Study of the $\bar{B}_q^* \to DM$ decays with perturbative QCD approach

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研究背景

- B_q^*和B_q（$b\bar{q}$,其中$q = u, d, s$），以前大家关注的都是B_q介子，对B_q^*介子研究很少。B_q的来源主要是$\Upsilon(4S)$和$\Upsilon(5S)$衰变首先产生B_q^*介子，B_q^*进而衰变得到B_q。
- $\Delta B = 0$, $m_{B_q^*} - m_{B_q} \lesssim 50$ MeV
  $\Delta B = 1$, $\tau_{B_q^*} \sim \mathcal{O}(10^{-17} s)$
  以电磁衰变为主导，也进行弱相互作用衰变
- 可以检验处理强子矩阵元的计算方法，也可以为重味物理提供一个平台、更多的研究对象。

研究现状

- 实验方面：

Table 1: 在$\Upsilon(5S)$共振态下产生B_q^*的事例数

	$B_{u,d}^*$	B_s^*
SuperKEKB($10ab^{-1}$)	3.3×10^9	1.2×10^9
LHC($1ab^{-1}$)	9.8×10^{13}	2.2×10^{13}

Ed.A.Bevan *et al*, Eur.Phys.J.C.74,3026

研究现状

- **理论方面：**
- Benjamin Grinstein 等人计算了$B^* \to \ell\bar{\nu}$,发现$B_u^{*-} \to \ell^-\bar{\nu}$的分支比为$0.6^{+0.3}_{-0.2} \times 10^{-9}$。
- 研究的B_q^*的两体非轻弱衰变主要是$b \to c$ 的过程。
- $B_q \to DM$唯象模型原则上适用于$B_q^* \to DM$。譬如微扰QCD, QCD因子化方法,软共线有效理论，等等。

B.Grinstein and J.Martin Camalich, Phys.Rev.Lett 116 141801(2016)

研究方法

- 有效哈密顿量
- 强子矩阵元
- 衰变振幅

有效哈密顿量

- $B_q^* \to DM$衰变过程的有效哈密顿量为：

$$
\begin{aligned}
\mathcal{H}_{eff} &= \frac{G_F}{\sqrt{2}} \sum_{q'=d,s} V_{cb} V_{uq'}^* \{C_1(\mu) Q_1(\mu) + C_2(\mu) Q_2(\mu)\} + H.c. \\
Q_1 &= [\bar{c}_\alpha \gamma_\mu (1-\gamma_5) b_\alpha][\bar{q}'_\beta \gamma^\mu (1-\gamma_5) u_\beta] \\
Q_2 &= [\bar{c}_\alpha \gamma_\mu (1-\gamma_5) b_\beta][\bar{q}'_\beta \gamma^\mu (1-\gamma_5) u_\alpha]
\end{aligned}
$$

$$V_{cb} V_{ud}^* = A\lambda^2 (1 - \lambda^2/2 - \lambda^4/8) + \mathcal{O}(\lambda^7)$$

$$V_{cb} V_{us}^* = A\lambda^3 + \mathcal{O}(\lambda^7)$$

强子矩阵元

- 不可避免涉及到多个能标，m_b,m_W,Λ_{QCD}，将四夸克算符强子矩阵元中包含的微扰和非微扰贡献进行有效的分离，目前采用基于硬散射方法将强子矩阵元写成硬散射核和强子波函数的卷积形式。衰变振幅即因子化为三部分。

$$A_i \propto \int \prod_j dx_j db_j C_i(t) \mathcal{H}_i(t_i, x_j, b_j) \Phi_j(x_j, b_j) e^{-S_j}$$

