Production of charmonium-like mesons (X,Y,Z) in B_c decays

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Outline

- **Theoretical framework (Proof of factorization of B_c decays)**
- **Form factors of $B_c \rightarrow$ X,Y,Z**
- **Numerical results**
- **Summary**

Experimental status

state	mass (MeV)	width (MeV)	production/decay mode	Exp
$X(3872)$	$3872.0 \pm 0.6 \pm 0.5$	< 2.3 95% C.L.	$B \to KX \to K\pi\pi J/\psi$	Belle
	3873.4 ± 1.4	–	$B \to KX \to K\pi\pi J/\psi$	BaBar
	–	–	$B \to X \to \pi\pi\pi J/\psi$	Belle
	–	–	$B \to X \to \gamma J/\psi$	Belle
	$3871.3 \pm 0.7 \pm 0.4$	–	$p\bar{p} \to X \to \pi\pi J/\psi$	CDF
	$3871.8 \pm 3.1 \pm 3.0$	–	$p\bar{p} \to X \to \pi\pi J/\psi$	DØ
	avg = 3871.9 ± 0.5			
$X(3940)$	$3943 \pm 6 \pm 6$	< 52	$e^+e^- \to J/\psi X \to J/\psi D\bar{D}^*$	Belle
$Y(3940)$	$3943 \pm 11 \pm 13$	$87 \pm 22 \pm 26$	$B \to KY \to K\pi\pi\pi J/\psi$	Belle
$Z(3930)$	$3931 \pm 4 \pm 2$	$20 \pm 8 \pm 3$	$\gamma\gamma \to Z \to D\bar{D}$	Belle
$Y(4260)$	$4259 \pm 8 \pm 4$	$88 \pm 23 \pm 5$	$e^+e^- \to \gamma_{ISR} Y \to \gamma_{ISR} J/\psi\pi\pi$	BaBar

Theoretical studies

- Tetraquarks, hybrids, glueballs, molecular states and charmonium …
- Mostly focus on the decay properties of the X,Y,Z's
- We will study the production properties of them, but assuming charmonium

Production in B decays

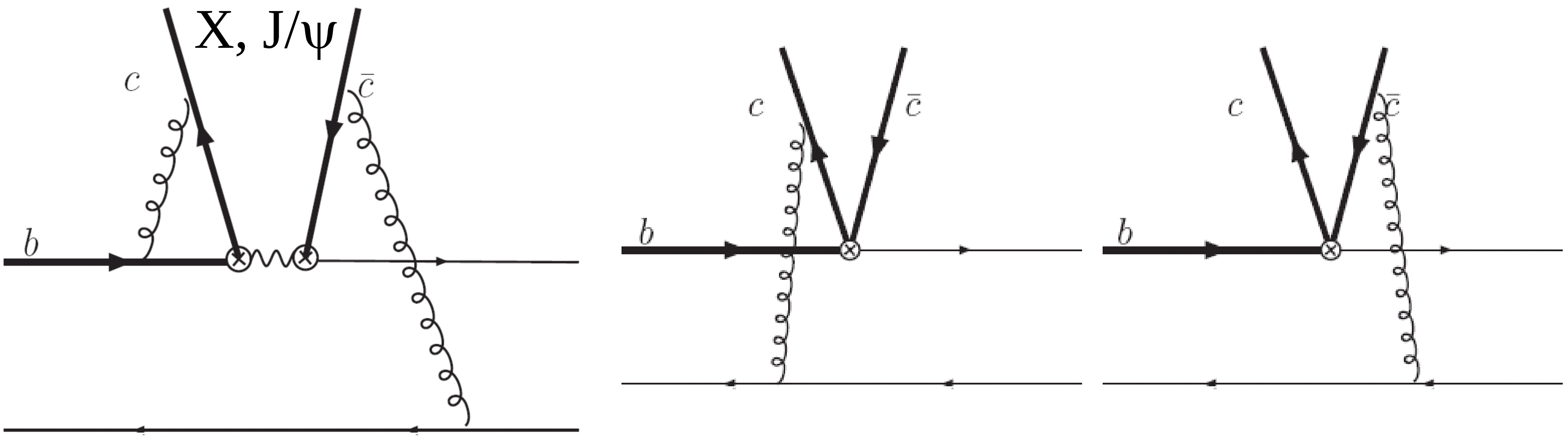
There are two B factories: BaBar and Belle. They have accumulated a large number of events. Utilizing these data, we could uncover the structure of mysterious mesons

