非相对论量子色动力学(NRQCD)有效理论

Reporter : 卢俊良

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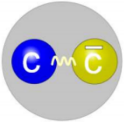

Table 1: Quarkonium energy scales

	$c\bar{c}$	$b\bar{b}$	$t\bar{t}$
M	1.5 GeV	4.7 GeV	180 GeV
Mv	0.9 GeV	1.5 GeV	16 GeV
Mv^2	0.5 GeV	0.5 GeV	1.5 GeV

$$\text{Charmonia:} \quad v^2/c^2 \sim 0.3$$

$$\text{Bottomonia:} \quad v^2/c^2 \sim 0.1$$

Introduction to the NRQCD factorization approach to heavy quarkonium #1

E. Braaten (Ohio State U.) (Nov, 1996)

Contribution to: 3rd International Workshop on Particle Physics Phenomenology • e-Print: hep-ph/9702225 [hep-ph]

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Outline

- M(表征重夸克的产生和湮灭),
- Mv (v在静止框架下，根据$\lambda = \frac{\hbar}{Mv}$，则$\frac{1}{Mv}$表征重夸克偶素的大小),
- Mv^2 (表征重夸克偶素相邻径向激发态或角动量激发态的能级差),

$M >> Mv >> Mv^2$

描述带有重夸克的拉矢量可写为:

$$\mathcal{L}_{QCD} = \mathcal{L}_{light} + \bar{\psi}(i\gamma^{\mu} D_{\mu} - M)\psi,$$

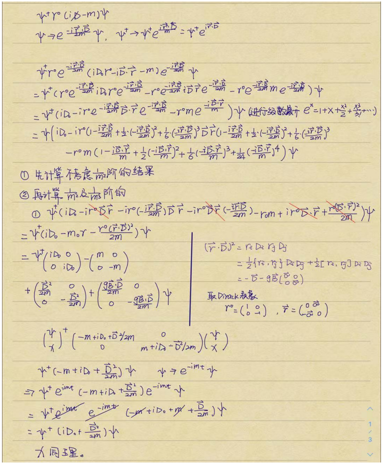
NRQCD可通过QCD的拉矢量做两步修改得到:

1.截断

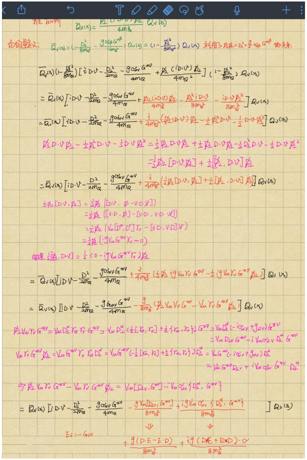
2.FWT变换

$$\mathcal{L}_{NRQCD} = \mathcal{L}_{light} + \mathcal{L}_{heavy} + \delta\mathcal{L},$$

$$\mathcal{L}_{light} = -\frac{1}{2} TrG_{\mu\nu} G^{\mu\nu} + \Sigma \bar{q} i \not{D} q,$$



$$\mathcal{L}_{heavy} = \psi^{+}(iD_0 + \frac{\mathbf{D}^2}{2M})\psi + \chi^{+}(iD_0 - \frac{\mathbf{D}^2}{2M})\chi,$$



$$
\begin{aligned}
\delta\mathcal{L} \;=\; & \frac{c_1}{8M^3}\psi^\dagger(\mathbf{D}^2)^2\psi \;+\; \frac{c_2}{8M^2}\psi^\dagger(\mathbf{D}\cdot g\mathbf{E} - g\mathbf{E}\cdot\mathbf{D})\psi \\
& + \frac{c_3}{8M^2}\psi^\dagger(i\mathbf{D}\times g\mathbf{E} - g\mathbf{E}\times i\mathbf{D})\cdot\boldsymbol{\sigma}\psi \;+\; \frac{c_4}{2M}\psi^\dagger(g\mathbf{B}\cdot\boldsymbol{\sigma})\psi \\
& + \text{charge conjugate terms,}
\end{aligned}
$$

Table 3: Estimates of the magnitudes of NRQCD operators for matrix elements between heavy-quarkonium states.