物理图像

- $\bar{B}_q^* \to D_q M(\mathrm{T})$

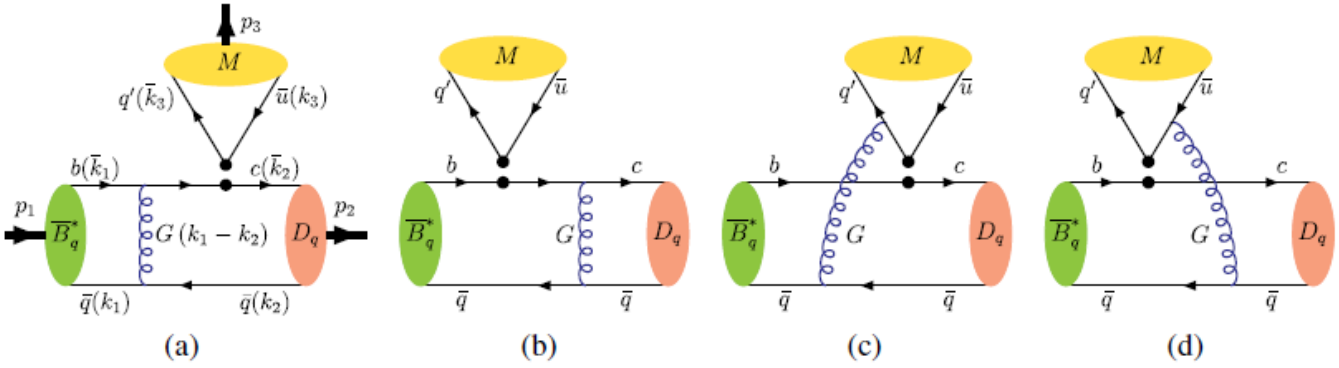

Figure 1: $\bar{B}_q^* \to D_q M$色允许图

物理图像

- $\bar{B}_q^* \to D^0 M_q(\mathrm{C})$

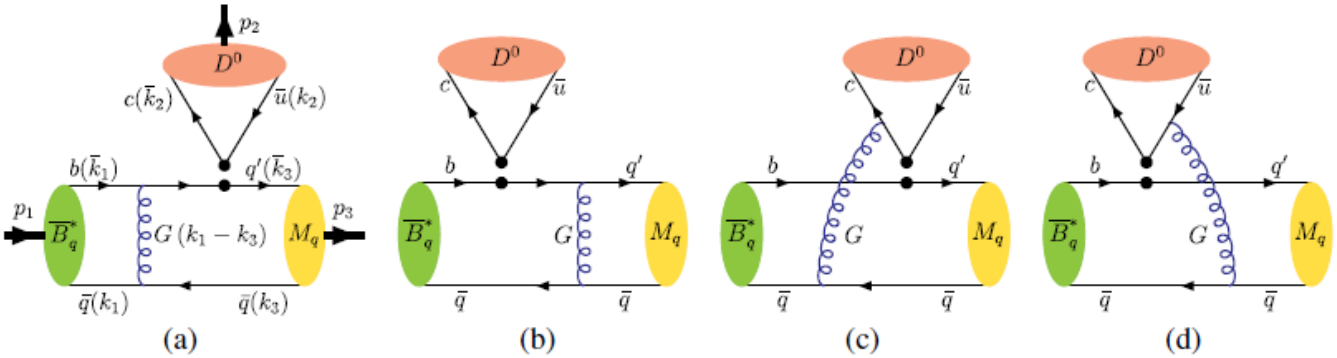

Figure 2: $\bar{B}_q^* \to D^0 M_q$色压低图

物理图像

- $\bar{B}_q^* \to DM(\mathrm{A})$

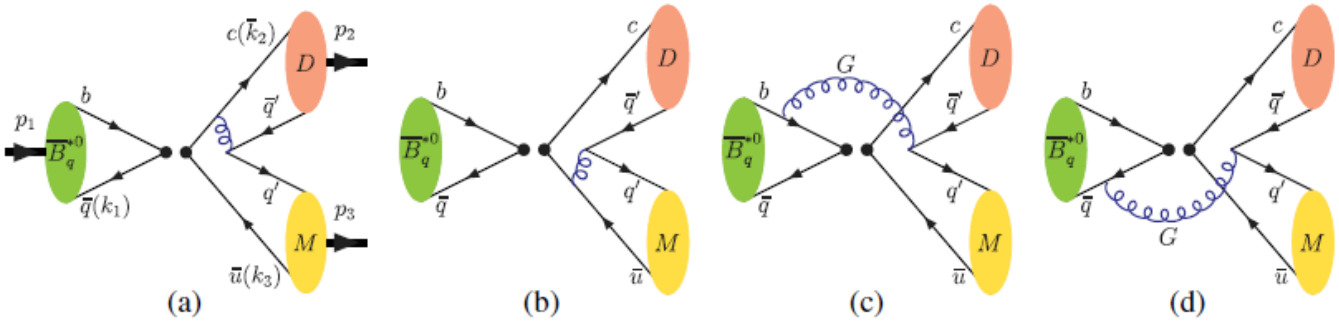

Figure 3: $\bar{B}_q^* \to DM$湮灭图

过程分析

Table 2: $B_q^* \to DP$

	过程	图像	CKM
1	$B_u^{*-} \to D^0\pi^-$	T、C	$V_{cb}V_{ud}^* \sim \lambda^2$(I)
2	$B_u^{*-} \to D^0K^-$	T、C	$V_{cb}V_{us}^* \sim \lambda^3$ (II)
3	$\bar{B}_d^{*0} \to D^+\pi^-$	T、A	$V_{cb}V_{ud}^* \sim \lambda^2$(I)
4	$\bar{B}_d^{*0} \to D^+K^-$	T	$V_{cb}V_{us}^* \sim \lambda^3$ (II)
5	$\bar{B}_d^{*0} \to D^0\pi^0$	C、A	$V_{cb}V_{ud}^* \sim \lambda^2$(I)
6	$\bar{B}_d^{*0} \to D^0\bar{K}^0$	C	$V_{cb}V_{us}^* \sim \lambda^3$(II)
7	$\bar{B}_d^{*0} \to D_s^+K^-$	A	$V_{cb}V_{ud}^* \sim \lambda^2$(I)
