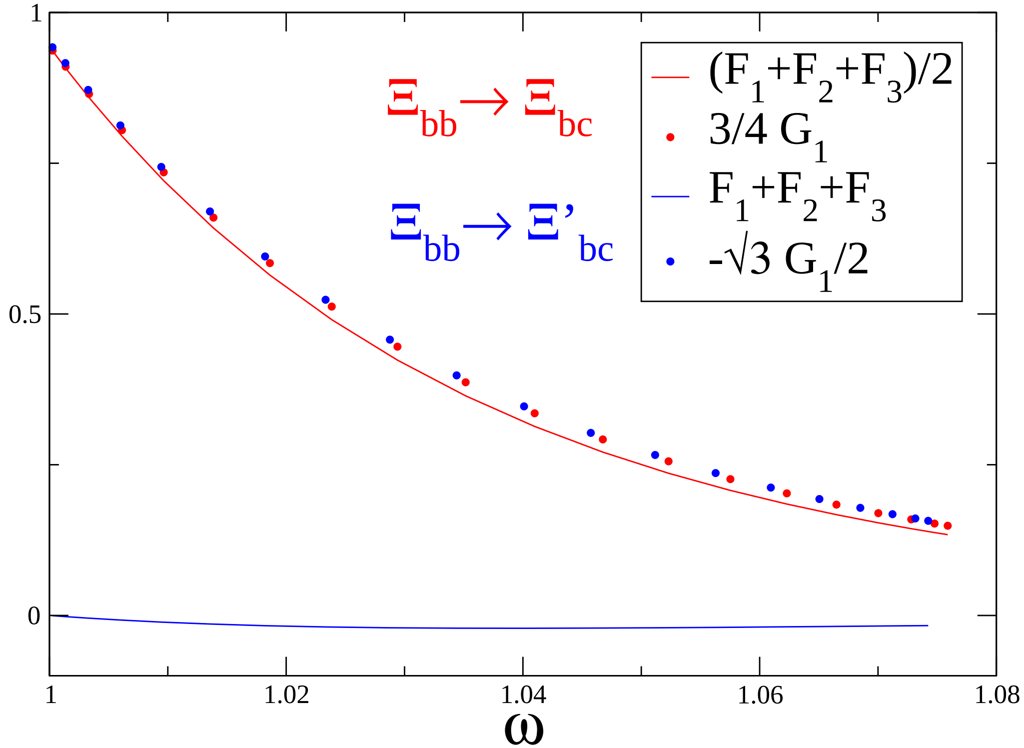


$\Longleftarrow$ Jacobi's coordinates, $Q, Q' = c, b$.

$$r_{12} \ll r_1, r_2 \rightarrow \mathbf{\Psi^{\Xi}_{Qc}}(\mathbf{r_1},\mathbf{r_2},\mathbf{r_{12}}) \approx \overbrace{\Phi_{Qc}(r_{12})}^{\textbf{Qc}\text{ DIQUARK}} \underbrace{\phi(r_{Qcq})}_{\text{RELATIVE MOTION OF } \textbf{q} \text{ AND A POINTLIKE } \textbf{Qc} \text{ DIQUARK}} \overbrace{\varphi_{Qc}(\vec{r}_{12}\cdot\vec{r}_{Qcq})}^{\text{VARIATIONAL}}$$

$$\left\langle \mathbf{\Xi_{cc}}, r'\ \vec{p}'\,|\,\bar{c}\gamma^\mu(1-\gamma_5)b(0)|\,\mathbf{\Xi_{bc}^{(\prime)}}, r\ \vec{p}\right\rangle = \bar{u}_{r'}^{\Xi_{cc}}(\vec{p}')\Big\{\gamma^\mu\left(\mathbf{F_1(w)}-\gamma_5\mathbf{G_1(w)}\right)$$
$$+v^\mu\left(\mathbf{F_2(w)}-\gamma_5\mathbf{G_2(w)}\right)+v'^\mu\left(\mathbf{F_3(w)}-\gamma_5\mathbf{G_3(w)}\right)\Big\}u_r^{\Xi_{bc}^{(\prime)}}(\vec{p})$$





... $1/2 \to 3/2$ spin transitions

$$\left\langle \mathbf{\Xi}^*_{\mathbf{cc}}, r' \; \vec{p}\,' \,|\, \bar{c}\gamma^\mu(1-\gamma_5)b(0) | \, \mathbf{\Xi}^{(\prime)}_{\mathbf{bc}}, r \; \vec{p} \right\rangle = \bar{u}^{\Xi^*_{cc}}_{\lambda r'}(\vec{p}\,') \mathbf{\Gamma}^{\lambda\,\mu} u^{\Xi^{(\prime)}_{bc}}_{r}(\vec{p})$$