mass(MeV)	width(MeV)	production/decay mode	significance	experiment
$3872.0 \pm 0.6 \pm 0.5$	< 2.3 95% C.L.	$B^{\pm} \to K^{\pm} X \to K^{\pm}\pi^{+}\pi^{-} J/\psi$	10σ	Belle
$3871.3 \pm 0.7 \pm 0.4$	resolution	$p\bar{p} \to X \to \pi^{+}\pi^{-} J/\psi$	11.6σ	CDFII
$M(J/\psi) + 774.9 \pm 3.1 \pm 3.0$	resolution	$p\bar{p} \to X \to \pi^{+}\pi^{-} J/\psi$	5.2σ	DØ
3873.4 ± 1.4	–	$B^{-} \to K^{-} X \to K^{-}\pi^{+}\pi^{-} J/\psi$	3.5σ	BaBar

However

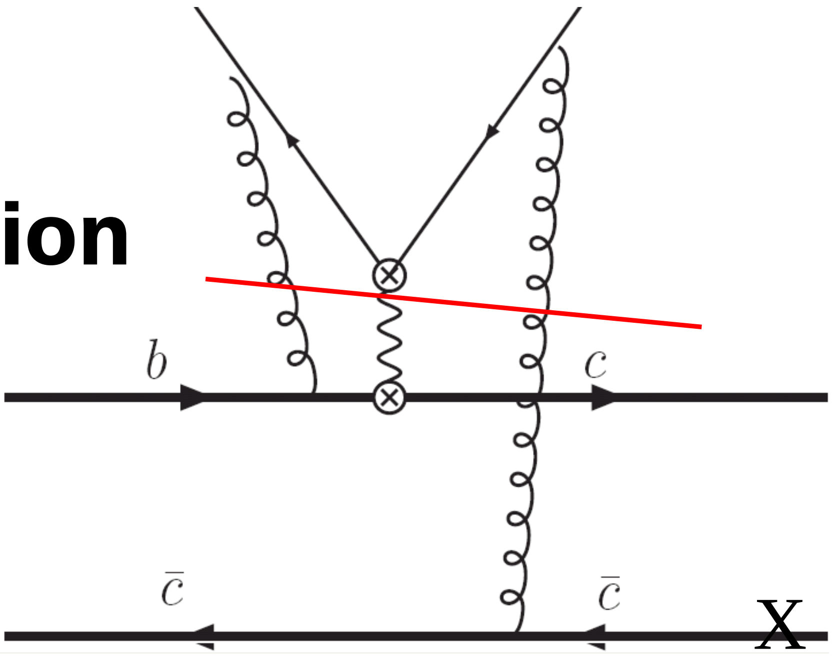
Color octet contribution is dominant in B decays, which gives large theoretical uncertainties

Although the B factories provide many events, but the theoretical studies are hampered by our understanding of non-perturbative QCD



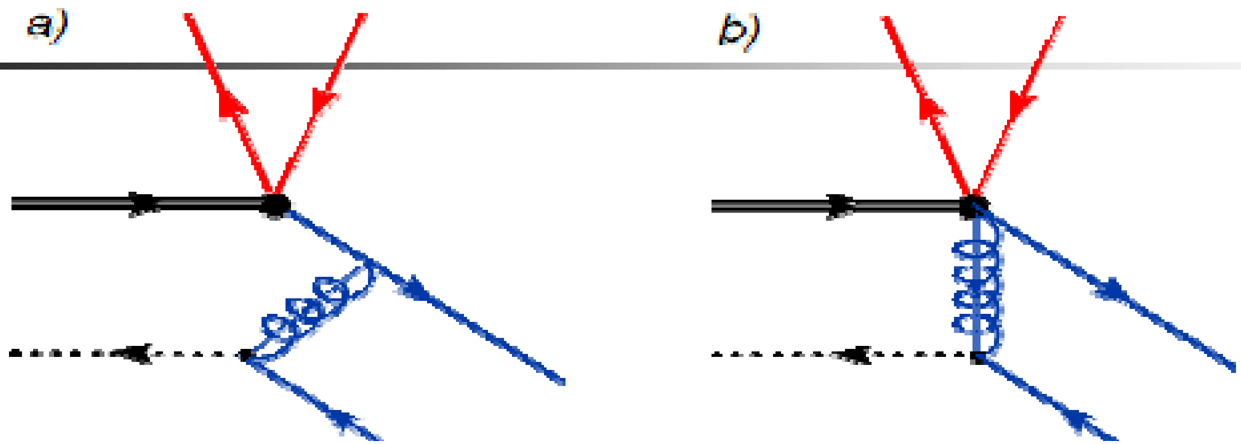
LHC-b experiment will produce a large number of B_c in the near future