8	$\bar{B}_s^{*0} \to D_s^+\pi^-$	T	$V_{cb}V_{ud}^* \sim \lambda^2$ (I)
9	$\bar{B}_s^{*0} \to D_s^+K^-$	T	$V_{cb}V_{us}^* \sim \lambda^3$ (I)
10	$\bar{B}_s^{*0} \to D^+\pi^-$	A	$V_{cb}V_{us}^* \sim \lambda^3$ (II)
11	$\bar{B}_s^{*0} \to D^0\pi^0$	A	$V_{cb}V_{us}^* \sim \lambda^3$ (II)
12	$\bar{B}_s^{*0} \to D^0K^0$	C	$V_{cb}V_{ud}^* \sim \lambda^2$ (I)

波函数

$$\langle 0|\bar{q}_i(z)b_j(0)|\bar{B}^*_q(p,\epsilon^{\parallel})\rangle = \frac{f_{B^*_q}}{4}\int d^4k e^{-ik\cdot z}\{\not{\epsilon}^{\parallel}[m_{B^*_q}\Phi^v_{B^*_q}(k) - \not{p}\Phi^t_{B^*_q}(k)]\}_{ji}$$

$$\langle 0|\bar{q}_i(z)b_j(0)|\bar{B}^*_q(p,\epsilon^{\perp})\rangle = \frac{f_{B^*_q}}{4}\int d^4k e^{-ik\cdot z}\{\not{\epsilon}^{\perp}[m_{B^*_q}\Phi^V_{B^*_q}(k) - \not{p}\Phi^T_{B^*_q}(k)]\}_{ji}$$

$$\langle D_q(p)|\bar{c}_i(0)q_j(z)|0\rangle = i\frac{f_{D_q}}{4}\int d^4k e^{+ik\cdot z}\{\gamma_5[\not{p}\Phi^a_{D_q}(k) + m_{D_q}\Phi^p_{D_q}(k)]\}_{ji}$$