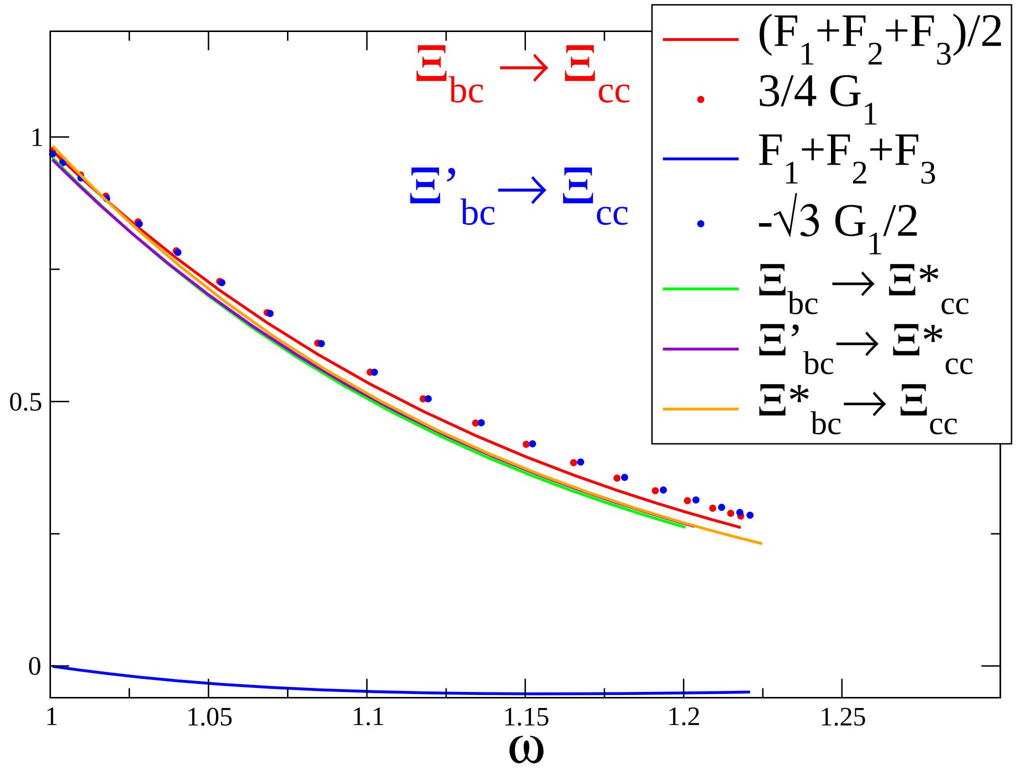
$$\mathbf{\Gamma}^{\lambda\,\mu} = \left(\frac{\mathbf{C^V_3}(\omega)}{m_{\Xi^{(\prime)}_{bc}}} (g^{\lambda\,\mu} \not{q} - q^\lambda \gamma^\mu) + \frac{\mathbf{C^V_4}(\omega)}{m^2_{\Xi^{(\prime)}_{bc}}} (g^{\lambda\,\mu} q p' - q^\lambda p'^\mu) \right.$$

$$\left. + \frac{\mathbf{C^V_5}(\omega)}{m^2_{\Xi^{(\prime)}_{bc}}} (g^{\lambda\,\mu} q p - q^\lambda p^\mu) + \mathbf{C^V_6}(\omega) g^{\lambda\,\mu} \right) \gamma_5$$