Charmonium production in B_c decays are **dominated** by **factorizable** contribution



the production of charmonia in B_c decays can provide a unique insight to these mesons

Soft collinear effective theory (SCET)



$$\langle M_1 M_2 | O_i | B \rangle = C_i^I(u) \otimes \Phi_{M_2}(u) \zeta^{B\to M_1}(0) + C_i^{II}(u,\tau) \otimes \Phi_{M_2}(u) \otimes \zeta_J^{B\to M_1}(\tau, 0)$$

Non-perturbative part

Perturbative part:

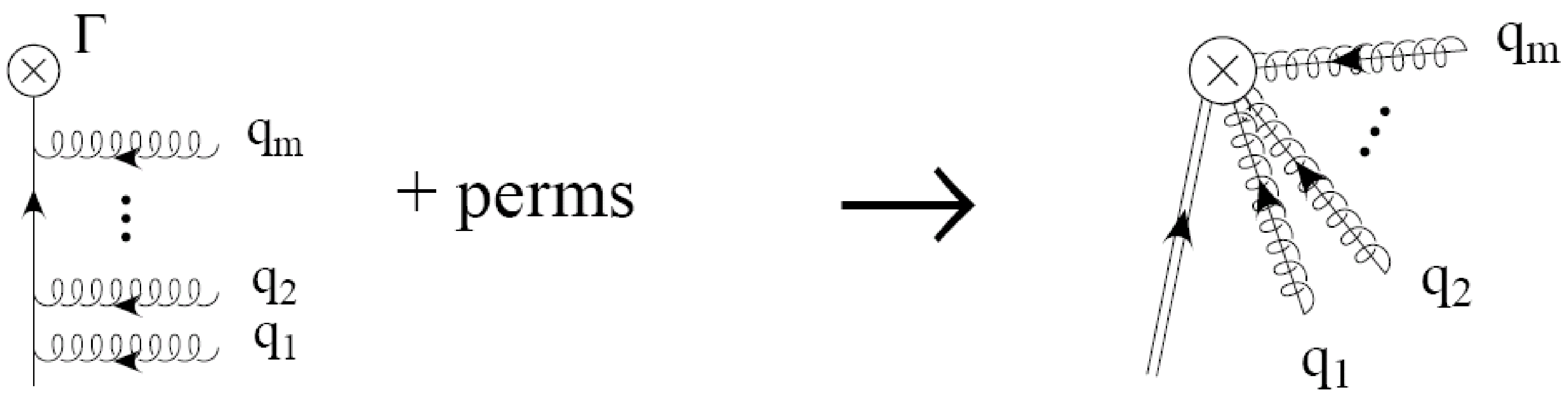
$$\zeta_J^{B\to M_1}(\tau, 0) = J(\tau,\omega,v) \otimes \Phi_B(\omega) \otimes \Phi_{M_1}(v)$$

Proof of factorization at soft-collinear-effective-theory

- In SCET, the light and fast-moving meson is described by collinear field. While the heavy mesons are described by the heavy quark field and soft field just as in the heavy-quark-effective-theory
- Interactions between heavy quark and collinear field can be summed as in the following figure

A matching calculation which shows how *SCET works*

- **On the left, collinear gluons hit an incoming soft heavy quark. Integrating out the off-shell quark propagators gives the effective theory operator on the right which contains a factor of W_c**