波函数

$$\langle P(p)|\bar{q}_i(0)q'_j(z)|0\rangle = \frac{1}{4}\int d^4k e^{+ik\cdot z}\{\gamma_5[\not{p}\Phi_P^a(k) + \mu_P\Phi_P^p(k) + \mu_P(\not{n}_+\not{n}_- - 1)\Phi_P^t(k)]\}_{ji}$$

$$\langle V(p,\epsilon^{\parallel})|\bar{q}_i(0)q'_j(z)|0\rangle = \frac{1}{4}\int d^4k e^{+ik\cdot z}\{\not{\epsilon}^{\parallel} m_V\Phi_V^v(k) + \not{\epsilon}^{\parallel}\not{p}\Phi_V^t(k) + m_V\Phi_V^s(k)\}_{ji}$$

$$\langle V(p,\epsilon^{\perp})|\bar{q}_i(0)q'_j(z)|0\rangle = \frac{1}{4}\int d^4k e^{+ik\cdot z}\{\not{\epsilon}^{\perp} m_V\Phi_V^V(k) + \not{\epsilon}^{\perp}\not{p}\Phi_V^T(k) + \frac{im_V}{p\cdot n_+}\gamma_5\varepsilon_{\mu\nu\alpha\beta}\gamma^{\mu}\epsilon^{\perp\nu}p^{\alpha}n_+^{\beta}\Phi_V^A(k)\}_{ji}$$

DAs

$$
\begin{aligned}
\Phi^{v,T}_{B^*_q}(x) &= Ax\bar{x}exp\Big\{-\frac{1}{8\omega^2_{B^*_q}}(\frac{m_q^2}{x}+\frac{m_b^2}{\bar{x}})\Big\} \\
\Phi^a_P(x) &= if_P 6x\bar{x}\sum_{i=0} a_i^P C_i^{3/2}(\xi) \\
\Phi^v_V(x) &= if_V 6x\bar{x}\sum_{i=0} a_i^{\|} C_i^{3/2}(\xi) \\
C_0^j(\xi) &= 1 \\
C_1^j(\xi) &= 2j\xi \\
C_2^j(\xi) &= 2j(j+1)\xi^2 - j
\end{aligned}
$$

其中$\omega_{B^*_q} \approx m_{B^*_q}\alpha_s(m_{B^*_q})$, $\xi = x - \bar{x} = 2x - 1$

衰变振幅表达式

- $\bar{B}_q^* \to DP$

$$\mathcal{A}(B_u^{*-} \to D_u^0 \pi^-) = \mathcal{F} V_{cb} V_{ud}^* \Big\{ \sum_i \mathcal{M}_{i,P}^T + \sum_j \mathcal{M}_{j,P}^C \Big\}$$

$$\mathcal{A}(\bar{B}_d^{*0} \to D_s^+ K^-) = \mathcal{F} V_{cb} V_{ud}^* \sum_i \mathcal{M}_{i,P}^A$$

$$\mathcal{F} = \frac{G_F}{\sqrt{2}} \frac{\pi C_F}{N_c} f_{B_q^*} f_D$$

$$\mathcal{M}_{a,P}^T = 2 m_1 p \int_0^1 dx_1 \int_0^1 dx_2 \int_0^\infty b_1 db_1 \int_0^\infty b_2 db_2 H_f^T(\alpha_T, \beta_a^T, b1, b2) E_f^T(t_a^T)$$
$$\times \alpha_s(t_a^T) a_1(t_a^T) \phi_{B_q^*}^v(x_1) \{ \phi_D^a(x_2)(m_1^2 \bar{x}_2 + m_3^2 x_2) + \phi_D^p(x_2) m_2 m_b \}$$

Jf.Sun,*et al* Phys Rev d96,036010(2017)

