Nonleptonic charmless B decays (and their search at LHCb)

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Introduction

B_c^+ ($\bar{b}c$) very interesting meson

- Only a few experimental features investigated up to now: mass, width, bounds on a few channel (J/ψ with 1 or 3 π, $D^{*+}\bar{D}^0\ldots$)
- Will be produced and studied at LHCb
- Shares dynamical features with the better known quarkonia, but different decays (only weak interaction and not strong interaction)
- Theoretical investigations on lifetime, decay constants, semileptonic form factors (OPE, sum rules, lattice...)

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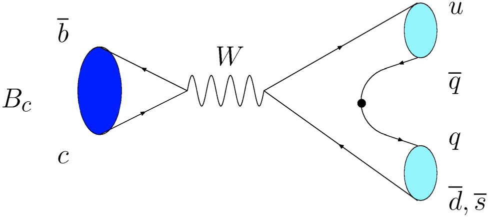
Less investigated: non-leptonic charmless decays into light mesons

- Pure annihilation processes, similar to $B_d \to K^+K^-$, $B_d \to D_s^- K^+$, $B_u \to D_s^- K^0$
- Sheds light on theoretical methods used to assess annihilation for other (non annihilation-dominated) non-leptonic modes
- Decays within the reach of LHCb

Non-leptonic charmless B_c decays

SDG, J. He, E. Kou, P. Robbe, arXiv:0907.2256 [hep-ph]



32 decay channels if lightest pseudoscalar and vector octets

	$S=1$	$S=0$
PP	$K^+\pi^0, K^+\eta, K^+\eta', K^0\pi^+$	$\pi^+\pi^0, \pi^+\eta, \pi^+\eta', K^+\bar{K}^0$
VV	$K^{*+}\rho^0, K^{*+}\phi, K^{*+}\omega, K^{*0}\rho^+$	$\rho^+\rho^0, \rho^+\phi, \rho^+\omega, K^{*+}\bar{K}^{*0}$
VP	$K^{*+}\pi^0, K^{*+}\eta, K^{*+}\eta', K^{*0}\pi^+$	$\rho^+\pi^0, \rho^+\eta, \rho^+\eta', K^{*+}\bar{K}^0$
	$\rho^0K^+, \phi K^+, \omega K^+, \rho^+K^0$	$\rho^0\pi^+, \phi\pi^+, \omega\pi^+, \bar{K}^{*0}K^+$

Matrix element

$\langle h_1 h_2 | \mathcal{H}_{\text{eff}} | B_c \rangle$ with $\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} \left[V_{ud} V_{cb}^* \mathcal{O}^{\Delta S=0} + V_{us} V_{cb}^* \mathcal{O}^{\Delta S=1} \right]$
with current-current operators with following $SU(3)$ tensor structure

$$\begin{aligned} \mathcal{O}^{\Delta S=0} &= \bar{u}\gamma_\mu(1-\gamma_5)d\, \bar{c}\gamma^\mu(1-\gamma_5)b \qquad (Y, I, I_3) = (0, 1, 1) \\ \mathcal{O}^{\Delta S=1} &= \bar{u}\gamma_\mu(1-\gamma_5)s\, \bar{c}\gamma^\mu(1-\gamma_5)b \qquad (Y, I, I_3) = (0, 1/2, 1/2) \end{aligned}$$

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Wigner-Eckart th: all decay amplitudes in terms of 3 reduced matrix elts

- $S = \langle 8_S || \mathcal{O}^8 || 1 \rangle$ from symmetric product of the 2 octet mesons.
- $A = \langle 8_A || \mathcal{O}^8 || 1 \rangle$ from antisymmetric product
- $I = \langle 8_I || \mathcal{O}^8 || 1 \rangle$ from product of an octet and a singlet mesons

The values of the reduced matrix elements depend on $\mathcal{O}^{\Delta S=0}$ vs $\mathcal{O}^{\Delta S=1}$ and nature of final state (PP, VP or VV)