Operator	Estimate
ψ	$(Mv)^{3/2}$
χ	$(Mv)^{3/2}$
D_0 (acting on ψ or χ)	Mv^2
$\mathbf{D}$	Mv
$g\mathbf{E}$	M^2v^3
$g\mathbf{B}$	M^2v^4
gA_0 (in Coulomb gauge)	Mv^2
$g\mathbf{A}$ (in Coulomb gauge)	Mv^3

由场的归一化关系$\int d^3x\psi^+(x)\psi(x)=1$可得,$\psi^2\sim\int\frac{1}{d^3x}$, 又因为$\lambda=\frac{\hbar}{Mv}$,得到尺度大小$\sim\frac{1}{p}$,

即$\int d^3x\sim\frac{1}{p^3}$,因此$\psi^+(x)\psi(x)\sim p^3$,则$\psi\sim p^{3/2}\sim(Mv)^{3/2}$

$$\delta\mathcal{L}_{4-fermion} = \sum \frac{Im(f_n(\Lambda))}{M^{d_n-4}}\mathcal{O}_n(\Lambda)$$

$\mathcal{O}_n$是所有可能的四费米子算符，d_n是算符$\mathcal{O}_n$的量纲，M^{d_n-4}的引入保证f_n是无量纲的。

下面只给出S波和P波低阶（按照速度标度率）的几个算符的形式。对于S波，最低阶算符的量纲为六，四费米相互作用项为：

$$\begin{aligned}(\delta\mathcal{L}_{4-fermion})_{d=6} &= \frac{f_1(^1S_0)}{M^2}\mathcal{O}_1(^1S_0) + \frac{f_1(^3S_1)}{M^2}\mathcal{O}_1(^3S_1) \\ &+ \frac{f_8(^1S_0)}{M^2}\mathcal{O}_8(^1S_0) + \frac{f_8(^3S_1)}{M^2}\mathcal{O}_8(^3S_1)\end{aligned}$$

其中四费米算符用夸克场和反夸克场显式写出为：

$$\begin{aligned}\mathcal{O}_1(^1S_0) &= \psi^+\chi\chi^+\psi. \\ \mathcal{O}_1(^3S_1) &= \psi^+\boldsymbol{\sigma}\chi\cdot\chi^+\boldsymbol{\sigma}\psi. \\ \mathcal{O}_8(^1S_0) &= \psi^+\boldsymbol{T}^\alpha\chi\chi^+\boldsymbol{T}^\alpha\psi. \\ \mathcal{O}_8(^3S_1) &= \psi^+\boldsymbol{\sigma}\boldsymbol{T}^\alpha\chi\cdot\chi^+\boldsymbol{\sigma}\boldsymbol{T}^\alpha\psi.\end{aligned}$$

$$\begin{aligned}\Gamma(H \to LH) &= 2Im\langle H|\delta\mathcal{L}_{4-fermion}|H\rangle \\ &= \sum \frac{2Im(f_n(\Lambda))}{M^{d_n-4}}\langle H|\mathcal{O}_n(\Lambda)|H\rangle\end{aligned}$$

上式中，$|H\rangle$是指重夸克偶素，已经包含了所有的Fock态展开，而$|LH\rangle$是指一切可能的末态轻强子。$Im(f_n(\Lambda))$是短距离系数，可通过完整QCD和NRQCD衰变宽度匹配得到。长程矩阵元$\langle H|\mathcal{O}_n(\Lambda)|H\rangle$与具体过程无关，可以通过格点或者势模型计算。

对于S波重夸克偶素的衰变，例如J/ψ,主要贡献来自S波算符。因子化公式为：

$$\Gamma(J/\psi \to LH) = \frac{2Imf_1(^3S_1)}{m^2}\langle J/\psi|\mathcal{O}_1(^3S_1)|J/\psi\rangle$$

量纲为六的电磁相互作用的四费米算符为：

$$(\delta\mathcal{L}^{EM}_{4-fermion})_{d=6} = \frac{f_1(^1S_0)}{M^2}\psi^+\chi|0\rangle\langle 0|\chi^+\psi + \frac{f_1(^3S_1)}{M^2}\psi^+\boldsymbol{\sigma}\chi|0\rangle\langle 0|\chi^+\boldsymbol{\sigma}\psi \quad (2.17)$$

其中八重态算符如$\psi^+\boldsymbol{T}^a\chi|0\rangle\langle 0|\chi^+\boldsymbol{T}^a\psi$插入真空态后为0，因为重夸克偶素是色单态，真空态也是色单态，所以电磁衰变的有效拉氏量只包含色单态的算符。