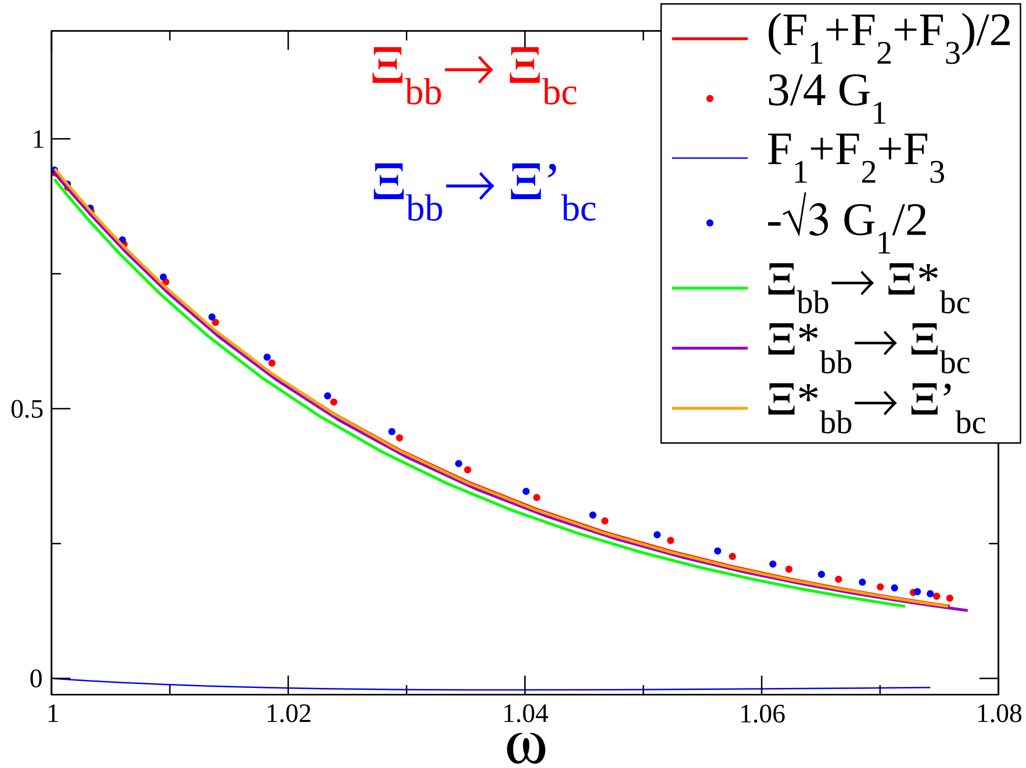
$$+ \left(\frac{\mathbf{C^A_3}(\omega)}{m_{\Xi^{(\prime)}_{bc}}} (g^{\lambda\,\mu} \not{q} - q^\lambda \gamma^\mu) + \frac{\mathbf{C^A_4}(\omega)}{m^2_{\Xi^{(\prime)}_{bc}}} (g^{\lambda\,\mu} q p' - q^\lambda p'^\mu) + \mathbf{C^A_5}(\omega) g^{\lambda\,\mu} + \frac{\mathbf{C^A_6}(\omega)}{m^2_{\Xi^{(\prime)}_{bc}}} q^\lambda q^\mu \right)$$

and $3/2 \to 1/2$ transitions...

$$\langle \mathbf{\Xi}_{\mathbf{cc}}, r' \; \vec{p}\,' \,|\, \bar{c}\gamma^\mu(1-\gamma_5)b(0) | \, \mathbf{\Xi}^*_{\mathbf{bc}}, r \; \vec{p} \rangle = \bar{u}^{\Xi_{cc}}_{r'}(\vec{p}\,') \hat{\mathbf{\Gamma}}^{\lambda\,\mu} u^{\Xi^*_{bc}}_{\lambda,r}(\vec{p})$$