Symmetry properties of outgoing states

Wigner-Eckart theorem : compute Clebsch-Gordan coefficients for projection of given 8×8 and 8×1 final state onto octet operators

CG coeff = usual $SU(2)$ coeff $\times$ so-called isoscalar coeff

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Symmetry properties of wave function for out-going states

- PP (1 amplitude): wave function of final state symmetric, only S
- VP (1 amplitude): contributions from S and A
- VV (3 amplitudes):
  - wave function symmetric for S and D waves: S contributes
  - wave function antisymmetric for P wave: A contributes

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- *PP* (1 amplitude): wave function of final state symmetric, only *S*
- *VP* (1 amplitude): contributions from *S* and *A*
- *VV* (3 amplitudes):
  - wave function symmetric for *S* and *D* waves: *S* contributes
  - wave function antisymmetric for *P* wave: *A* contributes

If states with $\eta, \eta', \phi, \omega$, *I* involved each time *S* is

NB : Single-angle scheme for $\eta, \eta', \omega, \phi$ to get ideal mixing for vector and fair phenomenological description of pseudoscalars

PP modes

Mode	Amplitude	Mode	Amplitude
$K^+\pi^0$	$\sqrt{\frac{3}{10}}S^{PP}$	$\pi^+\pi^0$	0
$K^0\pi^+$	$\sqrt{\frac{3}{5}}S^{PP}$	$K^+\bar{K}^0$	$\sqrt{\frac{3}{5}}S^{PP}$
$K^+\eta$	$-\frac{2}{3\sqrt{5}}S^{PP}+\frac{\sqrt{2}}{3}I^{PP}$	$\pi^+\eta$	$\frac{4}{3\sqrt{5}}S^{PP}+\frac{\sqrt{2}}{3}I^{PP}$
$K^+\eta'$	$\frac{1}{3\sqrt{10}}S^{PP}+\frac{4}{3}I^{PP}$	$\pi^+\eta'$	$-\frac{1}{3}\sqrt{\frac{2}{5}}S^{PP}+\frac{4}{3}I^{PP}$

- Amplitudes must be multiplied by $G_F/\sqrt{2}$ and CKM factor $V_{uD}V_{cb}^*$
- Relation $A(B_c^+\to K^0\pi^+)=\sqrt{2}A(B_c^+\to K^+\pi^0)=\hat{\lambda}A(B_c^+\to K^+\bar{K}^0)$ with Cabibbo suppression $\hat{\lambda}=V_{us}/V_{ud}$.
- Similar results for *VP* and *PP* results

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- Similar results for VP and PP results

Knowing S,A,I for one type of mesons (PP, VP, VV) is enough to compute all amplitudes in $SU(3)$ limits

How to estimate these quantities ? 2 ways…

First way: Estimate from $B^0 \to K^+K^-$ (1)

Two pure annihilation known processes (annihil not negligible)

$$Br(B^0 \to K^+K^-) = (0.15^{+0.11}_{-0.10})\times 10^{-6}, Br(B^0 \to D_s^- K^+) = (3.9\pm 2.2)\times 10^-$$

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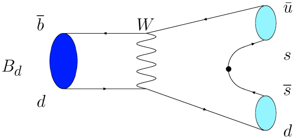

$$\frac{Br(B_c \to K^+\overline{K}^0)}{Br(B^0 \to K^+K^-)} \simeq \underbrace{\left(\frac{V_{cb}}{V_{ub}}\right)^2}_{\sim 100} \underbrace{\left(\frac{f_{B_c}}{f_B}\right)^2}_{\sim 4} \underbrace{\frac{\tau_{B_c}}{\tau_{B_d}}}_{\sim 0.3} \frac{1}{\xi^2}$$

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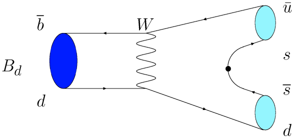

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ξ: fudge factor to take into account that