Proof of factorization at B_c decays

- **At the leading power of $1/m_b$,** the decay matrix element can be decomposed into the $B_c \rightarrow (c\bar{c})$ **form factor** and a **convolution** of a **short distance coefficient**
- with the **light-cone wave function** of the emitted light meson:

$$\langle X(\bar{c}c)M|H_{eff}|\bar{B}_c\rangle = \phi_M(u) \otimes T(u) F^{B_c \to X}$$

$B_c \rightarrow$ *cc-bar* Form factors

The form factors for $B_c \to J/\psi$ and $B_c \to X(3872)$ (1^{++} state) transitions induced by the vector and axial-vector currents are defined by:

$$\langle J/\psi(P'', \varepsilon''^*)|V_\mu|B_c^-(P')\rangle = -\frac{1}{m_{B_c}+m_{J/\psi}}\epsilon_{\mu\nu\alpha\beta}\varepsilon''^{*\nu}P^\alpha q^\beta V^{PV}(q^2), \tag{5}$$

$$\begin{aligned}\langle J/\psi(P'', \varepsilon''^*)|A_\mu|B_c^-(P')\rangle &= i\{(m_{B_c}+m_{J/\psi})\varepsilon''^*_\mu A_1^{PV}(q^2) - \frac{\varepsilon''^*\cdot P}{m_{B_c}+m_{J/\psi}}P_\mu A_2^{PV}(q^2) \\ &\quad -2m_{J/\psi}\frac{\varepsilon''^*\cdot P}{q^2}q_\mu[A_3^{PV}(q^2) - A_0^{PV}(q^2)]\},\end{aligned} \tag{6}$$

$$\begin{aligned}\langle X(P'', \varepsilon'')|V_\mu|B_c^-(P')\rangle &= (m_{B_c}-m_X)\varepsilon^*_\mu V_1^{PA}(q^2) - \frac{\varepsilon^*\cdot P'}{m_{B_c}-m_X}P_\mu V_2^{PA}(q^2) \\ &\quad -2m_X\frac{\varepsilon^*\cdot P'}{q^2}q_\mu\left[V_3^{PA}(q^2) - V_0^{PA}(q^2)\right],\end{aligned} \tag{7}$$

$$\langle X(P'', \varepsilon'')|A_\mu|B_c^-(P')\rangle = -\frac{i}{m_{B_c}-m_X}\epsilon_{\mu\nu\rho\sigma}\varepsilon^{*\nu}P^\rho q^\sigma A^{PA}(q^2). \tag{8}$$

where $P = P' + P''$, $q = P' - P''$ and the convention $\epsilon_{0123} = 1$ is adopted.

Extraction of Form factors

- **Future Experimental semi-leptonic B_c decays**
- **Lattice QCD**
- **QCD sum rules and light-cone sum rules:**

  Y. M. Wang, CDL, arXiv:0707.4439 [hep-ph]
- **light-front quark model:**

  W. Wang, Y. L. Shen and CDL, EPJC 51:841,2007
- …

$B_c \to$ X,Y,Z *form factors* in light-cone sum rules

	decay modes	$f_+(0)$	$f_-(0)$
X,Y = $\mathbf{0}^{-+}$	$B_c \to \eta_c'$ ($^1s_0$)	$0.82^{+0.03+0.02+0.01+0.17}_{-0.01-0.02-0.01-0.19}$	0
	$B_c \to X(3940)(3^1S_0)$	$0.46^{+0.01+0.00+0.00+0.10}_{-0.01-0.01-0.01-0.11}$	0
0^{++}	$B_c \to \chi_{c0}'(2^3P_0)$	$2.6^{+0.1+0.0+0.0+0.2}_{-0.1-0.1-0.1-0.2}$	0