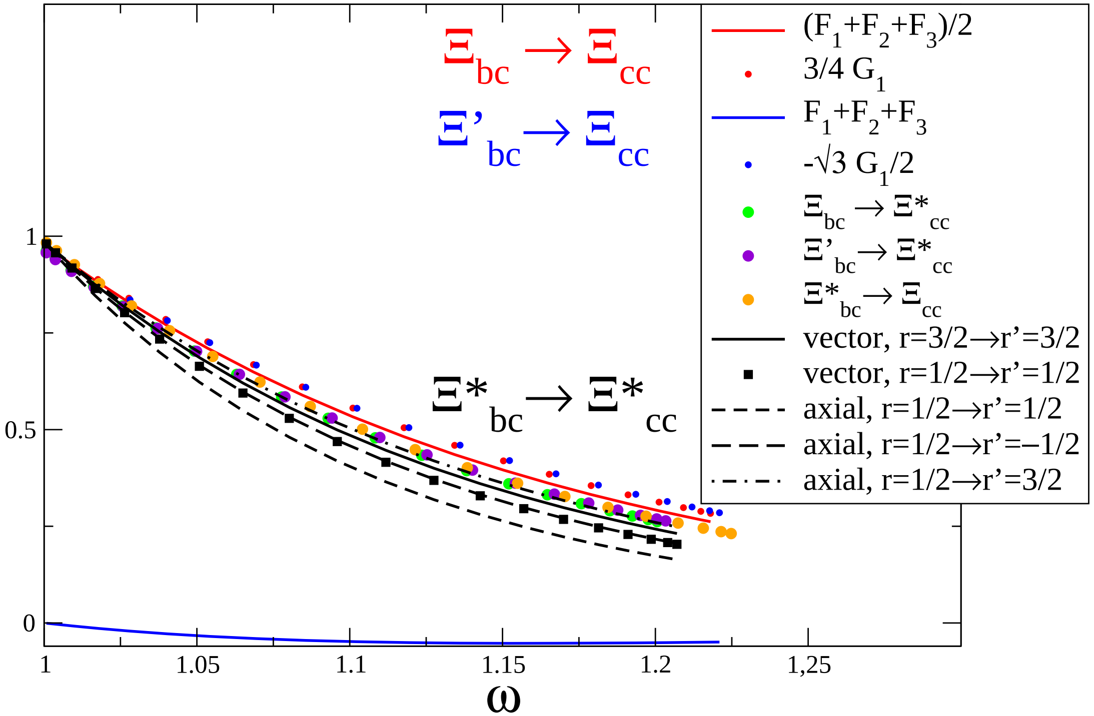


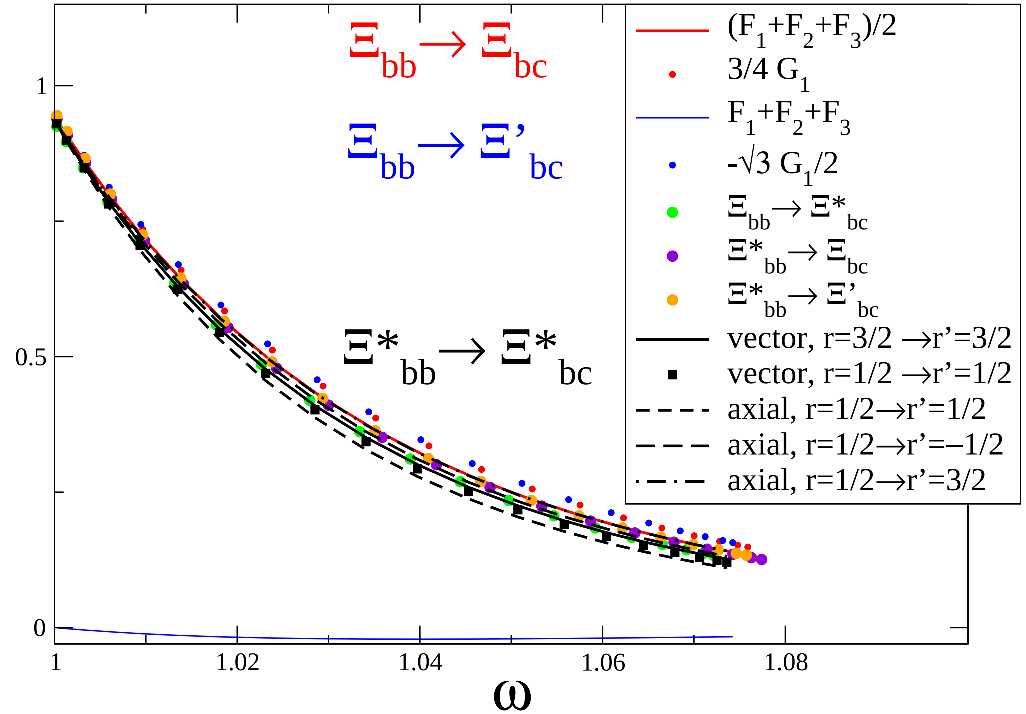
$\Xi_{bc} \rightarrow \Xi_{cc}$
$\Xi'_{bc} \rightarrow \Xi_{cc}$
$(F_1+F_2+F_3)/2$
$3/4\ G_1$
$F_1+F_2+F_3$
$-\sqrt{3}\ G_1/2$
$\Xi_{bc} \rightarrow \Xi^*_{cc}$
$\Xi'_{bc} \rightarrow \Xi^*_{cc}$
$\Xi^*_{bc} \rightarrow \Xi_{cc}$
1
0.5
0
1.05
1.1
1.15
1.2
1.25
ω