$B^0 \to K^+K^-$ with t-channel W vs $B_c \to K^+\overline{K}^0$ with s-channel

- One gluon exchange: $\xi = C_1/C_2 \simeq 4$
- Non perturbative effects: since $C_2 < C_1$, C_2 more sensitive than C_1 to nonperturbative effects, so that ξ closer to 1

First way: Estimate from $B^0 \to K^+K^-$ (2)

$$Br(B_c \to K^+\overline{K}^0) \simeq Br(B^0 \to K^+K^-)\frac{1.2 \times 10^2}{\xi^2} \gtrsim Br(B^0 \to K^+K^-) \times 7.5$$

- from $Br(B^0 \to K^+K^-)$, lower limit of $Br(B_c \to K^+\overline{K}^0) = O(10^{-6})$
- leading to $S^{PP} \gtrsim 0.085\ \mathrm{GeV}^3$ $[(PP) = (\overline{K}^0 K^+)]$
- Assume a (naive) dimensional estimate $|S^{PP}| \simeq \sqrt{2}|S^{PV}| \simeq |S_0^{VV}|$
- Use Zweig rule to determine the singlet contributions I
  $[Br(B_c^+ \to \phi\pi^+(\rho^+))$ very suppressed$]$

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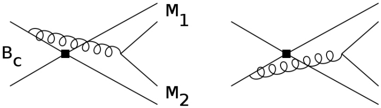
[B_d annihil] $\quad BR(\phi K^+) \simeq \mathcal{O}(10^{-7} - 10^{-8})$, $\quad BR(\bar{K}^{*0}K^+) \simeq \mathcal{O}(10^{-6})$
$BR(\bar{K}^0 K^+) \simeq \mathcal{O}(10^{-6})$, $\quad BR(\bar{K}^{*0}K^{*+}) \simeq \mathcal{O}(10^{-6})$

Second way: QCD factorisation (1)

QCD factorisation estimate for weak annihilation for B into light mesons (neglect all transverse momenta and take only one gluon exchange)



$$\langle h_1 h_2 | \mathcal{H}_{\rm eff} | B_c \rangle = i \frac{G_F}{\sqrt{2}} V_{cb}^* V_{ud(s)} f_{B_c} f_{h_1} f_{h_2} \frac{C_F}{N_C^2} C_2 A_i^1 (h_1 h_2)$$

$A_i^1 (h_1 h_2)$ convolution of kernel with twist-3 and -4 distrib ampl of mesons

$$A_i^1 = \pi \alpha_s \int dx\, dy \left\{ \phi_{M_1}(y) \phi_{M_2}(x) \left[\frac{1}{y[(\bar{x}+y)z_b - \bar{x}y]} - \frac{1}{\bar{x}[(\bar{x}+y)z_c - \bar{x}y]} \right] \right.$$
$$\left. + r^{M_1} r^{M_2} \phi_{m_1}(y) \phi_{m_2}(x) \left[\frac{2(1-z_b)}{(\bar{x}+y)z_b - \bar{x}y} - \frac{2(1-z_c)}{(\bar{x}+y)z_c - \bar{x}y} \right] \right\}$$

for M_1 and M_2 pseudoscalars (sign changes if M_1 and/or M_2 vectors)

Second way: QCD factorisation (2)

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- Asymptotic twist-3 and twist-4 distribution amplitudes, where y (x) part of long. momentum of M_1 (M_2) carried by valence quark
- Chiral enhancement factors for twist-4 pseudoscalar

$$r^\pi = \frac{2m_\pi^2}{m_b \times 2m_q} \qquad r^K = \frac{2m_K^2}{m_b(m_q+m_s)} \qquad \left(r^V = \frac{2m_V}{m_b}\frac{f_V^\perp}{f_V} \right)$$

- b and c-quark masses relative masses

$$z_b = \frac{m_b}{m_b+m_c} \qquad z_c = 1 - z_b = \frac{m_c}{m_b+m_c}$$

Second way: QCD factorisation (3)