X,Y = 1^{++}, $\mathbf{1}^{+-}$	$A(0)$	$V_1(0)$	$V_2(0)$
$B_c \to X(3872)(2^3P_1)$	$-0.53^{+0.02+0.01+0.01+0.02}_{-0.03-0.00-0.00-0.02}$	$-3.76^{+0.12+0.05+0.02+0.01}_{-0.18-0.02-0.00-0.01}$	$-0.53^{+0.02+0.01+0.01+}_{-0.03-0.00-0.00-}$
$B_c \to X/Y(3940)(2^3P_1)$	$-0.51^{+0.02+0.01+0.01+0.02}_{-0.02-0.00-0.01-0.02}$	$-3.87^{+0.11+0.05+0.02+0.15}_{-0.19-0.03-0.02-0.15}$	$-0.51^{+0.02+0.01+0.01+}_{-0.02-0.00-0.01-}$
$B_c \to h_c(3527)(^1p_1)$	$0.28^{+0.01+0.01+0.01+0.01}_{-0.01-0.00-0.00-0.01}$	$1.51^{+0.04+0.04+0.02+0.06}_{-0.02-0.04-0.02-0.06}$	$0.28^{+0.01+0.01+0.01+0}_{-0.01-0.00-0.00-0}$

$B_c \to X,Y,Z$ *form factors* in light-cone sum rules

$Y = 1^{--}$

decay mode	$V(0)$	$A_1(0)$	$A_2(0)$
$B_c \to Y(4260)(3^3D_1)$	$4.1^{+0.1+0.7+0.4+0.3}_{-0.1-0.6-0.3-0.3}\times 10^{-2}$	$1.7^{+0.1+0.3+0.2+0.1}_{-0.0-0.3-0.1-0.1}\times 10^{-2}$	$4.1^{+0.1+0.7+0.4+0.3}_{-0.1-0.6-0.3-0.3}\times$
$B_c \to \psi(2^3S_1)$	$0.90^{+0.03+0.02+0.02+0.04}_{-0.02-0.03-0.02-0.05}$	$0.38^{+0.01+0.01+0.00+0.02}_{-0.01-0.02-0.01-0.02}$	$0.90^{+0.03+0.02+0.02+0}_{-0.02-0.03-0.02-0}$
$B_c \to \psi(1^3D_1)$	$2.3^{+0.1+0.1+0.1+0.1}_{-0.0-0.2-0.1-0.1}\times 10^{-2}$	$1.0^{+0.0+0.1+0.1+0.0}_{-0.0-0.1-0.1-0.0}\times 10^{-2}$	$2.3^{+0.1+0.1+0.1+0.1}_{-0.0-0.2-0.1-0.1}\times$

$B_c \to X(3940)\ l\nu_l$ in light-cone sum rules

0^{-+}

$B_c \to X(3940)(3^1S_0)e\bar{\nu}_e$	$1.8^{+0.1+0.0+0.8+0.6}_{-0.1-0.1-0.9-0.7} \times 10^{-4}$
$B_c \to X(3940)(3^1S_0)\tau\bar{\nu}_\tau$	$5.0^{+0.4+0.0+2.1+1.7}_{-0.2-0.2-2.4-2.0} \times 10^{-6}$

More than 1 order of magnitude difference between the two kinds of quantum number assignments

1^{++}

$B_c \to X/Y(3940)(2^3P_1)e\bar{\nu}_e$	$6.1^{+0.5+0.1+0.3+2.1}_{-0.3-0.2-0.3-2.4} \times 10^{-3}$
$B_c \to X/Y(3940)(2^3P_1)\tau\bar{\nu}_\tau$	$2.3^{+0.2+0.0+0.2+0.8}_{-0.2-0.0-0.2-0.9} \times 10^{-4}$

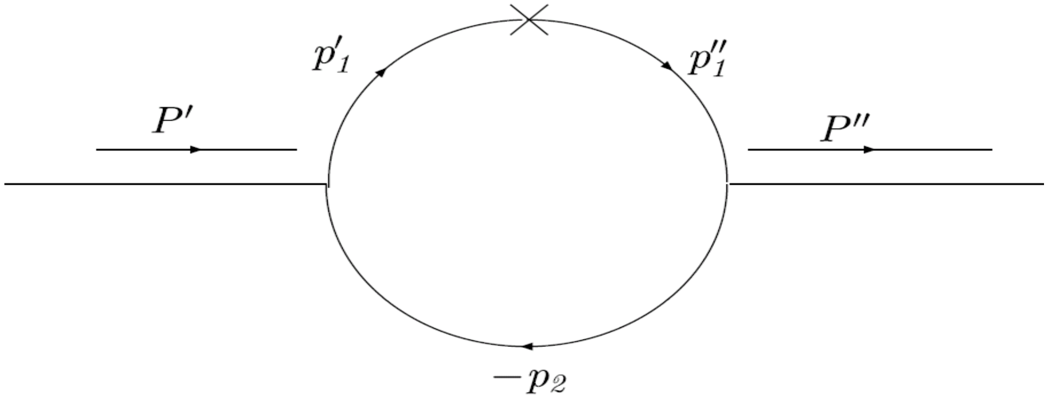
Form factor calculation in light front quark model