量纲为八的电磁相互作用的四费米算符为

$$\begin{aligned}(\delta\mathcal{L}^{EM}_{4-fermion})_{d=8} &= \frac{f_{EM}(^3P_0)}{M^4}\frac{1}{3}\psi^+(-\frac{i}{2}\overleftrightarrow{\boldsymbol{D}})\cdot\boldsymbol{\sigma}\chi|0\rangle\langle 0|\chi^+(-\frac{i}{2}\overleftrightarrow{\boldsymbol{D}})\cdot\boldsymbol{\sigma}\psi \\ &+ \frac{f_{EM}(^3P_2)}{M^4}\psi^+(-\frac{i}{2}\overleftrightarrow{\boldsymbol{D}}^{(i}\sigma^{j)})\chi|0\rangle\langle 0|\chi^+(-\frac{i}{2}\overleftrightarrow{\boldsymbol{D}}^{(i}\sigma^{j)})\psi \\ &+ \frac{g_{EM}(^1S_0)}{M^4}\frac{1}{2}[\psi^+\chi|0\rangle\langle 0|\chi^+(-\frac{i}{2}\overleftrightarrow{\boldsymbol{D}})^2\psi + H.C.] \\ &+ \frac{g_{EM}(^3S_1)}{M^4}\frac{1}{2}[\psi^+\boldsymbol{\sigma}\chi|0\rangle\langle 0|\chi^+\boldsymbol{\sigma}(-\frac{i}{2}\overleftrightarrow{\boldsymbol{D}})^2\psi + H.C.] \\ &+ \cdots\end{aligned}$$

重夸克偶素H到电磁末态的衰变类似到轻强子的衰变，也可以因子化为：

$$\Gamma(H \to EM) = \sum \frac{2Im(f_{EM,n}(\Lambda))}{M^{d_n-4}} \langle H|\psi^+\mathcal{K}_n'\chi|0\rangle\langle 0|\chi^+\mathcal{K}_n\psi|H\rangle$$

其中$\mathcal{K}_n'$，$\mathcal{K}_n$是由单位色矩阵，自旋矩阵以及协变微商**D**的多项式和其他场产生

$$\mathcal{A}(Q\bar{Q} \to Q\bar{Q})|_{pert.QCD} = \sum_n \frac{2Im(f_n(\Lambda))}{M^{d_n-4}} \langle Q\bar{Q}|\mathcal{O}_n(\Lambda)|Q\bar{Q}\rangle \,|_{pert.NRQCD}$$

$O(\alpha_s v^2)$ correction to pseudoscalar quarkonium decay to two photons #1

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Abstract

We investigate the $\mathcal{O}(\alpha_s v^2)$ correction to the process of pseudoscalar quarkonium decay to two photons in nonrelativistic QCD (NRQCD) factorization framework. The short-distance coefficient associated with the relative-order v^2 NRQCD matrix element is determined to next-to-leading order in α_s through the perturbative matching procedure. Some technical subtleties encountered in calculating the $\mathcal{O}(\alpha_s)$ QCD amplitude are thoroughly addressed.

$$\Gamma[\eta_Q \to \gamma\gamma] = \frac{F(^1S_0)}{m^2}\left|\langle 0|\chi^\dagger\psi|\eta_Q\rangle\right|^2 + \frac{G(^1S_0)}{m^4}\mathrm{Re}\left\{\langle\eta_Q|\psi^\dagger\chi|0\rangle\langle 0|\chi^\dagger(-\tfrac{i}{2}\overleftrightarrow{\mathbf{D}})^2\psi|\eta_Q\rangle\right\}$$

标记η_Q和末态两光子的能动量分别为P、k_1、k_2，光子的极化矢量为ε_1、ε_2，则在$\eta_Q \to \gamma\gamma$的衰变振幅中，唯一可能的张量结构是$\mathcal{M} \sim \epsilon^{\mu\nu k_1 P}\varepsilon^*_{1\mu}\varepsilon^*_{2\nu}$，在$\eta_Q$的静止系，可利用下面关系：

$$\hat{\mathbf{k}}_1 \cdot \boldsymbol{\varepsilon}_1^* \times \boldsymbol{\varepsilon}_2^* = \frac{2}{M^2_{\eta_Q}}\epsilon^{\mu\nu\alpha\beta}P_\mu k_1\nu\varepsilon^*_{1\alpha}\varepsilon^*_{2\beta}.$$

其中$\hat{\mathbf{k}}_1 = \frac{\boldsymbol{k}_1}{|\boldsymbol{k}_1|}$，是$\boldsymbol{k}_1$方向上的单位矢量。因此在$\eta_Q$的静止系，衰变振幅正比于动力学不变量$\hat{\mathbf{k}}_1 \cdot \boldsymbol{\varepsilon}_1^* \times \boldsymbol{\varepsilon}_2^*$。