A few differences in B_c decays compared to the $B_{u,d}$ decays

- B_c much simpler: only O_2 contributes, only CKM factor $V_{cb}^* V_{uD}$
- Recover QCD factorisation estimates for O_2 weak-annihilation in B_u decays when taking $z_c \to 0$, $z_b \to 1$)

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Can compute contribution and recast it into $SU(3)$ analysis

$$S^{VP} = 0.036\ \mathrm{GeV}^3 \quad S^{PP} = 0.021\ \mathrm{GeV}^3 \quad S_0^{VV} = 0.025\ \mathrm{GeV}^3$$

[One-gluon] $BR(\phi K^+) = 5 \times 10^{-9}$, $BR(\bar{K}^{*0} K^+) = 9.0 \times 10^{-8}$
$BR(\bar{K}^0 K^+) = 6.3 \times 10^{-8}$, $BR(\bar{K}^{*0} K^{*+}) = 9.1 \times 10^{-8}$

Comparison of the two methods

$$Br(B_c \to \bar{K}^{*0} K^+)_{QCDF} \sim 10^{-7} \qquad Br(B_c \to \bar{K}^{*0} K^+)_{B_d} \simeq 10^{-6}$$

- B_d annihilation
  - charm quark treated as light
  - takes into account some long-distance effects
  - very naive relation between matrix elements of O_1 and O_2, and between PP, VP and VV modes.
- QCD factorisation
  - charm quark treated as heavy
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Rather different estimates : QCDF one order below B_d annihilation

- In agreement with what is seen for pure annihilation $B_d \to K^+ K^-$
  $Br(B_d \to K^+ K^-)_{QCDF} \sim 10^{-8} \qquad Br(B_d \to K^+ K^-)_{B_d} \simeq 10^{-7}$
- Final-state interaction may increase significantly factorisation based estimates ($B \to K \chi_c$ and $D_s^+ \to \rho^0 \pi^+$)

Charmless nonleptonic B_c decays at LHCb

Which channel for LHCb ?

- all two-body PP final states contain one neutral particle
- LHCb has good efficiencies for charged K- and/or π-tags (when avoiding low-p_T neutral particles) at LHCb
- small width of ϕ and $\overline{K}^{*0}$ simplifies reconstruction

$$B_c^+ \to \phi K^+,\ \overline{K}^{*0} K^+,\ \overline{K}^0 \pi^+,\ \rho^0 K^+,\ \rho^0 \pi^+,\ \phi\pi^+$$
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$B_c^+ \to \overline{K}^{*0} K^+$ channel might be the best candidate

LHCb "analysis"

Theoretical estimate of the B_c cross section, dominated by gg-fusion

- $gg \to b\bar{b}$ followed by fragmentation (dominant at low-p_T)
- $\bar{b} \to B_c \bar{c}$ (dominant at large p_T)
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Such a study has been done for $B_c \to J/\psi\pi^+$

- From expected $Br(B_c \to J/\psi\pi^+) \simeq 1$ %, over 1000 events after one year run of LHCb
- scaling this observation to our process, $Br(B_c^+ \to \overline{K}^{*0} K^+) = 10^{-6}$ yields a few events per year at LHCb.

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Analysis of LHCb data may set first experimental limits
on some of these decays ($B_c \to \bar{K}^{*0}K^+$)
providing information on annihilation mechanisms at work

Back-up

Octet-singlet mixing

$\eta, \eta', \omega, \phi$ = mixtures of $SU(3)$ octet (η^8 or ω^8) and singlet (η^0 or ω^0)

$$|\eta^8\rangle, |\omega^8\rangle \propto |u\bar{u} + d\bar{d} - 2s\bar{s}\rangle/\sqrt{6} \qquad |\eta^0\rangle, |\omega^0\rangle \propto |u\bar{u} + d\bar{d} + s\bar{s}\rangle/\sqrt{3}$$