$\Xi_{bb} \rightarrow \Xi_{bc}$
$\Xi_{bb} \rightarrow \Xi'_{bc}$
$(F_1+F_2+F_3)/2$
$3/4\ G_1$
$F_1+F_2+F_3$
$-\sqrt{3}\ G_1/2$
$\Xi_{bb} \rightarrow \Xi^*_{bc}$
$\Xi^*_{bb} \rightarrow \Xi_{bc}$
$\Xi^*_{bb} \rightarrow \Xi'_{bc}$
1
0.5
0
1.02
1.04
1.06
1.08
ω

and $3/2 \to 3/2$ transitions, $\Xi^*_{bc} \to \Xi^*_{cc}$ ~ 50 FF's





HQSS constraints on semileptonic decay widths

$$\Gamma = \frac{G_F^2}{32\pi^4}|V_{cb}|^2 \frac{m_{\Xi_{cc}^{(*)}}}{m^2_{\Xi_{bc}^{(*\prime)}}} \int_1^{\omega_{max}} d\omega \, \sqrt{\omega^2-1} \, \mathcal{L}^{\mu\nu} \underbrace{\mathcal{H}_{\mu\nu}}_{\text{hadron FF's}}$$

$$\begin{aligned} \mathcal{L}^{\mu\nu} &= \int \frac{d^3k_1}{2E_1}\frac{d^3k_2}{2E_2}\,\delta^{(4)}(q-k_1-k_2)\left(k_1^\mu k_2^\nu + k_1^\nu k_2^\mu - g^{\mu\nu} k_1\cdot k_2 + i\epsilon^{\mu\nu\alpha\beta}k_{1\alpha}k_{2\beta}\right) \\ &= A(q^2)\, g^{\mu\nu} + B(q^2)\,\frac{q^\mu q^\nu}{q^2} \end{aligned}$$

For the actual doubly heavy baryon masses $\omega_{max} \approx 1.22\,(1.08)$ for $bc \to cc\,(bb \to bc)$ transitions. The different differential decay widths $d\Gamma/d\omega$ show a maximum at around $\omega \approx 1.05\,(1.01) \Longrightarrow$

$\boxed{\eta(\omega) \to \mathcal{H}_{\mu\nu}}$ and approximating

$$m_{\Xi_{bb}} \approx m_{\Xi^*_{bb}} \;;\; m_{\Xi_{bc}} \approx m_{\Xi'_{bc}} \approx m_{\Xi^*_{bc}} \;;\; m_{\Xi_{cc}} \approx m_{\Xi^*_{cc}}$$

predict that some ratios between different decay widths should be approximately 1...

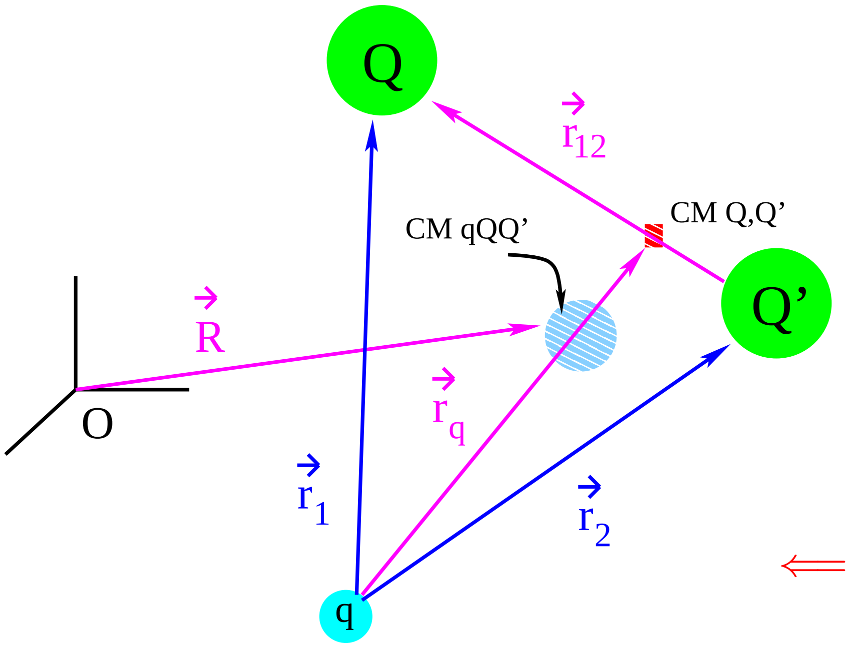
$bc \to cc$	Hernández et al. arXiv:0706.2805 [hep-ph] Ξ	Hernández et al. arXiv:0706.2805 [hep-ph] Ω	Ebert et al. PRD70 (2004) 014018 Ξ	Ebert et al. PRD70 (2004) 014018 Ω	Guo et al. PRD58 (1998) 114007 Ξ	Guo et al. PRD58 (1998) 114007 Ω
$\frac{\Gamma(B'_{bc}\to B^*_{cc}\,l\bar\nu_l)}{3\,\Gamma(B_{bc}\to B^*_{cc}\,l\bar\nu_l)}$	$1.04^{+0.03}_{-0.01}$	$1.04_{-0.03}$	0.79	0.82	0.68	—
$\frac{\Gamma(B_{bc}\to B^*_{cc}\,l\bar\nu_l)}{\frac{2}{3}\,\Gamma(B'_{bc}\to B_{cc}\,l\bar\nu_l)}$	$0.82^{+0.06}_{-0.01}$	$0.84^{+0.13}_{-0.01}$	1.22	1.17	**2.72**	—
$\frac{\Gamma(B^*_{bc}\to B_{cc}\,l\bar\nu_l)}{\frac{1}{2}\,\Gamma(B_{bc}\to B^*_{cc}\,l\bar\nu_l)}$	$1.14^{+0.08}$	$1.16^{+0.04}_{-0.06}$	1.05	1.08	**3.90**	—
$\frac{\Gamma(B^*_{bc}\to B^*_{cc}\,l\bar\nu_l)}{\Gamma(B_{bc}\to B_{cc}\,l\bar\nu_l)+\frac{1}{2}\,\Gamma(B_{bc}\to B^*_{cc}\,l\bar\nu_l)}$	$0.89^{+0.11}$	$0.94^{+0.13}_{-0.01}$	1.01	1.01	1.08	—