衰变振幅表达式

$$i\mathcal{A}_\lambda(B_u^{*-} \to D_u^0 \rho^-) = \mathcal{F} V_{cb} V_{ud}^* \Big\{ \sum_i \mathcal{M}_{i,\lambda}^T + \sum_j \mathcal{M}_{j,\lambda}^C \Big\}$$

$$\mathcal{A}_\lambda(B_q^* \to DV)$$

$$= \mathcal{A}_L(\epsilon_{B_q^*}^{\parallel}, \epsilon_V^{\parallel}) + \mathcal{A}_N(\epsilon_{B_q^*}^{\perp}, \epsilon_V^{\perp}) + i\mathcal{A}_T \varepsilon_{\mu\nu\alpha\beta} \epsilon_{B_q^*}^{\mu} \epsilon_V^{\nu} p_{B_q^*}^{\alpha} p_V^{\beta}$$

$$\mathcal{M}_{a,L}^T = \int_0^1 dx_1 \int_0^1 dx_2 \int_0^\infty b_1 db_1 \int_0^\infty b_2 db_2 H_f^T(\alpha_T, \beta_a^T, b1, b2) E_f^T(t_a^T) \alpha_s(t_a^T)$$
$$\times a_1(t_a^T) \phi_{B_q^*}^v(x_1) \{ \phi_D^a(x_2)(m_1^2 s \bar{x}_2 + m_3^2 t x_2) + \phi_D^p(x_2) m_2 m_b m_u \}$$

$$\mathcal{M}_{a,N}^T = m_1 m_3 \int_0^1 dx_1 \int_0^1 dx_2 \int_0^\infty b_1 db_1 \int_0^\infty b_2 db_2 H_f^T(\alpha_T, \beta_a^T, b1, b2)$$
$$\times E_f^T(t_a^T) \alpha_s(t_a^T) a_1(t_a^T) \phi_{B_q^*}^V(x_1) \phi_D^a(x_2)$$

输入参数

Table 3: $\bar{B}_q^* \to DP$衰变过程的输入参数

CKM parameter	$A = 0.811 \pm 0.026$	$\lambda = 0.22506 \pm 0.00050$
mass of the particles	$m_{\pi^\pm} = 139.57\text{MeV}$	$m_{K^\pm} = 493.677 \pm 0.016\text{MeV}$
$m_b = 4.78 \pm 0.06\text{GeV}$	$m_{\pi^0} = 134.98\text{MeV}$	$m_{K^0} = 497.611 \pm 0.013\text{MeV}$
$m_c = 1.67 \pm 0.07\text{GeV}$	$m_\rho = 775.26\text{MeV}$	$m_{K^{*0}} = 895.81 \pm 0.19\text{MeV}$
$m_s \simeq 0.51\text{GeV}$	$m_{K^{*\pm}} = 891.66 \pm 0.26\text{MeV}$	$m_{B_s^*} = 5415.4^{+1.8}_{-1.5}\text{MeV}$
$m_{u,d} \simeq 0.31\text{GeV}$	$m_{B^*_{u,d}} = 5324.65 \pm 0.25\text{MeV}$	$m_{D_s} = 1968.27 \pm 0.10\text{MeV}$
$---$	$m_{D_d} = 1869.58 \pm 0.09\text{MeV}$	$m_{D_u} = 1864.83 \pm 0.05\text{MeV}$
decay constant	$f_\pi = 130.2 \pm 1.7\text{MeV}$	$f_K = 155.6 \pm 0.4\text{MeV}$
$f_{K^*} = 220 \pm 5\text{MeV}$	$f^T_{K^*} = 185 \pm 10\text{MeV}$	$f_\rho = 216 \pm 3\text{MeV}$
$f^T_\rho = 165 \pm 9\text{MeV}$	$f_{D_s} = 249.0 \pm 1.2\text{MeV}$	$f_{D_{u,d}} = 211.9 \pm 1.1\text{MeV}$
$---$	$f_{B^*_{u,d}} = 175 \pm 6\text{MeV}$	$f_{B_s^*} = 213 \pm 7\text{MeV}$
Gegenbauer moment	$a_2^{\pi,K} = 0.25 \pm 0.15$	$a_2^{\parallel,\rho} = 0.15 \pm 0.07$
$a_1^K = -0.06 \pm 0.03$	$a_2^{\perp,\rho} = 0.14 \pm 0.06$	$a_1^{\parallel,K^*} = -0.03 \pm 0.02$
$a_2^{\parallel,K^*} = 0.11 \pm 0.09$	$a_1^{\perp,K^*} = -0.04 \pm 0.03$	$a_2^{\perp,K^*} = 0.10 \pm 0.08$