For our purpose (order of magnitudes), one-angle scheme

$$\begin{aligned} |\eta(\omega)\rangle &= \cos\theta_{p(v)}|\eta^8(\omega^8)\rangle + \sin\theta_{p(v)}|\eta^0(\omega^0)\rangle \\ |\eta'(\phi)\rangle &= -\sin\theta_{p(v)}|\eta^8(\omega^8)\rangle + \cos\theta_{p(v)}|\eta^0(\omega^0)\rangle \end{aligned}$$

(Simple) values for the angles: $\tan\theta_p = 1/(2\sqrt{2})$, $\qquad \tan\theta_v = \sqrt{2}$.

- Ideal mixing of vector meson

$$\omega = (u\bar{u} + d\bar{d})/\sqrt{2} \qquad \phi = s\bar{s}$$

- Non-ideal mixing of (η, η'), linked to the $U(1)_A$ anomaly, in broad agreement with phenomenology (e.g., J/ψ radiative decays)

$$\eta = (u\bar{u} + d\bar{d} - s\bar{s})/\sqrt{3} \qquad \eta' = (u\bar{u} + d\bar{d} + 2s\bar{s})/\sqrt{6}$$

VP modes: strange modes

Mode	Amplitude
$K^{+*}\pi^0$	$\frac{1}{2}\sqrt{\frac{3}{5}}S^{VP}+\frac{1}{2\sqrt{3}}A^{VP}$
ωK^+	$-\frac{1}{2\sqrt{15}}S^{VP}-\frac{1}{2\sqrt{3}}A^{VP}+\sqrt{\frac{2}{3}}I^{VP}$
$\rho^0 K^+$	$\frac{1}{2}\sqrt{\frac{3}{5}}S^{VP}-\frac{1}{2\sqrt{3}}A^{VP}$
ϕK^+	$\frac{1}{\sqrt{30}}S^{VP}+\frac{1}{\sqrt{6}}A^{VP}+\frac{1}{\sqrt{3}}I^{VP}$
$K^{*+}\eta$	$-\frac{1}{3}\sqrt{\frac{2}{5}}S^{VP}+\frac{\sqrt{2}}{3}A^{VP}+\frac{1}{3}I^{VP}$
$\rho^+ K^0$	$\sqrt{\frac{3}{10}}S^{VP}-\frac{1}{\sqrt{6}}A^{VP}$
$K^{*+}\eta'$	$\frac{1}{6\sqrt{5}}S^{VP}-\frac{1}{6}A^{VP}+\frac{2\sqrt{2}}{3}I^{VP}$
$K^{*0}\pi^+$	$\sqrt{\frac{3}{10}}S^{VP}+\frac{1}{\sqrt{6}}A^{VP}$

VP modes: non-strange modes

Mode	Amplitude	Mode	Amplitude
$\rho^+\pi^0$	$\frac{1}{\sqrt{3}}A^{VP}$	$\omega\pi^+$	$\frac{1}{\sqrt{15}}S^{VP}+\sqrt{\frac{2}{3}}I^{VP}$
$\rho^0\pi^+$	$-\frac{1}{\sqrt{3}}A^{VP}$	$\phi\pi^+$	$-\sqrt{\frac{2}{15}}S^{VP}+\frac{1}{\sqrt{3}}I^{VP}$
$\rho^+\eta$	$\frac{2}{3}\sqrt{\frac{2}{5}}S^{VP}+\frac{1}{3}I^{VP}$	$K^{*+}\bar{K}^0$	$\sqrt{\frac{3}{10}}S^{VP}-\frac{1}{\sqrt{6}}A^{VP}$
$\rho^+\eta'$	$-\frac{1}{3\sqrt{5}}S^{VP}+\frac{2\sqrt{2}}{3}I^{VP}$	$\bar{K}^{*0}K^+$	$\sqrt{\frac{3}{10}}S^{VP}+\frac{1}{\sqrt{6}}A^{VP}$