- **To calculate the amplitude for the transition form factor, we need the following Feynman rules for the meson-quark-antiquark vertices**

$$i\Gamma'_P = H'_P\gamma_5, \quad \text{Pseudoscalar}$$

$$i\Gamma'_V = iH'_V[\gamma_\mu - \frac{1}{W'_V}(p'_1 - p_2)_\mu], \quad \text{Vector}$$

$$i\Gamma'_A = -H'_A[\gamma_\mu + \frac{1}{W'_A}(p'_1 - p_2)_\mu]\gamma_5 \quad \text{Axial} - \text{vector}$$



- **In light-front quark model, the transition amplitude can be expressed as the convolution of the wave functions**

$$\mathcal{B}_\mu^{PV} = -i^3 \frac{N_c}{(2\pi)^4} \int d^4 p_1' \frac{H_P'(iH_V'')}{N_1' N_1'' N_2} S_{\mu\nu}^{PV} \, \varepsilon''^{*\nu}, \qquad ($$

where $N_1'^{(\prime\prime)} = p_1'^{(\prime\prime)2} - m_1'^{(\prime\prime)2} + i\epsilon$, $N_2 = p_2^2 - m_2^2 + i\epsilon$ and

$$\begin{aligned} S_{\mu\nu}^{PV} &= (S_V^{PV} - S_A^{PV})_{\mu\nu} \\ &= \mathrm{Tr}\left[\left(\gamma_\nu - \frac{1}{W_V''}(p_1'' - p_2)_\nu\right)(\not p_1'' + m_1'')(\gamma_\mu - \gamma_\mu\gamma_5)(\not p_1' + m_1')\gamma_5(-\not p_2 + m_2)\right.\end{aligned}$$

$B_c \to X(3872)$ pi ($K^{(*)}$,rho) in light front quark model

X= 1^{++}

$$BR(B_c^- \to X(3872)\pi^-) = (1.7^{+0.7+0.1+0.4}_{-0.6-0.2-0.4}) \times 10^{-4}$$

$$BR(B_c^- \to X(3872)K^-) = (1.3^{+0.5+0.1+0.3}_{-0.5-0.2-0.3}) \times 10^{-5}$$

$$BR(B_c^- \to X(3872)\rho^-) = (4.1^{+1.6+0.3+0.1}_{-1.4-0.1-0.1}) \times 10^{-4}$$

$$BR(B_c^- \to X(3872)K^{*-}) = (2.4^{+0.9+0.2+0.5}_{-0.8-0.3-0.5}) \times 10^{-5}$$

X= 1^{--}

$$BR(B_c^- \to X(3872)\pi^-) = (1.4^{+0.6+0.0+0.4}_{-0.5-0.0-0.5}) \times 10^{-3}$$

$$BR(B_c^- \to X(3872)K^-) = (1.1^{+0.4+0.0+0.3}_{-0.4-0.0-0.4}) \times 10^{-4}$$

$$BR(B_c^- \to X(3872)\rho^-) = (3.5^{+1.4+0.0+1.1}_{-1.2-0.2-1.2}) \times 10^{-3}$$

$$BR(B_c^- \to X(3872)K^{*-}) = (2.0^{+0.8+0.0+0.6}_{-0.7-0.1-0.7}) \times 10^{-4}$$

Summary

- **The factorization tool is essential in hadronic B (B_c) decays**
- **We prove the factorization in $B_c \to X(c\bar{c})$ M decays**
- **We calculate the form factors using the light-front quark model and light cone sum rules**
- **There are large differences between the X,Y,Z production rates in B_c decays for different Lorentz structure**

Thank you!