在振幅层次上进行NRQCD因子化和匹配，因此在NRQCD框架下，只需保留连接真空和自旋单态η_c的算符矩阵元，衰变振幅有如下的因子化公式：

$$\mathcal{M}[\eta_Q \to \gamma\gamma] = \hat{\mathbf{k}}_1 \cdot \boldsymbol{\varepsilon}_1^* \times \boldsymbol{\varepsilon}_2^*\left[c_0\langle 0|\chi^\dagger\psi|\eta_Q\rangle + \frac{c_2}{m^2}\langle 0|\chi^\dagger(-\tfrac{i}{2}\overleftrightarrow{\mathbf{D}})^2\psi|\eta_Q\rangle + \mathcal{O}(v^4)\right]$$

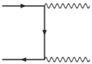
利用$\sum_{\rm Pol}\left|\hat{\mathbf{k}}_1\cdot\boldsymbol{\varepsilon}_1^*\times\boldsymbol{\varepsilon}_2^*\right|^2=2$，对末态光子极化矢量求和，乘以两体末态相空间，得到$\eta_Q\to\gamma\gamma$的衰变宽度：

$$\begin{aligned}\Gamma[\eta_Q\to\gamma\gamma] &= \frac{1}{2!}\int\frac{d^3k_1}{(2\pi)^3 2k_1^0}\frac{d^3k_2}{(2\pi)^3 2k_2^0}(2\pi)^4\delta^{(4)}(P-k_1-k_2)\sum|\mathcal{A}[\eta_Q\to\gamma\gamma]|^2\\ &= \frac{1}{8\pi}\left|c_0\langle 0|\chi^\dagger\psi|\eta_Q\rangle+\frac{c_2}{m^2}\langle 0|\chi^\dagger(-\tfrac{i}{2}\overleftrightarrow{\mathbf{D}})^2\psi|\eta_Q\rangle+\cdots\right|^2,\end{aligned}$$

$$\begin{aligned}F(^1S_0) &= \frac{m^2}{8\pi}|c_0|^2,\\ G(^1S_0) &= \frac{m^2}{4\pi}{\rm Re}[c_0c_2^*].\end{aligned}$$

$$\langle 0|\chi^\dagger\psi|Q\bar{Q}(^1S_0)\rangle=\sqrt{2N_c}\,(1+O(\alpha_s)),$$
$$\langle 0|\chi^\dagger(-\frac{i}{2}\overleftrightarrow{\mathbf{D}})^2\psi|Q\bar{Q}(^1S_0)\rangle=\sqrt{2N_c}\,\mathbf{q}^2\,(1+O(\alpha_s)),$$

$\sqrt{2N_c}$因子来自NRQCD中归一化态$Q\overline{Q}(^1S_0)$的自旋耦合和色因子。



a)

在完整QCD中，非相对论极限下的$Q\bar{Q}(^1S_0) \to \gamma(k_1,\varepsilon_1) + \gamma(k_2,\varepsilon_2)$的衰变振幅为：

$$\bar{v}(\bar{p}) T u(p) = \mathrm{Tr}\left[u(p)\bar{v}(\bar{p})T\right].$$

其中T是除去四分量旋量u, v外的旋量矩阵和色矩阵。

$$\begin{aligned}\Pi_1^{(1)}(p,\bar{p}) &= \sum_{s_1,s_2} u(p,s_1)\bar{v}(\bar{p},s_2)\langle\frac{1}{2},s_1;\frac{1}{2},s_2|00\rangle \otimes \frac{\mathbf{1}_c}{\sqrt{N_c}} \\ &= \frac{1}{8\sqrt{2}E^2(E+m)}(\not{p}+m)(\not{P}+2E)\gamma_5(\not{\bar{p}}-m) \otimes \frac{\mathbf{1}_c}{\sqrt{N_c}}\end{aligned}$$