The previous tables yield the simple relations

$$\begin{aligned} A(B_c^+\to K^{*0}\pi^+) &= \sqrt{2}A(B_c^+\to K^{*+}\pi^0)=\hat{\lambda}A(B_c^+\to \bar{K}^{*0}K^+) \\ A(B_c^+\to \rho^+K^0) &= \sqrt{2}A(B_c^+\to \rho^0K^+)=\hat{\lambda}A(B_c^+\to K^{*+}\bar{K}^0) \end{aligned}$$

VV modes

- 3 configurations, labeled by (common) helicity of final mesons
- Weak inter left-handed and h conserved in high-energy QCD
  $\Longrightarrow$Longitudinal ampl ($h=0$) dominates transverse (linked to $h\pm 1$)

Mode	S, D Amplitudes	P Amplitude
$K^{*+}\rho^0$	$\sqrt{\frac{3}{10}}S^{VV}_{0,2}$	$\frac{1}{\sqrt{6}}A^{VV}_1$
$K^{*+}\omega$	$-\frac{1}{\sqrt{30}}S^{VV}_{0,2}+\frac{2}{\sqrt{3}}I^{VV}_{0,2}$	$-\frac{1}{\sqrt{6}}A^{VV}_1$
$K^{*+}\phi$	$\sqrt{\frac{1}{15}}S^{VV}_{0,2}+\sqrt{\frac{2}{3}}I^{VV}_{0,2}$	$\sqrt{\frac{2}{3}}A^{VV}_1$
$K^{*0}\rho^+$	$\sqrt{\frac{3}{5}}S^{VV}_{0,2}$	$\frac{1}{\sqrt{3}}A^{VV}_1$
$\rho^+\rho^0$	0	$\sqrt{\frac{2}{3}}A^{VV}_1$
$\rho^+\omega$	$\sqrt{\frac{2}{15}}S^{VV}_{0,2}+\frac{2}{\sqrt{3}}I^{VV}_{0,2}$	0
$\rho^+\phi$	$-\frac{2}{\sqrt{15}}S^{VV}_{0,2}+\sqrt{\frac{2}{3}}I^{VV}_{0,2}$	0
$K^{*+}\bar{K}^{*0}$	$\sqrt{\frac{3}{5}}S^{VV}_{0,2}$	$-\frac{1}{\sqrt{3}}A^{VV}_1$

distinguishing partial waves by $\ell=0,1,2$

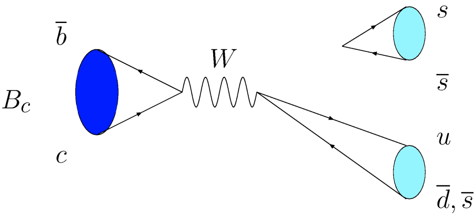
$$A(K^{*0}\rho^+)=\sqrt{2}A(K^{*+}\rho^0) \qquad \hat{\lambda}A(K^{*+}\bar{K}^0)=\sqrt{2}(-1)^\ell A(K^{*+}\rho^0)$$

Zweig rule (1)

S, A related to the 8×8, I to 1×8 in Wigner-Eckhart

Zweig rule for the $\Delta S = 0$ processes involving ϕ:

- $B_c^+ \to \phi\pi^+(\rho^+)$ from non-planar diagrams since $\phi = s\bar{s}$
- suppressed: at least three gluons perturbatively, $1/N_c$-suppressed



$$A(B_c^+ \to \phi\pi^+) = A(B_c^+ \to \phi\rho^+) = 0 \Longrightarrow I^{VP} = \sqrt{\frac{2}{5}} S^{VP}, I_{0,2}^{VV} = \sqrt{\frac{2}{5}} S_{0,2}^{VV}$$

In principle, possible also for η, η', but $1/N_c$-suppressed contrib related to anomaly can be large here

Zweig rule (2)