P.Ball and G.Jones,JHEP,0703,069

分支比公式

$$Br(B_q^* \to DP) = \sum_{Spin} \frac{1}{8\pi} \frac{p}{m_{B_q^*}\Gamma_{B_q^*}} |\mathcal{A}(B_q^* \to DP)|^2$$

$$Br(B_q^* \to DV) = \sum_{Spin} \frac{1}{8\pi} \frac{p}{m_{B_q^*}\Gamma_{B_q^*}} \{|H_0|^2 + |H_{\|}|^2 + |H_{\perp}|^2\}$$

$$H_0 = \mathcal{A}_L(\epsilon^{\|}_{B_q^*}, \epsilon^{\|}_V), \quad H_{\|} = \mathcal{A}_N(\epsilon^{\perp}_{B_q^*}, \epsilon^{\perp}_V), \quad H_{\perp} = \sqrt{2} m_{B_q^*} p \mathcal{A}_T$$

$$\Gamma_{B_u^*} \sim \Gamma(\bar{B}_u^* \to \bar{B}_u \gamma) \sim 450 eV$$

$$\Gamma_{B_d^*} \sim \Gamma(\bar{B}_d^* \to \bar{B}_d \gamma) \sim 150 eV$$

$$\Gamma_{B_s^*} \sim \Gamma(\bar{B}_s^* \to \bar{B}_s \gamma) \sim 100 eV$$

V.Simonis, Eur Phys J A 52,90(2016)

计算结果

Table 4: $\bar{B}_q^* \to DP$衰变过程的分支比

	衰变模式	类型	单位	数值
1	$B_u^{*-} \to D_u^0 \pi^-$	T-I	10^{-10}	$6.61^{+0.25+0.11+0.16}_{-0.92-0.79-0.69}$
2	$B_u^{*-} \to D_u^0 K^-$	T-II	10^{-11}	$5.38^{+1.97+0.05+0.55}_{-0.85-0.63-0.51}$
3	$\bar{B}_d^{*0} \to D_d^+ \pi^-$	T-I	10^{-9}	$2.22^{+0.52+0.02+0.27}_{-0.20-0.23-0.24}$
4	$\bar{B}_d^{*0} \to D_d^+ K^-$	T-II	10^{-10}	$1.69^{+0.38+0.01+0.15}_{-0.15-0.18-0.14}$
5	$\bar{B}_d^{*0} \to D_u^0 \pi^0$	C-I	10^{-12}	$4.04^{+3.19+0.38+1.32}_{-2.47-0.39-1.05}$
6	$\bar{B}_d^{*0} \to D_u^0 \bar{K}^0$	C-II	10^{-13}	$2.19^{+4.55+0.72+2.30}_{-0.44-0.51-1.40}$
7	$\bar{B}_d^{*0} \to D_s^+ K^-$	A-I	10^{-12}	$0.64^{+0.05+0.17+1.09}_{-0.04-0.16-0.42}$
8	$\bar{B}_s^{*0} \to D_s^+ \pi^-$	T-I	10^{-9}	$5.68^{+1.17+0.09+0.60}_{-0.46-0.50-0.56}$
9	$\bar{B}_s^{*0} \to D_s^+ K^-$	T-II	10^{-10}	$4.30^{+0.89+0.09+0.40}_{-0.35-0.37-0.38}$
10	$\bar{B}_s^{*0} \to D_d^+ \pi^-$	A-II	10^{-14}	$0.16^{+1.17+0.75+2.36}_{-0.02-0.15-0.08}$
11	$\bar{B}_s^{*0} \to D_u^0 \pi^0$	A-II	10^{-14}	$0.08^{+0.09+0.38+1.19}_{-0.01-0.08-0.04}$
12	$\bar{B}_s^{*0} \to D_u^0 K^0$	C-I	10^{-11}	$3.31^{+2.07+0.12+1.09}_{-1.88-0.24-0.77}$