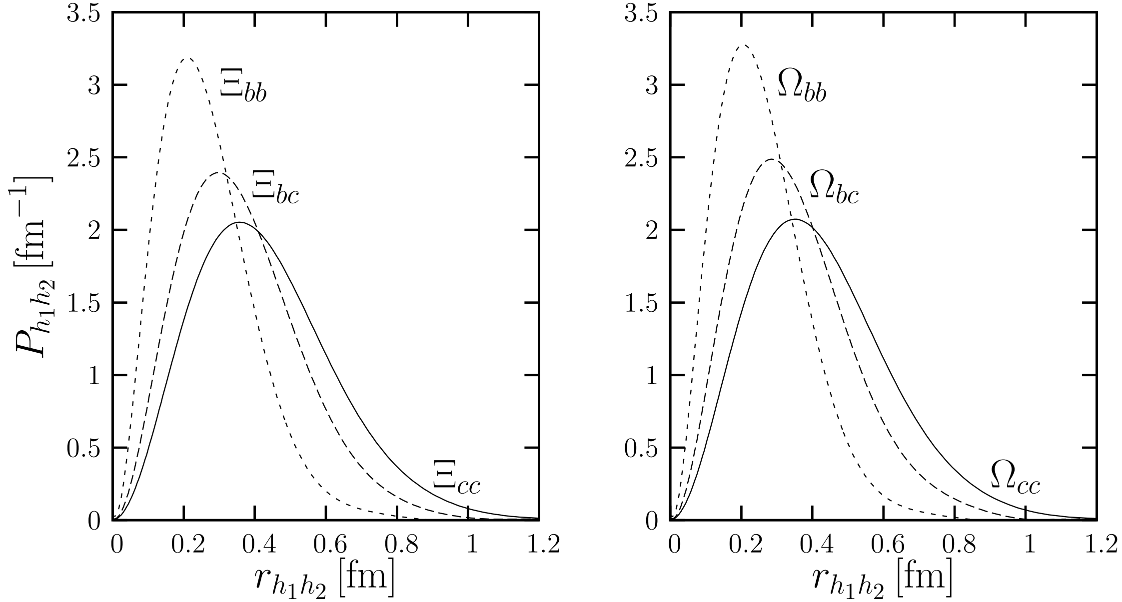
$bb \to bc$

	Hernández et al. arXiv:0706.2805 [hep-ph]		Ebert et al. PRD70 (2004) 014018		Guo et al. PRD58 (1998) 114007	
$bb \to bc$	Ξ	Ω	Ξ	Ω	Ξ	Ω
$\frac{\Gamma(B^*_{bb}\to B'_{bc}\, l\bar\nu_l)}{3\,\Gamma(B^*_{bb}\to B_{bc}\, l\bar\nu_l)}$	$1.00^{+0.01}_{-0.04}$	$1.00^{+0.03}_{-0.01}$	0.99	0.99	**0.05**	—
$\frac{\Gamma(B_{bb}\to B^*_{bc}\, l\bar\nu_l)}{\frac{2}{3}\,\Gamma(B_{bb}\to B'_{bc}\, l\bar\nu_l)}$	$0.86^{+0.08}_{-0.06}$	$0.86^{+0.05}$	0.96	0.99	**9.53**	—
$\frac{\Gamma(B^*_{bb}\to B_{bc}\, l\bar\nu_l)}{\frac{1}{2}\,\Gamma(B_{bb}\to B^*_{bc}\, l\bar\nu_l)}$	$1.14^{+0.04}_{-0.05}$	$1.13^{+0.01}_{-0.17}$	1.05	1.04	**3.82**	—
$\frac{\Gamma(B^*_{bb}\to B^*_{bc}\, l\bar\nu_l)}{\Gamma(B_{bb}\to B_{bc}\, l\bar\nu_l)+\frac{1}{2}\,\Gamma(B_{bb}\to B^*_{bc}\, l\bar\nu_l)}$	$0.94^{+0.07}_{-0.06}$	$0.93^{+0.11}_{-0.10}$	1.01	1.01	**0.31**	—

Diquark Picture and Link to B_c Meson Decays