Mode	Amplitude
$K^{*+}\eta$	$\frac{\sqrt{2}}{3}A^{VP}$
$K^{*+}\eta'$	$\frac{3}{2\sqrt{5}}S^{VP} - \frac{1}{6}A^{VP}$
ωK^+	$\frac{1}{2}\sqrt{\frac{3}{5}}S^{VP} - \frac{1}{2\sqrt{3}}A^{VP}$
ϕK^+	$\sqrt{\frac{3}{10}}S^{VP} + \frac{1}{\sqrt{6}}A^{VP}$

Mode	Amplitude
$\rho^+\eta$	$\sqrt{\frac{2}{5}}S^{VP}$
$\rho^+\eta'$	$\frac{1}{\sqrt{5}}S^{VP}$
$\omega\pi^+$	$\sqrt{\frac{3}{5}}S^{VP}$
$\phi\pi^+$	0

$$A(B_c^+ \to \rho^+\eta) = \sqrt{2}A(B_c^+ \to \rho^+\eta')$$

Mode	S, D Amplitudes	P Amplitude
$K^{*+}\omega$	$\sqrt{\frac{3}{10}}S^{VV}_{0,2}$	$-\frac{1}{\sqrt{6}}A^{VV}_1$
$K^{*+}\phi$	$\sqrt{\frac{3}{5}}S^{VV}_{0,2}$	$\sqrt{\frac{2}{3}}A^{VV}_1$
$\rho^+\omega$	$\sqrt{\frac{6}{5}}S^{VV}_{0,2}$	0
$\rho^+\phi$	0	0

Identification with results from QCD factorisation

Expressions for all the decay channels if we identify S, I, A and the O_2 reduced coefficients $b_2(h_1, h_2) = \frac{C_F}{N_C^2} C_2 A_i^1(h_1 h_2)$.

$$\langle h_1 h_2 | \mathcal{H}_{\rm eff} | B_c \rangle = i \frac{G_F}{\sqrt{2}} V_{cb}^* V_{ud(s)} f_{B_c} f_{h_1} f_{h_2} b_2(h_1, h_2)$$

Beneke, Buchalla, Neubert and Sachrajda

- Take QCDf expressions for the decay amplitudes of B_u decay into relevant final state
- Pick up the O_2 contribution (only one remaining for B_c

$$S^{PP} = \sqrt{\frac{5}{3}} N_{PP} b_2(PP) \qquad I^{PP} = \sqrt{\frac{2}{3}} N_{PP} b_2(PP)$$

$$S^{VP} = \sqrt{\frac{5}{6}} N_{VP}(b_2(PV) + b_2(VP)) \qquad A^{VP} = \sqrt{\frac{3}{2}} N_{VP}(b_2(PV) - b_2(VP))$$

$$I^{VP} = \sqrt{\frac{1}{3}} N_{VP}(b_2(PV) + b_2(VP)) \qquad S^{VV}_{S,D} = \sqrt{\frac{5}{3}} N_{VV} b_2^{S,D}(VV)$$

B_c production at LHCb

- LHC pp collider large cross section for the $b\bar{b}$ hadro-production
- Some collisions (not many) produce B_c (less than 1%)
- LHCb experiment ideal to study it

Theoretical estimate of the B_c cross section, dominated by gg-fusion

- $gg \to b\bar{b}$ followed by fragmentation (dominant at low-p_T)
- $\bar{b} \to B_c \bar{c}$ (dominant at large p_T)

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$\mathcal{O}(\alpha_s^4)$ computation of the $\bar{b} \to B_c b\bar{c}$

- $\sigma(pp \to B_c^+ X) \simeq 0.3 - 0.8\ \mu b$ for LHCb
- error from theoretical inputs such as choice of the α_s scale and B_c distribution function
- additional systematics from higher-twist and radiative corrections ?

Take value for the cross section at LHCb $\sigma(B_c) = 0.4\ \mu\mathrm{b}$