计算结果

Table 5: $\bar{B}_q^* \to DV$衰变过程的分支比

	衰变模式	类型	单位	this work	QCDF
1	$B_u^{*-} \to D_u^0 \rho^-$	T-I	10^{-9}	$2.02^{+0.55+0.02+0.23}_{-0.23-0.22-0.21}$	
2	$B_u^{*-} \to D_u^0 K^{*-}$	T-II	10^{-10}	$1.14^{+0.32+0.01+0.16}_{-0.13-0.13-0.14}$	
3	$\bar{B}_d^{*0} \to D_d^+ \rho^-$	T-I	10^{-9}	$6.80^{+1.55+0.03+0.79}_{-0.60-0.66-0.72}$	$15.1^{+2.5}_{-2.4}$
4	$\bar{B}_d^{*0} \to D_d^+ K^{*-}$	T-II	10^{-10}	$3.87^{+0.87+0.01+0.51}_{-0.33-0.36-0.46}$	$8.7^{+1.5}_{-1.4}$
5	$\bar{B}_d^{*0} \to D_u^0 \rho^0$	C-I	10^{-11}	$2.55^{+1.26+0.15+0.57}_{-1.06-0.09-0.47}$	
6	$\bar{B}_d^{*0} \to D_u^0 \bar{K}^{*0}$	C-II	10^{-12}	$3.58^{+1.77+0.22+1.14}_{-1.52-0.16-0.89}$	
7	$\bar{B}_d^{*0} \to D_s^+ K^{*-}$	A-I	10^{-12}	$5.55^{+0.94+0.50+2.57}_{-0.46-0.48-1.68}$	
8	$\bar{B}_s^{*0} \to D_s^+ \rho^-$	T-I	10^{-8}	$1.72^{+0.35+0.03+0.19}_{-0.14-0.13-0.17}$	$2.89^{+0.48}_{-0.45}$
9	$\bar{B}_s^{*0} \to D_s^+ K^{*-}$	T-II	10^{-9}	$1.00^{+21+0.02+0.13}_{-0.08-0.09-0.12}$	$1.66^{+0.28}_{-0.27}$
10	$\bar{B}_s^{*0} \to D_d^+ \rho^-$	A-II	10^{-13}	$2.39^{+0.79+0.47+0.90}_{-31-0.20-0.53}$	
11	$\bar{B}_s^{*0} \to D_u^0 \rho^0$	A-II	10^{-13}	$1.19^{+0.40+0.24+0.45}_{-0.15-0.10-0.27}$	
12	$\bar{B}_s^{*0} \to D_u^0 K^{*0}$	C-I	10^{-10}	$1.69^{+0.67+0.07+0.51}_{-0.61-0.09-0.41}$	

Q.Chang,*et al* Eur Phys J C 76,523(2016)

讨论分析

- $Br(\bar{B}_q^* \to DM)$与$Br(\bar{B}_q \to DM)$相比至少小5个量级
- Br(T-I)> Br(C-I)> Br(A-I)

  Br(X-I)> Br(X-II),X=T,C,A
- $\frac{Br(\bar{B}_u^{*-} \to D_u^0 \pi^-)}{Br(\bar{B}_u^{*-} \to D_u^0 K^-)} \approx \frac{f_\pi^2}{\lambda^2 f_K^2}$, $\frac{Br(\bar{B}_u^{*-} \to D_u^0 \rho^-)}{Br(\bar{B}_u^{*-} \to D_u^0 K^{*-})} \approx \frac{f_\rho^2}{\lambda^2 f_{K^*}^2}$
- $Br(\bar{B}_q^* \to DV) > Br(\bar{B}_q^* \to DP)$
- $f_0 \approx 90\%, f_\parallel \approx 9\%, f_\perp \approx 1\%$
- $Br(\bar{B}_s^{*0} \to D_s^+ \rho^-)$分支比相对较大，$\mathcal{O}(10^{-8})$

谢谢大家！