$$\eta(\mathbf{v}\cdot\mathbf{v}') = \int d^3r_1 d^3r_2 \exp[-i\vec{k}\cdot\vec{r}_{12}/2][\boldsymbol{\Psi}^{\boldsymbol{\Xi}}_{\mathbf{cc}}(\mathbf{r_1},\mathbf{r_2},\mathbf{r_{12}})]^* \, \boldsymbol{\Psi}^{\boldsymbol{\Xi}}_{\mathbf{bc}}(\mathbf{r_1},\mathbf{r_2},\mathbf{r_{12}})$$





$\Longleftarrow$ Jacobi's coordinates, $Q, Q' = c, b$.

$$r_{12} \ll r_1, r_2 \rightarrow \boldsymbol{\Psi}^{\boldsymbol{\Xi}}_{\mathbf{Qc}}(\mathbf{r_1},\mathbf{r_2},\mathbf{r_{12}}) \approx \overbrace{\Phi_{Qc}(r_{12})}^{\mathbf{Qc}\ \text{DIQUARK}} \underbrace{\phi(r_{Qcq})}_{\text{RELATIVE MOTION OF } \mathbf{q} \text{ AND A POINTLIKE } \mathbf{Qc} \text{ DIQUARK}} \overbrace{\varphi_{Qc}(\vec{r}_{12}\cdot\vec{r}_{Qcq})}^{\text{VARIATIONAL}\approx 1}$$

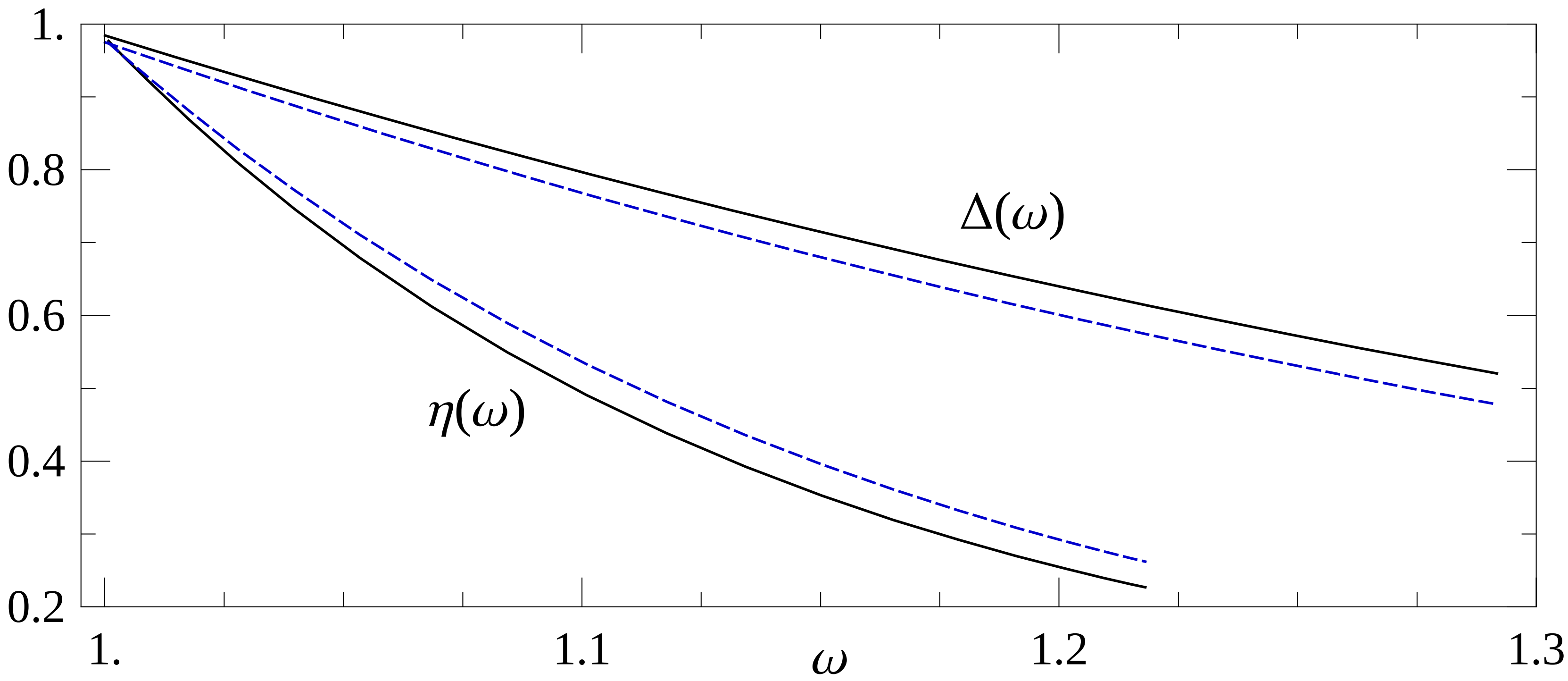
$$\eta(\mathbf{v}\cdot\mathbf{v}') = \int \mathbf{d^3 r_{12}} \exp[-\mathbf{i}\vec{\mathbf{k}}\cdot\vec{\mathbf{r}}_{\mathbf{12}}/\mathbf{2}][\mathbf{\Phi_{cc}}(\mathbf{r_{12}})]^*\mathbf{\Phi_{bc}}(\mathbf{r_{12}}) \underbrace{\int d^3r\phi^*(r)\phi(r)}_{\mathbf{1}}$$