其中$\mathbf{1}_c$ 是SU(3)群基础表示的单位矩阵，$\frac{1}{\sqrt{N_c}}$是色因子。

$$\mathcal{M}(Q\bar{Q}(^1S_0) \to \gamma\gamma)\,|_{FullQCD} = \mathrm{Tr}\left\{\Pi_1^{(1)}(p,\bar{p},\lambda)T\right\},$$

$$T^{(0)} = -ie^2e_Q^2\left[\not{\varepsilon}_2^*\frac{\not{p}-\not{k}_1+m}{-2p\cdot k_1}\not{\varepsilon}_1^* + \not{\varepsilon}_1^*\frac{-\not{\bar{p}}+\not{k}_1+m}{-2\bar{p}\cdot k_1}\not{\varepsilon}_2^*\right] \otimes \mathbf{1}_c$$

$$\mathcal{M}(Q\bar{Q}(^1S_0)\to\gamma\gamma)\,|_{q_4} = (e^2e_Q^2)\sqrt{N_c}\frac{m}{\sqrt{2}(E^4-(k_1\cdot q)^2)}\epsilon^{\mu\nu k_1 P}\varepsilon^*_{1\mu}\varepsilon^*_{2\nu}$$

$$= (e^2e_Q^2)\hat{\mathbf{k}}_1\cdot\boldsymbol{\varepsilon}_1^*\times\boldsymbol{\varepsilon}_2^*\sqrt{2N_c}\frac{mE^2}{(E^4-(k_1\cdot q)^2)}$$

$$\mathcal{M}[\eta_Q\to\gamma\gamma] = \hat{\mathbf{k}}_1\cdot\boldsymbol{\varepsilon}_1^*\times\boldsymbol{\varepsilon}_2^*\left[c_0\langle 0|\chi^\dagger\psi|\eta_Q\rangle+\frac{c_2}{m^2}\langle 0|\chi^\dagger(-\tfrac{i}{2}\overleftrightarrow{\mathbf{D}})^2\psi|\eta_Q\rangle+\mathcal{O}(v^4)\right]$$

$$\mathcal{M}[Q\bar{Q}(^1S_0)\to\gamma\gamma]\,|_{FullQCD}=\hat{\mathbf{k}}_1\cdot\boldsymbol{\varepsilon}_1^*\times\boldsymbol{\varepsilon}_2^*\left[\mathscr{A}_0+\frac{\boldsymbol{q}^2}{m^2}\mathscr{A}_2+O(\frac{\boldsymbol{q}^4}{m^4})\right]$$

$$\mathscr{A}_0^{(0)}=\sqrt{2N_c}\frac{4\pi e_Q^2\alpha}{m},$$

$$\mathscr{A}_2^{(0)}\Big|_{q_4\ \text{scheme}}=-\sqrt{2N_c}\frac{8\pi e_Q^2\alpha}{3m},$$

$$\mathbb{A}^{(0)}_{\text{NRQCD}}=\sqrt{2N_c}\left[c_0^{(0)}+c_2^{(0)}v^2+\cdots\right].$$

$$c_0^{(0)}=\frac{4\pi e_Q^2\alpha}{m},$$

$$c_2^{(0)}\Big|_{q_4\ \text{scheme}}=-\frac{8\pi e_Q^2\alpha}{3m},$$

- NRQCD的成功和挑战

A.理论值与实验值符合较好

B.相对于色单态而言，能很好解释其微分截面。

a.对于极化问题存在争议

b.矩阵元的选取

NRQCD框架下的χ_{cJ}衰变宽度的理论值与实验值的对比。

分支比	领头阶	次领头阶	PDG
$\frac{\Gamma(\chi_{c0}\to\gamma\gamma)}{\Gamma(\chi_{c2}\to\gamma\gamma)}$	3.75	5.43	4.43 ± 0.99
$\frac{\Gamma(\chi_{c0}\to LH)-\Gamma(\chi_{c1}\to LH)}{\Gamma(\chi_{c0}\to\gamma\gamma)}$	1300	2781	3600 ± 700
$\frac{\Gamma(\chi_{c2}\to LH)-\Gamma(\chi_{c1}\to LH)}{\Gamma(\chi_{c0}\to\gamma\gamma)}$	347	383	410 ± 100
$\frac{\Gamma(\chi_{c0}\to LH)-\Gamma(\chi_{c1}\to LH)}{\Gamma(\chi_{c2}\to LH)-\Gamma(\chi_{c1}\to LH)}$	3.75	7.63	8.9 ± 0.1
$\frac{\Gamma(\chi_{c0}\to LH)-\Gamma(\chi_{c2}\to LH)}{\Gamma(\chi_{c2}\to LH)-\Gamma(\chi_{c1}\to LH)}$	2.75	6.63	7.9 ± 1.5

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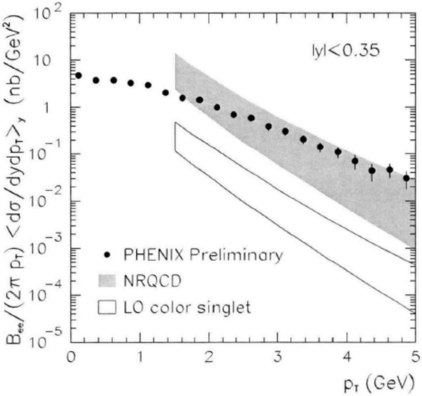
C. L. da Silva et al. [PHENIX Collaboration], Nucl. Phys. A **830**, 227 (2009).