where $\vec{r}=\vec{r}_{ccq}$ and in the d^3r integral we have replaced $\phi(r_{bcq})$ by $\phi(r)$ since $\vec{r}_{bcq}=\vec{r}_{ccq}+\mathcal{O}(\vec{r}_{12})$. **This approximation leads to uncertainties of $\mathcal{O}(r_{12}^2)$ after integration,**

$$\eta(\mathbf{v}\cdot\mathbf{v}') = \int \mathbf{d^3 r_{12}} \exp[-\mathbf{ik}\cdot\mathbf{r_{12}}/\mathbf{2}][\mathbf{\Phi_{cc}}(\mathbf{r_{12}})]^*\mathbf{\Phi_{bc}}(\mathbf{r_{12}})$$

which has an **identical form to the expression of the form factor Δ, unique form factor which describes the B_c to η_c and J/ψ semileptonic decays,** in terms of wavefunctions of the $\bar{b}c$ and $\bar{c}c$ bound states (Jenkins et al., NPB 390 (1993) 463).

This does not mean that η and Δ are identical because the QQ and $Q\bar{Q}$ potentials used to compute the diquark and meson wavefunctions are not the same. For example a $\lambda_i\lambda_j$ colour dependence (λ_i are the usual Gell-Mann matrices) would lead to $V^{QQ} = V^{Q\bar{Q}}/2$. [approx wfnt overlaps (solid lines) vs IW funcs (dahsed lines)]



The ω^2 **slope of the Δ form factor is indeed smaller than that of η**, but the ratio is around 1 to 3 rather than 1 to 6, so there are **significant corrections to the Coulomb wavefunction description.**

Conclusions

- Separate HQSS make it possible to describe all SL

  $$\Xi_{bc}^{(\prime *)} \to \Xi_{cc}^{(*)}\, l\, \bar{\nu}_l, \qquad \Omega_{bc}^{(\prime *)} \to \Omega_{cc}^{(*)}\, l\, \bar{\nu}_l$$

  decays **using a single form factor**. Similarly for **$bb \to bc$ decays.**

- We have discussed the **resemblance of the bc baryon decays to those of B_c mesons to η_c and J/ψ mesons**

- **Lattice QCD** simulations work best near the zero-recoil point and thus are well-suited to **check the validity of the results.**
- **QM calculations consistent with HQSS ?**
  - Results by **Hernández et al.** (FF's and decay width ratios), and **Ebert et al.** (decay width ratios), **compare well**, within expectations **with HQSS**
  - **We detect problems** either in the model or in the calculation performed by Guo et al.