: J/ψ在质心系能量$\sqrt{s} = 200Gev$下的pp对撞机上的微分截面。

Next-to-leading order QCD calculation of B_c to charmonium tensor form factors #1

Wei Tao (Nanjing Normal U.), Zhen-Jun Xiao (Nanjing Normal U.), Ruilin Zhu (Nanjing Normal U.) (Apr 13, 2022)

e-Print: 2204.06385 [hep-ph]

pdf cite 1 citation

Scrutinizing New Physics in Semi-leptonic $B_c \to J/\psi\tau\nu$ Decay #2

Ru-Ying Tang (Beijing, Inst. High Energy Phys. and Beijing, GUCAS), Zhuo-Ran Huang (APCTP, Pohang), Cai-Dian Lü (Beijing, Inst. High Energy Phys. and Beijing, GUCAS), Ruilin Zhu (Nanjing Normal U.) (Apr 8, 2022)

e-Print: 2204.04357 [hep-ph]

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Relativistic corrections to the form factors of B_c into S-wave Charmonium #1

Ruilin Zhu (Nanjing Normal U.), Yan Ma (Nanjing Normal U.), Xin-Ling Han (Nanjing Normal U.), Zhen-Jun Xiao (Nanjing Normal U.) (Mar 10, 2017)

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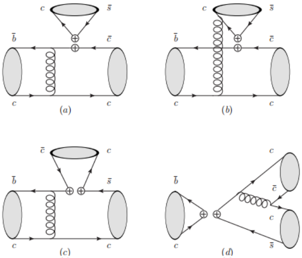

FIG. 2: Typical Feynman diagrams for $B_c^+ \to J/\psi + D_s^{+(*)}$, where two "$\oplus$" denote four-fermion weak interaction operators. There are four types of topologies: (a) factorizable diagrams; (b)non-factorizable diagrams; (c)color-suppressed diagrams; (d) annihilation diagrams.

Based on the NRQCD framework, we can calculate the amplitudes in Fig. 2 and numerical results indicate that the factorizable diagrams dominate the contribution of the decay widths of $B_c^+ \to J/\psi + D_s^{+(*)}$, but colour-suppressed and annihilation topologies diagrams contribute less than 10 percent. The factorizable diagrams can be factorized into the form factor part and the $D_s^{(*)}$ decay constant part. Thus we can employ the results of NLO QCD and relativistic corrections to the form factors, and obtain more precise predictions.

TABLE II: Comparisons of the results of the decay ratios of $B_c \to J/\psi + D_s^{(*)}$ with data and other theoretical predictions.

$R_{D_s^+/\pi^+}$	$R_{D_s^{*+}/\pi^+}$	$R_{D_s^{*+}/D_s^+}$	$\Gamma_{\pm\pm}/\Gamma$	Refs.
3.8 ± 1.2	10.4 ± 3.5	$2.8^{+1.2}_{-0.9}$	0.38 ± 0.24	ATLAS[25]
2.90 ± 0.62	–	2.37 ± 0.57	0.52 ± 0.20	LHCb[24].
2.6	4.5	1.7	–	Potential model [32]
1.3	5.2	3.9	–	QCD SR[33]
2.0	5.7	2.9	–	RCQM[34]
2.2	–	–	–	BSW[35]
2.06 ± 0.86	–	3.01 ± 1.23	–	LFQM[17]
$3.45^{+0.49}_{-0.17}$	–	$2.54^{+0.07}_{-0.21}$	0.48 ± 0.04	PQCD[7]
–	–	–	0.410	RIQM[2]
$3.07^{+0.21+0.14}_{-0.38-0.13}$	$11.8^{+1.0+2.3}_{-1.4-0}$	$3.85^{+0.04+0.54}_{-0.02-0}$	$0.601^{+0.001+0.033}_{-0.001-0.040}$	NRQCD NLO+RC